Engineering Noise Control Software
with references to the 6th edition textbook

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Causal Systems

A companion to the textbook
"Engineering Noise Control", 6th Edn.
by D.A. Bies, C.H. Hansen, C.Q. Howard and K.L. Hansen

User's Guide for Engineering Noise Control Software

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Chapter 0

About this Software

Thank you for purchasing a license for the software, "ENC" for engineering noise control. The purpose of this software is to provide an easy way of numerically evaluating many of the equations and algorithms incorporated in the sixth edition of the book, Bies et al. (2024). It is essential that the software is used with the textbook as a reference so that the theoretical basis for the calculations can be understood. This software is intended purely as a calculation aid. It is not intended to produce report-ready documentation, although the screen can be copied using the "Print Screen" button your keyboard and pasted into an application such as Microsoft Word, Adobe Photoshop or Corel Photopaint. The graphs can then be cut and pasted into a document or if Microsoft Word is used, the image can be cropped to just include the graph. Using ENC can replace hours of tedious hand calculations and lead to a more efficient work environment. In addition to saving time, the advantage of the software is that the calculations are correct every time and there is no need for them to be checked by someone else.

The software provided with this manual can be used to solve all kinds of problems encountered in engineering noise control work, including most of the example problems provided on www.causalsystems.com. In many places, the topics covered in the textbook are extended in ENC. In these cases, full explanations are provided in this user manual.

The table of contents is the best way of working out where a specific calculation may be found.

0.1 Installation of the Single User Version on a PC

ENC takes up about 60 MBytes of disk space.

To install the software, download the ENC zip file from the link on the Causal Systems web site that you were provided when you purchased the software. Unzip the file and then double click on the file, "setup.exe". If an earlier version of ENC is installed on your system and this version has the same number before the decimal point (e.g. you have version 6.0 and are now installing version 6.1) the first time setup.exe is run, the existing version of ENC will be uninstalled from your computer. Versions with the version number before the decimal point different from the one you are installing will not be uninstalled (e.g. you have version 5.6 and are now installing version 5.7). After successful UNinstallation, please run setup.exe again. Keep clicking on "next" (usually 3 times) and then a window will popup titled “Welcome to the device driver installation wizard”. On this window click “next” and another window should popup titled “Completing the device driver installation wizard”. Click on “finish” in this window. Then you need to find the KEYLOK security installer window and click on “close” in that window. Sometimes this window is hiding behind the ENC installer window and you need to move the ENC installer window to one side to see the KEYLOK window. After clicking on “close” in the KEYLOK window, you can click on “finish” in the ENC installation window.

Note that during installation, the default directory chosen by ENC may not be the one you would like. There is no problem changing this during the setup procedure. After installation, you should be able to access the program immediately from the “Start” menu of your computer. It is called “ENC”.

PLEASE READ THE FOLLOWING PARAGRAPH IF ENC IS HAVING PROBLEMS FINDING THE DONGLE.

If ENC cannot find the dongle after installation, the most common problem is that installation was not completed properly, even though it seems like ENC has been installed (it is available to use and works fine but just cannot find the security dongle). During installation, it is important that the KEYLOK security Installer window is closed first and then “finish” is clicked in the ENC installer window last. Any other way of closing or exiting the ENC installation will result in the dongle not found problem. On some computers, the KEYLOK window is hiding behind the ENC installation window and the ENC window must be moved to the side to reveal the KEYLOK window. Unfortunately, Causal Systems does not have control over where the third party installation software locates the installation windows on your system.

0.1.1 Unusual Dongle Installation Problem

You should not usually need to read this section. It is only for situations where the incorrect dongle driver has been accidentally installed. If, after following all the steps in the previous section, the dongle is still not recognised by ENC, and you have a green dongle, then follow the steps listed below.

1. Run the ENC setup.exe program again and uninstall ENC.

2. Remove the USB dongle from your computer.

3. Run the setup.exe program a second time to install ENC and the dongle driver On some computers, the dongle installation window can hide behind the main installation window. After installation, it is important that you first close this hidden window (just move the main installation window aside) and then click on “finish” on the main installation window. If you click on X to exit, it is likely that you will get the "dongle not found" problem again when you run the software.

4. After installation is finished, insert the dongle into the USB port and let Windows automatically install it. If this does not happen, you need to do the following:

(a) For Windows 7 and 8 systems, go to <control panel><administrative tools><computer management><device manager> and you should see an entry for the USB dongle (you may have to double left click on the "USBKey" item).

    For Windows10 and Windows11 systems, click on "Settings" which is above the power off button. Click on "Devices", then click on "Device Manager" (or if that is not an item, type "device manager" in the search box). Scroll down to "USB" or "USBKey", then click on ">". Device manager can also be found by typing it into the Windows search box at the bottom left of your screen which can be activated by pressing the windows key on your keyboard.

(b) Right click on the "USB Dongle software protection device" and then click on "uninstall".

(c) Then insert the dongle again and let Windows find and install the driver which it will do.

5. ENC should now work. If it does not, then restart your computer and repeat step 4 above or try steps 6 to 8 below.

6. Repeat step 4(a)

7. Right click on the "USB Dongle software protection device", click on the tick box to remove the driver from the system and then click on "uninstall".

8. Run the "install.exe" file, choose the "KEYLOCK 2 (USB w/Driver)" option and the installation type, "Standalone". Then click on "Begin Install" and follow the prompts. The "install.exe" file for the KEYLOCK dongle is available from the Causal Systems web site <www.causalsystems.com> on the "Installation Tips" page under item 3.

9. Repeat step 4(c) above.

10. If the preceding steps do not work, repeat the above but click "cancel" when the ENC installation asks you to install the dongle driver. Then repeat steps 8 and 9 above.

0.2 Installation of the Network Version

If you have a red network dongle, then please follow the instructions below. If more information is required, please visit www.causalsystems.com and click on "Installation tips" in the left hand menu. Scroll down to item 5 and download the file, "ENCusbnet_dongle.pdf".

To install the software, download the ENC zip file from the link on the Causal Systems web site that you were provided when you purchased the software, and then unzip the file. Note the following 3 important points.

1. Please do not attach the ENC USB Network dongle to the computer before and while you are installing ENC Server.

2. Read all steps below before installation.

3. ENC responds quite slowly during its search for the dongle if you don't have a USB dongle and/or network connected.

0.2.1 ENC Server Installation

1. Any computer can act as a server computer provided that it is always switched on and connected to the same network as the client computers.

2. Install ENC6.X software by running setup.exe on the ENC server computer.

3. Install the USB driver by running InstDrv_32bit.exe (for the 32 bit system) or InstDrv_64bit.exe (for the 64 bit system) under the ENC6.X/tools directory, and then tick "install USB driver".

4. Setup the configuration files svrcfg.ini and clicfg.ini under the ENC6.X/tools directory with a text editor or by running ENCConfig.exe (only if the server is a 32 bit system) under ENC6.X/tools. If using TCPIP protocol, the critical item to fill in here is the IP address of the server (by clicking the Client Tab and filling the Search list under the TCP/UDP panel). This can be found by running the system program, cmd.exe and typing in ipconfig.

5. Plug the ENC USB Network Dongle into the USB port of the ENC server machine. When you do this the only indication that the program has run will be the appearance of a small icon, which looks like a server, at the right bottom of screen, where you can click the "find key" to see whether the dongle can be found.

6. Copy the new configured clicfg.ini under ENC4.X/tools to ENC4.X folder of the ENC server.

7. Now ENC6.exe on the ENC server can be run.

8. If you encounter any problems, please visit www.causalsystems.com, click on "Installation tips" in the left hand menu and read items 5 and 6.

0.2.2 ENC Client Installation

1. Install the ENC6.X software by running setup.exe on all ENC Client computers.

2. Copy the new configured clicfg.ini under ENC6.X/tools from the ENC Server to the ENC6.X folder of each ENC Client.

3. Now ENC6.exe on ENC Client computers can be run.

0.3 Installation Problems

If either the single user or network version of ENC does not seem to be installing properly, please visit www.causalsystems.com and click “Installation tips” on the main menu on the left hand side of the screen.

0.4 General Guidelines for Use (Essential Reading)

NOTE THAT MANY CALCULATIONS USE THE DENSITY OF THE GAS AND SPEED OF SOUND IN THE GAS (USUALLY AIR) AS PART OF THE CALCULATION. VALUES FOR THESE QUANTITIES ARE SET IN THE TOOLS MENU (SEE BELOW). YOU MUST SET THESE VALUES CORRECTLY TO GET CORRECT RESULTS. DEFAULT VALUES ARE 1.206 kg/m^3 and 342.9 m/s RESPECTIVELY.

Another important item to note is that ENC ALWAYS uses the correction $10\log_{10}(\rho c/400)$ when calculating sound power level from sound pressure level and vice versa and the “Constants” button can be used to adjust the default values of any physical constants used in calculations. The text book sometimes ignores this correction as it is often only between 0.1 and 0.2 dB at room temperature in air.

Graphical as well as numerical outputs are provided. Numerical data can be stored on file for later access and plotting by a spreadsheet program such as excel. A quicker way of getting a graph in your word processor document is to double left click on any graph in ENC and then you can paste it into any application.

Alternatively the graphs and other on-screen results presented by the software can be printed directly and any part of the screen can be imported into a word processor by importing it first into Corel PhotoPaint. This is done by pressing the “print screen” key on your keyboard (sometimes requires pressing the “shift” key as well). Then in PhotoPaint click on “file”, then “new from clipboard”. Then select the part of the screen you would like to import and click on “edit” followed by “copy visible”. Then paste it into your document. The result is of good quality and suitable for a report. All graphics in this manual were produced in this way. If Microsoft photoeditor is used, the results obtained are of marginal quality. However, Adobe Photoshop should also be suitable.

Many of the calculations give a new result immediately any input data value is changed. However, more complex calculations and especially those involving the production of charts, require that you click on the “run” icon in the tool bar (or choosing the “run” option from the main menu) after you have changed all the input values to those wanted for the particular problem.

When a variable is labelled in blue type, that means it is a calculation result and should not be typed over. You can change the result by typing in a new value but it will not be valid, as it will not be reflected by the input data values. If you do make the mistake of typing in a box corresponding to a result, you can rectify the problem by changing one of the input values and/or clicking on the “run” symbol in the tool bar menu.

There are many places where some input data are redundant. In these cases, when you change one data entry, another may change to remain consistent with the others. For example, if you enter the percent open area and hole diameter for a perforated panel, the number of holes is defined and need not be entered. If you enter the number of holes as well, then one of the other items of input data will change.

When you enter a number in a data box and press “enter” or “run”, you may see the number of decimal places truncated in your input data. However, do not worry: ENC will use the accurate number you typed in for any calculations.

0.5 Saving Your Window and Input Data

At the very top of the screen is the software name, “ENC” which is short for “Engineering Noise Control Design” followed by the module name, the page name and the name of the file currently open. Typically, this file contains the input data for what you see on the screen, if you have saved it. It is also the name of the file you may have opened to obtain the input data on the screen. This file can be one of the example files included with the software or one saved from a previous session. If you see the words “Untitled New”, then you currently have no file open.

When saving the input data corresponding to what you see on the screen, by clicking on the “Save” icon in the tool bar at the top of the screen or by clicking on <File> <Save as>, be careful when entering the file name. It is not allowed to click on an existing file name and just change some characters. This will result in overwriting the file that is already there. You must type the file name from scratch in full and you must not click on an existing file unless you want it to be overwritten.

If you wish to save data that you see plotted, then click on the “Save” button at the bottom of the graph. Both 1/1 octave and 1/3 octave band data will be written to a file that you can open later using Microsoft Excel or Word. Alternatively, in many parts of ENC, you can double left click on the graph and paste it directly into your word processor with a high quality result.

Where equation numbers are given in this user guide, they refer to equations in “Engineering Noise Control”, 6^{th} edn. by D.A. Bies, C.H. Hansen, C.Q. Howard and K.L. Hansen.

Note that in many cases there are restrictions on allowable input data. This is to avoid program crashes as much as possible. Input data in many cases can be typed directly in the data box or the increment arrows on the side of the data box can be used.

0.6 On-Line Help

Extensive on-line help can be activated by pressing F1 on your keyboard or clicking on help in the menu bar of ENC. Clicking on the first line in the help menu will open the pdf version of the user manual which can be navigated using bookmarks and the pdf search capability. To open the bookmarks list in Acrobat, click on the 5^{th} icon from the left in the top menu bar of the pdf (show/hide navigation panel) and then click on the bookmark tab.

0.6.1 Main Menu at Top of Screen

The menu is made up of the six items shown at right.

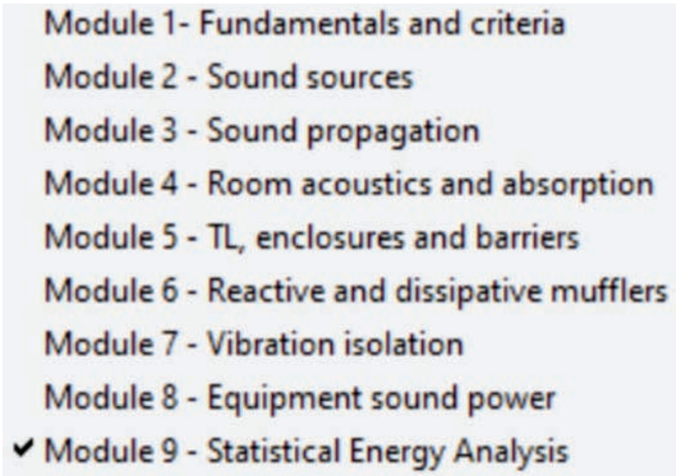
0.6.2 File Menu

The file menu is shown in the figure to the right and allows data for any window in any module to be saved (a .enc extension is necessary) and later retrieved using the "open" choice on the menu bar.

The name of the current file appears in the title bar right at the top of the ENC window. If this name is "Untitled New", then selecting "new" from the file menu will have no effect. However, if the current set up has been saved using a different file name, selecting "new" will allow you to start a new file based on the current setup.

It is often useful to have more than one ENC window open at one time so that calculations done in one module can be easily transferred to another and this is what the "launch ENC" button is for. If you need to do a calculation in another module for use in the current module, you can launch another ENC from within your existing ENC. You can then use the new ENC to do the calculation needed without upsetting the data already entered in the ENC that was being used originally. To do this, click the "launch ENC" button in the "file" menu at the top of the screen.

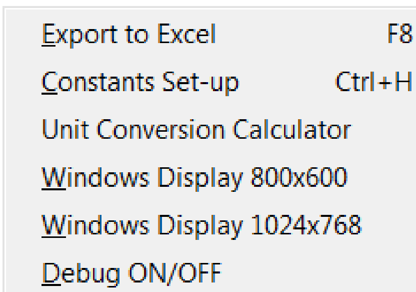
0.6.3 Options Menu



The options menu shown at right is used to select the module (from a choice of 9) that you want to work with.

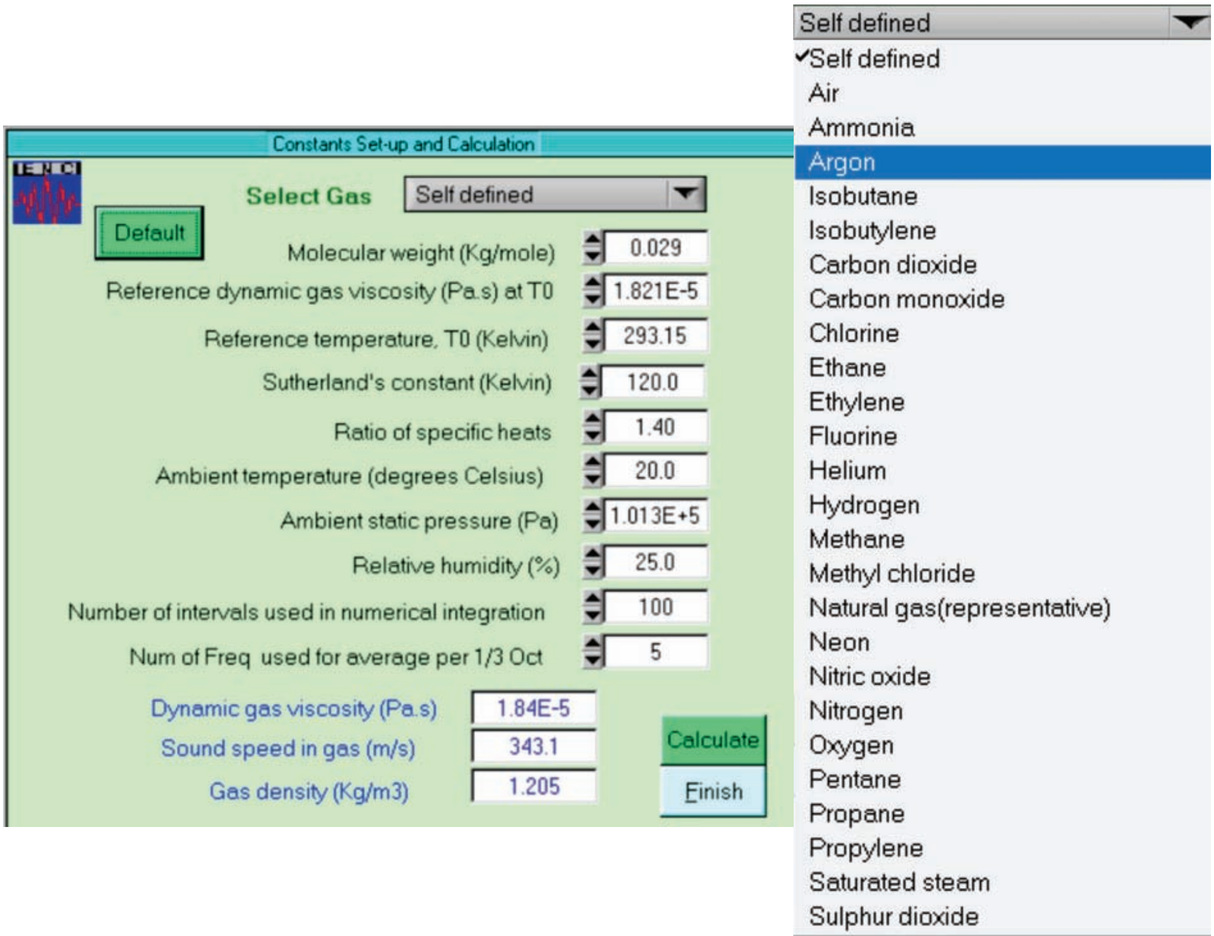
The "run" button on the main menu can be clicked on instead of the icon on the right of the tool bar to make sure that the results reflect new input data that you have entered.

0.6.4 Tools Menu



The "tools" menu at right includes a number of items. The first item, "Export to Excel", which is also activated by pressing the F8 key, allows most tables of values to be exported to Excel. Generally the table that is visible when the F8 key is pressed is the one that is exported to an .xls file.

The next item, "**C**onstants Set-up", allows adjustment of some physical constants such as the speed of sound and density of air, as illustrated in the following figure. Unfortunately there was an error in the viscosity calculations for ENC versions 5.7 to 6.2.



There are also many green "Constants" buttons that appear on most pages that you can click on to set up the constants values discussed below. When clicking on this item, the panel titled "Constants Set-up and Calculation" shown in the preceding figure appears. You can then type in the parameters that are appropriate for your problem. You can do this from any module or you can click on the "Constants" button on any page that you find it or you can key in [Cntrl]H from anywhere. All ENC calculations use the values in the "Constants Set-up and Calculation" window. The "speed of sound", "gas density" and "dynamic viscosity" are in blue font to indicate that they are calculated quantities. The speed of sound is calculated from the values you enter for molecular weight, ratio of specific heats and temperature of the gas in which the sound is travelling. The ENC default values are for air at 20°C and may be reinstated by clicking on the "Default" button in this window. To calculate the density of the gas in which the sound is travelling you need to enter the gas pressure (often but not always atmospheric) in addition to the other quantities mentioned above. Practically all calculations use the speed of sound and gas density data from this panel. To determine the speed of sound and gas density corresponding to the parameters you have selected, click on the "Calculate" button.

The reference dynamic gas viscosity is the one corresponding to the reference temperature (T0 Kelvin) for the gas you are using. The default value of the reference temperature for all gases in the table is 293.15K (or 20°C). As the dynamic gas viscosity is temperature dependent, the value appropriate to your calculation is determined using the following expression and the result shown in blue font in the third to last line of the pop-up window.

$$\mu = \mu_0 \frac{T_0 + C}{T + C} \left(\frac{T}{T_0}\right)^{1.5}$$

where μ is the dynamic gas viscosity at temperature T (Kelvin), μ_0 is the dynamic gas viscosity at temperature, T_0 (Kelvin) and C is Sutherland's constant that depends on the gas (see figure at right). The reference viscosity, μ_0, of all gases listed in the ENC "Constants Set-up" menu now corresponds to a reference temperature of $T_0 = 293.15$ K (or 20°C). The available gas types, together with their μ_0 and corresponding T_0 values, are listed in the table at right. Note that in ENC versions 5.7 to 6.2, the viscosity values on ENC must be multiplied by 10^{-10}, as the values in the table at right were mistakenly multiplied by 10^5 instead of 10^{-5}.

Gas	Viscosity (Pa s x 10^5) 20 deg C	Sutherland's constant (Kelvin)
Air	1.8205	120
Ammonia	0.99	370
Argon	2.23	114
Isobutane	0.73	336
Isobutylene	0.79	329
Carbon dioxide	1.47	240
Carbon monoxide	1.74	118
Chlorine	1.32	325
Ethane	0.919	287
Ethylene	1.03	259
Fluorine	2.28	129
Helium	1.96	79.4
Hydrogen	0.89	72
Methane	1.08	295
Methyl chloride	1.04	380
Natural gas (representat	1.59	198
Neon	3.13	56
Nitric oxide	1.89	128
Nitrogen	1.76	111
Oxygen	2.04	127
Pentane	0.66	128
Propane	0.8	341
Propylene	0.84	322
Saturated steam	0.97	1064
Sulphur dioxide	1.26	416

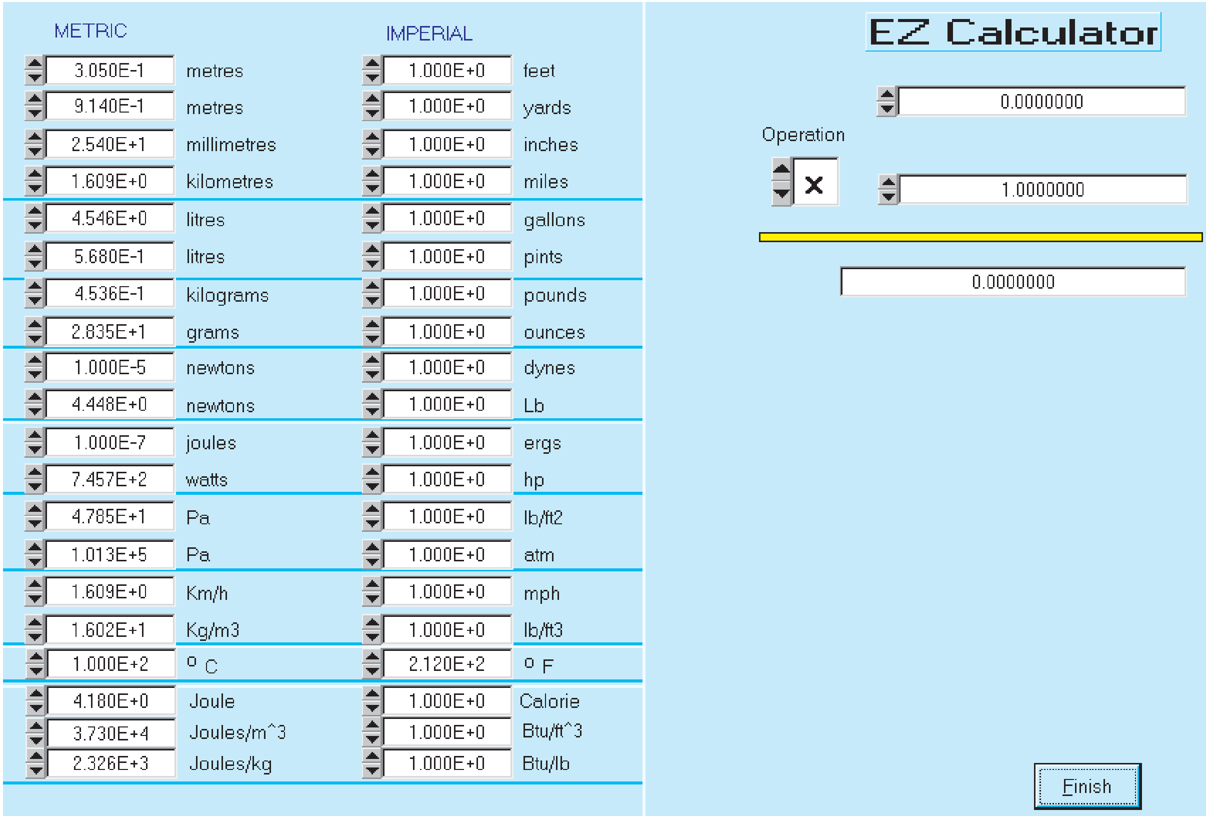
If you would like to use a different reference temperature and corresponding different viscosity for any gas, you can use the "self-defined" option.

Viscosity data are only used in modules 6 and 8, as well as in module 3, "Porous Material Absorber".

In module 8, the speed of sound in the ambient medium surrounding the sound source is assumed to be 343 m/s and the product of air density and speed of sound has been approximated as $\rho c = 400$. The relative humidity datum is only used in calculations involving outdoor sound propagation. In a number of cases (principally module 6), 1/3 octave band values are calculated by averaging data corresponding to a number of single frequencies in the band. The number of intervals used in numerical integration in a number of calculations can be set here. It is recommended that it be left at the default value. However, the default value may be increased if computation time is not an issue and high accuracy is important. The number of single frequencies used for a band average can also be set using the "Constants Set-up and Calculation" window. When you have completed entering the values for the various constants, click on "Finish".

When setting constants in this window, the new values are used for all subsequent calculations in any module of ENC until the constants menu is entered again and the values changed again.

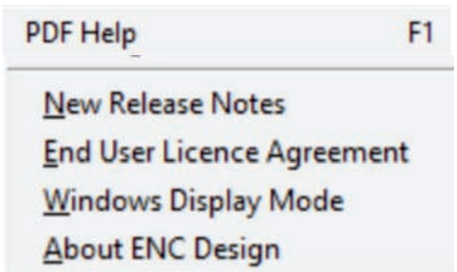
The tools menu also has a list of conversion factors for converting quantities expressed in the SI system of units to the British system of units. The "Unit conversion" window is shown in the following figure, and includes, for convenience, a simple calculator for multiply, divide, add and subtract operations.



The tools menu can also be used to select the optimum display resolution as there may be some distortion on a few wide screen displays.

The Debug ON / OFF item on the menu allows users to see the results of intermediate calculations. However, this is not recommended for general use and no support is provided to users for this option.

0.6.5 Help Menu



In the help menu shown at right, you can access the full user manual with book marks by pressing F1 on your keyboard or by clicking on "pdf help", which is the first line in the menu.

The "New Release Notes" item displays all of the improvements made to ENC since the first commercial release (Version 1.183). The "End user license agreement" is what you have agreed to in order to use ENC. The "Windows Display Mode" item explains how to set up windows to get the best out of ENC. Finally, the "About ENC Design" tells you what version of ENC you have.

0.7 Software Modules

The software is divided into nine modules that roughly follow the layout of the book, Engineering Noise Control, 6th Edition, by D.A. Bies, C.H. Hansen C.Q. Howard and K.L. Hansen. Each module is associated with unique tool bar symbols (see example below) that represent different calculation procedures from different sections of the book chapter or chapters associated with the particular module. You can select the module you want from the "Options" menu at the top of the screen. Each module has a number of windows which can be selected by clicking on the appropriate symbol on the tool bar. Each window has a number of panels, each of which represents a particular calculation.

The modules and the chapters of the book that they represent are listed in the following table.

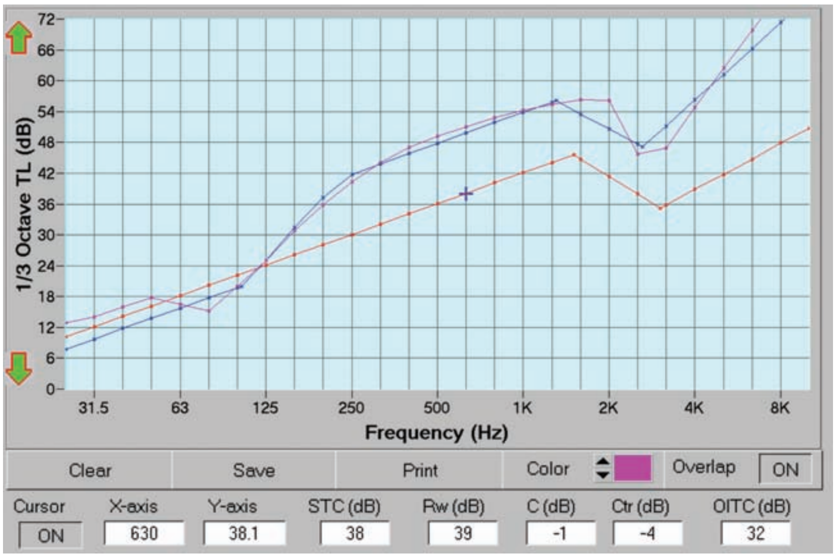
Module number	Book chapters represented
1	1, 2, 3
2	4
3	5
4	6, App D
5	7
6	8
7	9
8	10
9	11 (SEA only)

When you select a particular module, you will find that a page will pop up that represents one particular window in that module. Each window in the module is represented by an icon in the tool bar (see an example above for the module 5 tool bar). You can tell which window you are currently in because the corresponding icon in the tool bar will appear in one of the corners of the screen and the text under the icon in the menu bar will be highlighted in red.

The symbol on the far right is the " run" symbol on which you often need to click to make sure a new calculation occurs after you change some input parameters. The three icons to the left on the tool bar allow you to respectively, start a new calculation, open an old calculation previously stored on a file, and save the current calculation parameters for the entire page to file. If the "Save" button is greyed out, you may still save the parameters for the current page to a file by clicking on <File><Save as>. When inputting a new file name, you must TYPE THE ENTIRE FILE NAME. Do not click on an existing file name and change one or more characters (which we can usually do in Windows). Doing this will cause the file name that you clicked on to be overwritten and the new file name that you made will not exist. This is a problem with the software shell used to construct ENC.

0.8 Plotting

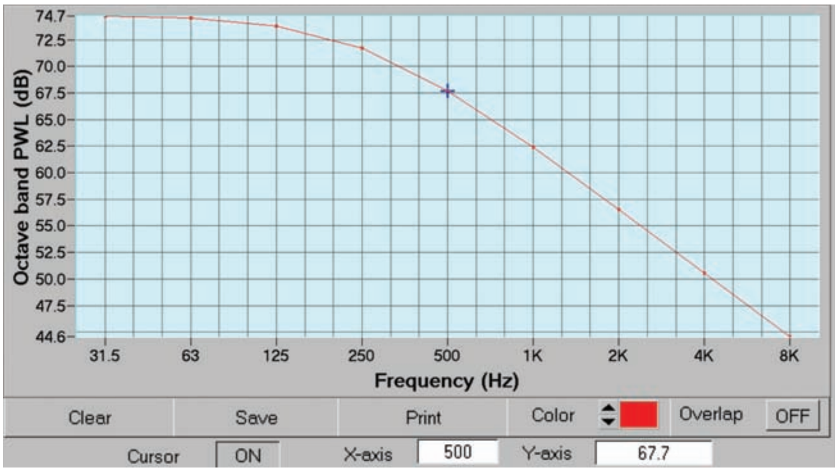
In most windows of the software, the calculated results are shown plotted on a graph. An example is shown below.



Multiple curves can be plotted by clicking on the "Overlap" button so it shows "ON". Different colours for each curve can be selected by clicking on the arrows on the "Colour" button prior to doing a new calculation. Clicking on the "Print" button allows you to print the entire ENC window, including the graph. Clicking on the "Save" button allows you to save the data used to construct the entire ENC window and will now save all curves that are visible . Clicking on "Clear" will clear all curves from the graph.

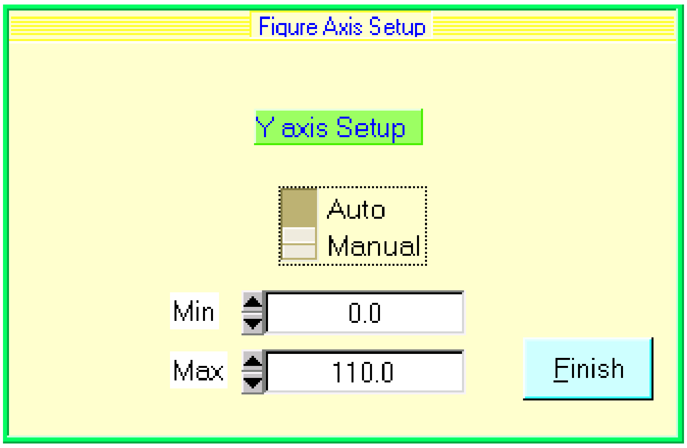
Many graphs also have a cursor button that can be turned "ON" by clicking on it, thus allowing you to obtain accurate values from the graph (sometimes 1/3-octave band values and sometimes only octave band values). Above many graphs you will also have the option of selecting the quantity to plot ("Display Contents" box).

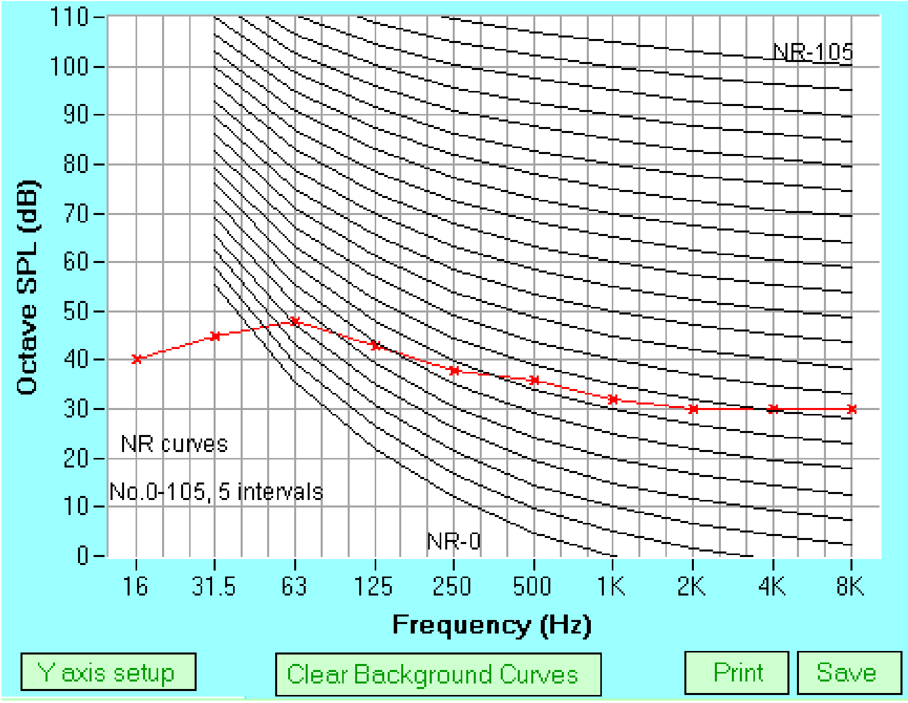
Please note that if a graph has tiny "x" symbols only at octave band centre frequencies (see following figure) and the cursor can only read values at octave band centre frequencies, then care must be taken in obtaining 1/3-octave band values. In cases where the y-axis represents noise reduction or transmission loss, the y-axis value where the curve crosses a 1/3-octave vertical line is likely to be a good approximation of the actual 1/3-octave value if the curve is smoothly increasing or decreasing but not if the curve slope varies greatly with frequency. On the other hand, whenever the y-axis represents sound pressure level or sound power level, it is not possible to interpolate between octave band cursor values to obtain 1/3-octave band values, as each octave band value represents the logarithmic sum of the three 1/3-octave band values that make up the octave band.



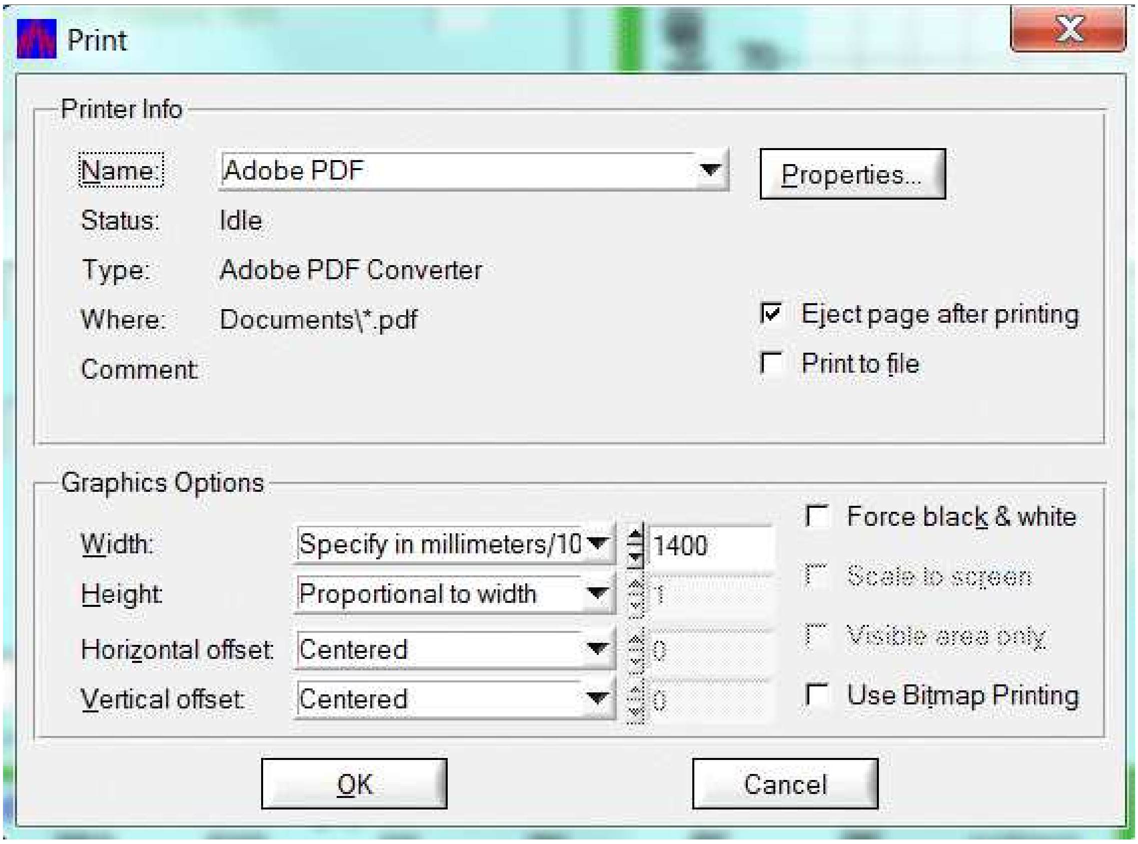
In modules 5 and 8, the graphs have arrows on the left side so you can adjust the range of the scale on the y-axis (see figure on previous page).

Other graphs have a “y-axis setup” button which allows you to adjust the upper and lower limits of the scale so that sensible numbers appear on the y-axis and the scale can be compressed or expanded (see next page). There is also an “auto/manual” switch in the pop-up window. When set to “auto” ENC will select the y-axis scale for you (see below).





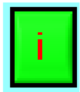
0.9 Printing a plot



Although this should be straightforward by clicking on the “Print” button under the plot on the screen, an incomplete plot can result or the program can lock up unless parameters are specified that produce a successful pdf file which is printed in landscape format and takes up most of the page. The same parameters seem to work for most postscript printers. The most important parameter to change is the <graphics Options><width>. Do not use the default “Entire paper” but use the “Specify in millimeters/10”.This means that you should specify the width you want in tenths of a millimeter. Thus if you want a width of 140.5 mm, you need to enter “1405” in this box. If you choose the default, “Entire paper”, then it is likely the program will not complete a pdf plot and if printing on a printer, the edges of the plot and y-axis title will be missing. The settings shown in the above figure are also satisfactory.

If you wish to export the plot to a file, it is best to double left click on the plot and it will export it to the clipboard from where it can be pasted into any document.

0.10 Importing and Exporting Data



You can import input data from a text file or export the input data that you manually input into ENC to a text file that can be imported directly into a spreadsheet, wherever you see the square green box with the character, “i” inside it. Right clicking on the green box containing the “i” symbol will export the table of data adjacent to the “i” box to a text file for which you can choose the name and which can be imported into any spreadsheet program. Left clicking the green box will upload data from the text file that you specify, which can be generated by saving the excel file as a tab delimited .txt file. This file must have exactly the same format as the exported file obtained by right clicking on the green box, so it is best to right click first with the default data to obtain the text file layout required for importing data. Then you can open the exported file in a spreadsheet program and enter your data manually by replacing the exported values where appropriate, without changing any column or row positions. The spreadsheet is then saved as a tab delimited .txt file and it can then be loaded into ENC by left clicking the green “i” button.

WARNING! If you import data or insert data manually into an ENC page, please check that none of your data results in an “inf” or “NaN” in any calculated data cell on the ENC page. If one of these lies in a cell that you do not use or need, then the remaining cells will be OK. However, if you save an ENC page using “file, save as” and the page contains even one “inf” or “NAN” value, the saved project is likely to be corrupted and unusable, even for data in cells where there were no “NaN” or “inf” values. So make sure you change the offending input data to values that are allowed; i.e. values that do not produce “inf” or “NaN” in any calculated cell.

On some pages, there is a blue box with an “o” inside. Clicking on this box will allow you to export the calculated data in the panel next to the box to a text file.

Chapter 1

Fundamentals & Criteria (Module 1)

1.1 Overview

The software in module 1 calculates all of the quantities discussed in chapters 1–3 of the 6^{th} edition textbook, ranging from the speed of sound in any medium to addition and subtraction of sound levels, A-weighting and noise criteria evaluation. The module consists of eight separate pages, all of which are accessed by clicking on an appropriate icon on the tool bar. Each window is discussed separately below. All Equation numbers refer to equations in the 6^{th} edition of the textbook.

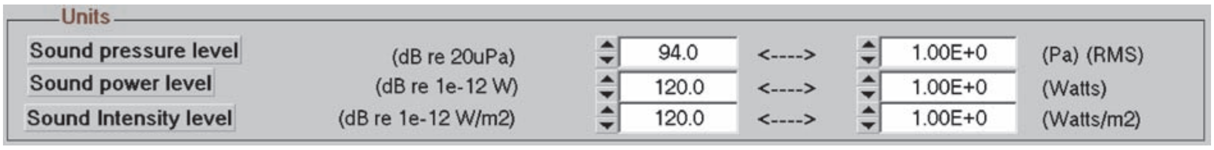
1.2 Fundamentals

(Chapter 1, 6^{th} edition textbook)

This window contains eight panels for eight separate calculations. The green "Constants" button near the middle of the page allows constants such as air temperature to be set up for any of the eight panels.

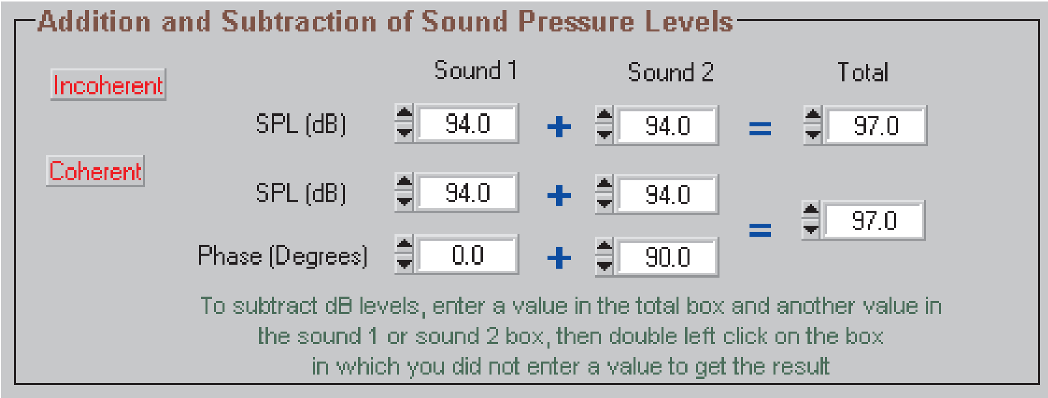
1.2.1 Units (Conversions of levels to linear quantities)

The top left panel of this window at the top allows you to convert SPL to RMS pressure in Pascals (Equation (1.87) in the 6^{th} edition of the textbook), Sound power level to watts (Equation Equation (1.88) in the 6^{th} edition of the textbook) and Sound intensity level to Watts/m^2 (Equation (1.90) in the 6^{th} edition of the textbook) and vice versa (see below).



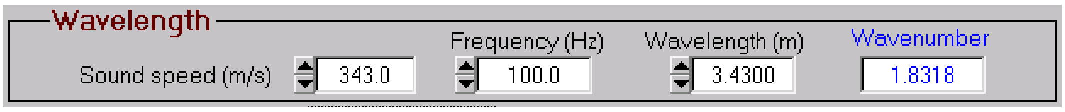
1.2.2 Addition and Subtraction of Sound Pressure Levels

The next panel below and on the left (see next page) allows you to add and subtract decibel levels for coherent (tonal — Equation (1.95) in the 6^{th} edition of the textbook) and incoherent sound (Equation (1.98) in the 6th edition of the textbook). You would normally use the incoherent sound button unless the two sounds to be added were tonal, of the same frequency and from synchronised sound sources. This procedure is discussed on pages 35–37 in the 6th edition textbook.



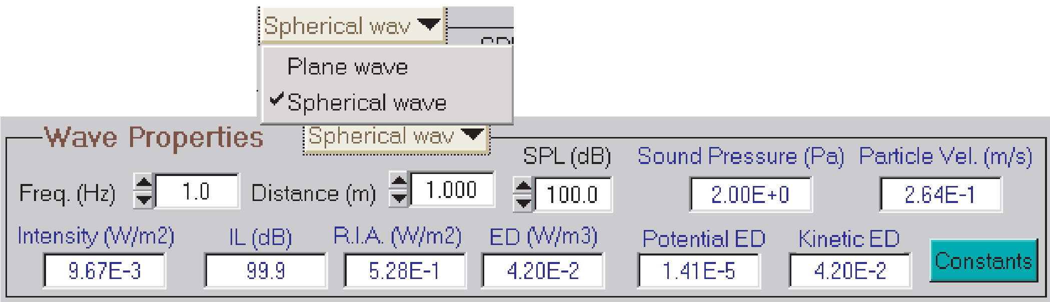
1.2.3 Wavelength, Frequency and Wavenumber

The next panel below and on the left, titled " wavelength" (see below) allows you to calculate wavelength and wavenumber from frequency and speed of sound. In fact frequency or wavelength, may be varied to give wavenumber and speed of sound.



1.2.4 Wave Properties

The next panel below and on the right (see below) is titled "Wave Properties" and allows you to calculate the following quantities (shown in blue) for plane and spherical waves for a specified sound pressure level, L_p. For spherical waves, the distance from the point source and frequency must also be specified.



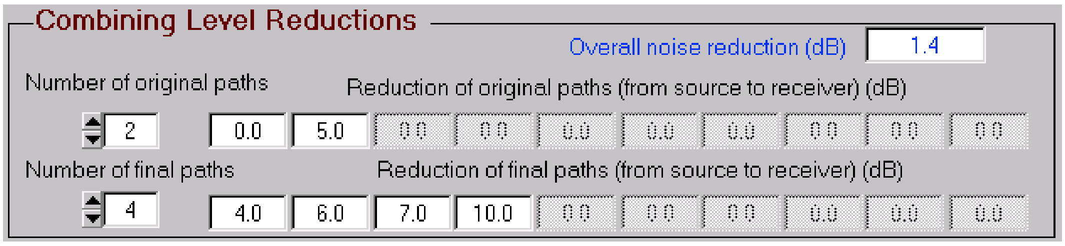
- RMS acoustic pressure (Equation (1.87) in the 6th edition of the textbook)
- Acoustic particle velocity (Equations (1.21) and (1.50) in the 6th edition of the textbook)

- Sound intensity (Equation (1.78) in the 6^{th} edition of the textbook)
- Sound intensity level (IL) (Equation (1.91) in the 6^{th} edition of the textbook)
- Reactive intensity amplitude (A.R.I.) (Equation (1.77) and Equation (1.75), second term in the 6^{th} edition of the textbook)
- Total energy density (ED) (Equation (1.64) in the 6^{th} edition of the textbook)
- Potential energy density (Equation (1.62) in the 6^{th} edition of the textbook)
- Kinetic energy density (Equation (1.61) in the 6^{th} edition of the textbook)

Note that this panel also includes the "Constants" button.

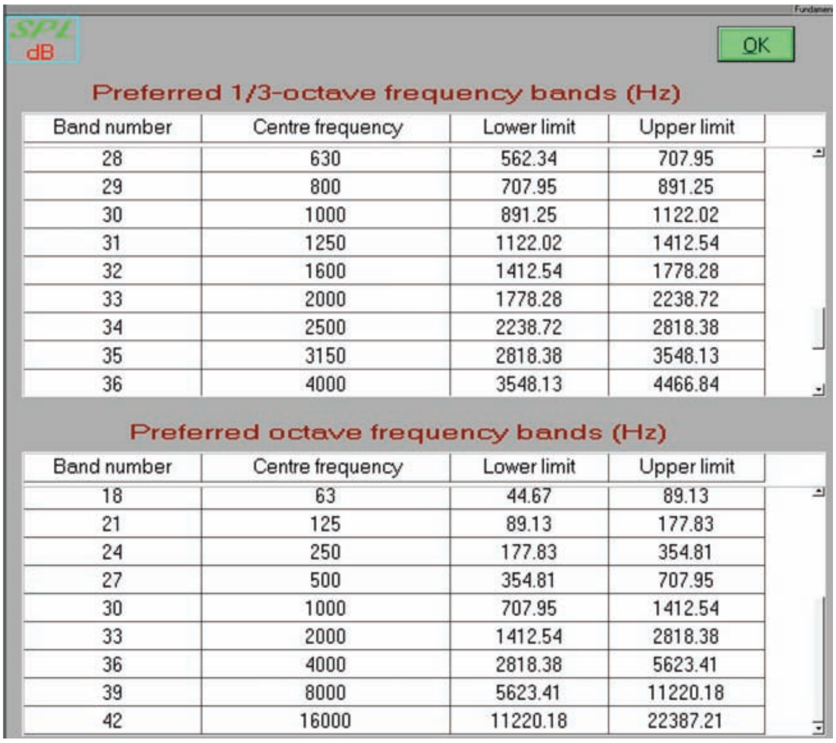
1.2.5 Combining Level Reductions

At the bottom of the left panel (see below), you can combine level reductions (page 37 in the 6^{th} edition textbook). You may need to do this when you have many paths from the source to the receiver and each path is characterised by a different noise reduction to the direct path. Combining level reductions allows you to calculate the sound level at the observer when the noise comes from a source via more than one path and you know the noise reduction associated with each path. You can also do complex calculations such as calculating the overall noise reduction due to the insertion of a finite size barrier if you know the reduction attributable to each path from source to receiver both before and after insertion of the barrier. This is discussed in detail on page 37 of the 6^{th} edition textbook.



1.2.6 Preferred Frequency Bands

As can be seen in the following figure, clicking on the "preferred frequency bands" green button at the bottom of the ENC page gives centre frequencies and upper and lower band limits for 1/3-octave and octave bands. The band limits shown are those corresponding to the more commonly used base-10 filters (ANSI/ASA S1.11, 2014).



Preferred 1/3-octave frequency bands (Hz)

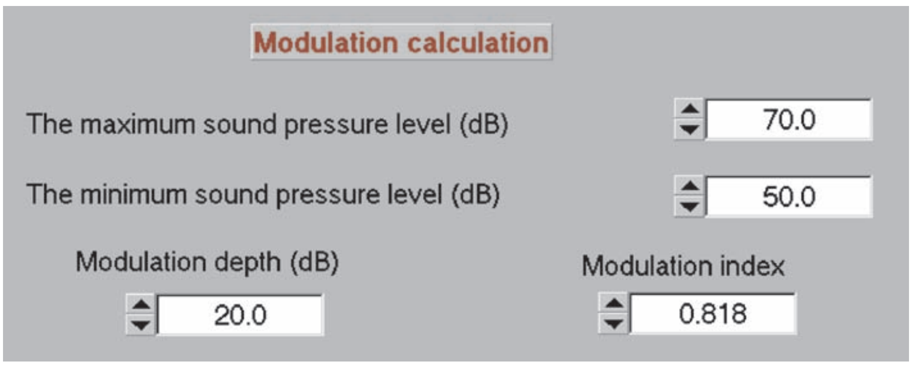
Band number	Centre frequency	Lower limit	Upper limit
28	630	562.34	707.95
29	800	707.95	891.25
30	1000	891.25	1122.02
31	1250	1122.02	1412.54
32	1600	1412.54	1778.28
33	2000	1778.28	2238.72
34	2500	2238.72	2818.38
35	3150	2818.38	3548.13
36	4000	3548.13	4466.84

Preferred octave frequency bands (Hz)

Band number	Centre frequency	Lower limit	Upper limit
18	63	44.67	89.13
21	125	89.13	177.83
24	250	177.83	354.81
27	500	354.81	707.95
30	1000	707.95	1412.54
33	2000	1412.54	2818.38
36	4000	2818.38	5623.41
39	8000	5623.41	11220.18
42	16000	11220.18	22387.21

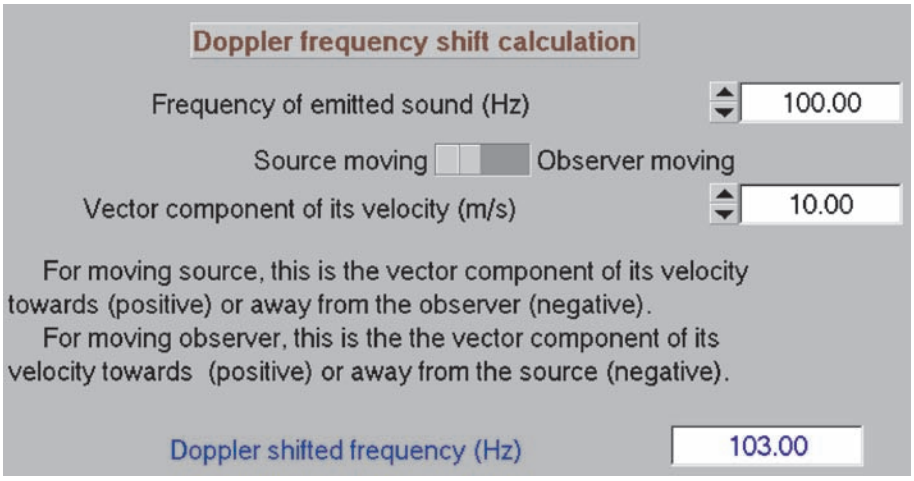
1.2.7 Modulation Calculation

As can be seen in the following figure, clicking on the "Modulation calculation" green button at the bottom of the ENC page gives, for a sinusoidally modulated noise signal, the modulation index and modulation depth for a specified maximum and minimum sound pressure level (see Equations (1.111) and (1.112) respectively, in the 6th edition textbook).



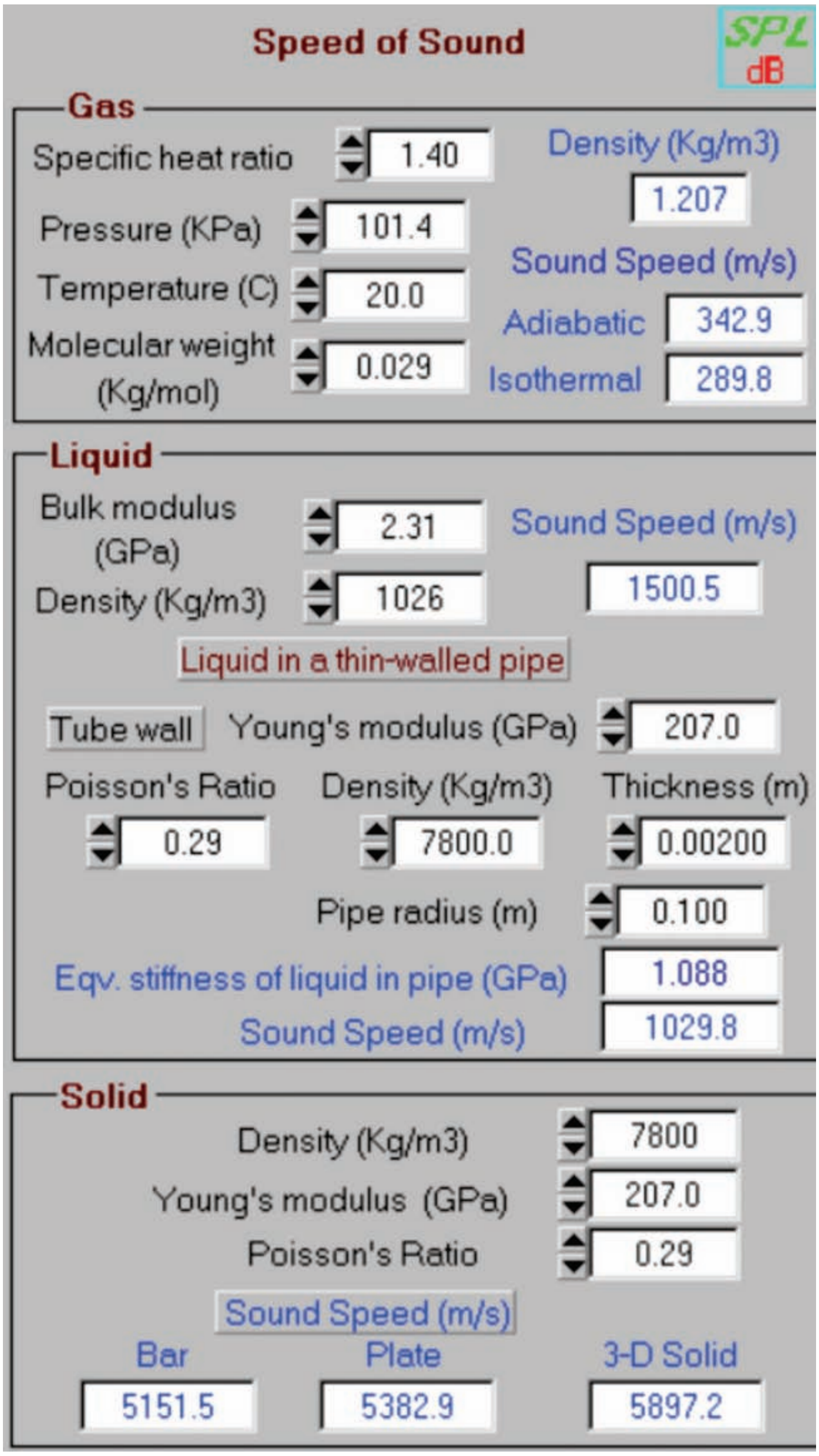
1.2.8 Doppler Frequency Shift

As can be seen in the following figure, clicking on the "Doppler frequency shift" green button at the bottom of the ENC page gives the frequency of sound heard by an observer if the source or observer is moving, for a specified source or observer velocity and specified source emission frequency (see Equations (1.116) and (1.117) in the 6th edition textbook).



1.2.9 Speed of Sound

On the right hand panel (see following figure), the speed of sound in gases (Equation2 (1.8) and (1.9)), bulk liquids (Equations (1.1) and (1.6)), liquids in a thin-walled tube (Equations (1.1) and (1.7)) and solids (Equations (1.1), (1.3)–(1.5)) is calculated from basic physical properties of the substance.

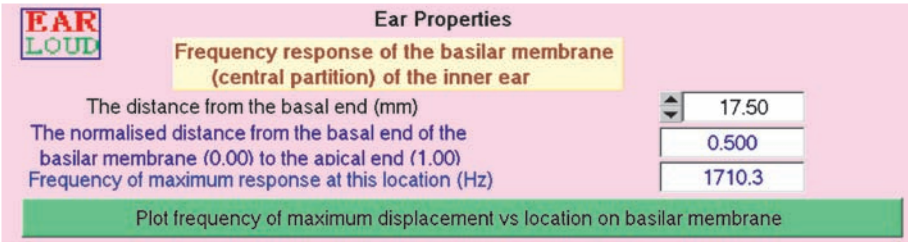


1.3 Ear

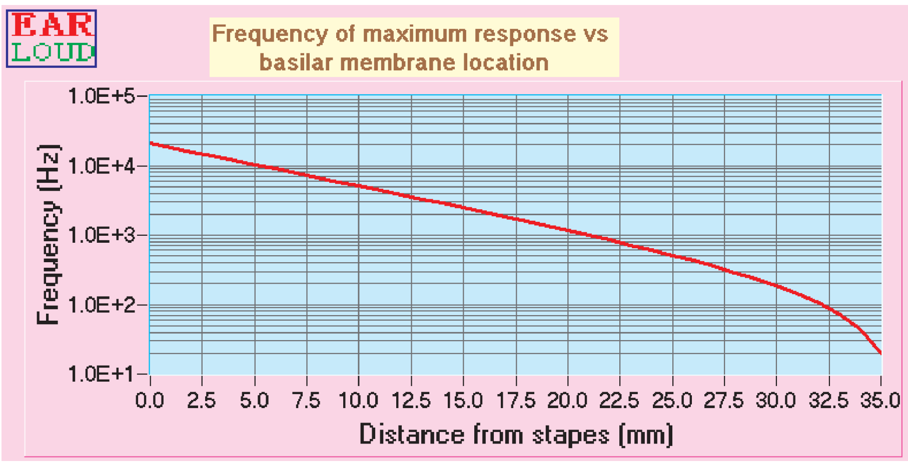
This is a new page in ENC5 and ENC6 and its purpose is to allow calculation of various properties of the ear as well as calculation of loudness of a spectrum that includes either or both pure tones and random noise.

1.3.1 Ear Properties

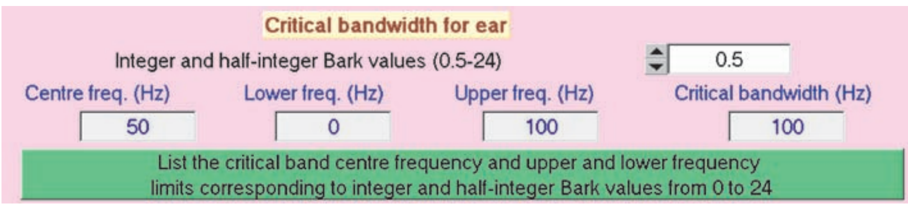
This section allows you to calculate the frequency of maximum response of the basilar membrane as a function of distance along the membrane from the basal end. You just need to enter the distance from the basal end in mm.



The frequency of maximum response vs basilar membrane location can be plotted as shown below by clicking on the button labelled "Plot frequency of maximum displacement vs location on basilar membrane".



You can also calculate the critical bandwidth of the ear for any specified bark value as shown in the following figure.

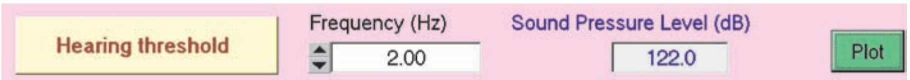


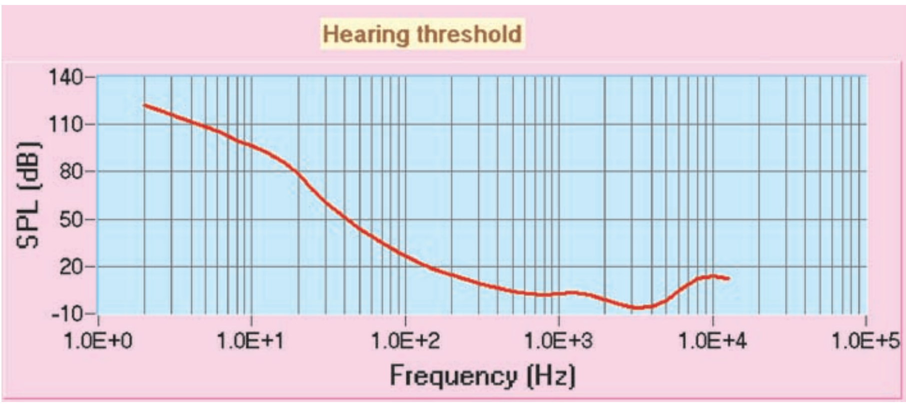
Clicking on the large green button at the bottom of this section will provide a table of critical bandwidths for bark values from 0.5 to 2, as shown in the following figure.

Critical frequency bands (Hz) corresponding to integer and half-integer Bark values

Bark	Centre frequency	Lower limit	Upper limit	Band width
0.5	50	0	100	100
1.0	100	50	150	100
1.5	150	100	200	100
2.0	200	150	250	100
2.5	250	200	300	100
3.0	300	250	350	100
3.5	350	300	400	100
4.0	400	350	450	100
4.5	450	400	510	110
5.0	510	450	570	120
5.5	570	510	630	120
6.0	630	570	700	130
6.5	700	630	770	140
7.0	770	700	840	140
7.5	840	770	920	150
8.0	920	840	1000	160
8.5	1000	920	1080	160
9.0	1080	1000	1170	170
9.5	1170	1080	1270	190

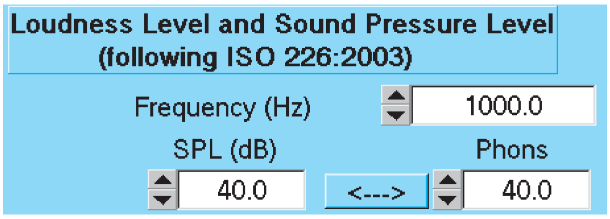
You can also calculate the Hearing Threshold in dB for a given frequency and plot the Hearing Threshold as a function of frequency as illustrated in the following figures.





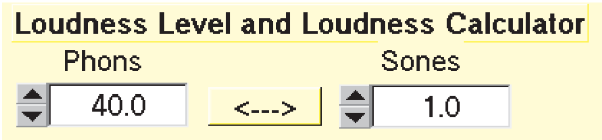
1.3.2 Loudness Level and Sound Pressure level

For any frequency that you specify, this section allows calculation of SPL from phons and vice versa.



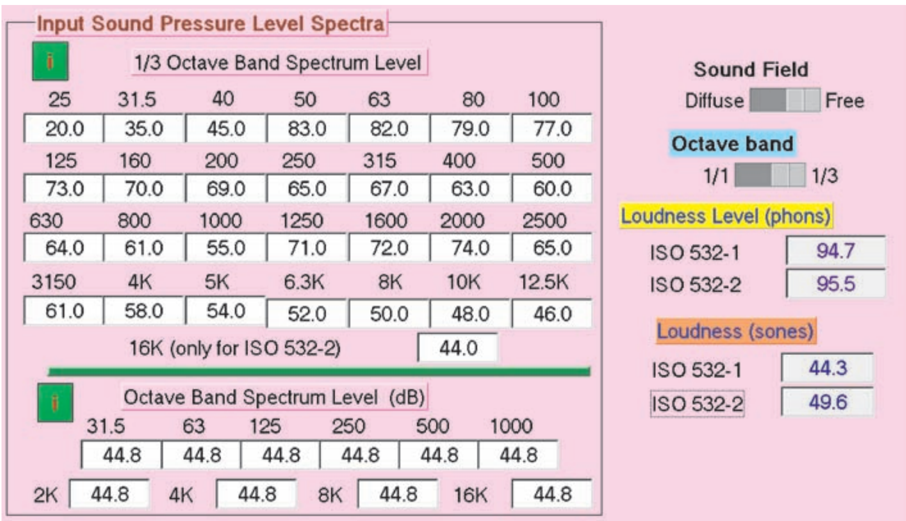
1.3.3 Loudness Level and Loudness Calculator

This section allows calculation of sones from phons and vice versa.



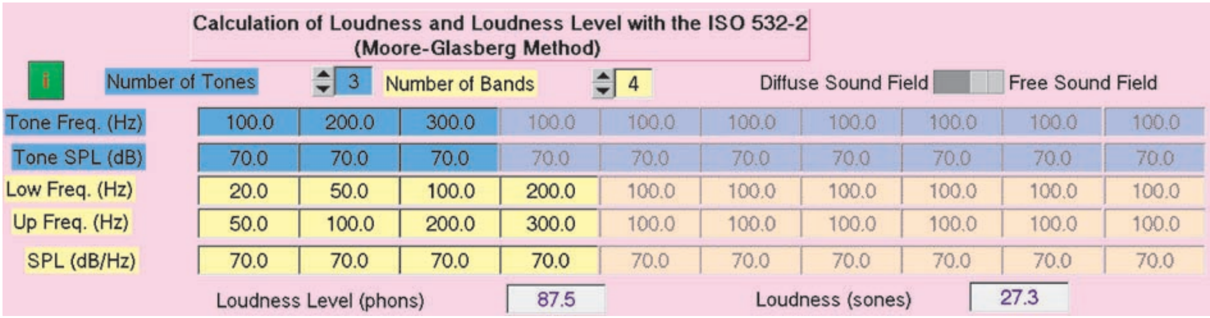
1.3.4 Calculation of Loudness for a Specified 1/3-Octave or Octave Band Spectrum

This section provides calculated loudness in sones and phons for a 1/3-octave or octave band spectrum using ISO 532(1975), ISO 532-1 and ISO 532-2 for either a diffuse sound field or a frontally incident (free) sound field. Only the ISO 532(1975) method is described in the 6th textbook.



1.3.5 Calculation of Loudness Level with ISO 532-2

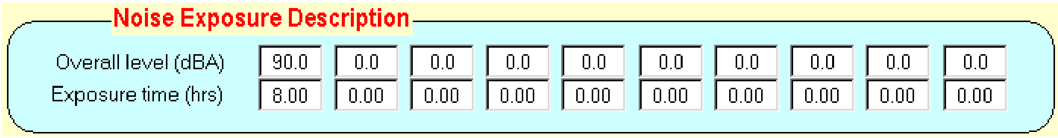
This section calculates loudness for specified bands of noise and tones acting together. The sound pressure levels, tonal frequencies and upper and lower frequency limits of each band of noise are specified by the user. Up to 10 different bands and tones are allowed as illustrated in the following figure.



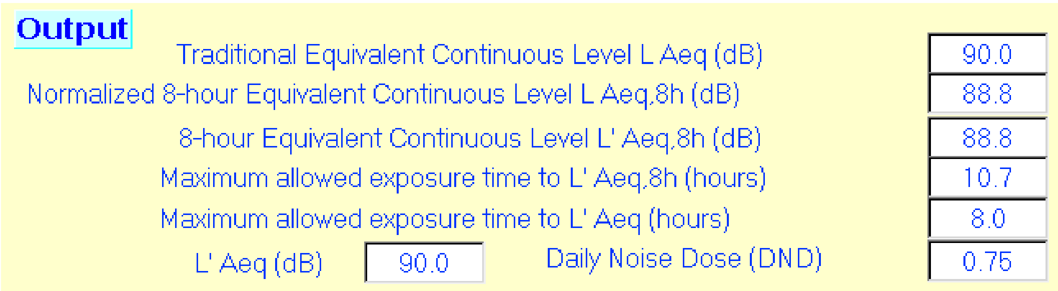
1.4 Hearing Damage (6th edition textbook, pages 92–105)

1.4.1 Noise Exposure

The table at the top of the panel (see below) is for specifying a noise exposure environment for an individual or group of people for whom hearing damage risk and allowed exposure time is to be calculated. All you need do is enter the noise level in a particular area and the amount of time per day that the individual spends in that area. The total time need not add up to 8 hours — if it does, then the first 2 results in the table below will be identical.



The right hand panel, second from the top (see below) is for presenting the results which are listed and explained below (using the same number IDs — 1 to 7 — as shown in the following figure).



1. Traditional equivalent continuous noise level for any specified number of hours, T (Equation (2.36) in the 6th edition of the textbook), where T_e is the total number of hours you have entered into the table.

2. Normalised 8-hour Equivalent continuous level (Equation (2.38) or (2.39) in the 6th edition of the textbook — where the exposure is averaged over 8 hours regardless of the total time in the above table).

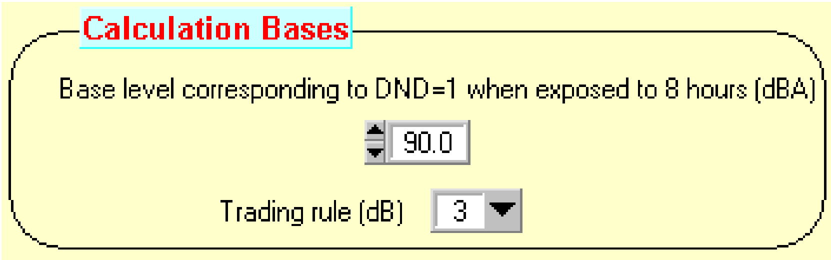
3. The 8-hour Equivalent continuous level, L'_{Aeq}, for a specified trading rule (Equation (2.76) in the 6th edition of the textbook).

4. Maximum allowed exposure time (Equation (2.81) in the 6th edition of the textbook) to the 8-hour Equivalent continuous level for a particular noise environment that is specified in the table at the top of the screen.

5. Maximum allowed exposure time (Equation (2.81) in the 6th edition of the textbook with the "8" replaced with the exposure time, T) to the Equivalent continuous level for a particular noise environment that is specified in the table at the top of the screen.

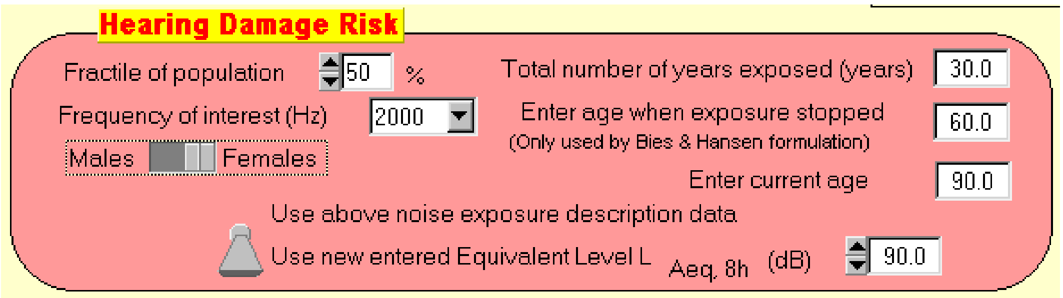
6. Daily noise dose (Equation (2.82) in the 6^{th} edition of the textbook). The rules used for the calculation are specified in the panel immediately to the left of the above panel and this panel is illustrated on the next page. The calculations done here are described on pages 101 and 102 of the 6^{th} edition textbook.

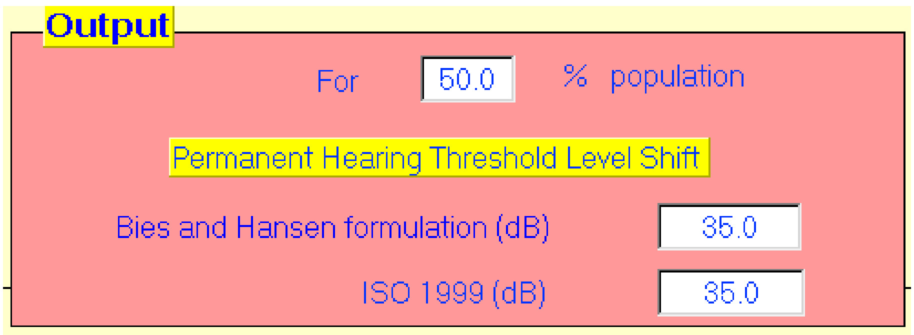
The figure shown below appears close to the top of the window and allows one to enter the base level (almost invariably 90 dB(A)) corresponding to a DND of 1.0 and the trading rule to be used for the above calculations.



1.4.2 Hearing damage risk

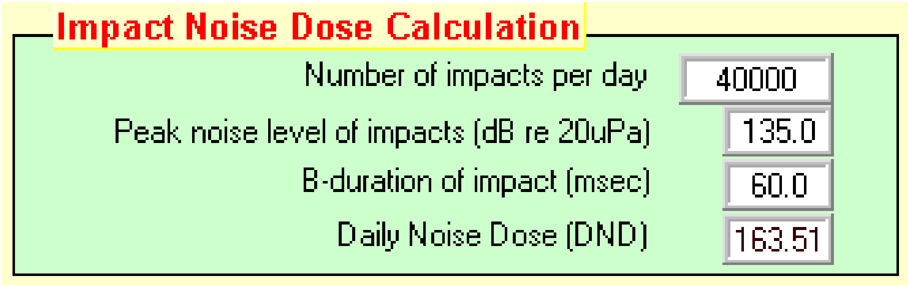
The two panels, third from the top (see below) are for calculating a group of people's risk of hearing damage when exposed to the environment described in the table at the top of the panel. Alternatively a new value for $L_{Aeq,8h}$ can be selected from the box in the left panel. Two calculation procedures (Equations (2.56)–(2.62) (ISO 1999) and Equations (2.66)–(2.72) (6^{th} edition textbook)) are used and each is described in the 6^{th} edition textbook, pages 94–98.

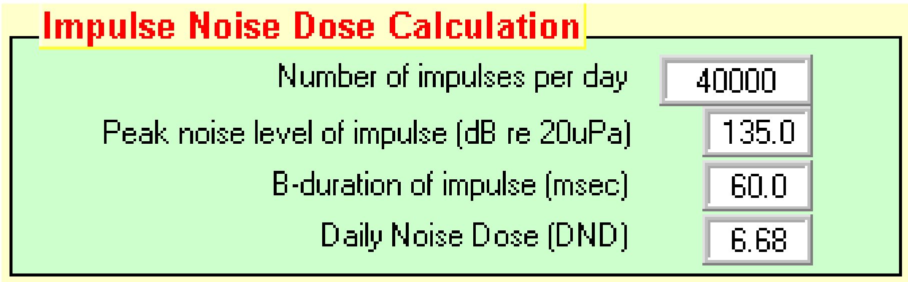




1.4.3 Impulse and Impact Noise

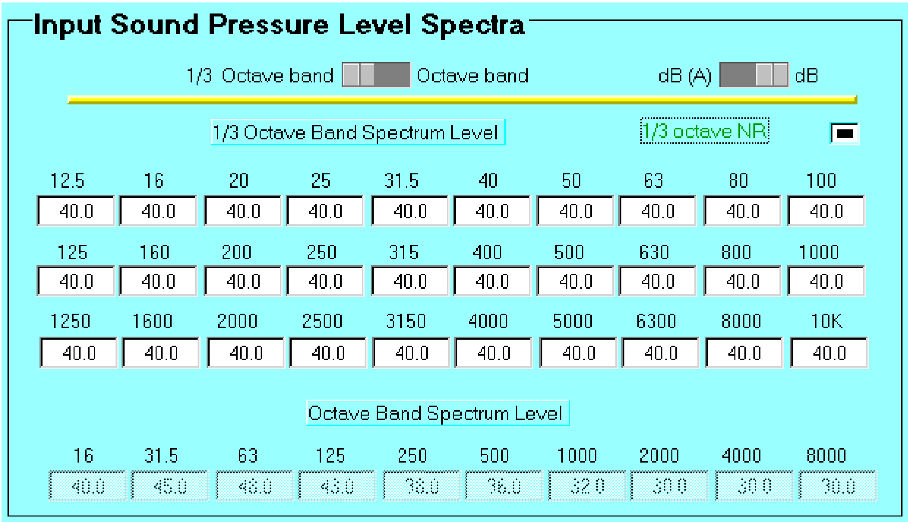
The bottom two panels shown below allow the calculation of the daily noise dose for impact and impulsive noise. The procedures are described on pages 101–102 in the 6th edition textbook. Enter values in three out of the four boxes and then double left click on the fourth box to get the result for the unknown quantity. Note that impulse noise follows the USA 5 dB trading rule for large numbers of impulses (6th edition textbook, Figure 2.23).



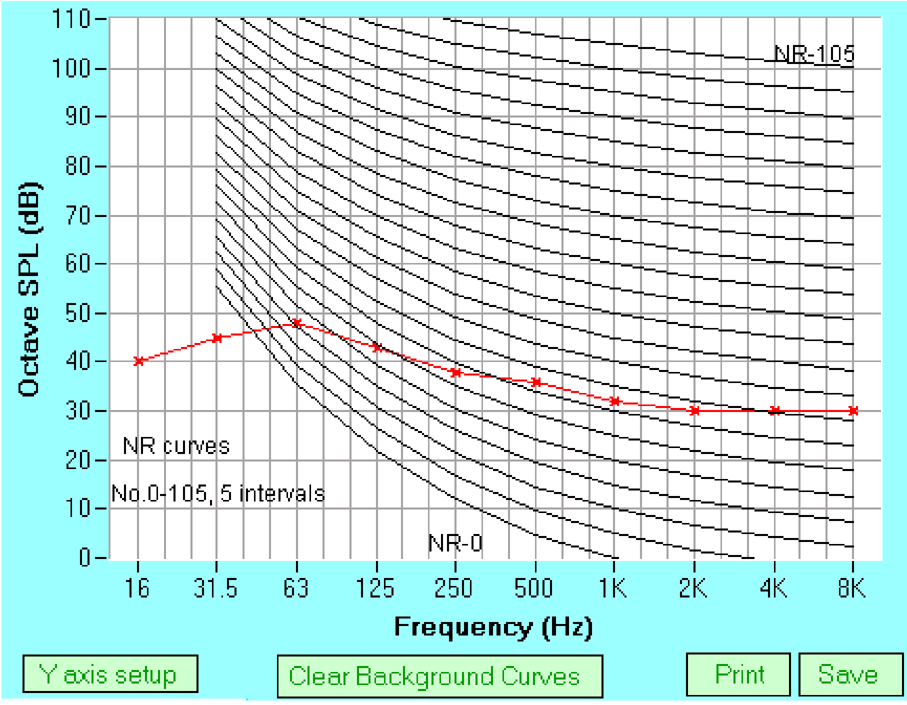


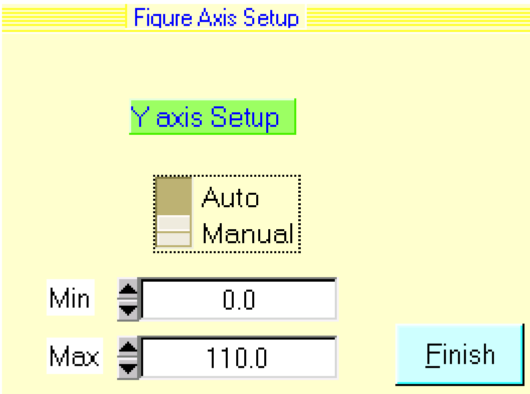
1.5 Noise Criteria (6th edition textbook, pages 123–133 and 137–141)

The top left panel on this page (see below) provides the opportunity to enter 1/3 octave or octave band linear or A-weighted spectrum levels. If 1/3-octave band levels are entered, they are converted to octave band levels prior to plotting and the resulting octave band levels are also included in the table in the bottom panel. However, there is one exception to this. If 1/3-octave NR curves are desired, then the “1/3-octave NR” button is clicked and the 1/3-octave band values are plotted together with 1/3-octave band NR curves (which are the octave band NR curves shifted down by 4.8 dB ($10 \log_{10} 3$)).



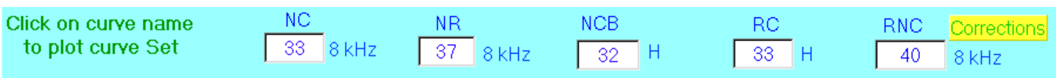
A plot of NR curves is illustrated in the following figure. Clicking on "y-axis setup" (see figure below the graph) allows you to choose the y-axis maximum and minimum values.





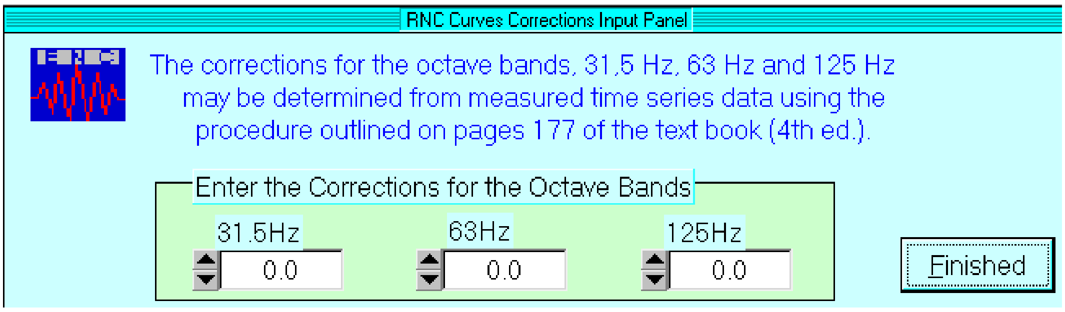
Only the linear band levels are plotted. If the "A-weighting" switch is selected in the top left panel, the values in the table in the top left panel will be A-weighted values and will not be the ones that are plotted. The panel (including the figure) can be printed by clicking on the "print" button below the figure. The "clear background curves" button is used to clear the NC, NR, NCB, RC or RNC curves from the figure when they are plotted.

The rating curves (octave band) are plotted by clicking on any one of the NC, NR, NCB, RC or RNC letters at the bottom left of the panel (see 6th edition textbook, pages 126–133 and ANSI S12.2) as shown in the following figure. Clicking the characters a second time will make the curves disappear.



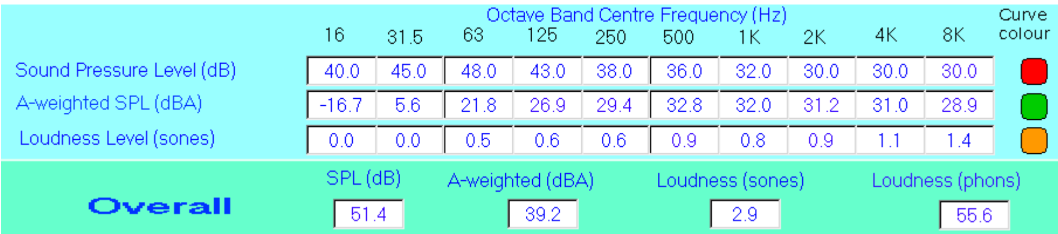
Next to each curve rating number is a letter. “O” means ”overrange — the data exceed the highest permissible rating curve. “R”, “N” and “H” mean the sound is respectively “rumbly”, “neutral” or “hissy”. “RV” indicates that feelable vibration exists. It is possible to have “R” , “H” and “RV” simultaneously but “N” will always appear either alone or with “RV” only. NC, NR and RNC curves are not associated with hissy /rumbly calculations. The frequency numbers to the right of the NR, NC and RNC boxes refer to the octave band where the level intersected the highest NR, NC or RNC curve.

For RNC curves, the allowed range is between 10 and 50. If any octave spectrum value in the frequency range 63 Hz and above exceeds the 50 curve, ENC writes “NA: >50” and if either the 16 Hz or 31.5 Hz spectrum values exceed the black line, ENC writes “NA: noisy”. Also for RNC curves, the values at 31.5 Hz, 63 Hz and 125 Hz must be corrected prior to plotting as outlined in the 6th edition textbook. This can be done by clicking the “corrections” button shown in the preceding figure to produce the pop up window below.



Click “finished” when you have entered the corrections as calculated following the procedure in the 6th edition textbook on page 133 in the 6th edition textbook.

The bottom left panel (see below) lists A-weighted levels corresponding to the linear spectrum. A-weighted levels are calculated using the 1/3 octave band linear spectrum, or the octave spectrum entered in the top left panel. If 1/3-octave band levels are entered in the top left panel, they are converted to octave band levels for use in the bottom panel. If A-weighted levels are entered in the top left panel, then the corresponding linear levels are calculated for the first line in the table below.



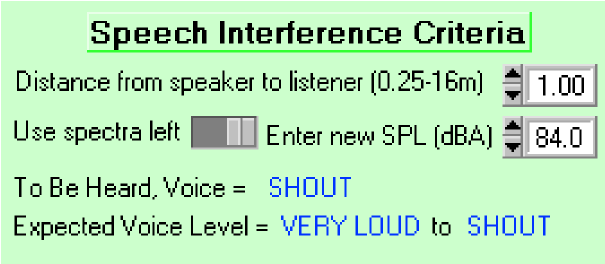
Octave Band Centre Frequency (Hz)	16	31.5	63	125	250	500	1K	2K	4K	8K	Curve colour
Sound Pressure Level (dB)	40.0	45.0	48.0	43.0	38.0	36.0	32.0	30.0	30.0	30.0	
A-weighted SPL (dBA)	-16.7	5.6	21.8	26.9	29.4	32.8	32.0	31.2	31.0	28.9	
Loudness Level (sones)	0.0	0.0	0.5	0.6	0.6	0.9	0.8	0.9	1.1	1.4	

Overall	SPL (dB)	A-weighted (dBA)	Loudness (sones)	Loudness (phons)
	51.4	39.2	2.9	55.6

The octave band loudness levels in sones are calculated from the octave band data in the top line in the table, using Figure 2.14, p. 79 in the 6th edition textbook. The data in the top three lines of the table will appear on the graph at right if you click on the coloured button adjacent to the line of data which you want plotted. The plot will have the same colour as the button you clicked on to make it. Click on the button a second time to remove the curve from the graph.

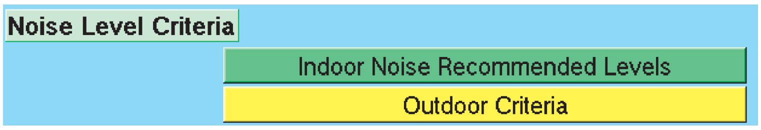
Overall linear and dB(A) levels are provided in boxes beneath the table in the bottom left panel (see previous page). The overall loudness level in sones is calculated using Equation (2.34) in the 6th edition textbook and the overall loudness in phons is calculated from the sone level using Equation (2.33) in the 6th edition textbook. Note that the loudness levels are calculated using the procedure described in ISO 532 (1975). Loudness calculations using the more recent ISO standards are calculated in the EAR page.

1.5.1 Speech Interference

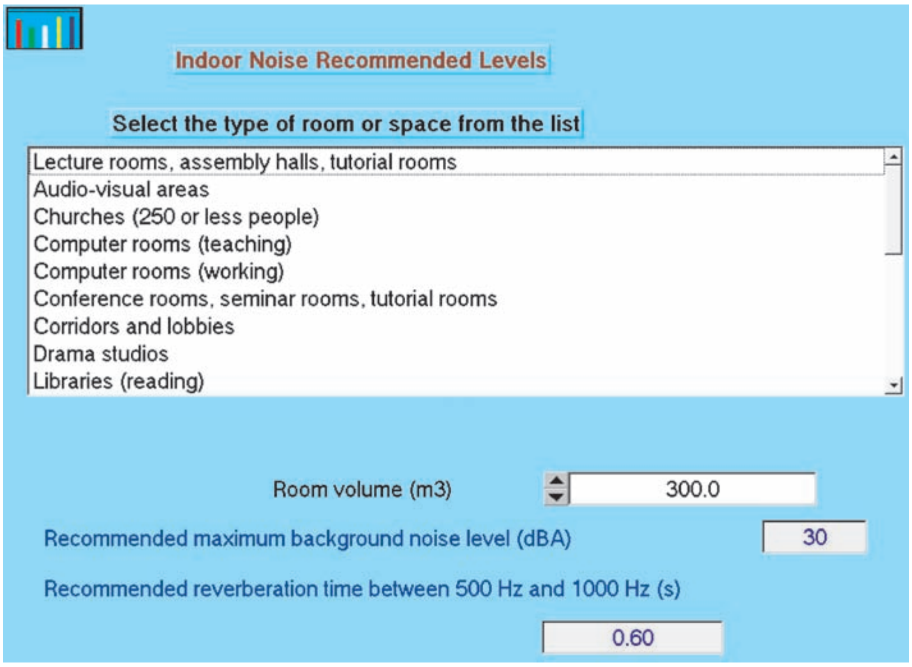


The next from bottom right panel (shown at right) is for calculating speech interference criteria as described on pages 115–116 of the 6th edition textbook (and ANSI S3.14). You have the choice of using the spectrum already entered at the left or you may enter a new A-weighted sound pressure level in the box.

1.5.2 Noise Level Criteria (Recommended Noise Levels)

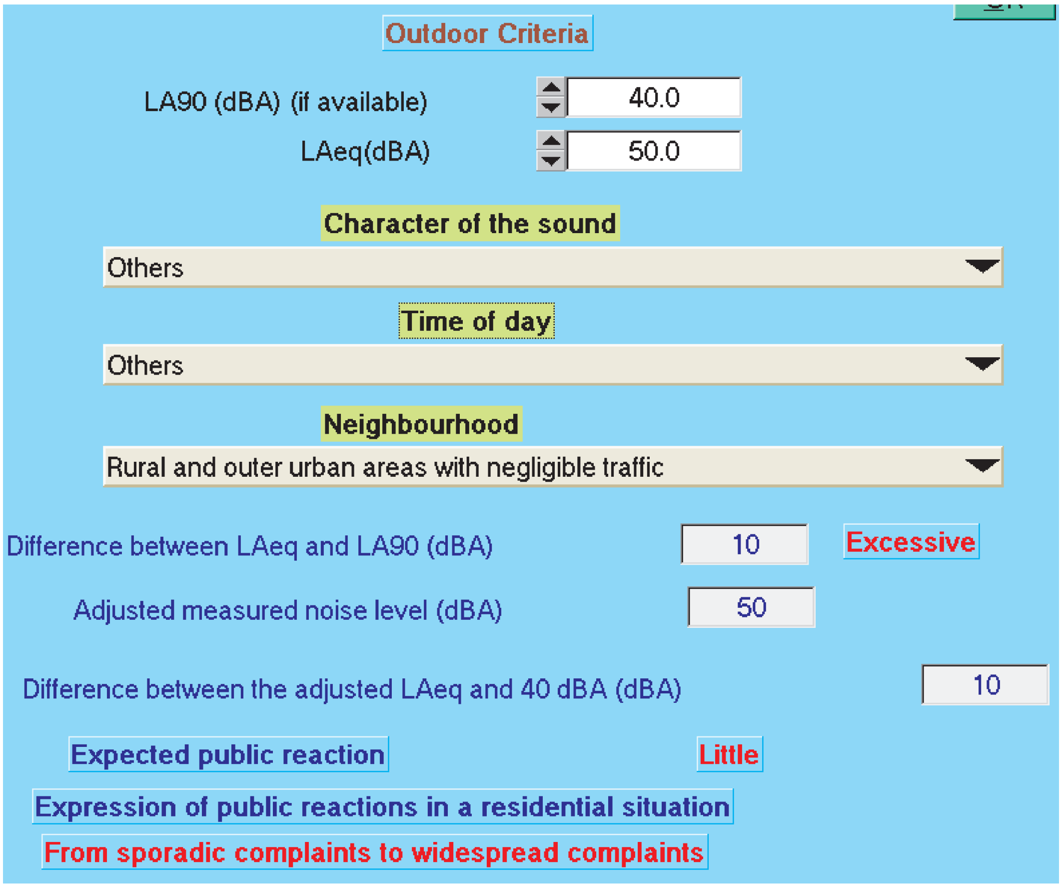


The bottom right panel (shown at right) provides buttons, which when clicked on, provide lists of recommended maximum A-weighted sound pressure levels for both indoor and outdoor environments. These do not include acceptable maximum levels in industrial workplaces, but the outdoor section provides acceptable levels of community noise resulting from the operation of industrial facilities.



For interior noise levels as shown in the figure at right, the type of space and the room volume must be input by the user and then the desired maximum interior A-weighted background (ambient) noise level and desired room reverberation time for some room types (between 500 and 1000 Hz) are provided by ENC.

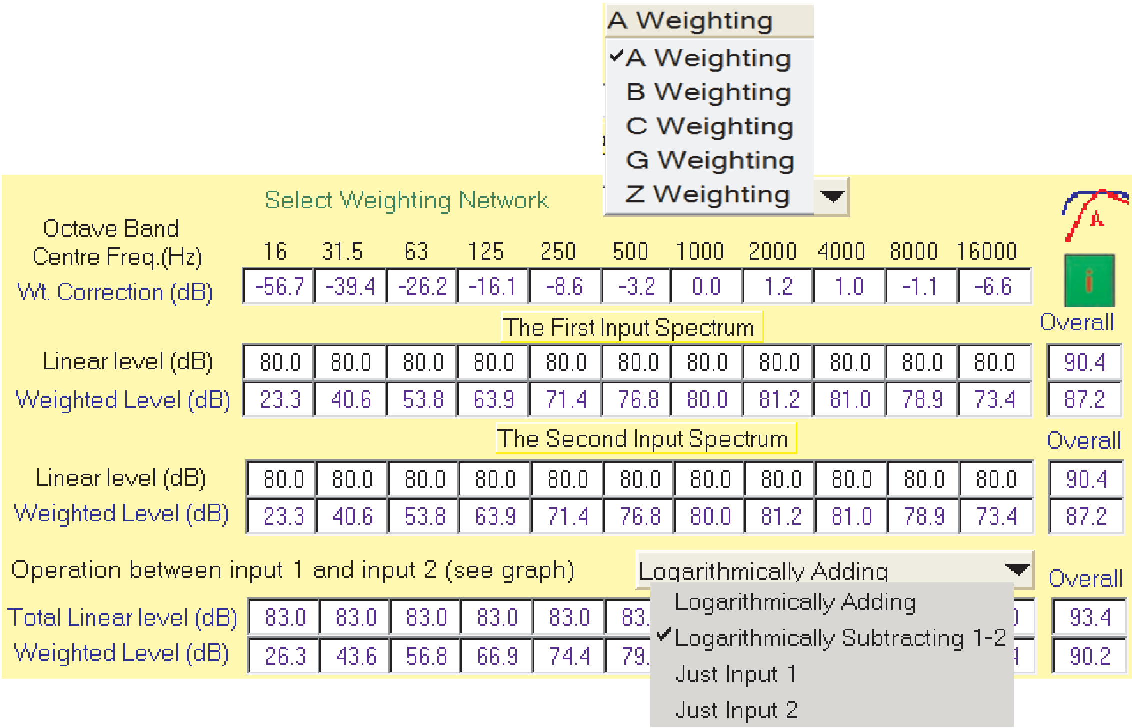
For exterior environmental levels, as shown in the figure below, the user must choose the character of the sound, the time of day and the type of location. The expected noise levels are also input to allow calculation of the adjusted L_{Aeq} and the difference between the adjusted L_{Aeq} and 40 dBA. This difference is then used to determine the expected public reaction and how this might be expressed. ENC will then calculate ENC also provides a comment on the difference between L_{Aeq} and L_{90}.



Click on “OK” when finished with the pop-up panel.

1.6 Weighting Networks (6th edition textbook, pages 81–82)

1.6.1 Spectral plotting



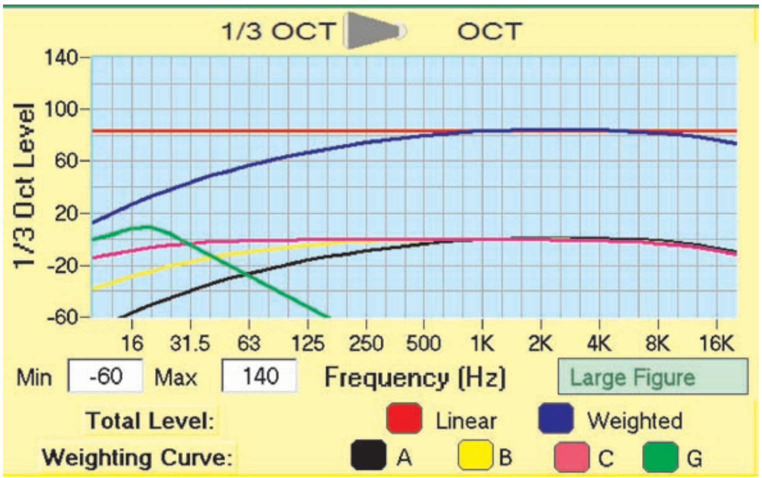
This window allows you to enter two octave or 1/3-octave band spectra, apply A, B, C or G weighting to them and plot both the linear and weighted spectra. Only the octave band table is illustrated above. Note that the Z-weighting is the same as the linear weighting from 10 Hz to 20 kHz.

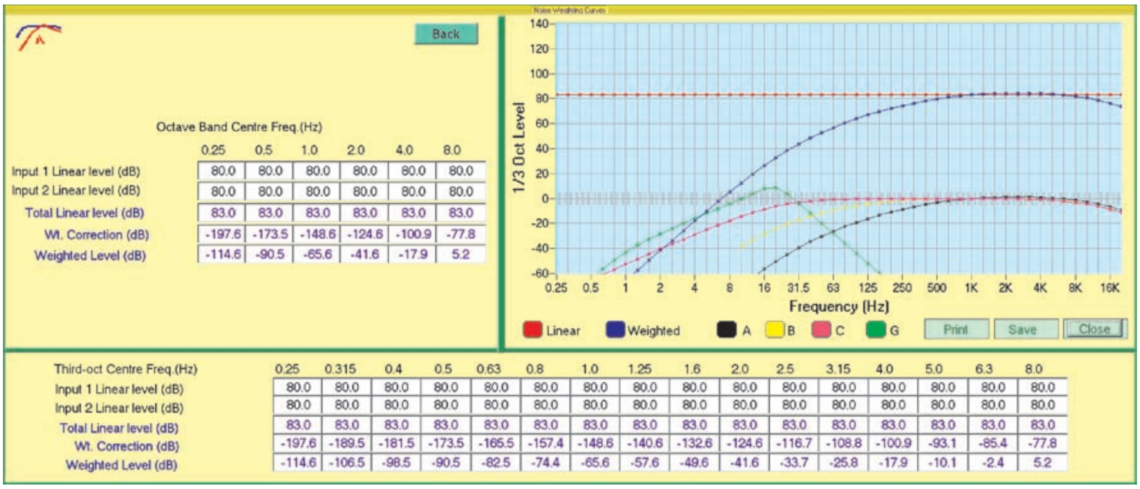
Right clicking on the green "i" button allows you to save the screen values to a project file and left clicking on the same button allows you to load a project file that you have saved previously.

You can also add the two spectra together logarithmically or subtract spectrum 2 from 1. If a value in spectrum 2 is greater than or equal to a value in spectrum 1, then the result of the subtraction operation will be "-inf". The spectrum values are entered in the appropriate table — the octave band table is shown above — the 1/3-octave band table is not shown here but it is similar to the octave one.

Below the 1/3-octave band table is a line (see following figure)that allows you to type in a particular frequency (in Hz) and ENC will then show which frequency band it is in (you can choose octave or 1/3-octave) as well as the band limits in Hz using base-10 filters.

The octave band results and weighting curves may both be plotted on the graph. You can select the curve you wish to plot by clicking on the appropriate coloured button beneath the graph. Clicking on the coloured button a second time will make the curve disappear. The graph is illustrated at right. Clicking on "Large Figure" brings up the window illustrated below where it can be seen that the plot may be printed or saved.



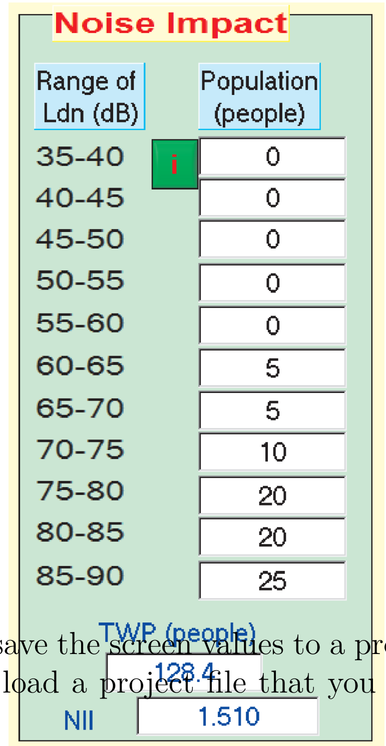


Note that you can set the plot limits to what is convenient and you can choose to plot 1/3-octave or octave band data. There are always 10 horizontal divisions so the increment from one horizontal division to the next will be the value you choose as the maximum minus the value you choose as the minimum, all divided by 10. This is how you can force the dB scale values to what you want them to be.

You can add or delete each one of the five curves on the graph by clicking on the appropriately coloured button below the graph.

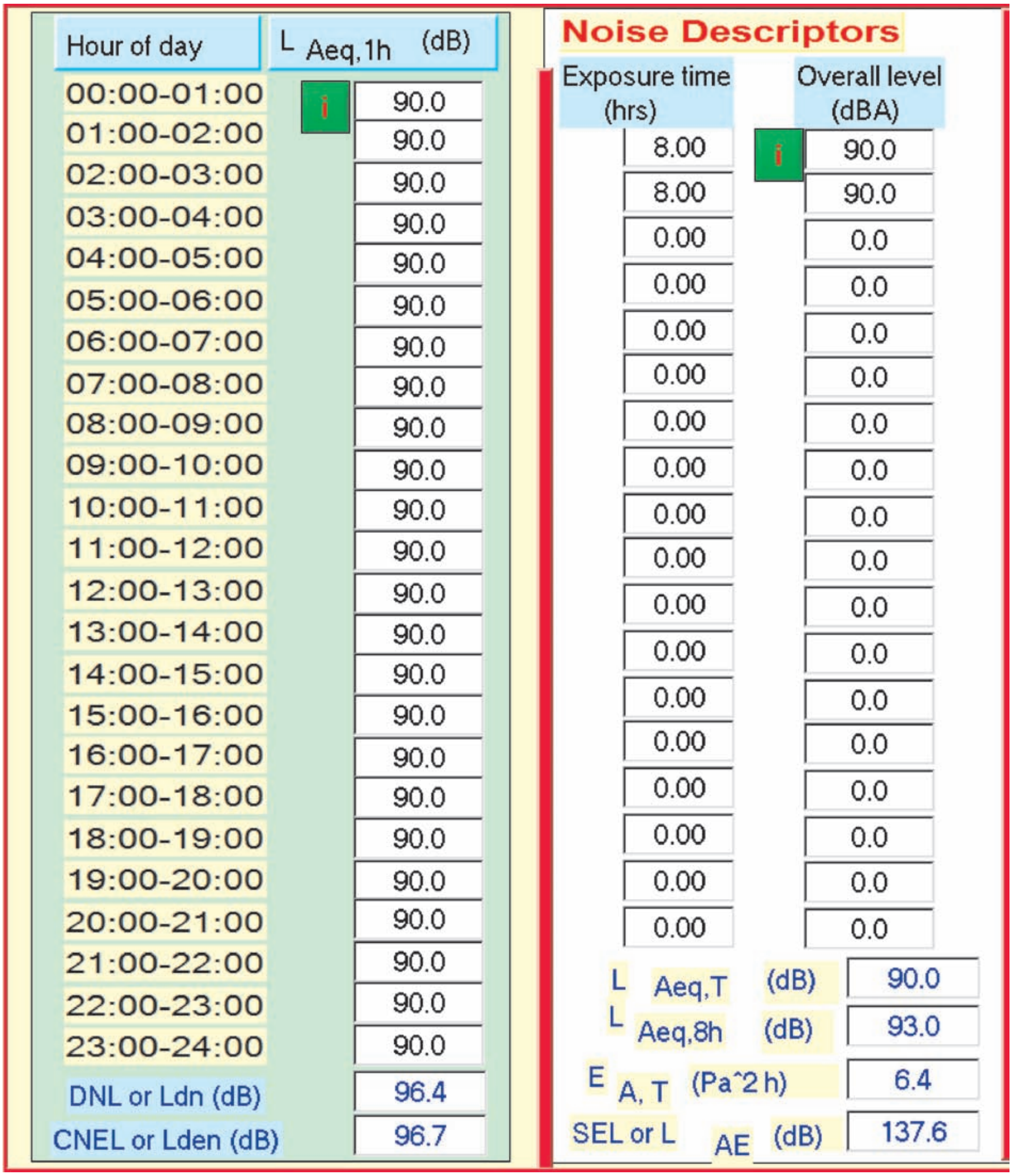
A larger, more detailed version of the graph that can be printed and saved is also available by clicking "Large Figure" beneath the graph.

1.7 Noise Descriptors (6th edition textbook, pages 83–88)



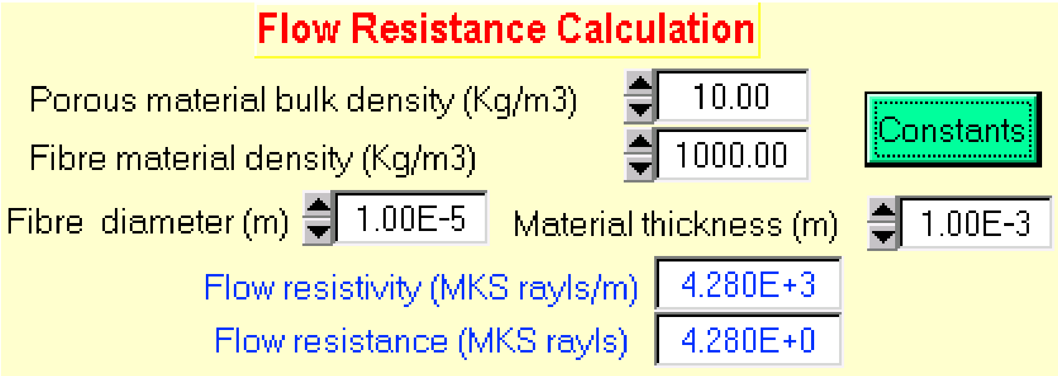
These descriptors can be calculated using this window by entering either hourly L_{dn} data in a table of (for environmental noise descriptors) or exposure time (hours) vs exposure level L_{Aeq} (dBA) in a separate table (for occupational noise). The figure at right and the figure on the following page illustrate the tables that need to be filled in with data. Results are labelled in blue text. Noise impact is calculated by determining how many people are exposed to particular ranges of L_{dn} and then filling in the table at right (see , pages 145–146 in the 6^{th} edition textbook). Note that the Overall level data in the noise descriptor table may be A-weighted or unweighted (linear). If unweighted, then the descriptors in blue font at the bottom of the table will not have "A" in the subscript string. Also note that $L_{\mathrm{EX,8h}} = L_{Aeq,\mathrm{8h}}$.

Right clicking on the green "i" button allows you to save the screen values to a project file and left clicking on the same button allows you to load a project file that you have saved previously.


Hour of day
L Aeq,1h (dB)
00:00-01:00 90.0
01:00-02:00 90.0
02:00-03:00 90.0
03:00-04:00 90.0
04:00-05:00 90.0
05:00-06:00 90.0
06:00-07:00 90.0
07:00-08:00 90.0
08:00-09:00 90.0
09:00-10:00 90.0
10:00-11:00 90.0
11:00-12:00 90.0
12:00-13:00 90.0
13:00-14:00 90.0
14:00-15:00 90.0
15:00-16:00 90.0
16:00-17:00 90.0
17:00-18:00 90.0
18:00-19:00 90.0
19:00-20:00 90.0
20:00-21:00 90.0
21:00-22:00 90.0
22:00-23:00 90.0
23:00-24:00 90.0
DNL or Ldn (dB) 96.4
CNEL or Lden (dB) 96.7
Noise Descriptors
Exposure time (hrs)
Overall level (dBA)
8.00 90.0
8.00 90.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
0.00 0.0
L Aeq,T (dB) 90.0
L Aeq,8h (dB) 93.0
E A, T (Pa^2 h) 6.4
SEL or L AE (dB) 137.6

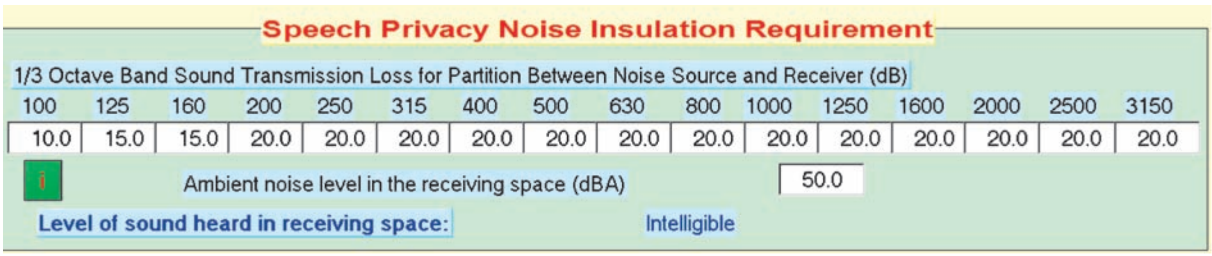
1.7.1 Flow Resistivity and Flow Resistance (6th edition textbook, pages 47–48)

Flow resistivity and flow resistance of a specified thickness of a fibrous porous material can be calculated using the panel on the centre right of this window (see figure below) by entering the density of the material and the fibres making it up together with the fibre diameter. The “material thickness“ label in ENC refers to the bulk material thickness. The “constants” button is used to set ambient temperature and speed of sound parameters.



1.7.2 Speech privacy (6th edition textbook, Table 2.23, page 134)

The speech privacy between two spaces separated by a partition can be estimated using the panel illustrated below. Enter the 1/3-octave band transmission loss value for the partition separating the two spaces of interest and then enter the ambient sound level (dBA) in the receiving room (containing the listener).

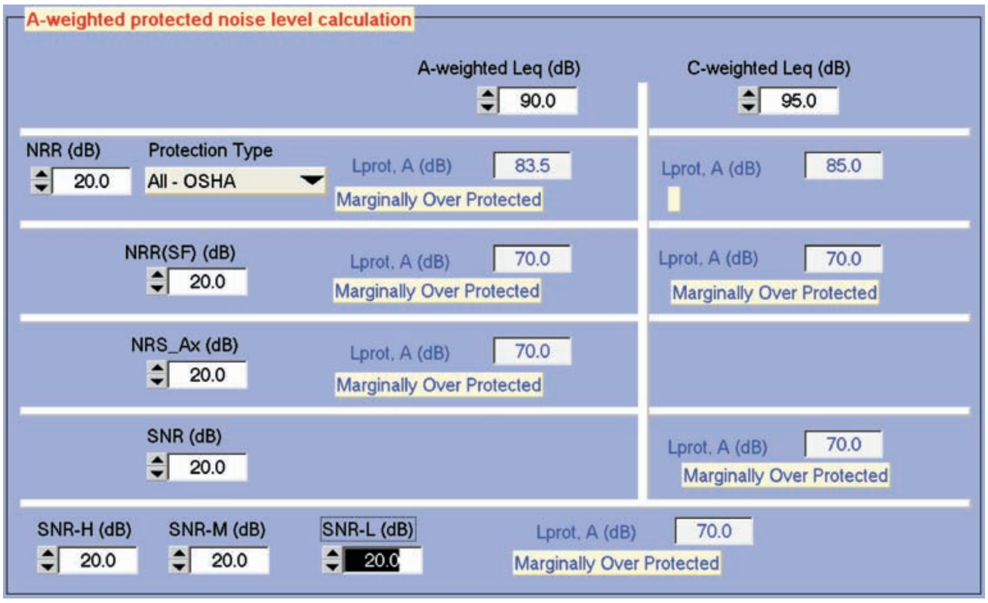


1.8 Hearing Protection Devices (6th edition textbook, page 107–115)

1.8.1 Calculation of the Protected Level

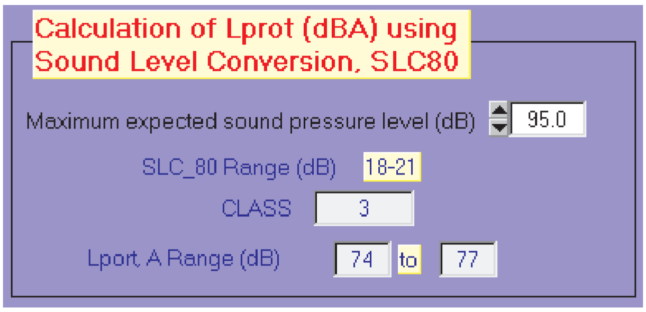
With this page, which is new in ENC5.0, it is possible to calculate the effective A-weighted sound pressure level level (protected level), $L_{\mathrm{prot},A}$, to which a wearer of a hearing protection device may be exposed, given the hearing protection device rating (supplied by the manufacturer) together with the A-weighted or C-weighted sound pressure level that the wearer would be exposed to without hearing protection.

You may choose from a number of different rating schemes or you may use all rating schemes simultaneously as shown in the following figure. However, it is likely that the manufacturer may only supply data for one rating scheme. In the bottom scheme in the following figure, it is necessary to enter the SNR for the Low, medium and high frequency ranges. A label of " marginally overprotected" is applied when the protected level, $L_{\mathrm{prot},A}$, is between 70 and 84 dBA and a label of "overprotected" is applied when the protected level, $L_{\mathrm{prot},A}$, is below 70 dBA.



In the calculation of $L_{\mathrm{prot},A}$ based on NRR, it is necessary to also specify a derating factor to the manufacturer's NRR value, depending on whether NIOSH or OSHA guidelines are to be satisfied (see Table 2.9, page 109 in the 6th edition textbook).

To calculate $L_{\mathrm{prot},A}$ using the SLC_{80} method, the additional input of maximum expected sound pressure level external to the protection is required as illustrated at right.

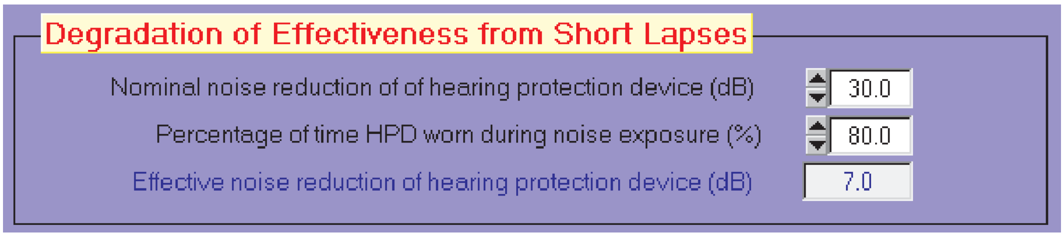


1.8.2 Percentage of Users Protected

Depending on the hearing protection rating system used, different percentages of people will achieve the noise reduction indicated by the rating scheme. You just need to enter the rating scheme and ENC will output the percentage of users who will achieve the rated noise reduction as shown in the following figure.

1.8.3 Calculation of the Effective Noise Reduction for Short Lapses in Wearing Hearing Protection

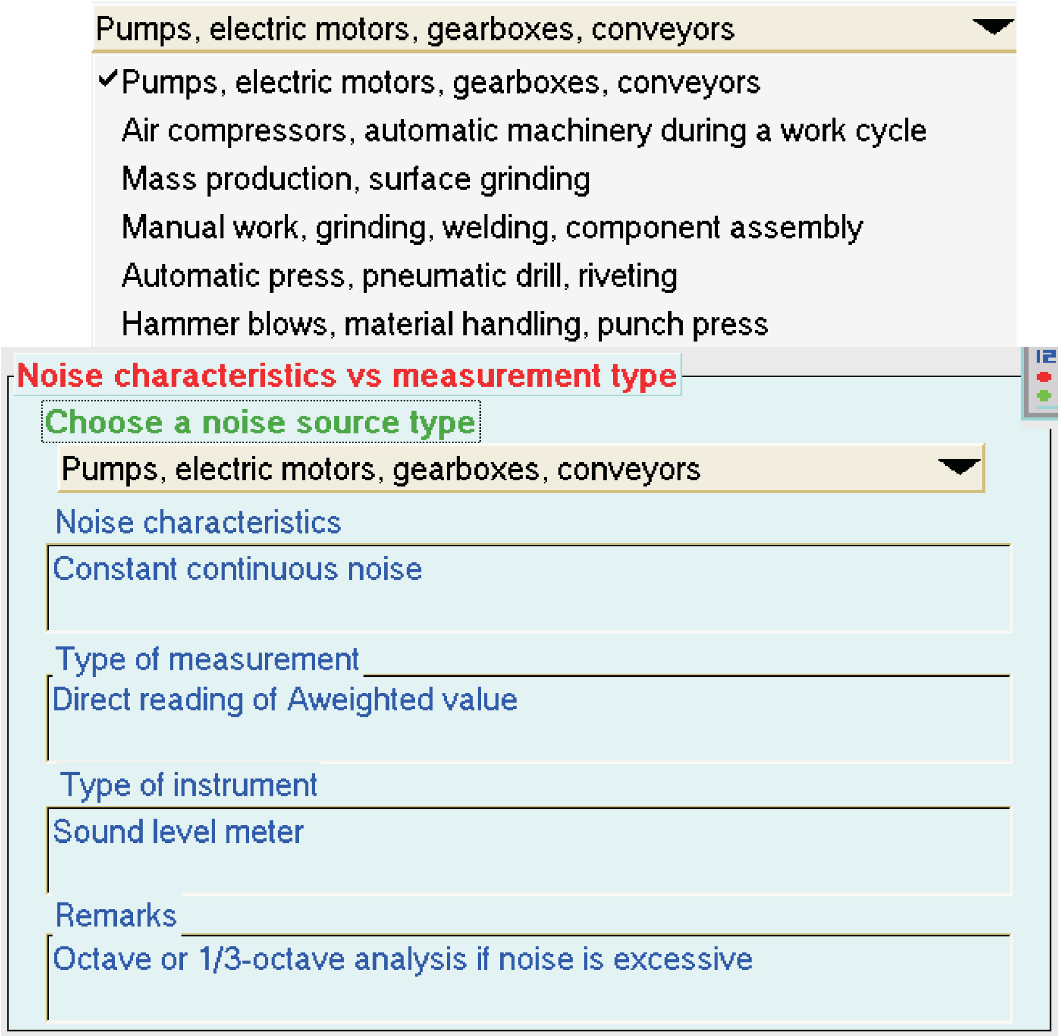
If the wearer of the hearing protection removes it for short periods of time, its effectiveness will be reduced. This part allows you to calculate the effective noise reduction of the hearing protection device given the nominal noise reduction of the device and the percentage of time that the hearing protection device is worn.



1.9 Instrumentation (6th edition textbook, page 147–183)

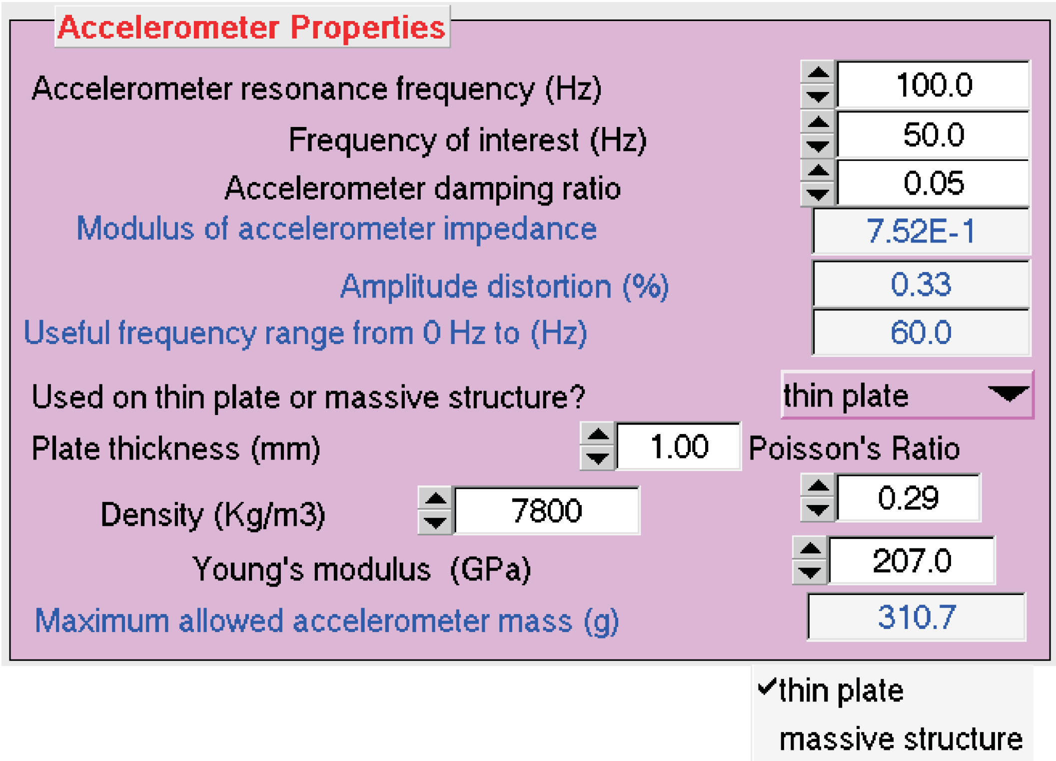
1.9.1 Noise Characteristics vs Measurement Type

This part of the page is based on Table 3.1, p. 163 in the 6th edition textbook. You choose a noise source type and ENC will use Table 3.1 to tell you what type of measurement should be used to characterise the noise, what type of instrument should be used to measure it and what type od data should be collected.



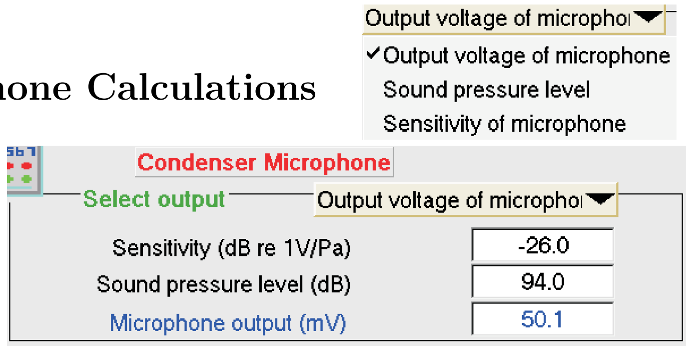
1.9.2 Accelerometer Properties

This part of the page allows calculation of the accelerometer impedance, the amplitude distortion in the acceleration measurement and the accelerometer useful frequency range. You need to input the accelerometer resonance frequency and its damping ratio as well as the frequency of interest for the output results.



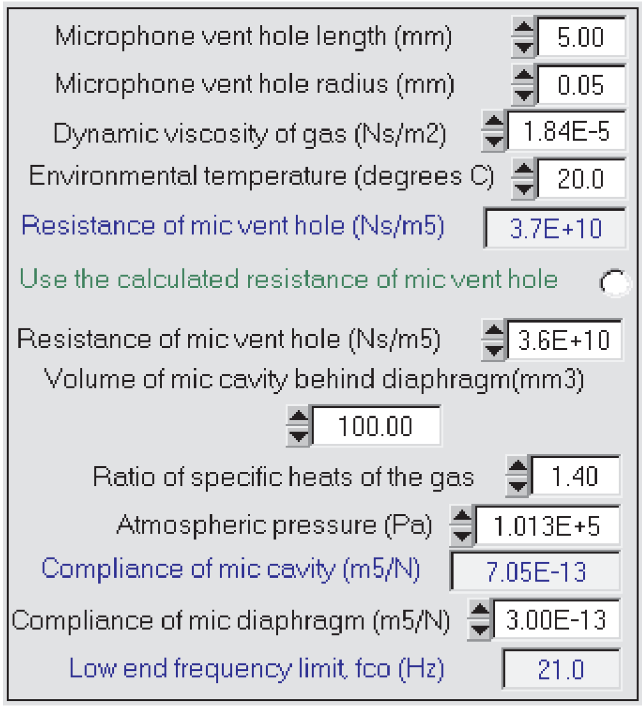
The maximum allowed accelerometer mass is also output by ENC once the type of structure and its properties, which are density, Poisson's ratio, Young's modulus and thickness (if it is a thin plate) are specified by the user.

1.9.3 Condenser Microphone Calculations



In the top section of the condenser microphone part (shown at right), You can enter any two of the three items of data and ENC will calculate the remaining item. The selected item for output is in blue font.

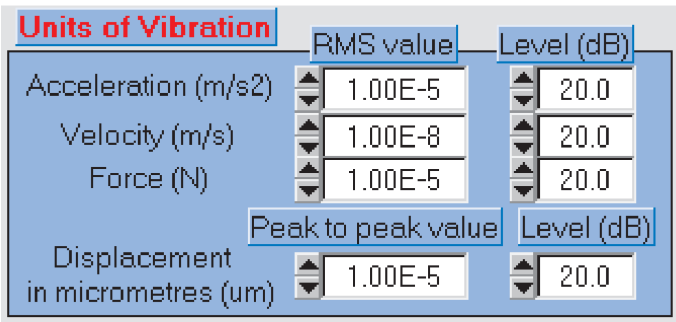
In the lower section of the condenser microphone part, you can calculate the resistance of the vent hole that equalises the mean pressure on the front and back sides of the microphone diaphragm. Alternatively, you can enter a value that you have for this resistance. Entering the microphone cavity volume and the properties of the medium in which the microphone is immersed allows ENC to calculate the cavity compliance. You need to enter the microphone diaphragm compliance and then ENC will use this together with the cavity compliance and the vent hole resistance to calculate the lower limiting frequency of the microphone response.



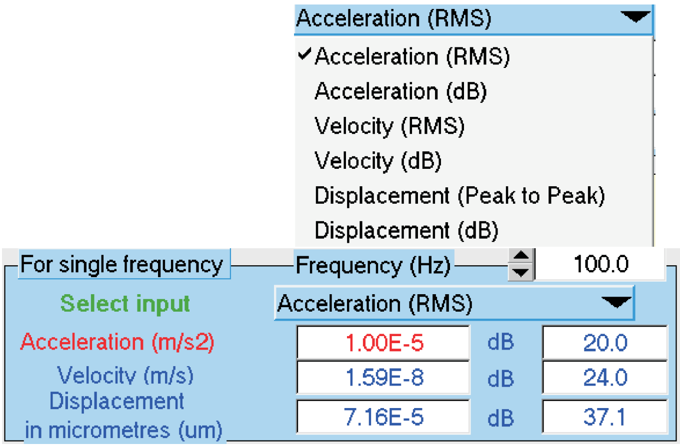
1.9.4 Units of vibration and Relationship Between Acceleration, Velocity and Displacement

The upper section of this part allows you to calculate the dB level for a given RMS value of acceleration, velocity, force or displacement, using the following reference quantities.

Quantity	Reference level	Units
Acceleration	10^{-6}	m/s^2
Velocity	10^{-9}	m/s
Displacement	10^{-6}	µm
Force	10^{-6}	N

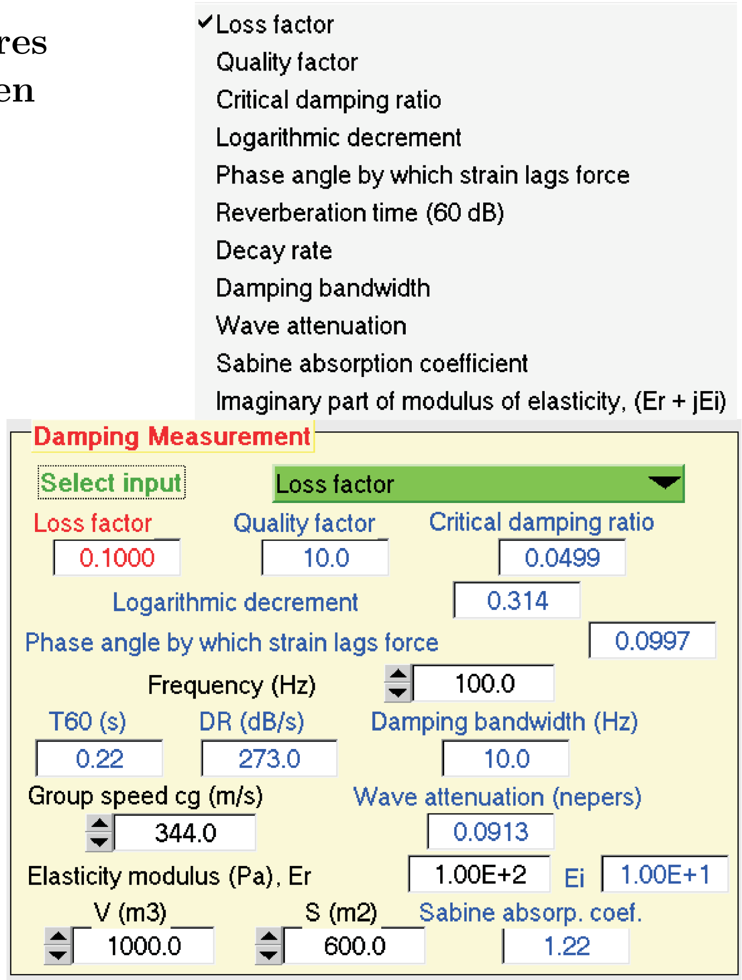


The lower section under the units of vibration heading allows you to select a frequency in Hz and then enter a vibration variable such as RMS or dB acceleration and the other vibration variables (velocity and displacement in this case) will be calculated for the selected frequency. The variable that is the input variable to be used to calculate the other quantities is indicated in red font.

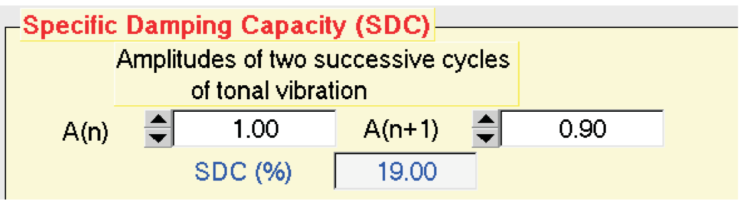


1.9.5 Damping Measures and Relations Between Different measures

This part of the page allows conversion between one measure of damping and any other measure and uses the relationships in Table 9.3 on Page 608 of the 6th edition textbook, where the symbols DR, E_i and E_r are also defined. The damping measure to be converted to other damping measures is selected as shown in the drop down menu in the figure at right. Additional data must be input to obtain some of the other damping measures. These data are in black font and the calculated data are in blue font. The choice of input damping measure to be converted to other damping measures is in red font.



At the bottom of the page, specific damping capacity (see figure at right) is treated separately as it cannot be obtained from the other damping measures. It is related to the difference in successive amplitudes of tonal vibration.



Chapter 2

Sound Sources & Sound Power (Module 2)

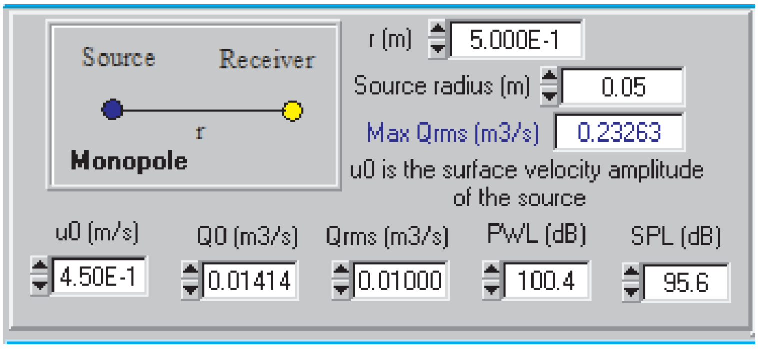
2.1 Overview

The software in module 2 is concerned with the calculations in Chapter 4 of the 6^{th} edition textbook. The software is divided into 4 separate windows, each of which is discussed below and each of which is represented by a unique icon on the tool bar. Simply click on the appropriate icon to select the window you want.

2.2 Point Sources (6^{th} edition textbook, pages 185–189)

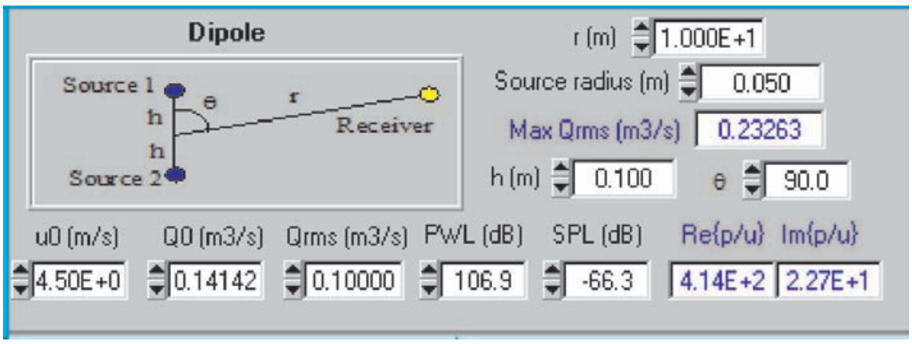
This window allows you to calculate the sound pressure level at a specified distance from a point sound source ignoring the effects of excess attenuation and the presence of reflecting planes, which are calculated on the “sound propagation” window. The types of source considered are monopole, dipole, oscillating sphere, quadrupole, line and vortex shedding. The relationship between source volume velocity and sound power is dependent on the source type. Clicking on the “Constants” button allows you to set the speed of sound and gas density for the calculations — see Section 0.6.4 of this manual for a full description. **I**MPORTANT: you must set the frequency and speed of sound before proceeding with any calculations in this panel (see below). Clicking on the “constants” button allows you to calculate the speed of sound by specifying the density, temperature and ratio of specific heats (1.4 for air).

2.2.1 Monopole Source (6th edition textbook, pages 185–189)



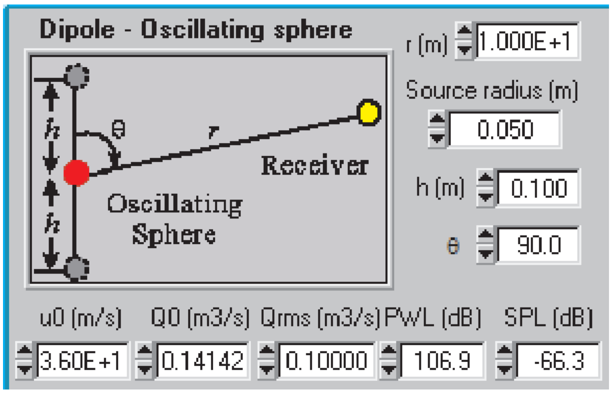
For a specified distance from a monopole source and for a specified source size (radius), you can calculate the relationship (equations 4.12, 4.13 and 4.14) between the surface velocity amplitude, u_0, of the source, the RMS source volume velocity (Q_{rms}), the source volume velocity amplitude (Q_0), the sound power level (PWL) and the sound pressure level (SPL) (as shown below). Simply enter in any one of these quantities, then for the distance, r, shown, the other two quantities will be calculated. The maximum possible RMS source volume velocity for the specified source radius is also shown (limited by the source surface velocity amplitude having to be less than or equal to the source radius).

2.2.2 Dipole Source (6th edition textbook, pages 190–196)



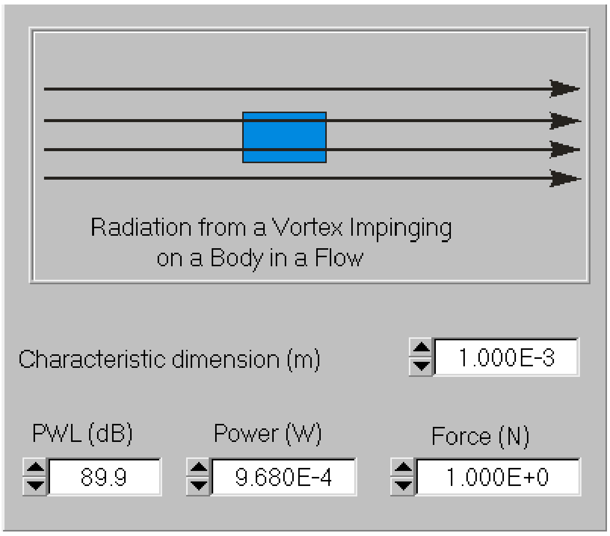
For a dipole source, the volume velocity, Q_{rms}, or Q_0 is the volume velocity of each of the monopoles making up the source and the surface velocity amplitude, u_0 is the velocity amplitude of each of the monopoles making up the source. You also need to define the distance, $2h$, between the monopole sources making up the dipole and the angle, θ, at which the sound pressure is measured. An additional output for the dipole source is the specific acoustic impedance at the specified distance, r, from the source.

The oscillating sphere represents a simple source oscillating sinusoidally between two locations that are close together (separated by $2h$) and requires a similar set of input data as the dipole source.



2.2.3 Radiation From a Vortex Impinging on a Rigid Body in Flow
(6th edition textbook, pages 194–196)

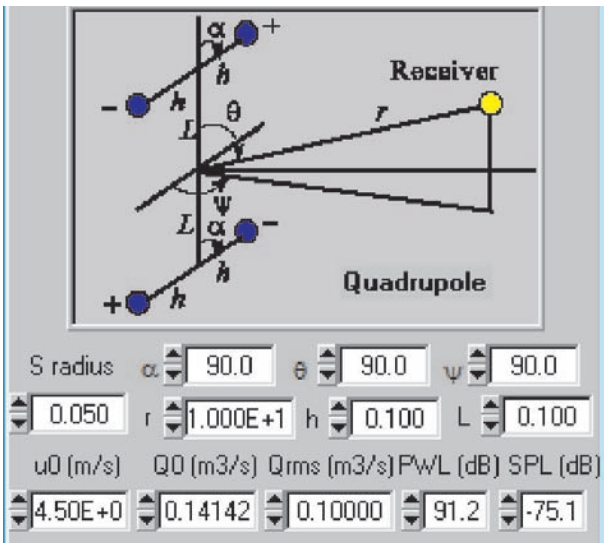
Here Equation (4.55) is evaluated. You may enter Sound power level, power in watts or force exerted by the vortex on the downstream body. ENC will then calculate the other two quantities.



2.2.4 Quadrupole Source (6th edition textbook, pages 196–200)

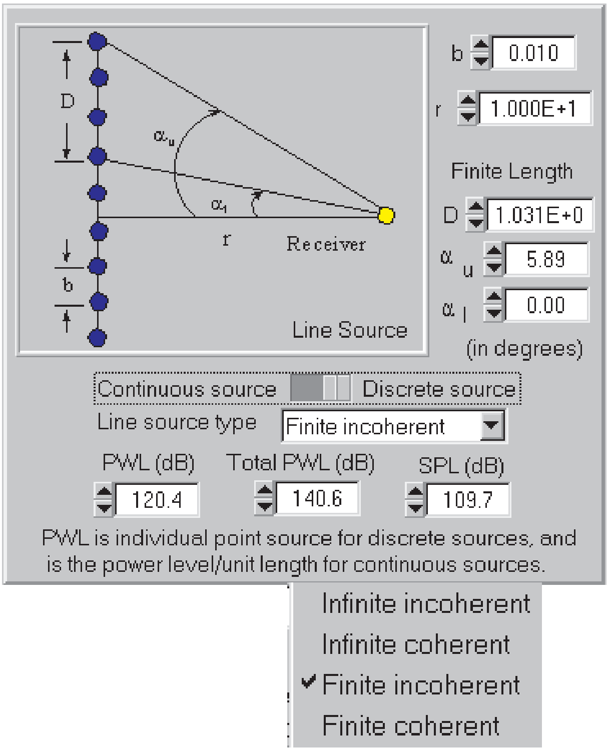
For the quadrupole source, which is made up of 2 dipole sources, you need to define the separation, $2h$, between the monopole sources making up each dipole and the distance, $2L$, between the two dipole sources. You also need to enter the angle, α, between the axis of the two dipoles making up the quadrupole and the quadrupole axis, as well as the angles, θ and ψ, that define the location of the sound pressure measurement.

If the angle, $\alpha = 0$, then you have a longitudinal quadrupole and if $\alpha = 90°$ degrees, you have a lateral quadrupole.



2.3 Line Sources and Directivity (6th edition textbook, pages 200–203, 214)

2.3.1 Line Source (6th edition textbook, pages 200–203)



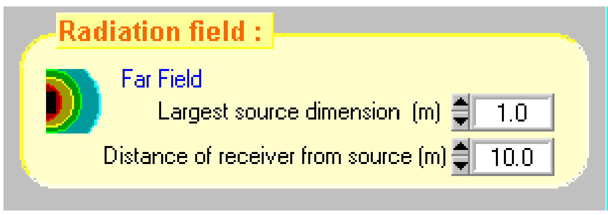
For the line source (see next page), there are 4 types of basic source (equations 4.80, 4.82 and 4.87):

1. incoherent infinite;
2. coherent infinite;
3. incoherent finite;
4. coherent finite;

Each source may be either continuous or made up of discrete sources. You must choose the option that suits your application. An example of a continuous source is a pipeline and an example of a discrete line source is traffic. If the line source is finite in length and made up of discrete monopoles, then you need to specify the separation distance, b, between adjacent monopoles, one of the angles, (α_ℓ or α_u) subtended by the source at the observation location and 2 out of 3 of the quantities: normal distance, r, from the source axis to the observer; length, D, of the line source; and the other angle (α_ℓ or α_u) not already entered. Note that for a source of infinite length, the software ignores the input data mentioned above, except for the (closest) distance, r, of the observer from the source axis and the source separation, b. Once the above data are entered, you can enter either the sound pressure level (dB) at the measurement location (observer) and read the source sound power level or enter the source sound power level and read the sound pressure level (dB) at the measurement location.

For a finite length coherent source, at distances greater than $0.5D$, the calculation is the same as for an incoherent finite length line source. For small distances ($< 0.1D$) from the line source axis, the calculation is the same for an infinite coherent line source. At in between distances, linear interpolation (dB vs distance) between the above two cases is used.

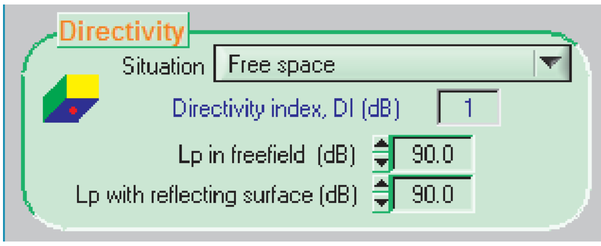
2.3.2 Radiation Field (6th edition textbook, pages 219–220)



As we move further from a sound source, we move from the near field to the far field. The near field is made up of a hydrodynamic part and a geometric part. This panel (see below) indicates which type of field the observer is in for a specified frequency, source size and distance from the acoustic centre of the source. The frequency is entered in the top right panel.

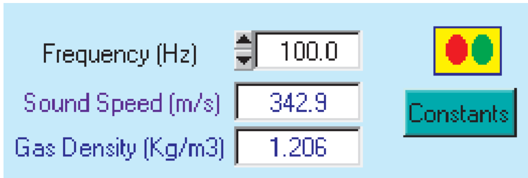
2.3.3 Directivity (6th edition textbook, page 214)

Here you can calculate the effect that reflecting surfaces adjacent to the sound source have on the sound pressure level at a fixed distance from the sound source.



2.4 Plane Sound Sources (6th edition textbook, pages 203–213)

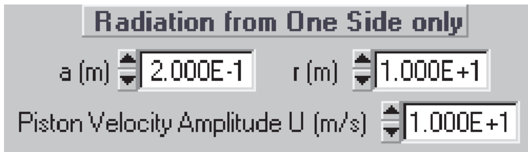
This panel calculates sound radiation fields for plane piston sources and also plane rectangular incoherent sources vibrating at a single frequency. IMPORTANT: you must set the frequency and speed of sound before proceeding with any calculations in this panel (use the top right panel). Clicking on the “constants” button allows you to calculate the speed of sound by specifying the density, temperature and ratio of specific heats (1.4 for air).



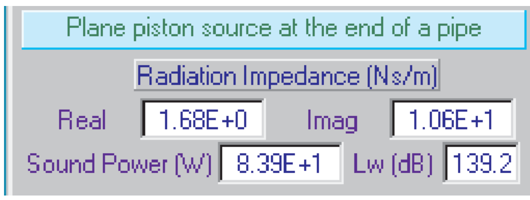
2.4.1 Coherent Piston Source (6th edition textbook, pages 203–209)

2.4.1.1 Input Data

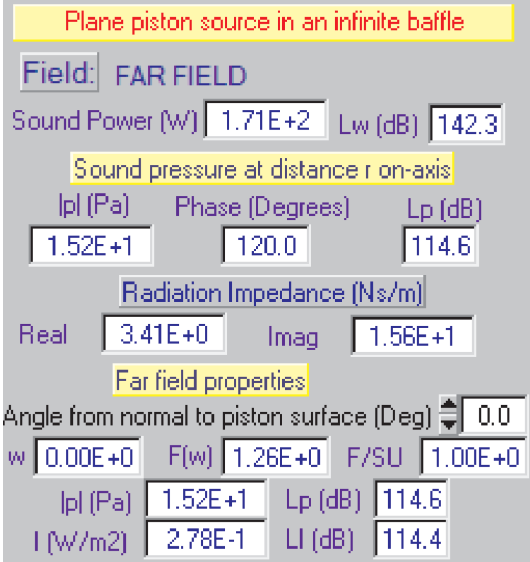
The piston source is a plane circular surface for which all points on the surface are vibrating in phase. As shown in the figure at right, the required input data are the radius of the plane piston, the distance at which the sound pressure is to be evaluated and the amplitude of the velocity of the piston surface. As the piston vibration is at a single frequency, the velocity amplitude is 1.414 times the RMS piston velocity. The frequency, sound speed and gas density set in the top right corner of this page are used in all calculations.



The radiation impedance and radiated sound power for a plane piston source mounted in the end of a pipe with no surrounding baffle is calculated and the results provided as shown in the figure at right.

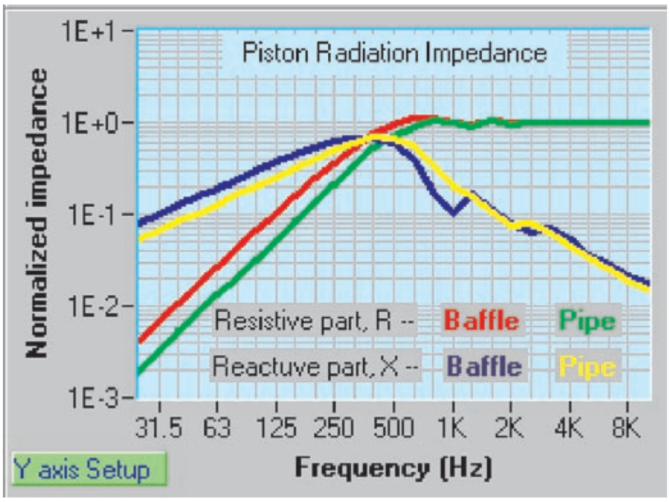


For a plane source vibrating with a uniform velocity amplitude, U, and mounted in an infinitely large baffle (in practice, larger than 3 wavelengths), the lower part of this panel allows you to calculate the sound power level, the sound power in watts (Equation (4.115)), the on-axis sound pressure amplitude, $|p|$, in Pa (Equation (4.101)) and the sound pressure level (dB) at distance r from the plane surface, the phase of the sound pressure (relative to the surface velocity), and both the real and imaginary parts of the radiation impedance (Equation (4.110)). The real part is is the radiation efficiency multiplied by $\pi a^2 \rho c$.

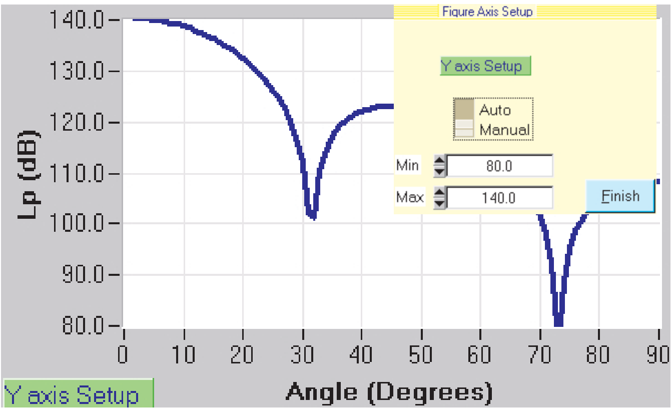


ENC calculates whether the receiver point is in the near field, transition field or far field ("Field" button) and uses Equation (4.101) for calculating on-axis sound pressure. The quantity to the right of the "Field" button tells you whether the specified distance, r (m) is in the far field or near field of the piston source (using relations on page 219 of the 6$^{\text{th}}$ edition textbook). If the location is in the near field or transition between near and far fields, the far field parameters at the bottom of the window are "greyed out". The off-axis pressure can only be calculated for the far field and this uses Equation (4.101).

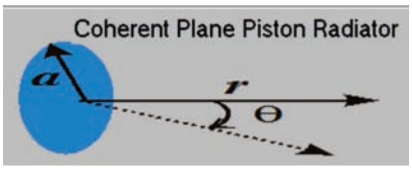
The normalised radiation impedance ($Z_R/(\rho c \pi a^2)$), where A is the piston radius, is numerically the same as the radiation efficiency and is plotted as a function of frequency as shown at right.



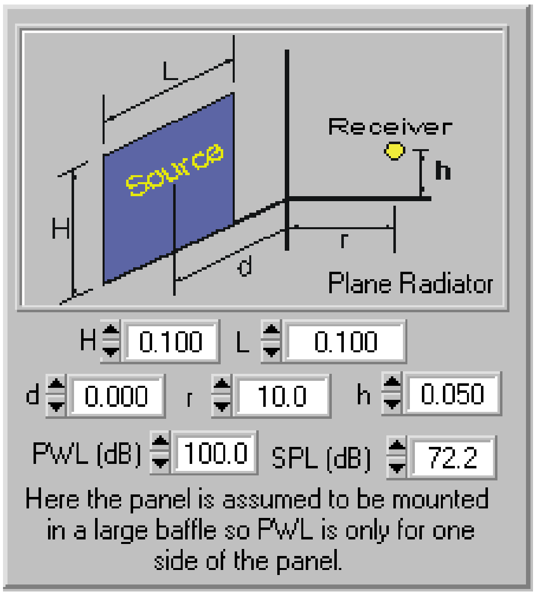
The blue and red lines in the radiation impedance figure represent sound radiation from one side of a piston sound source mounted in an infinitely large baffle. For practical purposes, a baffle that has a minimum dimension of three or more wavelengths is a good approximation to an infinitely large baffle. The green and yellow lines in this figure represent sound radiation from one side of a piston mounted in the end of a pipe with no baffle present.



The coherent piston source panel also provides (only for the case of the piston in an infinite baffle) the far field sound pressure amplitude and level as well as the sound intensity and level at a specified distance from the piston surface and specified angle θ, from the normal to the piston surface (see figure at right). The sound pressure level as a function of angular location is also plotted (see figure at right). Note that you can select the maximum and minimum values on the y-axis by clicking on "y-axis setup" button under the graph.



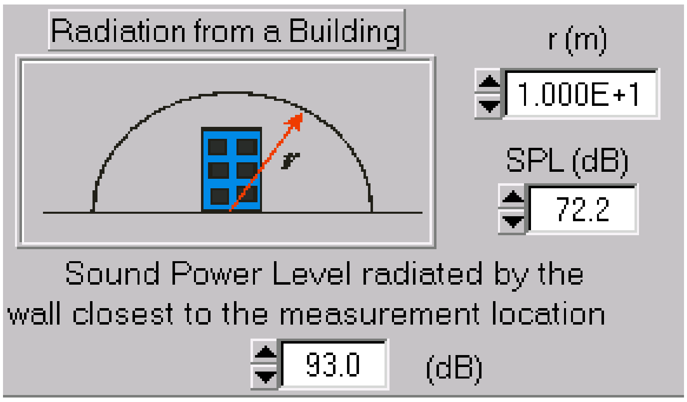
2.4.2 Incoherent Plane Radiator (6th edition textbook, pages 210–213)



This calculation (done in the left panel of the window) assumes that the source is an incoherent radiator, mounted in a large baffle and radiating from only one side. It is not for single frequency modal radiation, but is a good approximation for broadband sound radiation.

To calculate the relationship between the sound power radiated by a plane source and the sound pressure at the measurement point, you need to specify the distance of the centre of the source from the origin of the coordinate axes, which in turn are defined as being parallel to each of the two sides of the rectangular source and normal to its surface. The observer is assumed to lie in the plane formed by the vertical and normal axes and the source is assumed offset from this plane along the horizontal axis by a distance, d. The location of the observer (or measurement point) is defined by a distance, r, along the normal axis (see figure). You also need to enter the dimensions, $H \times L$, of the plane source and the height, h, of the receiver above the base of the rectangular source. If the source is not rectangular in shape, then you will obtain excellent results by approximating it as a rectangular source of the same area. Having input the data, you can enter either the sound pressure level (dB) at the observer location and read the source sound power level or enter the source sound power level and read the sound pressure level (dB) at the measurement location (calculated using Equations (4.121) and (1.87)).

2.4.3 Radiation From a Building (6th edition textbook, page 213)

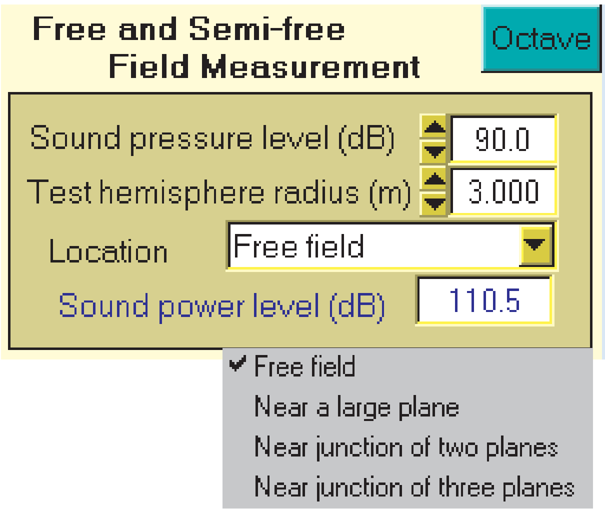


This panel allows you to calculate the sound pressure level at a distance, r, from a building. This calculation assumes that the building is on hard ground so the excess attenuation due to the ground is −3 dB. The distance from the building for which the calculation is valid is greater than the maximum building dimension. Excess attenuation effects would have to be included using module 3 — sound propagation. The excess attenuation due to the ground (if it is not concrete or asphalt) could be included by calculating it according to module 2 and then subtracting (−3) dB or adding 3 dB (that is making the excess attenuation less negative).

2.5 Sound Power Measurement (6th edition textbook, pages 221–238)

This panel enables you to calculate machine sound power levels from sound pressure measurements for a range of test methods. The test methods are divided into anechoic room, reverberation room, field and near field. Each of these are discussed below. The calculation can be done for any frequency by entering appropriate values into this panel or it can be done for all octave bands simultaneously by clicking on “octave”.

2.5.1 Free and Semi-Free Field (6th edition textbook, pages 223–226)



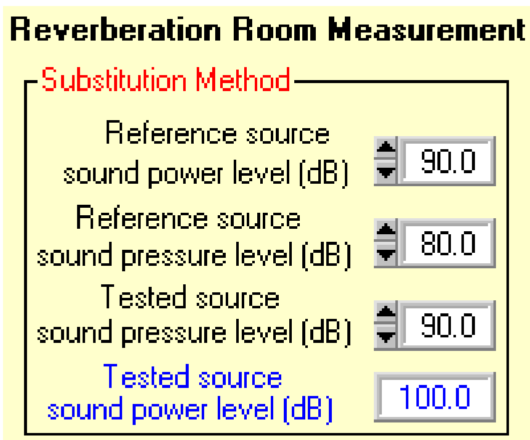
For measurements in free or semi-free field, Equations (4.142) to (4.144) in the 6th edition textbook are used. The average sound pressure level measured on a test hemisphere surrounding the source is entered in the panel along with the test hemisphere radius.

The average sound pressure level is calculated from a number of discrete measurements using Equation (4.142), which is evaluated in the “Easy SPL averager” panel shown below. Clicking on the “Constants” button in this figure allows you to set the speed of sound and gas density for the calculations — see Section 0.6.4 in this manual for a full description.

2.5.2 Reverberant Field (6th edition textbook, pages 226–230)

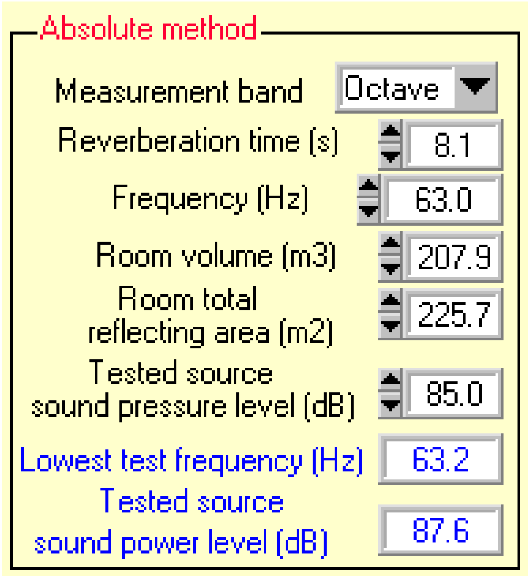
The two distinct methods for determining the sound power level from reverberant field measurements are described in the following paragraphs.

2.5.2.1 Substitution Method (6th edition textbook, pages 229 and 230)



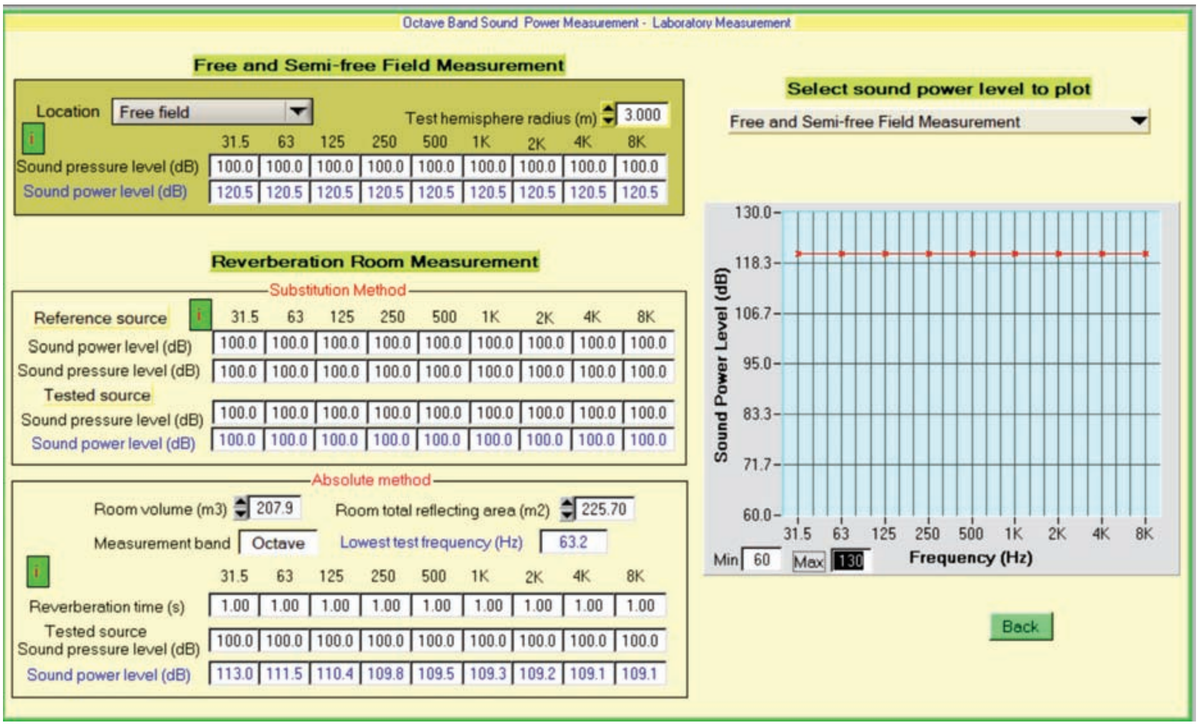
The substitution method involves placing a reference source of known sound power level in the octave or 1/3-octave band of interest in the room and measuring the resulting sound pressure level. The reference source is then replaced with the source to be tested and the sound pressure level is measured again. Equation (4.147) in the 6th edition textbook is then implemented in this panel to determine the sound power level for the tested source.

2.5.2.2 Absolute Method (6th edition textbook, pages 228–229)

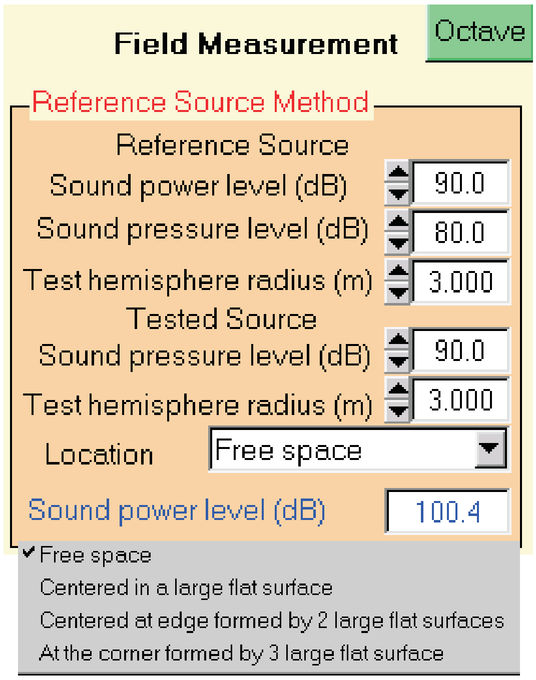


The absolute method involves measuring the room reverberation time with the machine to be tested in place and measuring the sound pressure level in the room with the machine in operation. There is a dialog box at the top asking whether the tests are in octave bands, 1/3-octave bands or discrete frequencies. The room volume and total area of all reflecting surfaces (including the room boundaries) must also be entered. The lowest frequency at which the test will provide valid results is calculated by ENC using the discussion on page 229 of the 6th edition textbook.

Octave band data can be calculated and plotted by clicking on "octave" at the top of the panel. When you do this the window shown in the following figure appears. The graph automatically plots the selected spectrum. You can adjust the upper and lower limits of the plot to suit your data.



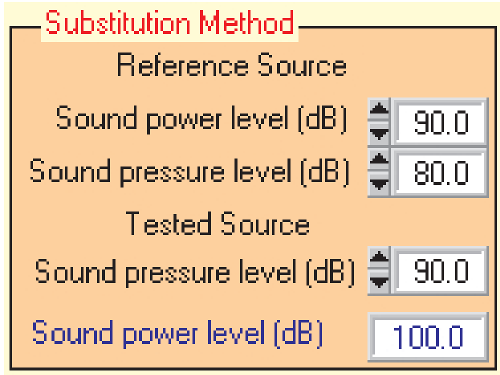
2.5.3 Field Measurement (6th edition textbook, pages 228–238)



There are three choices of method for making far field sound power measurements on a machine in-situ. These are each described below. The calculation can be done for any frequency by entering appropriate values into this panel or it can be done for all octave bands simultaneously by clicking on "octave" which produces the windows shown on the next page.

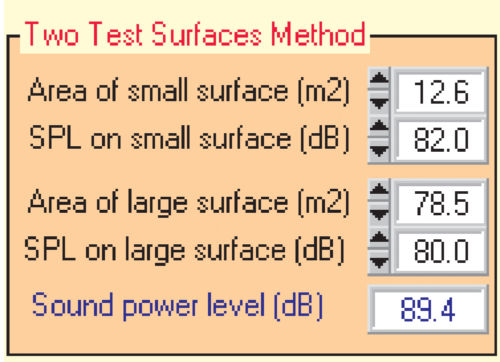
2.5.3.1 Reference Source Method (pages 228–229)

This method uses a reference source of known sound power output and the corresponding measured sound pressure level averaged over the room volume to determine the room constant (with the test machine switched off). This is then used with the sound pressure measurements with only the test source operating to determine the sound power level of the test source. Note that this method requires that all other equipment in the room be turned off during the measurements. The "location" information (see drop down menu at right) is needed so that the presence of 1 or more reflecting planes on the sound pressure level can be taken into account. This is done by adding 3dB to the direct field component for each reflecting plane.



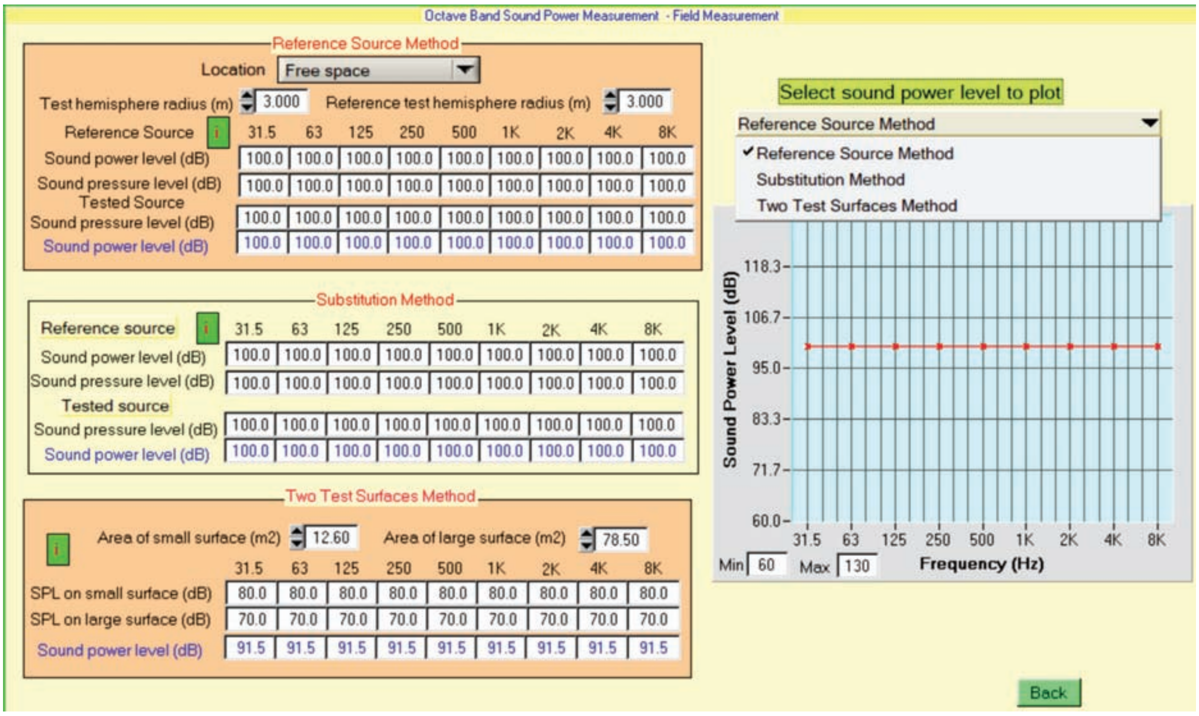
2.5.3.2 Substitution method (pages 229–230)

This method essentially replaces the test machine with a reference sound source of known sound power level. The sound pressure due to the machine and then due to the substituted reference source operating alone are then used to calculate the sound power of the machine (6th edition textbook, Equation (4.154)).



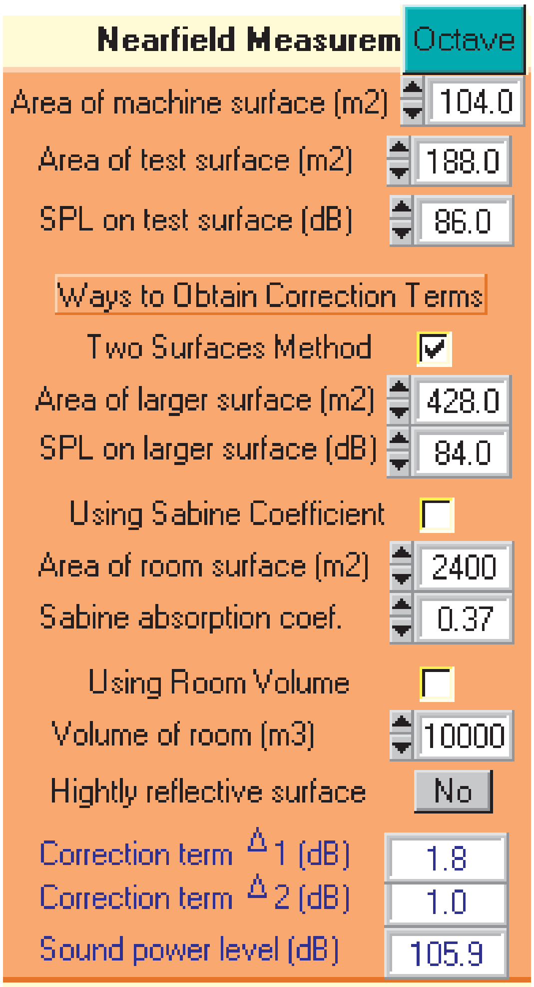
2.5.3.3 Two Test Surfaces Method (6th edition textbook, pp 230–231)

This method involves taking sound pressure level measurements over two test surfaces that completely surround the machine. The area of one test surface should be at least twice that of the other.

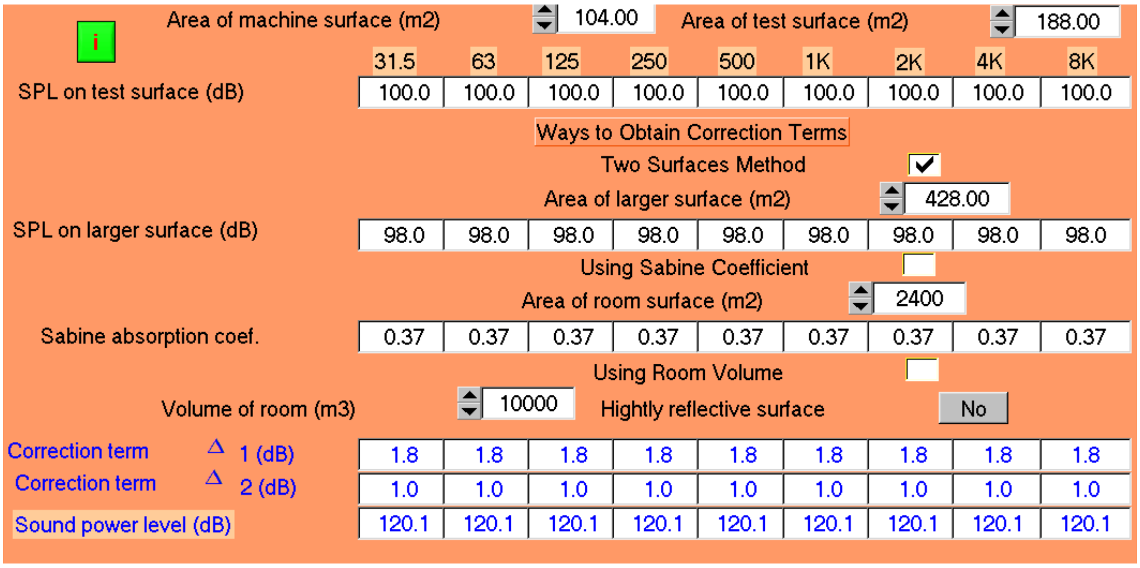


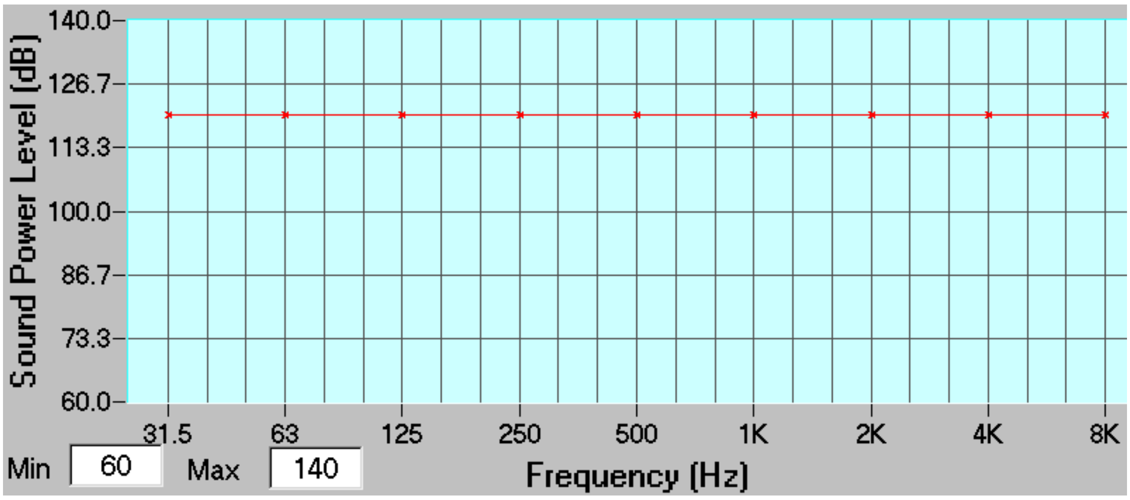
2.5.4 Near Field Measurement (6th edition textbook, pages 231–234)

This method evaluates Equation (4.160) and allows the user to select one of three possible ways of determining the value of the constant, Δ_1. The three methods are discussed in detail in the 6th edition textbook, and each requires different input data. The methods decrease in reliability from the top of the panel to the bottom. The method at the top of the panel requires sound pressure level measurements on two test surfaces, with the larger test surface having at least twice the area of the smaller one. The next method uses knowledge of the room surface area and average Sabine absorption coefficient to calculate correction term, Δ_1. Module 4 can be used to find the average absorption coefficient for cases where they are different for each of the room surfaces. The third method uses the values in Table 4.6, p.232 in the 6th edition textbook. The constant, Δ_2 is calculated using the values in Table 4.5, p.232 in the 6th edition textbook. The panel used for the calculations is shown at right.

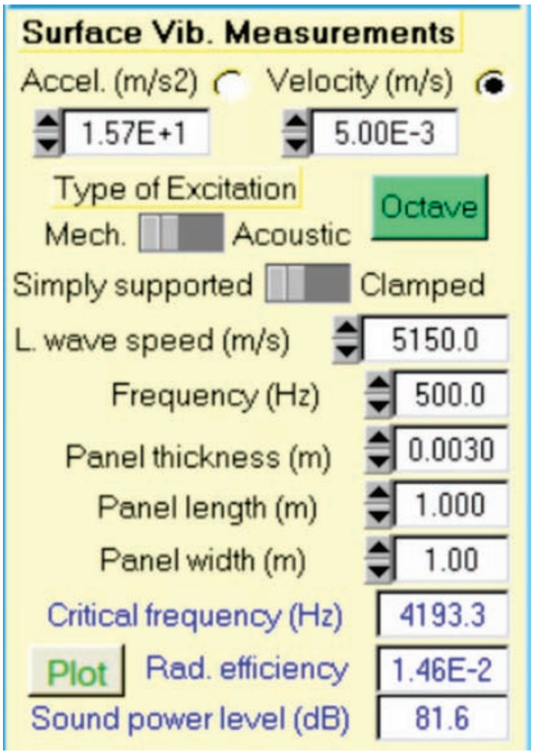


The calculation can be done for any frequency by entering appropriate values into this panel or it can be done for all octave bands simultaneously by clicking on “octave” which produces the window shown below. The octave band sound power level is plotted as shown in the figure on the next page.



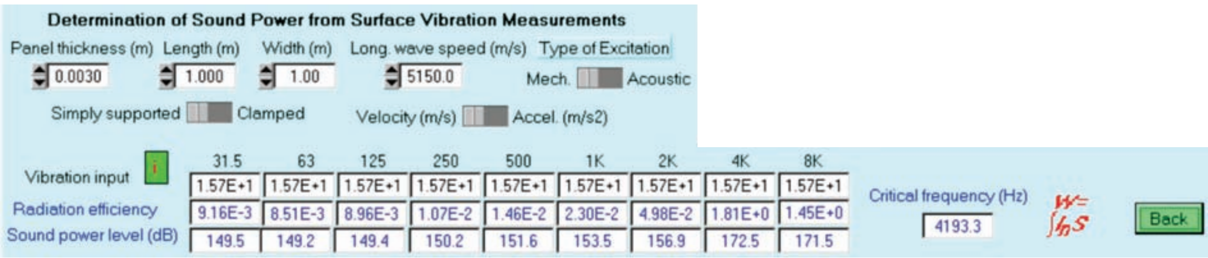


2.5.5 Determination of Sound Power From Surface Vibration Measurements (pages 241–244)



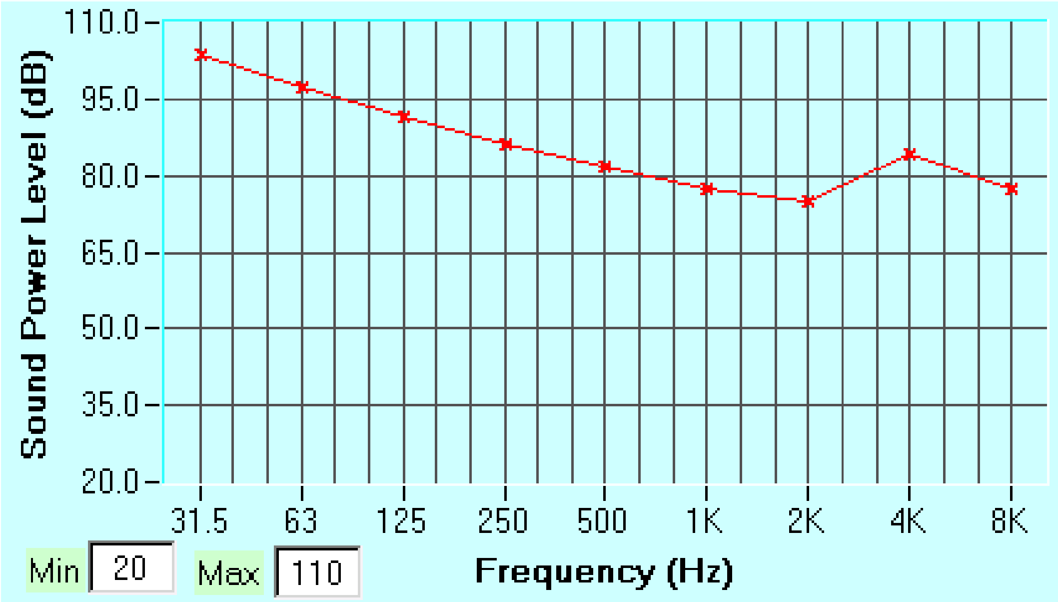
This panel (shown at right) effectively evaluates Equation (4.179) in the 6th edition textbook for sound radiation from a simply supported steel or aluminium panel. The calculation can be done for any frequency by entering appropriate values into this panel or it can be done for all octave bands simultaneously by clicking on "octave" which produces the window shown on the next page.

The most difficult parameter to estimate is the radiation efficiency, so this panel can only be used for sound radiation from rectangular shaped panels. In practice, most machine and enclosure panels have edge conditions that may be approximated as simply supported. The radiation efficiency may be calculated for mechanical excitation (resonant response) or acoustic excitation (forced response). You can choose which type of excitation using the Mech.–Acoustic slider. The radiation efficiency and sound power level outputs correspond to the chosen frequency of excitation (Hz) and the excitation level (velocity or acceleration), as well as the panel dimensions and longitudinal wave speed which are all entered by the user. A plot of the radiation efficiency as a function of frequency is obtained by clicking on the "Plot" button.

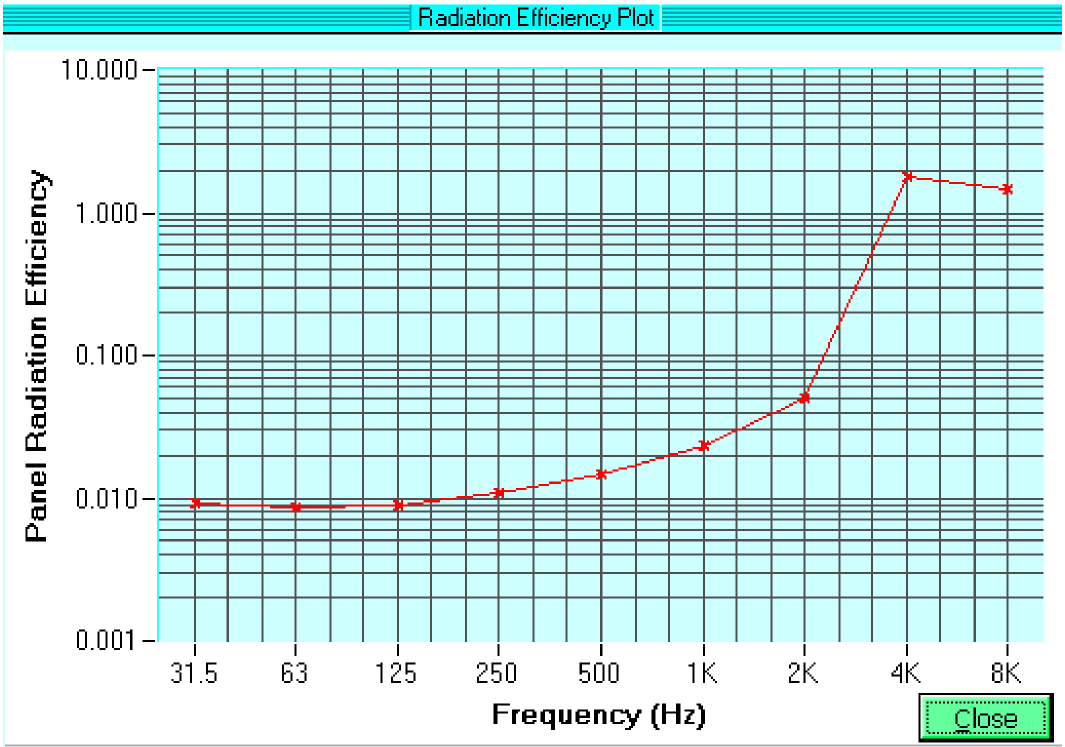


For clamped plate radiation efficiency calculations, the fundamental resonance frequency, f_{11}, for clamped plates is set equal to $Q \times f_{11}$ for simply supported plates, where $Q = 1.83$ for a square plate, $Q = 1.89$ for $a = 1.5b$, $Q = 1.99$ for $a = 2b$, $Q = 2.11$ for $a = 3b$, $Q = 2.23$ for $a = 6b$, $Q = 2.25$ for $a = 8b$ and $Q = 2.26$ for $a >= 10b$, where a and b are the plate dimensions. Interpolation is used to calculate f_{11} for in between values of the a/b ratio. Also for clamped edge plates in the frequency range below f_c, the radiation efficiency is set as 3 dB higher than that calculated for a simply supported plate (Equations on page 242 of the the 6th edition textbook).

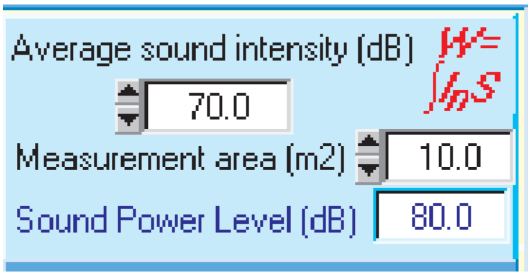
As input data, you must enter the frequency of interest and either the space averaged acceleration or the space averaged velocity. If acceleration is selected, velocity is calculated by the software and vice versa. You must also enter the longitudinal wave speed in the panel and the panel area, thickness and perimeter. The outputs are the panel radiation efficiency (or radiation ratio), the critical frequency and the radiated sound power. The radiated sound power is plotted in the window that appears when you click on "octave" (see following figure).



To see a plot of the radiation efficiency as a function of frequency for the panel you have specified, click on the "Plot" button and the following figure appears.

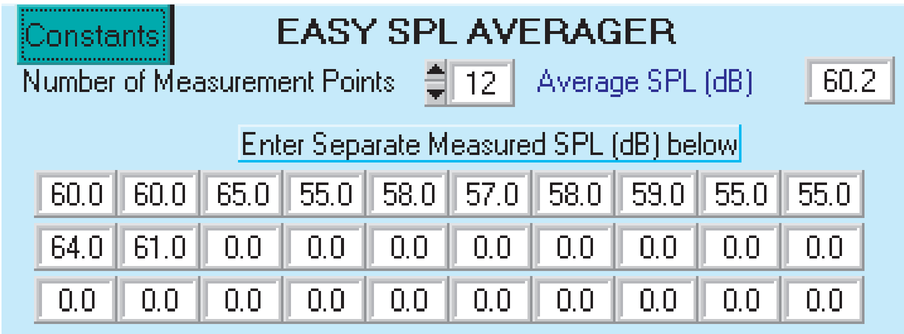


2.5.6 Determination of Sound Power From Sound Intensity Measurements



This calculation is done in the top right hand corner of the page (see figure at right). The input data are the average sound intensity, I_n over an imaginary surface (and normal to that surface) that completely surrounds the source and the area, S, of this imaginary surface. The output is the sound power level, L_W, radiated by the source and is calculated where $L_W = 10\log_{10}(I_nS) + 120$ (dB re 10^{-12} W).

2.5.7 Easy SPL Averager



To find the energy average of a number of sound pressure level or sound power level measurements (or any dB measurements), enter the number of measurements of interest and the dB values of each in the table (see discussion under free field measurement).

2.6 Rayleigh Integral

The purpose of this section is to allow a very approximate calculation of the sound power radiated by a number of connected plane surfaces as discussed in the textbook on page 692–693. ENC allows you to break up the construction into a number of plane surfaces. The larger the maximum dimension of the surface, the lower will be the upper frequency limit for which the analysis is valid. So to increase the upper frequency limit, the size of each plane surface must be reduced. The Rayleigh Integral analysis method is valid for plane surfaces mounted in an infinite rigid baffle and radiating into free space. It is assumed that sound radiating from the rear of the surface cannot interfere with sound radiating from the front side. The sound power radiated by one of the component surfaces is calculated by calculating the sound pressure radiated to some arbitrary point in the far field. Octave or 1/3-octave band analysis is assumed so the radiation from each component surface is assumed to be incoherent with that radiated by the other component surfaces. The assumption of incoherence is not often satisfied completely, so this method may result in some inaccuracy in the overall sound power estimate. However, the method can be very useful for determining expected overall sound power reductions that can be achieved by changing the vibration levels on one or more of the component surfaces. As octave or 1/3-octave band analysis is used, only RMS velocity inputs are required and no phase information is needed. The maximum dimension of each component surface is needed to establish the upper limiting frequency. The area of the component surface and the RMS surface velocity averaged over the area of the component are used to calculate the sound power radiated by the ith component to the far field using:

$$L_{W,i}(f) = 10\log_{10}\left[\frac{2\pi f^2\rho\,[v_{\text{RMS}}(f,i)]^2\Delta S_i^2}{c}\right] + 120$$

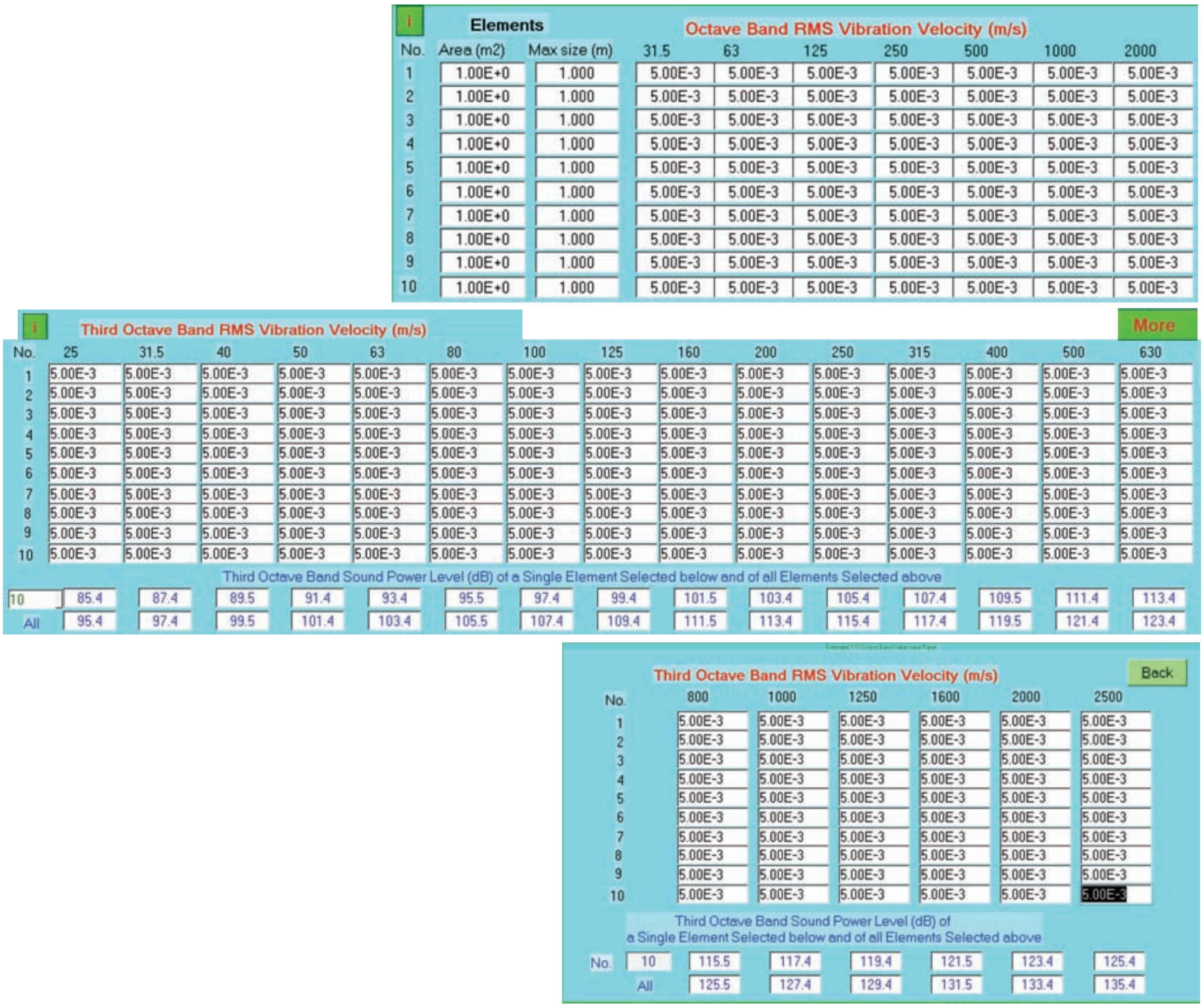
where ΔS_i is the component surface area, ρ is the density of air, c is the speed of sound in air, f is the band centre frequency and $v_{\text{RMS}}(f,i)$ is the RMS velocity averaged over the surface of the element.

The total radiated sound power, $L_W(f)$, for each frequency band, f, defined in the input data is:

$$L_W(f) = 10\log_{10}\sum_{i=1}^{N} 10^{L_{W,i}(f)/10}$$

If the plane surfaces make up an enclosure, it may be desired to determine the relative sound power levels radiated by each surface for the purpose of determining the effectiveness on interior noise levels of any application of vibration suppression or excitation force control. For this purpose, a very rough approximation is to assume that the same sound power is radiated into the interior of the enclosed space as would be radiated externally. It is also assumed that the effect of the absence of the infinite baffle would be the same for all surfaces, especially since sound radiated from the external side of the surface does not interfere with the sound field radiated to the interior of the enclosure. Such an approach has been used in the past to evaluate the potential effectiveness of noise control treatment of an armoured personnel carrier for the purpose of reducing interior noise levels.

The page for the Rayleigh Integral calculations is shown below. You can input RMS velocity data manually into ENC for each 1/3-octave or octave band of interest or you can use a spreadsheet formatted in exactly the same way as the file obtained by right clicking on the green box with the "i" in it, shown at right. There is one green box for octave band data and one for 1/3-octave band data. The main page shows octave band data from 31.5 Hz to 2 kHz and 1/3-octave band data from 25 Hz to 630 Hz. 1/3-octave band data from 800 Hz to 2.5 kHz can be entered by clicking on the "More" button.



No.	Elements: Area (m2)	Max size (m)	31.5	63	125	250	500	1000	2000
1	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
2	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
3	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
4	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
5	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
6	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
7	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
8	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
9	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
10	1.00E+0	1.000	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3

Octave Band RMS Vibration Velocity (m/s)

Third Octave Band RMS Vibration Velocity (m/s)

No.	25	31.5	40	50	63	80	100	125	160	200	250	315	400	500	630
1	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
2	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
4	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
5	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
6	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
7	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
8	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
9	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
10	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3

More

Third Octave Band Sound Power Level (dB) of a Single Element Selected below and of all Elements Selected above

10	85.4	87.4	89.5	91.4	93.4	95.5	97.4	99.4	101.5	103.4	105.4	107.4	109.5	111.4	113.4
All	95.4	97.4	99.5	101.4	103.4	105.5	107.4	109.4	111.5	113.4	115.4	117.4	119.5	121.4	123.4

Third Octave Band RMS Vibration Velocity (m/s)

Back

No.	800	1000	1250	1600	2000	2500
1	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
2	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
4	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
5	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
6	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
7	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
8	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
9	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3
10	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3	5.00E-3

Third Octave Band Sound Power Level (dB) of a Single Element Selected below and of all Elements Selected above

No. 10	115.5	117.4	119.4	121.5	123.4	125.4
All	125.5	127.4	129.4	131.5	133.4	135.4

ENC calculates the octave band sound power data for each plane surface component. For this calculation, either octave band RMS surface velocity can be used or, alternatively, 1/3-octave band data may be used. The choice is made by selecting the appropriate option from the drop-down menu (see following figure. You can click on the blue box containing the "o" symbol to export the calculated data to a text file.

ENC will calculate data for each element that has a box ticked in the sound power table shown on the next page. To tick or untick a box, just left click on the box.

Octave band sound power level with 1/1 octave band RMS vibration velocity (dB)
✔Octave band sound power level with 1/3 octave band RMS vibration velocity (dB)

31.5	63	125	250	500	1000	2000	Upper limit Freq. (Hz)	
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
92.5	98.5	104.5	110.5	116.5	122.5	128.5	85.7	✔
102.5	108.5	114.5	120.5	126.5	132.5	138.5	85.7	Overall

Overall	
dB	134.7
dBA	135.5

Chapter 3

Sound Propagation (Module 3)

3.1 Overview

The software in module 3 is concerned with the calculations in Chapter 5 of the 6^{th} edition textbook. The software is divided into 3 separate windows, each of which is discussed below and each of which is represented by a unique icon on the tool bar. Simply click on the appropriate icon to select the window you want. There are 3 main sections in this chapter corresponding to the 3 headings at the top of the page (ENC 6th version, CONCAWE and ISO9613). Each main section has similar sun headings so make sure that you are in the correct main section when reading sub heading material.

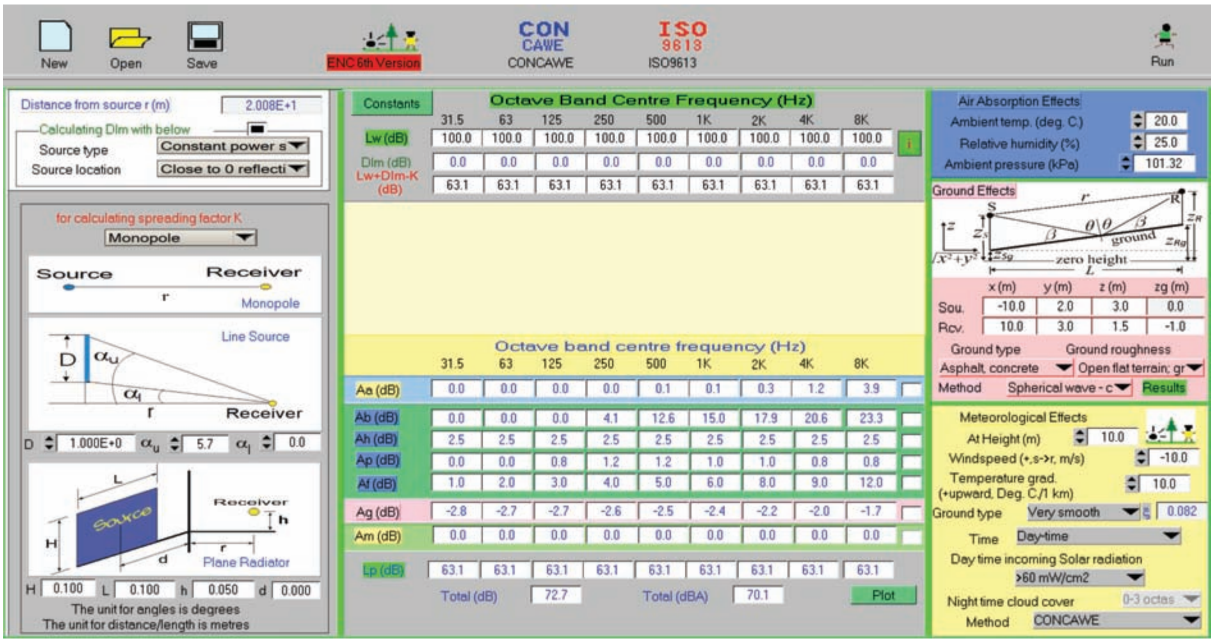
In all three pages, the z-coordinate is relative to an arbitrary origin, but it must be the same for everything on the page. Note that in some instances, the z-coordinate is set equal to 0.0 below the source, so in these cases all z-coordinates must be relative to that one. Also note that the z-coordinates of the source, receiver and barrier top, respectively, must be greater than the ground coordinates beneath them.

Please note that there are cases where the ground slope is sufficiently large with respect to the source and receiver heights above it, that there is no specular reflection point between the source and receiver. In these cases, ENC sets the grouns effect, Ag or K3, equal to zero.

3.2 ENC 6th Version Window

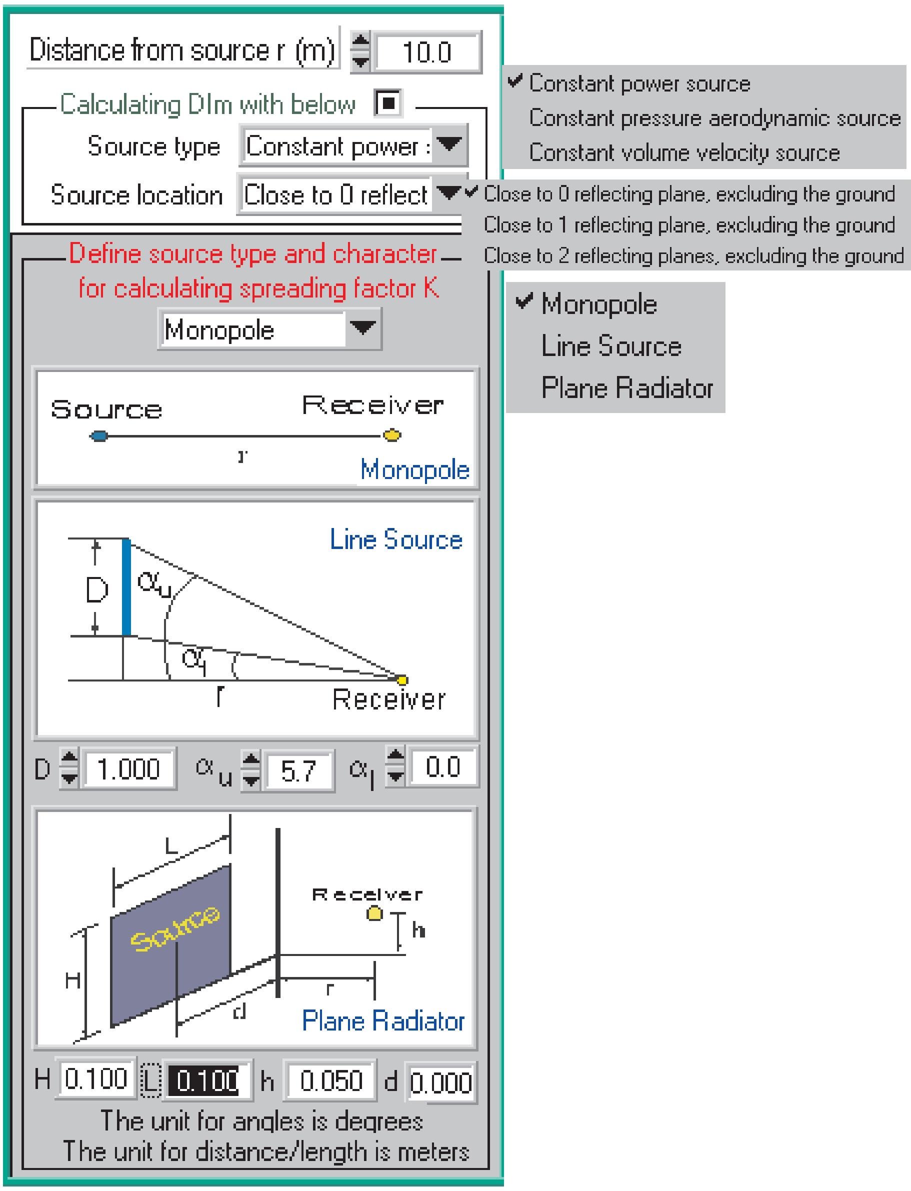
Note that values in blue font are calculated values and cannot be changed by typing over the value in the box. Values in data boxes with a grey background fill are set by ENC and cannot be changed. In the pink "Ground Effect" panel the source and receiver locations are set and the ground height under the source is constrained by ENC to be zero. All other heights must be entered relative to the ground height under the source. This is only the case for the "ENC 6th version" window. An error message will now be produced if the z-coordinate of the source is less than or equal to the z-coordinate of the ground beneath it and / or the z-coordinate of the receiver is less than or equal to the z-coordinate of the ground beneath it.

In this current version of ENC, meteorological Effects are no longer calculated separately when the turbulence option for |Rs| is selected in the Ag popup window, as the turbulence parameter accounts for meteorological effects, at least to the accuracy of the analysis in ENC.



This window calculates all of the attenuation factors of Equation (5.55) in the 6^{th} edition textbook and uses the results to calculate the sound pressure level at a single location from a single source, which is specified at the top left of the window, according to the 6th edition textbook, pages 258–314. You must enter the correct “distance from source” in the top left panel. The window is divided into three sections: left, centre and right panels. This window also allows calculation of plane and spherical wave reflection coefficients.

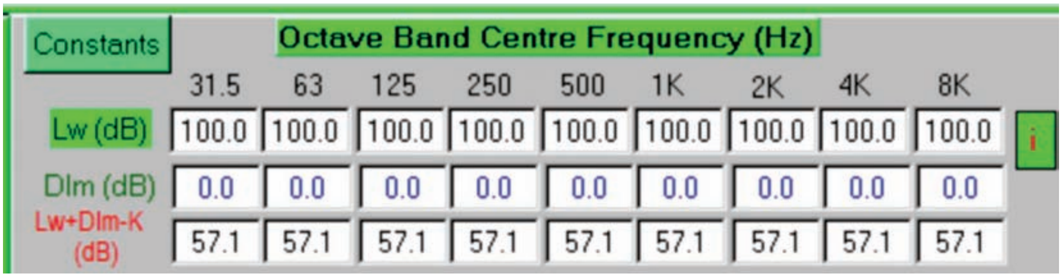
3.2.1 Left-hand Panel (source type)



The left panel (illustrated above) allows you to enter the distance between the source and receiver and information about the source type (constant power, constant volume velocity or constant pressure and monopole, line or plane) as well as any directivity effects due to close proximity of reflecting surfaces, EXCLUDING the ground. Note that the reflecting surfaces must be such that they do NOT block the line of sight from the source to the receiver. It is assumed that the reflecting surfaces are much closer to the source than the receiver (by a factor of at least 10). If the reflecting surface is closer to the receiver than this, the sound level at the receiver must be calculated by adding the contribution of the reflected wave with that of the direct wave (incoherently) as done in Module 1 of ENC. If the source is a constant volume velocity source and less than a quarter of a wavelength from the reflecting plane, then select “constant volume velocity source” and the DI_m value will be 6dB for each reflecting surface (as the reflecting surface will increase the power of the source by 3 dB as well as the directivity by 3dB — see discussion on pages 214–215 in the 6th edition textbook). If the source is an aerodynamic constant pressure type and closer than one quarter of a wavelength to the reflecting surface, select "constant pressure aerodynamic source" and the DI_m value will be 0 dB. If the source is of constant volume velocity type or constant pressure type and further than a quarter of a wavelength from the reflecting surface, select "constant power source". For constant power sources, the distance from the reflecting surface is not important as long as it is less than 1/10 of the receiver distance. You also need to enter whether the source is approximated by a monopole, line source or plane radiator. Depending on the source type selected, various parameters need to be entered to fully define it as shown on the panel. Note that at higher frequencies, reflecting planes do not affect large sources as they can already be directional and radiate little sound that can be reflected by an adjacent plane surface.

3.2.2 Centre Panel (Propagation Attenuation)

The centre panel (top part shown below) contains calculation results culminating in the sound pressure level at the receiver for a known source sound power level. You need to enter in the top section of the centre panel (see below) the sound power level of the source in octave bands (dB) and the source directivity index, DI_m, (dB), which does NOT include directivity due to the ground. If you have selected "calculating DIm with below" in the top left panel, then the appropriate quantity for DI_m will be entered by ENC into the middle panel in the row labelled "DIm (dB)". If you have a situation where there are additional directivity effects due to the sound source characteristics, then you should unselect "calculating DIm with below" so that is greyed out and manually enter the directivity values in the middle panel near the top. The values you enter will also include the effect of any nearby reflecting surfaces but will NOT include the effect of the ground. This is included in the "ground effects" section.



The top part of the table (see above figure) evaluates the right side of Equation (5.53) in the 6th edition textbook, except for the A_{Ei} part. The constant, A_{div} in that equation is represented as K in ENC and its value is dependent on the source type that you selected in the left hand panel and the presence or otherwise of reflecting surfaces that you specified in that panel.

Clicking on the "Constants" button (see preceding figure) allows you to set the speed of sound and gas density for the calculations — see Section 0.6.4 for a full description.

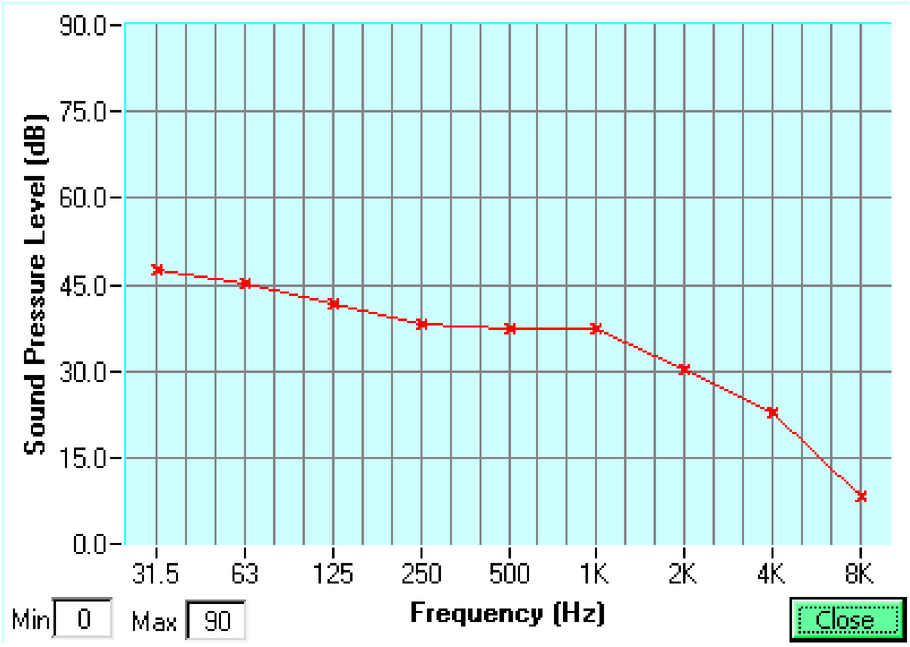
Right clicking on the green i button saves the data in the table in the above figure to a text file which can be imported into excel. The exported table also provides a template onto which you can enter your own data and import to the table by left clicking on the green i button.

The bottom half of the centre panel (see below) shows results for propagation attenuation calculations using various prediction schemes described in the right-hand panels (see Section 3.2.3.1) and implemented by entering the correct parameters in those panels. You must select the type of attenuation to be included by clicking on the appropriate box and making sure a tick appears in the box. Note that when the tick box corresponding to Ab is ticked, the Ag box should only be ticked if there is line of sight around one end of the barrier or for two or more paths over the top, as in all other cases, the barrier will block the ground reflected path that existed in the absence of the barrier. The line of sight for two paths over the top condition (direct path plus one ground-reflected path) would only occur if the barrier height were very small compared to the source and receiver heights.

The second to bottom line of the table is the sound pressure level (Lp in blue text) at the observer, calculated using Equation (5.54), which includes the attenuations corresponding to the ticked boxes subtracted from the third line of the table at the top of the window. The octave band sound pressure level may be seen graphically by clicking on the "Plot" button. The two total sound pressure level boxes at the bottom of the table give overall dB and dBA levels at the receiver location.

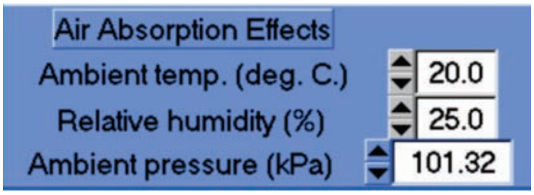
	Octave band centre frequency (Hz)									
	31.5	63	125	250	500	1K	2K	4K	8K	
Aa (dB)	0.0	0.0	0.0	0.1	0.1	0.2	0.7	2.4	7.7	☐
Ab (dB)	0.5	1.9	3.7	5.8	8.3	10.9	13.2	14.7	15.6	☐
Ah (dB)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	☐
Ap (dB)	0.0	0.0	0.8	1.2	1.2	1.0	1.0	0.8	0.8	☐
Af (dB)	1.0	2.0	3.0	4.0	5.0	6.0	8.0	9.0	12.0	☐
Ag (dB)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	☐
Am (dB)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	☐
Lp (dB)	57.1	57.1	57.1	57.1	57.1	57.1	57.1	57.1	57.1	
	Total (dB)	66.7			Total (dBA)	64.1			Plot	
Total Lp with meteorological effect correction by ISO 9613-2 (dBA)									63.4	

The "plot" button allows you to obtain a graph of the sound pressure level at the receiver as a function of octave band centre frequency. You can choose the maximum and minimum values for the y-axis scale by simply typing the value you want into the appropriate box at the bottom of the graph (see following figure).



3.2.2.1 Air Absorption Calculation

The values in the line labelled "Aa (dB)" in the table are obtained as discussed in the "Air absorption" Section 3.2.3.1 and uses data in the blue part of the right hand part of this window.



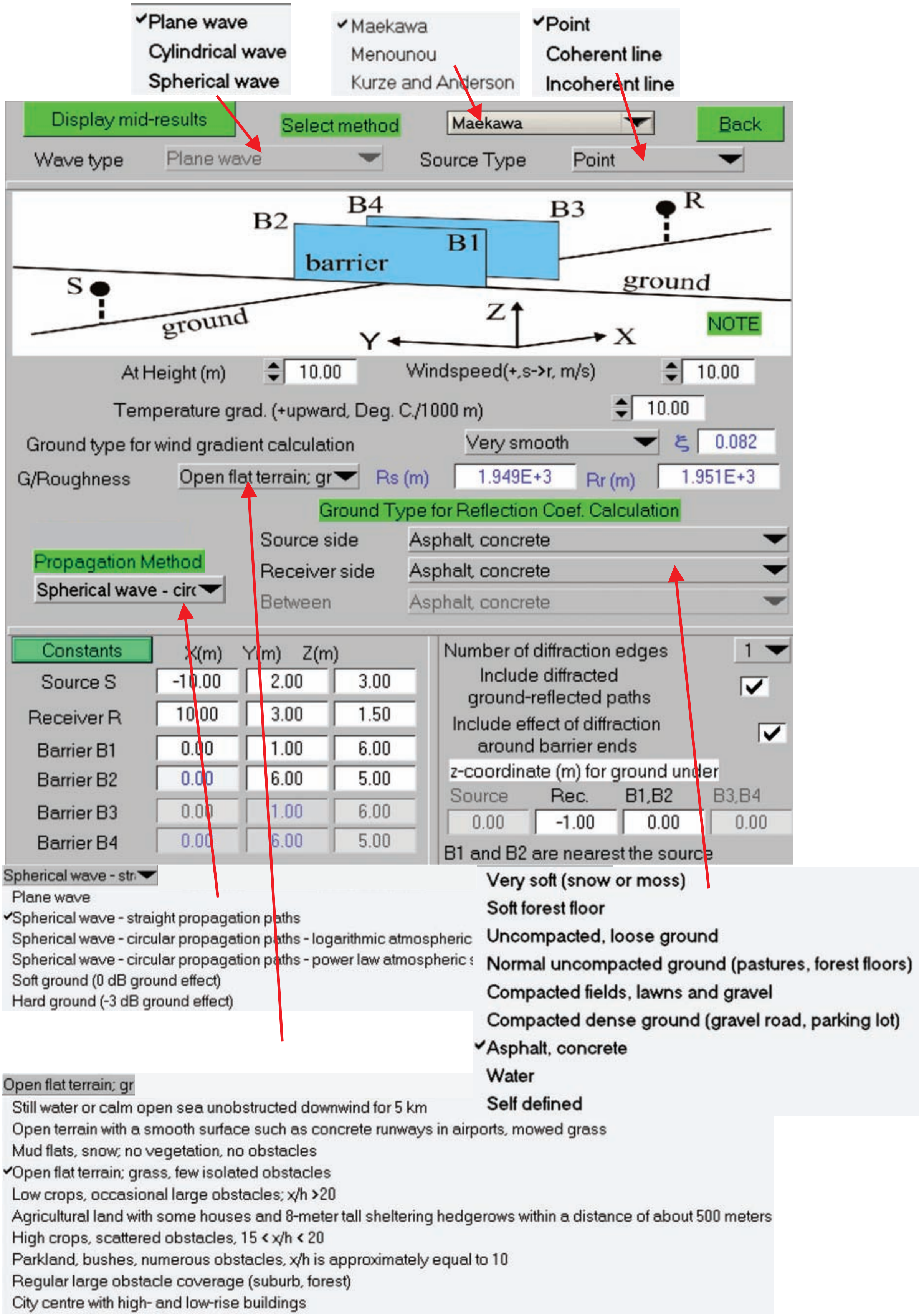
3.2.2.2 Barrier Attenuation Calculation (6^{th} edition textbook, pages 291–314)

The calculations of barrier attenuation in ENC version 6.1 onwards are based on the 6th edition textbook, where detailed descriptions of the analysis are provided. Updates in this edition of the textbook allow for sloping ground and include a detailed analysis of double diffraction barriers. The barrier popup page (see figure on page 69) for calculating the barrier attenuations is selected by clicking on Ab in the central panel of the main page.

The barrier calculations described in this section apply to sloping ground as well as flat ground. The ground may have different slopes on either side of the barrier. The ground beneath the two diffraction edges may also be different so that the ground slopes in between. It is assumed that the slopes between the source and barrier, between the two barriers and between the receiver and barrier are all straight lines, defined by the ground coordinates below the source, barriers and receiver.

For all calculation methods, if the "Include diffraction around barrier ends" tick box is NOT ticked (effectively an infinitely long barrier), only the three paths over the top of the barrier are used to calculate the overall barrier attenuation.

If a barrier is selected by ticking the box on the RHS of the Ab line in ENC, then the sources that are to be affected by the barrier must have negative values for their x-coordinates and the receivers that are to be affected by the barrier must have positive values for their x-coordinates. Thus, when a barrier is present, the coordinate origin should be on the ground at the base


Plane wave
Cylindrical wave
Spherical wave
Maekawa
Menounou
Kurze and Anderson
Point
Coherent line
Incoherent line
Display mid-results
Select method
Maekawa
Back
Wave type
Plane wave
Source Type
Point
B4
B2
B3
R
B1
barrier
S
ground
ground
Z
Y
X
NOTE
At Height (m)
10.00
Windspeed(+,s->r, m/s)
10.00
Temperature grad. (+upward, Deg. C./1000 m)
10.00
Ground type for wind gradient calculation
Very smooth
0.082
G/Roughness
Open flat terrain; gr
Rs (m)
1.949E+3
Rr (m)
1.951E+3
Ground Type for Reflection Coef. Calculation
Source side
Asphalt, concrete
Propagation Method
Receiver side
Asphalt, concrete
Spherical wave - circ
Between
Asphalt, concrete
Constants
X(m)
Y(m)
Z(m)
Source S
-10.00
2.00
3.00
Receiver R
10.00
3.00
1.50
Barrier B1
0.00
1.00
6.00
Barrier B2
0.00
6.00
5.00
Barrier B3
0.00
1.00
6.00
Barrier B4
0.00
6.00
5.00
Number of diffraction edges
1
Include diffracted ground-reflected paths
Include effect of diffraction around barrier ends
z-coordinate (m) for ground under
Source
Rec.
B1,B2
B3,B4
0.00
-1.00
0.00
0.00
B1 and B2 are nearest the source
Spherical wave - str
Plane wave
Spherical wave - straight propagation paths
Spherical wave - circular propagation paths - logarithmic atmospheric
Spherical wave - circular propagation paths - power law atmospheric
Soft ground (0 dB ground effect)
Hard ground (-3 dB ground effect)
Very soft (snow or moss)
Soft forest floor
Uncompacted, loose ground
Normal uncompacted ground (pastures, forest floors)
Compacted fields, lawns and gravel
Compacted dense ground (gravel road, parking lot)
Asphalt, concrete
Water
Self defined
Open flat terrain; gr
Still water or calm open sea unobstructed downwind for 5 km
Open terrain with a smooth surface such as concrete runways in airports, mowed grass
Mud flats, snow; no vegetation, no obstacles
Open flat terrain; grass, few isolated obstacles
Low crops, occasional large obstacles; x/h >20
Agricultural land with some houses and 8-meter tall sheltering hedgerows within a distance of about 500 meters
High crops, scattered obstacles, 15 < x/h < 20
Parkland, bushes, numerous obstacles, x/h is approximately equal to 10
Regular large obstacle coverage (suburb, forest)
City centre with high- and low-rise buildings

of the barrier (or if two diffraction edges are present, then on the ground at the diffraction edge closest to the source). The y-location of the origin is not important.

The calculated result displayed in the Ab line on the main page in ENC is the noise reduction due to installation of the barrier, including the effect of removing the original direct and ground reflected paths that existed prior to installation of the barrier as implemented using Equation (1.105) in the 6th edition textbook.

When the tick box on page 67, corresponding to the barrier attenuation, Ab, is ticked, the ground effect box corresponding to Ag should not be ticked, unless there is line of sight from the source to the receiver around one end of the barrier or for two of the four paths over the top of the barrier. In either of these cases, the barrier attenuation will be set equal to zero and you will need to make sure that the Ag box is ticked. For all other cases, the barrier blocks the direct and ground reflected rays that exist with no barrier and the Ag box should be unticked.

Even if the Ag box is not ticked, Ag in the main panel should be clicked on and "incoherent" chosen for the calculation of $|Rs|^2$. Do not choose the coherent or turbulent options to calculate $|Rs|^2$, as these require phase information, which will be incorrect if a barrier is between the source and receiver. That is, we can only use plane wave or incoherent spherical wave combination of direct and ground reflected rays when calculating Ab.

Clicking on the blue Ab(dB) button on the left column of the table on page 67, generates a new screen (see figure on page 69) in place of the table. This screen is designed to allow you to calculate the attenuation corresponding to a particular barrier configuration.

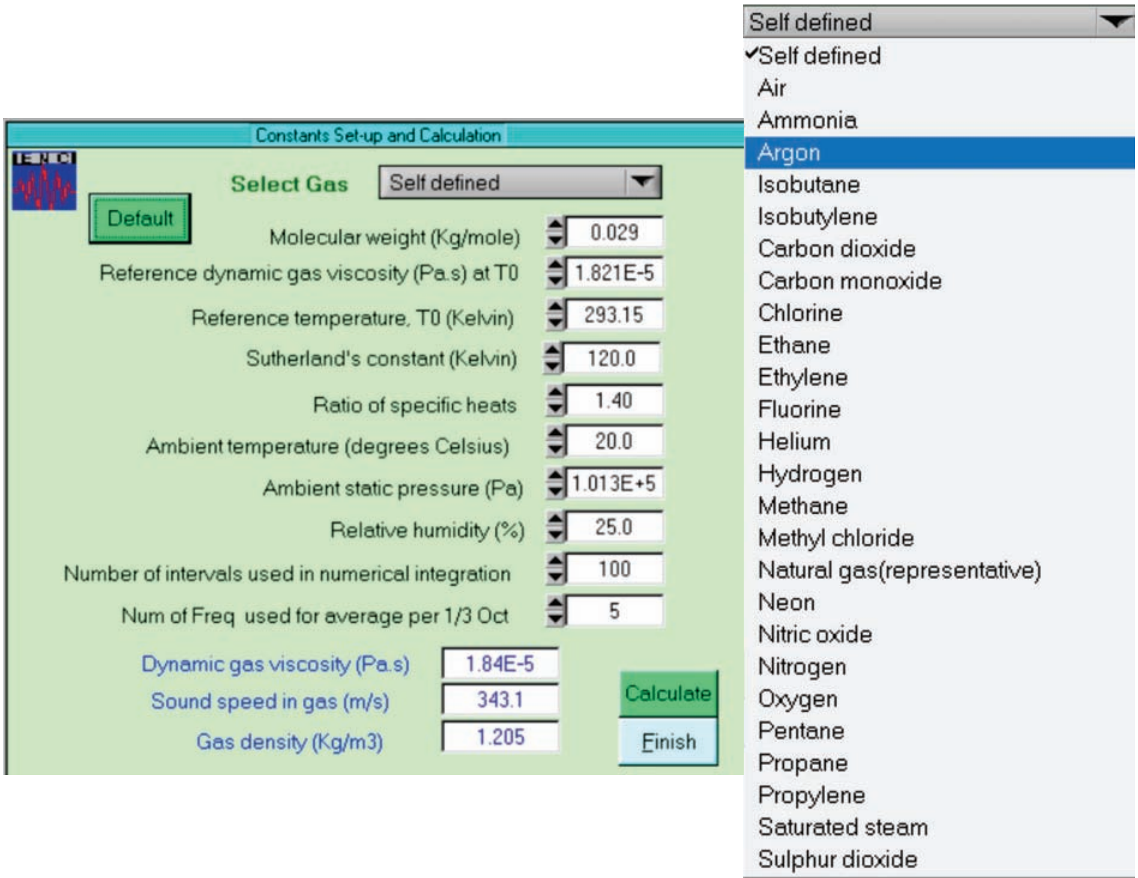
If you click on "Display mid results" (green box) on the figure on page 69, the panel shown on page 71 appears.

This allows you to observe the importance of each reflected path compared to the direct path over the top of the barrier in terms of attenuation (or lack of it). The second to last line in the figure also tells you where in relation to the barrier, the ground reflection is for the case with no barrier. This assists you in matching the ground type for use in the pink box part in the main page with the correct type in the barrier calculations, as the ground effect with no barrier is part of the barrier attenuation calculation. The intermediate results popup screen shown on the following figure shows detailed results for a frequency of 1000 Hz. "Ni" is the Fresnel number and the other variables are self evident if read in conjunction with the 6th edition textbook, Chapter 5, Section 5.3.5. If there is a value of 9999 shown for Ni for the ground-reflected paths around the barrier ends, that means that ENC could not find a reflected path (very rare), most likely because one does not exist. In this case, the contribution of the corresponding path to the overall barrier attenuation is zero. For the calculation of the location of the reflection point for the ground-reflected paths around the barrier ends, it is assumed that the slope of the ground is a straight line between the ground under the source and the ground under the receiver. For cases where there are different ground slopes on either side of the barrier, there will be a small error in the barrier attenuation for these paths.

When you have entered the barrier parameters, click on "back" to return to the table on the main page and you will see the barrier attenuation entered in the correct place in the table.

The window (see figure on page 72) for calculating the speed of sound and other

parameters used in the barrier calculations can be activated by clicking on the "constants" button.



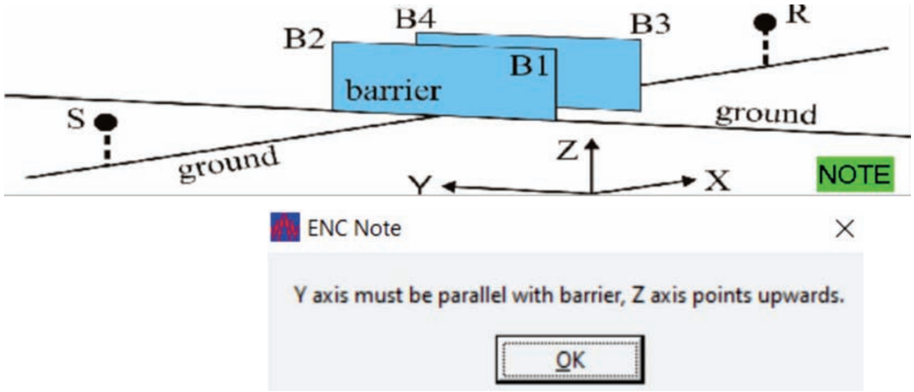
Error messages are now produced if the x-coordinate of barrier B1 or B3 is greater than the x coordinate of the receiver or if the x coordinate of barrier B1 or B3 is less than the x coordinate of the source.

A 24 dB maximum overall attenuation limit has now been applied to all barrier attenuation calculations.

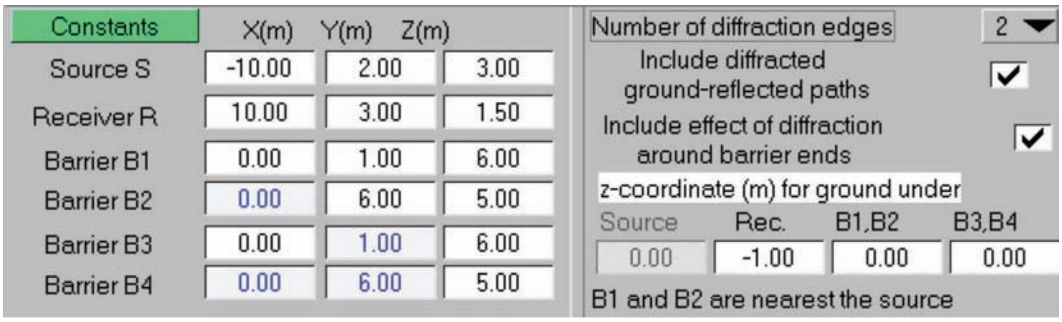
Before undertaking a barrier attenuation calculation, you must choose the particular barrier diffraction model you wish to use from a total of 3 different choices using the “select method” menu at the top of the screen as shown in the figure on page 69. Then, depending on the method chosen, you will need to enter the type of wave (plane cylindrical or spherical) or the type of source (point incoherent line or coherent line) – see figure on page 69.

The spherical wave of the Menounou model is equivalent to the point source of the Maekawa model and the cylindrical wave Menounou model is equivalent to the coherent line source of the Maekawa model. Thus, for each model choice, either the “Source type” or “Wave type” boxes are greyed out as only one of the two items can be used. The Kurze model provides results that are independent of the source or wave type.

The configuration used in the calculations is illustrated below. When you click on “NOTE”, a message will appear to explain the location of the origin of the coordinate system as shown in the following figure.



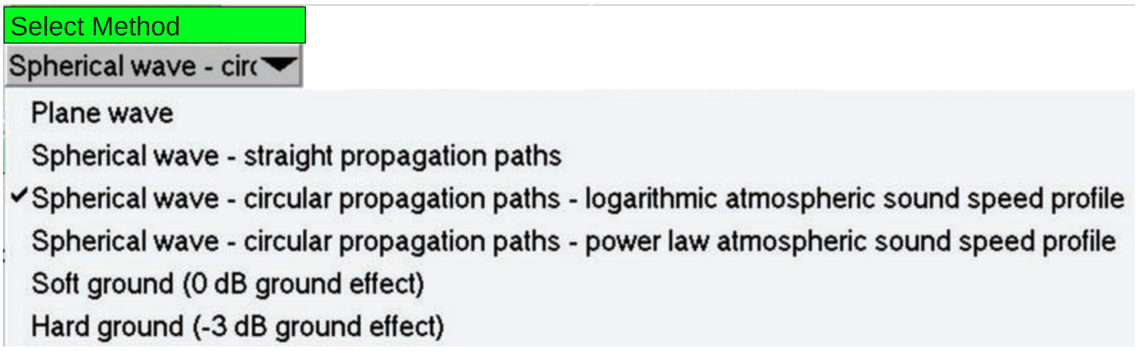
As noted in the figure, the Z-axis is normal to the ground surface and parallel to the plane of the barrier, the X-axis is parallel to the ground surface and normal to the barrier surface and the Y-axis is parallel to the ground surface and parallel to the barrier surface. The coordinates of the source and receiver as well as the top corners of the barrier are entered in the table at the bottom of the window as illustrated in the following figure.



If the “Number of diffraction edges” box has a 1 in it, ENC will calculate the attenuation due to a single barrier, assuming the barrier to be thin. If the barrier is thick or if there are two thin, parallel barriers separated by anything more than 0.1 m, then the “Number of diffraction edges” box should have a 2 in it. This is a different approach to that taken in ENC versions 5.5 and earlier for a thick barrier, where a simple correction was used to account for the additional attenuation obtained as a result of the thickness of the barrier. If the second barrier (closest to the receiver) is such that its top is below the straight line drawn from the top of the first barrier (closest to the source) to the receiver, then the second barrier is ignored in the calculations. If the first barrier (closest to the source) is such that its top is below the straight line drawn from the top of the second barrier (closest to the receiver) to the source, then the first barrier is ignored in the calculations.

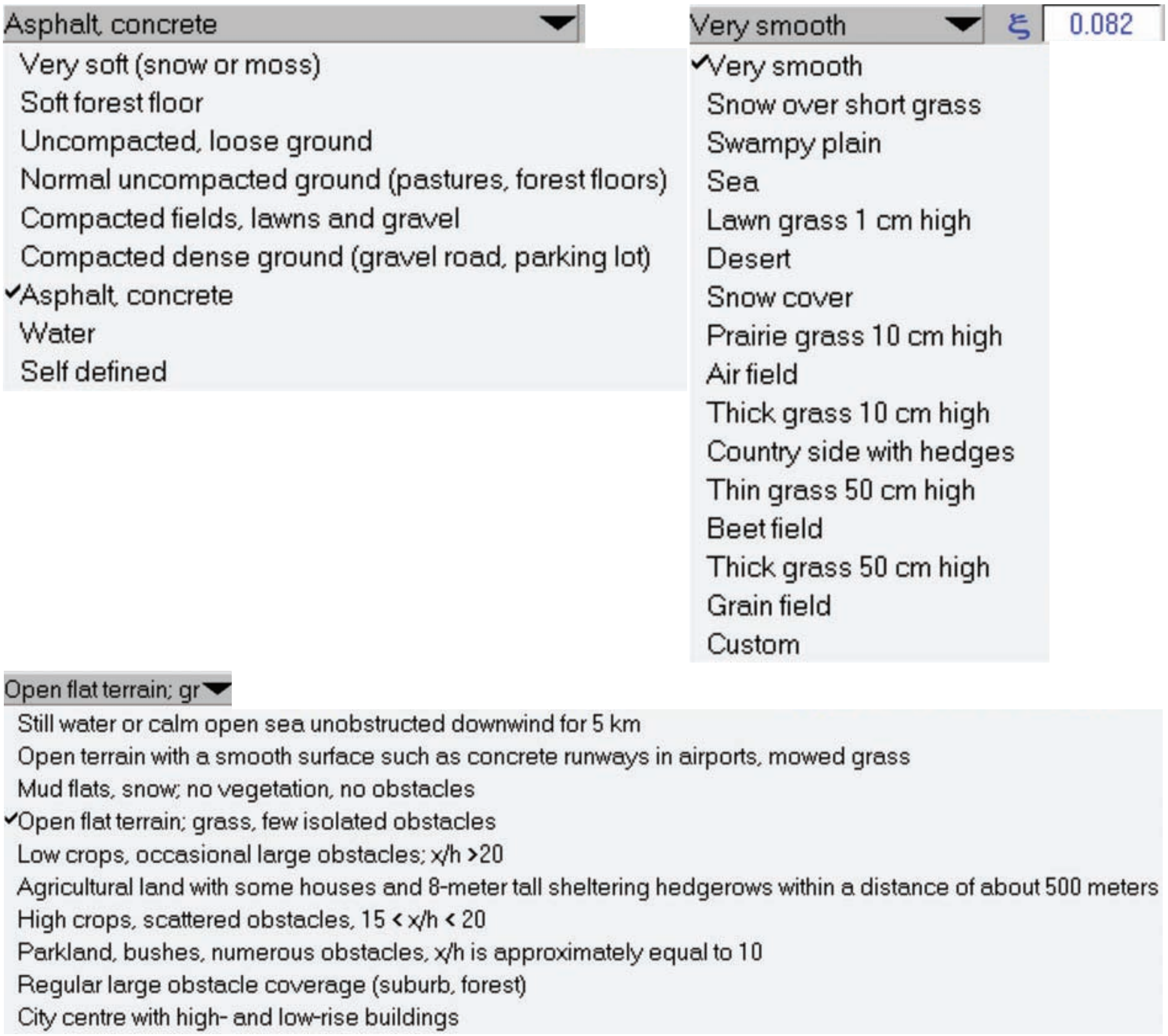
The coordinates of the barrier top nearest the source are entered in the barrier B1 and Barrier B2 boxes for the right hand and left hand ends, respectively (when the barrier is viewed from the source). If the “Number of diffraction edges” is 2, the coordinates of the barrier top nearest the receiver are entered in the barrier B3 and Barrier B4 boxes for the right hand and left hand ends, respectively (when the barrier is viewed from the source). It is assumed that the barrier faces are in the $x-z$ plane such that the x-coordinates of each end are the same, which is why it is only possible to enter the x-coordinate for one of the ends. The zero x-coordinate location should be on the ground under the noise source. The barrier attenuations due to all 8 paths around the finite length barrier are calculated as described on pages 291–314 in the 6th edition textbook and then the results are combined using Equation (1.105) or (5.178).

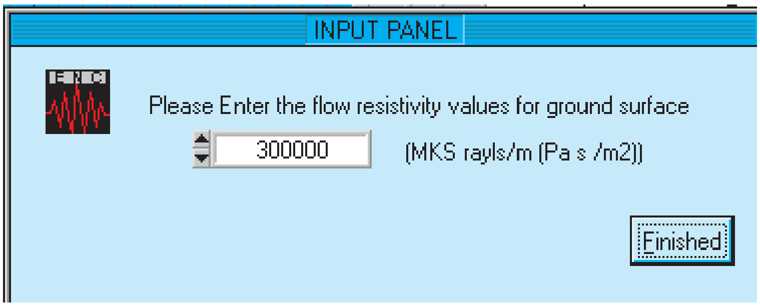
Before proceeding with the barrier attenuation calculations, it is necessary to specify the calculation method, which effectively describes the type of propagation path to be used. The choice is made using the "Propagation Method" menu on the centre left of the page, illustrated in the following figure.



If the plane wave option or either of the circular ray path options (one for a power law atmospheric wind profile and one for a logarithmic profile) are selected (see preceding figure), the barrier effect is calculated using straight ray paths with a correction to the source and receiver heights (textbook, p.313) to account for circular ray curvature reflection parameters (thus accounting for atmospheric wind and temperature gradients). Note that this height correction is only used for the direct ray over the barrier top. Rays around barrier ends not affected by wind and temperature gradients and reflected rays do not usually contribute sufficiently to warrant the correction.

There are three ground types that must be entered, depending on the quantity to be calculated. One is for ground reflection coefficient calculations (Table 5.2 in the textbook). This is labelled "Ground Type for Reflection Coef. Menu" and is used for calculating the ground reflection coefficient on the source and receiver sides of the barrier and also for the ground between the diffraction edges. One of the other ground types to be entered (labelled "Ground type for wind gradient calculation") is for calculating the atmospheric power law wind speed profile (Table 5.5 in the textbook) and other one (labelled "G/roughness") is for calculating the logarithmic atmospheric wind speed profile (Table 5.6 in the textbook). The list of choices in ENC that reflect these tables is illustrated in the following figure.





For the ground reflection calculations you can also define your own ground surface, for calculating the ground reflection coefficient, by clicking on the "Self defined" item at the bottom of the "Ground Type for Reflection Coef. Calculation" menu. When you do this, the box at right pops up and all you need do is enter the flow resistivity of the ground surface in MKS Rayls/m and then click on "finished".

Equation (5.178) requires the calculation of a reflection loss for when no barrier is in place. The ground type that is used for the calculations with no barrier in place must be the type specified at the location where the reflected ray strikes the ground. This may be the receiver side of the barrier if the ground reflection with no barrier is on the receiver side of the barrier, otherwise it is the ground type specified for the source side. ENC tells you on the intermediate results popup screen whether the ground reflection with no barrier is on the source or receiver side of the proposed barrier location so that the correct choice for the ground type can be made in the pink ground effect panel.

For paths involving ground reflections, the loss due to reflection is added arithmetically to the barrier attenuation. The attenuations for each path are combined together to give an overall barrier attenuation using Equation (5.178) in the 6th edition textbook.

It is not possible to include turbulence in the barrier attenuation model here. The reflection loss is calculated $-20\log_{10}(R_p)$ or $-20\log_{10}(Q)$, depending on whether a plane wave or a spherical wave reflection model is chosen. The effect of paths around all sides of the barrier as well as attenuations due to reflections from the ground are included in the final attenuation value you find in the table. For each path the attenuation is calculated using Figure 5.19 and Equations (5.142), (5.144) & (5.178).

If the "Include diffracted ground-reflected paths" box is ticked (see figure on page 69), ENC will include all diffracted ground reflected paths in the overall attenuation calculation. The non-diffracted ground reflected path that exists without the barrier and whose attenuation is used as part of the barrier overall attenuation calculation is included whether or not the box is ticked. If it is required to also exclude the effect of the non diffracted ground reflected path, just choose "soft ground (0 dB ground effect)" in the "Propagation Method" drop-down menu.

For all options in the “Propagation Method” drop down list near the centre left of the page (see figure on page 74), when the “Include ground reflected diffraction paths” and “Include diffraction around barrier ends” tick boxes are ticked, the barrier attenuations due to all 8 paths around the finite length barrier are calculated as described on pages 291–314 in the 6th edition textbook and then the results are combined using Equation (1.105) or Equation (5.178).

The ground cover categories for the radius of curvature calculations (“Ground type for wind gradient calculation”) are slightly different to the categories used for the ground reflection effects. This is a result of the available data in the literature for these very different calculations.

Thus, Table 5.5 in the textbook represents particular ground covers for calculating the wind shear coefficient, ξ, used along with the wind speed data (see figure on page 75) to calculate the power law atmospheric wind speed profile.

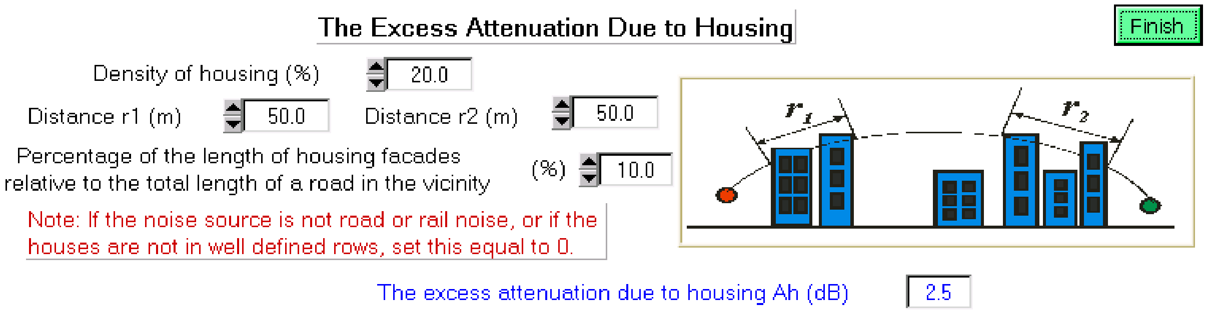
Table 5.6 in the textbook represents the ground roughness (see figure on page 75), used along with the wind speed data to calculate the logarithmic atmospheric wind speed profile. The atmospheric temperature profile is calculated using the temperature gradient data (see figure on page 69) and this is used together with the atmospheric wind speed profile to calculate the radius of curvature of the rays when the plane wave or either of the two circular propagation path model options are chosen for the “Propagation Method” (see the figure on page 74 and 6th edition textbook, page 267 and Equations (5.76) and (5.79)).

It is IMPORTANT to note that for the circular ray path options, the barrier noise reduction will not be accurate until you have entered the wind speed at a specified height (speed component in the direction from the source to the receiver — negative values represent a component blowing from the receiver to the source) and temperature gradient. However, you may exclude the effect of a sonic gradient by entering zero for the wind speed and temperature gradient. Note that for sound propagation around the side of barriers, wind and temperature gradients have no effect. For reflected paths and paths around the barrier ends, the actual source and receiver locations are used, NOT the new locations calculated for sound propagation over the top of the barrier in the presence of wind or temperature gradients (circular ray path options only).

The radius of curvature, R (in metres) (see Equation (5.73)) of the sound wave going over the top of the barrier as a result of wind and temperature gradients and the value of the exponent ξ (see Equation (5.79) and Table 5.5, p. 270 in the textbook) are provided for your interest in blue text in the barrier pop-up window (see page 69). If you wish to enter your own value of ξ, you will need to select "custom" on the menu for "ground type for wind gradient calculation" (see top right menu in the figure on page 75).

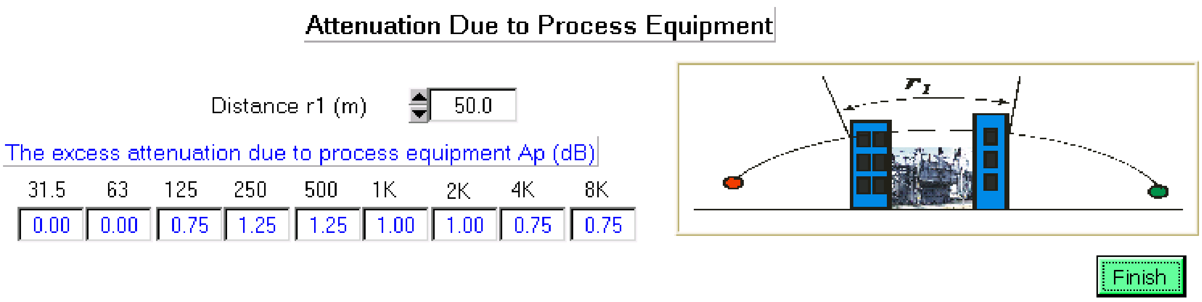
A negative radius of curvature (resulting from a negative atmospheric sonic gradient) implies that the sound rays will be curved upwards and the resulting barrier attenuation will increase. This is in contrast to the decrease in barrier attenuation that occurs when there is a positive radius of curvature and corresponding downward curved rays. Wind and temperature gradients, when a plane wave or circular propagation path option is chosen for the "Propagation Method", are taken into account automatically if you enter a non-zero value for the wind speed or temperature gradient. As mentioned earlier in this manual, the procedure in the ENC barrier page calculates an effective source height based on the sound ray curvature calculated from the wind and temperature gradients. If the effective source height is less than zero, it is set equal to zero. Interestingly, the effect on the overall attenuation of the barrier is not great in most cases. You need to enter the wind speed at 10 m and the temperature gradient in degrees C per 1000 m (see figure on page 69).

3.2.2.3 Attenuation Due to Housing (Ah) (6th edition textbook, page 327)



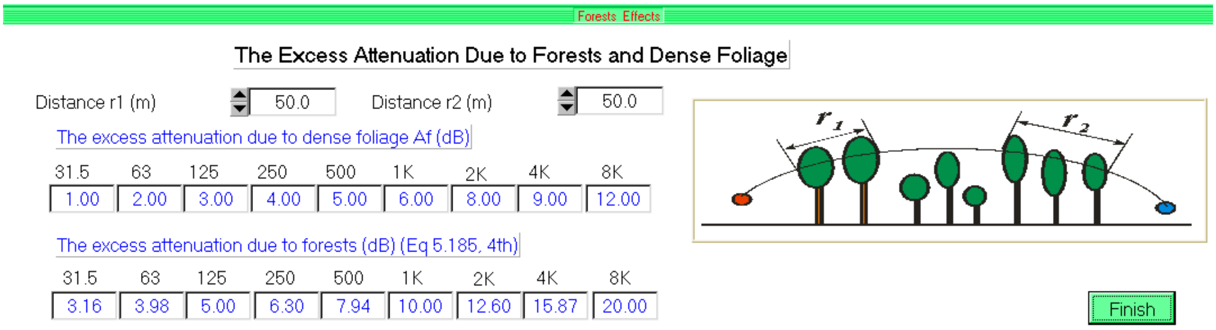
This panel (shown above) is activated by clicking on the "Ah(dB)" button on the left side of the centre panel. The attenuation due to housing is calculated according to ISO 2613-2 (1996). The quantities r_1 and r_2 represent the distances that the sound rays actually travel through buildings and these quantities are affected by the radius of curvature of the sound wave. To be able to estimate r_1 and r_2, it is necessary to use ENC to calculate the radius of curvature and then do a scale drawing similar to that done for the attenuation due to forests and shown in the figure on the next page. Note that the "percentage of the length......" data box should only be non-zero for road or rail noise where houses are in defined rows.

3.2.2.4 Attenuation Due to Process Equipment (Ap) (see ISO9613-2)



This panel (shown above) is activated by clicking on the "Ap(dB)" button on the left side of the centre panel. The attenuation due to process equipment is calculated according to ISO 2613-2 (1996). The quantities r_1 and r_2 represent the distances that the sound rays actually travel through buildings and these quantities are affected by the radius of curvature of the sound wave. To be able to estimate r_1 and r_2, it is necessary to use ENC to calculate the radius of curvature and then do a scale drawing similar to that done for the attenuation due to forests and shown in the figure above.

3.2.2.5 Attenuation Due to Forests (Af) (6th edition textbook, page 327)



This panel (shown above) is activated by clicking on the "Af(dB)" button on the left side of the centre panel. The attenuation due to forests and foliage is calculated according to ISO 2613-2 (1996). The quantities r_1 and r_2 represent the distances that the sound rays actually travel through trees and these quantities are affected by the radius of curvature of the sound wave. To be able to estimate r_1 and r_2, it is necessary to use ENC to calculate the radius of curvature and then do a scale drawing similar to that shown in the following figure.

3.2.2.6 Attenuation Due to Ground Effects (Ag)

Before clicking on Ag in the centre panel, it is best to first make the required choices in the pink panel to the right. This is discussed in more detail in Section 3.2.3.2 on page 80.

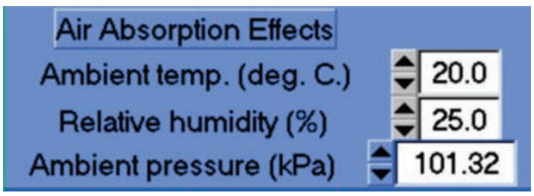
3.2.2.7 Attenuation Due to Meteorological Effects (Am)

The values in the "AM" line in the centre panel are determined using the data entered in the right hand panel discussed on pages 85 to 89.

3.2.3 Right-hand Panel

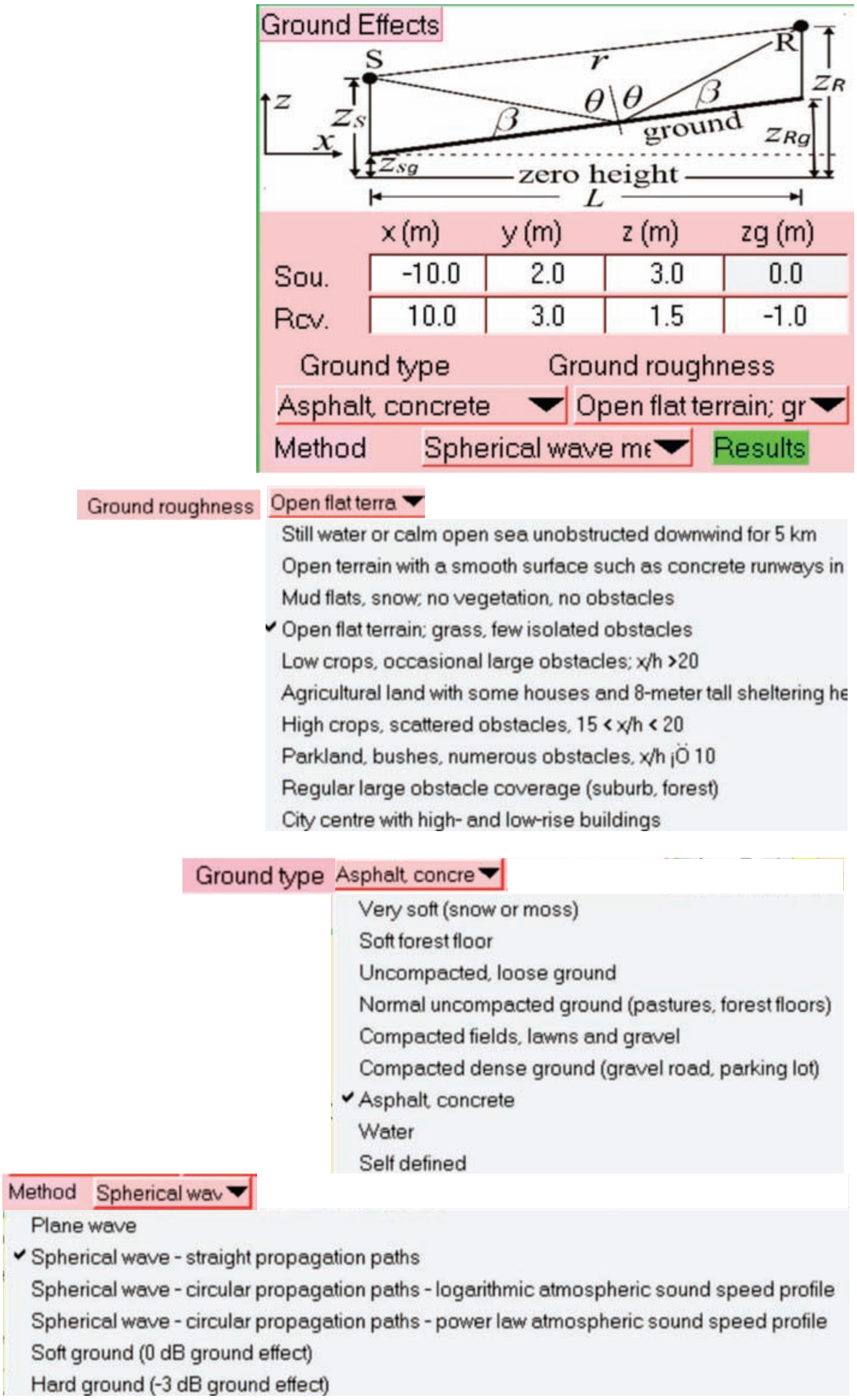
The right hand panel is where the calculations of attenuation due to air absorption, ground effects and meteorological effects are carried out.

3.2.3.1 Air Absorption Effects



The attenuation due to air absorption, A_a, is calculated using the panel shown at right (Sutherland's method). All that is needed is the air temperature and relative humidity (see 6th edition textbook, Table 5.3, p. 262 and ANSI S1.26 (1995)). The results are transferred by ENC to the "Aa" line in the centre panel.

3.2.3.2 Ground Effects



The excess attenuation due to the ground is dependent on the angle at which the reflected ray strikes the ground and this is affected by any curvature of the ray path. As ray path curvature is a meteorological effect, ground and meteorological effects cannot be separated when ray curvature is taken into account. In ENC, the third and fourth options under

"Method" (see figure on the previous page) include meteorological effects, as ray curvature is taken into account in those options. Thus, if either of these two options is chosen, the Am tick box in the centre panel is greyed out, as Am is included in Ag and should not also be included separately. If the "plane wave" option is chosen, meteorological effects are not included in the ground effect calculations, but the ray curvature due to atmospheric wind and temperature gradients is included in the barrier calculations.

In calculating the sound pressure level at the receiver, ENC assumes that there is only one reflected ray path. However, at large distances from the source, there may be more than one reflected ray path contributing to the total sound pressure level and this can add a few decibels to the prediction error. This issue will be addressed in future versions of ENC. The phase shift in the reflected ray due to reflection from the ground is taken into account in the current and previous versions of ENC and the upper limit on the ground effect, due to a 180 degree phase shift between the direct and ground reflected rays, is 30 dB, although it is unlikely that this will ever be reached, except in strong upwind conditions (wind blowing from the receiver to the source).

The problem of no ground reflection existing between the source and receiver when the ground slope and source / receiver heights are such that no ground ray reflected from the ground between the source and receiver can reach the receiver produces zero for the Ag value in the centre panel.

The attenuation due to ground effects, A_g, may be calculated using as described on pages 252–257, 262–265 in the 6^{th} edition textbook (see illustration above).

Before clicking on Ag in the centre panel, you should choose the desired options in the menus in the pink panel on the right side of the page as well as entering the x, y and z coordinates of the source and receiver. These coordinates should be the same as used for the barrier calculations (clicking on Ab in the centre panel). The vertical coordinate of the ground directly under the source and also under the receiver are needed so the ground slope and thus the ground reflection angle can be determined. A positive ground slope is shown in the figure, but negative slopes (ground under source higher than that under receiver) are also allowed. The distance, L, is calculated from the source and receiver x and y coordinates and the distance r is calculated from the source and receiver x, y and z coordinates.

Note that the zero z-coordinate is the ground coordinate directly beneath the sound source (for the ENC 6th edition page only).

The next step is to select which of the six propagation models is to be used from the list under "Propagation Method", illustrated in the figure on the previous page. The choices are:

1. Plane wave
2. Spherical wave - straight propagation paths
3. Spherical wave - circular propagation paths - logarithmic atmospheric sound speed profile
4. Spherical wave - circular propagation paths - power law atmospheric sound speed profile
5. Soft ground (0 dB ground effect)

6. Hard ground (-3 dB ground effect)

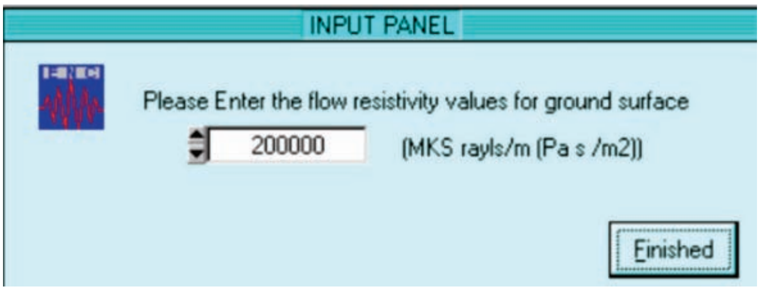
If either of the third or fourth options are chosen, ENC replaces the term, $k(r_S + r_R - d_{SR})$ in Equations (5.70) and (5.72) in the textbook with $2\pi f \Delta t$, where f is the frequency (Hz) and Δt is the propagation time difference (ground reflected ray minus the direct ray). Calculation of the propagation time requires the ray path to be divided into segments and the speed of sound calculated for each segment based on its altitude and the wind speed profile (see Equations (5.76), (5.83), (5.86) and (5.90) in the 6th edn textbook).

If the third "Method" option is chosen, you will also need to choose the type of ground for determining the ground roughness. Values corresponding to the listed ground cover types are listed in Table 5.6, page 270 in the textbook.

Clicking on the green "results" button in the pink panel produces the same popup panel as produced by clicking on "Ag" in the centre main panel.

If any of the first 4 method options are chosen, then you need to enter the type of ground surface at the reflection point from the "Ground type" drop down list shown in the figure on the previous page (see Tables 5.1 and 5.2, pages 250 and 251 in the 6^{th} edition textbook for some representative values of flow resistivity).

For the "self defined" option, it is necessary to enter only one data item and this is the flow resistance of the ground surface. This can be entered in the popup window illustrated at right. Typical flow resistance values for various ground surface types are provided in tables in Chapter 5 of the 6th edition textbook.

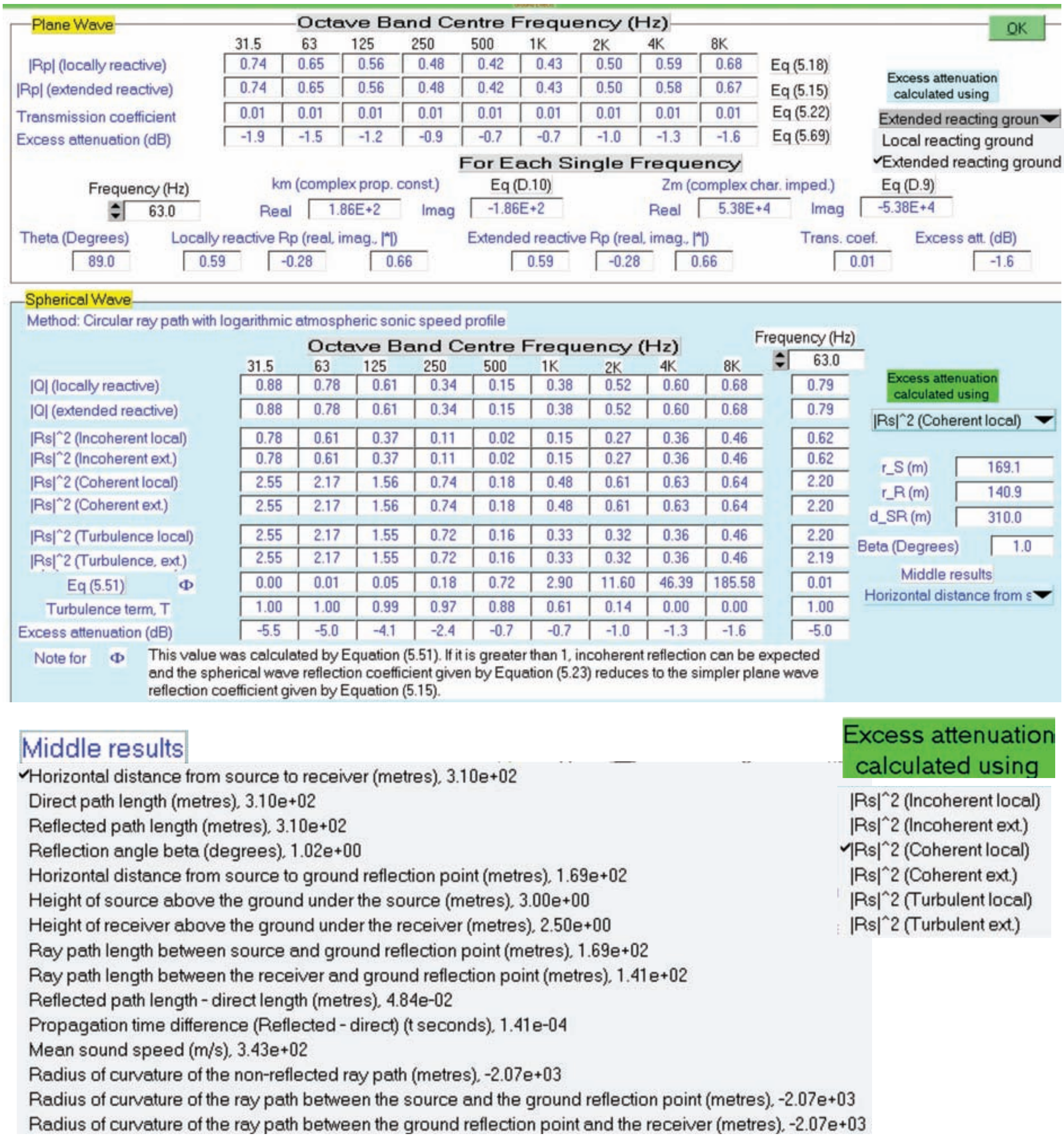


The detailed results for the plane wave and spherical wave reflection models may be obtained by clicking on the "Results" button or clicking on "Ag" in the centre panel. When you do this, the window on page 83 appears. In this window, the equation numbers refer to equations in the 6^{th} edition textbook. The values inserted by ENC into the "Ag (dB)" line in the centre panel correspond to the "Excess Attenuation (dB)" values that, in turn, correspond to the calculation method selected in the "Method" menu illustrated on page 80 and the popup window illustrated on page 83.

The "middle results" (see figure on next page) show most of the data used to calculate the results in the table. Note that the radius of curvature of the sound rays for circular ray path options are found for both atmospheric wind speed profile types using Equations (5.73) and (5.80) and adjusting ψ_S until d_c equals the actual horizontal distance between the source and receiver (or source and reflection point for the reflected ray).

Note that if the sonic gradient is negative, the circular ray path options should not be used as the corresponding results will be unreliable. For the straight ray path options, all radius of curvature values are set at 10^{10} metres and the last line in the figure below becomes "Critical angle for negative sonic gradient (degrees), otherwise ignore for positive sonic gradient", instead of what is shown on the figure.

For the "plane wave" method, the ground effect is calculated by estimating the plane wave reflection coefficient. The reflection coefficient is calculated for the two cases of local reacting ground and extended reacting ground and you can select which you prefer. If

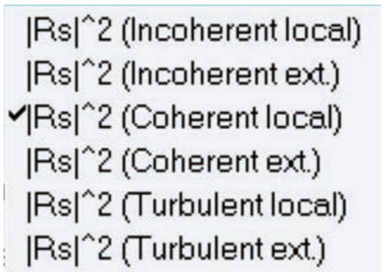


unsure, use the extended reactive model.

Values of reflection coefficients and the ground effect in dB averaged over 10 single frequencies in each octave band are shown in the table. Values of reflection coefficient (both locally reactive and extended reactive) are listed for any frequency you specify in the box beneath and to the left of the table. Also are shown, the ground reflection angle theta (angle from the vertical), values of the transmission coefficient (Equation (5.21)), complex propagation constant (Equation (D.10)) and complex characteristic impedance of the ground (Equation (D.9)). These latter quantities are a function only of the flow resistivity of the ground.

For the “ spherical wave” method, the ground effect is calculated by estimating the spherical wave reflection coefficient. The reflection coefficient, Q, is calculated for both extended reaction and local reaction models. The chosen reflection coefficient (local or extended reactive surface) is then used to estimate the excess attenuation as a result of three different cases:

1. assumption of incoherent combination of the direct and ground-reflected rays;
2. assumption of coherent combination of the direct and ground-reflected rays; and
3. assumption of partially coherent combination of the direct and ground-reflected rays, based on the expected atmospheric turbulence level.

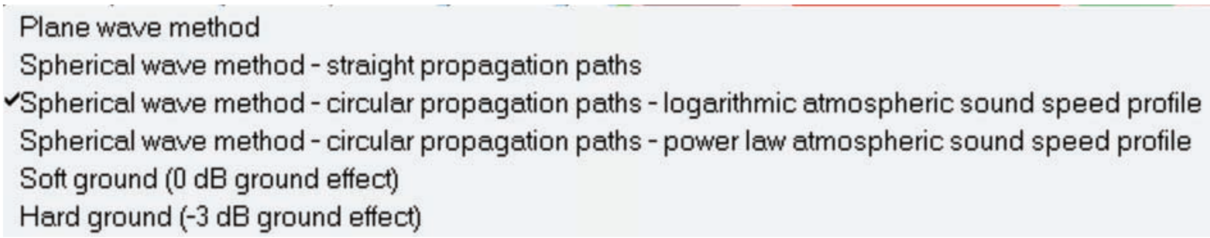


The excess attenuation that is inserted in the Ag slot on the main page and also in the last line of the table in the preceding figure corresponds to the option selected in the drop down menu under the green button (see figure at right).

The relevant equations are on pages 263–264 in the 6^{th} edition textbook. The values of $|R_S|$ shown in the figure at the top of the page represent the quantities in brackets (excluding the "1") on the RHS of the relevant equations in the textbook. For example, $|R_S|^2$ (Incoherent) corresponds to the term in brackets (excluding the "1") of Equation (5.69d) and $|R_S|^2$ (Turbulence) corresponds to the term in brackets (excluding the "1") of Equation (5.72) in the 6th edition textbook. Calculations averaged over 10 single frequencies in each octave band are shown in the table and values corresponding to a single specified frequency are shown to the right of the table. The desired frequency is selected by typing it into the box on the right hand side of this section, above the reflection coefficient values for single frequencies.

Note that in earlier versions of ENC, only propagation options that assumed straight ray paths (rather than curved) were allowed in the calculation of the relative phases of the rays arriving at the receiver, resulting in considerable uncertainty in the phase values. This is why the octave band values are obtained by averaging the results for 10 evenly spread frequencies within the band. Even for the assumption of circular ray paths (included as options in ENC 6.2 onwards), there is still be considerable uncertainty (but less than for straight ray paths) in the phase relationships of the various rays that may arrive at the receiver (with some rays experiencing more than one ground reflection). This is because the ray curvature at any location is a function of the wind and temperature gradient at that location and the ray path from source to receiver does not necessarily follow a circular arc. The use of a piecewise linear ray path as described in the 6th edn. textbook on pages 276-282 and 285-286, is one way of accounting for a varying radius of curvature of the ray path and this will be addressed in a later version of ENC. The option of a circular-arc ray path is included in all ENC versions after version 6.1, as illustrated in the drop down "method" menu (shown on page 85), which is from the pink ground "Ground Effects" panel on the main page.

The quantity, Φ, used in Equation (5.50) and calculated with Equation (5.51) in the 6th edition textbook, which is used to calculate the effect of turbulence on the total sound pressure arriving at the receiver, is displayed in the figure on page 83. For $\Phi >$ 1.0, incoherent reflection from the ground is assumed and Equation (5.69) is used to calculate the ground effect. For $\Phi < 0.1$, coherent reflection is assumed. For $0.1<\Phi<1.0$,

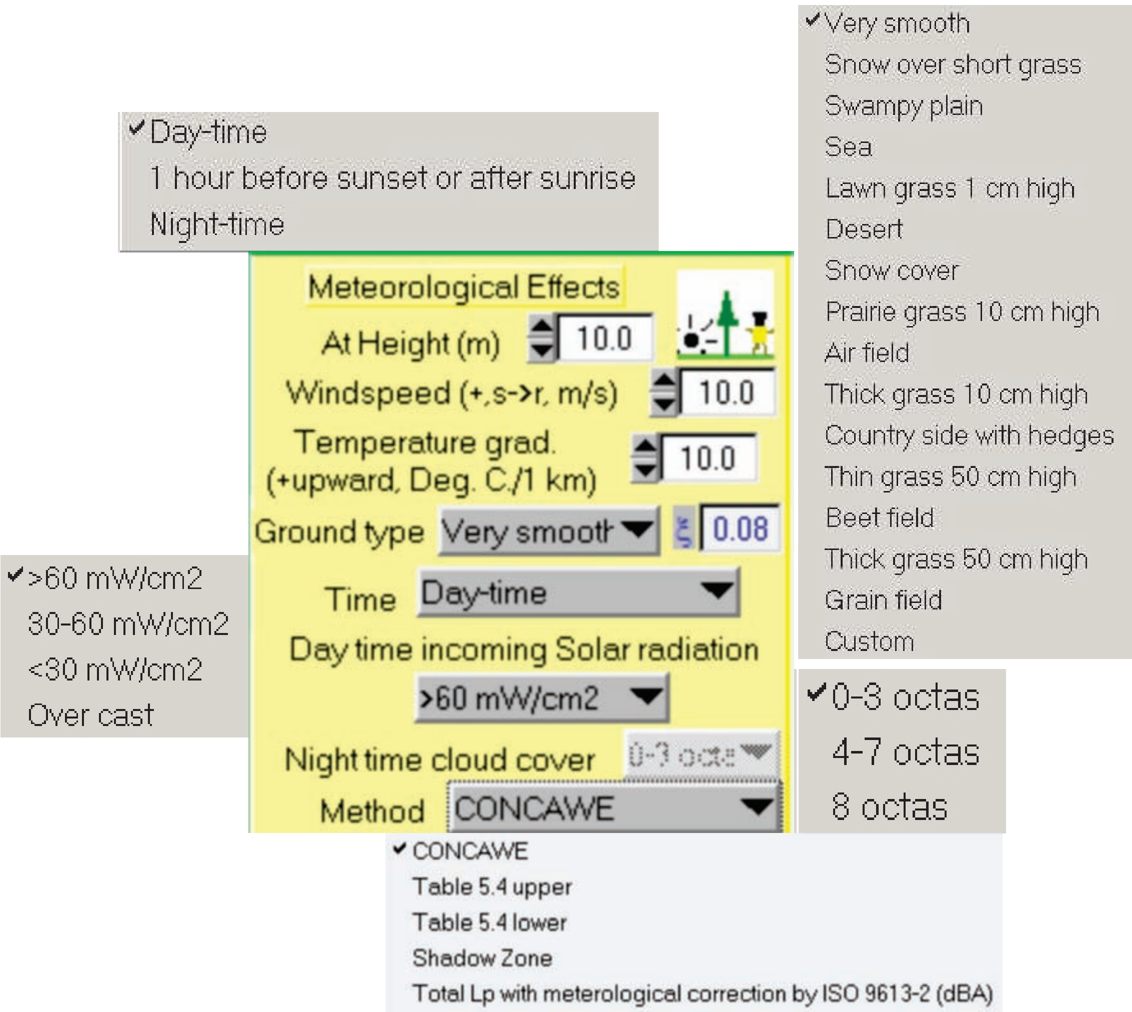


the reflection is somewhere between coherent and incoherent. However, Equation (5.70), is used for $\Phi < 1.0$.

For the 0 dB option, the ground effect is 0 dB which implies soft ground and for the -3 dB option, the ground effect is -3 dB, which implies hard ground.

Note that if the barrier attenuation (Ab) box is checked, the ground effects, Ag, box should only be ticked if there is line of sight between the source and receiver around one end of the barrier or for two or more paths over the top (direct path and one or more reflected paths).

3.2.3.3 Meteorological Effects



In this current version of ENC, meteorological Effects are no longer calculated separately when any circular ray path option is chosen for the calculation of |Rs| in the Ag popup window, as the ray curvature accounts for meteorological effects, at least to the accuracy of the analysis in ENC. Thus, in the main centre panel, the Am tick box is greyed out whenever a circular ray path option is selected in the “method” menu in the pink ground effect box.

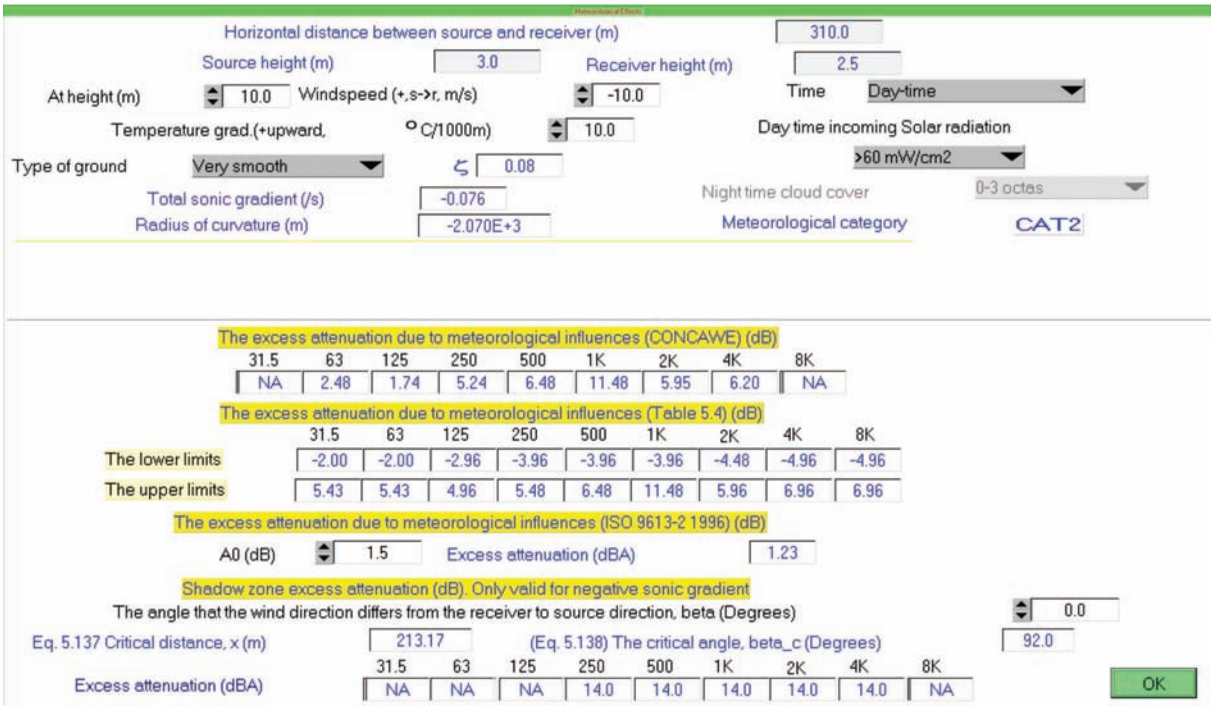
However, meteorological effects are calculated separately whenever a straight ray path option (including the plane wave option) is chosen (see figure on page 85). Even though it seems inconsistent for ENC to produce results for attenuation in the shadow zone when a straight ray path option is chosen, ENC does allow this option by allowing wind speed and temperature gradient data to be entered in the yellow panel. To be strictly correct, if a straight ray path option is chosen in the pink panel, the temperature gradient and wind speed options in the yellow panel should be set equal to zero as a straight ray path implies that these values are zero. However, sometimes it is of interest to see what the shadow zone attenuation is, even though straight ray paths may be preferred for the ground effect and barrier calculations. Thus, if wind speed and temperature gradient data are non-zero in the yellow panel, the radius of curvature of the non-ground-reflected ray will always be calculated and will appear in the window that pops up when Am is clicked on in the centre panel on the main page. If wind speed and temperature gradient data are zero in the yellow panel, then the radius of curvature of the sound ray is set equal to 10^{10} in the meteorological effects popup panel.

Note that if the sonic gradient is negative, the ground effect calculation is not accurate but it should be included as the ground reflected ray will contribute to the sound experienced by the receiver. Negative atmospheric sonic gradients result in large attenuations of sound, especially if the receiver is in the shadow zone, as a result of rays emitted by the source curving away from the ground. Thus, calculations for these cases are rarely needed in a practical situation, as there is more interest in predicting the louder sound resulting from a positive sonic gradient.

The attenuation, A_m, due to meteorological effects may be calculated using one of 5 different methods and the panels shown in the previous and following figures. Previous versions of ENC had a sixth choice (Table 5.9 in the 5th edition textbook) but this option is no longer considered valid so it has been omitted in later versions of ENC.

If the “Ground type” is selected as “custom”, that allows you to enter whatever value you wish for the wind shear coefficient, ξ, used to calculate the wind gradient (see Equations (5.79) and (5.85) in the 6^{th} edition textbook). Values of the wind shear coefficient for various ground types are listed in Table 5.5 on page 270 of the textbook. Note that the wind shear coefficient, ξ, is used to account for ray curvature in barrier noise reduction calculations and also to calculate the combined ground and meteorological effects when the “Method”, “Spherical wave-circular propagation path-power law atmospheric sound speed profile” is selected. It results in reduced barrier performance in downwind conditions (wind blowing in a direction from source to receiver). The wind and temperature gradient data for use in the barrier attenuation calculations must be entered separately in the window that appears when “Ab” in the centre panel is clicked on.

Detailed results for all methods are available when you click on “Am” in the centre panel, which results in the window shown in the following figure popping up. Note that only one of the rows of octave band values is used for the overall sound pressure level calculations and the selected row is dependent on which "method" was selected in the yellow "Meteorological Effects" box, as illustrated in the preceding figure. Referring to Table 5.10 on page 319 in the 6th edition textbook, the strong, moderate and slight incoming solar radiation refer to greater than 60, 30–60 and less than 30 mW/cm^2, respectively. In table 5.9 in the 6th edition textbook, "Latitude of the sun" refers to the angle that the sun makes between the line from the sun to the observer and the line from the observer to the horizon immediately below the sun.



The first method for calculating the attenuation due to meteorological effects is based on a calculation of the atmospheric sonic gradient from your input of the atmospheric temperature gradient (which can be negative as well as positive, with positive representing a temperature inversion or increasing temperature with increasing altitude), wind speed, and height at which the wind speed was measured (preferably 10 m). These data are entered in the panel shown above. Note that the wind speed is positive if blowing from the source to the receiver and is the proportion of the wind vector pointing from source to receiver.

Note that the type of ground also needs to be selected from the drop down menu (shown on the previous page) as this affects the sonic gradient.

The wind shear coefficient from Table 5.5, p. 270 in the 6th edition textbook is used to calculate the sonic gradient caused by the wind gradient. This gradient is only used when calculating ray curvature in the barrier insertion loss calculations.

The second method is based on the CONCAWE model described in the 6th edition textbook on pages 318–319 of the 6th edition textbook. The required input data are the time of day and the wind speed at the height that you specify in the text box above "wind speed" (usually 10 metres height). The wind speed to be entered in the box is the component in the direction from the source to the receiver. If the component is upwind (receiver to source), then the wind speed is negative. For daytime, the incoming solar radiation value is required and for nighttime, the extent of cloud cover (with 8 octas being overcast and 4 octas being half cloudy) is required. These are selected from the dialog boxes illustrated on the previous page. The temperature gradient value is not used in this calculation.

The third and fourth methods are simply a restatement of Table 5.4, page 266 in the 6^{th} edition textbook.

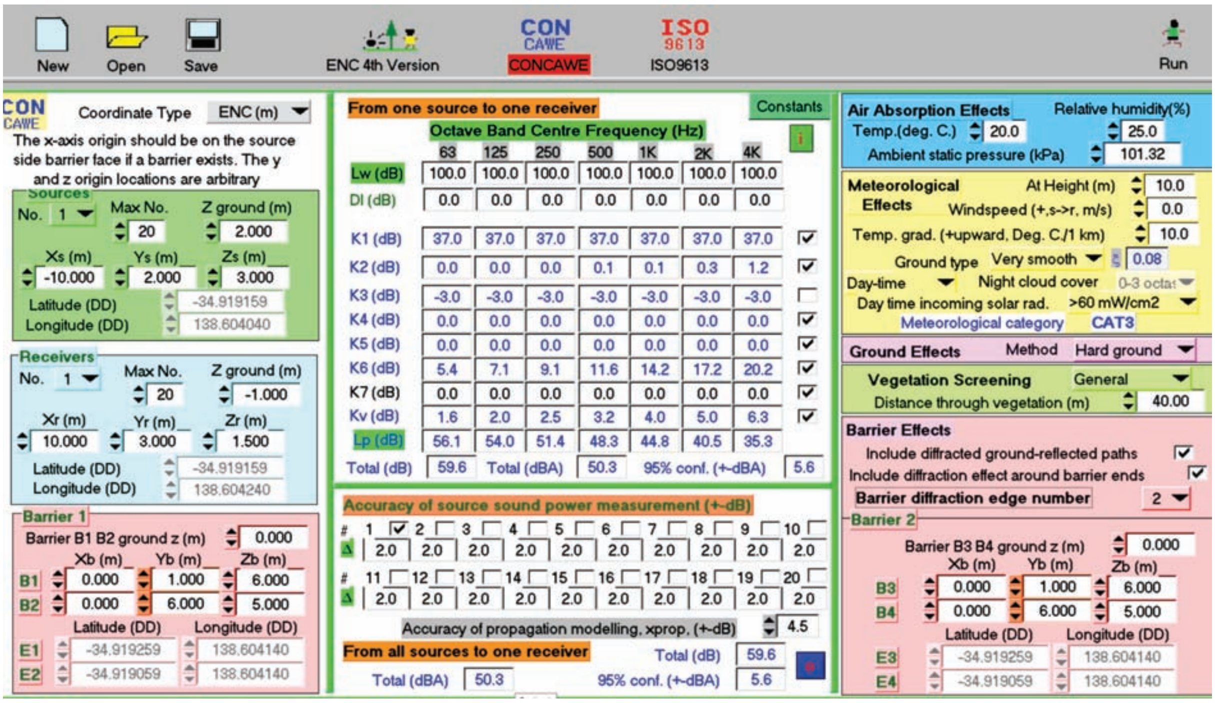
The **fifth method is only valid for upwind sound propagation** where the atmospheric wind and temperature gradients are such that a negative sonic gradient is produced. The gradient value is in blue font, 6 lines down from the top of the page. The attenuation calculations are based on shadow zone theory as outlined in the 6th edition textbook on pages 290–291.

The sixth method is specified by ISO 9613-2 and is only applicable to overall dB(A) calculations. Note that it cannot be used for the ISO octave band calculations as these assume worst case meteorological conditions. The value calculated using this method is added to the overall A-weighted sound calculated from the octave band results determined by assuming worst case meteorological conditions. A value for A0 (see figure on previous page and Equation (5.226) in the 6^{th} edition textbook) may be estimated from an elementary analysis of the local meteorological statistics. For example, if the meteorological conditions favourable to propagation (downwind from source to receiver or temperature inversion) are found to occur for 50% of the time period of interest, and the attenuation during the other 50% is higher by 10 dB or more, then the sound energy which arrives for meteorological conditions unfavourable to propagation may be neglected, and A0 will be approximately + 3 dB. If conditions that are favourable to sound propagation occur for 70% of the time, and for the other 30% of the time, the attenuation is much greater, then A0 =1.5 dB. In practice, A0 is never usually larger than 2 dB.

Detailed results for all methods are shown in the pop up panel that appears when you click on “Am” in the centre panel of the main window (see preceding figure). The excess attenuation values inserted by ENC in the Am line in the centre panel correspond to the option chosen in the “method” drop down list in the yellow box on the main page.

3.3 CONCAWE Window

Note that values in blue font are calculated values and cannot be changed by typing over the value in the box.

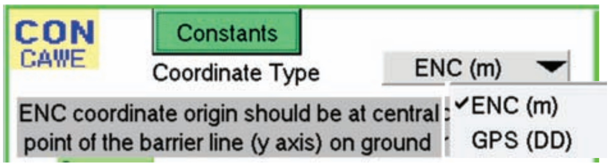


This window calculates the sound pressure level, using the CONCAWE propagation model for up to 20 receiver locations and up to 20 sources in different locations operating simultaneously. Octave band sound pressure levels (in the range 63 Hz to 8 kHz), overall linear levels and overall A-weighted levels are calculated for each receiver location (maximum 20) as a result of up to 20 noise sources. All noise sources are treated as point sources.

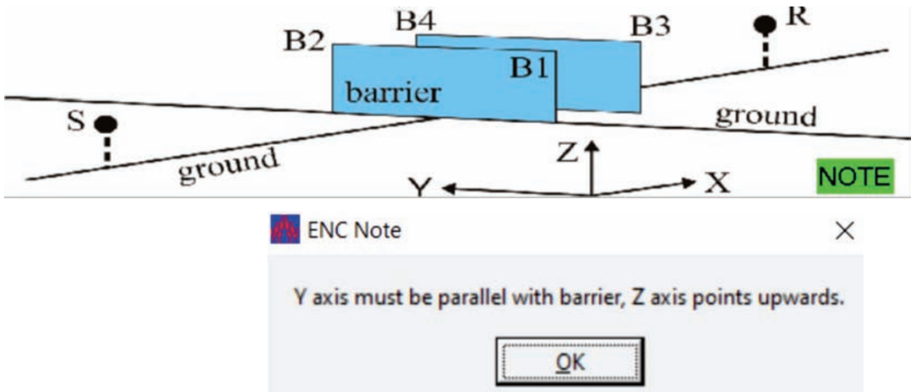
Note that only the point source option and the Maekawa method is allowed for barrier attenuation calculations and an error message will now be produced if the z-coordinate of the source is less than or equal to the z-coordinate of the ground beneath it and / or the z-coordinate of the receiver is less than or equal to the z-coordinate of the ground beneath it. A 24 dB maximum overall attenuation limit has now been applied to all barrier attenuation calculations.

The window is divided into a number of segments and each will be treated separately here.

3.3.1 Coordinate Type

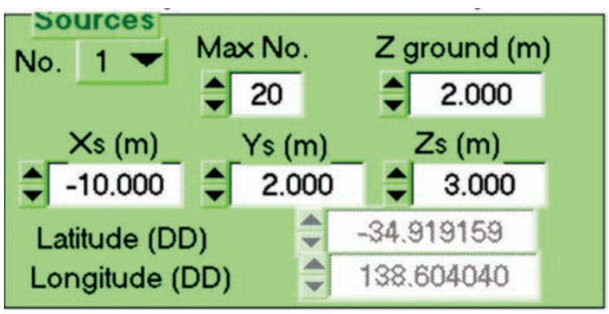


As illustrated in the figure at right, you have a choice of coordinate types for the source, barrier and receiver locations. Choosing “ENC(m)” means that you would like to enter source, receiver and barrier coordinates with respect to a physical origin location. If a barrier is to be included in the calculations, the preferred (but not essential) origin location is must be ground level near the centre of the barrier baseline. However, it is essential that the x, y and z coordinates are defined in the directions shown in the figure below with respect to the source, receiver and barrier (if it exists) locations. If no barrier exists, then there is no preference for the location of the coordinate origin, but the z-axis is always the vertical one and if a barrier exists, the zero x-coordinate must be on the barrier face nearest the source.



Choosing "DD" as the coordinate type means that you wish to enter all $(x,\ y)$ coordinate locations in terms of degrees latitude and longitude. In this case, no $(x,\ y)$ origin location is needed. However, a vertical origin location is needed for the z-direction and ENC will work out the x and y-axis orientations and origin in the $x-y$ plane so that the y-axis is parallel to the barrier face (if one exists) and the coordinate origin is at the base of the barrier an halfway along it.

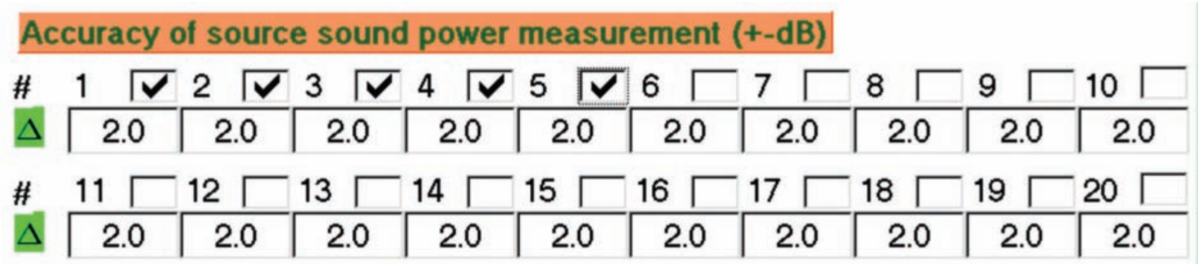
3.3.2 Sources



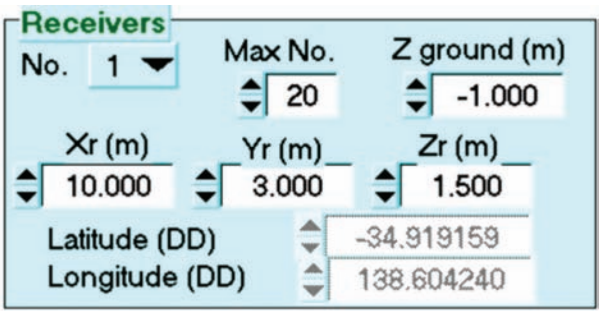
As indicated on the figure at right, you can enter the coordinates of each source to be considered, as well as the z-coordinate of the ground directly under the source, in the type of units that you require (metres with respect to an origin or degrees latitude and longitude). Note that the values are coordinates with respect to an origin and are NOT distances or heights above ground. The sources are numbered from 1 to a maximum number of 20. The number of the source that is associated with the coordinates is in the box to the right of "No.". You can enter the maximum number of sources that are to be included in the analysis in the box to the right of "Max No.". This number will then match the number of the boxes that are allowed to be ticked in the lower centre panel. Only sources corresponding to the boxes that are ticked in the lower centre panel will be included in the sound pressure level calculation at the receiver currently being considered.

If a barrier exists, then the y-axis is parallel to the barrier and the preferred x coordinate origin is the face of the barrier closest to the source. If no barrier exists, there is no preferred location for the origin. The orientation of the x and y axes is also not important if no barrier exists, provided that they are orthogonal to one another and orthogonal to the vertical axis, z, and provided that the same origin and axes are used for all sources and all receivers.

You must enter the source sound power level in the location indicated on the centre panel for the source number that is showing in the figure at right. You can select the number of sources that you wish to consider by typing in the number in the "Max No." box shown in the above figure. This number will also be reflected in the maximum number of tick boxes available in the figure shown below, which shows that 6 sources are to be considered. The figure above right shows that we are currently considering source number 1, and that we have chosen coordinate type to be distance from an origin in metres (which is why the "DD" coordinates are greyed out). You can select another source by clicking on the ▼ symbol shown on the figure above right (next to "No. 1") and a drop down menu with source numbers from 1 to 20 will appear.



3.3.3 Receivers



As indicated on the figure at right, you can enter the coordinates of each receiver number to be considered (up to a maximum of 20), as well as the z-coordinate of the ground directly under the receiver, in the type of units that you require (metres with respect to an origin or degrees latitude and longitude). Note that the values are coordinates with respect to an origin and are NOT distances or heights above ground. The receivers are numbered from 1 to a maximum number of 20. The number of the receiver that is associated with the coordinates is in the box to the right of "No.". You can enter the maximum number of receivers that are to be included in the analysis in the box to the right of "Max No.". in the type of units that you require (metres with respect to an origin or degrees latitude and longitude). This receiver number is the one that is used for the data input and the results displayed in the centre panel. You need to enter the data in the centre panel for each receiver of interest. ENC will remember the data associated with each receiver and will write it to a file that can be saved by clicking on the blue "o" button located at the bottom of the centre panel.

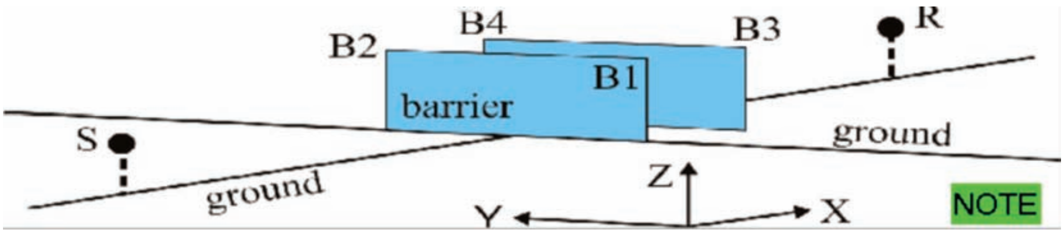
If a barrier exists, then the y-axis is parallel to the barrier and the preferred x coordinate origin is the face of the barrier closest to the source. If no barrier exists, there is no preferred location for the origin. The orientation of the x and y axes is also not important if no barrier exists, provided that they are orthogonal to one another and orthogonal to the vertical axis, z, and provided that the same origin and axes are used for all sources and all receivers.

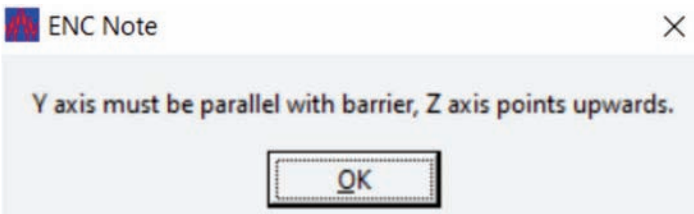
ENC will calculate octave band, overall linear and overall A-weighted sound pressure levels and overall A-weighted uncertainties for the total contribution of all sources to each receiver. In addition, the contributions of each source to all receivers are placed in an output file. Note that data are also given in the output file for receiver numbers that you did not define. Please ignore these data.

You can select the receiver number from the drop down menu in the receiver segment shown in the figure above (the ▼ symbol shown next to “No. 1”). You can then enter the coordinate locations for this receiver and ENC will store these for later calculations.

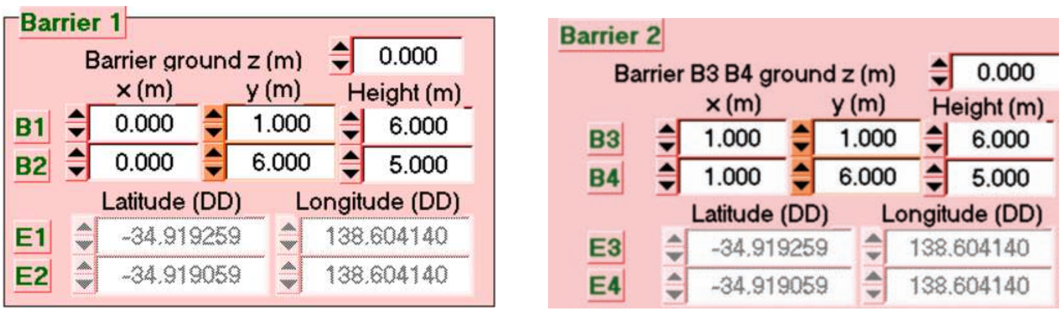
3.3.4 Barrier

This version of ENC allows for a double barrier calculated using the Maekawa model which uses differences in the diffracted and direct paths to calculate a Fresnel number. The Fresnel number is then used to calculate the attenuation due to diffraction. The two diffraction edges are illustrated in the figure below.



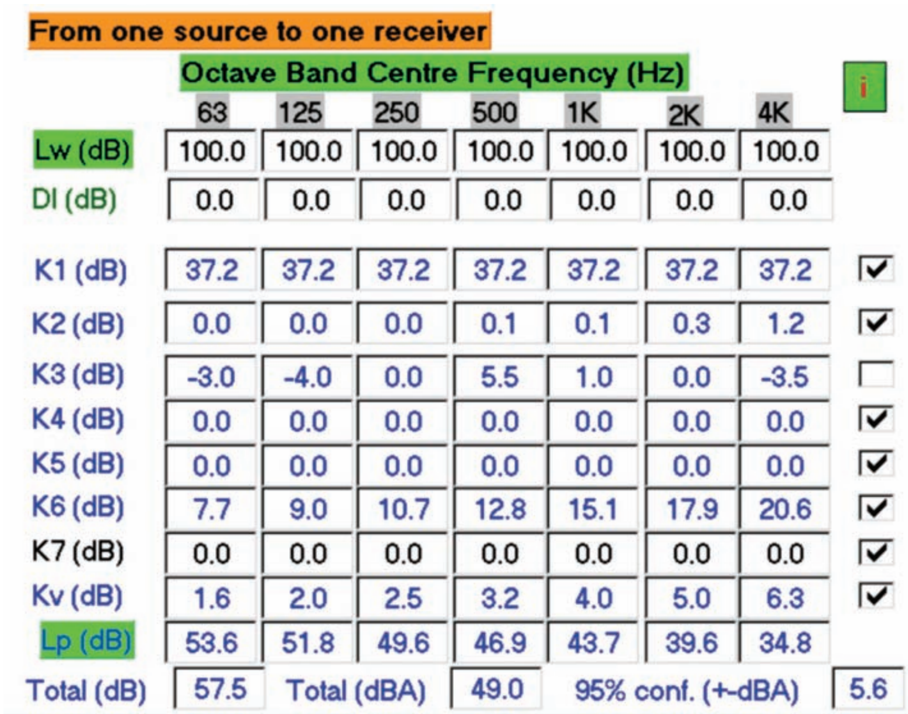


The pink segments illustrated in the following figure are used to enter the coordinates of the top edge of the barrier (and the two top edges when there are two diffraction edges), as well as the z-coordinate at the ground under the barrier. For a double barrier, barrier1 is the diffraction edge nearest the source and for a single barrier, the barrier2 panel is greyed out so no data can be entered.



The origin of the coordinates is arbitrary, but it must be the same as that used for the source and receiver locations and the barrier calculations when the K6 line in the centre panel has a ticked box. However, the zero x-coordinate must be the face of the barrier nearest the source when a barrier exists. The y-axis is parallel to the barrier face and the x-axis is normal to it. If a barrier is selected by ticking the box on the RHS of the K6 line in ENC, then the sources that are to be affected by the barrier must have negative values for their x-coordinates and the receivers that are to be affected by the barrier must have positive values for their x-coordinates.

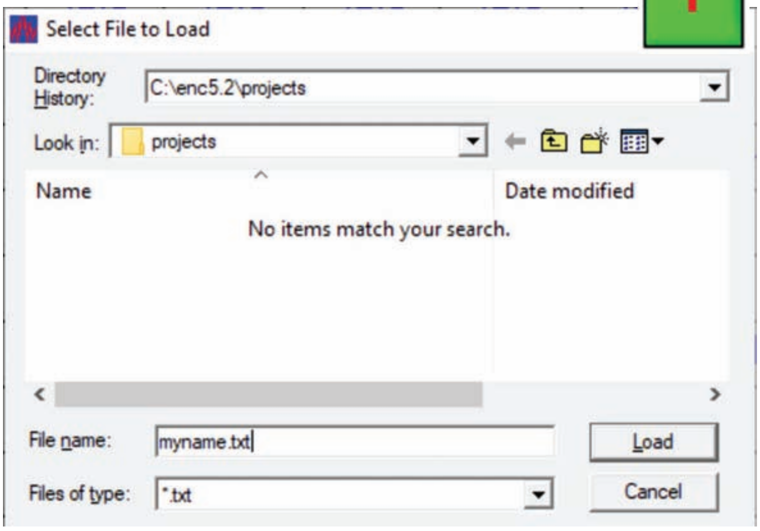
3.3.5 Top Segment of Centre Panel



The segment shown above is where you may enter the octave band source sound power levels (top line) and the directivity factor from the selected source to the selected receiver (second line). You may then tick the appropriate boxes to include any attenuation effects that are relevant for the particular source receiver pair that are being considered. The source number being considered is the one selected from the drop down list in the "Sources" segment discussed above and the receiver number is the one selected from the drop down list in the "Receiver" segment discussed above. Attenuation effects are identified in pages 317–321 of the 6th edition textbook. The K6 effect is the attenuation due to a barrier between a source and receiver – see Section 3.4.4. Only one barrier (single or double diffraction edge) is allowed for any one calculation. The K3 ground attenuation box should only be ticked if there is line of sight between the source and receiver around one side of the barrier or two or more paths over the top (non-ground-reflected path and at least one ground-reflected path).

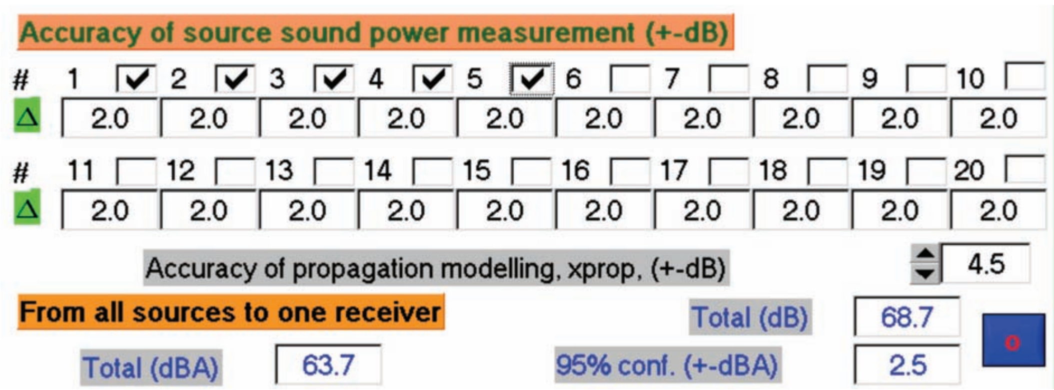
The very bottom line in the figure above shows overall linear and A-weighted results for the selected receiver location due to the selected source. The 95% confidence limits are calculated for the overall A-weighted level using Equation (5.278) in the 6th edition textbook, and multiplying the result of Equation (5.278) by 1.96, as explained on p. 143. The propagation model and source sound power accuracies (in dB) used to calculate the parameters in Equation (5.278) in the textbook are entered by the user in the bottom segment of the centre panel, shown in the figure in the next section.

Right clicking on the "i" symbol shown at right brings up a box that allows you to save the sound power level and directivity data. Left clicking on the "i" symbol shown at right brings up the box shown beneath it. If you have data stored from a previous session, you can load it here. Note the format of the data to be loaded must be the same as in the file created by right clicking the "i" symbol.



Be careful when entering the file name. It is not allowed to click on an existing file name and just change some characters. This will result in overwriting the file that is already there. You must type the file name from scratch in full and you must not click on an existing file unless you want it to be overwritten. The same procedure applies if you click on the "Save" icon in the tool bar at the top of the screen to save the page settings.

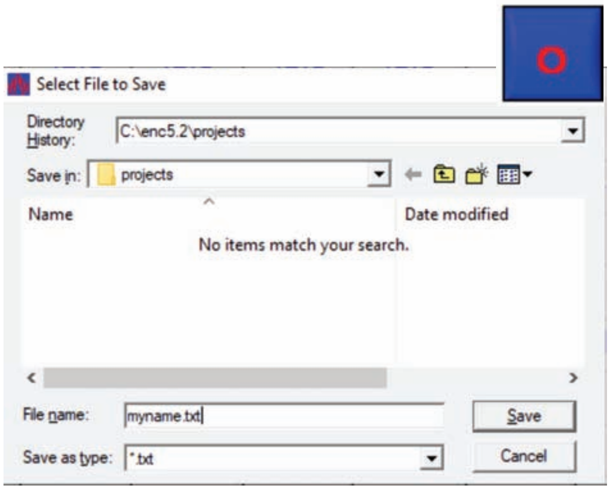
3.3.6 Bottom Segment of Centre Panel



The bottom segment of the centre panel, illustrated in the preceding figure, contains check boxes that show a tick mark when clicked and indicate that the source number that is ticked will be included in the total sound pressure level at the receiver, which is shown on the bottom two lines of the above figure. The relevant receiver number is the number currently selected in the blue receiver segment on the left part of the window. The 95% confidence limits are calculated for the overall A-weighted level using Equations (5.278) and (5.279) in the 6th edition textbook, and multiplying the result of Equation (5.278) by 1.96.

The row of boxes to the right of the Δ symbol in the above figure are the estimated accuracies of the sound power levels in dB, entered by you. You will also need to enter the expected accuracy of the propagation model for calculating the sound pressure level at a single receiver due to a single source.

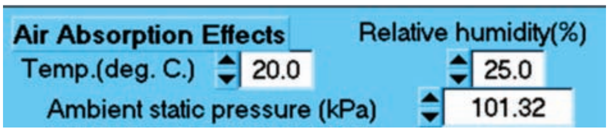
Left clicking on the "o" symbol shown at right brings up the box beneath it. You can select a file name that will contain the output data in text format, which has too many entries to show here. When entering a file name, you must type the complete name in the box. Do not select a file with a similar name and then change the name as it will result in overwriting of the file that you selected, even though you changed the file name.



3.3.7 Spherical Spreading Effect (K1)

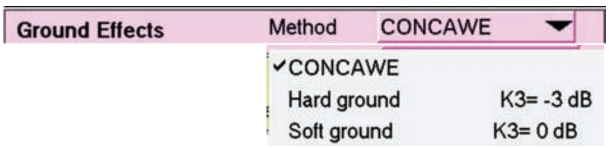
The K1 effect is that due to spherical spreading of a point source only ($= 10 \log_{10} 4\pi d_{\rm SR}^2$, where $d_{\rm SR}$ is the source–receiver separation distance).

3.3.8 Air Absorption (K2)



The attenuation resulting from air absorption (top right of the window) is calculated using the equations and procedures outlined in the standards, ISO 9613-1 and ANSI S1.26. In those standards, the absorption for an octave band is calculated at the exact band centre frequency, whereas in ENC it is calculated at the nominal band centre frequency (with very little difference). The values entered in the Air absorption effects segment illustrated at right are automatically repeated in the constants panel and vice versa.

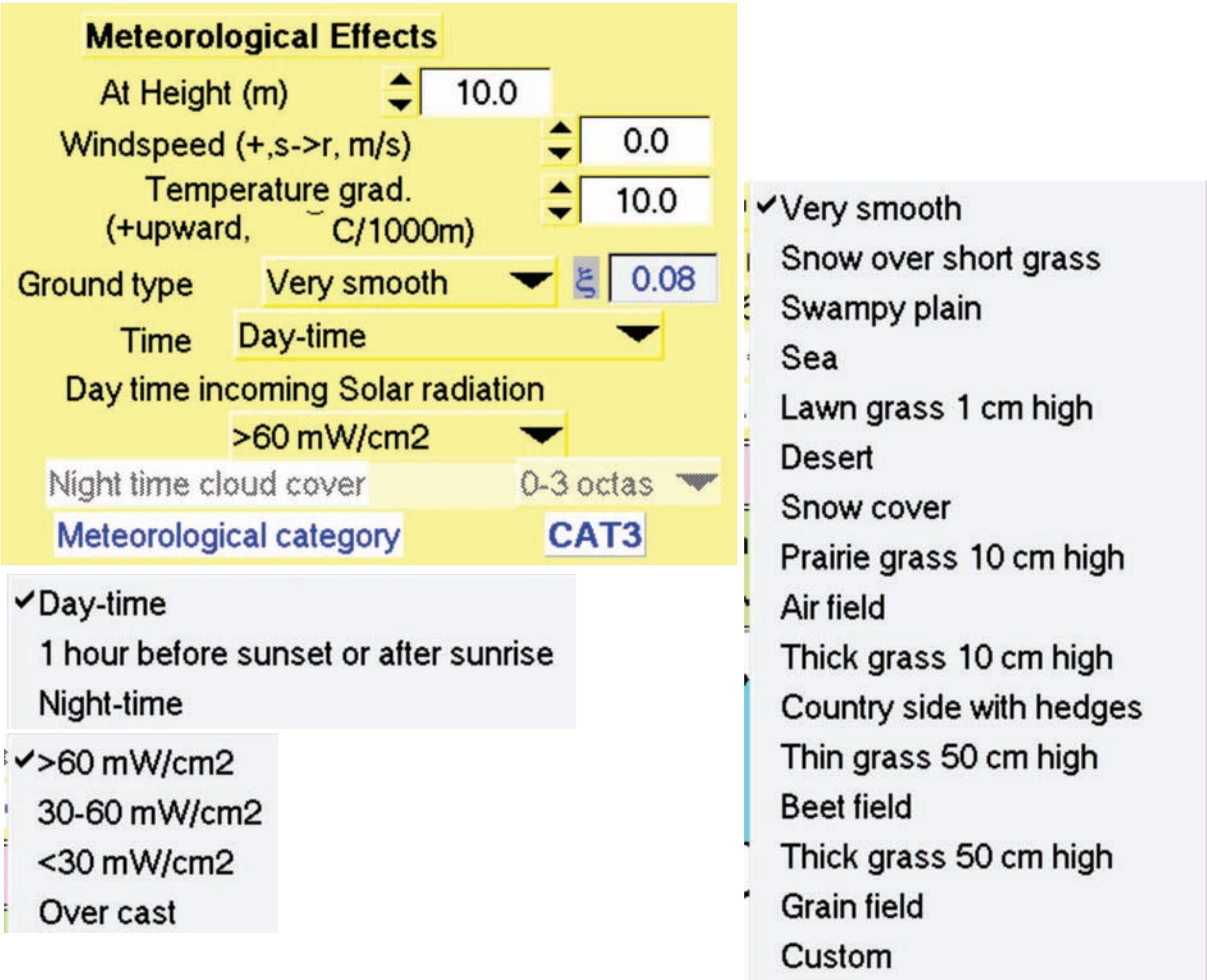
3.3.9 Ground Effects (K3)



You may choose between hard ground, soft ground and the CONCAWE curves for ground in the vicinity of a typical processing plant (Figure 5.19 in the 6th edition textbook). The CONCAWE choice is not recommended as the results are based on experimental data for one specific industrial plant. However, this choice is included as it is part of the original CONCAWE model. Note that the choice of ground type used here is also used for calculating the ground reflection losses for the ground reflected paths in the barrier calculations.

3.3.10 Meteorological Effects (K4)

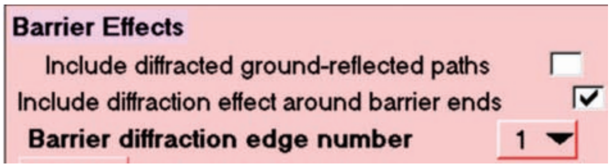
To calculate the attenuation due to meteorological effects (see following figure), you need to choose the height for the specified wind speed (Usually 10 m), the component of the wind speed in the direction from the source to the receiver (positive for a downwind component), the ground type, the time period (day, sunset/sunrise, night) and daytime incoming solar radiation or nighttime cloud cover ("1 octa" means 1/8 of the sky is covered with cloud). ENC will use these data to calculate K4 according to CONCAWE as well as for calculating the radius of curvature of the non-reflected sound ray path over the top of the barrier in the barrier calculation part (K6). The ground type must be entered here and this needed to account for the effect of sound ray curvature on the barrier noise reduction.



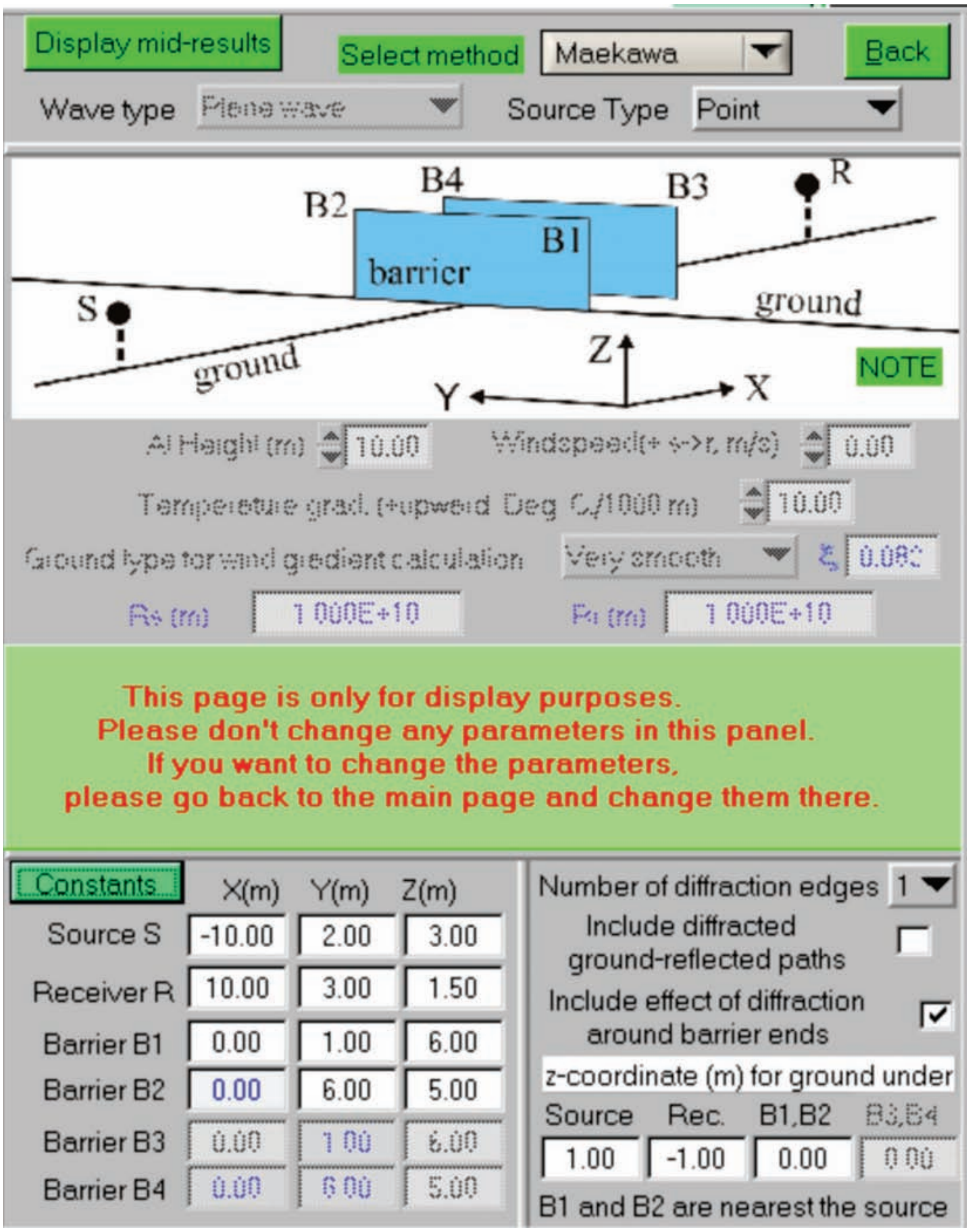
3.3.11 Source Height Effects (K5)

The K5 effect is that due to the source height and is calculated as described on pages 319 and 320 of the 6th edition textbook.

3.3.12 Barrier Effects, (K6)



When you click on K6, the window in the following figure pops up. This window is for display purposes only. **Please do not change any parameters (including source, receiver or barrier coordinates) or any menu choices in this window.** All parameters and menu choices are either fixed or set elsewhere on the main page.



ENC calculates the attenuation due to a single barrier that may have one or two diffraction edges or two parallel barriers relatively close together. The calculations use barrier coordinates relative to the same origin as used for the source and receiver coordinates and follow procedures in the 6th edition of the textbook on pages 264–270. The source and receiver heights are adjusted to account for wind and temperature gradients as described on pages 312–314 in the textbook. The barrier thickness is accounted for using double diffraction analysis. The analysis method used in this CONCAWE section is the Maekawa method. The barrier attenuations due to all 8 paths around the finite length barrier are calculated as described on pages 293–312 in the 6th edition textbook and then the results are combined using Equation (1.105) or Equation (5.178). It is important to note that the maximum allowed octave band barrier attenuations of 20 dB for single diffraction and 25 dB for a thick barrier (recommended in ISO9613-2) only apply to the path over the top with no ground reflections.

If the "Include diffracted ground-reflected paths" box is ticked, ENC will include all diffracted ground reflected paths in the overall attenuation calculation. The non-diffracted ground reflected path that exists without the barrier and whose attenuation is used as part of the barrier overall attenuation calculation is included whether or not the box is ticked.

As the barrier calculation includes the effect of ground on either side of it, and excludes the effect of ground without the barrier, the ground effect that exists for the case with no barrier cannot be used unless there is line of sight between the source and receiver around one end or for two or more paths over the top. Thus, when the barrier box (Ab) is checked, the ground effect box should not be checked unless the one of the line of sight conditions is satisfied or the ground effect will be accounted for twice.

If a barrier is selected by ticking the box on the RHS of the K6 line in ENC, then the sources that are to be affected by the barrier must have negative values for their x-coordinates and the receivers that are to be affected by the barrier must have positive values for their x-coordinates. More details about barrier calculations are provided on pages 68 to 169.

3.3.13 In-plant Screening, K7

The value recommended by CONCAWE for in-plant screening is zero and this is the default value in ENC. However, there is a capability for you to enter non-zero values if you wish.

3.3.14 Vegetation Screening, (Kv)

ENC will calculate the attenuation due to vegetation screening according to the procedure on page 321 of the 6th edition textbook. ENC gives a choice between "General" and "Long grass or shrubs". The "General" selection is intended for forests.

3.4 ISO9613 window

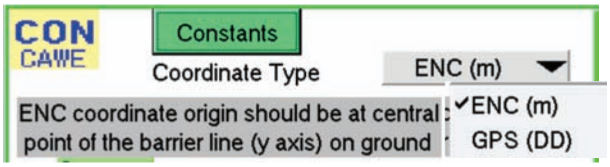
Note that values in blue font are calculated values and cannot be changed by typing over the value in the box.

This window calculates the sound pressure level, using the ISO9613 (1996) propagation model for up to 20 receiver locations and up to 20 sources in different locations operating simultaneously. Octave band sound pressure levels (in the range 63 Hz to 8 kHz), overall linear levels and overall A-weighted levels are calculated for each receiver location (maximum 20) as a result of up to 20 noise sources. All noise sources are treated as point sources.

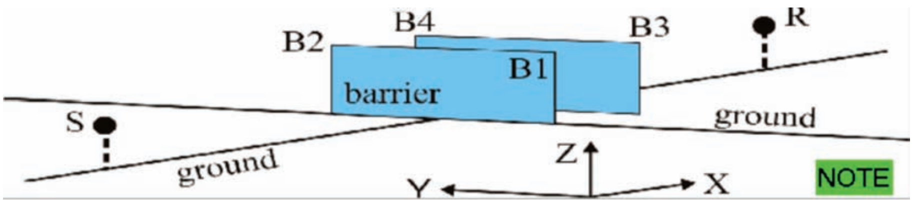
Note that only the point source option and the ISO9613 method is allowed for barrier attenuation calculations and an error message will now be produced if the z-coordinate of the source is less than or equal to the z-coordinate of the ground beneath it and / or the z-coordinate of the receiver is less than or equal to the z-coordinate of the ground beneath it. A 24 dB maximum overall attenuation limit has now been applied to all barrier attenuation calculations.

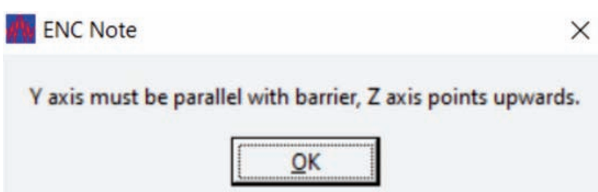
The window is divided into a number of segments and each will be treated separately here.

3.4.1 Coordinate Type



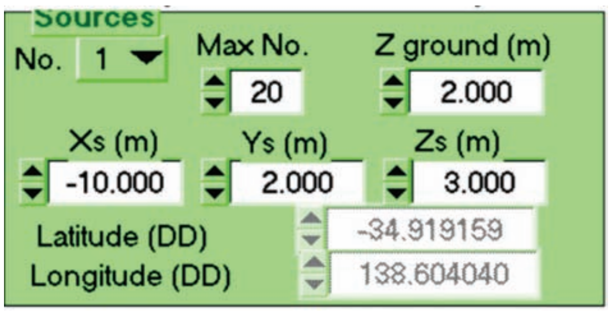
As illustrated in the figure at right, you have a choice of coordinate types for the source, barrier and receiver locations. Choosing "ENC(m)" means that you would like to enter source, receiver and barrier coordinates with respect to a physical origin location. If a barrier is to be included in the calculations, the preferred (but not essential) origin location is must be ground level near the centre of the barrier baseline. However, it is essential that the x, y and z coordinates are defined in the directions shown in the figure below with respect to the source, receiver and barrier (if it exists) locations. If no barrier exists, then there is no preference for the location of the coordinate origin, but the z-axis is always the vertical one and if a barrier exists, the zero x-coordinate must be on the barrier face nearest the source.





Choosing "DD" as the coordinate type means that you wish to enter all $(x,\ y)$ coordinate locations in terms of degrees latitude and longitude. In this case, no $(x,\ y)$ origin location is needed. However, a vertical origin location is needed for the z-direction and ENC will work out the x and y-axis orientations and origin in the $x - y$ plane so that the y-axis is parallel to the barrier face (if one exists) and the coordinate origin is at the base of the barrier an halfway along it.

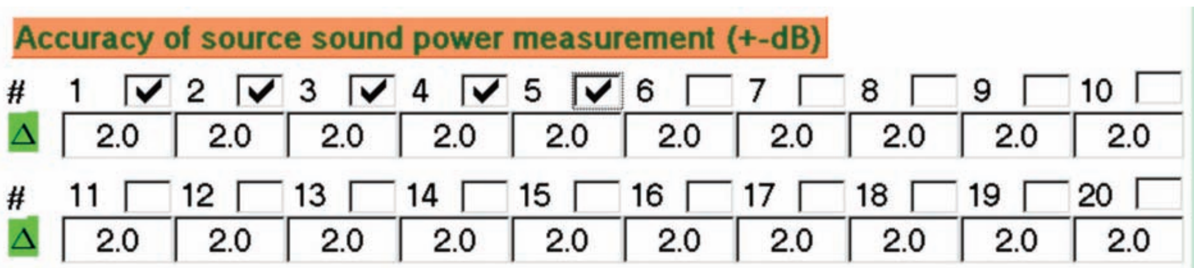
3.4.2 Sources



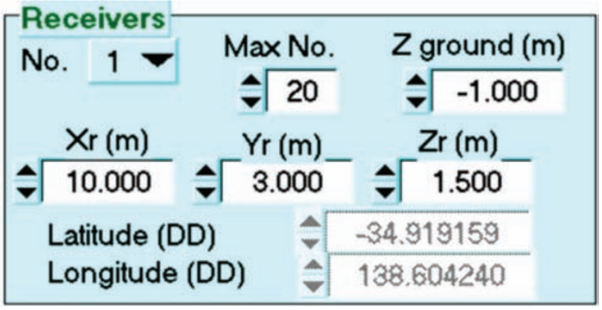
As indicated on the figure at right, you can enter the coordinates of each source to be considered, as well as the z-coordinate of the ground directly under the source, in the type of units that you require (metres with respect to an origin or degrees latitude and longitude). Note that the values are coordinates with respect to an origin and are NOT distances or heights above ground. The sources are numbered from 1 to a maximum number of 20. The number of the source that is associated with the coordinates is in the box to the right of "No.". You can enter the maximum number of sources that are to be included in the analysis in the box to the right of "Max No.". This number will then match the number of the boxes that are allowed to be ticked in the lower centre panel. Only sources corresponding to the boxes that are ticked in the lower centre panel will be included in the sound pressure level calculation at the receiver currently being considered.

If a barrier exists, then the y-axis is parallel to the barrier and the preferred x coordinate origin is the face of the barrier closest to the source. If no barrier exists, there is no preferred location for the origin. The orientation of the x and y axes is also not important if no barrier exists, provided that they are orthogonal to one another and orthogonal to the vertical axis, z, and provided that the same origin and axes are used for all sources and all receivers.

You must enter the source sound power level in the location indicated on the centre panel for the source number that is showing in the figure at right. You can select the number of sources that you wish to consider by typing in the number in the "Max No." box shown in the above figure. This number will also be reflected in the maximum number of tick boxes available in the figure shown below, which shows that 6 sources are to be considered. The figure above right shows that we are currently considering source number 1, and that we have chosen coordinate type to be distance from an origin in metres (which is why the "DD" coordinates are greyed out). You can select another source by clicking on the ▼ symbol shown on the figure above right (next to "No. 1") and a drop down menu with source numbers from 1 to 20 will appear.



3.4.3 Receivers



As indicated on the figure at right, you can enter the coordinates of each receiver number to be considered (up to a maximum of 20), as well as the z-coordinate of the ground directly under the receiver, in the type of units that you require (metres with respect to an origin or degrees latitude and longitude). Note that the values are coordinates with respect to an origin and are NOT distances or heights above ground. The receivers are numbered from 1 to a maximum number of 20. The number of the receiver that is associated with the coordinates is in the box to the right of "No.". You can enter the maximum number of receivers that are to be included in the analysis in the box to the right of "Max No.". in the type of units that you require (metres with respect to an origin or degrees latitude and longitude). This receiver number is the one that is used for the data input and the results displayed in the centre panel. You need to enter the data in the centre panel for each receiver of interest. ENC will remember the data associated with each receiver and will write it to a file that can be saved by clicking on the blue "o" button located at the bottom of the centre panel.

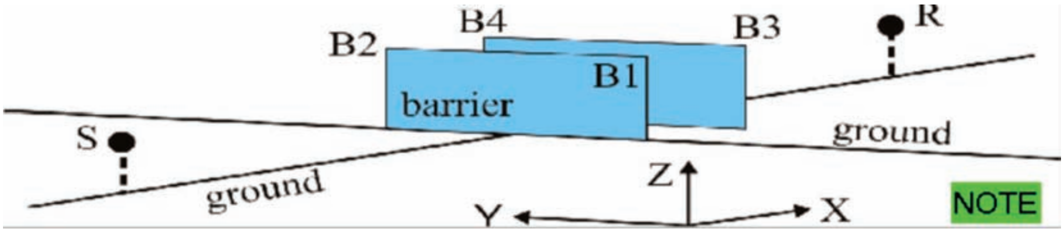
If a barrier exists, then the y-axis is parallel to the barrier and the preferred x coordinate origin is the face of the barrier closest to the source. If no barrier exists, there is no preferred location for the origin. The orientation of the x and y axes is also not important if no barrier exists, provided that they are orthogonal to one another and orthogonal to the vertical axis, z, and provided that the same origin and axes are used for all sources and all receivers.

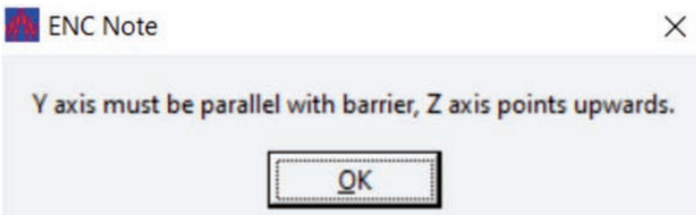
ENC will calculate octave band, overall linear and overall A-weighted sound pressure levels and overall A-weighted uncertainties for the total contribution of all sources to each receiver. In addition, the contributions of each source to all receivers are placed in an output file. Note that data are also given in the output file for receiver numbers that you did not define. Please ignore these data.

You can select the receiver number from the drop down menu in the receiver segment shown in the figure above (the ▼ symbol shown next to "No. 1"). You can then enter the coordinate locations for this receiver and ENC will store these for later calculations.

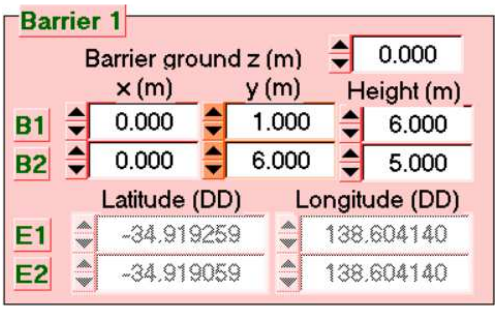
3.4.4 Barrier

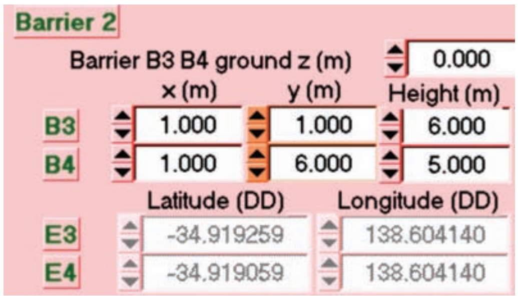
This version of ENC allows for a double barrier calculated using the ISO 9613-2 model, which uses differences in the diffracted and direct paths to calculate a barrier attenuation. The two diffraction edges are illustrated in the following figure.



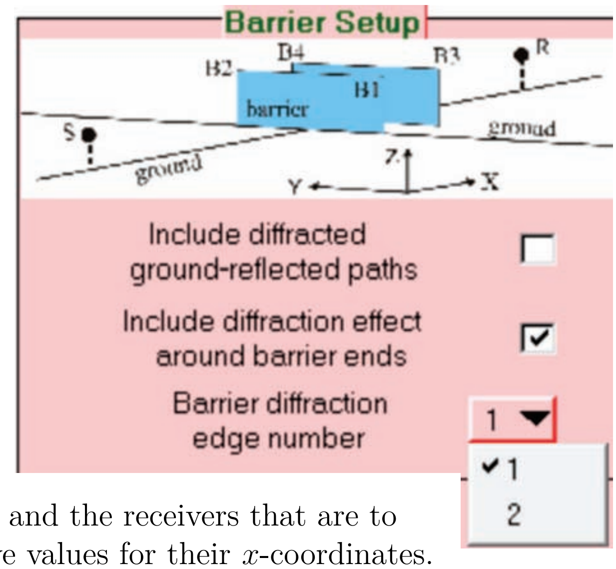


The pink segments illustrated in the following figure are used to enter the coordinates of the top edge of the barrier (and the two top edges when there are two diffraction edges), as well as the z-coordinate at the ground under the barrier. For a double barrier, barrier1 is the diffraction edge nearest the source and for a single barrier, the barrier2 panel is greyed out so no data can be entered.



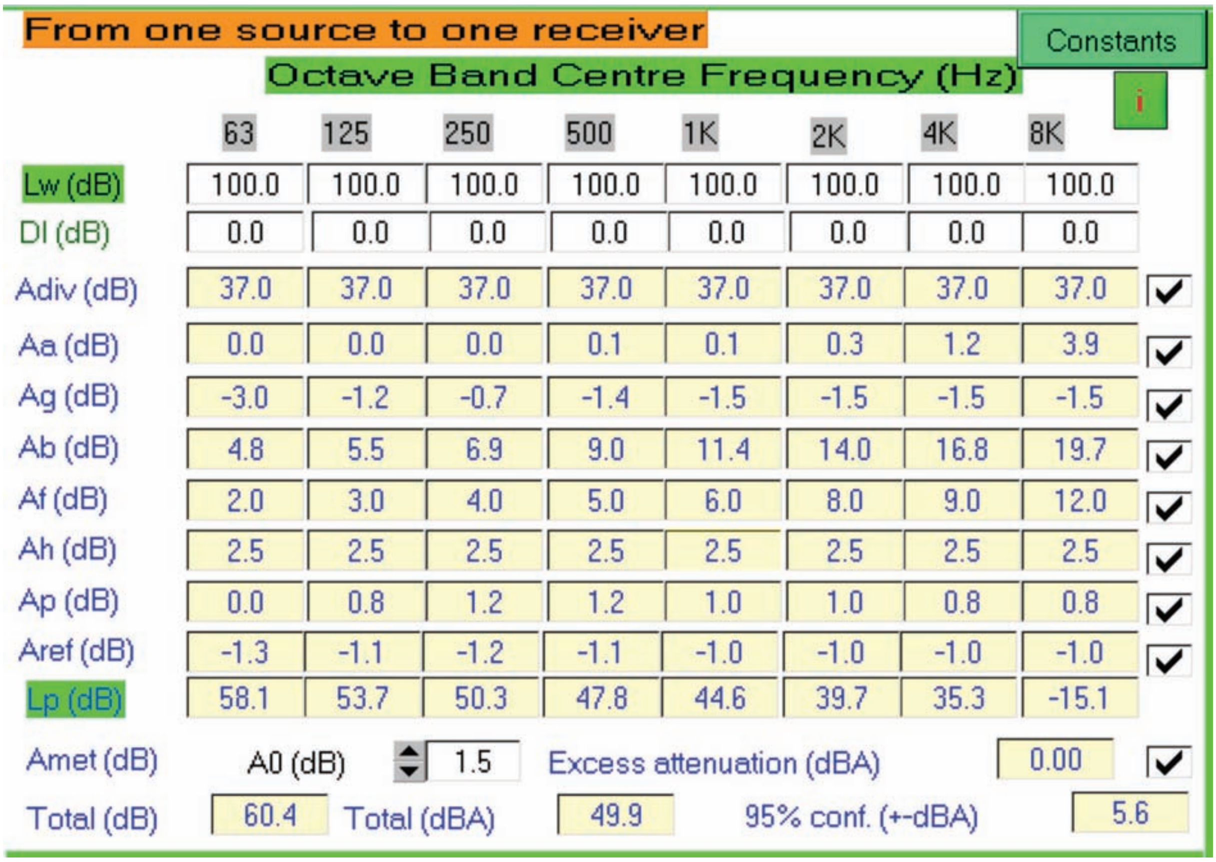


The y and z locations of the origin of the coordinates is arbitrary, but it must be the same as that used for the source and receiver locations and the barrier calculations when the Ab line in the centre panel has a ticked box. However, the zero x-coordinate must be the face of the barrier nearest the source when a barrier exists. The y-axis is parallel to the barrier face and the x-axis is normal to it. If a barrier is selected by ticking the box on the RHS of the Ab line in ENC, then the sources that are to be affected by the barrier must have negative values for their x-coordinates and the receivers that are to be affected by the barrier must have positive values for their x-coordinates.



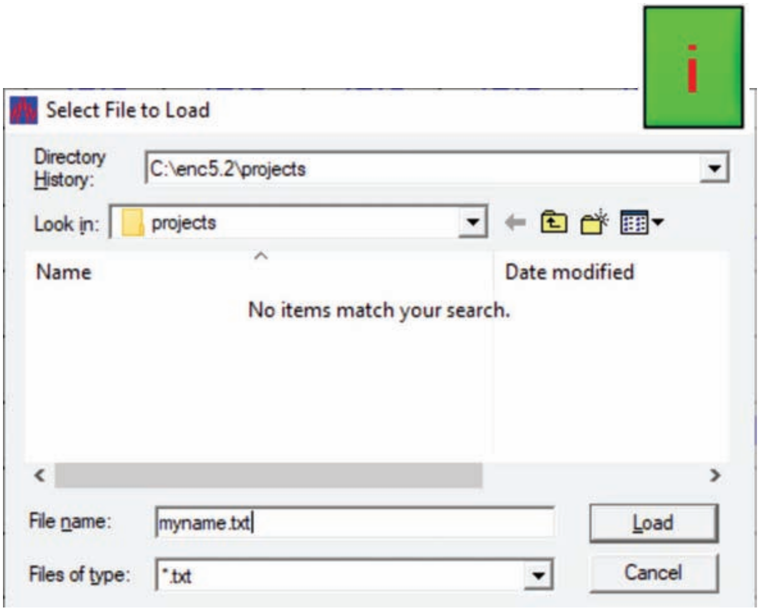
More details about ISO barrier calculations are provided in Section 3.4.10

3.4.5 Top Segment of Centre Panel



The segment shown above is where you may enter the octave band source sound power levels (top line) and the directivity factor from the selected source to the selected receiver (third line). You may then tick the appropriate boxes to include any attenuation effects that are relevant for the particular source receiver pair that are being considered. The source number being considered is the one selected from the drop down list in the "Sources" segment discussed above and the receiver number is the one selected from the drop down list in the "Receiver" segment discussed above. Attenuation effects are identified in pages 323–329 of the 6th edition textbook and are discussed separately in following sections. Note that if the box on the RHS of the Ab line is ticked, the box on the RHS of the Ag line must also be ticked., according to the procedure outlined in ISO9613-2.

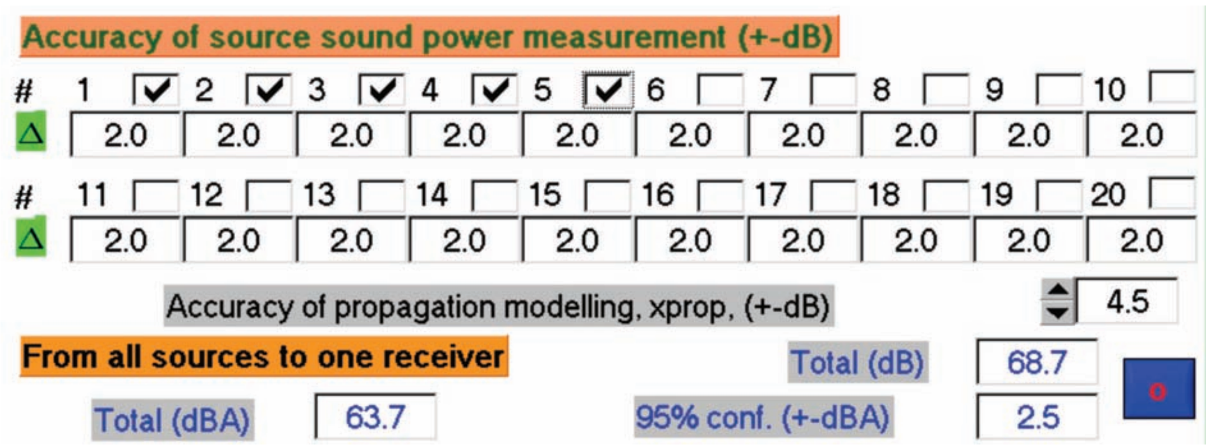
The very bottom line in the figure above shows overall linear and A-weighted results for the selected receiver location due to the selected source. The 95% confidence limits are calculated for the overall A-weighted level using Equation (5.278) in the 6th edition textbook, and multiplying the result of Equation (5.278) by 1.96. The propagation model and source sound power accuracies (in dB) used to calculate the parameters in Equation (5.278) in the textbook are entered by the user in the bottom segment of the centre panel, shown in the figure in the next section.



Right clicking on the “i” symbol shown at right brings up a box that allows you to save the sound power level and directivity data. Left clicking on the “i” symbol shown at right brings up the box shown beneath it. If you have data stored from a previous session, you can load it here. Note the format of the data to be loaded must be the same as in the file created by right clicking the “i” symbol. Be careful when entering the file name. It is not allowed to click on an existing file name and just change some characters. This will result in overwriting the file that is already there. You must type the file name from scratch in full and you must not click on an existing file unless you want it to be overwritten. The same procedure applies if you click on the “Save” icon in the tool bar at the top of the screen to save the page settings.

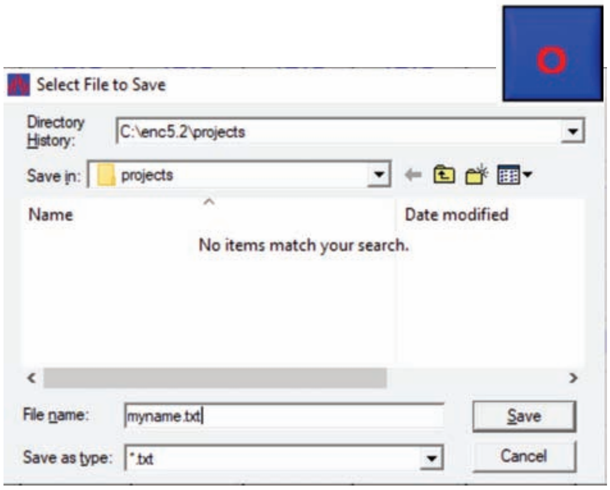
The various attenuation effects are labelled on the left of the above figure and most of the values may be calculated by clicking on the relevant label and entering the required values in the pop-up window. Other values are automatically entered by ENC when you choose other parameters in the main window. Each is considered separately in the sections following the next section.

3.4.6 Bottom Segment of Centre Panel



The bottom segment of the centre panel, illustrated above, contains check boxes that show a tick mark when clicked and indicate that the source number that is ticked will be included in the total sound pressure level at the receiver, which is shown on the bottom two lines of the above figure. The relevant receiver number is the number currently selected in the blue receiver segment. The 95% confidence limits are calculated for the overall A-weighted level using Equations (5.278) and (5.279) in the 6th edition textbook, and multiplying the result of Equation (5.278) by 1.96.

The row of boxes to the right of the Δ symbol in the above figure are the estimated accuracies of the sound power levels in dB, entered by you. You will also need to enter the expected accuracy of the propagation model for calculating the sound pressure level at a single receiver due to a single source.

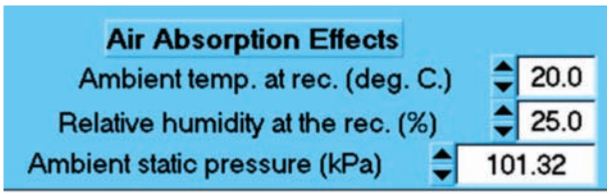


Left clicking on the "o" symbol shown at right brings up the box beneath it. You can select a file name that will contain the output data in text format, which has too many entries to show here. When entering a file name, you must type the complete name in the box. Do not select a file with a similar name and then change the name, as this will result in overwriting of the file that you selected, even though you changed the file name.

3.4.7 Spherical Spreading, (Adiv)

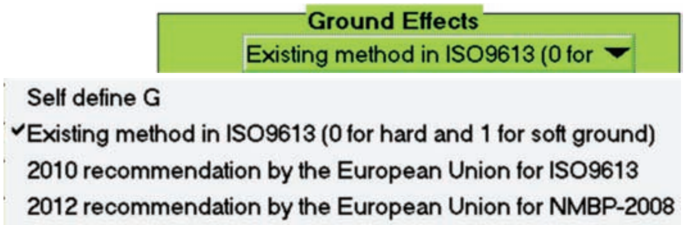
The Adiv effect is that due to spherical spreading from a point source ($= 10 \log_{10} 4\pi d_{\rm SR}^2$, where $d_{\rm SR}$ is the source–receiver separation distance). This quantity is calculated automatically by ENC based on the source receiver separation distance calculated from the source and receiver location coordinates and available in the output file obtained by clicking on the red o symbol in the small dark blue box at the bottom of the window.

3.4.8 Air Absorption (Aa)



The attenuation resulting from air absorption (top right of the window) is calculated using the equations and procedures outlined in the standards, ISO 9613-1 and ANSI S1.26. In those standards, the absorption for an octave band is calculated at the exact band centre frequency, whereas in ENC it is calculated at the nominal band centre frequency (with very little difference). The atmospheric pressure value that is in the constants panel is the one that is used here. The default value is 101.325 kPa.

3.4.9 Ground Effects (Ag)

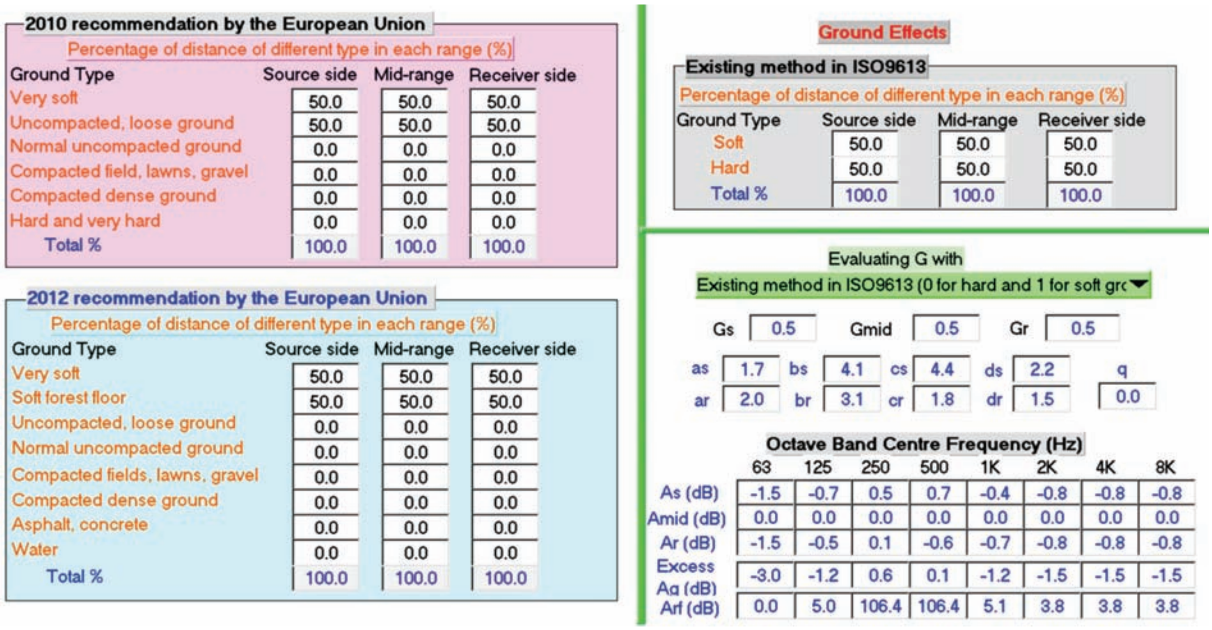


As can be seen from the figure at right, you have 4 choices for the definition of the parameter, G.

For the ISO method, the ground effect is calculated using values of the

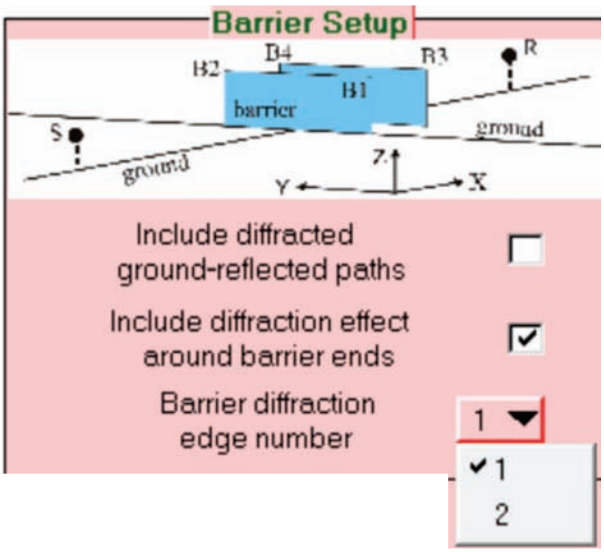
G parameters that correspond to the choice you make for the ground effect calculation method. The method is explained on pages 323–324 of the 6th edition textbook.

Clicking on Ag in the centre panel produces the popup window shown below. This panel shows all the data used for three of the four choices. For the self-defined option for G, you must enter G values for the ground within 30 source heights of the source, within 30 receiver heights of the receiver and in between.



3.4.10 Barrier Effects (Ab)

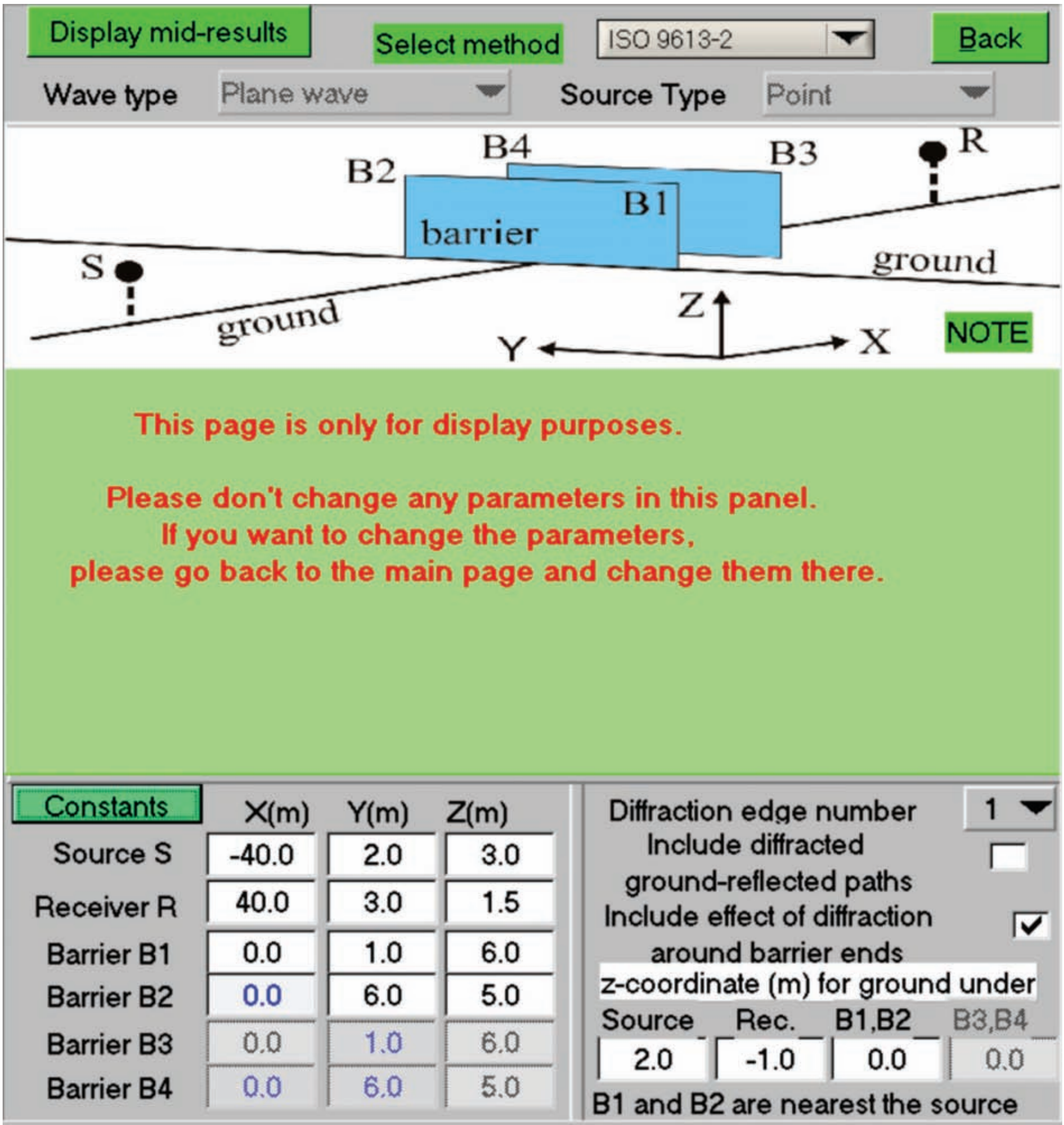
If a barrier is selected by ticking the box on the RHS of the Ab line in ENC, then the sources that are to be affected by the barrier must have negative values for their x-coordinates and the receivers that are to be affected by the barrier must have positive values for their x-coordinates.



In addition, you must make 3 choices as shown on the pink panel at right. The "diffraction edge number must be 1 or 2, corresponding to 1 or 2 diffraction edges. If the "include diffracted ground reflected paths" box is not ticked, the C_2 factor in Equation (5.230) in the 6th edition textbook is set equal to 20 and D_{zi} is calculated for the non-ground-reflected path over the barrier top and the non-ground-reflected path around each end of the barrier.

When you click on Ab in the centre panel, the window shown in the following figure pops up. Please do not change any parameters or menu selections in this panel as all available choices must be made in other parts of the page.

Note that ENC follows ISO for this calculation so no ray curvature or atmospheric effects are used when calculating barrier attenuations.

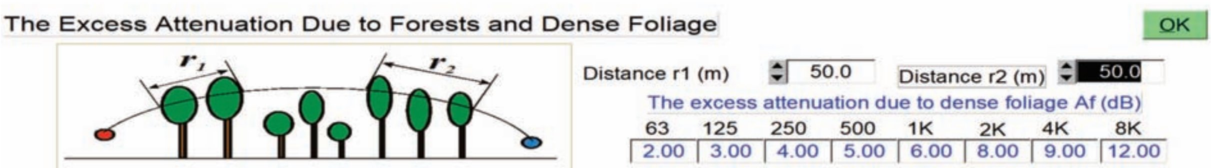


As instructed by ISO9613-2, the Ag value is subtracted from the D_{zi} value corresponding to the path over the top of the barrier and is then combined with the two values of D_{zi}, corresponding to the non-ground-reflected paths around the barrier ends, using the second term on the RHS of Equation (1.105) or Equation (5.178) in the 6th edition textbook. If the term in brackets in Equation (5.230) is less than 0.01, ENC will set it equal to 0.01.

If the “Include diffracted ground-reflected paths” box is not ticked, the C_2 factor is set equal to 40 and the barrier attenuation for each path (ground-reflected and non-ground-reflected) is calculated separately. The attenuations corresponding to the four paths over the top are combined (using the second term on the RHS of Equation (1.105) or Equation (5.178) in the 6th edition textbook) and the Ag value is subtracted from the result to obtain Ab1. The attenuations of the four paths around the barrier ends are combined (using the second term on the RHS of Equation (1.105) or Equation (5.178) in the 6th edition textbook) to obtain Ab2. The attenuations Ab1 and Ab2 are then combined to obtain Ab.

ENC will calculate the attenuation due to a single barrier that may have a finite thickness or two diffraction edges. The coordinates of the barrier correspond to the diffraction edge closest to the source and the x-axis (which is parallel to the ground and the face of the barrier on the source side) runs at ground level along the face of the barrier on the source side. Only one barrier is allowed for each calculation. The calculations follow the procedure on pages 264–270 in the 6th edition textbook. The barrier thickness is accounted for using the double diffraction analysis outlined in the ISO9613 propagation model (see pages 293–312 in the 6th edition textbook).

3.4.11 Vegetation Screening Effects (Af)

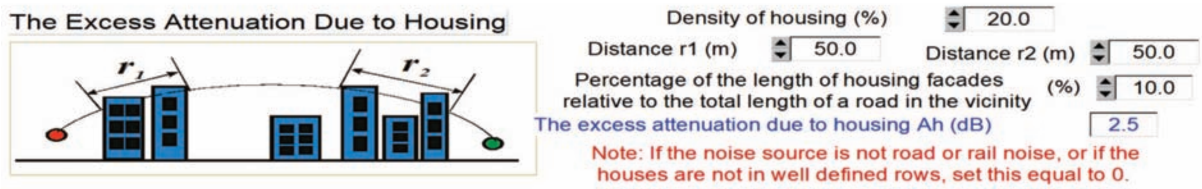


The attenuation due to screening by forests and dense foliage can be calculated by clicking in Af in the upper centre panel of the ISO window, and on the top panel of the window that pops up, entering the two distances, r_1 and r_2 for travel through the foliage.

The distance of travel through the foliage is not equal to the extent of the foliage between the source and receiver. It depends on the height of the source and receiver and the radius of curvature of the propagating ray as a result of wind and temperature gradients. ISO 9613-2 (1996) recommends that a radius, R_c of 5 km be used for downwind propagation. The centre (always below the higher of the source and receiver) of the circular arc, representing the sound ray path from the source to the receiver, is found using a scaled drawing, as the intersection of two lines of length equal to 5 km, with one line intersecting the source location and the other intersecting the receiver location. The lengths of the circular arcs, r_1 and r_2 can then be found using product of R_c with the angle (in radians) subtended at the circular arc centre by radial lines from each end of circular arc under consideration. The distance $r_f = r_1 + r_2$, where r_1 and r_2 are defined in the above figure.

The most recent values of r_1 and r_2 entered for any source–receiver combination will be the ones used for all source–receiver combinations.

3.4.12 Housing Screening Effects (Ah)



The attenuation due to screening by housing can be calculated by clicking in Ah in the upper centre panel of the ISO window, and on the centre panel of the window that pops up, entering the two distances, r_1 and r_2 for travel through the housing as well as the density of housing, expressed as the percentage of the total plan area of houses between the source and receiver and the total ground area. An additional attenuation term is included if the houses are in well defined rows. This is calculated by ENC if a non zero term is entered in the box titled, “percentage of the length of housing facades relative to the total length of road or rail in the vicinity”. If the noise source is not road or rail noise or if the houses are not in well defined rows, this term is set = 0.

The housing attenuation must be the same for all sources and receivers and should only applied to the A-weighted level. This is achieved in ENC by applying the same attenuation to all octave band levels, which means that when housing attenuation is applied, the octave band levels are not reliable.

The most recent values of input data entered for any source–receiver combination will be the ones used for all source–receiver combinations.

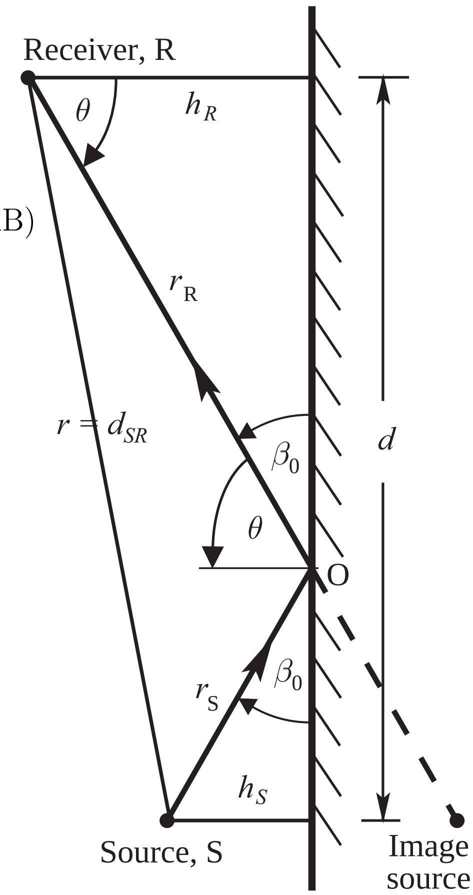
3.4.13 Process Equipment Screening Effects (Ap)

The attenuation due to screening by process equipment can be calculated by clicking in Ap in the upper centre panel of the ISO window, and on the bottom panel of the window that pops up, entering the distance, r_1 for travel through the process equipment. This attenuation must be the same for all sources and receivers.

The most recent values of r_1 and r_2 entered for any source–receiver combination will be the ones used for all source–receiver combinations.

3.4.14 Effect of Reflections Other Than Ground Reflections

The ISO model describes two possible types of reflection that can contribute to the sound level experienced at a receiver. The excess attenuation is given by:



$$A_{\text{ref}} = -10\log_{10}\left[1 + \left(\frac{d_{SR}}{r_S + r_R}\right)^2 (1-\alpha_r)10^{\text{DI}_r/10}\right] \quad \text{(dB)}$$

where $d_{SR} = \sqrt{(x_S - x_R)^2 + (y_S - y_R)^2 + (z_S - z_R)^2}$ and r_S and r_R, as well as the angle, θ, between the line from the source to the reflection point (for a plane surface) or cylinder centre (in the x, y plane) are shown in the following two figures and calculated by ENC based on the source and receiver coordinates.

Plane reflecting surface. The absorption coefficient, α_r, of the reflecting surface is entered by the user and must be less than 0.8. Approximate values used by ENC are provided by ISO9613-2 and are listed in the table on the next page. If the point of reflection does not lie on the reflecting surface, ENC will set the reflection coefficient = 0 and return an error message.

The minimum dimension, $\ell_{\min}$, of the reflecting plane must satisfy the following expression, otherwise the contribution of the reflection to the excess attenuation is set = 0.

$$\frac{1}{\lambda} > \left[\frac{2}{(\ell_{\min}\cos\theta)^2}\right]\left[\frac{r_S r_R}{r_S + r_R}\right] \tag{3.1}$$

Table 3.1 Estimates of sound absorption coefficient (ISO9613)

Object	α_r
Flat, hard walls with no openings	0.0
Walls of building with windows and small additions or bay	0.2
Factory walls with 50% of surface consisting of openings, installations or pipes	0.6

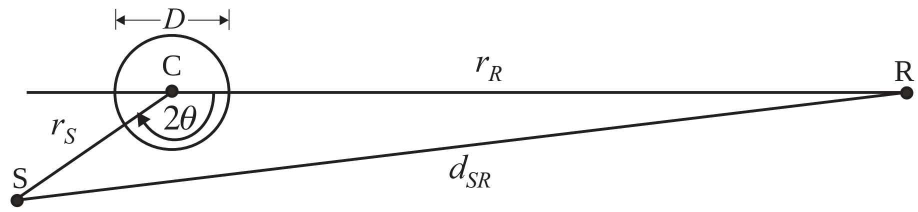
Vertical Cylinder Reflection (only considered if the cylinder is much closer to the source than it is to the receiver). The calculation uses the x, y and z-coordinates of the source and receiver, the x and y coordinates of the cylinder centre and the z-coordinate,

z_t, of the top of the cylinder. The minimum of the z_t and D dimensions, must satisfy Equation (3.1). If not, ENC sets $A_{\text{ref}} = 0$.

The absorption coefficient, α_r, for reflection from a vertical cylinder is calculated by ENC from the following expression (ISO9613-2):

$$\alpha_r = 1 - \frac{D \sin(90 - \theta)}{2r_S} \tag{3.2}$$

where D is the cylinder diameter and θ is defined in the following figure.



$$\theta = 0.5 \cos^{-1}\left[\frac{r_S^2 + r_R^2 - d_{SR}^2}{2r_S r_R}\right] \qquad \text{degrees} \tag{3.3}$$

where distances from the source and receiver to the cylinder centre and the source receiver distance are calculated using:

$$r_S = \sqrt{(x_S - x_c)^2 + (y_S - y_c)^2 + (z_S - z_c)^2} \tag{3.4}$$

$$r_R = \sqrt{(x_R - x_c)^2 + (y_R - y_c)^2 + (z_R - z_c)^2} \tag{3.5}$$

$$d_{SR} = \sqrt{(x_S - x_R)^2 + (y_S - y_R)^2 + (z_S - z_R)^2} \tag{3.6}$$

The x and y-coordinates of the cylinder centre must be entered by the user and ENC calculates the height, z_c, of the reflection point using:

$$z_c = z_S + \frac{r_{Sxy}}{r_{Rxy} + r_{Sxy}}\left[z_R - z_S\right] \tag{3.7}$$

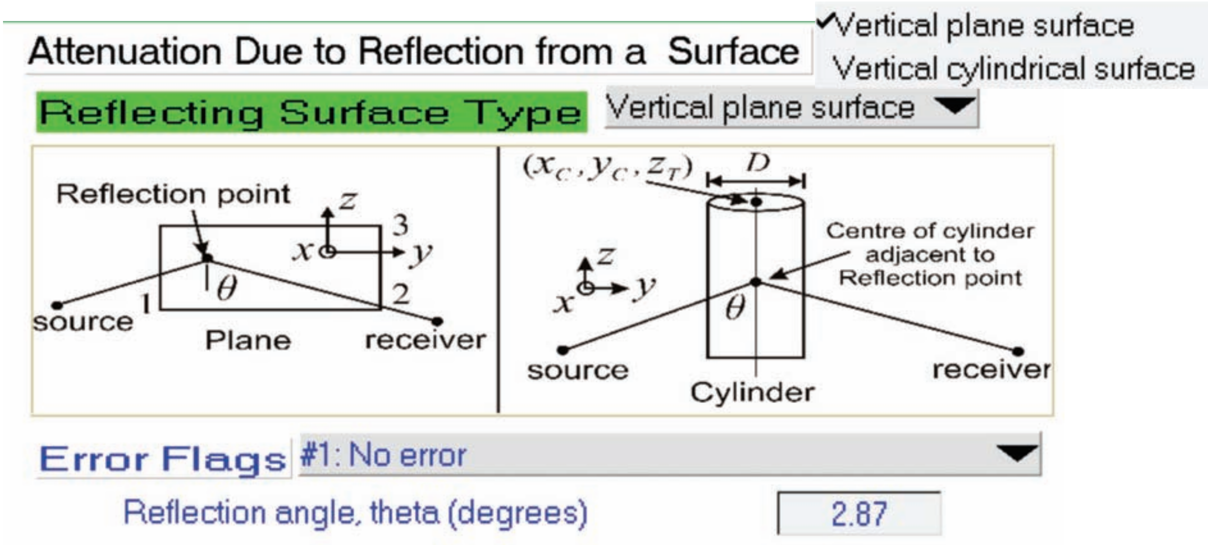
where

$$r_{Sxy} = \sqrt{(x_S - x_c)^2 + (y_S - y_c)^2} \tag{3.8}$$

$$r_{Rxy} = \sqrt{(x_R - x_c)^2 + (y_R - y_c)^2} \tag{3.9}$$

If $z_c > z_t$, the cylinder reflection excess attenuation is set = 0.

If "Aref" is clicked on in the centre screen, the window in the following figure pops up. On this screen you can enter the details of the vertical reflecting surface, its location and its type (plane or cylindrical). These details are used to calculate the values that appear in the Aref line.



DI=directivity index from source to reflecting surface

	63	125	250	500	1K	2K	4K	8K
DI (dB)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Alpha	0.30	0.40	0.35	0.40	0.50	0.50	0.50	0.50
Aref (dB)	-1.28	-1.12	-1.21	-1.12	-0.95	-0.95	-0.95	-0.95

x, y and z coordinates of corner 1 (m)	18.000	-5.000	0.000
x, y and z coordinates of corner 2 (m)	18.000	5.000	0.000
x, y and z coordinates of corner 3 (m)	18.000	5.000	6.000
x, y and z of the reflection point (m)	18.00	2.78	1.83
Distance of source, receiver to reflec. point (m)		28.03	8.01

For the rectangular shaped plane surface (assumed to be mounted on the ground) you must enter the Directivity index of the source towards the reflecting surface and the absorption coefficient of the reflecting surface for the incident angle, θ. The coordinates of corners 1, 2 and 3 of the plane reflecting surface are also required, noting that corner 2 must be between corners 1 and 3. ENC outputs (in blue font) the coordinates of the reflection point as well as the distance of the source and receiver to the reflection point.

For the cylindrical surface (assumed to be mounted on the ground with its central axis in the vertical direction), you must enter the Directivity index of the source towards the reflecting surface, the x and y coordinates of the cylinder centre, the z-coordinate of the top of the cylinder and the diameter of the cylinder. ENC outputs (in blue font) the coordinates of the reflection point as well as the distance of the source and receiver to the reflection point. The cylinder absorption coefficient is calculated according to ISO9613-2. An absorption coefficient of 1.0 for a cylinder reflection indicates that no energy is reflected in the direction of the receiver, rather than indicating that the surface absorbs all incident energy.

The meaning of each of the 4 error flags is listed below.

1. Reflected ray cannot arrive at receiver (zero attenuation for Aref at all frequencies). This could mean that there is no line of sight from the source to the receiver due to

the reflecting surface location. It could also mean that the reflecting surface is not in a location where any reflection from it could arrive at the receiver.

2. One or more surface absorption coefficients are greater than 0.8 (zero attenuation for Aref at some frequencies). As absorption coefficients are entered by the user for the plane surface, this will most likely occur for the cylindrical surface where "effective" absorption coefficients are calculated by ENC.

3. Receiver is closer than twice the source distance to the reflecting surface (zero attenuation for Aref at all frequencies).

4. Reflecting surface is too small to result in a reflection at some frequencies (zero attenuation for Aref at some frequencies).

3.4.15 Meteorological Effects (Amet)

The ISO propagation model assumes worst case meteorological effects for the octave band calculations. However, the long time average of the overall A-weighted level can be reduced due to meteorological effects occurring less than 100% of the time by selecting a value for A0 (see figure below).

ISO9613-2 only allows meteorological effects to be applied to the long time average of the overall A-weighted level and not the octave band levels. The value of A_0 ranges between 0 and 5 dB with values over 2 being very rare. ENC uses a default value of 1.5 dB. The value chosen is dependent on the % of time that downwind propagation occurs for a long time average of several months to a year. A value of 0 dB corresponds to downwind propagation occurring 100% of the time and a value of 5 dB corresponds to downwind propagation never occurring. The Amet correction is subtracted from the overall A-weighted sound pressure level calculated by taking account of all the other excess attenuations.

Chapter 4

Room Acoustics & Absorption (Module 4)

4.1 Overview

This software may be accessed by choosing “module 4” from the “options” dialog box. The software automates all of the calculations in Chapter 6 of the 6^{th} edition textbook as well as the calculations implicit and explicit in Appendix D. The treatment is divided into 5 windows, each of which are represented by a unique icon in the tool bar. To access a particular window, just click on the appropriate icon in the tool bar. Each window will be described in the text to follow.

4.2 Room Modal Properties

This section calculates modal properties of rectangular and cylindrical rooms.

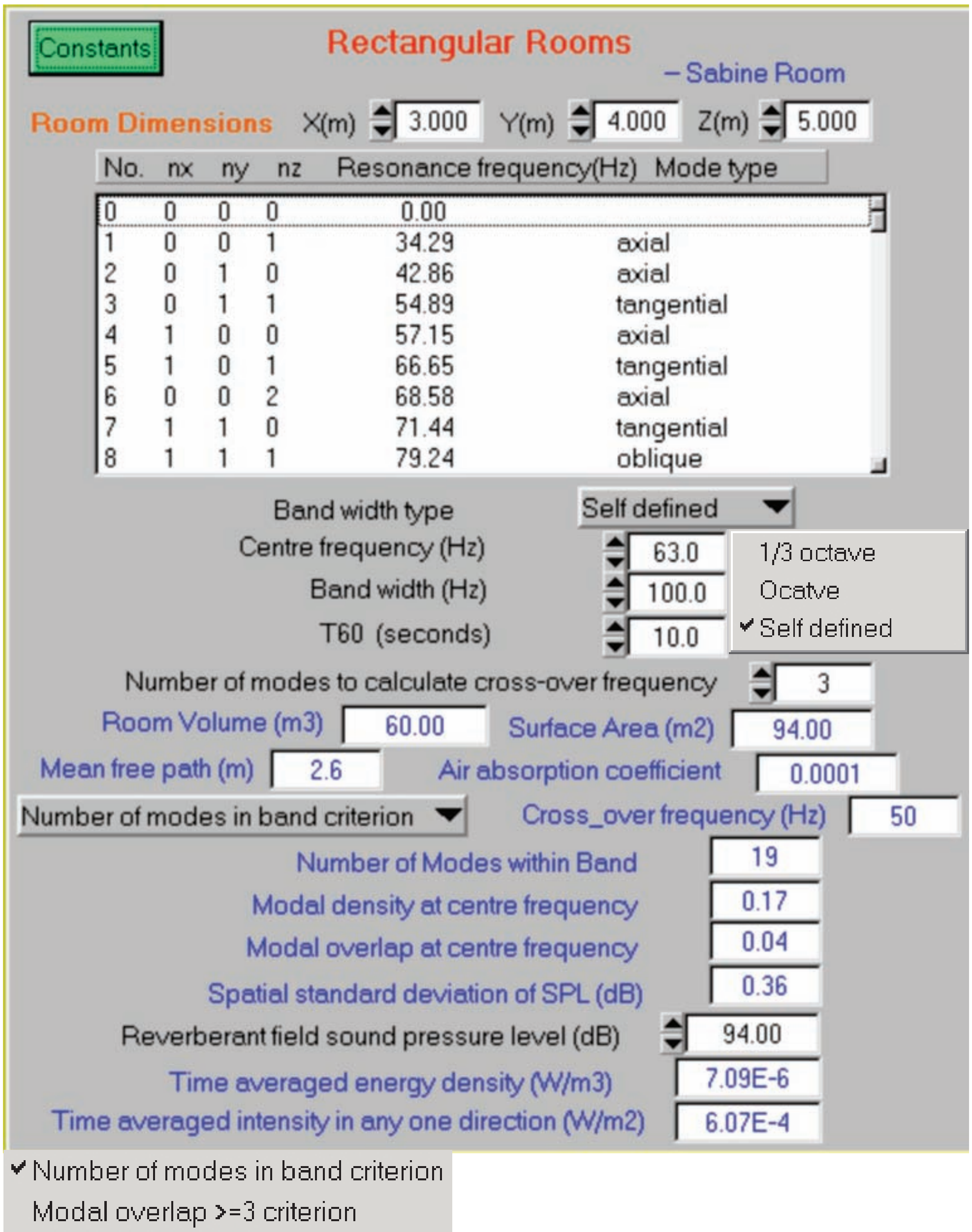
4.2.1 Rectangular room

This subsection calculates the first 100 resonance frequencies and mode type (axial, tangential or oblique) for a rectangular room of any shape. It also applies to long and flat rooms. Mean free path, crossover frequency (from modal response to diffuse response), number of modes in a band, modal density at the band centre frequency, modal overlap (see pages 356–358, 367–368 in the 6^{th} edition textbook) and spatial standard deviation of the SPL (Equation (6.26)) are all calculated. Note that you have a choice as to how many modes are needed to be resonant in a defined band for the sound field to be considered diffuse (usually between 3 and 6) for the purposes of calculating the cross-over frequency. For noise of a bandwidth narrower than 1/3-octave the cross-over frequency should be defined as when the modal overlap is equal to 3. You need to select this criterion by clicking on the pop-up box beneath “mean free path”.

Entering the reverberant field sound pressure level allows you to calculate time averaged energy density and time averaged intensity for sound travelling in any given direction (Equations (6.34) and (6.35) respectively). The bandwidth used for calculating the number of modes can be selected in terms of Hz or as octave or 1/3-octave. Do not change values in boxes with no arrows at the side.

Clicking on the "Constants" button in the following figure allows you to set the speed of sound and gas density for the calculations of the entire window — see Section 0.6.4 in this manual for a full description.

Note that at the top of the left and right panels, blue text indicates whether or not the room dimensions satisfy the Sabine room criterion that no dimension should be more than three times any other. For non-Sabine rooms, the last 4 items calculated at the bottom of the table may be inaccurate. Note that these last terms do not include any contribution from the direct fields of the sound sources contributing to the sound field.



4.2.2 Cylindrical room

These rooms are discussed briefly in the 6th edition textbook. For the cylindrical room, the same expressions as used for a rectangular room are used for calculating mean free path (Equation (6.36)), cross over frequency, number of modes within a band , modal density (Equation (6.22)), modal overlap, spatial standard deviation (Equation (6.26)), time averaged energy density (Equation (6.34)) and effective time averaged intensity (Equation (6.35)). Note that for a cylindrical room, the effective perimeter, L, is given by $L = 4(\pi a + \ell)$, where ℓ is the cylinder length and a is the radius.

The mean free path calculation is accurate, as Equation (6.36) in the 6th edition textbook applies to any shaped room. The other calculated quantities are only approximate as the formulae strictly only apply to rectangular shaped rooms. However, experience shows the approximations to be good ones.

The cross-over frequency is calculated on the basis of the specified number of modes in a band (3 to 6 for 1/3 or octave band analysis) or a modal overlap greater than 3 for narrower bands. The number of modes in a band is calculated using Equation (6.21).

For a cylindrical room, the resonance frequencies are given as:

$$f(n_z, m, n) = \frac{c}{2}\sqrt{\left(\frac{n_z}{\ell}\right)^2 + \left(\frac{\psi_{mn}}{a}\right)^2}$$

where n_z is the number of axial nodes, ℓ is the cylinder length and a is the cylinder radius.

The characteristic values ψ_{mn} are functions of the mode numbers m, n, where m is the number of diametral pressure nodes and n is the number of circumferential pressure nodes.

Values of ψ_{mn} are given in the following tables for a much larger number of modes than given in the 6th edition textbook. The quantity, n_z, is the number of nodal planes normal to the axis of the cylinder.

Note that the expressions for mode numbers and modal density are approximate only and become more accurate as the room shape becomes more irregular. However, even for rooms of regular shape, the actual mode number and modal density fluctuate about the theoretical prediction plotted as a function of frequency and the prediction becomes more accurate as the frequency increases.

Values of ψ_{mn}

m\n	0	1	2	3	4	5	6	7
0	0	1.2197	2.2331	3.2383	4.2411	5.2428	6.2439	7.2448
1	0.5861	1.6971	2.7172	3.7261	4.7312	5.7345	6.7368	7.7385
2	0.9722	2.1346	3.1734	4.1923	5.2036	6.2112	7.2166	8.2207
3	1.3373	2.5513	3.6115	4.6428	5.6623	6.6757	7.6856	8.6931
4	1.6926	2.9547	4.0368	5.0815	6.1103	7.1305	8.1455	9.1571
5	2.0422	3.3486	4.4523	5.5108	6.5494	7.5769	8.5976	9.6139
6	2.3877	3.7353	4.86	5.9325	6.9811	8.0163	9.0431	10.0643
7	2.7304	4.1165	5.2615	6.3477	7.4065	8.4495	9.4827	10.5091
8	3.0709	4.4931	5.6576	6.7574	7.8263	8.8774	9.917	10.9488
9	3.4096	4.8659	6.0494	7.1624	8.2414	9.3006	10.3467	11.384
10	3.7468	5.2355	6.4372	7.5633	8.6523	9.7194	10.7722	11.815
11	4.0828	5.6023	6.8217	7.9605	9.0594	10.1345	11.1939	12.2423
12	4.4178	5.9667	7.2031	8.3544	9.463	10.5461	11.6121	12.6662
13	4.7518	6.329	7.5819	8.7454	9.8636	10.9545	12.0271	13.0868
14	5.0851	6.6894	7.9584	9.1337	10.2613	11.36	12.4392	13.5046
15	5.4177	7.0481	8.3326	9.5196	10.6565	11.7629	12.8486	13.9196
16	5.7497	7.4052	8.7049	9.9032	11.0493	12.1633	13.2555	14.332
17	6.0811	7.761	9.0754	10.2849	11.4399	12.5614	13.66	14.7421
18	6.4121	8.1155	9.4443	10.6646	11.8285	12.9574	14.0623	15.15
19	6.7425	8.4688	9.8116	11.0426	12.2152	13.3514	14.4626	15.5558
20	7.0726	8.821	10.1776	11.419	12.6001	13.7435	14.861	15.9596
21	7.4022	9.1723	10.5422	11.7939	12.9834	14.1339	15.2575	16.3616
22	7.7316	9.5226	10.9055	12.1674	13.3652	14.5227	15.6524	16.7618
23	8.0605	9.8721	11.2678	12.5395	13.7454	14.9099	16.0456	17.1603
24	8.3892	10.2207	11.629	12.9104	14.1243	15.2956	16.4373	17.5573
25	8.7176	10.5686	11.9891	13.2801	14.5019	15.68	16.8276	17.9528
26	9.0458	10.9158	12.3483	13.6487	14.8783	16.063	17.2164	18.3468
27	9.3736	11.2623	12.7066	14.0162	15.2535	16.4448	17.604	18.7395
28	9.7013	11.6082	13.0641	14.3827	15.6276	16.8254	17.9903	19.1309
29	10.0287	11.9535	13.4208	14.7483	16.0007	17.2049	18.3754	19.521

Values of ψ_{mn} (Cont.)

m\n	8	9	10	11	12	13	14	15
0	8.2454	9.2459	10.2463	11.2466	12.2469	13.2471	14.2473	15.2475
1	8.7399	9.7409	10.7417	11.7424	12.743	13.7435	14.744	15.7444
2	9.2239	10.2264	11.2286	12.2303	13.2318	14.2331	15.2342	16.2352
3	9.699	10.7038	11.7078	12.7111	13.714	14.7164	15.7186	16.7204
4	10.1664	11.1739	12.1802	13.1856	14.1901	15.1941	16.1976	17.2006
5	10.6269	11.6377	12.6467	13.6543	14.6609	15.6666	16.6717	17.6761
6	11.0814	12.0957	13.1076	14.1179	15.1267	16.1344	17.1412	18.1473
7	11.5306	12.5485	13.5637	14.5767	15.588	16.5979	17.6066	18.6144
8	11.9748	12.9967	14.0152	15.0312	16.0451	17.0573	18.0681	19.0778
9	12.4147	13.4405	14.4626	15.4816	16.4983	17.5129	18.5259	19.5376
10	12.8505	13.8805	14.9061	15.9284	16.9478	17.9651	18.9804	19.9941
11	13.2826	14.3168	15.3461	16.3717	17.3941	18.4139	19.4316	20.4475
12	13.7114	14.7498	15.7829	16.8118	17.8372	18.8597	19.8799	20.898
13	14.1369	15.1796	16.2166	17.2488	18.2773	19.3026	20.3253	21.3458
14	14.5596	15.6066	16.6474	17.6831	18.7147	19.7428	20.7681	21.7909
15	14.9795	16.0309	17.0755	18.1147	19.1495	20.1805	21.2083	22.2335
16	15.3969	16.4526	17.5012	18.5439	19.5818	20.6157	21.6462	22.6738
17	15.8119	16.872	17.9244	18.9706	20.0117	21.0485	22.0817	23.1118
18	16.2246	17.2891	18.3454	19.3952	20.4395	21.4792	22.5151	23.5477
19	16.6353	17.7041	18.7643	19.8176	20.8652	21.9079	22.9465	23.9815
20	17.0439	18.117	19.1812	20.238	21.2888	22.3345	23.3758	24.4135
21	17.4507	18.5281	19.5962	20.6566	21.7106	22.7592	23.8033	24.8435
22	17.8557	18.9374	20.0093	21.0733	22.1305	23.1822	24.229	25.2717
23	18.259	19.345	20.4208	21.4883	22.5488	23.6034	24.653	25.6983
24	18.6606	19.7509	20.8306	21.9016	22.9653	24.0229	25.0753	26.1232
25	19.0608	20.1553	21.2388	22.3133	23.3803	24.4409	25.496	26.5465
26	19.4595	20.5582	21.6455	22.7235	23.7937	24.8573	25.9152	26.9683
27	19.8568	20.9596	22.0508	23.1323	24.2057	25.2723	26.333	27.3886
28	20.2527	21.3597	22.4547	23.5397	24.6163	25.6859	26.7493	27.8075
29	20.6474	21.7585	22.8573	23.9457	25.0255	26.0981	27.1643	28.225

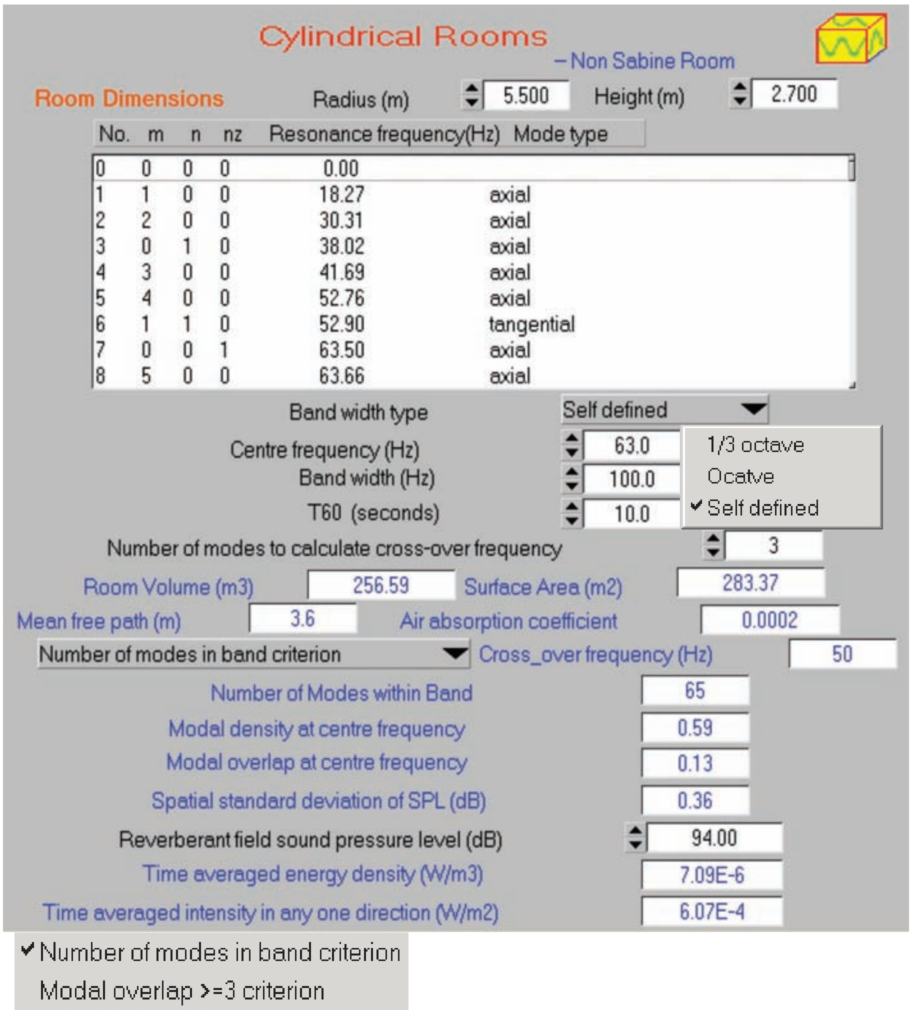
Values of ψ_{mn} (Cont.)

m\n	16	17	18	19	20	21	22	23
0	16.2477	17.2478	18.2479	19.248	20.2481	21.2482	22.2483	23.2484
1	16.7447	17.745	18.7453	19.7455	20.7457	21.7459	22.7461	23.7463
2	17.236	18.2368	19.2375	20.2381	21.2387	22.2392	23.2396	24.2401
3	17.7221	18.7236	19.7249	20.7262	21.7273	22.7283	23.7292	24.73
4	18.2034	19.2058	20.208	21.21	22.2118	23.2134	24.2149	25.2163
5	18.6801	19.6837	20.6869	21.6898	22.6925	23.6949	24.6972	25.6992
6	19.1527	20.1575	21.1619	22.1659	23.1696	24.1729	25.176	26.1788
7	19.6214	20.6277	21.6334	22.6386	23.6433	24.6477	25.6517	26.6554
8	20.0864	21.0943	22.1014	23.1079	24.1138	25.1193	26.1243	27.129
9	20.5481	21.5576	22.5662	23.5741	24.5813	25.588	26.5941	27.5998
10	21.0065	22.0177	23.028	24.0373	25.0459	26.0538	27.0611	28.0679
11	21.4619	22.475	23.4869	24.4978	25.5078	26.517	27.5256	28.5335
12	21.9145	22.9294	23.943	24.9555	25.967	26.9777	27.9875	28.9967
13	22.3643	23.3812	24.3966	25.4108	26.4238	27.4359	28.4471	29.4576
14	22.8116	23.8304	24.8477	25.8636	26.8783	27.8918	28.9044	29.9162
15	23.2564	24.2773	25.2965	26.3141	27.3304	28.3455	29.3596	30.3726
16	23.6989	24.7219	25.743	26.7624	27.7804	28.7971	29.8126	30.8271
17	24.1392	25.1643	26.1874	27.2086	28.2283	29.2466	30.2636	31.2795
18	24.5774	25.6046	26.6297	27.6528	28.6742	29.6942	30.7127	31.73
19	25.0136	26.043	27.0701	28.0951	29.1183	30.1398	31.1599	32.1787
20	25.4478	26.4794	27.5085	28.5354	29.5604	30.5837	31.6054	32.6257
21	25.8802	26.914	27.9452	28.974	30.0008	31.0258	32.0491	33.0709
22	26.3109	27.3469	28.3801	29.4109	30.4395	31.4662	32.4911	33.5145
23	26.7398	27.778	28.8134	29.8461	30.8766	31.905	32.9316	33.9565
24	27.1671	28.2076	29.245	30.2797	31.3121	32.3422	33.3705	34.3969
25	27.5928	28.6355	29.6751	30.7118	31.746	32.7779	33.8078	34.8359
26	28.017	29.062	30.1036	31.1424	32.1785	33.2122	34.2438	35.2734
27	28.4397	29.487	30.5308	31.5715	32.6095	33.645	34.6783	35.7095
28	28.8611	29.9106	30.9565	31.9993	33.0391	34.0764	35.1114	36.1443
29	29.281	30.3328	31.3809	32.4257	33.4674	34.5066	35.5433	36.5778

Values of ψ_{mn} (Cont.)

m\n	24	25	26	27	28	29
0	24.2484	25.2485	26.2486	27.2486	28.2487	29.2487
1	24.7464	25.7466	26.7467	27.7468	28.7469	29.747
2	25.2405	26.2408	27.2412	28.2415	29.2418	30.242
3	25.7308	26.7315	27.7322	28.7328	29.7334	30.7339
4	26.2176	27.2188	28.2199	29.221	30.2219	31.2228
5	26.7011	27.7029	28.7045	29.7061	30.7075	31.7088
6	27.1815	28.1839	29.1862	30.1883	31.1903	32.1921
7	27.6588	28.662	29.665	30.6678	31.6704	32.6728
8	28.1333	29.1373	30.1411	31.1446	32.1479	33.151
9	28.6051	29.61	30.6146	31.6189	32.623	33.6268
10	29.0743	30.0801	31.0856	32.0908	33.0956	34.1002
11	29.5409	30.5478	31.5543	32.5604	33.5661	34.5714
12	30.0052	31.0132	32.0207	33.0277	34.0343	35.0405
13	30.4673	31.4764	32.4849	33.4929	34.5004	35.5075
14	30.9271	31.9374	32.947	33.956	34.9645	35.9725
15	31.3849	32.3963	33.407	34.4171	35.4267	36.4356
16	31.8406	32.8533	33.8652	34.8764	35.8869	36.8969
17	32.2944	33.3083	34.3214	35.3337	36.3453	37.3563
18	32.7463	33.7615	34.7758	35.7893	36.802	37.8141
19	33.1963	34.2129	35.2285	36.2431	37.257	38.2701
20	33.6447	34.6626	35.6794	36.6953	37.7103	38.7245
21	34.0914	35.1106	36.1287	37.1458	38.162	39.1773
22	34.5364	35.557	36.5765	37.5948	38.6122	39.6286
23	34.9799	36.0019	37.0227	38.0423	39.0609	40.0785
24	35.4218	36.4453	37.4674	38.4883	39.5081	40.5268
25	35.8623	36.8872	37.9106	38.9328	39.9539	40.9738
26	36.3013	37.3276	38.3525	39.376	40.3983	41.4194
27	36.739	37.7668	38.793	39.8178	40.8414	41.8637
28	37.1753	38.2045	39.2322	40.2583	41.2831	42.3067
29	37.6103	38.641	39.67	40.6976	41.7237	42.7485

The cylindrical room panel is illustrated in the following figure.



Note that at the top of the left and right panels, blue text indicates whether or not the room dimensions satisfy the Sabine room criterion that no dimension should be more than three times any other. For non-Sabine rooms, the last 4 items calculated at the bottom of the table may be inaccurate. Note that these last terms do not include any contribution from the direct fields of the sound sources contributing to the sound field. All the items shown in the figure above are fully described in the "rectangular room" section immediately preceding this section.

4.3 Sound in rooms

This section calculates sound pressure levels and reverberation times in rooms of any shape. It is divided into two main sections. The section including the left hand side and bottom of the window applies to the steady state sound field in a room and is used to relate the sound pressure level to the sound power level for sound sources in the room for various types of room. It is also used to calculate direct field and reverberant field sound pressure levels for specified source sound power levels.

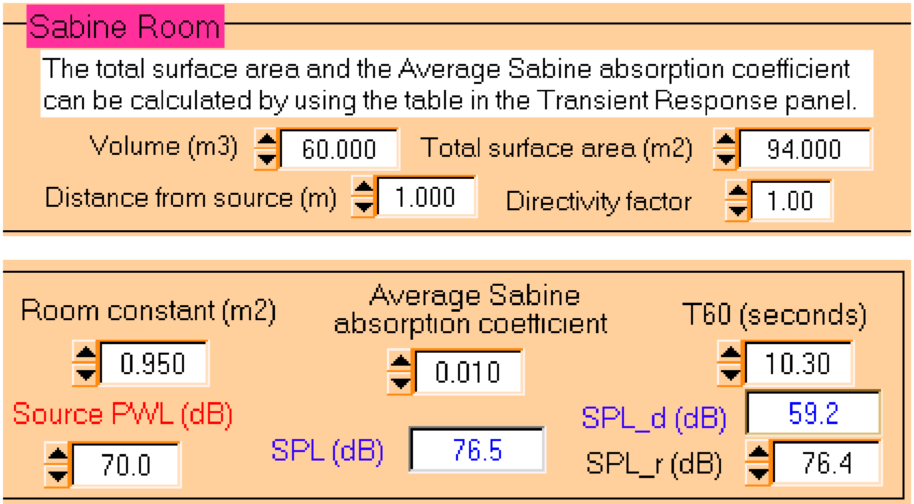
The panel on the right of the window applies to transient or decaying sound fields in rooms. It relates absorption coefficients to reverberation times for various room types.

4.3.1 Steady-state response

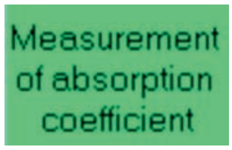
This section is divided into three panels: Sabine rooms, flat rooms and long rooms. Each will be discussed in turn below.

4.3.1.1 Sabine Rooms (Steady-State Response)

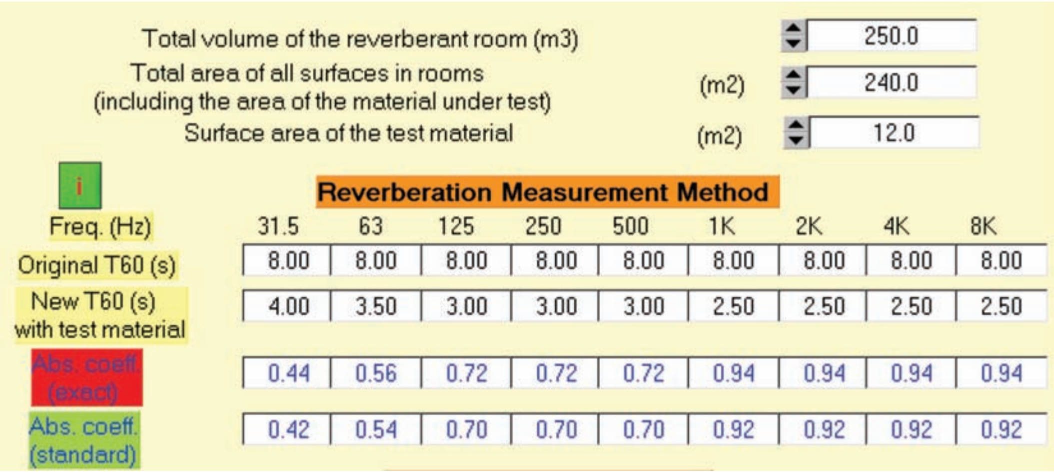
This panel (located at the bottom of the window and shown below), is intended for Sabine rooms; that is, rooms whose dimension in one direction is no greater than three times the dimension in any other direction. Given the source sound power level and room properties (entered in the panel by the user), the total, direct and reverberant sound pressure levels may be calculated at any given distance from the source using Equations (6.42) to (6.44) in the 6th edition textbook.



Any one of the quantities, "room constant", "average Sabine absorption coefficient" or "T_{60}" may be entered and the other two will be calculated automatically. However, choosing T_{60} values that are too small can result in unreasonable values for the reverberant sound field level. The average Sabine absorption coefficient and total room surface area may be calculated using the table in the "Transient response" panel. Alternatively, the reverberant field sound pressure level may be entered and the corresponding average absorption coefficient and reverberation time will then be calculated.



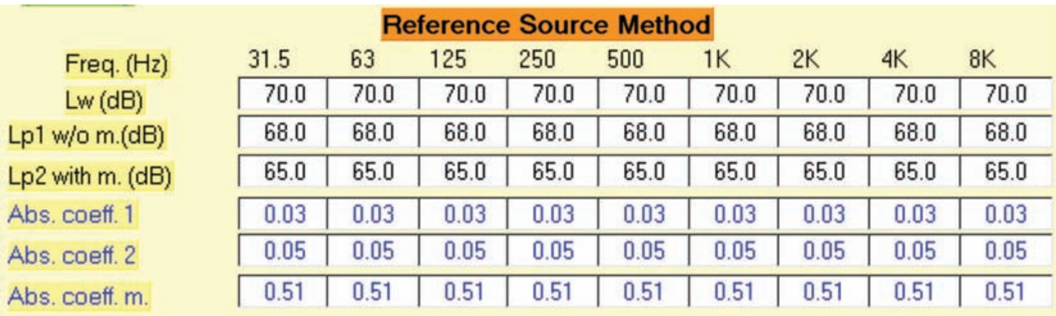
Clicking on the green button duplicated at right, results in the window on the next page popping up. This window may be used to calculate sound absorption coefficients from reverberation time measurements or with the use of a reference source in a reverberation room. For the reverberation time measurement method, measured reverberation times may be input with and without absorbing material and the absorbing material area is also input. Then two equations are used to calculate the absorption coefficient. Equation (6.81) in the 6th edition textbook gives an exact result and Equation (6.82) gives the result according to most current national and international standards (labelled "standard"). The min and max boxes beneath the graph on the next page allow you to change the scale on the graph y-axis. You can also select which absorption coefficient curve to display.



Total volume of the reverberant room (m3): 250.0
Total area of all surfaces in rooms (including the area of the material under test) (m2): 240.0
Surface area of the test material (m2): 12.0

Reverberation Measurement Method

Freq. (Hz)	31.5	63	125	250	500	1K	2K	4K	8K
Original T60 (s)	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
New T60 (s) with test material	4.00	3.50	3.00	3.00	3.00	2.50	2.50	2.50	2.50
Abs. coeff. (exact)	0.44	0.56	0.72	0.72	0.72	0.94	0.94	0.94	0.94
Abs. coeff. (standard)	0.42	0.54	0.70	0.70	0.70	0.92	0.92	0.92	0.92



Reference Source Method

Freq. (Hz)	31.5	63	125	250	500	1K	2K	4K	8K
Lw (dB)	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Lp1 w/o m.(dB)	68.0	68.0	68.0	68.0	68.0	68.0	68.0	68.0	68.0
Lp2 with m. (dB)	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
Abs. coeff. 1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Abs. coeff. 2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Abs. coeff. m.	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51

The room average room absorption coefficient may also be determined by using a reference sound source of known sound power output in octave bands (see above figure). Measured sound pressure levels, averaged in time and space in octave bands with the reference source operating for the cases of no sound absorbing material and then with the test specimen of sound absorbing material included, are also required as input. These levels must be more than 10 dB above background noise levels with the source not operating. The equation used to calculate the material absorption coefficient, $\bar{\alpha}$ is:

$$\bar{\alpha} = \frac{S\bar{\alpha}_2 - S\bar{\alpha}_1 + S_m\bar{\alpha}_1}{S_m} \tag{4.1}$$

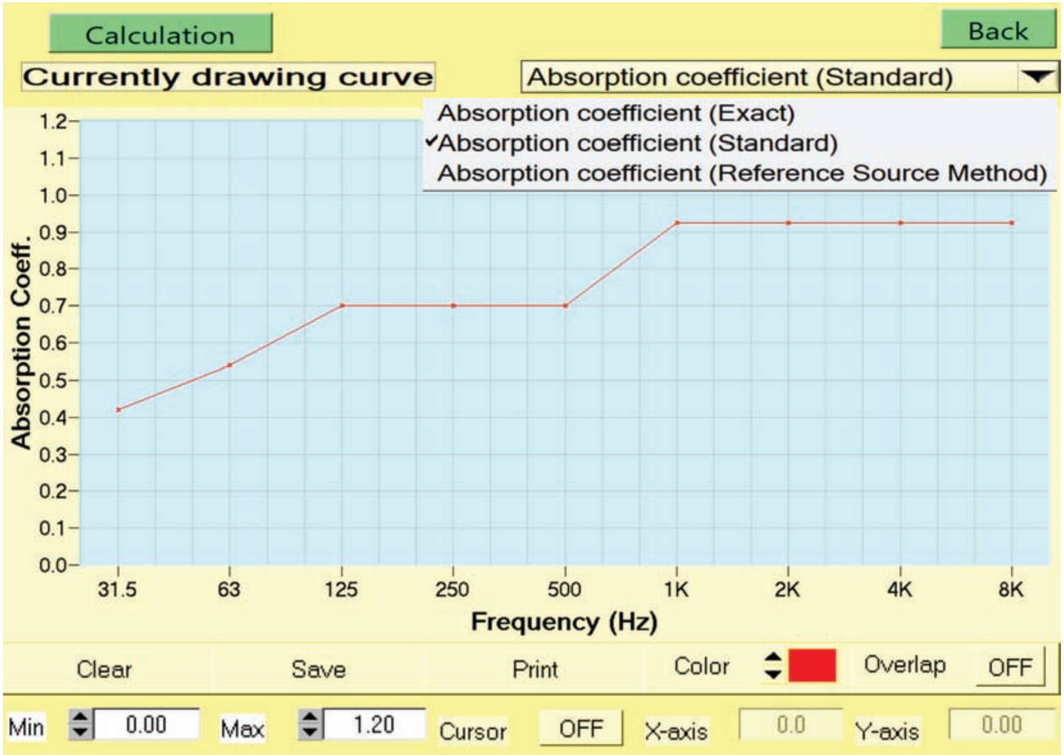
where S is the wall, floor and ceiling surface area of the empty room, S_m is the area of test material (usually 10 m^2), $\bar{\alpha}_1$ is the space average absorption coefficient in the room without the test material present and $\bar{\alpha}_2$ is the space average absorption coefficient in the room with the test material present. The quantities, α_1 and α_2 are calculated from the user provided reference source sound power levels in octave bands, L_W and the space and time averaged sound pressure level, L_p, in octave bands in the room with the reference source operating using:

$$R = 4 \times 10^{(L_W - L_p)/10} \tag{4.2}$$

and

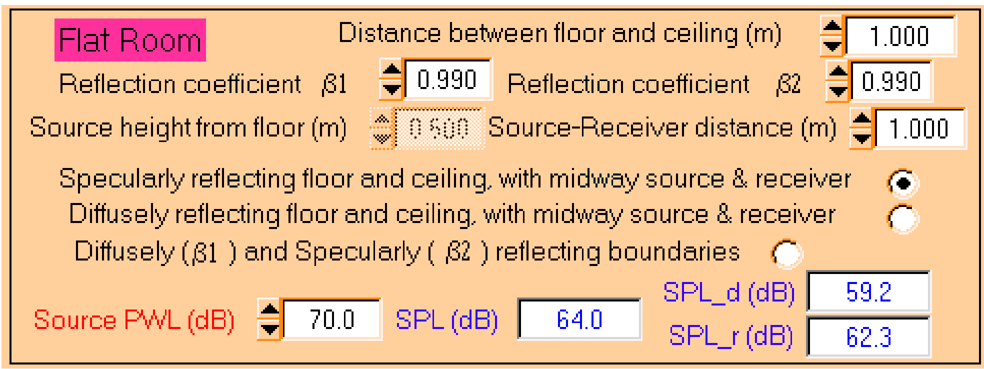
$$\bar{\alpha} = \frac{R}{S + R} \tag{4.3}$$

where R is the room constant and S is the room surface area. Results are plotted by ENC as shown in the following figure.



4.3.1.2 Flat Rooms (Steady-State Response)

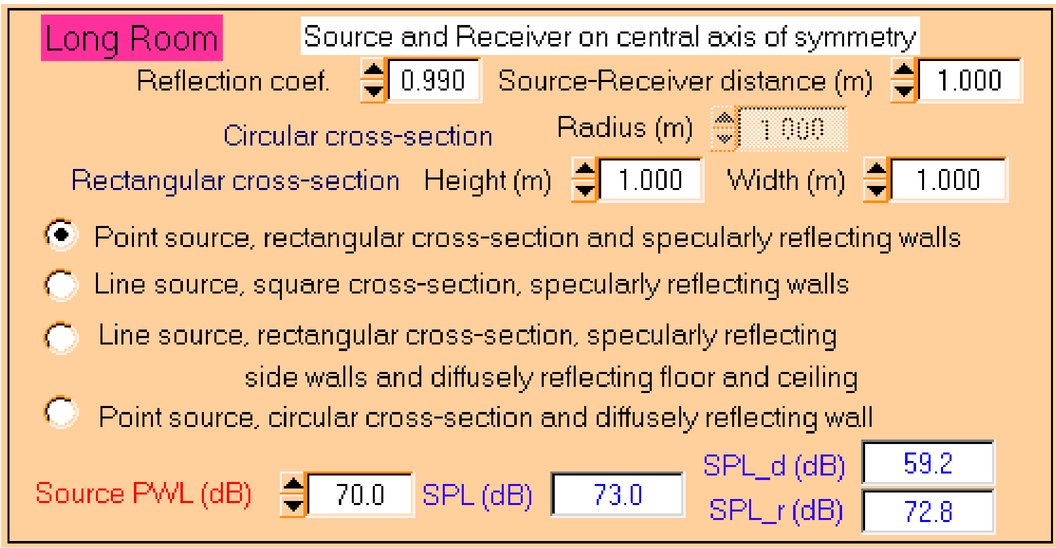
A flat room is one for which two dimensions are more than three times the third dimension. Both reverberant and direct sound levels are calculated in a flat room for a specified distance between the source and receiver and a specified source sound power level for various reflection conditions of the floor and ceiling. The results provided by ENC follow the analysis on pages 383–391 in the 6th edition textbook.



Where the floor and ceiling are either both specularly reflective or both diffusely reflective, results are only provided for cases where the source and receiver are located mid-way between the floor and ceiling. For specularly reflecting floor and ceiling, Equation (6.93) in the 6$^{\text{th}}$ edition textbook is used for the combined direct and reverberant fields. For a diffusely reflecting floor and ceiling where the two reflection coefficients $\beta_{e,1}$ and $\beta_{e,2}$ are equal, Equation (6.103) is used for the reverberant field, otherwise Equation (6.111) is used if the reflection coefficients are not equal. For the calculations corresponding to the case of one surface diffusely reflecting and the other specularly reflecting, Equation (6.113) in the 6$^{\text{th}}$ edition textbook is used for the reverberant field for r/a>1 and Table 6.3, p. 391 is used for r/a $<$ 1. This results in up to 2 dB error in the region of $r = a$. The direct field is calculated using Equation (4.14). Remember not to change values in boxes without arrows on the sides as these are results boxes and not input data.

4.3.1.3 Long Room (Steady-State Response)

A long room (see below) is one for which one dimension is more than three times greater than the other two. Both reverberant and direct sound levels are calculated in a long room for a specified distance between the source and receiver and a specified source sound power level for various reflection conditions of the side walls, floor and ceiling. The results provided by the software follow the analysis on pages 391–396 in the 6$^{\text{th}}$ edition textbook. Remember not to change values in boxes without arrows on the sides as these are results boxes and not input data. Where line sources are considered, they are assumed to occupy the full width of the room and be orientated perpendicular to the room axis. All calculations are for the source and receiver to be on the main axis of the tunnel-shaped space. For the case of a circular cross-section room and specularly reflecting walls and a point source, Equation (6.114) is used to calculate the direct and reverberant sound pressures and for the case of specularly reflecting walls and a line source, Equation (6.116) is used. For a circular cross-section, a point source and diffusely reflecting walls, Equation (6.118) is used for the reverberant field and Equation (4.14) for the direct field.

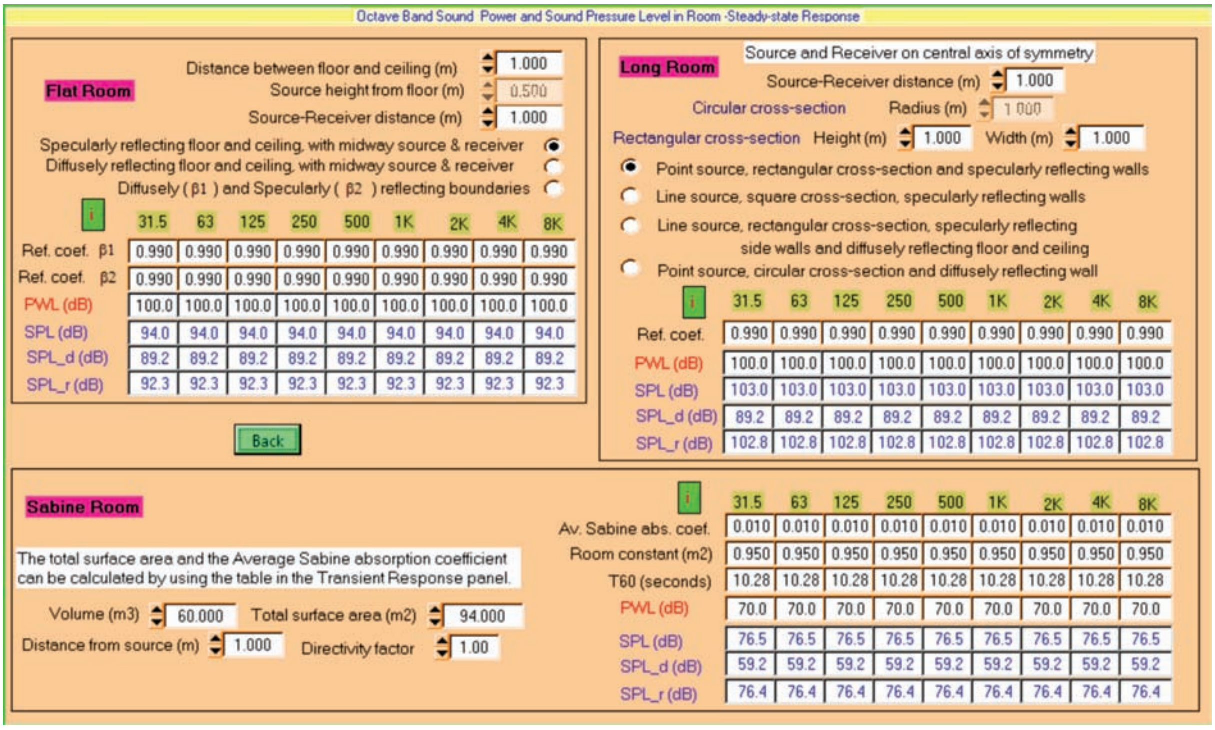


When a square cross-section room is selected, the value entered for the height is also used for the width and the width value is ignored. For a rectangular section room for with specularly reflecting side walls and diffusely reflecting floor and ceiling and either a point source, Equation (6.121) is used to calculate the reverberant field component and the term outside the brackets in Equation (4.14) is used to calculate the direct field.

Clicking on the octave green button at right brings up the window shown below. This window provides the capability to calculate octave band sound pressure levels in flat rooms and long rooms with room dimensions, reflection coefficient and omni-directional source sound power input data. There are several options provided for the user to choose from. These include whether boundaries are diffusely reflecting or specularly reflecting and for the long room, whether the source is a point or line source and whether the room cross section is circular or rectangular. Sabine rooms are also included and for this room you may choose whether to use average sabine absorption coefficients (which includes air absorption), room constants or reverberation times for the input data along with the octave band sound power output of the point source and the room volume, room surface area, distance of the measurement point from the source and source directivity factor in the direction of the receiver.

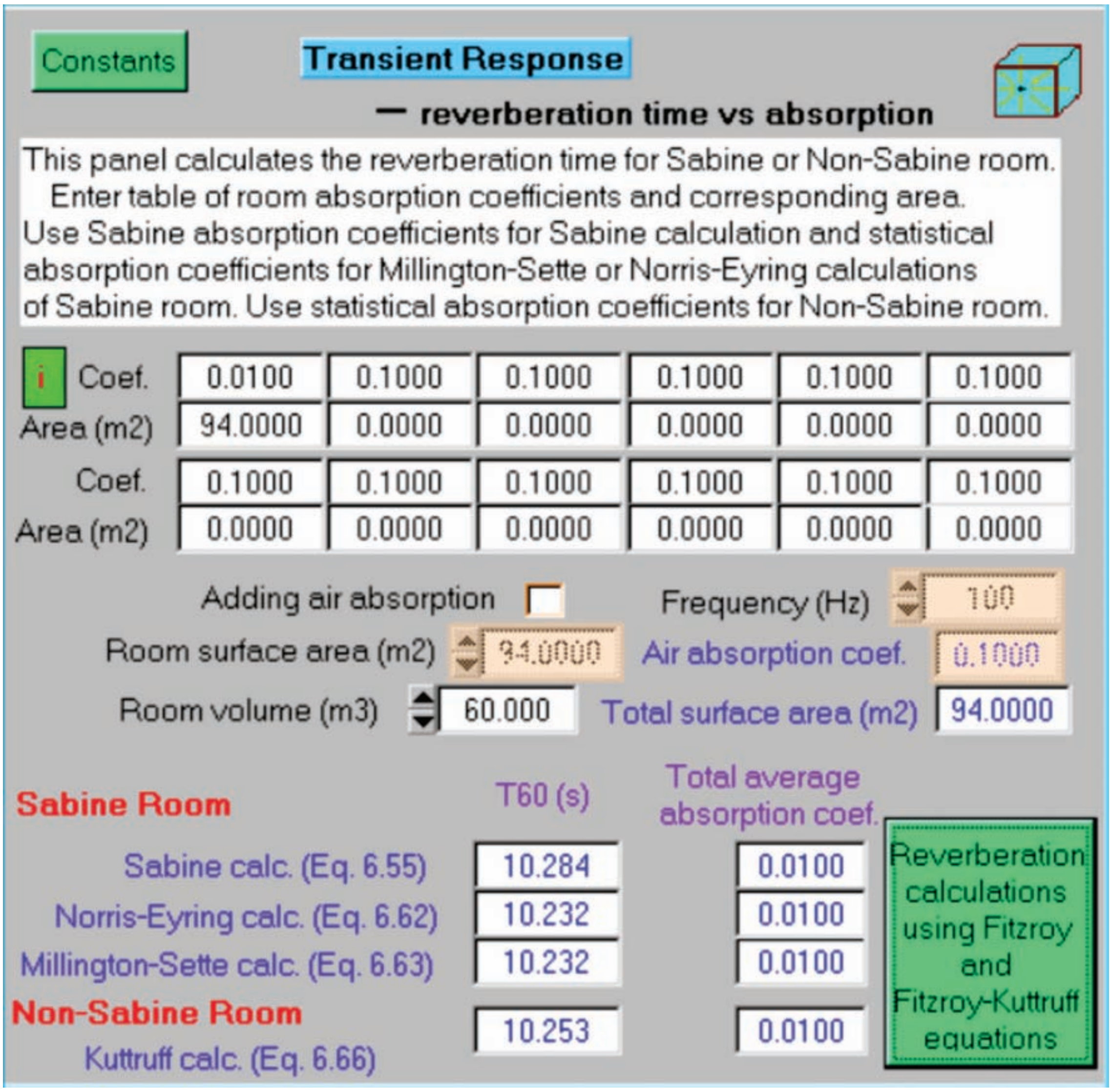
For all types of room, ENC provides as output, the direct field sound pressure level, the reverberant field sound pressure level and the total (direct + reverberant) sound pressure level.

Clicking on any of the red i symbols in a green box allows the user to specify a file for the input data. As mentioned at the end of chapter 1, the format for the input data is important. The correct format can be obtained by right clicking on the "i" symbol and saving the file. You can then replace numbers in this file with your numbers in the same places and then left click on the "i" symbol and load the new file.



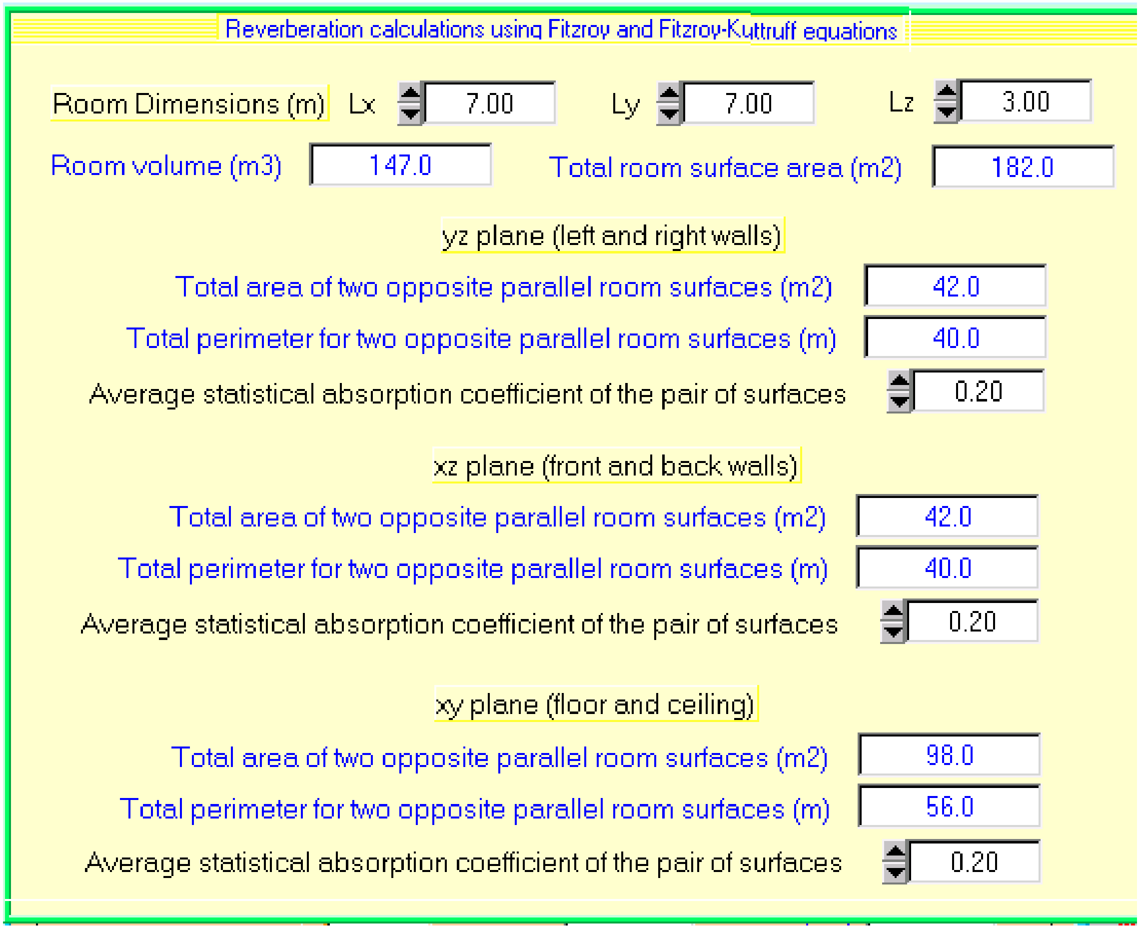
4.3.2 Transient Response

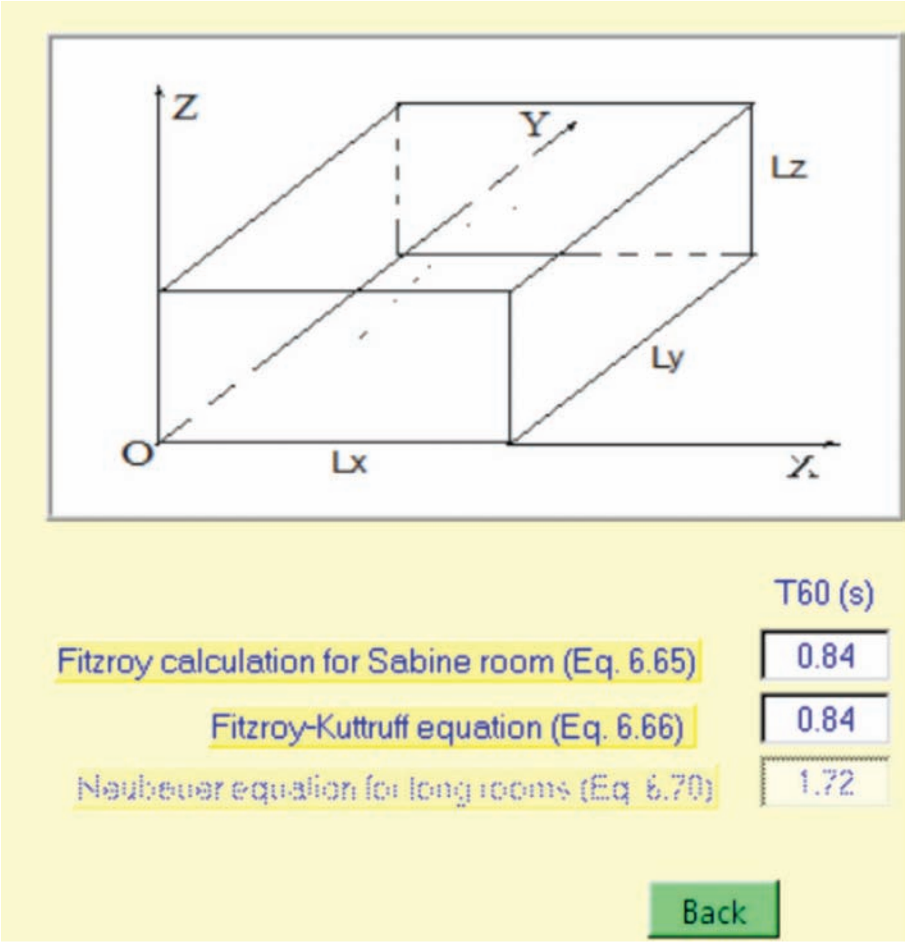
This panel (right side of the window and illustrated on the following page) calculates reverberation times and average absorption coefficients for any shape room, given the room volume and surface area and the absorption coefficient of all room surfaces (in tabular form, associating each area with a particular absorption coefficient). You may also add absorption areas that are not necessarily room walls, floor nor ceiling. For calculations using the Sabine formula (Equation (6.55) in the 6th edition textbook), the absorption coefficient entered in the table must be the Sabine absorption coefficient. For calculations using the Norris-Eyring or Millington-Sette (Equations (6.62) and (6.63) in the 6th edition textbook) or the Kuttruff non-Sabine room (Equation (6.66) or the Neubauer modification to the Kuttruff equation (Equation (6.70)) in the 6th edition textbook), the absorption coefficients entered in the table must be statistical coefficients and none can be greater than 0.95. If they are, then they are set equal to 0.95 prior to the calculations. The final result can include air absorption (Equation (6.38)) if you tick the indicated box.



Clicking on the "Constants" button allows you to set the speed of sound and gas density for the calculations of the entire window — see Section 0.6.4 in this manual for a full description.

Clicking on the green box labelled, “Reverberation calculations using Fitzroy and Fitzroy-Kuttruff equations” results in the window shown on the next page, popping up. In this window, the room volume, surface areas of opposite walls and total wall/ceiling/floor surface area are calculated from the room dimensions. The average sound absorption coefficient of opposite walls in the room must be entered as well.





With these data ENC will calculate the room reverberation time using two alternative empirical equations for Sabine type rooms and another empirical equation for flat or long rooms (one dimension less than or greater than three times the other two). The two equations for the Sabine room correspond to Equation (6.65) (Fitzroy equation) and Equation (6.66) (Fitzroy-Kuttruff equation) and the equation for flat or long rooms corresponds to Equation (6.70) (Neubauer equation) in the 6th edition textbook. These equations are often preferred by practitioners for architectural spaces as they seem to give more accurate results than obtained with equations derived from first principles. Note that the room dimensions that are selected will determine which results are available. This if the room dimensions are such that it is a Sabine room, the flat and long room calculations will be “greyed out” and not accessible.

Clicking on the “back” button will return you to the main screen.

4.4 Porous Material Sound Absorbers

This window calculates normal incidence absorption coefficients, random incidence absorption coefficients and normal impedances of porous acoustic material, using Equations (D.9), (D.10), (D.36), (D.50), (D91)–(D99), (5.15), (5.17) and (5.18) in the 6th edition textbook. Calculations in this panel are based on some constants with assumed values. Clicking on the “Constants” button (top right of the screen) allows you to set the speed of sound and gas density for the calculations of the entire window — see Section 0.6.4 in this manual for a full description. Note that the value for viscosity is also used here.

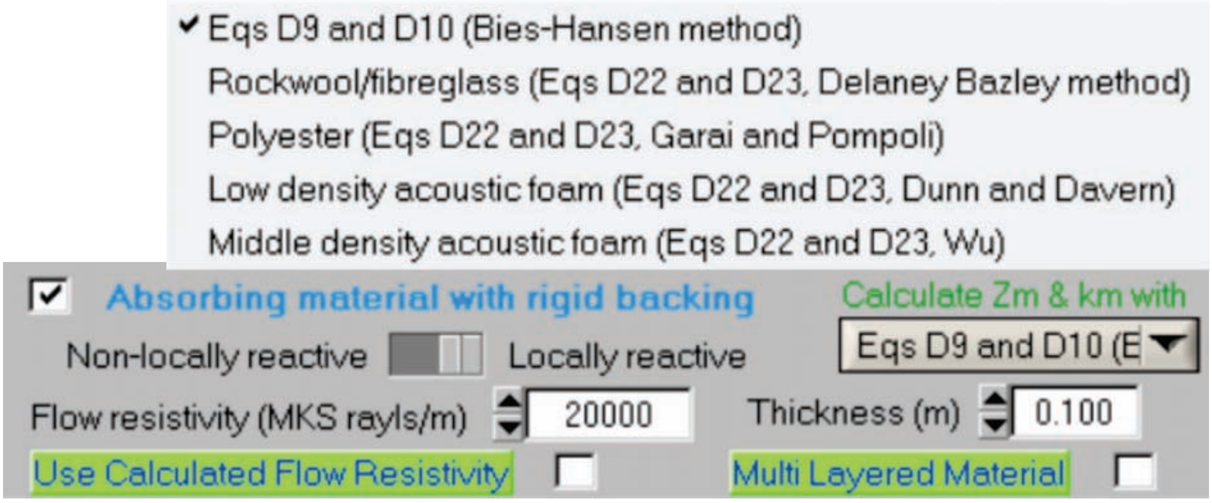
You may choose between flow resistance measured data or impedance tube measurements as the basis for the calculations by clicking the switch illustrated in the following figure.

4.4.1 Calculations based on flow resistance data

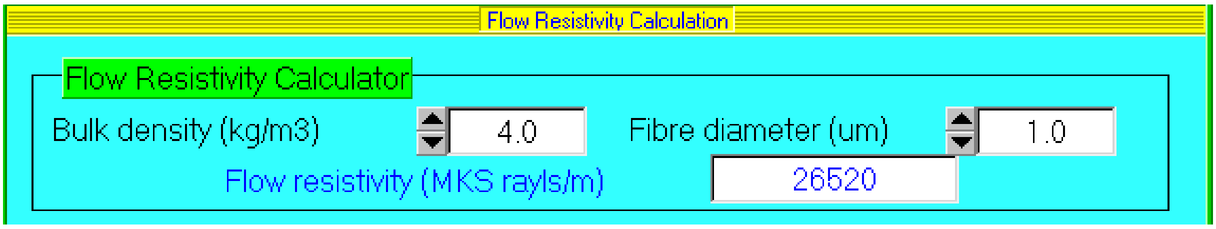
These calculations are explained in full in Appendix D of the 6^{th} edition textbook. The calculations involve calculating in octave bands, the statistical absorption coefficient associated with a porous acoustical material with or without the following:

- backing cavity (can be specified as partitioned or non-partitioned)
- impervious protective covering (such as plastic sheet)
- perforated panel (assumed to be spaced from the impervious covering with a mesh (at least 2mm thick and 13mm size squares).

You may choose any one or more of the above options simultaneously and when the input data are correct, the "run" symbol in the tool bar may be clicked on to produce a result. A partitioned backing cavity is one for which solid partitions normal to the surface of the sound absorbing material divide the backing cavity. The partitions must be closer together than half a wavelength at the highest frequency of interest. The impervious membrane may be defined in terms of speed of sound and density or selected from a list. You must enter the membrane thickness. For the perforated panel, you must enter the hole diameter, % open area and whether the holes are staggered or parallel. The hole spacing and density are then calculated by the software. You may also choose whether you wish the porous acoustic material to be treated as locally reactive or non-locally reactive (see following figure).



For calculating the properties of rockwool and fibreglass fibrous absorbing materials, you have a choice of calculation method. The Bies and Hansen method first calculates the characteristic impedance and propagation constant for the material using Equations (D.9) to (D.21) in Appendix D of the 6th edition textbook. The other method available is the Delaney and Bazely method (Equations D.22 and D.23 and Table D.1, line 1, p. 788) which is inaccurate at high and low values of flow resistance. For both methods, you must enter whether the material is locally or bulk reacting (as this affects the reflection coefficient used in the statistical absorption coefficient calculation of Equation (D.50)). You must also enter the material flow resistivity (defined page 47 of the 6th edition textbook) and the material thickness (see above figure). You can request ENC to calculate the material flow resistivity by clicking on the button, "Use calculated flow resistivity" whereupon the menu below will appear.



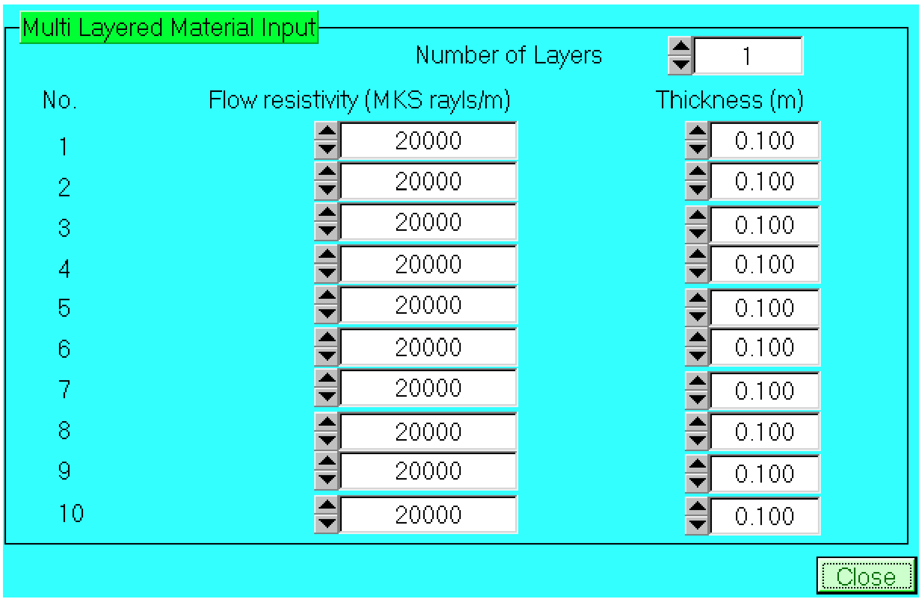
The flow resistivity calculator is based on Equation (D.8) in the 6th edition textbook and is only valid for fibrous materials such as polyester, rockwool and fibreglass. For materials with large diameter fibres, such as polyester, the same Equation (D.8) is used as for rockwool and fibreglass but the constants in Equation (D.8) are different as explained on page 786 of the 6th edition textbook.

If the porous acoustic material is polyester, a different analysis to that for rockwool and fibreglass applies and this can be selected from the menu. In this case Equations (D.22) and (D.23) and Table D.1, line 2, p. 788 in the 6th edition textbook are used.

If the porous acoustic material selected is polyurethane foam of low flow resistivity, then Equations (D.22) and (D.23) and Table D.1, line 3, p. 788 in the 6th edition textbook are used.

If the porous acoustic material selected is porous plastic foam of medium flow resistivity, then Equations (D.22) and (D.23) and Table D.1, line 3, p. 788 in the 6th edition textbook are used.

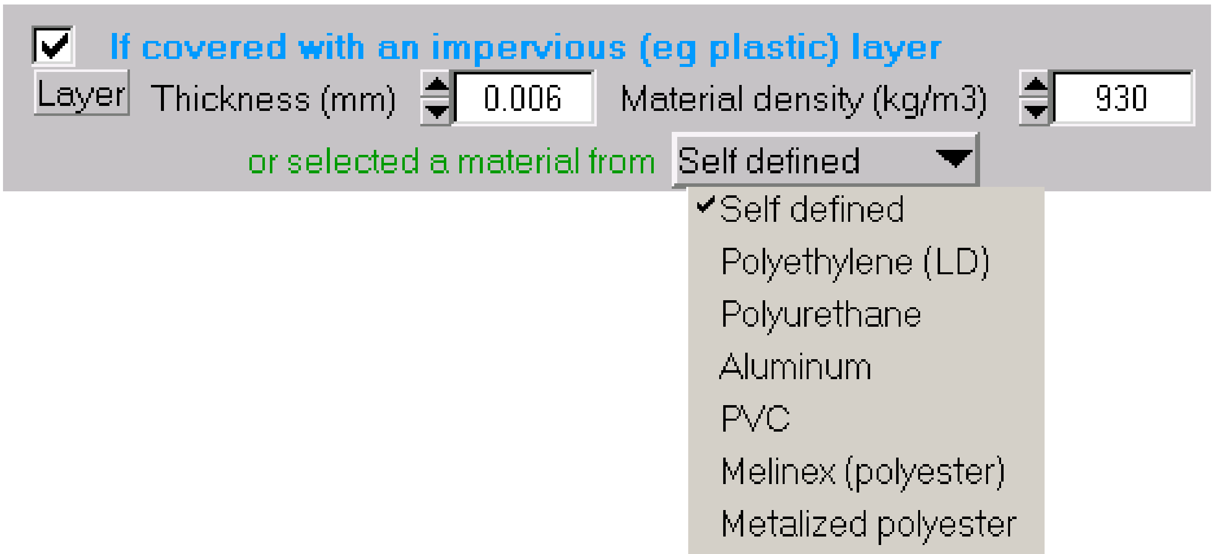
If the "Multi Layered Material" button is clicked the menu shown in the figure at right appears.



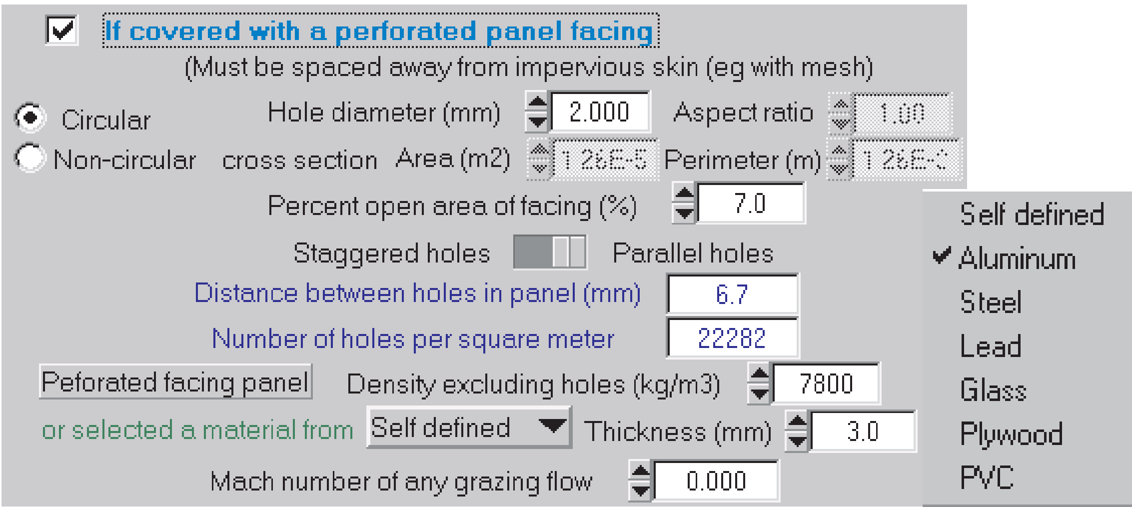
When the multi-layered option is chosen, the layer thicknesses in the pop-up window and Equation (D.95) in the 6th edition textbook are used to calculate the normal impedance at the outside face of the material. Click on "Close" when you have finished entering parameter values.

The statistical absorption coefficient is calculated from the reflection coefficient which, in turn, is calculated normal impedance at the face of the material. For a material that is infinitely thick, the specific normal acoustic impedance is equal to the characteristic impedance. However, this is not the case if the material is backed by a rigid surface or a cavity and the normal impedance must be calculated from the characteristic impedance using Equations (D.91)–(D.94) in the 6th edition textbook. Thus the next choice to make is whether the material is backed by a cavity which in turn has a rigid termination (see following figure). If the "backing cavity" option is not selected, ENC will assume that the material is backed by a rigid wall. If you select that the material is backed by a cavity, then you must enter the backing cavity depth (excluding the porous material) and whether it is partitioned or non-partitioned (see following figure). For these calculations Equations (D.91)–(D.94) are used together with Equation (D.50) and Equations (5.15) to (5.18) in the 6th edition textbook to calculate the statistical absorption coefficient.

For a porous acoustic material covered in a limp impervious membrane (such as polyethylene — see following figure), the normal impedance used in Equations (5.15) or (5.18) is calculated using Equation (D.96). You must click on the small square box in this panel, enter the layer thickness and select a material from the list (see following figure). If your material is not in the list, select the "self defined" button and enter the material density.



If a perforated sheet is added (spaced away from an impervious membrane if one exists), you need to click on the empty box labelled "if covered with a perforated panel facing" and enter whether the holes in the panel are circular or non-circular. If circular, you need to enter the diameter and if non-circular, you need to enter the hole aspect ratio, area and perimeter. Next, enter whether the hole pattern is parallel or staggered. ENC will calculate the distance between holes. Next select the perforated panel material type from the list. If your material is not there, select "self defined" and enter the material density (see following figure). Finally, enter the perforated panel thickness (mm) and the Mach number of any grazing flow across the perforations.

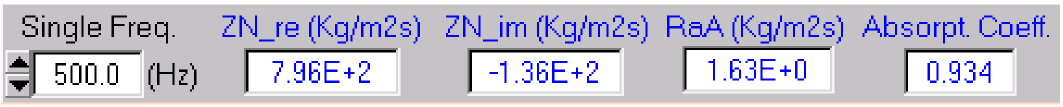


If a perforated sheet is added, then the specific normal impedance used in Equations (5.15) or (5.18) is calculated using Equation (D.99) in the 6^{th} edition textbook, where the effective length of the holes is given by Equation (8.30).

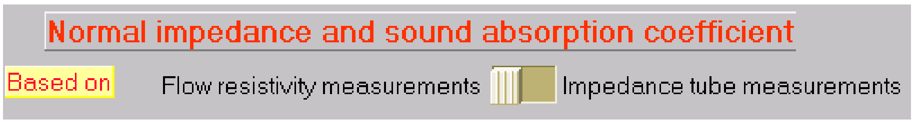
Note that calculation of the effect of the perforated panel in ENC is only valid for a panel open area of less than 20%. Also, the condition $fL/c < 0.1$ must be satisfied, where L is the depth of backing cavity behind the perforated sheet.

The total number of holes calculation is only accurate if the aspect ratio of the holes is close to unity. For other aspect ratios, the estimate will be incorrect. However, only the % open area is used in the sound absorption calculations, not the number of holes.

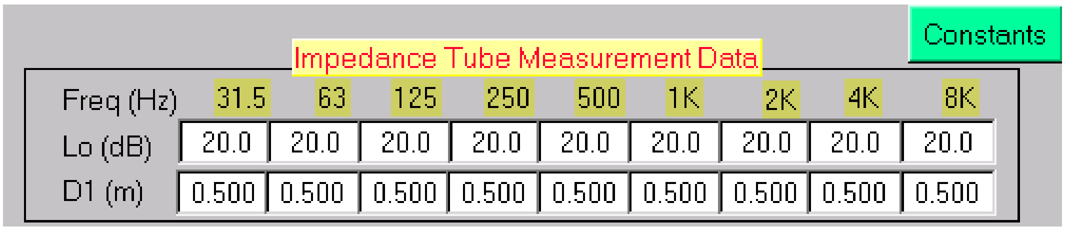
As well as the final result of statistical absorption coefficient being produced, a number of intermediate results are also provided for the selected frequency (see following figure).



4.4.2 Calculations based on impedance tube measurements



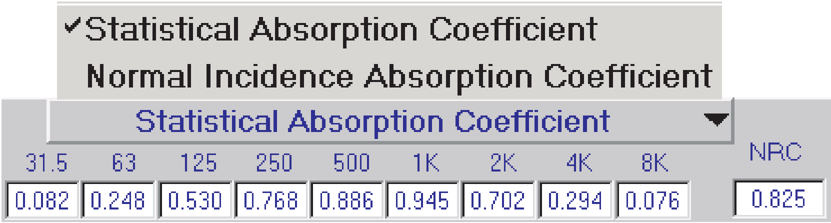
All of the impedance and statistical absorption coefficients described above can also be calculated using standing wave measurements made in an impedance tube. The switch on the top left of the window is set to "Impedance tube measurements" (see above figure). Then enter the measured data (standing wave ratio, Lo and distance, D1, from the face of the test material of the first minimum sound pressure level in the tube) for each octave band centre frequency in the table reproduced here in the figure on the next page. The equations used to calculate the normal impedances and statistical absorption coefficients for each octave band centre frequency are D.33–D.48 in the 6th edition textbook.



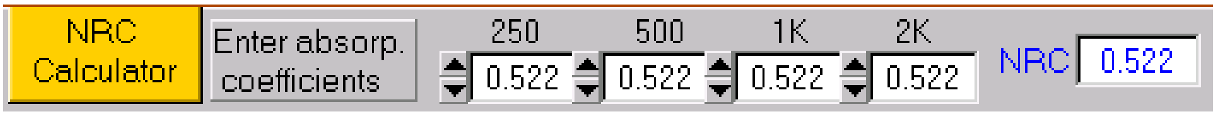
Clicking on the "Constants" button allows you to set the speed of sound and gas density for the calculations of the entire window (including those based on flow resistance measurements) — see Section 0.6.4 in this manual for a full description.

4.4.3 Calculation summary and results presentation

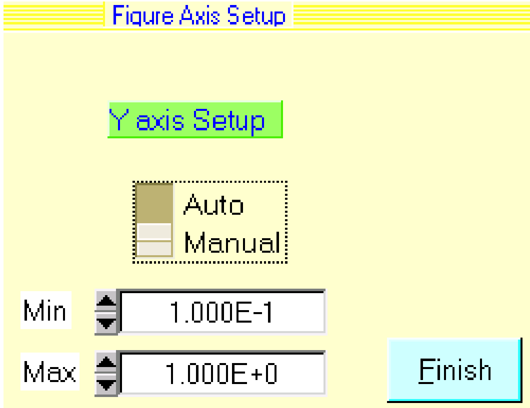
The absorption coefficients calculated using either method are also provided in a table of values corresponding to octave band centre frequencies (see following figure). The table also provides the NRC value for the material. You can switch between normal incidence and statistical absorption coefficient, and the values shown in the table depend on the position of the flow resistivity/impedance tube switch at the top of the window.



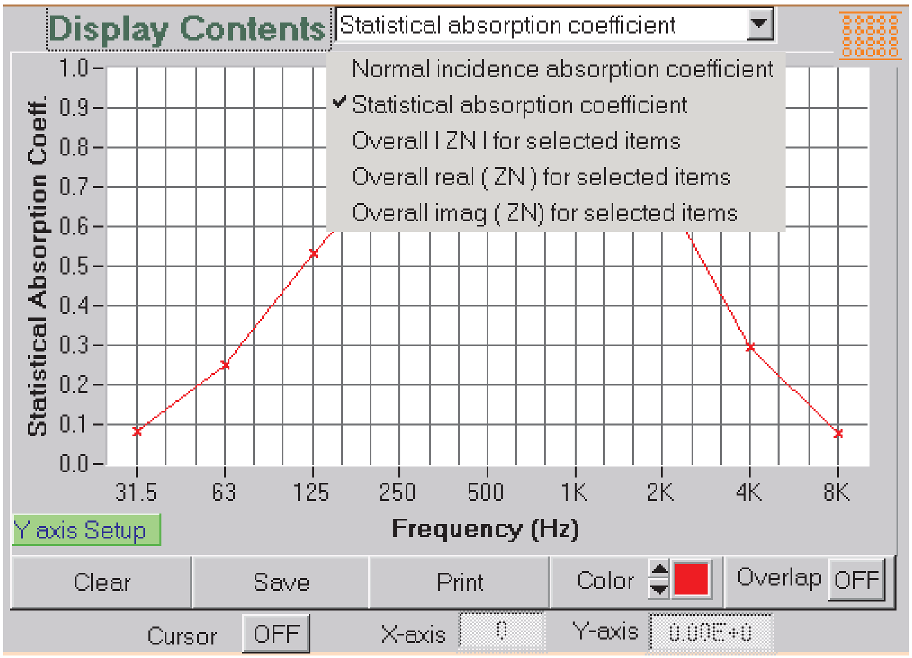
For convenience there is an NRC calculator at the bottom right of the window which can be used with any known values of absorption coefficients for the octave band centre frequencies, 250 Hz to 2 kHz (see below).



All of the calculated quantities are also available for display as a graph for octave band centre frequencies from 31.5 Hz to 8 kHz (see figure on the next page). The screen can be dumped to a printer or to the clipboard and/or the numerical results can be saved to a file for later use by a spreadsheet program such as Excel. If dumped to the clip board (by pressing the "print Scrn" key on your keyboard), you can cut out the parts you need for a report using software such as Corel PhotoPaint (which produces excellent results).

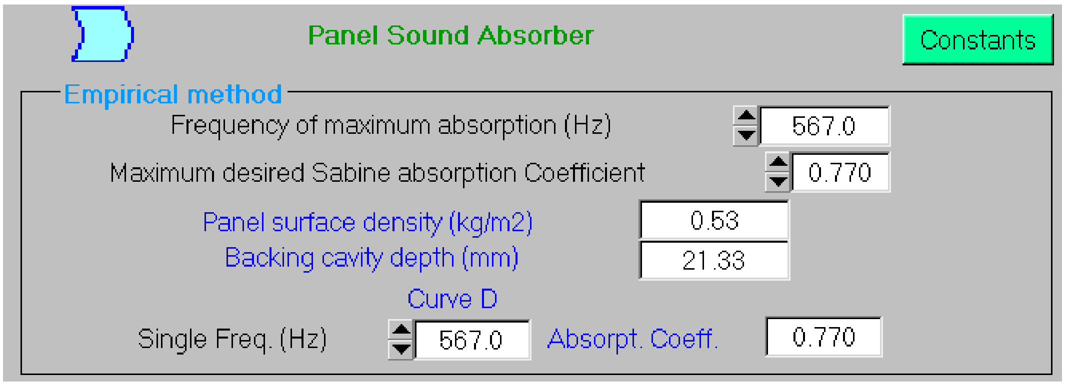


The y-axis maximum and minimum values can also be set by clicking on "y-axis setup" as shown at right.



4.5 Panel Absorber

This section is for the calculation of sabine absorption coefficients produced by a sound absorber made using a solid panel. There are two ways of doing the calculation. One relies on an empirical model and is based on Figures 6.12 and 6.13 in the 6th edition textbook (6th edition). The other method is analytical (6th edition textbook, pages 380–381) but requires much more detailed knowledge of the characteristics of the room and the panel used as the absorber. Both methods provide values of Sabine absorption coefficient. For the empirical method, all that is needed is the desired frequency of maximum absorption and the corresponding absorption coefficient (see following figure).



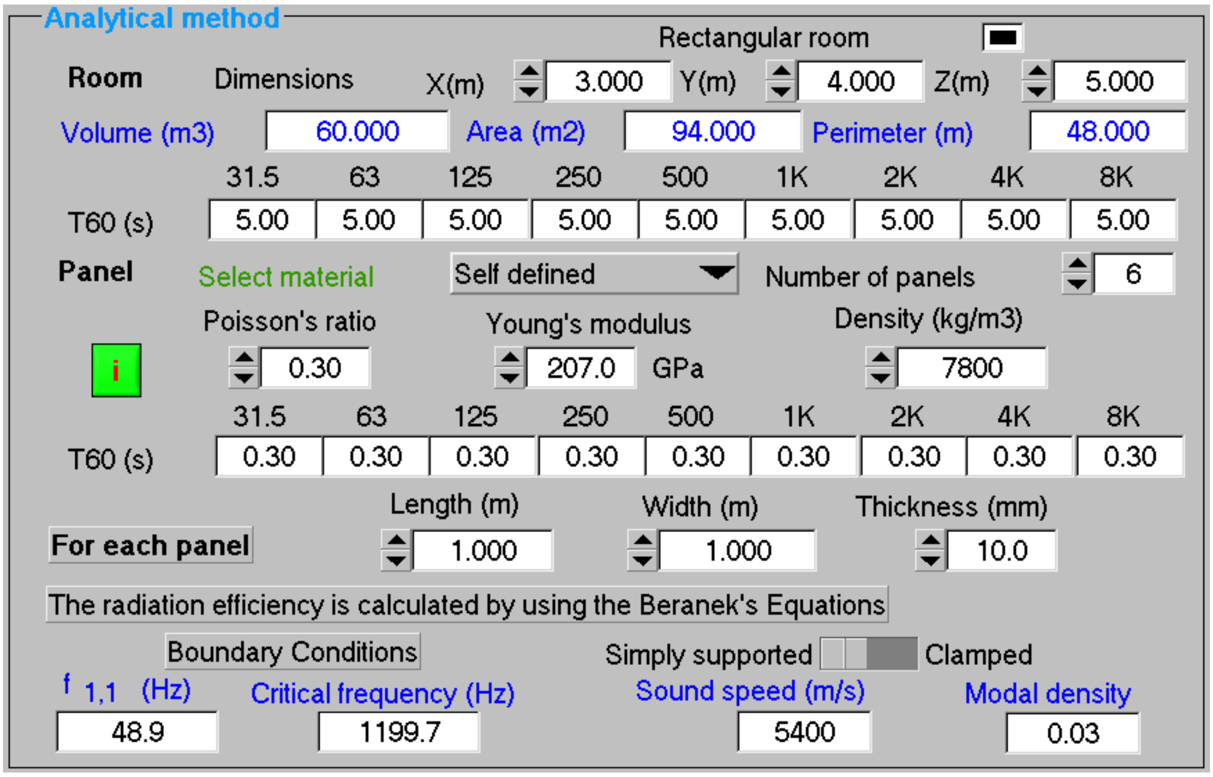
ENC allows interpolation between the curves in Figures 6.12 and 6.13 in the 6th edition textbook and the curve identified in blue text (see above figure — “Curve D”) is the nearest to the chosen maximum absorption coefficient. ENC interpolates linearly between the two nearest curves in order to find the optimal panel mass and cavity depth using Figure 6.13 in the 6th edition textbook.

Clicking on the “Constants” button (see above figure) allows you to set the speed of sound and gas density for the calculations of the entire window — see Section 0.6.4 in this manual for a full description.

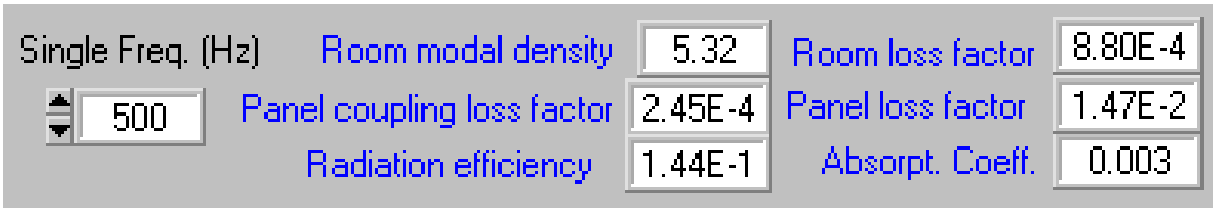
For the analytical method, the data indicated in the figure on the next page must be input. The required input data are either the room dimensions or its volume, surface area and perimeter. In addition, the room reverberation time, the absorbing panel material, absorbing panel area, thickness, perimeter and its mounted reverberation time in free space (not in a room) as well as the number of panels must be entered. The Sabine absorption coefficient is calculated using Equation (6.90) in the 6th edition textbook. The panel radiation efficiency, σ, is calculated using the following equations from Davy (2009), which are for a panel excited by an incident sound field.

$$\sigma = \log_e\left(\frac{1+\sqrt{1+q^2}}{F+\sqrt{F^2+q^2}}\right) + \frac{1}{B}\log_e\left(\frac{H+\sqrt{H^2+q^2}}{F+\sqrt{F^2+q^2}}\right)$$

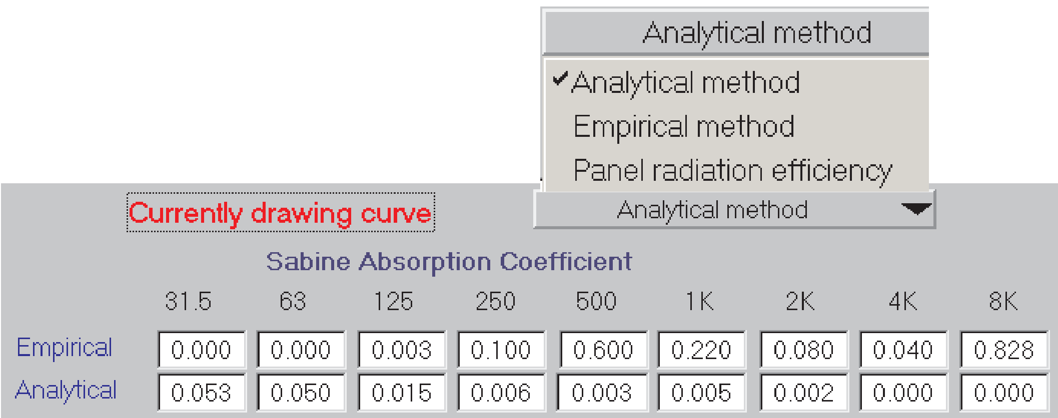
where $k = 2\pi/\lambda$, $H = \left[1.5\sqrt{4a/\lambda} - 0.124\right]^{-1}$, $q = \pi/(2k^2a^2)$, $F = 1.3\sqrt{\pi/(2ka)}$, $a = 0.5\sqrt{A_p}$, A_p is the plate area and $B = (H/F) - 1$. If $B = 0$ or if B is close to 0, the second term on the RHS of the above equation is replaced with $F/\sqrt{H^2+q^2}$.



For the analytical calculation, a number of useful intermediate results are provided (see following figure).



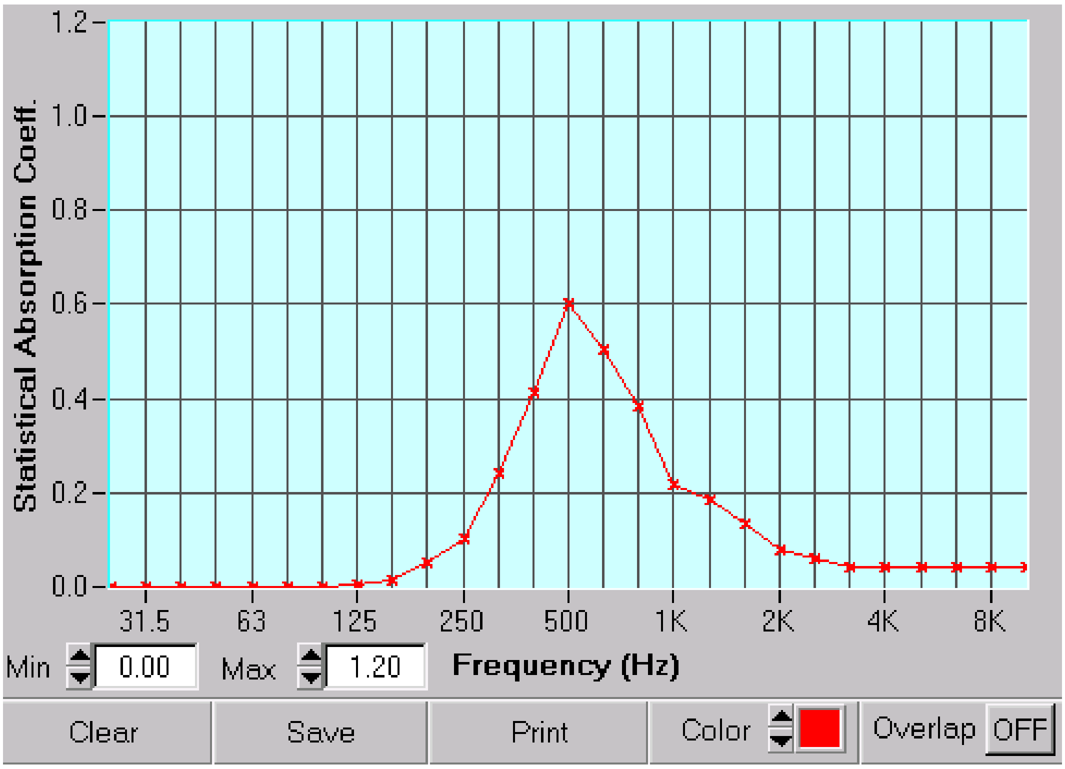
For both calculation methods, the octave band values of the Sabine absorption coefficient are included in the table (see following figure). The empirical method seems to give more realistic results.



The quantity to appear on the plot is chosen by selecting it from the menu shown on the previous figure, where it can be seen that "panel radiation efficiency" can also be selected.

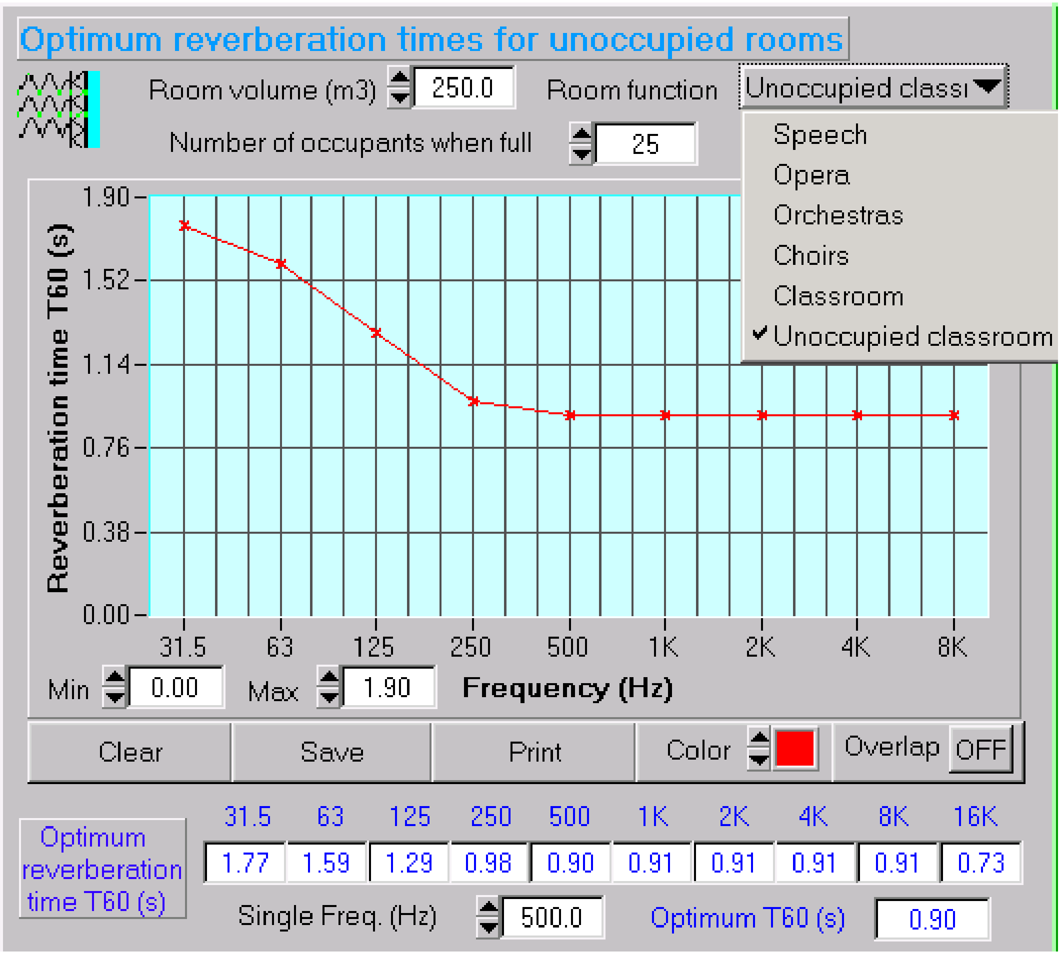
An example of the plot so generated is shown below. The screen can be dumped to a printer and/or the numerical results can be saved to a file for later use by a spreadsheet program such as Excel. The graph shows 1/3 octave band results as well as octave band results and values can be read accurately using the cursor. Maximum and minimum values for the y-axis are user selectable. For the analytical calculations, 1/3-octave band results are calculated using the corresponding octave band reverberation times, which represents an approximation, albeit a good one.

The value corresponding to any specific single frequency can be obtained by typing the desired frequency into the "single frequency" box (see following figure) and reading the corresponding Sabine absorption coeff. in the "Absorpt. coeff." box.

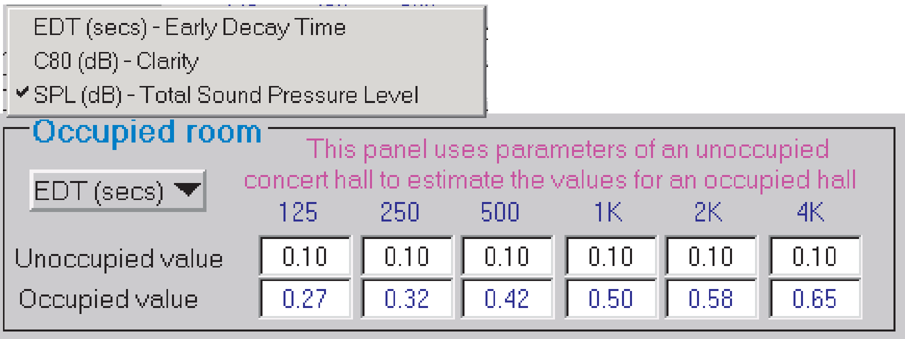


4.6 Applications

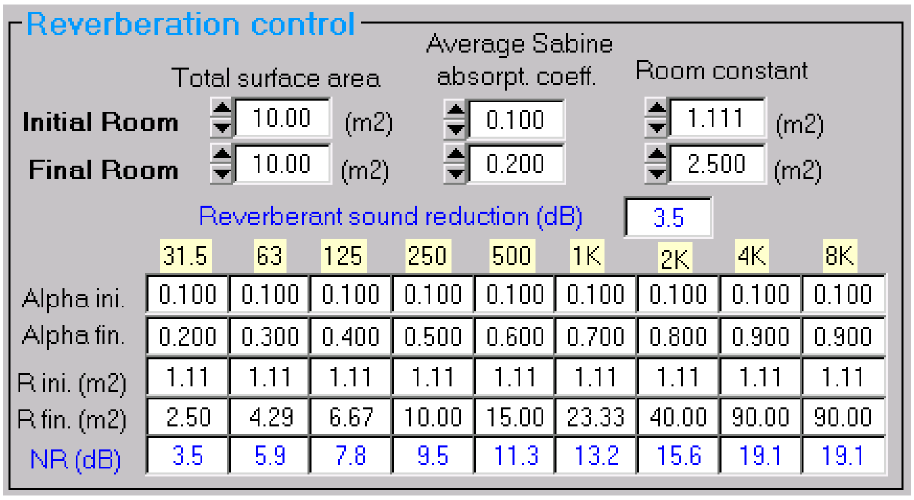
There are two applications of reverberation and sound absorption for which calculations are provided. The first application (see below) provides a rough guide (Equation (7.122) in the 4th edition textbook) for estimating optimum reverberation times in an occupied auditorium subject to various uses and a class room (both occupied and unoccupied). The optimum octave band values of T_{60} are plotted on the graph and included in the table and the value corresponding to any frequency can be obtained by typing the desired frequency into the "single frequency" box and reading the corresponding reverberation time in the "Optimum T_{60} " box (see following figure). The optimum reverberation time at 250 Hz is set at 10% above the value calculated using Equation (7.122) in the 4th edition textbook. At 125 Hz it is 50% and at 63 Hz it is 100% and at 31.5 Hz it is 120%. For the optimum reverberation times in occupied classrooms, the discussion following Equation (7.122) in the 4th edition textbook is used and for unoccupied classrooms, the optimum reverberation time is calculated from that for an occupied classroom using Equation (7.123) in the 4th edition textbook.



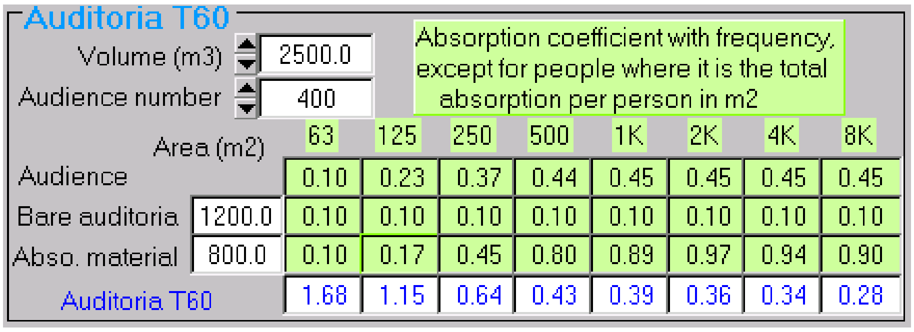
The second calculation (see following figure) allows three quantities of interest for an occupied auditorium to be calculated from the measured quantities in an unoccupied auditorium (most applicable to a concert hall). The quantity of interest may be selected from the drop down menu and the choice is between early decay time, clarity and total sound pressure level. This is discussed in the 4th edition textbook but has been excluded from the 6th edition.



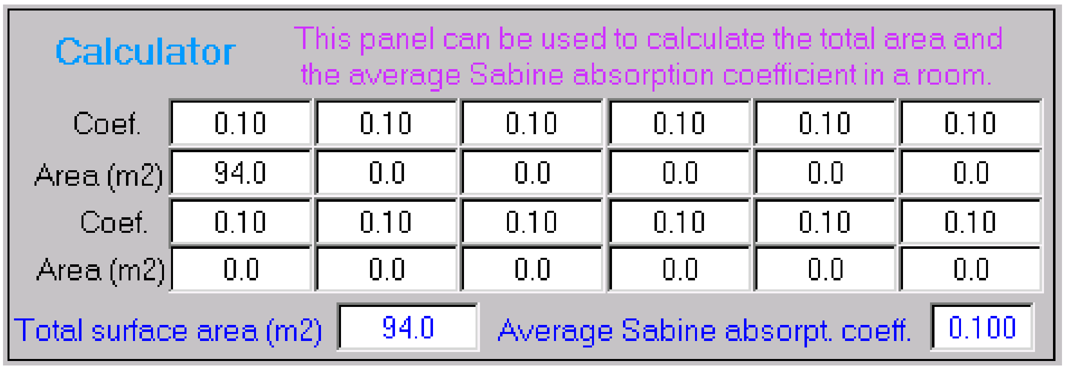
The third calculation (see following figure) allows one to estimate the reverberant field noise reduction as a result of adding a fixed amount of absorption (Equations (7.121) and (7.44) in the 4th edition textbook). Remember, only type in boxes with black numbers in them. In the table, you can enter either the room constant or the room average Sabine absorption coefficient but not both. You need to click on "Run" for the calculation to proceed after you have entered the appropriate numbers in all the boxes.



The fourth calculation (see following figure) allows actual reverberation times in auditoria to be calculated with a reasonable degree of accuracy using Equation (7.125) in the 4th edition textbook and a knowledge of the average absorption coefficients for the bare auditorium and also for the treated surfaces (and corresponding areas). The total absorption for each member of the audience and number of people in the audience also need to be entered for each octave band. The default absorption coefficients used in ENC are generally accepted values for seated people.



In the bottom right of the section is a calculator (Equation (6.86)) for averaging sound absorption coefficients (see following figure).



Chapter 5

TL, Enclosures, Barriers & Pipe Lagging (Module 5)

5.1 Overview

This module allows you to do the calculations described in chapter 7 of the 6th edition textbook. There are separate windows (and sections below) for single partition transmission loss (isotropic and orthotropic), double partition transmission loss, (single number descriptors, STC, IIC, R_w), composite and flanking transmission loss, enclosures, outdoor barriers, indoor barriers and pipe lagging. All windows have the same left hand panel, which is illustrated on the next page. For each type of calculation, the results appear plotted on the graph, either as 1/3-octave band or octave band data. The octave band values (which are averages of the corresponding 1/3-octave bands) are listed in the table below the figure. There are a number of aspects associated with the figure that are worthy of note.

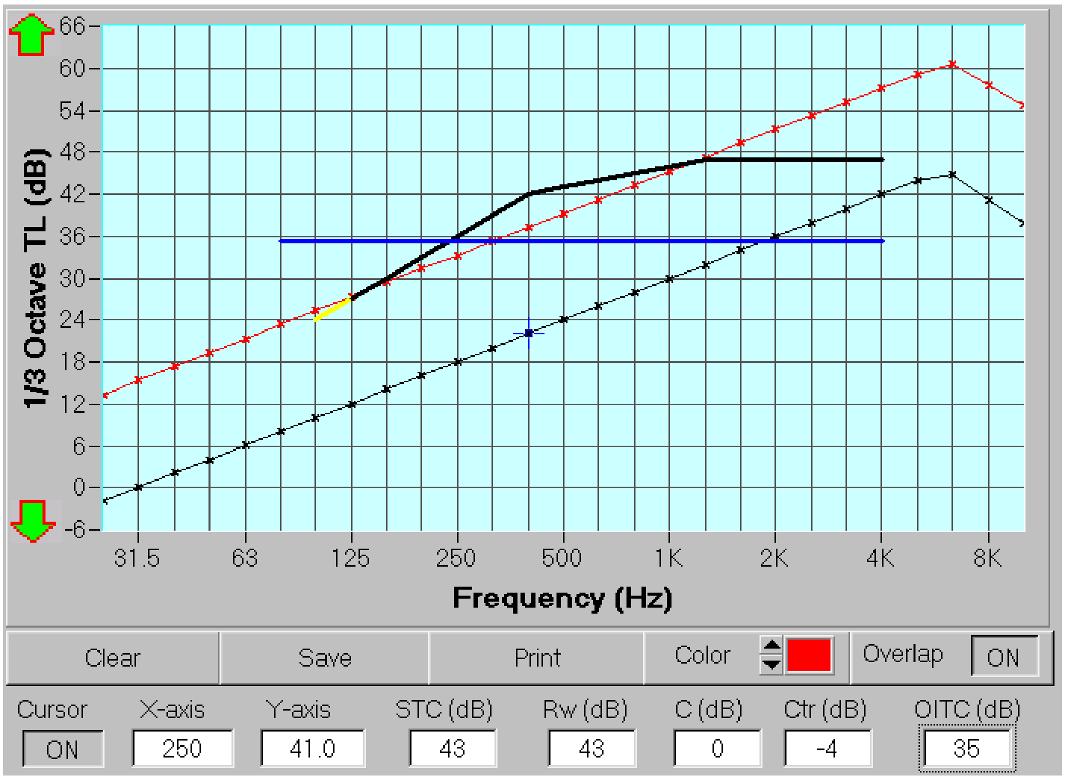
- A number of curves can be plotted on the figure simultaneously, allowing you to observe the effect of changing some parameters. However, to plot more than one curve on the figure, the "overlap" button at the bottom of the figure must be "ON". If it is "OFF", only the curve corresponding to the current data in the right panel will appear when the "run" icon is clicked on in the tool bar.

- Each curve can be assigned a unique colour using the "color" button beneath the figure.

- The cursor may be turned on so that the 1/3-octave band levels can be read accurately for each frequency. For cases such as the TL for composite panels window, the cursor will only read octave band values as these are the only input data available. The frequency and graph TL value corresponding to that frequency are displayed in boxes beneath the figure. To make the cursor register when it is first turned "ON", it is necessary to click somewhere on the figure and this is also how you move the cursor around. Note that if the cursor is "OFF", these numbers have no meaning.

- The STC as well as the ISO single number descriptors, R_w, C and C_{tr} corresponding to the TL curve are given in a box beneath the figure. In addition the OITC number is calculated and displayed. These descriptors apply to the curve which has the cursor on it rather than the last one drawn. However, if the cursor is never turned on, the descriptors apply to the last curve drawn. If the cursor is turned on and then off, the descriptors will apply to the curve where the cursor was located prior to it being turned off.

- Clicking on “Clear” beneath the figure clears all curves from the figure.
- Clicking on “Save” will prompt the user for a file name to which the data corresponding to the current screen will be saved. These data can then be imported into Excel.
- Double clicking on the graph will save it to the clipboard from where it can be pasted into any application.
- Clicking on “Print” will result in the screen below being printed.



In some cases the cursor may not display the same value as in the table below the figure. This is because the cursor value is a 1/3-octave band value and the table value is an octave band value, which is the average of three 1/3-octave band values.

Octave Band Transmission Loss

Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
TL (dB)	-0.2	5.8	11.7	17.7	23.7	29.7	35.7	41.6	40.4

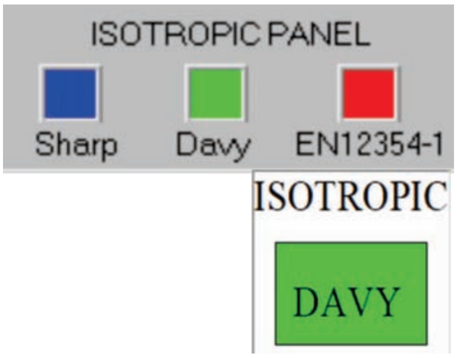
The STC, Rw and OIC curves can be inserted on the graph for any of the data curves by clicking on the corresponding name or the box containing the number below the particular descriptor (see the yellow, blue and black curves in the figure at the top of this page). Note that this option is available for whatever curve has the cursor on it. If the cursor is "OFF", then it is for the last curve that was plotted.

The TL values for a number of curves can be exported to an excel spreadsheet by pressing F8 or by clicking the "save" button under the graph.

In all windows of this module (except the "Composite" and "Enclosure" windows), you will find a button, labelled "Constants". Clicking on this brings up a window that allows you to set the speed of sound and gas density for the calculations — see Section 0.6.4 in this manual for a full description.

5.2 Partition Transmission Loss (Single Wall) (6$^{\text{th}}$ edition textbook, pages 420–429)

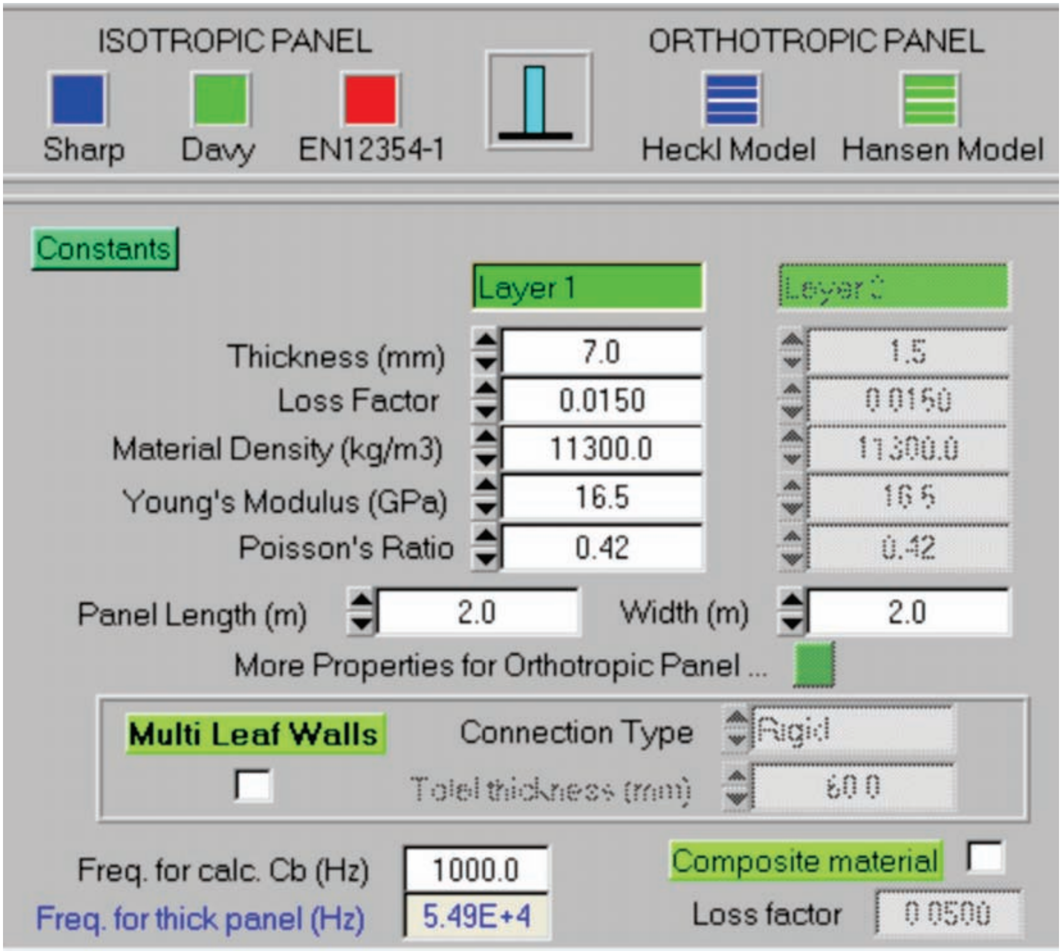
In this calculation, you have a choice between an isotropic (uniform) panel and an orthotropic panel (stiffened or corrugated). The window allows you to calculate the TL of a single partition that is isotropic or orthotropic and which has one or more layers (or leaves) of the same material connected rigidly of viscoelastically. There is also provision for different materials to be used in a two leaf panel (select "composite material" provided that the two different materials are rigidly connected). For each panel type, there is a choice of three different models (Sharp model, Davy model and the standard, EN12354-1 model) for the calculations. The advantages of each model are outlined below and the Davy model in ENC has been updated according to the Errata and Additions that follow the last chapter of this manual.

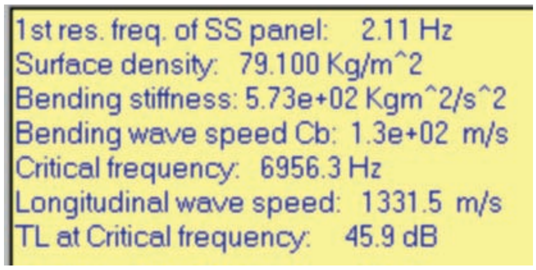


5.2.1 Isotropic Panel

For the **i**sotropic panel, you can choose between the Sharp, Davy and the EN12354-1 models. The Davy and EN12354-1 models are dependent on the area of one side of the panel. The model currently selected is displayed on the bottom right of the screen (see figure at right).

As can be seen on the figure on the next page, you also need to select whether or not you have a multi-leaf or composite panel configuration. These are explained in detail in the following pages. You also need to select the frequency at which you would like the bending wave speed calculated for display in the yellow box (see figure at right). ENC also calculates and displays the upper frequency limit at which the panel thickness limits the Transmission Loss (see page 428 in the 6$^{\text{th}}$ edition textbook). As can be seen by inspection of the yellow box on the next page, ENC displays a number of parameters that it uses in the TL calculations.



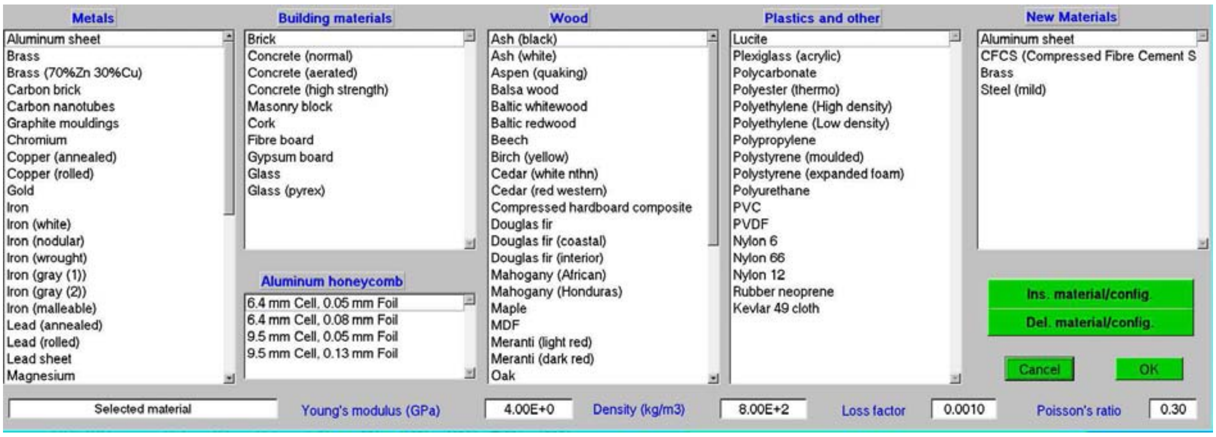


Click on "Constants" (see preceding figure) to set the speed of sound in air to be used in the calculations.

Note that in the Davy model, the panel must be larger than 1/6 of a wavelength of sound in air at the lowest frequency of interest. Values at lower frequencies will not be valid. The Davy model has undergone a number of important changes since version 4.4 of ENC software, due to published updates to the model..

To select the material you wish to use, right click (or double left click) in the green box above the materials properties table. This green box initially has "Layer 1" written in it but after selecting a material, it will have the material name in it as shown in the figure on the previous page.

When you right click on the green box above the materials properties table, the page illustrated below will pop up.



Left click on the material you want and then click on “OK”, the bottom right green button. If you wish to add your own material, click on the green ”Insert material/config” button and it will appear in the right hand “New Material” column of the table. If you wish to delete a material, left click on it in the list and then click on the “Del material/config” button.

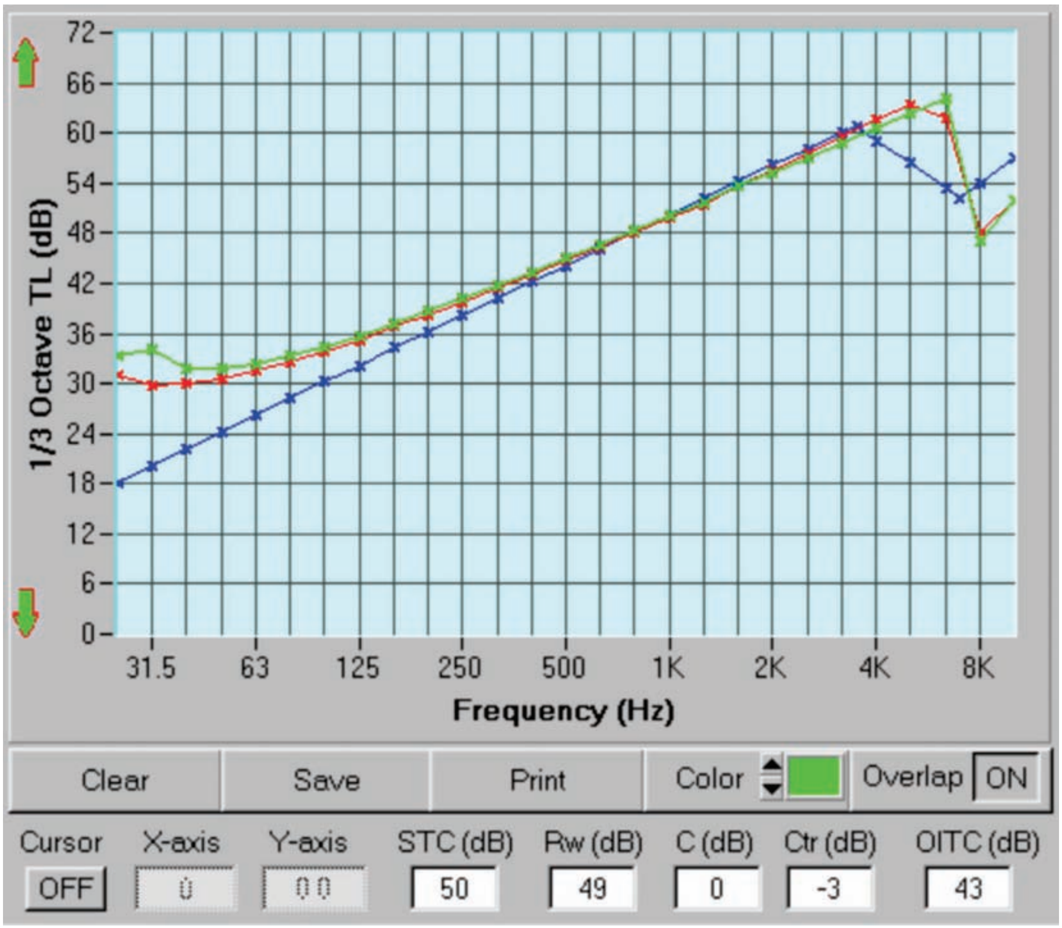
When you have selected the material you want, you can adjust its thickness (or any other parameter) by entering the required value in the table. Then click on “run” on the top right of the screen and a graph of TL plotted as a function of 1/3-octave band centre frequency will appear as shown on the next page.

If you wish to plot more than one curve on the same set of axes, click on the overlap button so that it shows “ON”. Note that you can also move to the double wall window while keeping the curves from the single wall calculations. This allows immediate comparison between single and double wall results. If you wish to read values from the curve, click on the cursor button so that it is “ON” and then click on the appropriate place on the curve. The x and y-axis values will then appear in the boxes under the graph.

Note that the data points corresponding to the critical frequency and half the critical frequency are plotted in addition to the 1/3-octave band centre frequency points for the Sharp analysis (but not the Davy analysis).

The “STC” value under the graph is the Sound Transmission Class and the Rw quantity is the ISO weighted sound reduction index (which is closely related to the STC but not the same). The coefficients C and Ctr correspond to the to the two correction factors defined on page 408 of the 6th edition textbook and in ISO717-1 (1996).

The octave band Transmission Loss values that appear in the table below the graph are calculated by averaging the values in the three one third octave bands that make up each octave band.



The calculations for the Sharp analysis use Equations (7.2), (7.3), (7.62) and (7.64) in the 6th edition textbook together with the procedure described under Figure 7.9, p. 425 in the 6th edition textbook. For the Davy analysis, Equations (7.69)–(7.72) are used. For both theories, Equations (7.67) and (7.68) are used to calculate the low frequency TL. Note that the TL values calculated using the Davy analysis and Sharp analysis deviate from one another around the panel critical frequency. Experimental data agree better with the Sharp analysis around the panel critical frequency whereas the Davy analysis agrees better with experimental data at low frequencies. For both Sharp and Davy analyses, ENC extends the frequency range of the calculations below the first panel resonance frequency (first quantity output in the yellow box shown three pages back) in line with the analysis on page 426 in the 6th edition textbook. The ISO12354-1 model option is described on page 383 of the 5th edition textbook and gives results almost identical to the Sharp method.

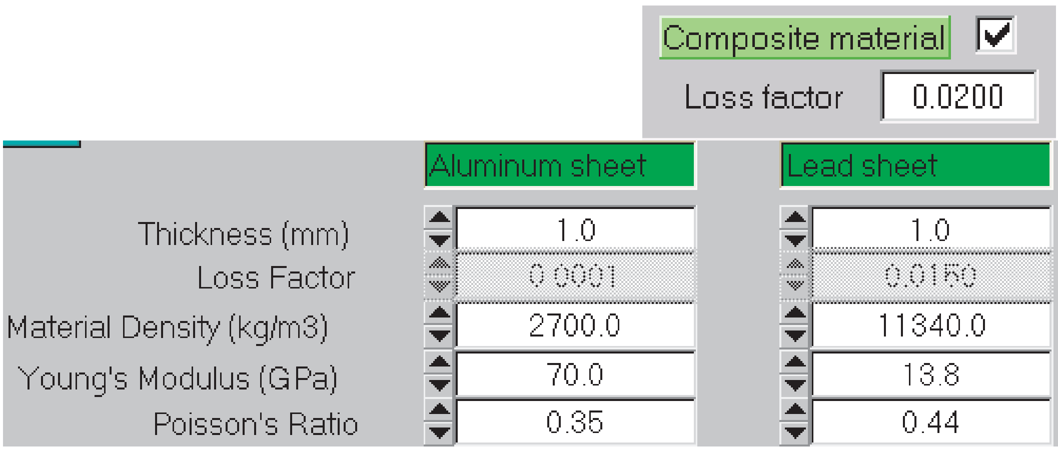
ENC also incorporates the TL limit due to the panel thickness as explained on page 428 in the 6th edition textbook.

5.2.2 Multi-leaf walls

This configuration consists of single walls that are made up of single panels either nailed or glued together or held together with viscoelastic material such as silastic. These walls have the same weight as a wall made up of a single panel equal to the combined thicknesses of the individual panels. However, the critical frequency for the multi-leaf wall, with flexibly connected leaves of identical material, is equal to that of the thickest leaf, so the TL behaviour of the two wall types is very different. The connection type can either be "flexible", "visco-elastic" or "rigid". If "flexible" (ie connected by a grid of glue spots or even nailed), the loss factor is doubled over that of a single panel. If "visco-elastic", the loss factor is set equal to 0.2. The word "rigid" used here refers to panels bonded so tightly together that they behave as a single panel. In this case, ENC automatically uses the total thickness and mass of the panel rather than the thickness of the thickest leaf, in the calculations of critical frequency and TL.

For the other two connection types (flexible and visco-elastic), the data specified in the data box apply only to the thickest leaf and the critical frequency calculation is based on these data. Note that this part of ENC can only calculate the TL for constructions for which the leaves are made of identical material, but the leaves do not have to have the same thickness and the number of leaves is unlimited.

5.2.3 Composite material wall



If it is desired to calculate the TL of a panel made up of two leaves of different material and if the materials are rigidly connected, then it is necessary to use the “composite material” box shown at right, which produces results based on Equations (7.7), (7.8), and (7.9) in the 6th edition textbook.

Clicking on this tick box will automatically bring up the two layer titles above the data box as shown on the figure on the previous page. Note that the “loss factor” line in the two column table is greyed out because you need to enter the value for loss factor of the composite construction in a second box as shown on the previous page.

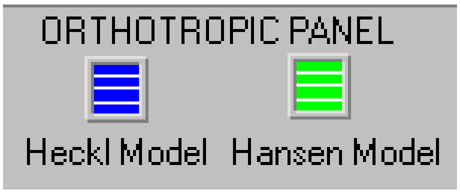
Right clicking on the green box at the top of either column will produce a pop up panel to allow you to select the material properties for each layer as shown on the previous page. You can modify any material properties and you can also add a new material for either layer 1 or layer 2 by following the procedure described on the previous page and making sure that the “composite material” box is ticked. However, don’t forget to save these new materials to the list before exiting this window by clicking on “file”, “save as”. Then you will be able to use these data later.

Note that an estimate of the loss factor for the composite construction must be entered.

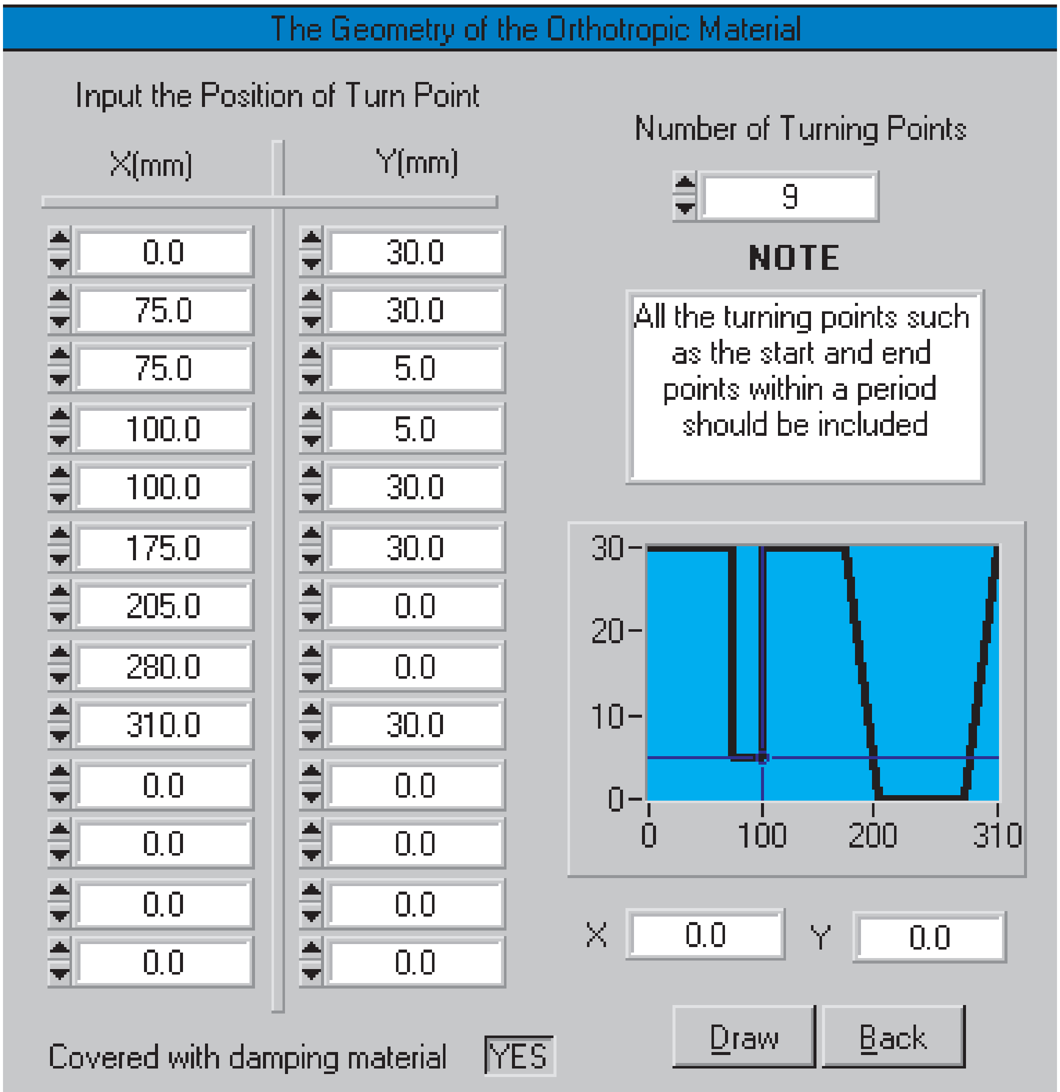
It is possible to have composite and multi-leaf options selected simultaneously. When this is done, it means that each leaf in the multi-leaf construction is made up of two layers, each of a different material bonded rigidly together.

You can add new materials to the layer 1 and layer 2 lists by clicking on the “Ins material/config” button and then in that window clicking on the “composite material” tick box and entering the data as for a single leaf panel. The new material name will appear in the “select material / config” window.

5.2.4 Orthotropic Panels



For the orthotropic panel, you can choose between the Heckl model (Equations (7.3), 7.5, 7.9–7.12, 7.78–7.80 and the explanation following them) and the Hansen model (Equations (7.3), (7.5), (7.9)–(7.12) and (7.47)–(7.60)). You can specify any panel cross sectional profile by clicking on the green "more properties" button to produce the screen shown in the following figure.

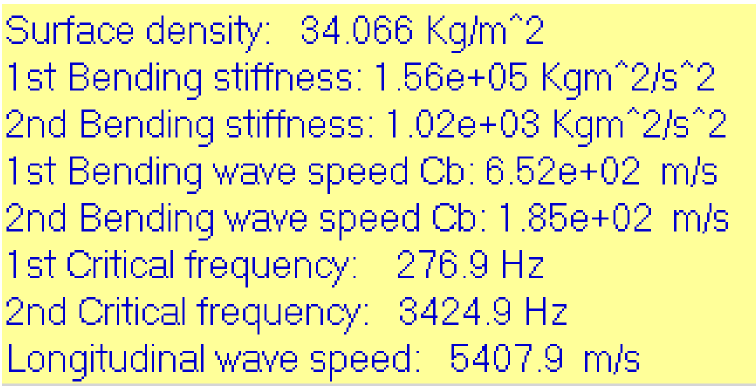


Basically the idea is to define x and y coordinates of each bend point (up to a maximum of 13) in the panel until they start to repeat again. Note that both start and end points of the repeating cycle need to be defined. For curved sections, you can define several points on the curve and that will be a good enough approximation for the purposes of the TL calculation. The y-coordinate is normal to the panel surface and the x-coordinate is in the plane of the panel normal to the corrugations. After you have defined a panel profile, click on the "draw" button to see it drawn in the small window. You need to specify whether or not the panel is covered with damping material by clicking on the appropriate button. When you have finished specifying the panel profile, click on the “back” button to return to the TL calculation. The TL is plotted out on the graph and octave band values are given in the table beneath the graph. The data points on the graph are at 1/3-octave band intervals with additional points plotted at locations where the graph has a sudden change in slope.

Note that multi-leaf, orthotropic panels are not considered here. However, it is possible to use ENC to calculate the TL of a composite orthotropic panel made up of two leaves of different material bonded rigidly together. Although the calculations are based on Equations (7.7), (7.8), and (7.9) in the 6^{th} edition textbook, some additional manipulations are necessary in order to be able to use these equations for an orthotropic panel. To derive the necessary relationships, Equation (7.7) is used to calculate the quantity, B_{eff} which is then substituted for B in Equation (7.2) and an equivalent Young’s modulus is thus obtained. This equivalent Young’s modulus is then used in Equations (7.10) and (7.12) in the 6^{th} edition textbook to calculate the maximum and minimum bending stiffness values for the orthotropic panel. Again an estimate of the loss factor for the composite construction must be entered.

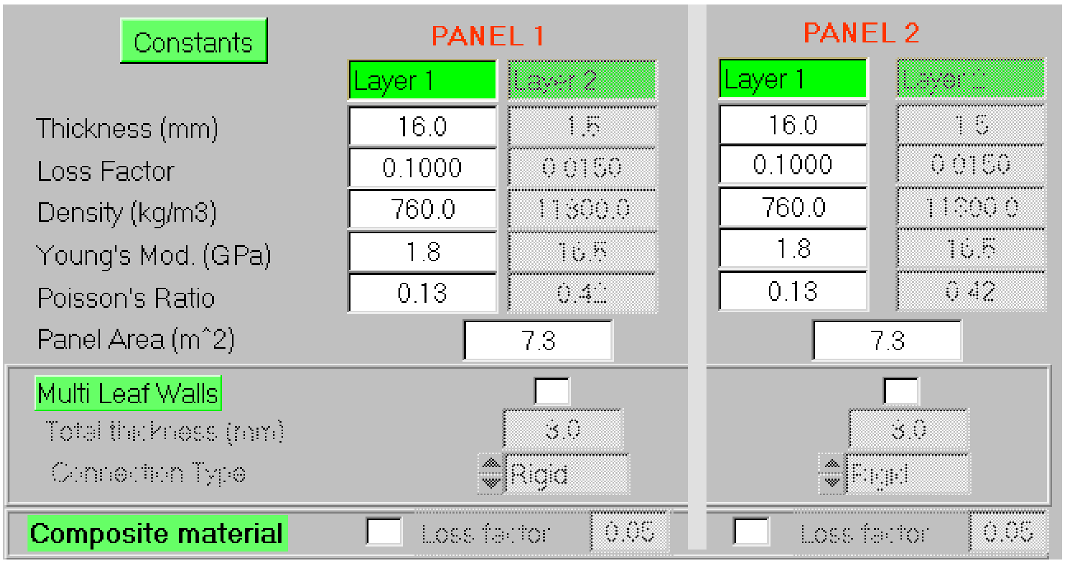
The calculation of the orthotropic panel resonance frequency, which is displayed in the intermediate results panel, Equation (7.47) in the 6^{th} edition textbook is used with the correction that the last term in brackets has a “2” in the numerator, which is missing in the 6^{th} edition textbook.

A number of intermediate calculation results are also provided as shown below.

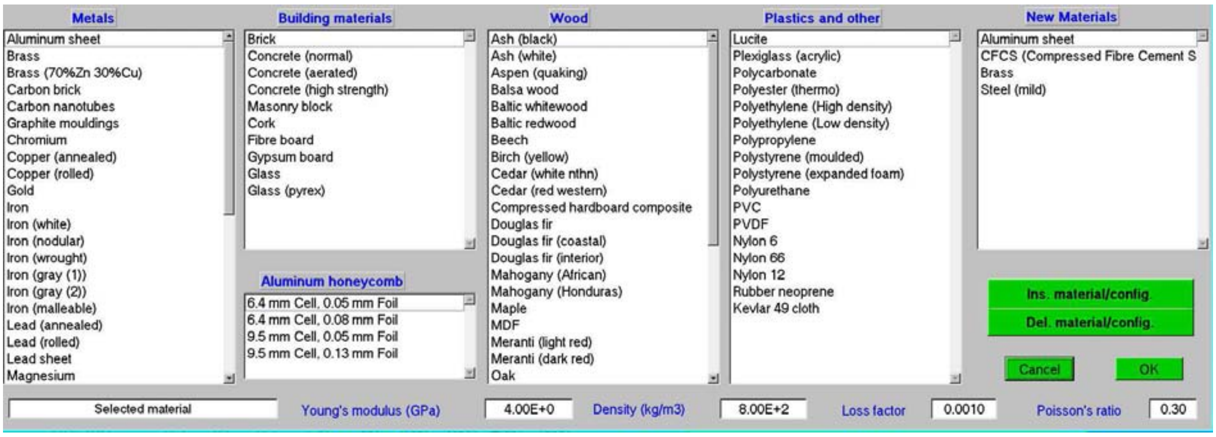


5.3 Double Wall (6th edition textbook, pages 429–441)

For the double wall, the properties of each panel and the way the two panels are connected together need to be specified. Also you have a choice of using the Sharp, Davy or ISO12354-1 models for the TL calculations. If the Davy model is chosen, the wall length and breadth must be entered as well. For the Sharp method, the procedure in the caption of Figure 7.11, p433 of the 6^{th} edition textbook is used. For the Davy method, Equations (7.88)–(7.104) are used. For the ISO12354 model, the procedure on pages 438–439 of the 6th edition textbook is used. However, for this model only Rw values that represent the increase over a single wall TL are provided. No octave or 1/3-octave values are obtained using this latter method for a double wall.

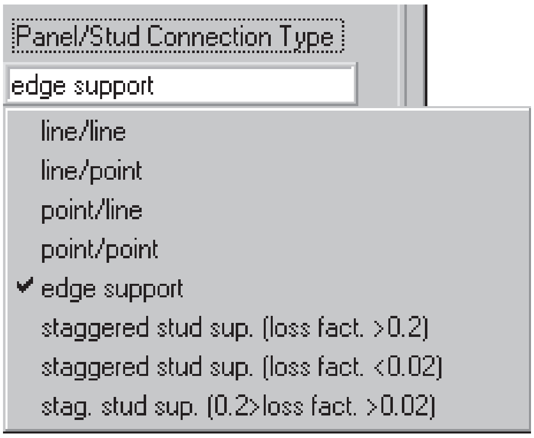


For the Sharp and Davy models, both single and multi-leaf panels are allowed. Each panel making up the double panel may be a composite panel with each composite panel made up of two different materials bonded rigidly together as for the single partition case. The panel material/configuration can be selected by right clicking (or double left clicking) on "layer 1" (and/or layer 2 if "composite material" is selected) and then selecting the desired material from the list (see following figure).

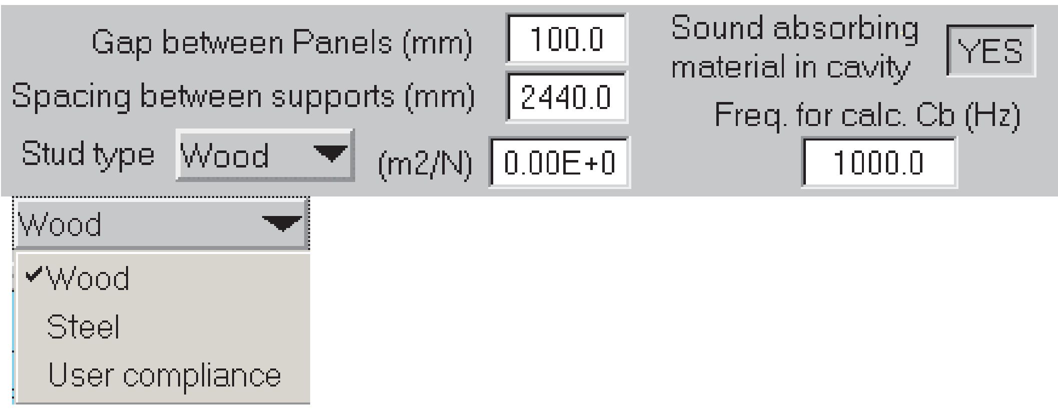


If the desired material is not there, then you can enter your own material by directly editing the data table containing the properties of a material in the list or by adding a new material to the pop-up list.

After selecting the material, you may choose the Davy method or the Sharp method to calculate the TL for the double wall. Note that for the calculations here using Davy's method, the 1.8 empirical correction factor mentioned in the equation for f_0 on page 431 of the 6th edition textbook has been replaced with the procedure outlined on page 435. Prior to doing the calculation, you must select the type of connection between the panels by clicking on the "Panel/stud connection type" box at the top right of the screen (see image on the next page). A pop-up menu will appear if you click inside the box rather than on the arrows to the left of the box. See the following figure on the right of the page for the choices corresponding to selection of the Sharp model. There are different choices when the Davy model is selected.



Other data must be entered as shown on the following figure. These data include gap between the two partitions (panel separation distance) making up the wall, the stud spacing (distance between supports), whether the studs are wood or steel or something for which you know the compliance (enter compliance if known). For steel studs the compliance used by ENC is 10^{-6}m^2/N and for wood it is 0. Note that the stud type is only needed if the Davy model is selected for the calculations.



Next, enter whether or not there is sound absorbing material in the cavity between the two partitions. Note that acceptable sound absorbing material consists of rockwool or fibreglass flexible batts, the thickness of which is at least 50% of the gap width between the panels. It is also assumed that the sound absorbing material is only in contact with one of the two partitions making up the double wall.

If there is no sound absorbing material in the cavity wall the TL is calculated as follows.

1. For $f \leq \pi f_\ell$ for all cases of πf_ℓ,
   $\mathrm{TL}(f) = \mathrm{TL_A} + 20\log_{10}(f/f_0)$

2. For $\pi f_\ell \leq 0.5 f_{c1}$ and $\pi f_\ell < f < 0.5 f_{c1}$,
   $\mathrm{TL}(f) = \mathrm{TL_A} + 20\log_{10}(\pi f_\ell/f_0) + 40\log_{10}(f/(\pi f_\ell))$

3. For $\pi f_\ell \leq 0.5 f_{c1}$ and $0.5 f_{c1} < f \leq f_{c2}$,
   $$\mathrm{TL}(f) = \mathrm{TL_B} - (\mathrm{TL_B} - \mathrm{TL_C}) \times \frac{(10\log_{10} f - 10\log_{10}(0.5 f_{c1}))}{(10\log_{10} f_{c2} - 10\log_{10}(0.5 f_{c1}))}$$

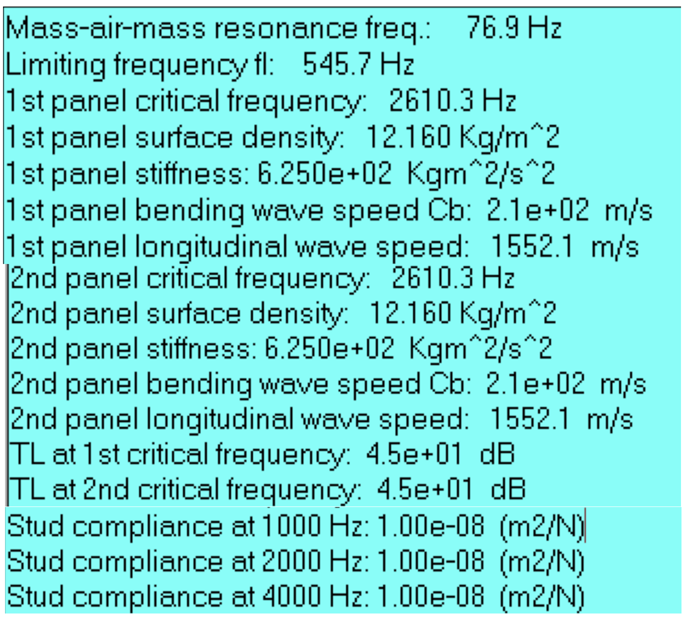
4. For $0.5 f_{c1} < \pi f_\ell \leq f_{c2}$ and $\pi f_\ell \leq f \leq f_{c2}$,
   $\mathrm{TL}(f) = \mathrm{TL_A} + 20\log_{10}(f/f_0)$
   $\mathrm{TL_B} = \mathrm{TL_A} + 20\log_{10}(0.5 f_{c1}/f_0)$
   $\mathrm{TL_C}$ is calculated as before using the new $\mathrm{TL_B}$

5. For $\pi f_\ell > f_{c2}$ and $f > f_{c2}$,
   $\mathrm{TL}(f) = \mathrm{TL_C} + 50\log_{10}(f/f_{c2})$
   $\mathrm{TL_B} = \mathrm{TL_A} + 20\log_{10}(0.5 f_{c1}/f_0)$
   $\mathrm{TL_C}$ is calculated as before using the new $\mathrm{TL_B}$

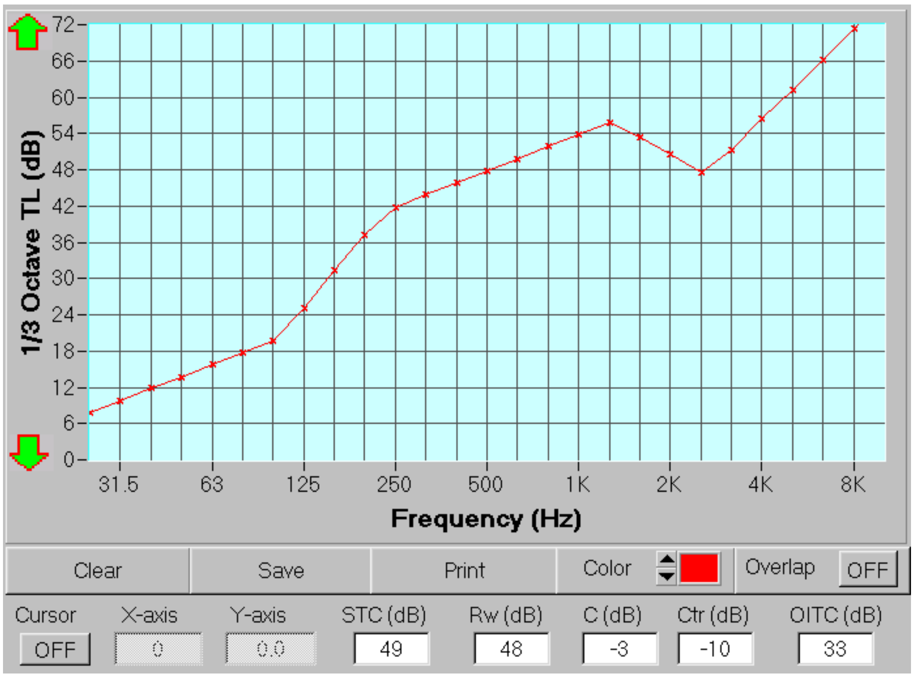
Click on “Constants” to set the speed of sound in air to be used in the calculations.

When you are ready for the TL calculation to proceed, click on “run” in the tool bar at the top of the window. The critical frequencies of each panel, the bending wave speeds in each panel at the frequency you specified and the frequencies, f_0 (mass-air-mass resonance frequency), f_c and f_ℓ as well as a number of other useful parameters are given in the aqua box at the bottom of the screen shown in the figure below. Most important is the TL at the critical frequencies as these often are not represented adequately on the graphs which only plot the TL at 1/3-octave band centre frequencies. Data for the stud compliance are only provided when the Davy analysis is chosen.

In addition, data points for the Sharp analysis are plotted wherever the curve changes shape so that the curve appears continuous.



The TL is plotted out on the graph illustrated below and octave band values are given in the table beneath the graph. Curves can be superimposed on those for the single wall by clicking "overlap" to ON.

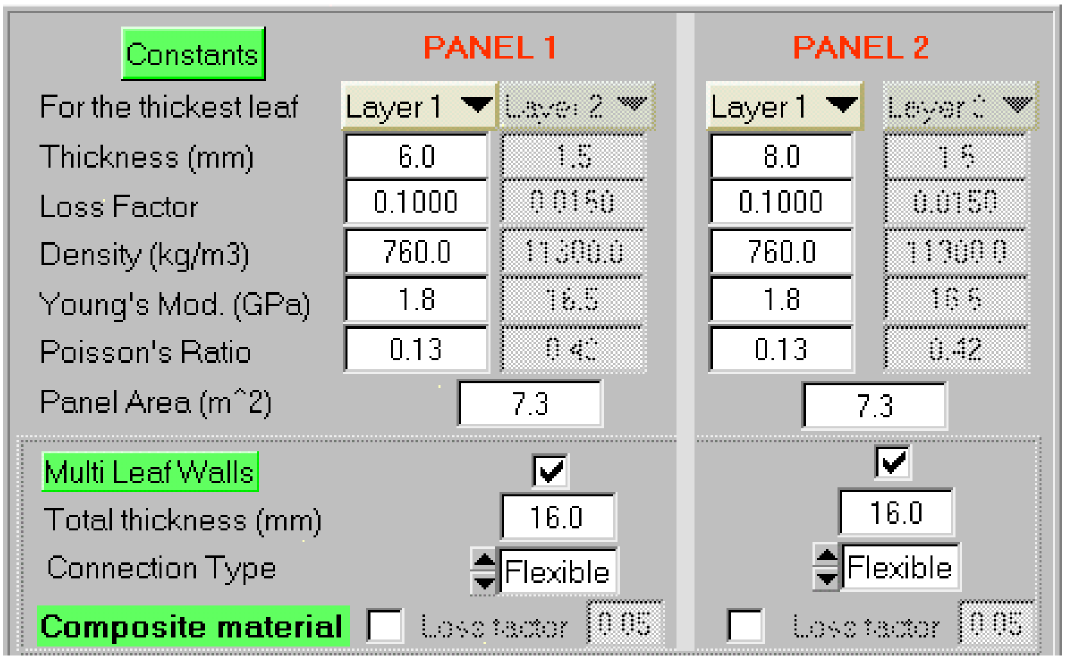


Octave Band Transmission Loss

Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
TL (dB)	9.4	15.4	23.1	40.0	47.5	53.5	49.9	54.5	69.5

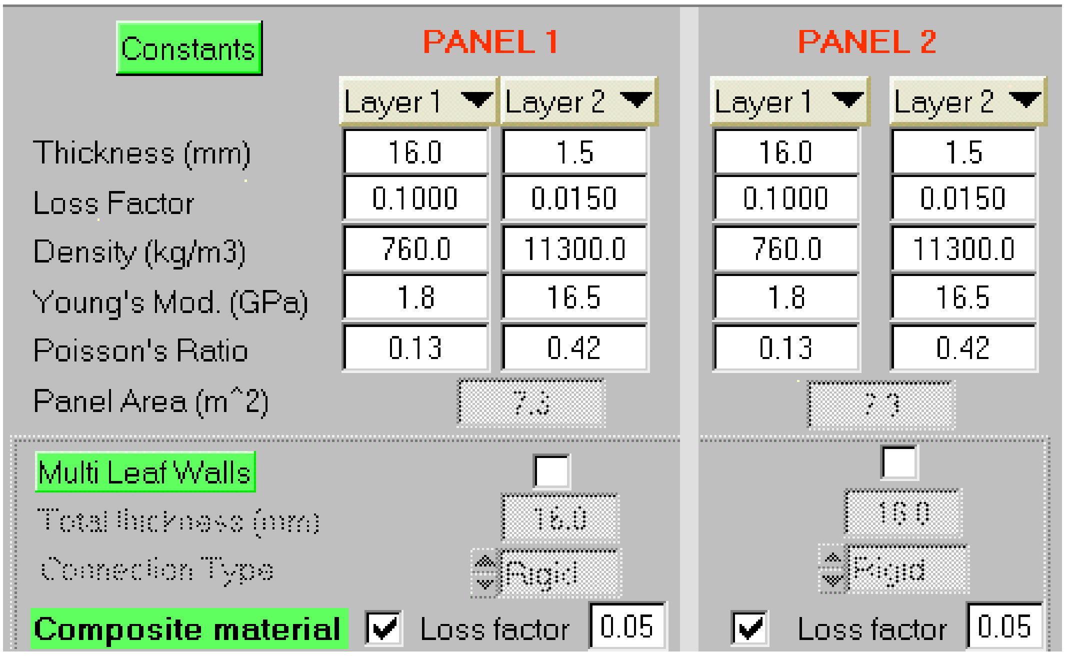
5.3.1 Multi-leaf Panels (6th edition textbook, page 440)

Note that multi-leaf panels are made up of leaves of the same material but not necessarily the same thickness. When the "multi-leaf wall" option is selected (see following figure), you must enter the total thickness of all the leaves making up one panel and then in the data boxes you need to enter the detailed data for the thickest leaf as this is used to calculate the critical frequency of the panel. As for the single partition, if the rigid connection option is selected, the panel is treated as a single leaf panel of thickness equal to the sum of the thicknesses of all the leaves.

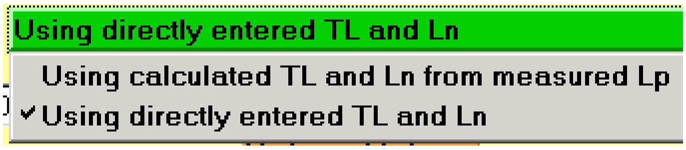


5.3.2 Composite Material (6th edition textbook, page 440)

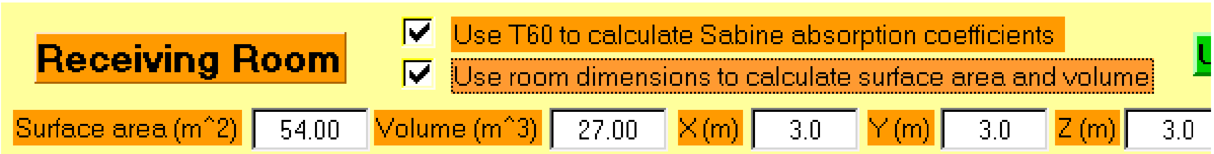
The "composite material" option (see figure below) allows for panels made up of a maximum of two leaves but the leaves may be of different materials and they must be bonded rigidly together. For this option the loss factor also needs to be selected. Note that if the multi-leaf panel is selected at the same time as the composite panel, then ENC will assume that each leaf in the multi-leaf panel is made up of two layers, each of a different material, bonded rigidly together and you will then need to enter the properties for each layer.



5.4 STC, R_w, IIC $L_{n,w}$ and $L_{nT,w}$ (6th edition textbook, pages 406–408, 413–414)



This window allows the calculation of STC, R_w, IIC $L_{n,w}$ and $L_{nT,w}$ using either directly entered TL or L_n data or from measurements of the sound pressure level in the receiving room and also in the source room (for STC and R_w). In the latter case the average absorption coefficient of the receiver room is also needed. This can be entered directly or reverberation times can be entered and ENC will calculate the corresponding absorption coefficient. Choices of input data are made by selecting from the menu shown at right and by clicking appropriate tick box as shown below. which applies only to the receiver room. In fact all of the brown data apply to the receiver room.



As shown in the figure above, it is also necessary to know the receiver room surface area and volume. This can be calculated by ENC from dimensions for a rectangular room or entered directly.

Once the choices are made, the receiver room data must be entered in the appropriate (brown colour)1/3-octave and/or octave band table as shown in the following figure. Note that L_p, the space averaged sound pressure level in the receiver room, must also be measured and entered in the table below if the “calculated TL and L_n” option is selected.

1/3 Octave Values

Fq. (Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1K	1250	1.6K	2K	2.5K	3150	4K	5K
A. coef.	0.04	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
T60 (s)	2.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Lp (dB)	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0	62.0	61.0	60.0	59.0	58.0	57.0	54.0	51.0	48.0	45.0	42.0	39.0	39.0

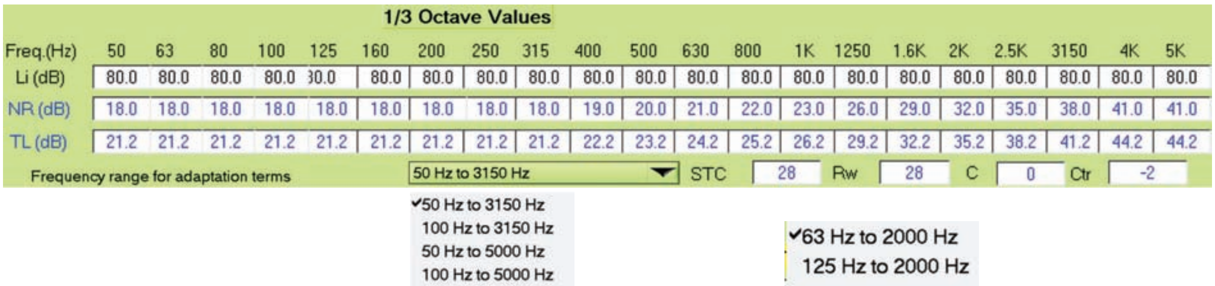
The row labelled “A. Coeff.” is the space averaged Sabine absorption coefficient for the receiver room.

Octave Values

63	125	250	500	1K	2K	4K
0.10	0.10	0.10	0.10	0.10	0.10	0.10
1.00	1.00	1.00	1.00	1.00	1.00	1.00
62.0	62.0	62.0	60.0	57.0	48.0	48.0

All of the above values apply to the receiver room and only need to be entered if the option, “Using calculated TL and Ln from measured Lp” is selected. Note that in order to calculate TL, it is also necessary to enter the test partition area in the box below the brown table (see 6th edition textbook, Equation (7.16)). This is not needed for the impact isolation case (see Equation (7.30)).

To calculate the **TL from measured data**, it is necessary to enter the space averaged sound pressure level, L_i, that is measured in the source room (first row in the green table in the following figures — the first one shown is for 1/3-octave band values and the next one is for octave band values) so that NR can be calculated. The NR is the difference between L_p (last row of the brown table) and L_i. The TL is then calculated using Equation (7.17) in the 6th edition textbook. The calculation of STC and R_w is done as described on pages 413–414 in the 6th edition textbook.

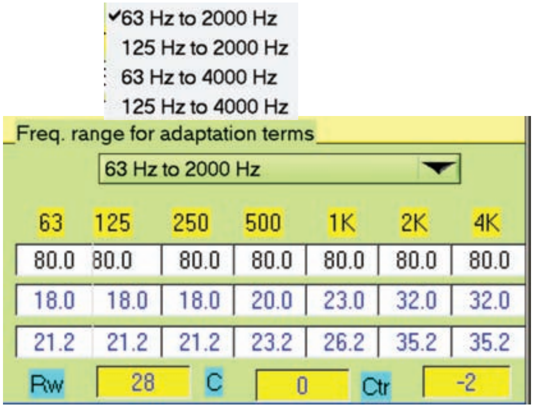


1/3 Octave Values

Freq.(Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1K	1250	1.6K	2K	2.5K	3150	4K	5K
Li (dB)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
NR (dB)	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	19.0	20.0	21.0	22.0	23.0	26.0	29.0	32.0	35.0	38.0	41.0	41.0
TL (dB)	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	22.2	23.2	24.2	25.2	26.2	29.2	32.2	35.2	38.2	41.2	44.2	44.2

Frequency range for adaptation terms: 50 Hz to 3150 Hz; STC 28; Rw 28; C 0; Ctr -2

✓50 Hz to 3150 Hz
100 Hz to 3150 Hz
50 Hz to 5000 Hz
100 Hz to 5000 Hz



✓63 Hz to 2000 Hz
125 Hz to 2000 Hz
63 Hz to 4000 Hz
125 Hz to 4000 Hz

Freq. range for adaptation terms: 63 Hz to 2000 Hz

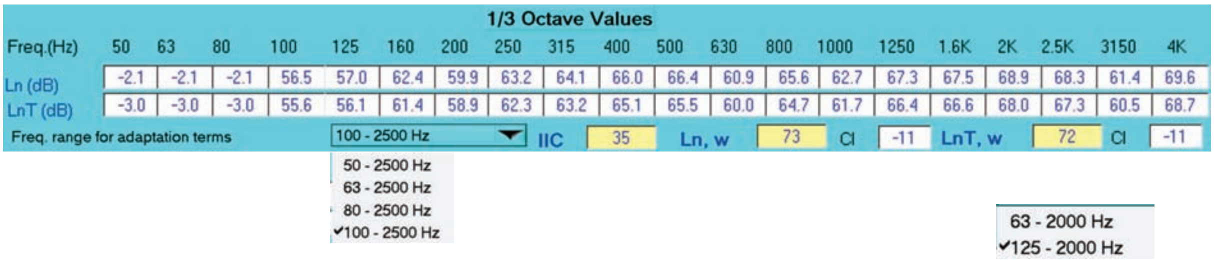
63	125	250	500	1K	2K	4K
80.0	80.0	80.0	80.0	80.0	80.0	80.0
18.0	18.0	18.0	20.0	23.0	32.0	32.0
21.2	21.2	21.2	23.2	26.2	35.2	35.2

Rw 28; C 0; Ctr -2

If the "Using directly entered TL and Ln" option is chosen at the top of the window, then you only need to enter the TL values in the table above in order to determine the corresponding STC and R_w values. The STC values are the USA standard and they are similar to the R_w values which are calculated according to the ISO standard. The main difference between STC and R_w is that the first criterion on page 407 in the 6th edition textbook does not apply to the ISO calculation. Another difference is the frequency range of the data used to calculate IIC is from 125 Hz to 4000 Hz, whereas that for calculating R_w is from 100 Hz to 3150 Hz. A third difference is that R_w is qualified by two correction numbers, C and C_{tr} that depend on the characteristics of the noise. However, the values of these correction terms also depend on the frequency range for which measured data are available, which is why ENC gives users a choice between 4 frequency ranges (see above figure). However, the R_w value is the same for all frequency ranges and is based on 1/3 octave band data for the frequency bands 100 Hz to 3150Hz inclusive and octave band data from 125 Hz to 2000 Hz inclusive.

Note that only the ISO standard allows octave band calculations which is why STC is not listed for octave bands.

To determine **Impact Insulation Class (IIC) the Weighted normalised impact sound pressure level ($L_{n,w}$) or the Weighted standardised impact sound pressure level ($L_{n,T}$)**, you can either used the measured L_p and absorption coefficient values in the receiver room and enter the values in the same brown table as for the TL calculations or you can enter the L_n values directly into the table, which is illustrated in the following figure for 1/3-octave bands and the figure after that for octave bands. Remember to select the option you want at the top of the window. The ISO equivalent to IIC is referred to as $L_{n,w}$ (see ages 364 and 365 in the 6th edition textbook). There is also a descriptor mentioned in the ISO standard, which is based on the measurement of reverberation time in the receiving room, which is called, $L_{nT,w}$ and ENC calculates this as well.

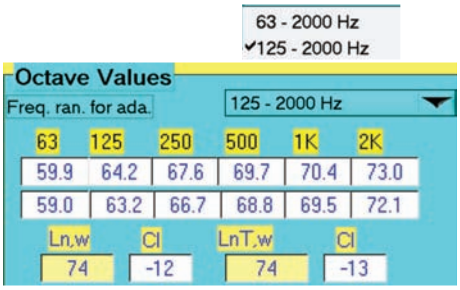


1/3 Octave Values

Freq.(Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1.6K	2K	2.5K	3150	4K
Ln (dB)	-2.1	-2.1	-2.1	56.5	57.0	62.4	59.9	63.2	64.1	66.0	66.4	60.9	65.6	62.7	67.3	67.5	68.9	68.3	61.4	69.6
LnT (dB)	-3.0	-3.0	-3.0	55.6	56.1	61.4	58.9	62.3	63.2	65.1	65.5	60.0	64.7	61.7	66.4	66.6	68.0	67.3	60.5	68.7

Freq. range for adaptation terms: 100 - 2500 Hz | IIC 35 | Ln, w 73 | CI -11 | LnT, w 72 | CI -11

50 - 2500 Hz
63 - 2500 Hz
80 - 2500 Hz
✓100 - 2500 Hz



63 - 2000 Hz
✓125 - 2000 Hz

Octave Values

Freq. ran. for ada. 125 - 2000 Hz

63	125	250	500	1K	2K
59.9	64.2	67.6	69.7	70.4	73.0
59.0	63.2	66.7	68.8	69.5	72.1

Ln,w	CI	LnT,w	CI
74	-12	74	-13

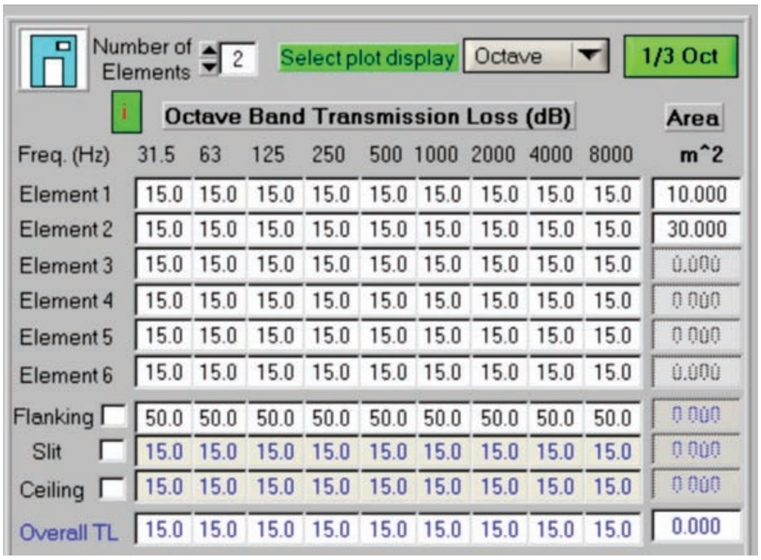
Note that only ISO allows use of octave band data to calculate the single number descriptor so no IIC value appears under the octave band table. The main difference between IIC and $L_{n,w}$ is that the second criterion on page 413 in the 6th edition textbook does not apply to the ISO calculation.

When the "Using calculated TL and Ln from measured Lp" option is selected at the top of the page, in addition to the measured Lp, it is also necessary to input the measured receiver room absorption coefficient (in the brown table) to calculate $L_{n,w}$ and the receiver room reverberation time (in the brown table) to calculate $L_{nT,w}$.

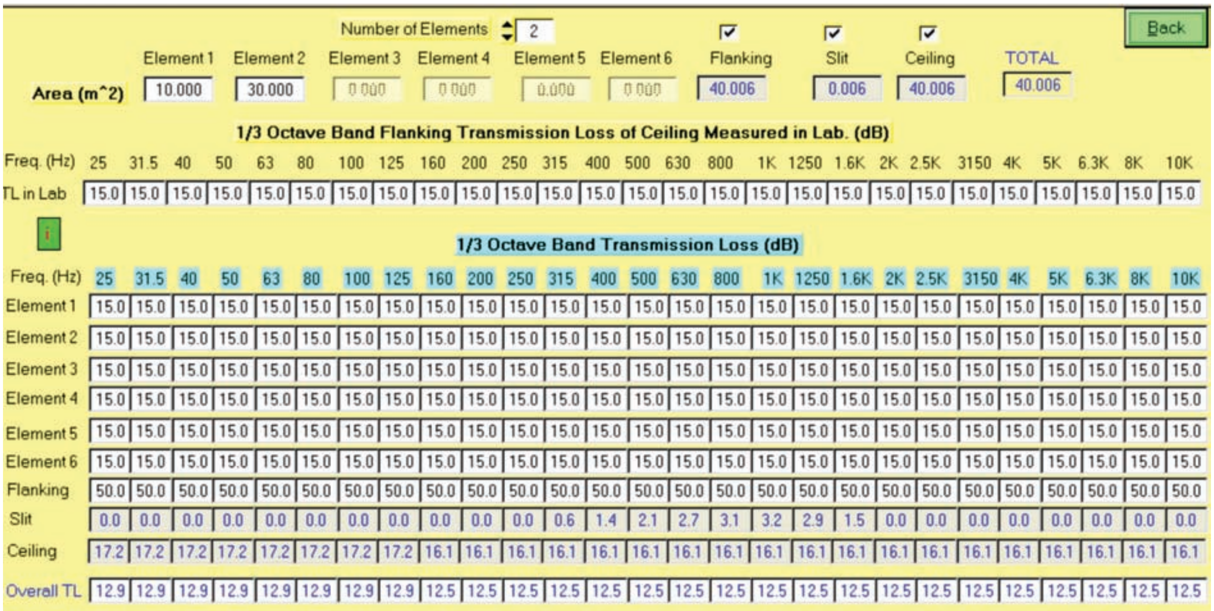
Note that according to the relevant standards, all single number descriptors are reported as values rounded to the nearest integer.

For the ISO descriptors, a spectral adjustment term C_I (see ISO 717-2:1996), can also be calculated according to the standard, using 4 different frequency ranges of measured data for the 1/3-octave band correction and 2 different frequency ranges of measured data for the octave band correction. The frequency ranges for the 1/3 and octave band adjustment terms (not for $L_{n,w}$ or $L_{nT,w}$) are selected from the drop down menus shown in the above figures. This spectral adjustment term is introduced to account for the additional annoyance due to walking on uncovered or insufficiently covered wood or concrete floors and ranges in value from -15 dB to 0 dB. It is to be added arithmetically to the $L_{n,w}$ or $L_{nT,w}$ rating. ENC does not do this addition but provides both values. This correction term is not discussed in the 6th edition textbook.

5.5 Composite / Flanking (6th edition textbook, pages 440, 450–451)



The purpose of this calculation is to determine the overall TL of a partition made up of several segments, all with different TLs (eg a wall with a window and door), using Equation (7.115) in the 6th edition textbook. The first thing to do is enter the number of elements with different values of TL that you wish to combine to obtain an overall TL (see the figure at right). Next you should select whether you want to present octave band or 1/3 octave band data on the graph (see the figure at right). If you wish to work with 1/3 octave band values in the table, you must click on the "1/3-octave" button shown in the following figure and the 1/3-octave band window shown in the figure below appears.

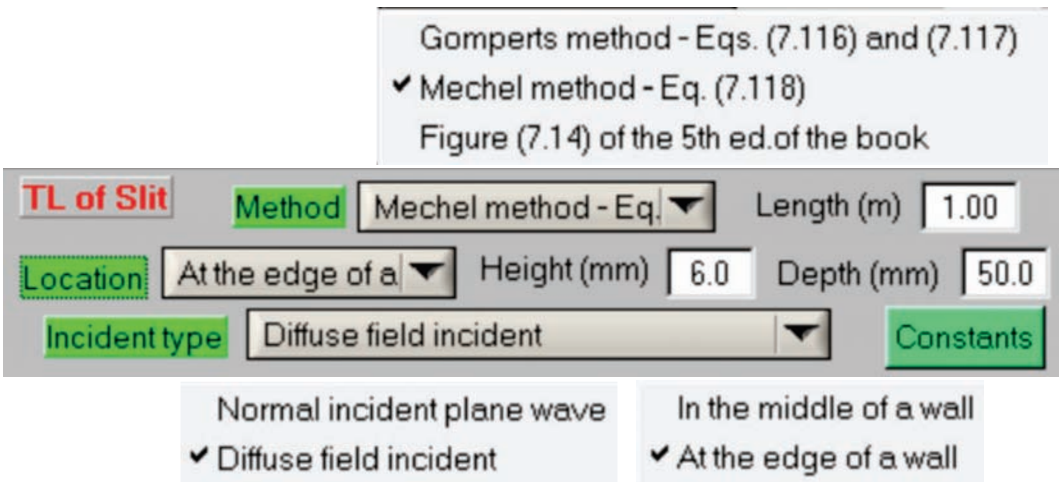


Next the TL values (for "element 1, element 2", etc in octave or 1/3-octave bands) for each segment making up the partition (eg windows, wall, door) are input into the table. The tables for octave bands and 1/3-octave bands are shown in the preceding two figures, respectively.

The area of each segment is also input in the right hand column in the octave band table and into a separate table for the 1/3-octave band calculations (illustrated in the preceding figure).

The last 3 lines above the total line in both the octave and 1/3-octave tables include three forms of flanking and care must be taken by the user not to double count as it is possible to tick all 3 boxes simultaneously and thus include all types of flanking simultaneously. All 3 rows of data except for the user defined flanking TL (labelled "flanking") are in blue text meaning they are calculated data and these calculations are undertaken in the two panels under the table containing the TL values for all the individual elements making up the table. The area associated with the user defined flanking is in blue text as it must be the same as the total area of the elements making up the partition (similarly for the ceiling flanking). Note that it is unlikely that you will need to tick both the ceiling flanking and the user defined flanking ("flanking") boxes but there may be some times when both boxes are ticked such as when there is flanking via a ceiling path as well as flanking via other paths. Note that the user defined flanking TL is that measured in the lab when the panel is replaced by a very high TL panel (see STC/IIC window in Module 4). This flanking TL may be calculated from the measured sound pressure levels in the rooms on either side of the panel using the "IIC & STC" window in module 4 of ENC.

The calculations for slit TL, and suspended ceiling flanking TL are done in the two panels immediately below the part illustrated in the preceding figure. The slit (or crack) TL data are associated with an area and are used with Equation (7.115) to calculate the overall TL of a wall or panel that includes the crack and/or slit. The area of the slit or crack is calculated by ENC based on the dimensions given in the relevant calculation panels. There are three different calculation procedures that appear in the literature for calculating the TL of a crack or slit. These are described on pages 456 and 457 in the 6th edition textbook. If the slit TL is included separately in the table in ENC, it is important that it is not also included in the user defined flanking TL. The flanking TL calculation for a slit requires you to choose which calculation method you wish to use and then to enter the slit location with respect to the wall edge, the type of incident sound field and the slit dimensions, as illustrated in the following figure.The slit TL depends on the wavenumber which, in turn, depends on the type of gas and temperature so there is a green "constants" button that may be clicked to set the gas type and temperature.

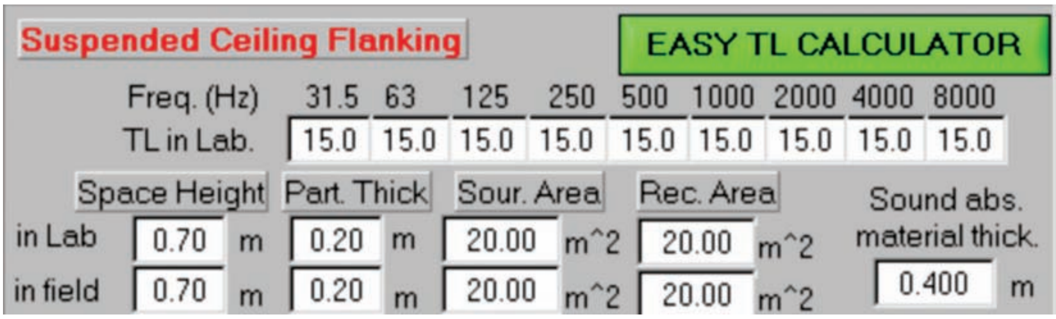


If the crack is at the edge of a wall (meaning that it is adjacent to another plane surface), the effective height of the gap is doubled when calculating the TL using the

Figure 7.15 (p. 456) method, and the transmission coefficient, τ, is doubled when using the Mechel method. For the Gomperts method, the coefficient, n in Equation (7.145) in the textbook is halved from 1 to 0.5 when the slit is at the edge of a plane surface (and adjacent to another plane surface). In all three methods, the actual slit height is used when calculating the slit area. Note that the slit TL values are automatically entered by ENC into the octave and 1/3-octave tables illustrated on the previous pages.

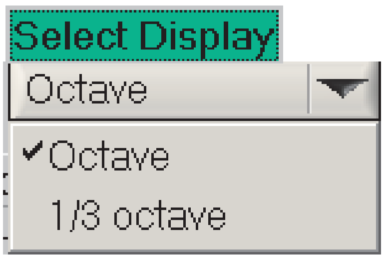
The type of incident sound field also affects the slit TL calculation for the Gomperts method only and the options are a normally incident plane wave or an incident diffuse field.

The second to bottom row in the table for both octave and 1/3-octave cases contains calculated flanking TL results for a suspended ceiling which are done in the panel below the slit panel (see illustration below).



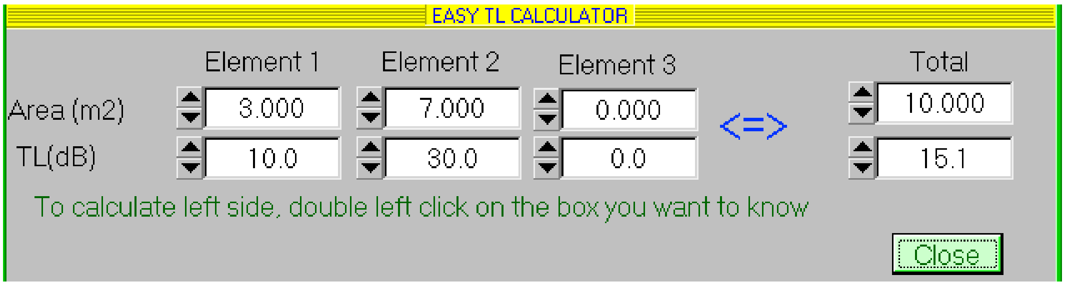
Flanking due to a suspended ceiling (row immediately above the overall TL row) is calculated by ENC in this window using Equations (7.118)–(7.121). The area normalisation is done by ENC in the panel at the bottom of this window so there is no area to be entered in the table for this row. This takes the laboratory measured flanking TL for a suspended ceiling and uses it to calculate the expected flanking TL in an actual installation. The input data needed to calculate the suspended ceiling flanking TL in the field includes the laboratory measured flanking TL, calculated using Equations (7.118)–(7.121) (with A being the area of the partition in the field over which the suspended ceiling is located, not necessarily the area used in the laboratory). In addition, the following quantities need to be entered for the laboratory test situation and the field situation: height of the space above the suspended ceiling (Space Height); thickness of the wall partition where it attaches to the suspended ceiling (Part. Thick); surface area of the source room (Sour. Area); surface area of the receiving room (Rec. Area); thickness of absorbing material above the suspended ceiling which must be the same for the test facility and the field installation (sound abs. material thick).

The overall TL in the bottom of the octave band and 1/3 octave band tables is plotted out on the graph on the left of the screen and you may select to plot octave or 1/3-octave band values on the graph by clicking on the box to the right of the green "select display" button at the top of the screen which will bring up the menu shown at right. Note that values for STC, R_w, C, C_{tr} and OITC are provided beneath the graph. All of these quantities are explained in the 6th edition textbook, pages 406–410.



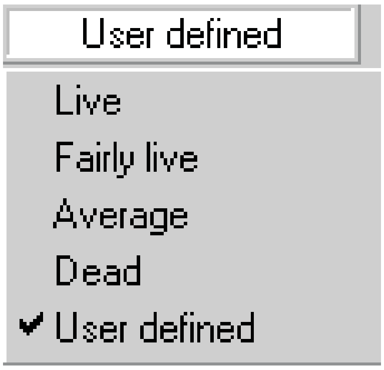
Note that the OITC button at the bottom of the graph is greyed out when the octave band plot is selected as it is only applicable to 1/3-octave band data.

Clicking on the green button labelled "EASY TL CALCULATOR" brings up the window shown below. This calculator enables you to calculate in both directions for a 2 or 3 element system (see below). That is, you can determine the required TL of a door, given the overall TL needed and the TL of the wall that is to contain the door. Using this calculator is a bit complicated, but worth mastering. First you enter the areas of each element in the top line. Then you enter the TLs that you know. If you know the total TL, but not one of its constituents, then to find the unknown TL, double left click on the box that is to contain it. If you want to calculate the total TL after filling 2 or 3 of the constituent boxes on the left, then just click on the right pointing arrow. The same operation can be done with the areas, but note that the TL calculation only updates when clicking on the right arrow. For calculations based on knowing the totals and wishing to find one of the constituents, the area and TL calculations must be done separately. It is not necessary to click on "run" in the tool bar to use this calculator.



5.6 Enclosures (6th edition textbook, pages 451–461)

This panel is used to calculate the expected noise reduction of an enclosure, given the TL of its walls and its internal acoustic conditions. The internal acoustic conditions can be specified in terms of absorption coefficients (entered in the table at the bottom of the window) or in a general sense by clicking on the "Enclosure internal acoustic conditions" box as shown in the figure at right.



The noise reduction of the enclosure is then calculated using Equation (7.135) in the 6th edition textbook, where the quantity, C, is based on the selected enclosure internal conditions (Table 7.8 in the 6th edition textbook) and listed as "Correction (dB)" in the table below.

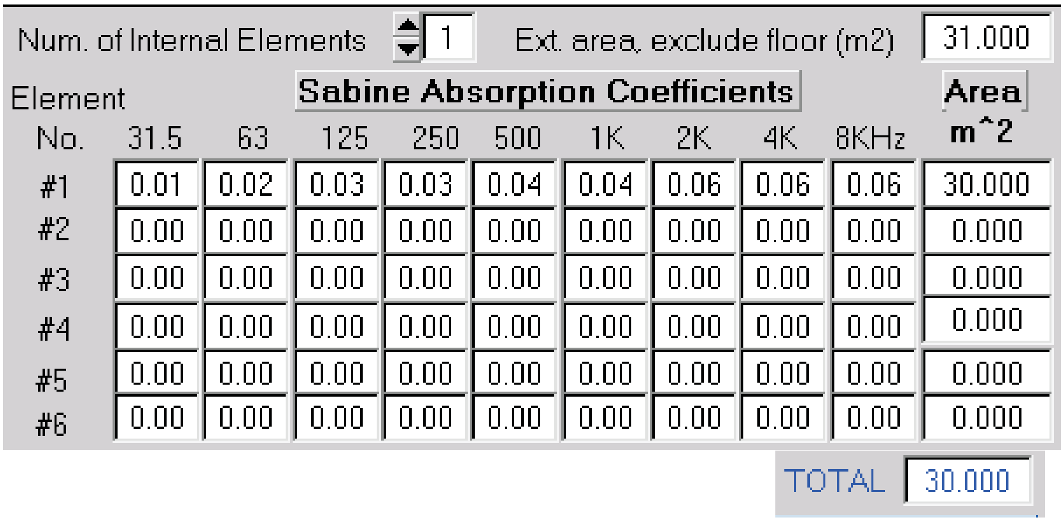
	31.5	63	125	250	500	1000	2000	4000	8000
Wall TL (dB)	30.0	35.0	39.0	42.0	43.0	45.0	46.0	47.0	47.0
Correction (dB)	15.0	13.0	11.0	9.0	7.0	5.0	4.0	3.0	3.0
NR (dB)	15.0	22.0	28.0	33.0	36.0	40.5	43.5	48.0	56.0

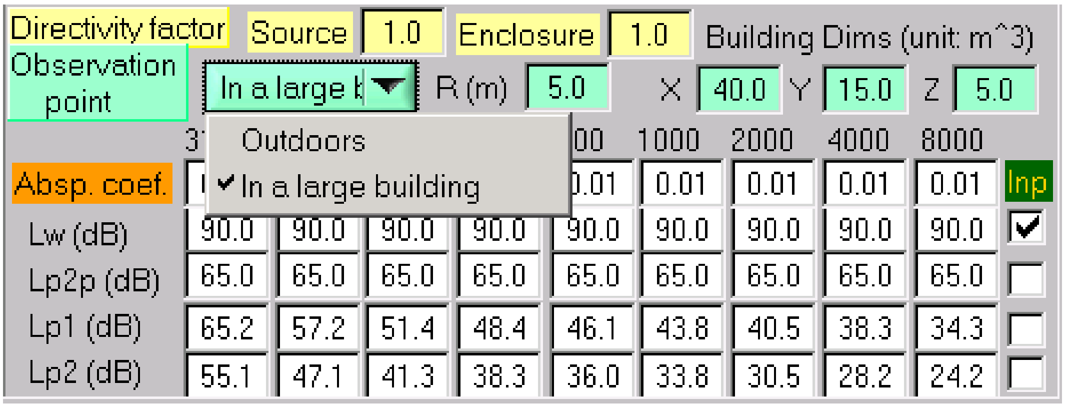
If the enclosure is lined with acoustically absorbing material, the TL of the enclosure wall will increase slightly at higher frequencies (see Table 7.7 in the 5th edition textbook which is linearly adjusted for different thickness blankets). For a medium density blanket, ENC will include this effect in the NR value in the table above. The user may enter any thickness desired for the blanket — 50 mm is shown as an example below.

The enclosure noise reduction calculation (Equation (7.135) in the 6th edition textbook) is performed by clicking on "run" in the tool bar and the result is displayed on the graph to the left of the screen.

When the internal enclosure conditions are "user defined", it is necessary for the user to enter the enclosure external surface area, "Ext. area, exclude floor (m2)", as well as absorption coefficients and corresponding surface areas (inside the enclosure) in the table at the bottom of the screen (see next page). The correction is then calculated using Equation (7.127) in the 6th edition textbook.

Note that the "number of internal elements" refers to the number of rows in the table (working from the top row downwards) that are to be included in the calculations.



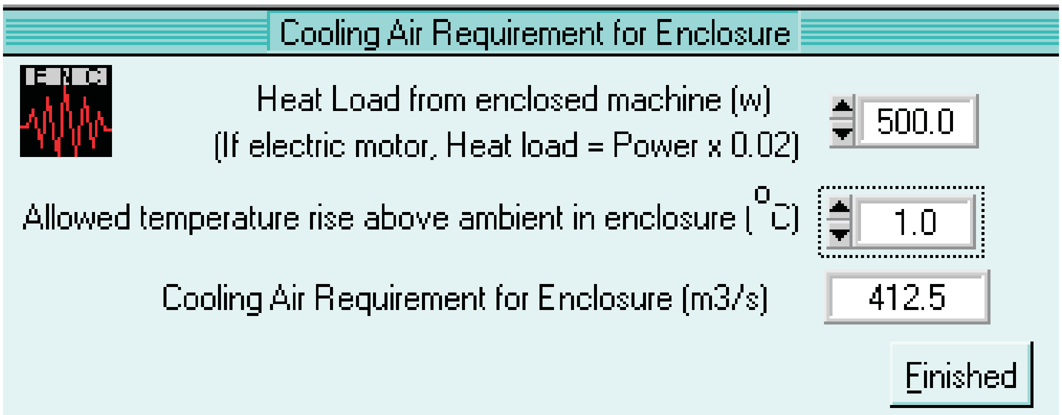


In addition to calculating the enclosure noise reduction, it is also possible to get sound pressure levels on the enclosure outer surface (Lp1) or at some distant point either in free space or in a large room (Lp2), as well as at the same location without the enclosure in place (Lp2p). You need to select from the menu, observation point = "outdoors" or observation point = "in a large building" (see below). If the latter is chosen, the building dimensions and the mean Sabine absorption coefficient must be entered. Note that none of these outdoor sound predictions include the excess attenuation effects. If the observation point is more than 50 m from the enclosure, then it is necessary to include the excess attenuation effects by using module 3 and calculating the enclosure radiated sound power using Equation (7.130) in the 6$^{\text{th}}$ edition textbook.

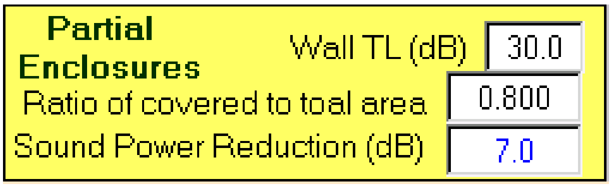
You can also apply a directivity factor (NOT directivity index) to the source inside the enclosure (to be used for calculations for the "no enclosure" case) or a directivity factor may be applied to the enclosure sound radiation itself. You also need to enter the distance, R(m) of the observer from the enclosure surface or from the source for the case with no enclosure. As an input to the calculation, you must input, for each octave band, one of the following (chosen by clicking on the corresponding tick box): Source sound power level (Lw); Sound pressure level at the receiver location with no enclosure (Lp2p); Sound pressure level at the receiver location with the enclosure in place (Lp2); Sound pressure level immediately outside the enclosure (Lp1)

5.6.1 Cooling Air Requirements

Cooling air requirements for enclosures containing heat generating equipment such as electric motors can be determined by clicking on the bright blue button at the bottom of the window, labelled "Cooling air requirement". This brings up the window shown below, which evaluates Equation (7.148).



5.6.2 Partial Enclosures



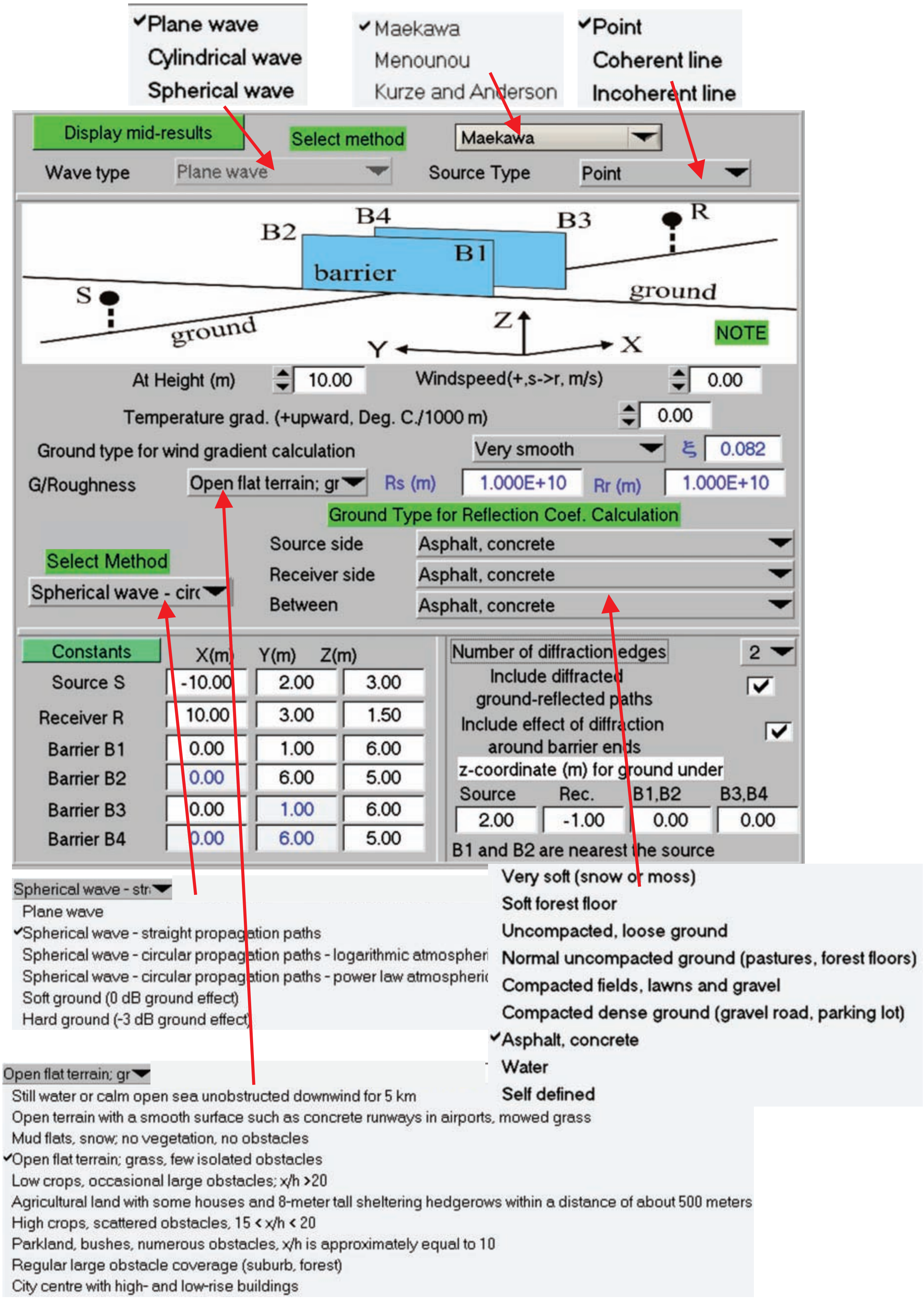
When a sound source is only partially enclosed, it is possible to calculate the overall sound power reduction of the enclosure for a specified wall TL. This is not the sound pressure level reduction as this will vary, depending on the orientation of the observer to the enclosure opening(s). To calculate the sound power reduction, you need to enter the wall TL and the ratio of covered to open area area as shown in the figure at right.

5.7 Outdoor Barriers (6th edition textbook, pages 293–312)

The barrier calculations described in this section are the same as in the ENC 6th version page of Module 3 and they work well for sloping ground as well as flat ground. The ground may have different slopes on either side of the barrier. The ground beneath the two diffraction edges may also be different so that the ground slopes in between the two barriers. It is assumed that the slopes between the source and barrier, between the two barriers and between the receiver and barrier are all straight lines, defined by the ground coordinates below the source, barriers and receiver.

The calculations in ENC version 6.1 onwards are based on the 6th edition textbook, where detailed descriptions of the analysis are provided. Updates in this edition of the textbook allow for sloping ground and include a detailed analysis of double diffraction barriers.

For all calculation methods, if the "Include diffraction around barrier ends" tick box is NOT ticked (effectively an infinitely long barrier), only the three paths over the top of the barrier are used to calculate the overall barrier attenuation.


Plane wave
Cylindrical wave
Spherical wave
Maekawa
Menounou
Kurze and Anderson
Point
Coherent line
Incoherent line
Display mid-results
Select method
Maekawa
Wave type
Plane wave
Source Type
Point
B2
B4
B3
R
B1
barrier
S
ground
ground
Z
Y
X
NOTE
At Height (m)
10.00
Windspeed(+,s->r, m/s)
0.00
Temperature grad. (+upward, Deg. C./1000 m)
0.00
Ground type for wind gradient calculation
Very smooth
0.082
G/Roughness
Open flat terrain; gr
Rs (m)
1.000E+10
Rr (m)
1.000E+10
Ground Type for Reflection Coef. Calculation
Select Method
Spherical wave - circ
Source side
Asphalt, concrete
Receiver side
Asphalt, concrete
Between
Asphalt, concrete
Constants
X(m)
Y(m)
Z(m)
Source S
-10.00
2.00
3.00
Receiver R
10.00
3.00
1.50
Barrier B1
0.00
1.00
6.00
Barrier B2
0.00
6.00
5.00
Barrier B3
0.00
1.00
6.00
Barrier B4
0.00
6.00
5.00
Number of diffraction edges
2
Include diffracted ground-reflected paths
Include effect of diffraction around barrier ends
z-coordinate (m) for ground under
Source
Rec.
B1,B2
B3,B4
2.00
-1.00
0.00
0.00
B1 and B2 are nearest the source
Spherical wave - str
Plane wave
Spherical wave - straight propagation paths
Spherical wave - circular propagation paths - logarithmic atmospher
Spherical wave - circular propagation paths - power law atmospheric
Soft ground (0 dB ground effect)
Hard ground (-3 dB ground effect)
Very soft (snow or moss)
Soft forest floor
Uncompacted, loose ground
Normal uncompacted ground (pastures, forest floors)
Compacted fields, lawns and gravel
Compacted dense ground (gravel road, parking lot)
Asphalt, concrete
Water
Self defined
Open flat terrain; gr
Still water or calm open sea unobstructed downwind for 5 km
Open terrain with a smooth surface such as concrete runways in airports, mowed grass
Mud flats, snow; no vegetation, no obstacles
Open flat terrain; grass, few isolated obstacles
Low crops, occasional large obstacles; x/h >20
Agricultural land with some houses and 8-meter tall sheltering hedgerows within a distance of about 500 meters
High crops, scattered obstacles, 15 < x/h < 20
Parkland, bushes, numerous obstacles, x/h is approximately equal to 10
Regular large obstacle coverage (suburb, forest)
City centre with high- and low-rise buildings

The source that is to be affected by the barrier must have a negative values for its x-coordinate and the receiver must have a positive value for its x-coordinates. Thus, when a barrier is present, the coordinate origin should be on the ground at the base of the barrier (or if two diffraction edges are present, then on the ground at the diffraction edge closest to the source). The y-location of the origin is not important.

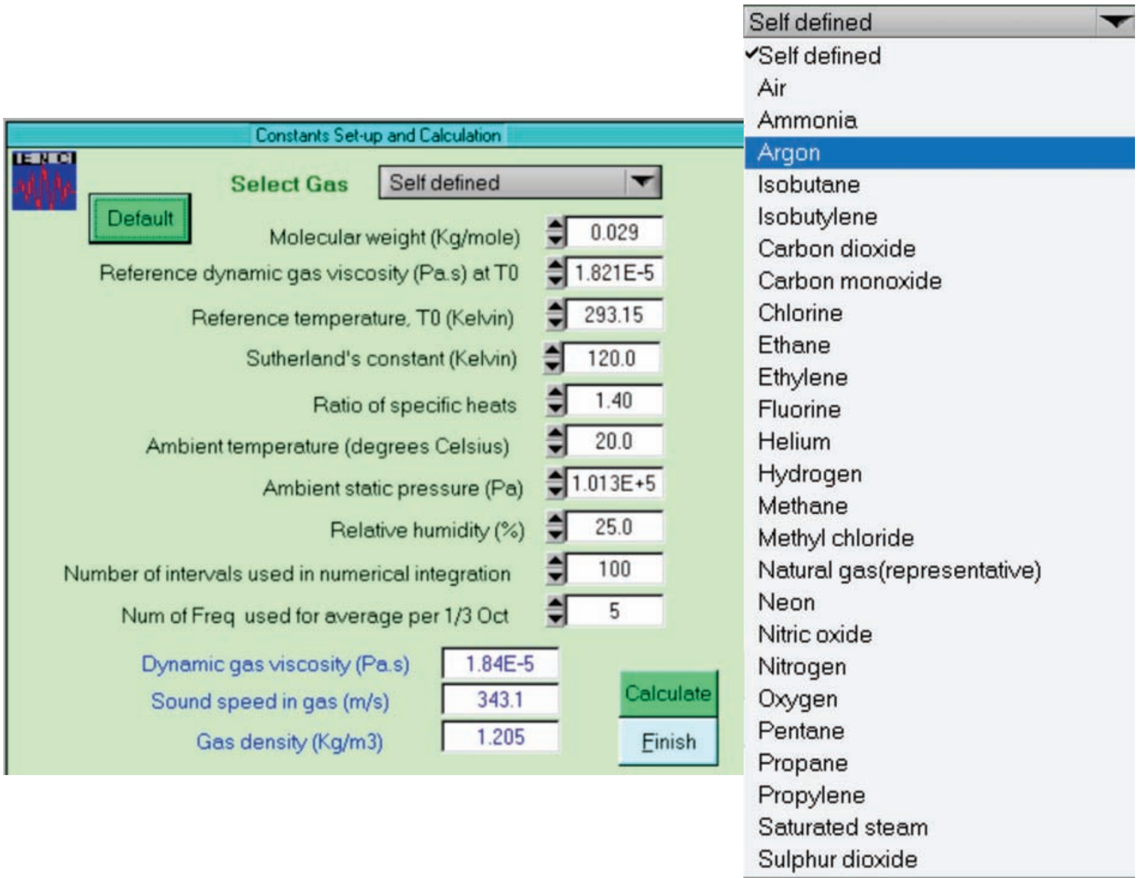
The barrier calculation includes the effect of ground on either side of it, as well as the effect of the barrier blocking out the ground reflected ray when there is no barrier at all. The calculated result displayed in ENC is the noise reduction due to installation of the barrier, including the effect of removing the original direct and ground reflected paths that existed prior to installation of the barrier as implemented using Equation (1.105) in the textbook. The ground type must be selected for the source and receiver sides of the barrier and also for the area between the diffraction edges to allow for calculation of the attenuation of ground-reflected paths around the ends and over the top of the barrier.

If you click on "Display mid results" (green box) on the figure on page 69, the panel shown below appears.

This allows you to observe the importance of each reflected path compared to the direct path over the top of the barrier in terms of attenuation (or lack of it). The second to last line in the figure also tells you where in relation to the barrier, the ground reflection is for the case with no barrier. This assists you in matching the ground type for use in the pink box part in the main page with the correct type in the barrier calculations, as the ground effect with no barrier is part of the barrier attenuation calculation. The intermediate results popup screen shown on the following figure shows detailed results for a frequency of 1000 Hz. “Ni” is the Fresnel number and the other variables are self evident if read in conjunction with the 6th edition textbook, Chapter 5, Section 5.3.5. If there is a value of 9999 shown for Ni for the ground-reflected paths around the barrier ends, that means that ENC could not find a reflected path (very rare), most likely because one does not exist. In this case, the contribution of the corresponding path to the overall barrier attenuation is zero. For the calculation of the location of the reflection point for the ground-reflected paths around the barrier ends, it is assumed that the slope of the ground is a straight line between the ground under the source and the ground under the receiver. For cases where there are different ground slopes on either side of the barrier, there will be a small error in the barrier attenuation for these paths.

When you have entered the barrier parameters, click on “back” to return to the table on the main page and you will see the barrier attenuation entered in the correct place in the table.

The window (see figure below) for calculating the speed of sound and other parameters used in the barrier calculations can be activated by clicking on the “constants” button.



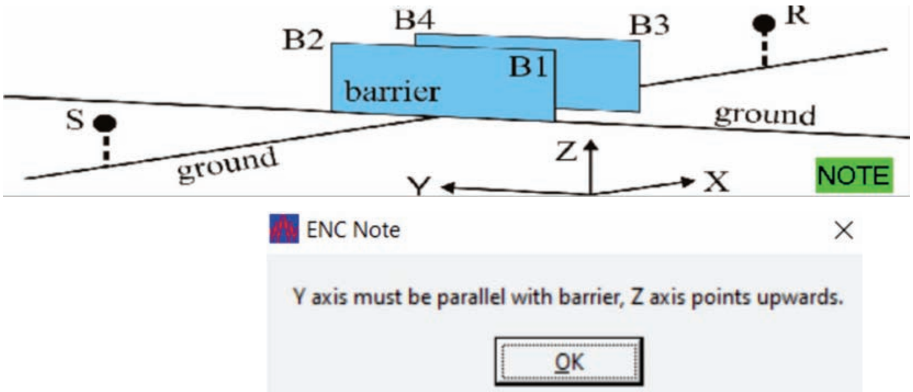
Error messages are now produced if the x-coordinate of barrier B1 or B3 is greater than the x coordinate of the receiver or if the x coordinate of barrier B1 or B3 is less than the x coordinate of the source. This has also been added to Module 5 - outdoor barrier.

A 24 dB maximum overall attenuation limit has now been applied to all barrier attenuation calculations.

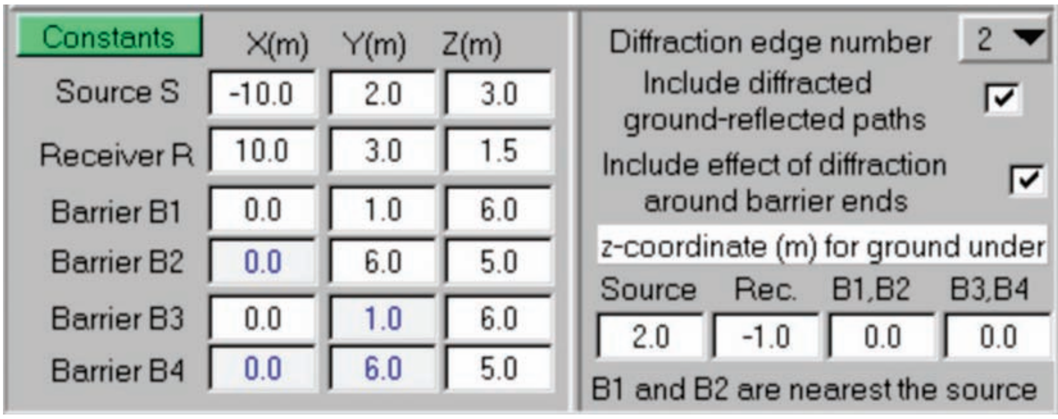
Before undertaking a barrier attenuation calculation, you must choose the particular barrier diffraction model you wish to use from a total of 3 different choices using the "select method" menu at the top of the screen as shown in the figure on page 167. Then, depending on the method chosen, you will need to enter the type of wave (plane cylindrical or spherical) or the type of source (point incoherent line or coherent line) – see figure on page 167. The ISO9613 method is not available here but is the method used in the ISO9613 page in module 3.

The spherical wave of the Menounou model is equivalent to the point source of the Maekawa model and the cylindrical wave Menounou model is equivalent to the coherent line source of the Maekawa model. Thus, for each model choice, either the "Source type" or "Wave type" boxes are greyed out as only one of the two items can be used. The Kurze model provides results that are independent of the source or wave type.

The configuration used in the calculations is illustrated below. When you click on "NOTE", a message will appear to explain the location of the origin of the coordinate system as shown in the following figure.



As noted in the figure, the Z-axis is normal to the ground surface and parallel to the plane of the barrier, the X-axis is parallel to the ground surface and normal to the barrier surface and the Y-axis is parallel to the ground surface and the barrier surface. The coordinates of the source and receiver as well as the top corners of the barrier are entered in the table at the bottom of the window as illustrated in the following figure.

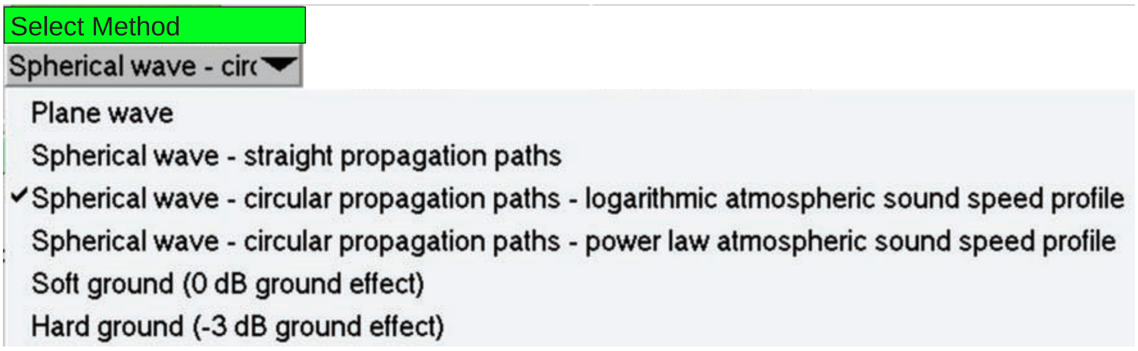


If the "Number of diffraction edges" box has a 1 in it, ENC will calculate the attenuation due to a single barrier, assuming the barrier to be thin. If the barrier is thick or if there are two thin, parallel barriers separated by anything more than 0.1 m, then the "Diffraction edge number" box should have a 2 in it. This is a different approach to that taken in ENC versions 5.5 and earlier for a thick barrier, where a simple correction was used to account for the additional attenuation obtained as a result of the thickness of the barrier. If the second barrier (closest to the receiver) is such that its top is below the straight line drawn from the top of the first barrier (closest to the source) to the receiver, then the second barrier is ignored in the calculations. If the first barrier (closest to the source) is such that its top is below the straight line drawn from the top of the second barrier (closest to the receiver) to the source, then the first barrier is ignored in the calculations.

The coordinates of the barrier top nearest the source are entered in the barrier B1 and Barrier B2 boxes for the right hand and left hand ends, respectively (when the barrier is viewed from the source). If the "Number of diffraction edges" is 2, the coordinates of the barrier top nearest the receiver are entered in the barrier B3 and Barrier B4 boxes for the right hand and left hand ends, respectively (when the barrier is viewed from the source). It is assumed that the barrier faces are in the $x - z$ plane such that the x-coordinates of each end are the same, which is why it is only possible to enter the x-coordinate for one of the ends. The zero x-coordinate location should be on the ground under the noise source. The barrier attenuations due to all 8 paths around the finite length barrier are calculated as described on pages 291–314 in the 6th edition textbook and then the results are combined using Equation (1.105) or Equation (5.178).

Before proceeding with the barrier attenuation calculations, it is necessary to specify the calculation method, which effectively describes the type of propagation path to be used. The choice is made using the "Propagation Method" menu on the centre left of the page, illustrated in the following figure.

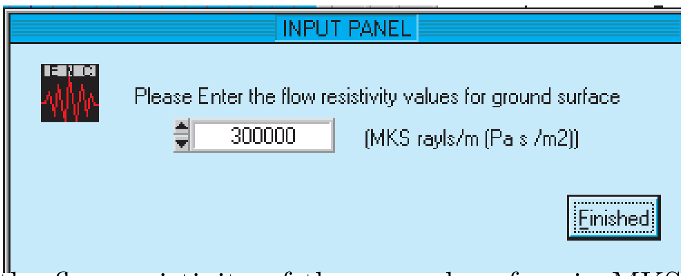
If the plane wave option or either of the circular ray path options (one for a power law atmospheric wind profile and one for a logarithmic profile) are selected (see preceding figure), the barrier effect is calculated using straight ray paths with a correction to the source and receiver heights (textbook, p.313) to account for circular ray curvature reflection parameters (thus accounting for atmospheric wind and temperature gradients). Note that this height correction is only used for the direct ray over the barrier top. Rays around barrier ends not affected by wind and temperature gradients and reflected rays do



not usually contribute sufficiently to warrant the correction.

There are three ground types that must be entered, depending on the quantity to be calculated. One is for ground reflection coefficient calculations (Table 5.2 in the textbook). This is labelled "Ground Type for Reflection Coef. Menu" and is used for calculating the ground reflection coefficient on the source and receiver sides of the barrier and also for the ground between the diffraction edges. One of the other ground types to be entered (labelled "Ground type for wind gradient calculation") is for calculating the atmospheric power law wind speed profile (Table 5.5 in the textbook) and other one (labelled "G/roughness") is for calculating the logarithmic atmospheric wind speed profile (Table 5.6 in the textbook). The list of choices in ENC that reflect these tables is illustrated in the figure on page 75.

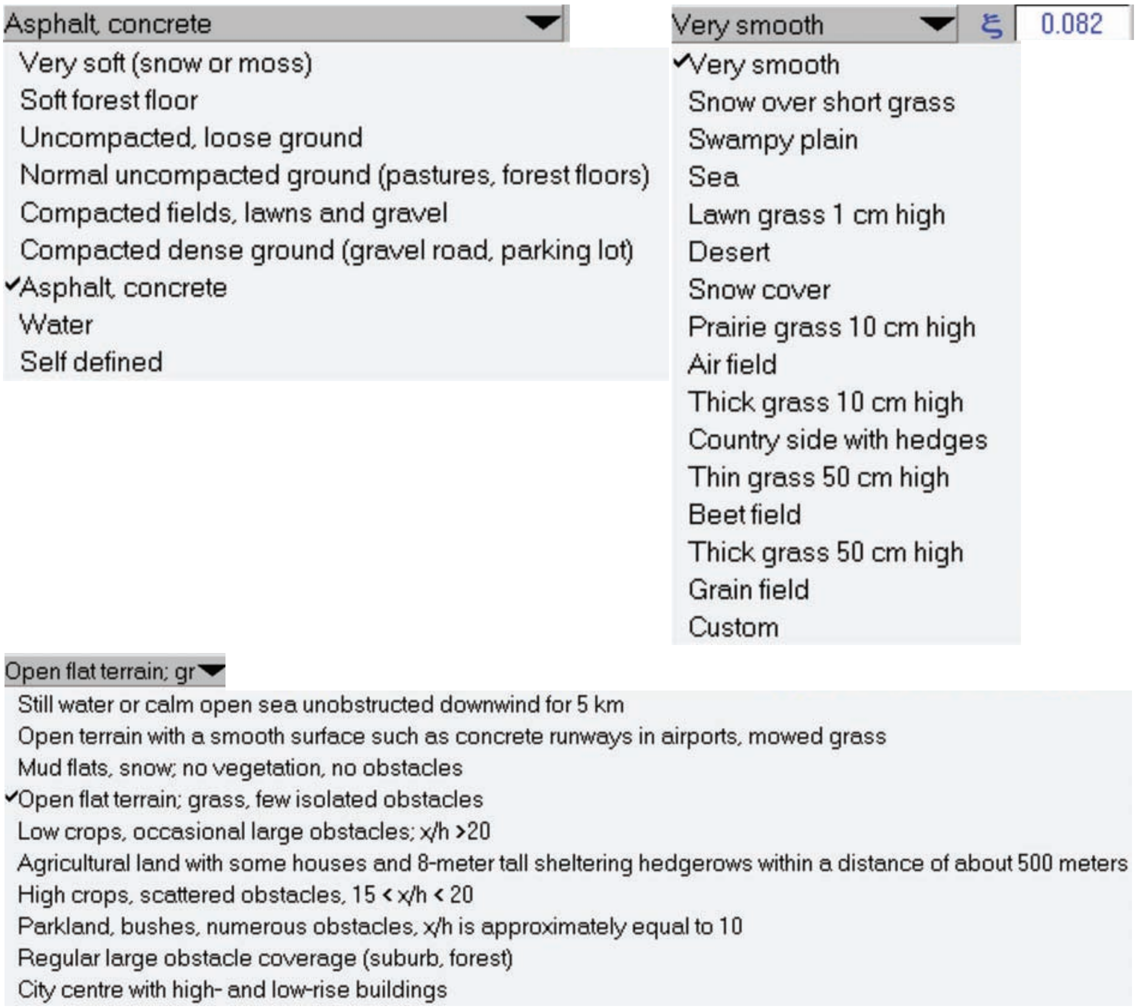
For the ground reflection calculations you can also define your own ground surface, for calculating the ground reflection coefficient, by clicking on the "Self defined" item at the bottom of the "Ground Type for Reflection Coef. Calculation" menu. When you do this the box at right pops up and all you need do is enter the flow resistivity of the ground surface in MKS Rayls/m and then click on "finished".



Equation (5.178) requires the calculation of a reflection loss for when no barrier is in place. The ground type that is used for the calculations with no barrier in place must be the type specified at the location where the reflected ray strikes the ground. This may be the receiver side of the barrier if the ground reflection with no barrier is on the receiver side of the barrier, otherwise it is the ground type specified for the source side. ENC tells you on the intermediate results popup screen whether the ground reflection with no barrier is on the source or receiver side of the proposed barrier location.

For paths involving ground reflections, the loss due to reflection is added arithmetically to the barrier attenuation. The attenuations for each path are combined together to give an overall barrier attenuation using Equation (5.178) in the 6th edition textbook.

It is not possible to include turbulence in the barrier attenuation model here. The reflection loss is calculated $-20\log_{10}(R_p)$ or $-20\log_{10}(Q)$, depending on whether a plane wave or a spherical wave reflection model is chosen. The effect of paths around all sides of the barrier as well as attenuations due to reflections from the ground are included in the final attenuation value you find in the table. For each path the attenuation is calculated



using Figure 5.19 and Equations (5.142), (5.144) & (5.178).

If the "Include diffracted ground-reflected paths" box is ticked (see figure on page 167), ENC will include all diffracted ground reflected paths in the overall attenuation calculation. The non-diffracted ground reflected path that exists without the barrier and whose attenuation is used as part of the barrier overall attenuation calculation is included whether or not the box is ticked. If it is required to also exclude the effect of the non diffracted ground reflected path, just choose "soft ground (0 dB ground effect)" in the "Propagation Method" drop-down menu.

For all options in the "Propagation Method" drop down list near the centre left of the page (see figure on page 172), when the "Include ground reflected diffraction paths" and "Include diffraction around barrier ends" tick boxes are ticked, the barrier attenuations due to all 8 paths around the finite length barrier are calculated as described on pages 291–314 in the 6th edition textbook and then the results are combined using Equation (1.105) or Equation (5.178).

The ground cover categories for the radius of curvature calculations ("Ground type for wind gradient calculation") are slightly different to the categories used for the ground reflection effects. This is a result of the available data in the literature for these very different calculations.

Thus, Table 5.5 in the textbook represents particular ground covers for calculating the wind shear coefficient, ξ, used along with the wind speed data (see figure on page 173) to calculate the power law atmospheric wind speed profile.

Table 5.6 in the textbook represents the ground roughness (see figure on page 173), used along with the wind speed data to calculate the logarithmic atmospheric wind speed profile. The atmospheric temperature profile is calculated using the temperature gradient data (see figure on page 69) and this is used together with the atmospheric wind speed profile to calculate the radius of curvature of the rays when the plane wave or either of the two circular propagation path model options are chosen for the "Propagation Method" (see the figure on page 74 and 6^{th} edition textbook, page 267 and Equations (5.76) and (5.79)).

It is IMPORTANT to note that for the circular ray path options, the barrier noise reduction will not be accurate until you have entered the wind speed at a specified height (speed component in the direction from the source to the receiver — negative values represent a component blowing from the receiver to the source) and temperature gradient. However, you may exclude the effect of a sonic gradient by entering zero for the wind speed and temperature gradient. Note that for sound propagation around the side of barriers, wind and temperature gradients have no effect. For reflected paths and paths around the barrier ends, the actual source and receiver locations are used, NOT the new locations calculated for sound propagation over the top of the barrier in the presence of wind or temperature gradients (circular ray path options only).

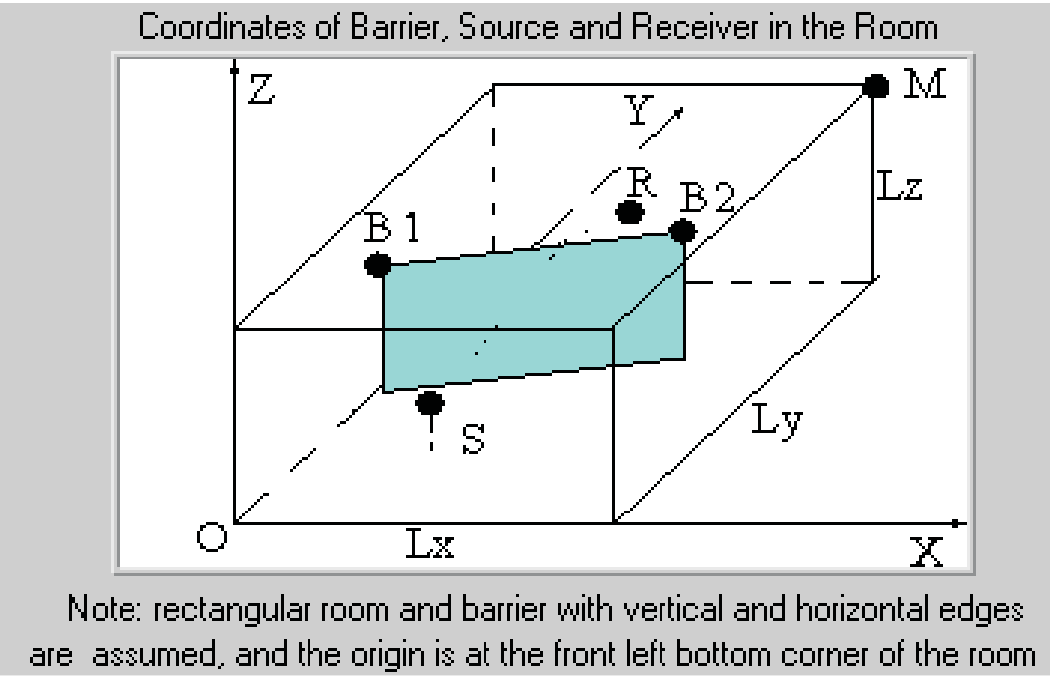
The radius of curvature, R (in metres) (see Equation (5.73)) of the sound wave going over the top of the barrier as a result of wind and temperature gradients and the value of the exponent ξ (see Equation (5.79) and Table 5.5, p. 270 in the textbook) are provided for your interest in blue text in the barrier pop-up window (see page 167). If you wish to enter your own value of ξ, you will need to select "custom" on the menu for "ground type for wind gradient calculation" (see top right menu in the figure on page 173).

A negative radius of curvature (resulting from a negative atmospheric sonic gradient) implies that the sound rays will be curved upwards and the resulting barrier attenuation will increase. This is in contrast to the decrease in barrier attenuation that occurs when there is a positive radius of curvature and corresponding downward curved rays. Wind and temperature gradients, when a plane wave or circular propagation path option is chosen for the "Propagation Method", are taken into account automatically if you enter a non-zero value for the wind speed or temperature gradient. As mentioned earlier in this manual, the procedure in the ENC barrier page calculates an effective source height based on the sound ray curvature calculated from the wind and temperature gradients. If the effective source height is less than zero, it is set equal to zero. Interestingly, the effect on the overall attenuation of the barrier is not great in most cases. You need to enter the wind speed at 10 m and the temperature gradient in degrees C per 1000 m (see figure on page 167).

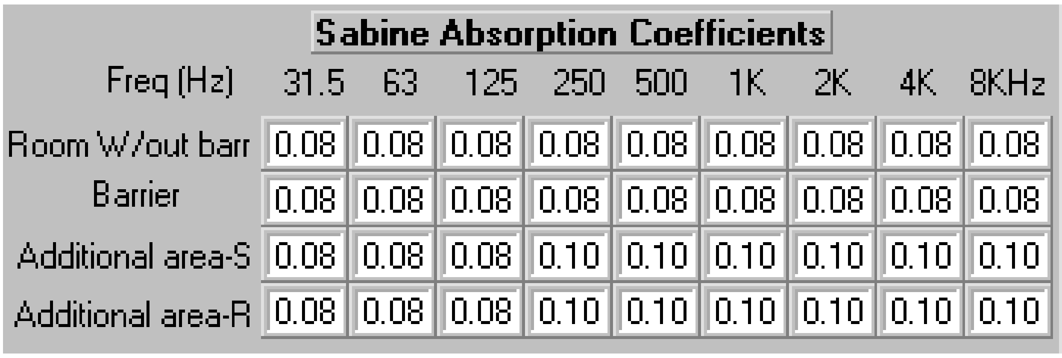
5.8 Indoor Barrier (6th edition textbook, pages 461–462)

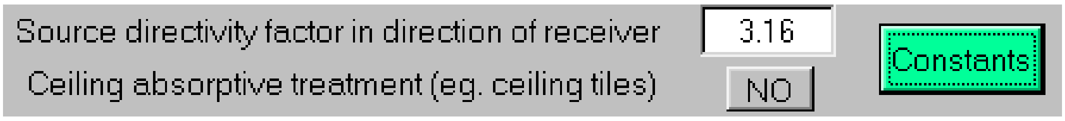
This window is used to calculate the noise reduction due to a barrier mounted indoors. The barrier configuration used is shown in the following figure. The room is assumed to be rectangular and the origin of the coordinate system used for defining the source, receiver and barrier locations is at a room corner on the source side of the barrier as shown in the figure. The barrier is assumed to be a plane partition, resting on the floor and normal to the floor as shown in the figure. The room dimensions and the coordinates of the top corners of the barrier as well as the source and receiver must be defined and input in the table shown at right. Make one corner of the room the origin of your coordinate system such that all coordinate locations are positive.

	X(m)	Y(m)	Z(m)
Room Size M	20.0	50.0	5.0
Source S	10.0	20.0	1.0
Receiver R	8.0	30.0	1.5
Barrier B1	5.0	25.0	3.0
Barrier B2	15.0	25.0	3.0

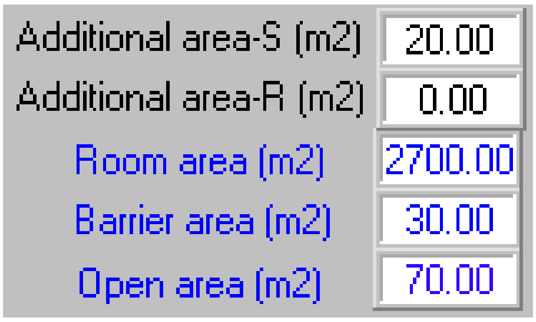


You need to enter the $\bar{\alpha}$ for the bare room (room boundaries only) for each octave band and also the $\bar{\alpha}$ for each side of the added partition (barrier). The software will use the room surface area to calculate the $S\bar{\alpha}$ for the bare room and for each side of the barrier for the room with the barrier. The value of surface area, S, used in the calculations is the room surface area for the bare room and the room surface area plus barrier area for each side of the barrier for the room with barrier. It is assumed that the $S\bar{\alpha}$ in the room without the barrier is uniformly distributed. If this is not the case or if there are additional surfaces in the room you may enter the $\bar{\alpha}$ of the additional area that should be added to each side of the barrier to account for these effects (see above table). Beneath the table you also need to include the source directivity in the direction of the receiver (see following figure) and whether or not the ceiling is treated with sound absorbing material. The barrier insertion loss is then calculated using Equations (7.149)–(7.151). The "Constants" button may be clicked on to calculate and set the speed of sound used in the calculations.





The additional surface areas corresponding to the $\bar{\alpha}$ of the additional area on each side of the barrier (see previous figure) is input in the bottom right section of the panel (see figure at right). This additional area does not include the barrier itself as that is already included in the analysis. The bottom three lines are calculated from the data input for the room (see figure on previous page). There you must enter the room size and the coordinates of the source and receiver locations as well as the two top corners of the barrier. It is assumed that the barrier is resting on the floor.



Ceiling absorption prevents the wave reflected from the ceiling from having a significant influence on the sound level at the receiver. So if ceiling absorption is used, the increase in noise reduction is the minimum of the following two quantities:

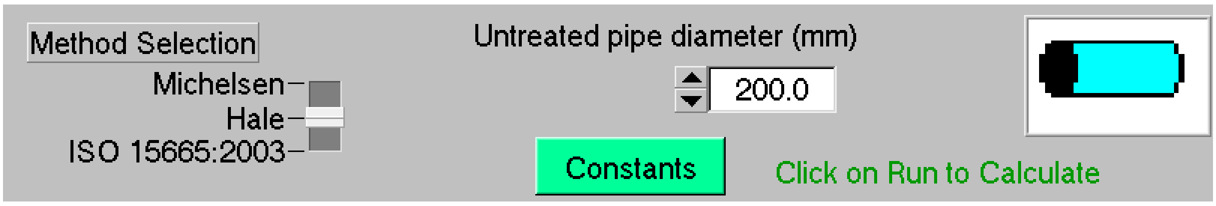
- 1/3 of the noise reduction with no ceiling treatment;
- 4 dB for 250 Hz, 5 dB for 500 Hz, 6 dB for 1000 Hz and 7 dB for 2000 Hz and higher frequencies. (see 6th edition textbook, page 461–462)

When you are satisfied with all input parameters, click on "run" in the tool bar. Then the barrier IL results in octave bands will be plotted on the graph on the left of the screen and listed in the table beneath the graph.

5.9 Pipe Lagging (6th edition textbook, pages 462–465)

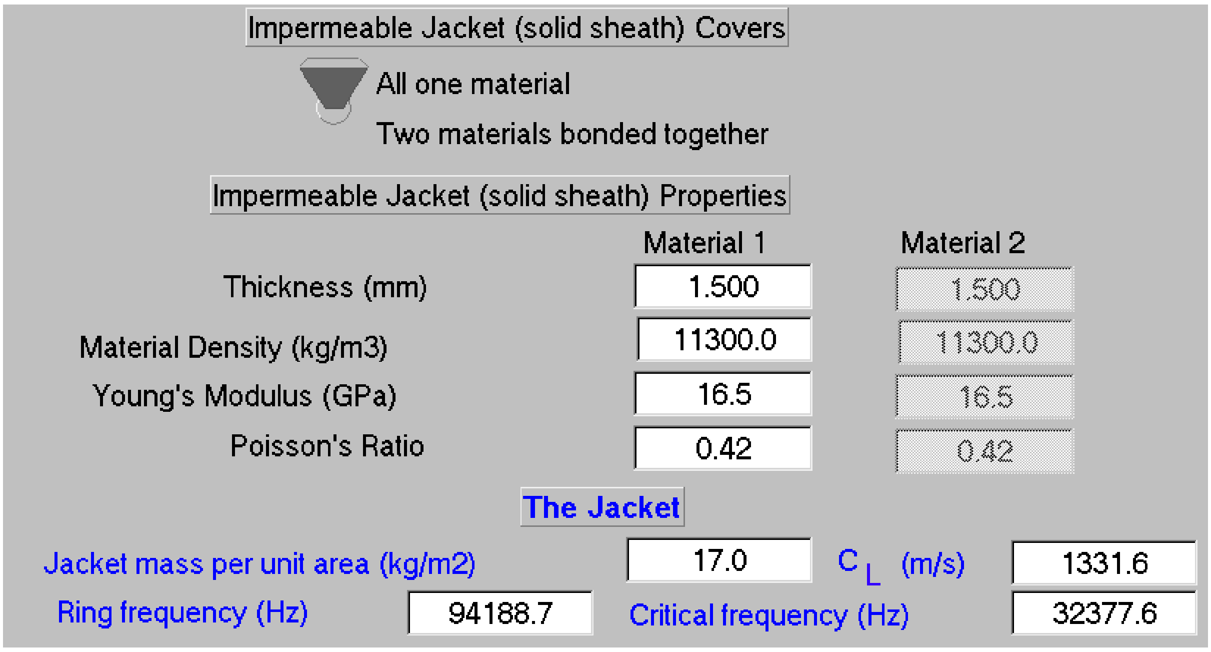
This window is intended to provide an estimate of the noise reduction achieved when a pipe is covered with a layer of sound absorbing material which, in turn, is covered with a limp, impervious skin. Care must be taken in the choice of rockwool and fibreglass as the binder sometimes disintegrates in service, leaving the impervious skin resting on the original pipe, resulting in very little residual noise control performance. Also you should consider using shaped acoustic foam in place of shaped rockwool or fibreglass as its performance is often better. However, the calculation procedures used here are not applicable to acoustic foam wrappings (as no satisfactory theory exists) and the three procedures used here for the rockwool and fibreglass wrappings are semi-empirical and approximate at best.

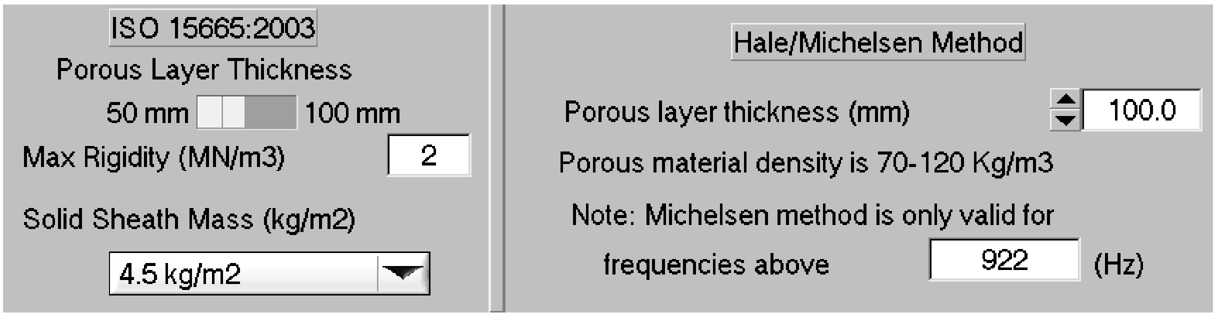
The calculations are based on the assumption that the fibreglass or rockwool material has a density of between 70 and 120 kg/m^3. The actual density is not used in any of the three calculation procedures, although the ISO 15665 procedure limits its rigidity. It is also assumed that the fibreglass or rockwool material is covered with a limp impervious membrane (jacket) of substantial mass. Usually a surface weight of 4.5-10 kg/m^2 is used and the material is usually aluminium or a bonded lead/aluminium sheet. The chosen calculation method and the bare pipe diameter is entered in the section at the top, right side of the panel (see following figure). Clicking on "Constants" allows you to calculate and set the speed of sound to be used in these calculations.



You can enter the properties of either type of jacket in the table on the bottom right of the screen (see next page) and you can specify whether the jacket is made of one or two materials using the toggle above the table (see next page).

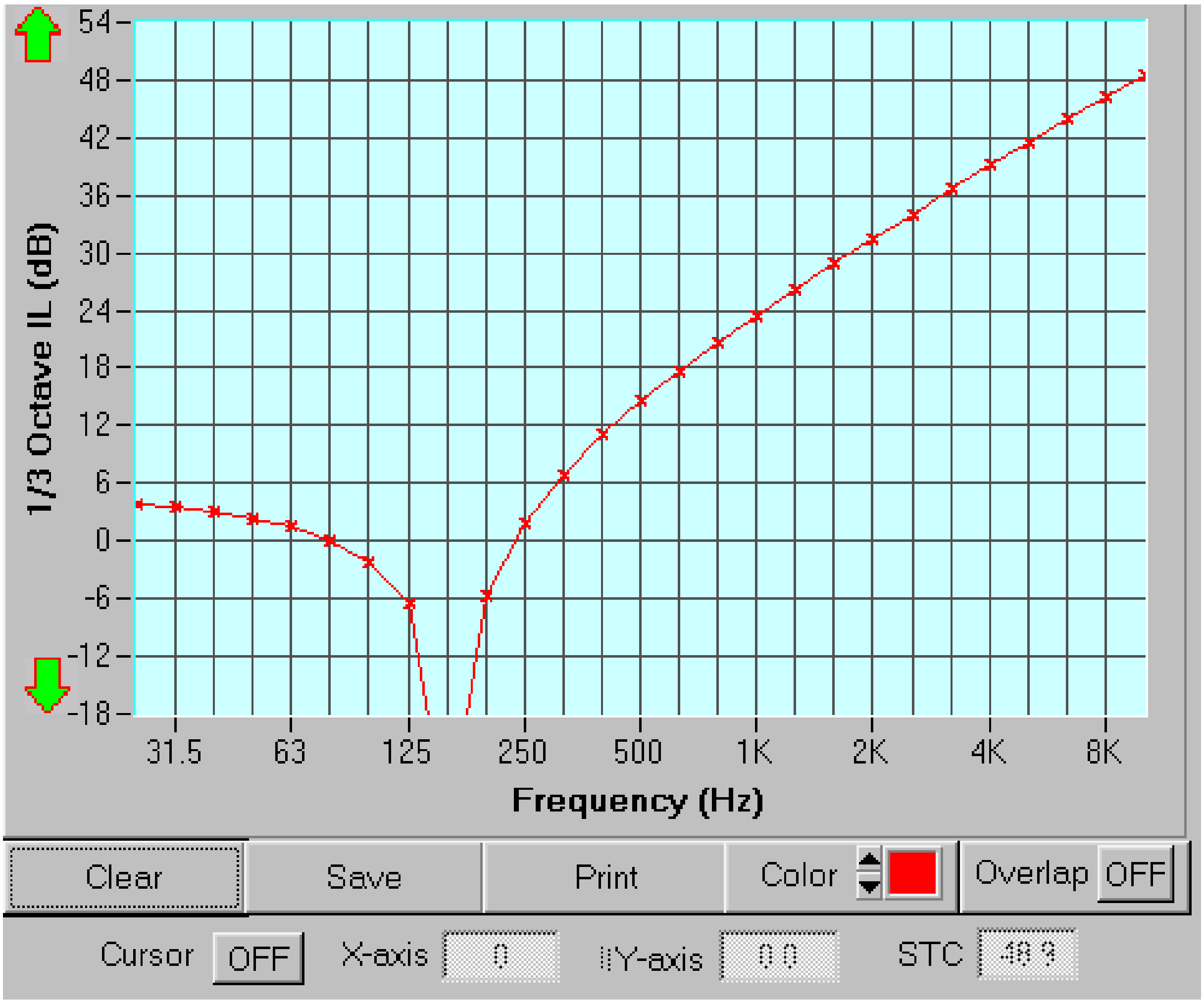
You have three choices of calculation method, the ISO 15665:2003 method, the Hale method (Equations (7.152)–(7.159) in the 6th edition textbook) or the Michelson method (Equation (7.160)), with the input data for all three methods shown on the next page. The Michelson method is more reliable than the Hale method, but when compared to measured data it is a bit conservative. It also has a lower frequency limit below which the calculations are invalid (see following figure). It seems that the ISO method is perhaps the most reliable, but there are insufficient data available to verify this.





The Hale method is unreliable and often overestimates the actual IL. The calculation method is selected by clicking on the "method selection" switch in the middle of the window. Note that the Michelson method is characterized by a lower limiting frequency below which the results are not valid. This must be remembered when interpreting the plotted and tabulated results in the graph (see next page). These results appear when you click on the "run" button in the tool bar.

Note that you can scroll the scale for the IL by clicking on either of the green squares to the left of the graph. A number of curves can be plotted on the same axes by turning overlap to "ON". For the jacket material, results are provided at the bottom of the right side of the panel for mass per unit area, speed of sound, critical frequency and ring frequency.



1/3 Octave IL (dB)
54
48
42
36
30
24
18
12
6
0
-6
-12
-18
31.5
63
125
250
500
1K
2K
4K
8K
Frequency (Hz)
Clear
Save
Print
Color
Overlap
OFF
Cursor
OFF
X-axis
Y-axis
STC

Chapter 6

Reactive & Dissipative Mufflers (Module 6)

6.1 Overview

This module enables calculation of the impedances of individual reactive muffler elements, the Insertion Loss of reactive and dissipative mufflers, flow noise, duct break-in / break-out noise, exhaust stack directivity and the Insertion Loss of plenum chambers using the procedures described in chapter 8 of the 6$^{\text{th}}$ edition textbook.

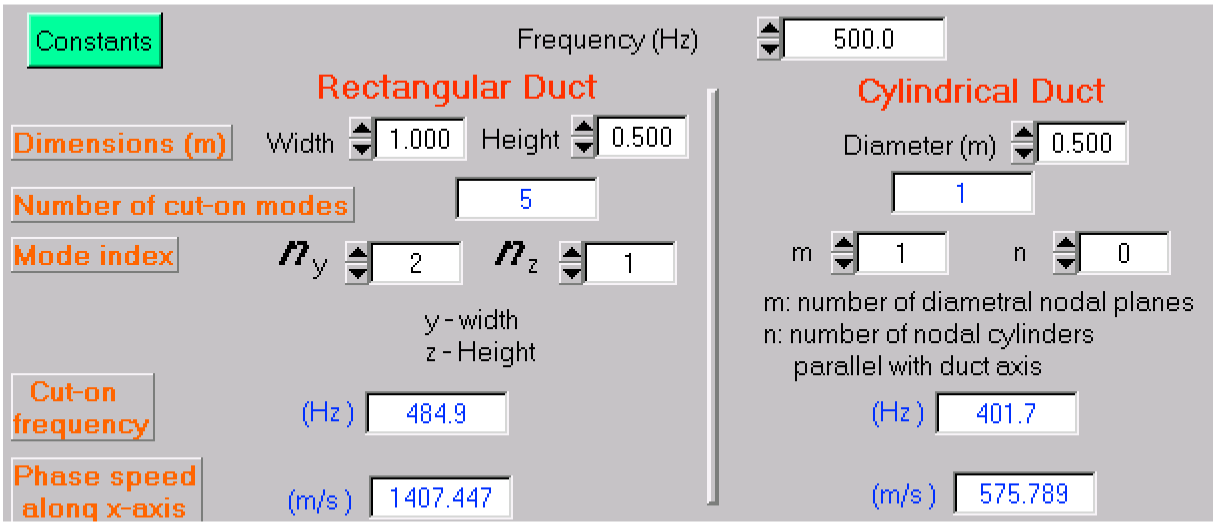
6.2 Duct Modal (pages 534–537 in the 6$^{\text{th}}$ edition textbook)

This panel enables you to calculate the cut-on frequency of a specified higher order mode in a rectangular or cylindrical duct. In addition you can calculate the phase speed of the specified mode at a specified frequency as well as the number of cut-on modes that are propagating at the specified frequency. This panel also allows you to calculate the speed of sound in gases, solids and liquids, which is a duplicate of the speed of sound panel in "Module 1 — Fundamentals".

To use this module simply enter the cross-sectional dimensions of the duct, the frequency of interest and the mode index of the mode you wish to consider as shown on the following figure.

For rectangular ducts, the analysis uses Equations (8.227), (8.229) and (8.231) in the 6$^{\text{th}}$ edition textbook.

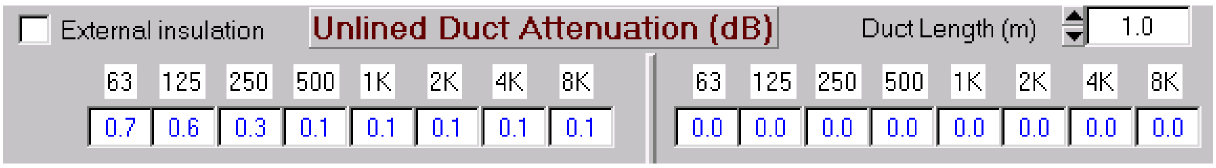
For cylindrical ducts, the analysis uses Equations (8.228), (8.230) and (8.233) in the 6$^{\text{th}}$ edition textbook, where r is the radius of the cylinder, c is the speed of sound in free space and $\alpha m, n$ is a constant dependent on the modal index and is listed in the following table.



m	n				
	0	1	2	3	4
0	0	3.83	7.02	10.17	13.32
1	1.84	5.33	8.53	11.71	14.86
2	3.05	6.71	9.97	13.17	16.35
3	4.2	8.02	11.35	14.59	17.79
4	5.32	9.28	12.68	15.96	19.2
5	6.42	10.52	13.99	17.31	20.58
6	7.5	11.73	15.27	18.64	21.93
7	8.58	12.93	16.53	19.94	23.27
8	9.65	14.12	17.77	21.23	24.59

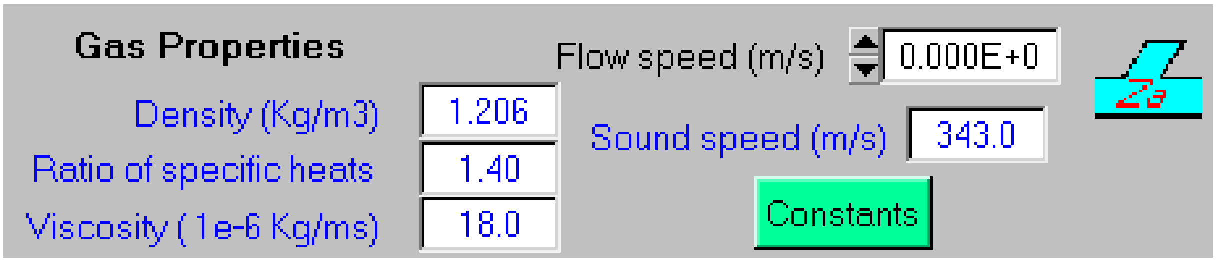
where m is the number of diametral nodes and n is the number of cylindrical nodes parallel to the x-axis.

The panel also allows you to calculate the attenuation due to an unlined duct with and without lagging on the outside. To calculate the unlined duct attenuation for the duct cross sectional dimensions entered above, enter the duct length (see below) and indicate whether or not external insulation exists. This is discussed on pages 539 and 541 of the 6$^{\text{th}}$ edition textbook.



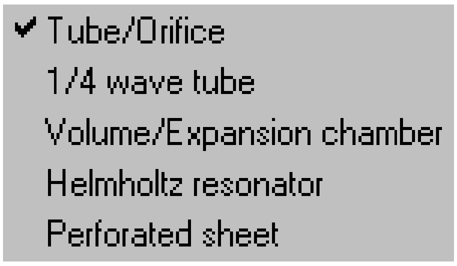
6.3 Impedance (6$^{\text{th}}$ edition textbook, pages 473–482)

This panel enables you to calculate the normal incidence, lumped element impedance for elements that make up reactive mufflers. The first thing to do is specify the properties of the gas flowing in or past the element by clicking on the "Constants" button to bring



up the "Constants set-up window. In addition, the flow speed needs to be entered as illustrated in the following figure.

There are 5 elements (see figure at right) for which you can calculate the impedance: tubes/orifices, 1/4-wave tubes, volumes/ expansion chambers, Helmholtz resonators and perforated sheets. When inputting parameters, please note carefully the units for each quantity. Generally SI units are used but in many cases millimetre units are used instead of metres.



The maximum valid frequency for the results when lumped analysis is used corresponds to no dimension of the element exceeding $\lambda/4$. When 1-D wave analysis is used, the maximum valid frequency corresponds to the cut-on frequency for higher order mode propagation in the element. For volumes, the criterion is the same as for lumped analysis.

In this module the values plotted on the graph are not 1/3-octave band averages - they are single frequency values at the 1/3-octave band centre frequencies.

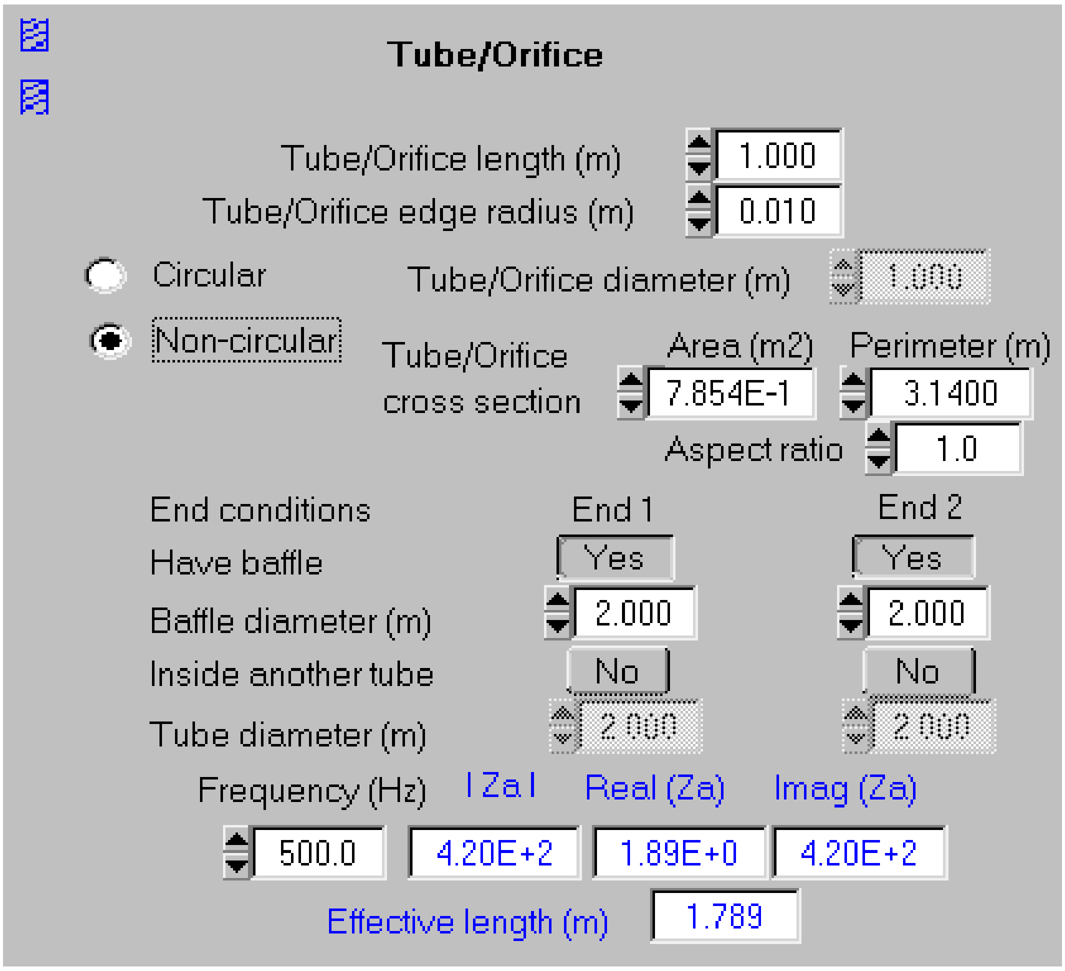
Values at the octave band centre frequencies are displayed below the graph. Note that the values are single frequency values with no band averaging. The impedances calculated in this module are all normal incidence impedances. End corrections calculated using the equations in the 6$^{\text{th}}$ edition textbook are modified for flow by multiplying by $(1-M)^2$.

6.3.1 Tube/Orifice

For the panel shown in the following figure, the input parameters need some explanation (pages 473–476 in the 6$^{\text{th}}$ edition textbook). The reactive part of the acoustic impedance for specified gas properties and flow is calculated using the first term on the right of Equation (8.20) in the 6$^{\text{th}}$ edition textbook, where the effective length of the hole is given by Equation (8.11). The resistive part is calculated using Equation (8.34) in the 6$^{\text{th}}$ edition textbook.

The length parameter in ENC is the actual tube length with no end correction or the thickness of the orifice plate for an orifice. The edge radius parameter is used for calculating the resistive part of the impedance (Equation (8.34) in the 6$^{\text{th}}$ edition textbook). If it is unknown, use 10 mm.

Next you must specify whether the tube or orifice is circular or not — this is necessary to allow the end correction to be calculated correctly. If the cross-sectional shape is circular, you need to specify its diameter; if it is non-circular, then you need to specify the cross-sectional area and perimeter. Equation (8.27) in the 6$^{\text{th}}$ edition textbook is then used by ENC to calculate an equivalent radius of the orifice or tube.



For all cross-sectional shapes, you need to specify the diameter of the baffle around each end of the tube or around each side of the orifice. If the baffle is non-circular, then you can use Figure 8.5, p. 478 and Equation (8.27) in the 6th edition textbook to calculate the diameter of a circle of the same area. If the orifice or tube pierces a baffle inside another larger diameter tube, then the orifice diameter cannot be more than 0.6 times the larger tube diameter, and ENC uses Equation (8.25) in the 6th edition textbook to calculate the end correction. If the orifice or tube is not in a larger tube and the baffle is bigger than three times the orifice diameter, then ENC uses Equation (8.25) with $\xi = 0$ to calculate the effective length. If the orifice or tube is radiating into free space with no baffle, then ENC uses Equation (8.28). For baffles of diameter smaller than three times the orifice diameter, linear interpolation between the above two cases is used to calculate the effective length.

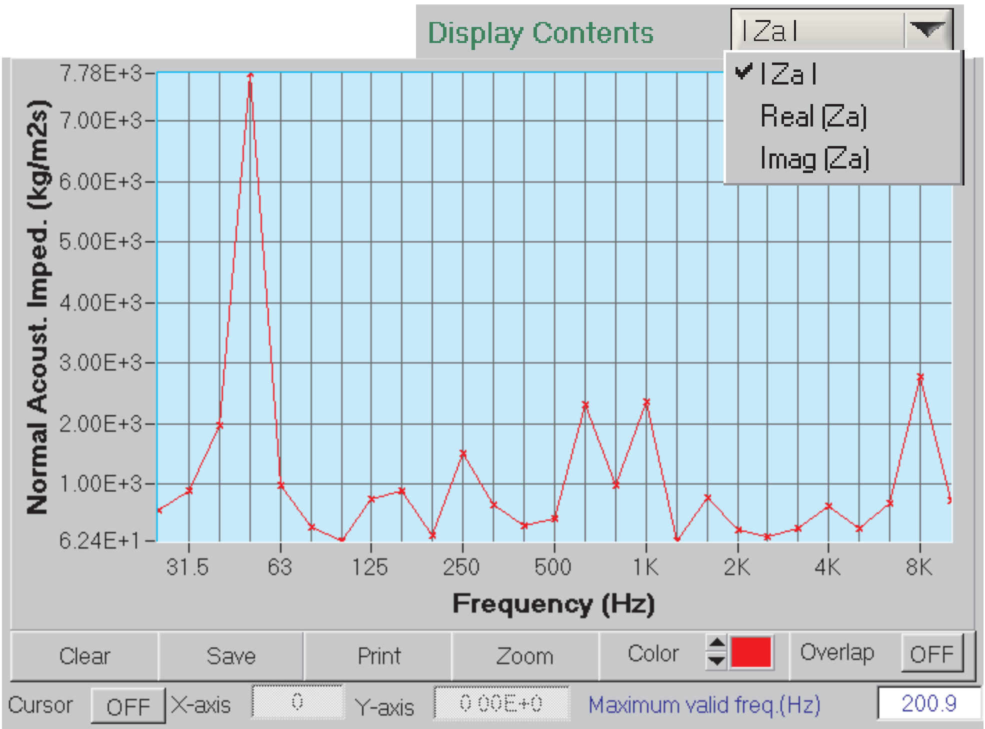
If you enter "yes" to the "inside another tube" question, then it is assumed that the orifice or tube is in a baffle, which, in turn, is mounted inside another outer tube (and the baffle diameter is the same as the inside diameter of the outer tube) and the outer tube diameter should be entered. To select the option corresponding to a baffle in free space, select"no" for the "inside another tube" question and then select "yes" for the "have baffle" question. If there is no baffle and the orifice is not inside a tube, enter "no" to the "inside another tube" question and "no" for the "have baffle" question. Note that if "yes" is selected for the "inside another tube" question, then the "have baffle" question is "greyed out" and vice versa.

ENC calculates the effective length increase for each side of an orifice or each end of a tube, which is why input data are needed for each end. The resulting effective length of the tube or orifice calculated by ENC is given at the bottom of the panel. Also at the bottom of the panel, is given the real, imaginary and modulus of the impedance for any frequency entered in the "frequency" box.

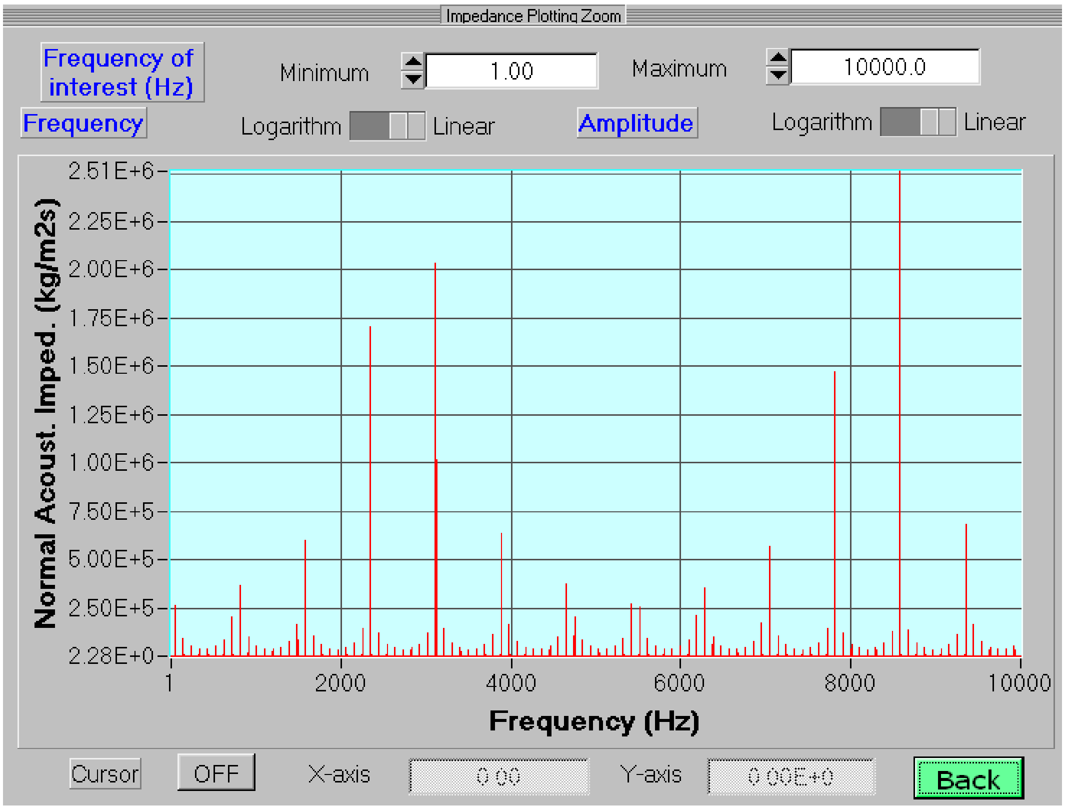
With the required input data entered, click on "run" in the tool bar and the impedance will be plotted at 1/3-octave band intervals on the graph (shown on the following figure).The values plotted on the graph are not 1/3-octave band averages — they are single frequency values at the 1/3-octave band centre frequencies. Note that you must select the desired parameter to be plotted from the data window above the graph as shown in the figure. If you want to select logarithmic axes for the plot or plot data at a finer resolution than 1/3-octave or choose the frequency range for the plot, click on the "zoom" button at the bottom of the graph and the zoomed window will appear, shown in the figure on the next page.

As 1-D wave analysis is used here, the maximum valid frequency for the results, is when higher order modes begin to propagate as defined by Equations (8.231) and (8.233) in the 6th edition textbook. For very short tubes or orifices (less than half a wavelength long) the upper limiting frequency corresponds to the orifice diameter being equal to $\lambda/4$. The maximum valid frequency is calculated by ENC and displayed below the graph.

Values at the octave band centre frequencies are displayed below the graph. Note that the values are single frequency values with no band averaging.



The impedances calculated in this module are all normal incidence impedances. Impedance values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the tube/orifice panel shown two pages back.

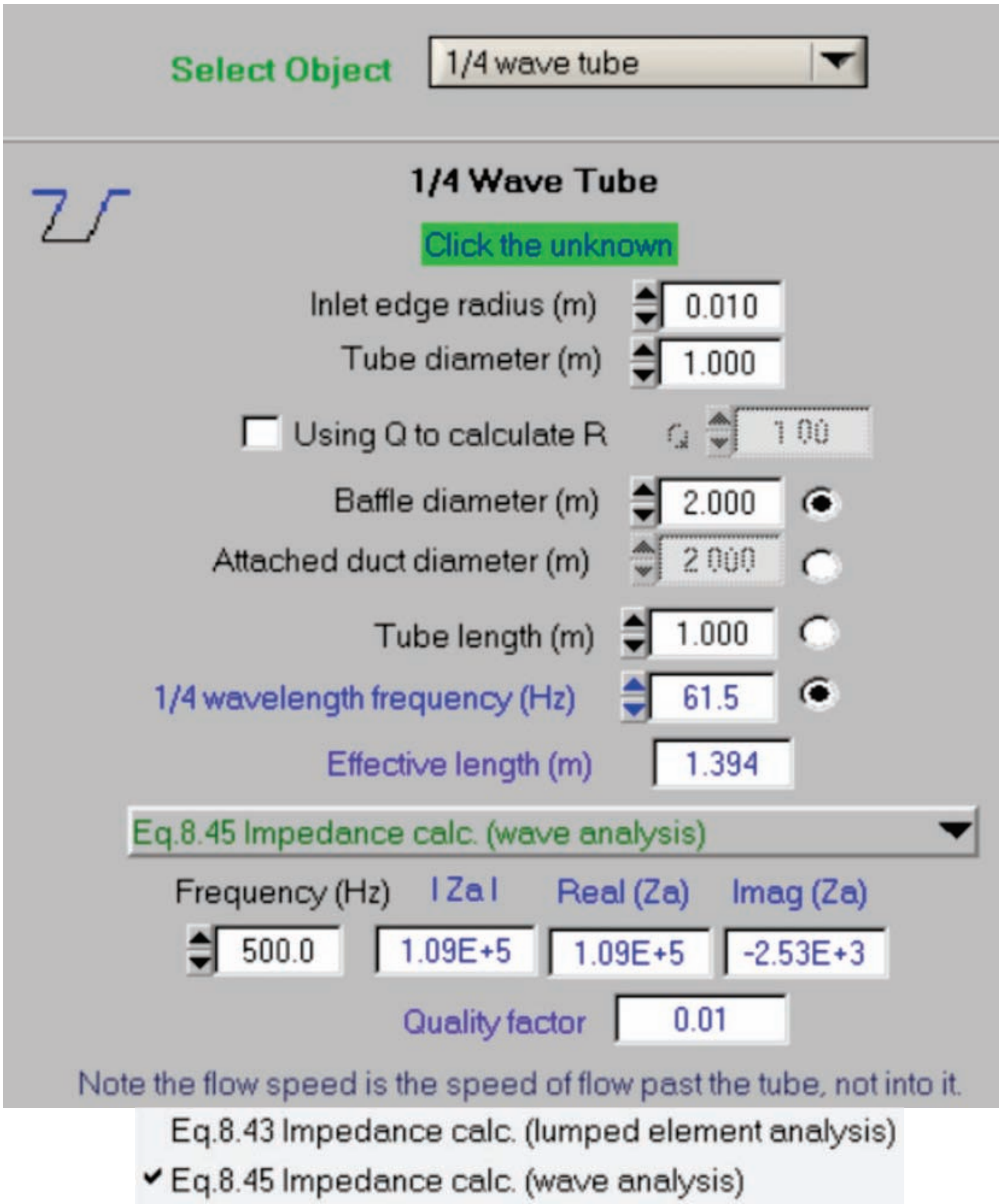


6.3.2 1/4-wave Tube Calculations (see following figure and 6th edition textbook, pages 483–492)

For the 1/4-wave tube calculations, the inlet edge radius is the radius of the edge where the 1/4-wave tube joins the structure (usually a duct) on which it is mounted. If you do not know the value, use 10 mm. After specifying the tube diameter, you may specify the length and have the software calculate the corresponding resonance frequency or you may specify the resonance frequency you desire and the software will calculate the required length. Just click on the appropriate circle to the right of the data boxes. The quantity calculated by the software is in blue text.

You also need to choose whether to use lumped element analysis or wave analysis by selecting from the menu shown in the figure. Equation (8.45) in the 6th edition textbook (2^{nd} term on the right) is the basis of the lumped element calculation of the reactive impedance and Equation (8.44) is the basis for the 1-D wave calculation, while Equation (8.34) is used to calculate the resistive impedance.

Note that the effective length of the tube is the actual length plus an end correction calculated using Equation (8.53) multiplied by $(1 - M)^2$ to account for grazing flow past the mouth of the tube. As it is a calculated quantity, it appears in ENC in blue text. The range of allowed diameter for the 1/4-wave tube ranges from 0.2 to 5 times the duct diameter to which it is attached. For a 1/4-wave tube not attached to a duct wall, the end correction for no baffle (or baffle diameter equal to the tube diameter) is calculated using Equation (8.28) and for a very large baffle (of diameter greater than 3 times the tube diameter, Equation (8.25) is used with $\xi = 0$. Linear interpolation for the end correction is used for baffle diameters between one and three times the tube diameter. For a quarter wave tube attached to the side of a duct, the end correction is calculated using Equation (8.25) (multiplied by $(1 - M)^2$ to account for flow past the mouth of the tube) where in this case, ξ is set $= 0$. For a 1/4-wave tube attached to a duct wall, the end correction is calculated using Equation (8.52) in the 6$^{\text{th}}$ edition textbook (again, multiplied by $(1-M)^2$ to account for flow past the mouth of the tube).



The quality factor at resonance is provided at the bottom of the panel and is calculated using Equation (8.57) in the 6$^{\text{th}}$ edition textbook. Sometimes ENC calculates quality factors that, based on experience, seem too high, so if you prefer, you may enter a value for the quality factor and ENC will use that to calculate the resistive impedance and

Insertion Loss. ENC then calculates the acoustic resistance at the resonance frequency of the resonator using Equation (8.57) in the 6^{th} edition textbook. The resistance values at other frequencies are then calculated by multiplying the resistance at the resonance frequency calculated using Equation (8.57) by the ratio of the resistance calculated using Equation (8.34) at frequency of interest to the resistance calculated using Equation (8.34) at the resonance frequency.

With the required input data entered, click on "run" in the tool bar and the impedance will be plotted at 1/3-octave band intervals on the graph. Note that you must select the desired parameter to be plotted from the data window above the graph.

The maximum valid frequency for the lumped analysis is limited to the largest dimension of the 1/4-wave tube being $\lambda/4$. For the 1-D wave analysis, the maximum valid frequency corresponds to the frequency at which cross modes begin to propagate in the 1/4-wave tube or the attached duct. The frequency corresponding to the maximum valid frequency is indicated beneath the graph.

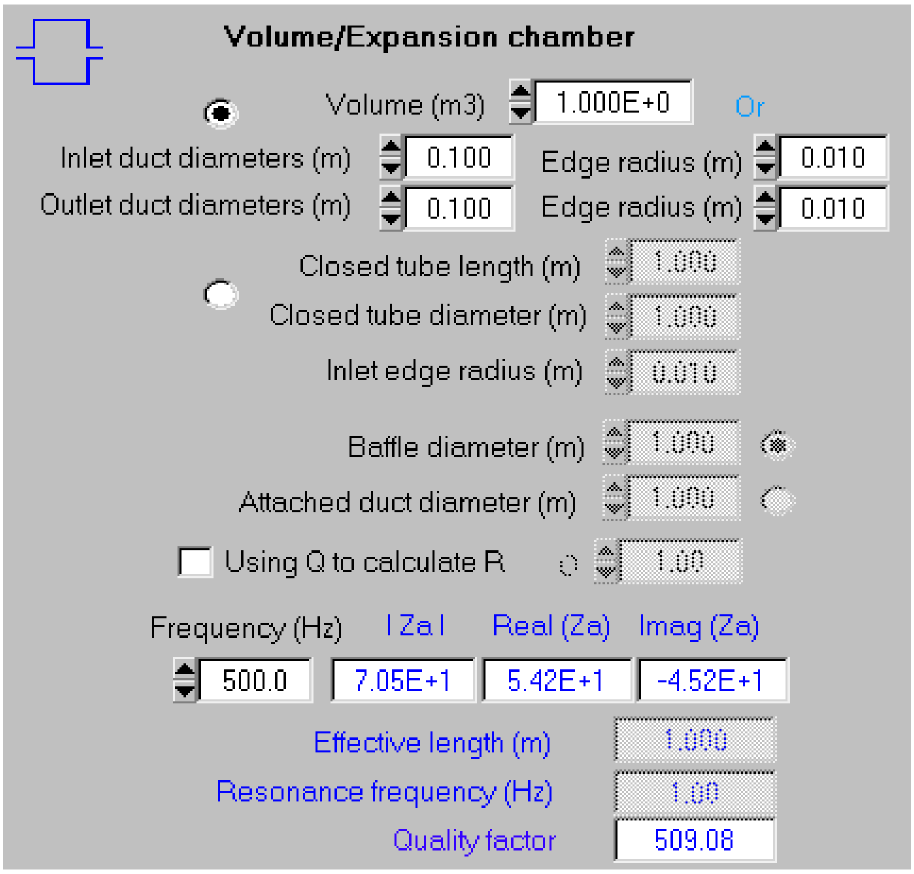
The values plotted on the graph are not 1/3-octave band averages — they are single frequency values at the 1/3-octave band centre frequencies.

Values at the octave band centre frequencies are displayed below the graph. Note that the values are single frequency values with no band averaging.

The impedances calculated in this module are all normal incidence impedances.

Impedance values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the 1/4-wave panel shown on the previous page.

6.3.3 Volume/Expansion Chamber (see following figure and 6th edition textbook, pages 494–500)



For the volume/expansion chamber impedance calculations you must first select (by clicking on the circle next to your choice) whether you have an expansion chamber attached to an inlet and outlet duct or a tube closed at one end that is not necessarily designed specifically as a quarter wave tube at some specified frequency. If a closed tube is selected, you must select whether it has a baffle around its opening or if it is attached to the wall of a duct (and its opening looks into the duct).

If you have an expansion chamber connected to an inlet and outlet duct, you must enter the expansion chamber volume, and the diameters and edge radii of the inlet and exit ducts. The inlet and exit duct diameter data are only used for determining the acoustic resistance (see Equation (8.34) in the 6th edition textbook) associated with the expansion chamber.

The quality factor at resonance is only calculated for the closed end tube option as it would be necessary to know the lengths of the attached ducts to calculate a quality factor for the expansion chamber.

For the closed end tube option, the quality factor is provided at the bottom of the panel and is calculated using Equation (8.57) in the 6th edition textbook, where R_s is the acoustic resistance of the closed end tube and S is its cross sectional area. Alternatively, you may enter a value for the quality factor in the preceding panel if you wish and ENC will calculate the corresponding resistance and use that to calculate the resistive impedance.

The resistive impedance values at other frequencies are then calculated by multiplying the resistance at the resonance frequency calculated using Equation (8.58) in the 6^{th} edition textbook by the ratio of the resistance calculated using Equation (8.34) at the frequency of interest to the resistance calculated using Equation (8.34) at the resonance frequency.

The reactive impedance is calculated using Equation (8.43), in the 6^{th} edition textbook, for the expansion chamber with inlet and outlet ducts and the second term in Equation (8.45) for the closed end tube. The flow Mach number is that corresponding to flow through the inlet and exit ducts for the expansion chamber and past the tube opening for the closed end tube (which is only closed at one end).

In this panel, you are also able to calculate the acoustic impedance of a tube closed at one end that is not designed specifically as a quarter wave tube at some specified frequency. To use this option click on the circle next to the tube specifications.

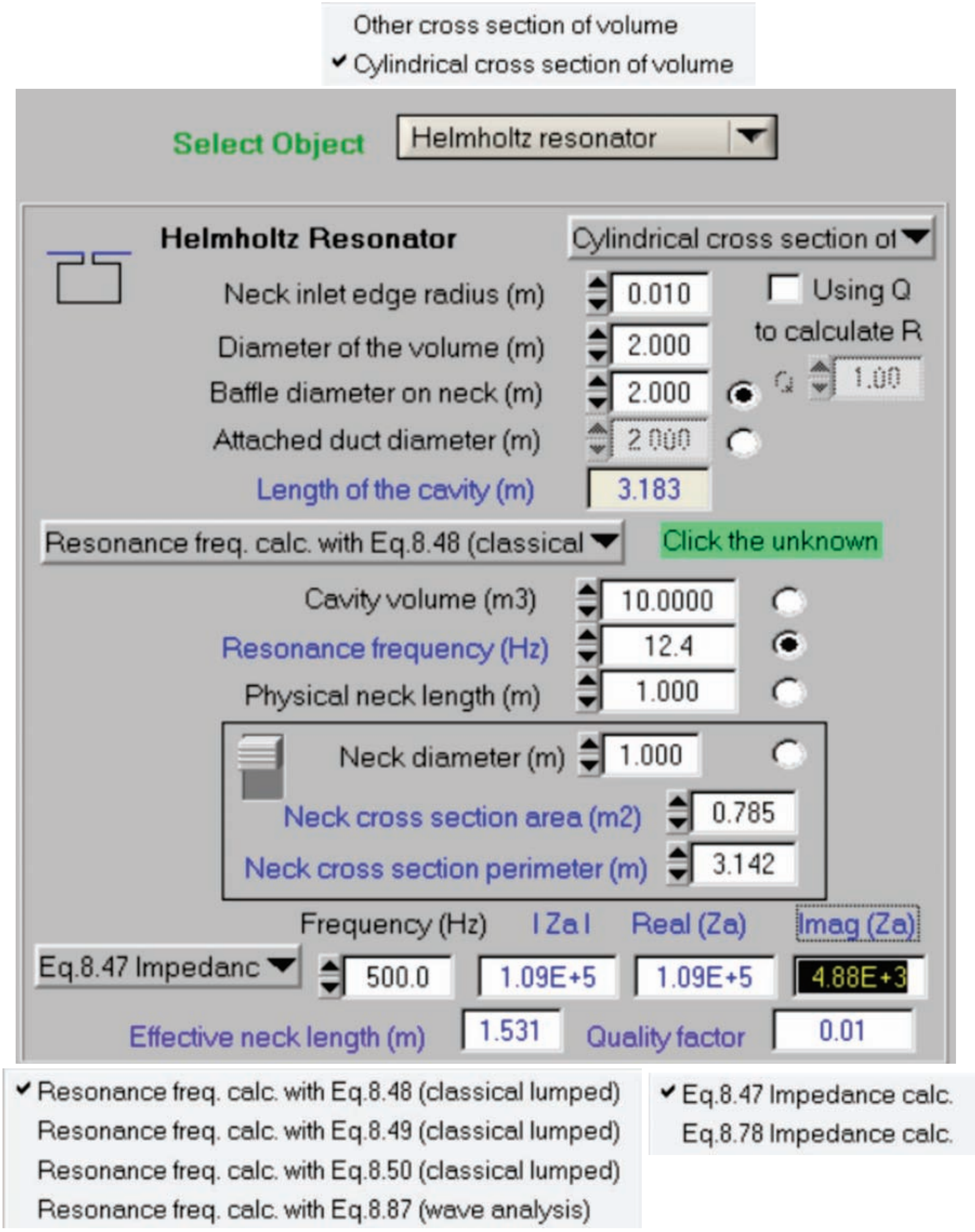
With the required input data entered, click on "run" in the tool bar and the impedance will be plotted at 1/3-octave band intervals on the graph. Note that you must select the desired parameter to be plotted from the data window above the graph. Values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the volume/expansion chamber panel illustrated above.

The maximum valid frequency (indicated below the graph) of the expansion chamber (with inlet and outlet ducts) analysis is the smaller of the frequency corresponding to the cube root of the volume being equal to $\lambda/4$ and the frequency at which cross modes begin to propagate in the inlet and outlet ducts. The maximum valid frequency for the closed end tube analysis is the frequency at which cross modes begin to propagate in the closed end tube.

Note that if the tube option is selected, the effective length of the tube is the actual length plus an end correction calculated using Equation (8.53) multiplied by $(1 - M)^2$ to account for grazing flow past the mouth of the tube. As it is a calculated quantity, it appears in ENC in blue text. The range of allowed diameter for the 1/4-wave tube ranges from 0.2 to 5 times the duct diameter to which it is attached. For a 1/4-wave tube not attached to a duct wall, the end correction for no baffle (or baffle diameter equal to the tube diameter) is calculated using Equation (8.28) and for a very large baffle (of diameter greater than 3 times the tube diameter, Equation (8.25) is used with $\xi = 0$. Linear interpolation for the end correction is used for baffle diameters between one and three times the tube diameter. For a quarter wave tube attached to the side of a duct, the end correction is calculated using Equation (8.28) (multiplied by $(1 - M)^2$ to account for flow past the mouth of the tube) where in this case, ξ is set $= 0$. For a 1/4-wave tube attached to a duct wall, the end correction is calculated using Equation (8.52) in the text (again, multiplied by $(1 - M)^2$ to account for flow past the mouth of the tube).

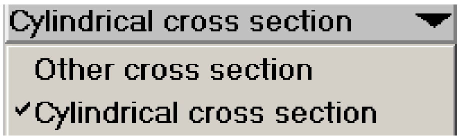
6.3.4 Helmholtz Resonator (see following figure and 6th edition textbook, pages 483–492)

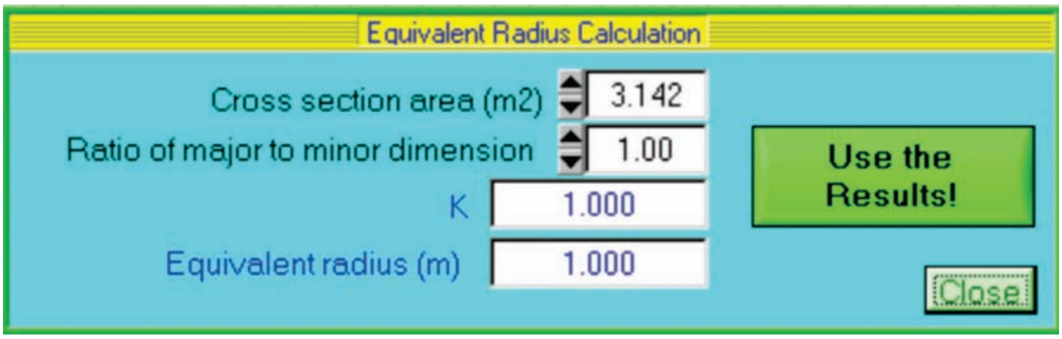
The Helmholtz resonator panel (see following figure enables you to design a Helmholtz resonator by specifying its resonance frequency or calculate the resonance frequency of a specified design. A Helmholtz resonator is made up of a neck and backing volume. The backing volume is also referred to as a cavity.



First, you must specify the neck inlet edge radius. If it is unknown, use 10 mm.

Next, you must choose whether the resonator volume (cavity) is cylindrical in cross section or a different cross section. If cylindrical, then you need to enter the cross sectional diameter of the volume. If "other cross section" is selected, you must click on the green label, "Effective c/s diameter of the volume (m)" button and then in the pop-up window (see below), enter the cross sectional area of the volume and the aspect ratio (major to minor cross sectional dimension, which must be between 1.0 and 2.5). These quantities are used to estimate an equivalent radius of the cross-section and factor, K, of Figure 8.5 on page 478 in the 6^{th} edition textbook, which, in turn, is used to estimate the effective end correction for the neck attached to the volume. Before closing the window, it is important to click on the "use the results" button.





The length of the resonator is calculated from the user entered volume and actual or effective cross sectional area.

Note that the effective length of the resonator neck is the actual length plus an end correction at each end. The end correction for the end attached to the resonator cavity is calculated using Equation (8.51).

For a resonator not attached to a duct, the end correction for the end opposite the cavity and with no baffle (or baffle diameter equal to the neck diameter) is calculated using Equation (8.28) and for a very large baffle (of diameter greater than 3 times the neck diameter, Equation (8.25) is used with ξ=0. Linear interpolation for the end correction is used for baffle diameters between one and three times the tube diameter.

For a Helmholtz resonator attached to the side of a duct, the end correction at the duct end is calculated using Equation (8.52), corrected for grazing flow by multiplying the RHS by $(1-M)^2$. The end correction for the other end is calculated using Equation (8.52) with no Mach number correction. As the total end correction is a calculated quantity, it appears in ENC in blue text.

Impedances in this module in the presence of through flow or grazing flow of Mach number, M, are calculated by substituting $(1 - M)\ell_e$ for ℓ_e in all places. Thus, in the presence of through flow or grazing flow of Mach number, M, the same equations as provided in the 6^{th} edition textbook for impedances without mean flow being present can be used by substituting $(1 - M)\ell_e$ for ℓ_e in all places.

The next step is to select the equation to use for the resonance frequency calculation and the equation to use for the impedance calculation. Basically, the choice is between a lumped element analysis or a 1-D wave analysis (see figure above). Equations (8.47)–(8.50) apply for lumped element analysis, while Equations (8.78) and (8.87) apply for 1-D wave analysis and are considered to be more accurate. Note that for a non circular cross section cavity (or volume), Equations (8.49) and (8.50) cannot be used so you cannot choose either the second or third item in the resonance frequency menu if the "non circular cross section" option is chosen.

Next, you need to click on the circle corresponding to the quantity you wish ENC to calculate. The text corresponding to this quantity will turn blue and all other text will be black. You need to input data for all the values described by black text. The length of the cavity is calculated from its volume and cross sectional area and is an output of ENC. It cannot be selected as an input. However, you have a choice between entering "neck diameter" or "neck cross-sectional area" and "neck cross section perimeter". The latter two quantities are used for necks of non-circular cross section. Use the switch to the left (see figure on previous page) to indicate your choice. Note that if you choose "neck diameter" as the quantity for the software to calculate, it is assumed circular in cross-section and you will not be able to move the switch to the non-circular cross-section option.

Note that the you can choose the lumped element analysis (Equation (8.47)) or the wave analysis (Equation (8.78)) for calculating the resonator impedance. If you choose the "Eq.(8.47)" option, the first term on the RHS of Equation (8.20) is substituted for the last term on the RHS of Equation (8.47) in the 6th edition textbook.

The maximum valid frequency of this analysis (if any of the first 3 items of the resonance frequency menu are selected) is limited to a frequency corresponding to the cube root of the volume being equal to $\lambda/4$ or the cut-on frequency of the first higher order mode propagating in the neck, which is defined by Equation (8.228) in the 6^{th} edition textbook. If the last item in the resonance frequency menu is selected, the maximum valid frequency This frequency is indicated below the graph.

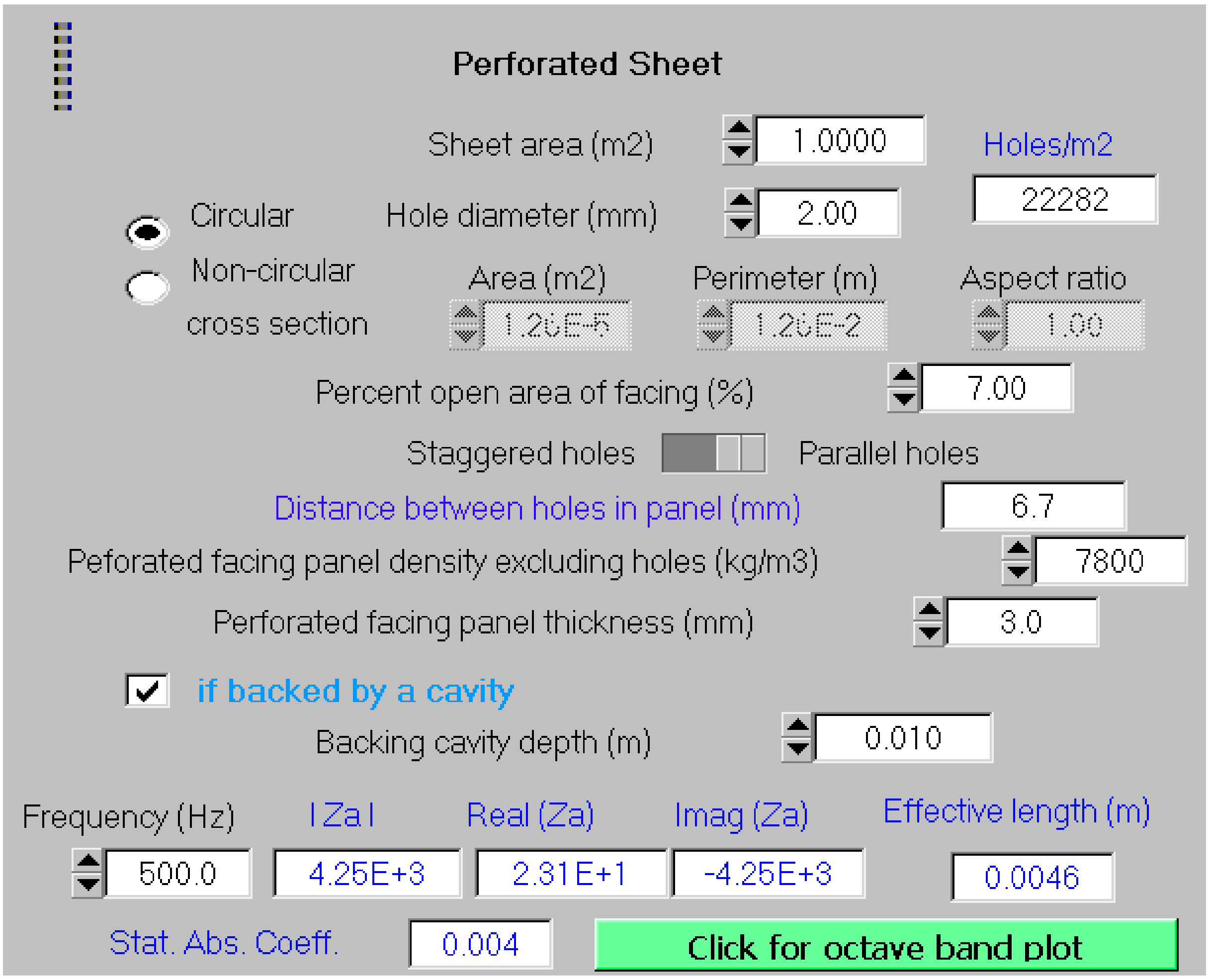
With the required input data entered, click on "run" in the tool bar and the impedance will be plotted at 1/3-octave band intervals on the graph. Note that you must select the desired parameter to be plotted from the data window below the graph. Values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the Helmholtz resonator panel shown above.

Note that ENC also calculates the quality factor for the resonator (at resonance only). The equation used for this is Equation (8.57) in the 6^{th} edition textbook.

Sometimes ENC calculates quality factors that, based on experience, seem too high, so if you prefer, you may enter a value for the quality factor and ENC will use that to calculate the resistive impedance and Insertion Loss. ENC then calculates the acoustic resistance at the resonance frequency of the resonator using Equation (8.57) in the 6^{th} edition textbook. The resistance values at other frequencies are then calculated by multiplying the resistance at the resonance frequency calculated using Equation (8.57) by the ratio of the resistance calculated using Equation (8.34) at frequency of interest to the resistance calculated using Equation (8.34) at the resonance frequency.

6.3.5 Perforated Sheet

The perforated sheet panel (see following figure) enables you to calculate the impedance looking into a perforated panel backed by a cavity and rigid wall. The reactive impedance for the perforated sheet is calculated using Equation (8.24) in the 6th edition textbook. The resistive impedance, R_a for a single hole is calculated using Equation (8.33) in the 6th edition textbook. The effective length of the holes is calculated using Equation (8.30).



You need to enter the length of each hole (the perforated facing panel thickness), the hole edge radius (use 10 mm if unsure) and whether the holes are staggered or parallel. If the holes are circular, click in the circle next to "Circular" and enter the diameter. If the holes are another shape, click on the circle next to "non-circular" and enter the hole cross sectional area, perimeter and aspect ratio. For non-circular holes, Equation (8.27) is used to calculate an effective radius.

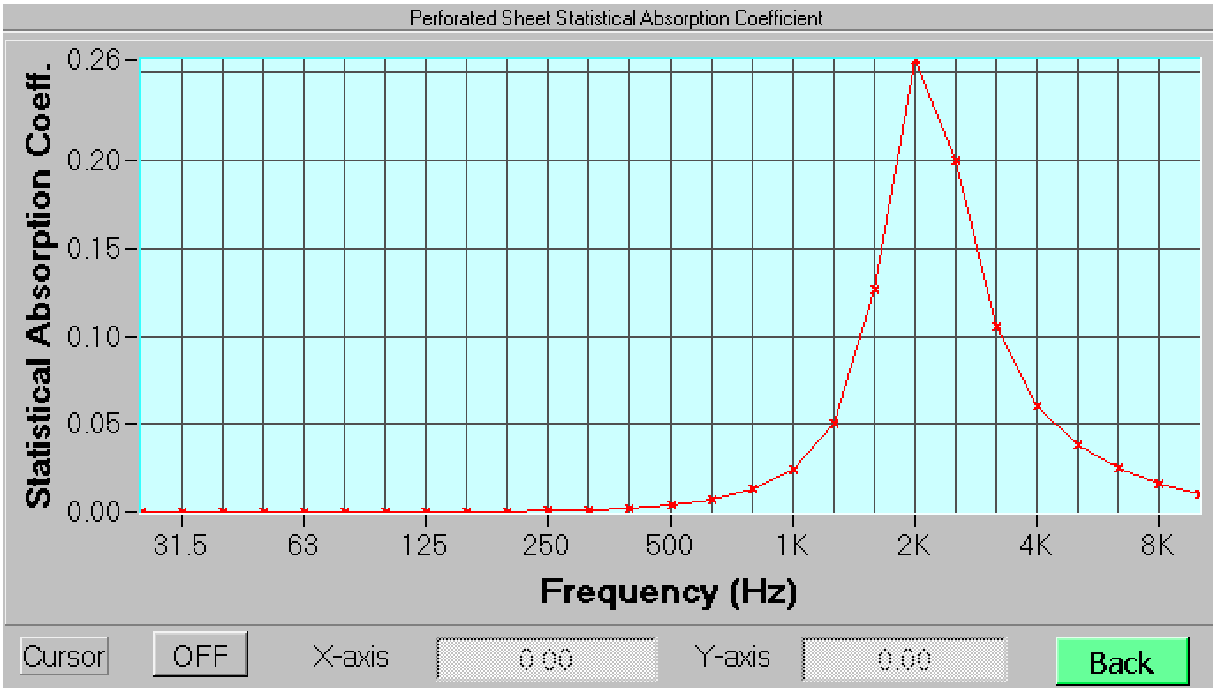
If a backing cavity exists, click on the square box next to "if backed by a cavity" and enter its depth and whether it is partitioned or not to prevent propagation parallel to the plane of the facing. It is assumed that the cavity behind the perforated sheet is terminated by a rigid wall. If no backing cavity is selected, the impedance is calculated for the perforated panel backed by infinite free space (see Equation (8.24) in the 6th edition textbook). If a backing cavity is selected, the impedance of the cavity (Equation

(D.92) in the 6th edition textbook multiplied by the cavity cross sectional area) is added arithmetically to that of the perforated sheet.

Note that the normal impedance is the same for a partitioned or non partitioned cavity. It is only the impedance for waves that are non normally incident that is different for the two cases and of course this means that the statistical absorption coefficient will be different for the two cases as is found in Module 4 — Porous Material Absorber.

At the bottom right of the panel, you can enter any frequency of interest, then click on "Run" and ENC will display the modulus of the acoustic impedance and the real and imaginary parts as well as the calculated statistical absorption coefficient (see figure on the previous page). The real part, imaginary part or the modulus of the impedance can be selected for the graph on the left of the window an as for other plots in this window, the zoom button can be used to obtain a log plot, a higher resolution plot and to specify the frequency range for the plot. Again, the maximum valid frequency for the analysis is shown below the graph. This is the frequency corresponding to the hole diameter being equal to $\lambda/4$.

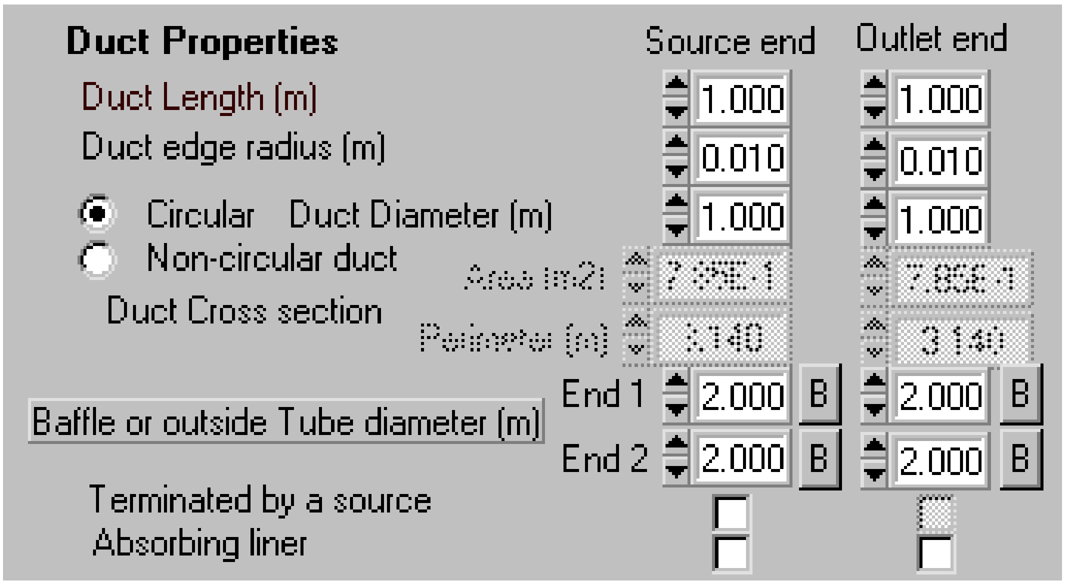
A plot of the statistical absorption coefficient with calculated data at the octave band centre frequencies only can be obtained by clicking on the "click for octave band plot" button — see following figure.



6.4 Reactive Mufflers (6th edition textbook, pages 482–505)

This panel enables you to calculate as a function of frequency, the Insertion Loss of a 1/4-wave tube, a Helmholtz resonator, an expansion chamber, a low pass filter and a small engine exhaust system as described on pages 482–505 in the 6th edition textbook. Note that none of the calculations provide accurate results once any dimension in the muffler exceeds one quarter of a wavelength of sound.

The first thing to do is to enter the properties of the duct connecting the muffler to the noise source (source end) and the duct between the muffler outlet and the atmosphere (outlet end), as shown in the following figure. Each of the ducts has two ends (end 1 being nearest the source), and you need to select whether the duct is circular or non-circular. If the ducts are circular, select the "Circular" option and enter the diameters of each. If the ducts are non-circular, enter cross-sectional area and perimeter of each.



The equivalent diameter of a baffle or an outer tube (if any) at each end of each duct needs to be entered (see 6th edition textbook page 478 for equivalent diameter calculations). The letter "B" corresponds to the tube terminated in a baffle and the letter "T" corresponds to the tube being in a baffle inside another tube. Click on the letter to toggle between "B" and "T". This allows the effect on the effective lengths of the tubes of expansion chambers and low pass filter mufflers that may be connected to the ends of the tubes.

For side branch mufflers such as 1/4-wave tubes and Helmholtz resonators, the baffle or outside tube diameter should be set equal to the duct diameter on which the resonator is mounted for 'source end, end 2' and for 'outlet end, end 1'. No end correction is calculated for the duct ends nearest the side branch resonator as the upstream and downstream ducts effectively join together at the side branch.

Note that for all muffler types, if the duct end is not in a baffle or a tube, select "B" and set the baffle diameter equal to the duct diameter (or the equivalent diameter if the duct is non-circular).

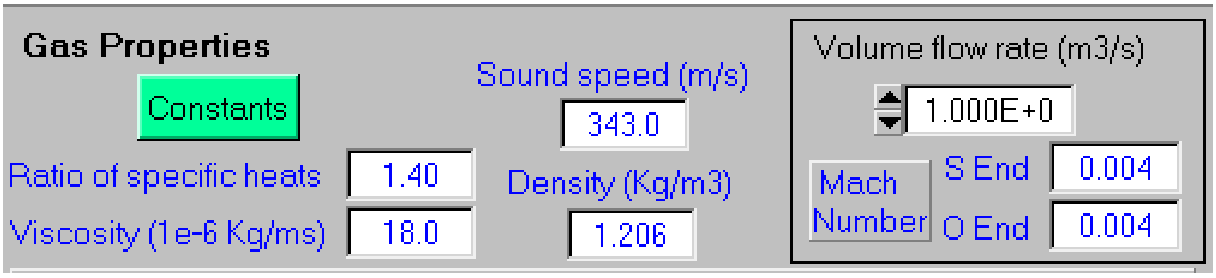
End corrections are calculated using Equations (8.25) and (8.28) in the 6th edition textbook multiplied by $(1 - M)^2$ to account for the effects of flow (whether through or grazing flow).

You also need to enter the length of each duct and the edge radii where they connect to the muffler and exhaust to atmosphere — use 0.01 m for the edge radius if unsure.

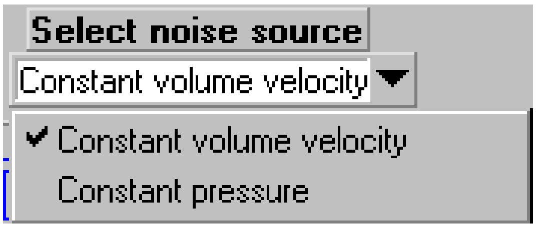
You can also specify if the upstream pipe is terminated by the source (fan or compressor). If so, ENC assumes a reflection coefficient of 1.0 at that end. If not, ENC assumes that the end is open. If you select the "absorbing liner", the analysis assumes that no waves reflected from the end of the duct reach the muffler.

Note that if a small engine exhaust is being designed, none of the data in the "duct properties" panel are used.

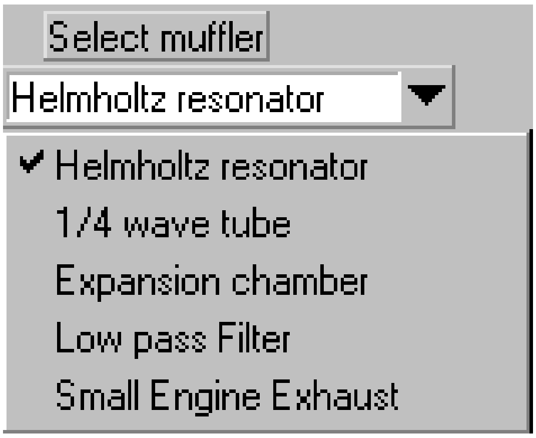
The next thing to do is to enter the properties of the gas flowing through the muffler (top right panel) by clicking on the "Constants" button to bring up the "Constants set-up window. In addition, the volume flow rate must be entered (see following figure). Note that the flow rate is in m^3/sec, not m/s.



The next step is to select the type of noise source: constant volume velocity (reciprocating compressor) or constant pressure (axial or centrifugal fan) by clicking on the box to the right of "Select noise source"as shown in the figure at right. Note that this only affects IL (Insertion Loss) and not TL (Transmission Loss) calculations.



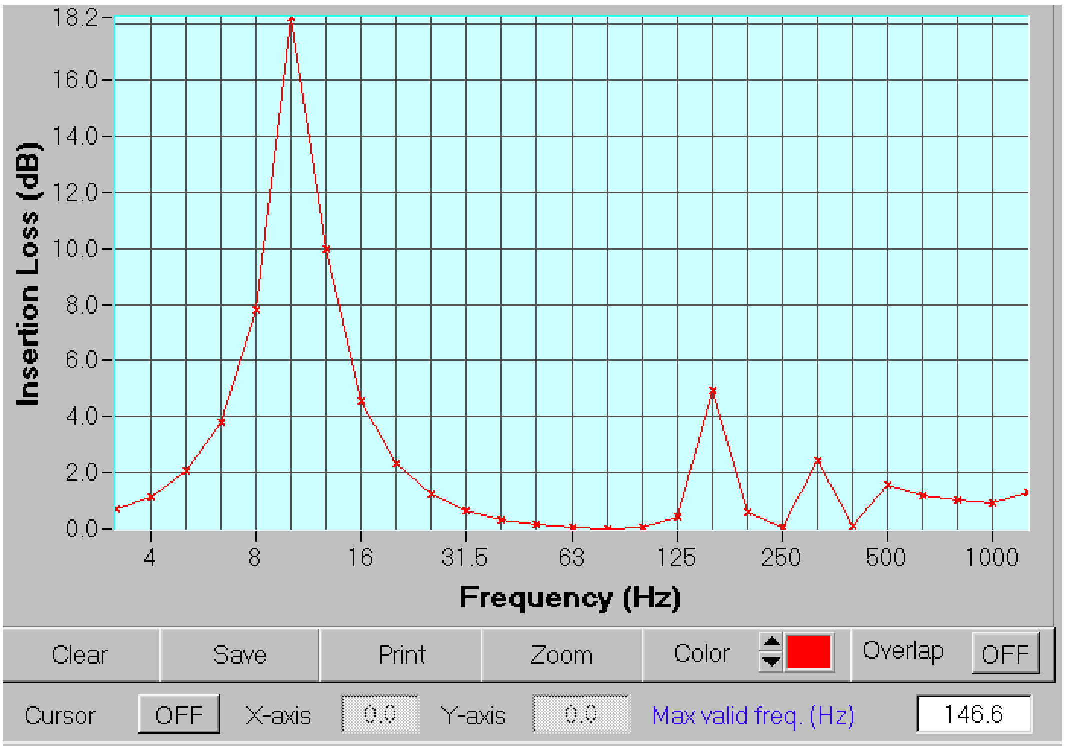
Next select the muffler type (1/4-wave tube, Helmholtz resonator, expansion chamber, low pass filter or small engine exhaust) as shown in the figure at right.

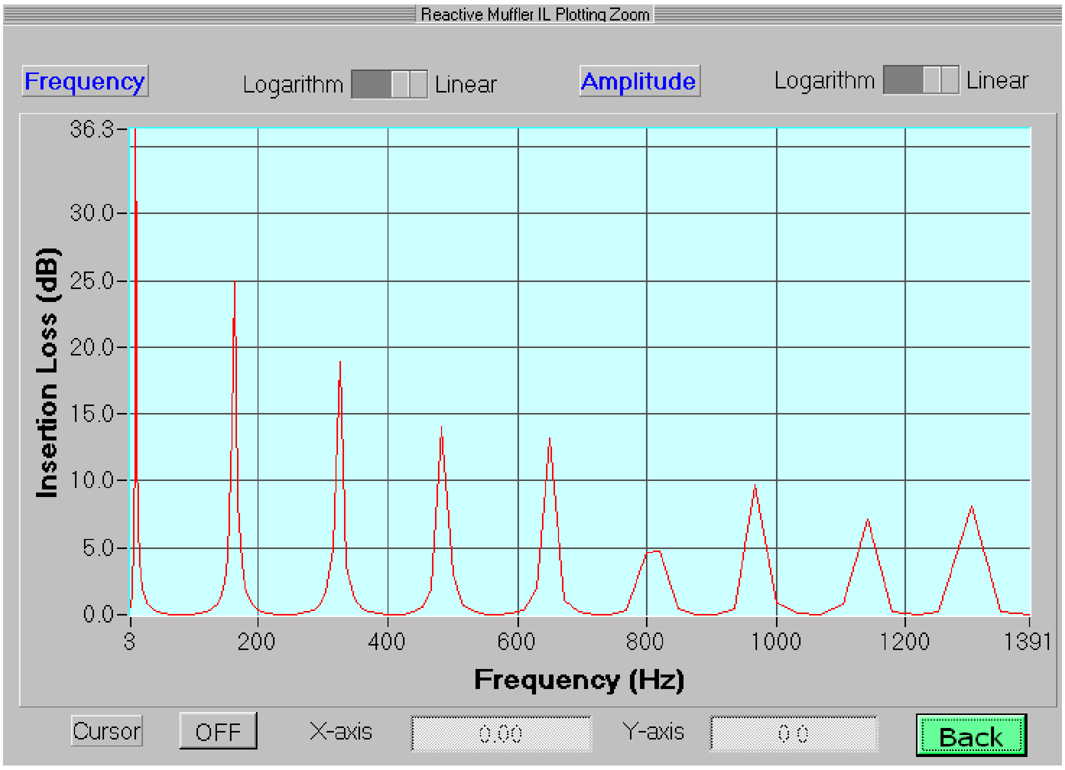


One third octave average Insertion Loss values (averaged over 7 frequencies) are plotted on the graph (see next page) for the muffler type selected. Octave band values (averaged over 20 single frequencies in each band) are provided in the table below the graph.

If you want to select logarithmic axes for the plot or plot data at a finer resolution than 1/3-octave, click on the "zoom" button at the bottom of the graph and the zoomed window will appear, shown as the last figure on the next page.

The maximum valid frequency of the analysis for the Insertion Loss is limited to the frequency corresponding to the largest dimension of any volume being equal to $\lambda/4$ or the cut-on frequency of higher order modes in the inlet and outlet ducts (see Equations (8.231) and (8.233) in the 6th edition textbook).





For the TL calculations based on 1-D wave analysis, the maximum valid frequency corresponds to the frequency at which cross modes begin to propagate in expansion chambers or inlet and outlet ducts (see Equations (8.231) and (8.233) in the 6^{th} edition textbook). The frequency corresponding to the maximum valid frequency is indicated beneath the graph as the "maximum valid frequency".

On the graph, the 1/3-octave band values have been averaged over 7 frequencies in each band. The IL or TL values corresponding to any specified frequency are displayed on the bottom left of the window.

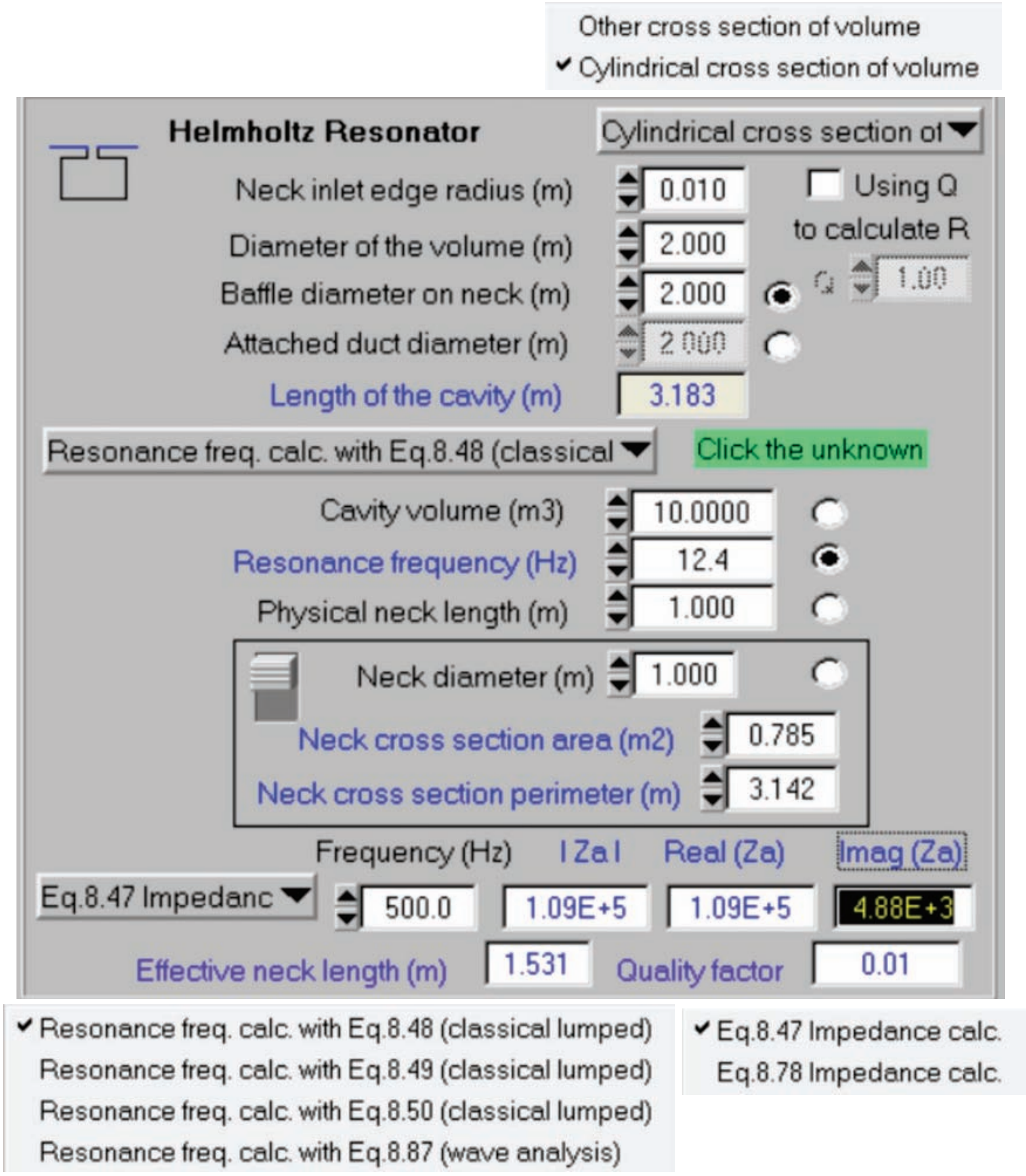
You also need to select the volume flow rate through the muffler using the top right part of the panel.

Note that the flow speed is in cubic metres per second, not metres per second!

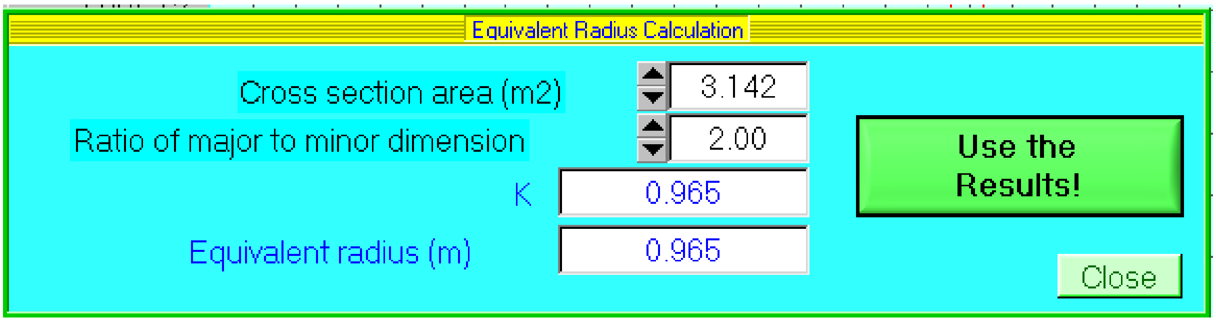
6.4.1 Helmholtz Resonator (See the 6th edition textbook, pages 483–492)

This part (see figure below) enables you to design a Helmholtz resonator by specifying its resonance frequency or calculate the resonance frequency of a specified design. It then calculates and plots the Insertion Loss as a function of frequency.

First, you must specify the neck inlet edge radius (see following figure). If it is unknown, use 0.01 m.



Next, you must choose whether the resonator volume (cavity) is cylindrical in cross section or a different cross section. If cylindrical, then you need to enter the cross sectional diameter of the volume. If "other cross section" is selected, you must click on the green label, "Effective c/s diameter of the volume (m)" button and then in the pop-up window (see below), enter the cross sectional area of the volume and the aspect ratio (major to minor cross sectional dimension, which must be between 1.0 and 2.5). These quantities are used to estimate an equivalent radius of the cross-section and factor, K, of Figure 8.5 on page 478 in the 6^{th} edition textbook, which, in turn, is used to estimate the effective end correction for the neck attached to the volume. Before closing the window, it is important to click on the "use the results" button.



The length of the resonator is calculated from the user entered volume and actual or effective cross sectional area.

Note that the effective length of the resonator neck is the actual length plus an end correction at each end calculated respectively using Equations (8.51) and (8.52), with Equation (8.52) only adjusted for grazing flow of Mach number, M, by multiplying the RHS by $(1 - M)^2$. As it is a calculated quantity, it appears in ENC in blue text.

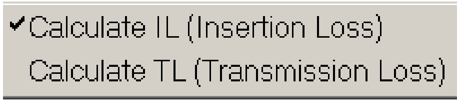
Next, you must enter the diameter of the part of the duct to which the resonator is attached. This is usually the same as the diameter of the inlet and outlet ducts entered in the "Duct Properties" section of the panel. If the duct is non-circular in cross-section, use the cross-sectional dimension from the side containing the resonator to the opposite side. This information is used to calculate the effective length of the neck at the duct end as described on pages 485–486 of the 6^{th} edition textbook.

The next step is to select the equation to use for the resonance frequency calculation and the equation to use for the impedance calculation. Basically, the choice is between a lumped element analysis or a 1-D wave analysis (see previous figure). Equations (8.48)–(8.50) apply for lumped element analysis, while Equation (8.87) applies for 1-D wave analysis and are considered to be more accurate. Note that for a non circular cross section cavity (or volume), Equations (8.49) and (8.50) cannot be used so you cannot choose either the second or third item if the "non circular cross section" option is chosen.

Next you need to click on the circle corresponding to the quantity you wish the software to calculate. The text corresponding to this quantity will turn blue and all other text will be black. You need to input data for all the values described by black text. However, you have a choice between entering "neck diameter" or "neck cross-sectional area" and "neck perimeter". The latter two quantities are used for necks of non-circular cross section. Use the switch to the left (see above figure) to indicate your choice. Note that if you choose "neck diameter" as the quantity for the software to calculate, it is assumed circular in cross-section and you will not be able to move the switch to the non-circular cross-section option. The neck end correction is used in the calculations, but you need to use the ‘‘impedance” panel of this module to see it displayed. The neck length shown here is the physical length, not the effective length.

You next need to choose what impedance calculation will be used for the Transmission Loss (TL) calculations or Insertion Loss (IL) calculations. Equation (8.47) uses lumped element analysis while Equation (8.78) uses 1-D wave analysis.

Finally, you need to choose whether or not you would like TL calculations or IL calculations.



The equations used for the insertion loss calculations are Equations (8.63) and (8.65) in the 6th edition textbook and for the TL calculation, it is Equation (8.80) in the 6th edition textbook. The quality factor is calculated using Equation (8.57) in the 6th edition textbook.

Sometimes ENC calculates quality factors that, based on experience, seem too high, so if you prefer, you may enter a value for the quality factor and ENC will use that to calculate the resistive impedance and Insertion Loss. ENC then calculates the acoustic resistance at the resonance frequency of the resonator using Equation (8.57) in the 6th edition textbook. The resistance values at other frequencies are then calculated by multiplying the resistance at the resonance frequency calculated using Equation (8.57) by the ratio of the resistance calculated using Equation (8.34) in the 6th edition textbook at the frequency of interest to the resistance calculated using Equation (8.34) at the resonance frequency.

The resistive and reactive impedances and the quality factor for the resonator are calculated during the IL and TL calculations, but you need to use the “**I**mpedance” panel of this module to see the impedance values.

With the required input data entered, click on “run” in the tool bar and the 1/3-octave average Insertion Loss will be plotted at 1/3-octave band intervals on the graph. Values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the Helmholtz resonator panel shown previously.

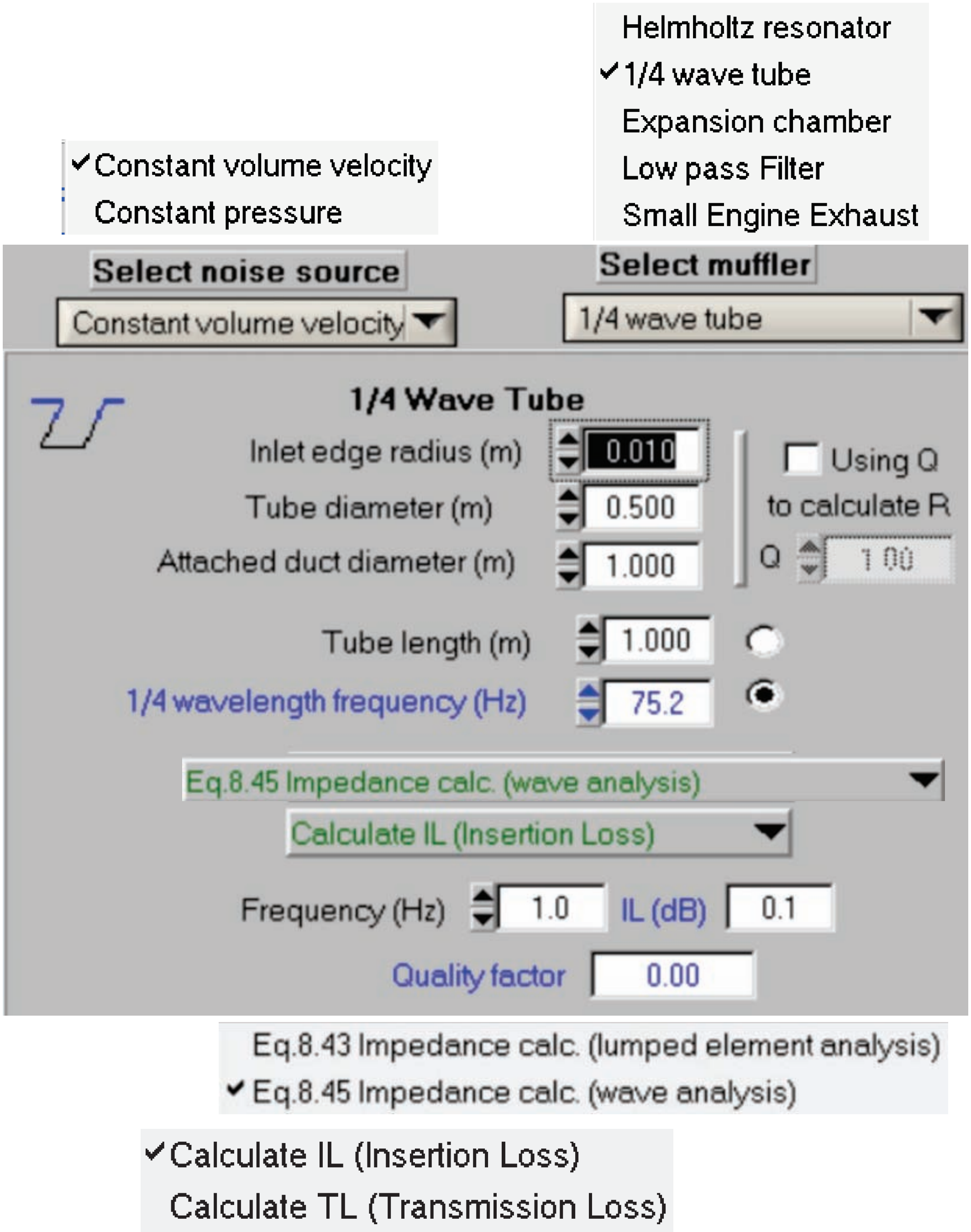
The maximum valid frequency for the lumped analysis for the Insertion Loss or Transmission Loss is is limited to the largest dimension of any resonator component being $\lambda/4$. For the 1-D wave analysis, the upper limiting frequency corresponds to the frequency at which cross modes in the resonator volume begin to propagate (Equations (8.231) and (8.233) in the 6th edition textbook). The frequency corresponding to the upper limiting frequency is indicated beneath the graph.

Note that the flow speed is in cubic metres per second, not metres per second!

6.4.2 1/4-Wave Tube (see below) Insertion Loss calculations (pages 487–489 in 6th edition textbook)

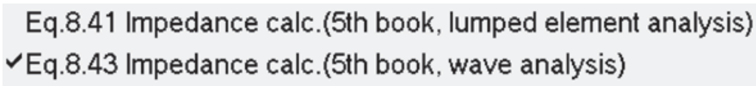
For the 1/4-wave tube (see figure on next page), the inlet edge radius is the radius of the edge where the 1/4-wave tube joins the structure (usually a duct) on which it is mounted. If you do not know the value, use 10 mm.

Next, you must enter the diameter of the part of the duct to which the 1/4-wave tube is attached. This is usually the same as the diameter of the inlet and outlet ducts entered in the “Duct Properties” section of the panel. If the duct is non-circular in cross-section, use the cross-sectional dimension from the side containing the 1/4 wave tube to the opposite side. This information is used to calculate the effective length of the 1/4-wave tube at the duct end as described on pages 485–486 of the 6th edition textbook.

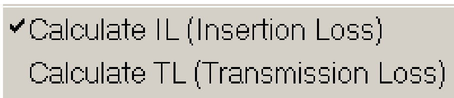


After specifying the 1/4-wave tube diameter, you may specify the length and have the software calculate the corresponding resonance frequency or you may specify the resonance frequency you desire and the software will calculate the required length. Just click on the appropriate circle to the right of the data boxes. The quantity calculated by the software is in blue text. The paragraph above Equation (8.46) in the 6th edition textbook is the basis of this calculation. The end correction for the tube may be calculated using the "impedance" panel and is based on Equation (8.28) in the 6th edition textbook.

The quality factor at resonance is provided at the bottom of the panel and is calculated using Equation (8.58) in the 6th edition textbook. Sometimes ENC calculates quality factors that, based on experience, seem too high, so if you prefer, you may enter a value for the quality factor and ENC will use that to calculate the resistive impedance and Insertion Loss. ENC then calculates the acoustic resistance at the resonance frequency of the resonator using Equation (8.58) in the 6th edition textbook. The resistance values at other frequencies are then calculated by multiplying the resistance at the resonance frequency calculated using Equation (8.58) by the ratio of the resistance calculated using Equation (8.34) at frequency of interest to the resistance calculated using Equation (8.34) at the resonance frequency.



You next need to choose what impedance calculation will be used for the Transmission Loss (TL) calculations or Insertion Loss (IL) calculations. Equation (8.43) uses lumped element analysis while Equation (8.45) uses 1-D wave analysis.



Finally, you need to choose whether or not you would like TL calculations or IL calculations.

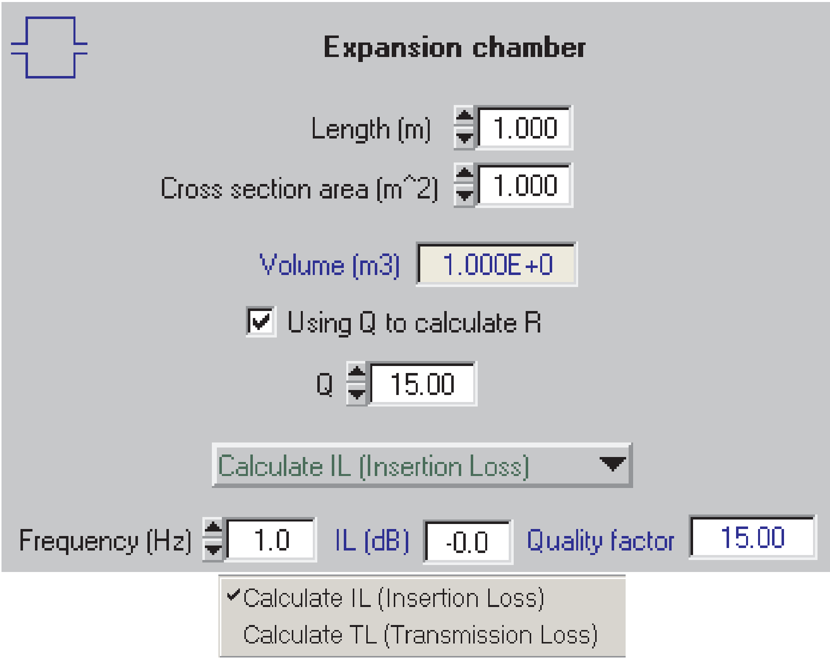
The equations used for the insertion loss calculations are Equations (8.63) and (8.65) and for the TL calculation, it is Equation (8.76) in the 6th edition textbook. The quality factor is calculated using Equation (8.58) in the 6th edition textbook.

The resistive and reactive impedances for the 1/4-wave tube are calculated during the insertion loss calculations, but you need to use the "**I**mpedance" panel of this module to see the impedance values. If you prefer, you may enter a value for the quality factor and ENC will use that to calculate the resistive impedance and Insertion Loss.

With the required input data entered, click on "run" in the tool bar and the 1/3-octave average Insertion Loss will be plotted at 1/3-octave band intervals on the graph with octave band averages tabulated below the graph. Values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the 1/4-wave panel illustrated on the previous page.

The maximum valid frequency for the lumped analysis for the Insertion Loss or Transmission Loss is limited to the largest dimension of the 1/4-wave tube being $\lambda/4$. For the 1-D wave analysis, the upper limiting frequency corresponds to the frequency at which cross modes in the 1/4-wave tube or the inlet and outlet ducts begin to propagate (Equations (8.231) and (8.233) in the 6th edition textbook). The frequency corresponding to the maximum valid frequency is indicated beneath the graph.

6.4.3 Expansion Chamber (see following figure) (6th edition textbook, pages 494–500)



The expansion chamber panel (see above figure) calculates the Insertion Loss and Transmission Loss for an expansion chamber inserted into a duct. The input data required are the expansion chamber volume for the Insertion Loss calculation and expansion chamber length and cross sectional area for the Transmission Loss calculation. For the case of a closed end tube mounted to the side of a duct, the insertion loss is the same as for a 1/4-wave tube discussed previously. **Note that the flow rate (entered in the top tight of the page) is in cubic metres per second, not metres per second!**

The maximum valid frequency of the analysis for the Insertion Loss is is limited to the largest dimension of the expansion chamber being equal to $\lambda/4$ or the frequency at which cross modes begin to propagate in the inlet or outlet ducts (see Equations (8.231) and (8.233) in the 6th edition textbook). The frequency corresponding to the upper limiting frequency is indicated beneath the graph.

You may see displayed the impedance of the components used to make up the expansion chamber muffler by using the "**I**mpedance" panel of this module.

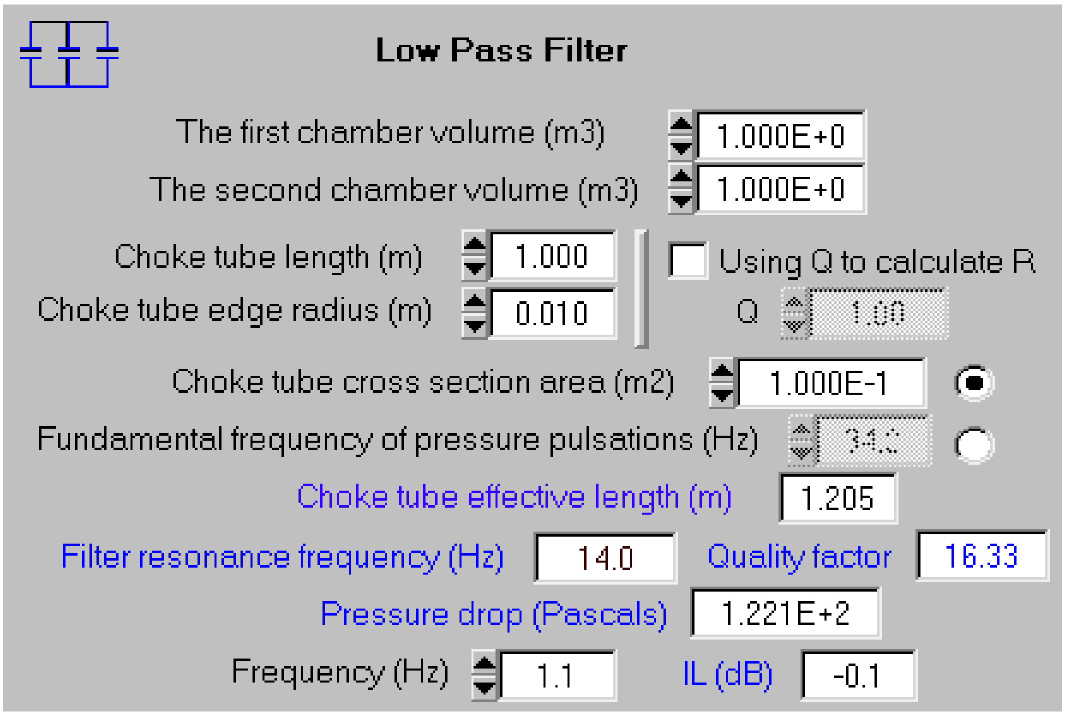
The quality factor at resonance is provided at the bottom of the panel and is calculated using Equation (8.58) in the 6th edition textbook, where R_s is the acoustic resistance of the tail pipe, ℓ is the tail pipe length, A is the tail pipe cross-sectional area and V is the expansion chamber volume, all in consistent units. Note that this expression is approximate and the error increases as the tail pipe length increases.

Alternatively, you may enter a value for the quality factor in the preceding panel if you wish and ENC will calculate the corresponding resistance and use that to calculate the insertion loss. The quality factor for the expansion volume muffler is applicable to its first resonance frequency (the first minimum in the TL curve).

With the required input data entered, click on "run" in the tool bar and the 1/3-octave average Insertion Loss values (averaged over 7 frequencies) will be plotted at 1/3-octave band intervals on the graph with octave band averages tabulated below the graph. Values corresponding to intermediate frequencies can be determined by typing in the frequency of interest in the expansion chamber panel illustrated above.

6.4.4 Low Pass Filter (6th edition textbook, pages 501–505)

This panel (see following figure) is used for the design of a low pass filter to remove pressure pulsations from piping systems (usually due to reciprocating compressors). You need to enter the volumes of the two chambers involved and the choke tube dimensions. Then you have a choice of either entering the fundamental frequency of the pressure pulsations or the choke tube cross-sectional area. If you enter the former, ENC will calculate an appropriate choke tube diameter so that resonance frequency of the filter is 0.65 times the frequency of the pulsations. If the resulting choke tube diameter is too small (to satisfy pressure drop considerations) you will have to use a longer choke tube and/or larger volumes. If you choose to enter the choke tube diameter, ENC will calculate the frequency of pressure pulsations, which is 1.54 times the resonance frequency of the filter.



Click on "run" in the tool bar and the software will calculate the Quality factor, resonance frequency, pressure drop and Insertion Loss for the selected frequency. The quality factor corresponds to the resonance frequency of the entire system (muffler and connecting ductwork). The resonance frequency corresponds to the first minimum in the TL curve. The frequency calculated using Equation (8.132) in the 6th edition textbook is usually an overestimate (by up to 50%).

Calculated 1/3-octave average Insertion Loss values will be plotted at 1/3-octave band intervals on the graph with octave band averages tabulated below the graph.

The quality factor at resonance is provided at the bottom of the panel and is calculated using Equation (8.58) in the 6th edition textbook, where R_s is the acoustic resistance of the choke tube, ℓ_e is the choke tube length, S is the tail pipe cross-sectional area and V is the expansion chamber volume, all in consistent units. Note that this expression is approximate and the error increases as the choke tube length increases. You may also enter a value for the overall quality factor and in this case ENC will calculate the effective acoustic resistance using the above equation for use in calculating the insertion loss. The resistance values at other frequencies are then calculated by multiplying the resistance at the resonance frequency calculated using Equation (8.58) by the ratio of the resistance calculated using Equation (8.34) at frequency of interest to the resistance calculated using Equation (8.34) at the resonance frequency.

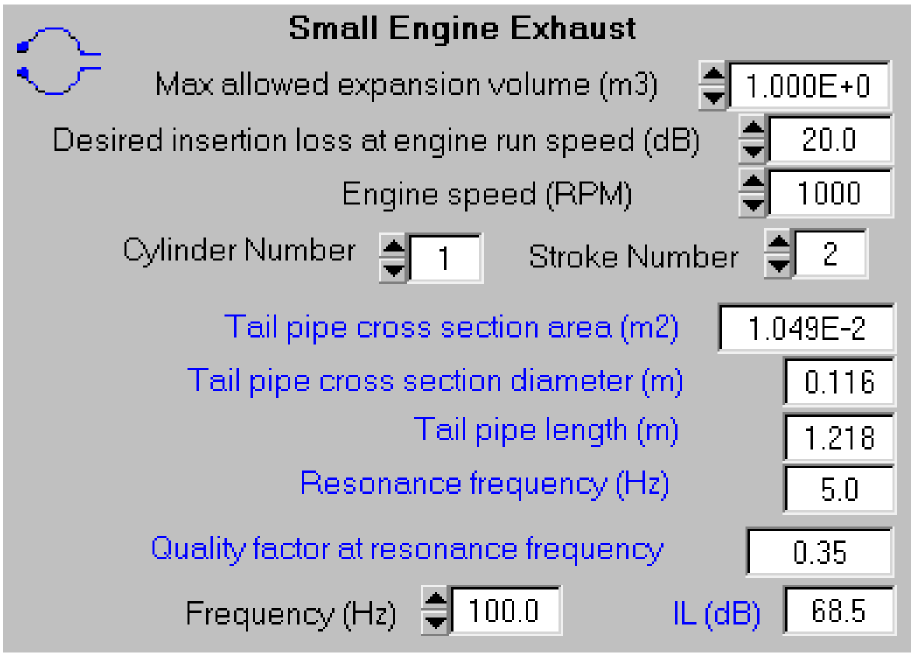
The maximum valid frequency corresponds to the smaller of the largest volume dimension being equal to $\lambda/4$ or the onset of higher order mode propagation in the inlet and outlet ducts and/or choke tube. This frequency is calculated by ENC and displayed under the graph.

Note that the flow speed input is a volume flow in cubic metres per second, not metres per second!

6.4.5 Small Engine Exhaust (See 6th edition textbook, pages 500–501)

The configuration for the small engine exhaust is the same as used in the expansion chamber panel, except that a constant volume velocity source is assumed and an attempt is made to optimise the insertion loss while minimizing the pressure loss.

You must input the parameters in black text (see following figure) and the software will calculate those in blue text. The required inputs are engine speed and the Insertion Loss that you desire for this engine speed as well as the maximum allowable expansion chamber volume.



The quality factor is calculated as for the Helmholtz resonator using the impedance of the exhaust pipe as the inductance and the expansion chamber volume as the capacitance. The duct properties data for the diameter of the tail pipe are not used. However, the edge radius from the duct properties panel and the tail pipe diameter calculated in this panel are used for calculating the quality factor. If you do not know what this is, enter 10 mm in the duct properties panel.

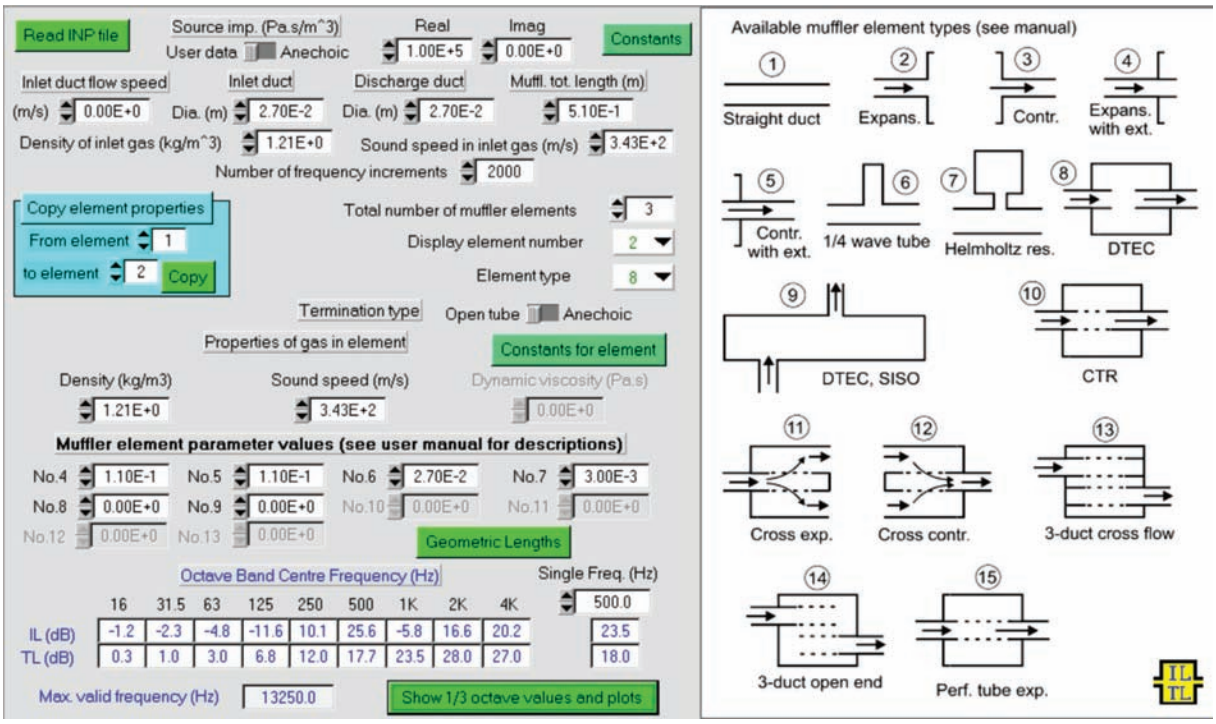
Note that you will get nonsensical results if you use a zero volume flow rate. **N**ote that the flow speed input is a volume flow in cubic metres per second, not metres per second!

With the required input data entered, click on "run" in the tool bar. ENC will calculate the tail pipe diameter and length as well as the resonance frequency of the exhaust system. The calculated 1/3-octave band averaged Insertion Loss will be plotted at 1/3-octave band intervals on the graph and octave band averages will be provided in the table beneath the graph. Insertion Loss values for individual frequencies are output for any frequency value entered in the box at the bottom of the small engine exhaust panel (see preceding figure).

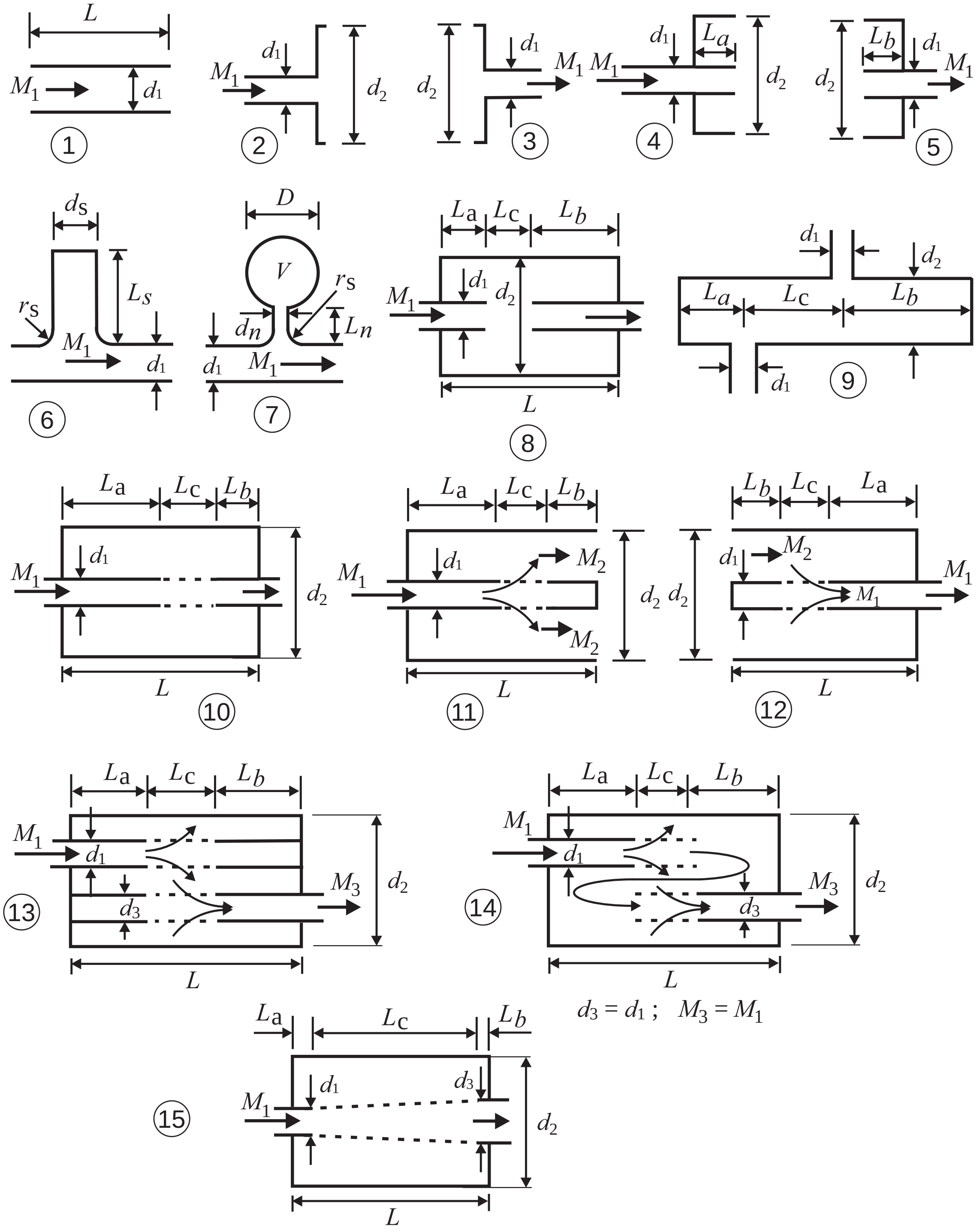
The maximum valid frequency is the smaller of the frequency corresponding to the cube root of the volume being equal to $\lambda/4$ or the cut-on frequency of higher order modes in the tail pipe.

If you wish to calculate the insertion loss for a fixed expansion chamber volume and tail pipe parameters, then use the expansion chamber selection in this panel.

6.5 4-Pole Analysis - Reactive Mufflers (6th edition textbook, pages 506–524)



This page in ENC allows users to apply the 4-pole method to calculate the TL and IL of a muffler system consisting of any number of basic elements such as tubes, sudden expansions, sudden contractions temperature gradients and perforated tubes (up to a maximum of 200 elements), as illustrated in the figures on page 207. The muffler elements currently available to join together to make up a muffler system are shown in the figures on page 207, which are duplicated in ENC. Dimensions of the muffler elements referred to in the tables on pages 209 and 210 are shown in the figure on page 208.



Note that ENC assumes circular-section tubes. However, it is possible to apply the analysis to tubes of different cross-section by entering an equivalent diameter, d, where $d = \sqrt{(4/\pi) \times \text{area of non-circular cross section}}$.

Parameters 4 to 8 descriptions

Type No.	Descr.	Parameter 4	Parameter 5	Parameter 6	Parameter 7	Parameter 8
1	Straight duct	Duct dia., d_1(m)	Duct length*, L(m)	–	–	–
2	Sudden expansion	Upstream duct dia., d_1(m)	Chamber diameter d_2(m)	Duct axis offset d_o(m)	–	–
3	Sudden contraction	Chamber diameter d_2 (m)	Downst. duct dia., d_1(m)	Duct axis offset d_o(m)	–	–
4	Sudden exp. with extension	Upstream duct dia., d_1(m)	Chamber diameter d_2(m)	Length tube in chamber L_a(m)	Inlet tube thickness t_w(m)	–
5	Sudden contr. with extension	Chamber diameter d_2(m)	Downst. duct dia. d_1(m)	Length tube in chamber L_b(m)	Exit tube thickness t_w(m)	–
6	1/4-wave tube	Duct dia. under res., d_1(m)	Resonator entry dia. d_s(m)	Resonator length* L_s(m)	Edge radius, resonator entry, r_s(m)	Perf. plate hole dia. d_h(m)
7	Helmholtz resonator	Duct dia. under res, d_1(m)	Neck diameter d_n(m)	Neck length* L_n(m)	Cavity diameter* D(m)	Cavity volume* V(m^3)
8	Double-tuned exp. chamber (DTEC)	Chamber diameter d_2(m)	Chamber length* L(m)	Inlet tube diameter d_1(m)	Inlet tube thickness t_w(m)	Correction to inlet tube extension (m)
9	side input side exit DTEC	Chamber diameter d_2(m)	Chamber length* L(m)	Inlet tube diameter d_1(m)	Inlet tube thickness t_w(m)	Correction to inlet tube location (m)
10	Conc. tube resonator (CTR)	Chamber diameter d_2(m)	Chamber length* L(m)	Perf. tube diameter d_1(m)	Perf. tube hole dia. d_h(m)	Perf. hole separation d_s(m)
11	Cross flow expansion	Chamber diameter d_2(m)	Length tube in chamber* L_a+L_b+L_c(m)	Length perf. tube L_c(m)	Length stub tube L_b(m)	Perf. tube diameter d_1(m)
12	Cross flow contraction	Chamber diameter d_2(m)	Length tube in chamber* L_a+L_b+L_c(m)	Length perf. tube L_c(m)	Length stub tube L_b(m)	Perf. tube diameter d_1(m)
13	3-duct cross flow	Chamber diameter d_2(m)	Chamber length* L(m)	Inlet tube diameter d_1(m)	Inlet ext. length (up to perf.) L_a (m)	Exit ext. length (up to perf.) L_b (m)
14	3-duct open ends	Chamber diameter d_2(m)	Chamber length* L(m)	Inlet tube diameter d_1(m)	Inlet ext. length (up to perf.) L_a (m)	Exit ext. length (up to perf.) L_b (m)
15	Perf. tube + expansion chamber	Chamber diameter d_2(m)	Chamber length* L(m)	Inlet tube diameter d_1(m)	Exit tube diameter d_3(m)	Perf. tube hole dia. d_h(m)

Parameters 9 to 13 descriptions

Type No.	Descr.	Parameter 9	Parameter 10	Parameter 11	Parameter 12	Parameter 13
1	Straight duct	–	–	–	–	–
2	Sudden exp.	–	–	–	–	–
3	Sudden contr.	–	–	–	–	–
4	Sudden exp. with extension	–	–	–	–	–
5	Sudden contr. with extension	–	–	–	–	–
6	1/4-wave tube	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hexagonal	Perf. plate thickness t(m)	Flow resistance MKS Rayls	–
7	Helmholtz resonator	Edge radius, resonator entry, r_s(m) or perf. plate hole dia. d_h(m)	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hex.	Perf. plate thickness t(m)	Flow resistance MKS Rayls
8	Double-tuned exp. chamber (DTEC)	Correction to exit tube extension (m)	–	–	–	–
9	side input side exit DTEC	Correction to exit tube location (m)	–	–	–	–
10	Conc. tube resonator (CTR)	Perf. grid 1=square 2=hexagonal	Perf. tube thickness t(m)	Correct. to inlet tube ext. (m)	Correct. to exit tube ext. (m)	–
11	Cross flow expansion	Perf. tube hole dia. d_h(m)	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hex.	Perf. tube thickness t(m)	–
12	Cross flow contraction	Perf. tube hole dia. d_h(m)	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hex.	Perf. tube thickness t(m)	–
13	3-duct Cross flow	Exit tube diameter d_3(m)	Perforated tube, hole dia.d_h(m)	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hex.	Perf. tube thickness t(m)
14	3-duct open ends	Exit tube diameter d_3(m)	Perforated tube, hole dia.d_h(m)	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hex.	Perf. tube thickness t(m)
15	Perf. tube + expansion chamber	Perf. hole separation d_s(m)	Perf. grid 1=square 2=hexagonal	Perf. tube thickness t(m)	Inlet ext. length L_a (m)	Exit ext. length L_b (m)

For the calculation of insertion loss, is necessary to include the tube between the source and muffler system as well as the tube from the muffler system to the discharge as additional muffler elements in the overall muffler system. The radiation impedance is calculated using the properties of the gas in the discharge tube.

Below is a detailed description of each data entry item, beginning at the top left of the figure on page 208.

1. *Read INP file.* Clicking on this item will load the data that is currently in the input file (fourpole.inp) that can be found in the ENC6.x directory. These data can be manually changed, but it is probably more convenient to enter the data changes on the GUI and save them by clicking on "Run". Remember that the page shown on the GUI can be saved by clicking on "File", then "save" on the top line of the GUI.

2. *Source impedance*, Real and Imaginary. If the switch is set to choose "User data", the real and imaginary components of this impedance may be entered in the two adjacent data boxes. In practice, this impedance varies greatly with frequency and only affects the IL calculations. To obtain accurate IL values at a particular frequency, the source impedance is entered for that frequency and the IL results will only apply to that frequency. To obtain an approximate idea of the 1/3-octave and octave band IL levels, it is recommended to use the default values of 10^5 for the real part and 0.0 for the imaginary part.
   Alternatively, if the switch is set to "Anechoic", calculations will be undertaken assuming that the upstream impedance seen by the muffler has a real part given by $\rho c/S$ and an imaginary part of zero. ENC will calculate the real part and enter it in the box under the title, "Real".

3. *Inlet duct flow speed (m/s).* This is the speed of flow in the inlet tube that precedes the muffler system or is the first element in the muffler system.

4. *Inlet duct diameter (m).* This is diameter of the inlet tube that precedes the muffler system or is the first element in the muffler system.

5. *Discharge duct diameter (m).* This is diameter of the duct that exits to free space.

6. *Muffler tot. length (m).* This is the total muffler length from the beginning of the inlet tube to the exit of the discharge tube. It is only used for IL calculations.

7. *Density of inlet gas (kg/m^3).* This is the density of gas on inlet to the muffler inlet tube.

8. *Sound speed in inlet gas (m/s).* This is the speed if sound in the gas on inlet to the muffler inlet tube. It can be obtained by clicking on the green "Constants" button.

9. *Number of frequency increments.* This is the number of data points to be used across the entire frequency range from 11.2 Hz to 5623 Hz (octave band centre frequencies from 16 Hz to 4000 Hz). For calculating octave and 1/3-octave band levels, the IL or TL is averaged over the same number of values in each 1/3-octave band with the values spaced such that the logarithm of the frequency increment is constant.

However, the plots are made with data spaced at constant frequency intervals where the frequency increment between data values is constant. The maximum allowable value is 10000.

10. *Total number of muffler elements.* A muffler system is composed of basic building blocks called "muffler elements". Available elements are illustrated and numbered in the illustrations to the right of the data input GUI. The value in this data box is the number of muffler elements that make up the total muffler system. The maximum allowable value is 200.

11. *Display element number.* The muffler elements that make up your muffler system must be numbered (beginning with 1) from the sound source side to the discharge side. This data box contains the number that you have designated to this element in your muffler system. The elements used must include the straight pipe connecting the sound source to your muffler and the discharge pipe from your muffler to the atmosphere. The incorporation of these pipes only affects the IL, not the muffler TL. The number in this data box is the muffler element to which the properties of gas in element and muffler element parameter values apply.

12. *Element type.* This value in this data box is the number that identifies the particular muffler element. It is the number in the illustrations to the right of the GUI, which identifies the element type.

13. *Termination type.* This switch allows users to choose either an open ended tube termination or an anechoic termination. The open-ended tube radiation impedance is used for the "Open tube" selection and for the "Anechoic" selection, the real impedance is $\rho c/S$ and the imaginary impedance is zero.

14. *Constants for element.* Clicking on this button allows you to determine the "sound speed (m/s)" and the "density (kg/m^3) of the gas in the muffler element identified as the number in item 11 above. These numbers are automatically entered in the corresponding data boxes. The numbers can also be entered manually in the data boxes if desired.

15. *Muffler element parameters 4 to 13.* These parameters are described in the tables on pages 209 and 210. Note that all input muffler element dimensions are actual physical dimensions. Extension tube lengths for tubes with extensions into expansion chambers are increased by ENC to account for end corrections prior to calculating TL and IL values. For DTEC and CTR muffler elements, the physical lengths corresponding to the optimal design are output in a separate table.

16. *Single freq.* (Hz). This allows one to enter a frequency value and obtain the corresponding IL or TL (blue font below the frequency value).

The input data for calculating the muffler system TL and IL are in the text file, "fourpole.inp". This file can be modified by the user outside of ENC and then ENC can use the new data by clicking on the green "Read INP file" on the ENC GUI. The first line in the input file contains (in order) the following quantities.

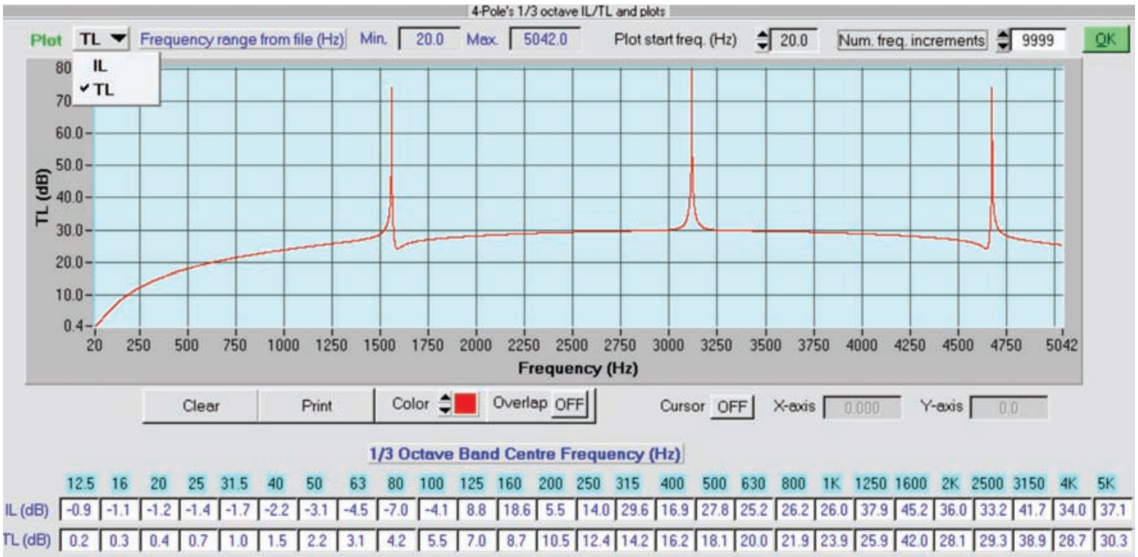
1. Number of muffler elements making up the muffler system. The maximum allowable value is 200.
2. Density of gas in the muffler system inlet tube (kg/m^3).
3. Speed of sound in the muffler system inlet tube (m/s).
4. Flow speed in the muffler system inlet tube (m/s).
5. Diameter of the muffler system inlet tube (m).
6. Diameter of the muffler system discharge tube (m).
7. Total length of the muffler system (m).
8. The real part of the source impedance (Pa-s/m^3).
9. The imaginary part of the source impedance (Pa-s/m^3).
10. Number of frequencies to use in calculations of 1/3-octave and octave values as well as in single frequency plots. The maximum allowable value is 10000.
11. The single frequency for which values if IL and/or TL are required.

The second and subsequent lines of the input data file contain the following values, with one line for each muffler element. On each line the values, in order, are:

1. Density of gas (kg/m^3) in the muffler element.
2. Speed of sound in the muffler element (m/s).
3. Dynamic viscosity of gas (Pa-s) in the muffler element (element types 6 and 7) or not used (element types 1–5 and 8–14).
4. The remaining values on each line are provided in the same order in the tables on pages 209 and 210.

The available output data are listed below.

1. The Octave band average data are shown in the table at the bottom of the page.
2. Clicking on the "Geometric lengths" button (see figure on page 207) will produce a list of required geometric lengths, L_a, L_b and L_c for muffler element types 8–14 (see figures on page 208), which will produce the IL and TL results shown on the GUI and plots. There is one line of data for each element with a type number in the range 8–14, which is used in the overall muffler system.
3. The 1/3-octave values and narrow band plots are shown on a separate popup page (see following figure) when the "Show 1/3 octave values and plots" button is clicked.



The IL values require calculation of the radiation impedance at the muffler discharge to the atmosphere. This calculation requires a knowledge of the speed of sound at the muffler system exit. The value used in ENC is the speed of sound entered on the GUI for the last muffler element a9which should be the one closest to the system discharge.

Each muffler element is characterised by between 5 and 13 parameters. The first 3 parameters are the density of gas in the muffler, the speed of sound and the dynamic viscosity of the gas in the muffler, with the viscosity value only used for muffler element types 6 and 7. These first three parameters are entered on the GUI near the centre of the page. The remaining parameters (4-13, described in the tables on pages 209 and 210) must be entered on the GUI below the first three. A dash entry in the tables indicates that the parameter is not required for the calculations.

The muffler element dimension used to calculate the normalised frequency is indicated by an asterisk in the table on page 209. This dimension is denoted L in the following equation which is used to calculate the normalised frequency, f_{norm}. Note that muffler element types 2, 3, 4 and 5 do not have any parameters identified with an asterisk as these elements cannot be used in isolation.

$$f_{\text{norm}} = 2Lf/c \tag{6.1}$$

where f is the frequency and c is the speed of sound.

The normalised frequency is only relevant and calculated for muffler element type number 1 and those with a type number greater than 5. For the Helmholtz resonator element (type number 7), three dimensions are used to calculate the normalised frequency. These are the neck length, the chamber diameter and the chamber volume. The chamber diameter and volume are used to calculate the effective chamber length and this is added to the neck length to obtain the dimension used to calculate the normalised frequency. For muffler systems with more than 1 normalised length, the smallest one is used. The inlet and discharge tubes are not considered in the frequency normalisation process.

The maximum valid frequency for the analysis is based on ensuring that plane waves dominate the response and this occurs at a frequency, $f_{\max}$ dependent on the muffler element with the largest diameter, $d_{\max}$, by $f_{\max} = c/d_{\max}$.

6.5.1 Sudden Expansion and Contraction Notes (Element types 2–5)

Equation (8.147) in the textbook, which describes the transmission matrix for sudden expansions and contractions can be made more accurate by taking into account the evanescent higher order modes that are generated due to the sudden cross-sectional area change. The adjusted equation, used in ENC calculations is (for $M_d < 0.2$)(Munjal, 2008, p. 800):

$$\mathbf{T} = \begin{bmatrix} 1 & K_d M_d Z_d + \mathrm{j}0.27\omega H(\alpha)/r \\ 0 & 1 \end{bmatrix}$$

where r is the diameter of the smaller tube, R is the diameter of the larger tube, $\alpha = r/R$, $H(\alpha) = 1.0 - 1.25\alpha$ for co-axial tubes. For non-coaxial tubes $H(\alpha)$ is:

$$\begin{aligned} H(\alpha) = {} & 1.442 + 3.516\delta - 5.403\alpha - 0.068kr - 11.067\delta^2 + 10.462\alpha^2 - 0.099(kr)^2 \\ & + 2.517\delta\alpha - 0.197\delta\, kr + 1.024\alpha\, kr + 7.774\delta^3 - 8.15\alpha^3 - 0.05(kr)^3 \\ & - 0.841\delta^2\alpha + 0.131\delta^2\, kr - 3.378\delta\alpha^2 - 1.311\alpha^2\, kr \\ & + 0.141(kr)^2\,\delta - 0.067(kr)^2\alpha - 0.031\delta\alpha\, kr \end{aligned}$$

where $\delta =$ (offset distance)$/(R - r)$.

For the cases involving tube extensions into the expansion chamber, the physical inlet or discharge tube extension lengths are input in the muffler element parameter data on the GUI. ENC then adjusts this length using a tube end correction to obtain the equivalent acoustic lengths for use in the analysis. However, extension lengths are not included separately for the case for the muffler elements involving perforated elements. For these types of muffler, the non-perforated part of the extension (excluding the stub part) is included as part of the inlet or discharge duct, as illustrated by the shaded ducts in the figure on page 226. ENC also adjusts these lengths by end corrections to account for the acoustic length of the extension tube, as discussed in Section 6.5.4.

6.5.2 1/4-Wave Tube and Helmholtz Resonator Notes (element types 6 & 7)

For both the 1/4-wave tube and Helmholtz resonator, it is possible to include at the entrance to the resonator, a perforated sheet and/or a layer of sound absorbing material. If no perforated sheet or sound material is included at the resonator entrance, it is important that for the 1/4-wave tube, parameters 11 and 12 are set equal to zero and for the Helmholtz resonator, parameters 12 and 13 are set equal to zero.

Parameter 9 of the Helmholtz resonator is the inlet edge radius for cases where no perforated sheet on the inlet, but when there is a perforated sheet present, there is no edge into the neck and the resistive impedance is controlled by the perforation impedance. Thus, in the presence of a perforated sheet, parameter 9 is the perforated tube hole diameter.

Parameter 12 for the 1/4-wave tube and parameter 13 for the Helmholtz resonator are the flow resistance (material flow resistivity multiplied by its thickness) of any acoustic material placed at the entrance of the resonator. In practice, acoustic material is not used by itself. It is usually used together with a perforated sheet so it can be fixed to the perforated sheet.

6.5.3 DTEC Muffler Element Notes (element types 8 & 9)

A DTEC muffler can be constructed using muffler element types 4, 1 and 5, with optimal acoustic lengths, $L_a = L/2$, $L_b = L_c = L/4$, where L is the total length of the expansion chamber. ENC adjusts the geometric lengths, L_{ga}, L_{gb} and L_{gc}, using an end correction (Equation 8.162 in the textbook) prior to undertaking the calculations. Note that one end correction is added by ENC to each of the L_{ga} and L_{gb} values and two end corrections are subtracted by ENC from the L_{gc} value to obtain the acoustic lengths used in the IL and TL calculations.

Alternatively, muffler element type 8 (or type 9) may be used, where the lengths of the two extensions into the chamber are already optimised and the corresponding geometric (or physical) lengths are provided in the popup table obtained by clicking on the "Geometric Lengths" button on the GUI. If the type 8 muffler element is used, the expansions and contractions associated with the inlets and discharges are included in the type 8 (or type 9) muffler element and do not need to be added separately. However, if the inlet and outlet tubes have different diameters and/or wall thicknesses, then the DTEC muffler must be constructed using muffler element types 4, 1 and 5. In this case, it is important that the L_a, L_b and L_c tube lengths entered into ENC are the physical lengths. The "optimal" tube lengths may be adjusted by the user using non-zero values for parameters 8 and 9. Note that a positive value implies an increase in the extension tube length while a negative value implies a decrease.

Flow through the muffler reduces the end correction values by a factor of $(1 - M^2)$, where M is the flow Mach number, and this is taken into account in ENC.

It is also possible to have a SISO-DTEC muffler element type 9 for which the inlet and discharge tubes are below and above the chamber, respectively as illustrated in the figure on page 208. For this case, the physical lengths and acoustic lengths are identical and the physical lengths are not adjusted in ENC to obtain acoustic lengths, but the physical distances of the inlet and exit tubes from the ends of the expansion chamber can be adjusted to optimise the TL versus frequency graph, by using non-zero correction values for parameters 8 and 9. Note that a positive value implies an increase in the distance, while a negative value implies a decrease.

6.5.4 CTR, Cross-Expansion, Cross-Contraction and Perforated Tube Muffler Element Notes (element types 10, 11, 12 & 15)

For the CTR muffler element (**type number 10**), it is assumed that the perforated tube diameter is the same as that of the discharge and inlet tubes. Also for muffler element types 10, 11, 12 and 15 the expansions and contractions associated with the inlets and discharges are included in the particular muffler element and do not need to be added separately.

For **muffler element type 10**, the acoustic lengths, L_a, L_b and L_c for optimal tuning are obtained using a correction, Δ_{1D} (see following equation) to obtain, $L_a = L/2 - \Delta_{1D}$, $L_b = L/4 - \Delta_{1D}$ and $L_c = L/4 + 2\Delta_{1D}$.

$$\begin{aligned}\Delta_{1D} = 10^{-5}&\left[1 - 4.278\left(P_{\text{open}}/100\right)^{-0.5454}\right]\left[1 + 59.89t_w^{0.6891}\right]\\ &\times\left[1 - 306.61d_1^{0.497}\right]\left[1 + 75.98d_h\right]\left[1 - 1.124(d_2/d_1)^{-2.95}\right]\\ &\times\left[1 + 1.623\times10^{-4}L^{-3.197}\right]\end{aligned}$$

If necessary, lengths L_a and L_b can be further fine-tuned for optimal TL by using non-zero correction values for parameters 8 and 9. However, it is usually best to leave these additional correction values equal to zero.

The physical lengths, corresponding to the optimal acoustic lengths, are obtained in ENC by using Equations (8.197) – (8.200) in the textbook. If parameters 8 and 9 are non-zero, their values are added to the physical lengths as well as the acoustic lengths. For muffler elements 10, 13 and 15, the Mach number in the expansion chamber is always zero. Muffler elements 11 and 12 usually need to both exist together in a muffler system and be connected by a tube (element number 1), so in these cases the Mach number in the chamber is non-zero. The stub tube referenced in the table on page 210 is the part of the end of the extension tube that is not perforated.

Muffler element type 15 must be used when muffler element type 10 results in zero for lengths L_a and L_b, (seen by clicking on the "Geometric lengths" button), as the muffler expansion chamber is too short to allow optimal tuning. Muffler element type 15 can also be used for situations where the design requires the perforated tube to extend the full length of the muffler or when it is desired to specify the lengths of non-perforated tubes that extend into the expansion chamber or when the inlet and outlet duct diameters are different, resulting in a conically-shaped perforated section. The analysis requires similar input data as needed for muffler element type 10 (except that the exit tube diameter, d_3, is needed and the last two items are the lengths of non-perforated tube extending into the expansion chamber – inlet length followed by discharge length, which can be any positive number, including zero). These lengths are adjusted in ENC using perforated tube end corrections, L01 and L03, respectively, prior to undertaking the analysis, in much the same way as is done for muffler element type 10. The length adjustments are not permitted to result in lengths, L_a or L_b, being less than zero. If L_a or L_b is less than zero, it is set equal to zero. The effective perforated tube length is then $L_c = L - L_a - L_b$, where L is the expansion chamber length. If the perforated tube diameter varies from the inlet to the exit (due to inlet and exit ducts having different diameters), ENC obtains an approximate result by setting the perforated tube diameter equal to an average of the diameters of the inlet and exit of the perforated tube. Note that if the expansion chamber length is too short for the tube diameters involved (and/or the extension tube lengths used), the TL and IL values are likely to be close to zero over the entire frequency range.

For element types 11 and 12, No adjustment to tube lengths is made due to flow, as most of the flow is cross flow and its effect on the end tube end correction is not quantifiable. However, the effect is likely to be small.

The 4-pole transmission matrix used by ENC for muffler type numbers 10 – 12 and 15 is a corrected version of Equation (8.185), given by:

$$\begin{bmatrix} p_u \\ S_u u_u \end{bmatrix} = \begin{bmatrix} 1 & M_u\rho c/S_u \\ M_u S_u/\rho c & 1 \end{bmatrix} \begin{bmatrix} T_a & T_b \\ T_c & T_d \end{bmatrix} \begin{bmatrix} 1 & M_d\rho c/S_d \\ M_d S_d/\rho c & 1 \end{bmatrix}^{-1} \begin{bmatrix} p_d \\ S_u u_d \end{bmatrix}$$

And Equations (8.187) – (8.189) also need to be replaced by the following:

$$
\begin{aligned}
T_b &= (T_{13} + B_1 A_2)(\rho c/S_d) \\
T_c &= (T_{31} + A_1 B_2)(S_u/(\rho c)) \\
T_d &= (T_{33} + B_1 B_2)(S_u/S_d)
\end{aligned}
$$

For muffler element type 10, $M_d = 0$, so the matrix involving this quantity becomes the identity matrix and has no effect on the result.

The cross flow expansion and contraction elements (muffler element types 11 and 12) are not discussed in the textbook, but are discussed in (Munjal, 2014, p.120–129). The equations are similar to those on pages 516–519 in the textbook (corrected according to the textbook errata following the Appendix near the end of this manual) with the following exceptions.

For both expansion and contraction cross flow elements the following equations should be used.

1. Equation (8.166) (for grazing flow over the perforations) should be replaced with the following equation for cross (or through) flow:

$$Z_A = \frac{\rho c}{S_d}\left[\frac{0.514 d_1 M_1 + \mathrm{j}k(t_w + 0.75 d_h) L_c P_{\mathrm{open}}/100}{L_c (P_{\mathrm{open}}/100)^2}\right]$$

2. Equation (8.172) should be replaced with:

$$
\begin{aligned}
\alpha_5 &= \frac{\mathrm{j}M_2}{1 - M_2^2} \times \frac{k_b^2 - k^2}{k} \\
\alpha_7 &= -\frac{\mathrm{j}M_2}{1 - M_2^2} \times \frac{k_b^2 + k^2}{k}
\end{aligned}
$$

3. Equation (8.173) should be replaced with:

$$\alpha_6 = -\frac{k_b^2 - k^2}{1 - M_2^2}$$

4. Equation (8.174) should be replaced with:

$$\alpha_8 = \frac{k_b^2}{1 - M_2^2}$$

5. Equation (8.183) should be replaced with:

$$A_{4,i}(x) = -\frac{\psi_{2,i} \mathrm{e}^{\beta_i x}}{\mathrm{j}k + M_2 \beta_i}$$

   where M_2 is the Mach number of the flow in the chamber and the other variables have been defined in the textbook.

In the tables on pages 209 and 210, most of the parameters are self-explanatory and illustrated in the figures on page 208. Parameters that need further explanation are the corrections to the inlet and discharge tube lengths for muffler element types 10–12. These are usually set to zero but can be used to try adjusting the tuned lengths to optimise the muffler TL for a particular frequency range, which must be done by trial and error. However, the tuned lengths The perforated tube hole grid type parameter is explained in the textbook on pages 516 and 517.

For the cross flow expansion element only (type 11), which is not discussed in the textbook, Equations (8.186) – (8.196) should be replaced with the following equations.

$$\begin{aligned}
T_a &= T_{12} + A_1 A_2 \\
T_b &= (T_{14} + B_1 A_2)(\rho c / S_2) \\
T_c &= (T_{32} + A_1 B_2)(S_1 / \rho c) \\
T_d &= (T_{34} + B_1 B_2)(S_1 / S_2) \\
A_1 &= (X_1 T_{22} - T_{42}) / F_1 \\
A_2 &= T_{11} + X_2 T_{13} \\
B_1 &= (X_1 T_{24} - T_{44}) / F_1 \\
B_2 &= T_{31} + X_2 T_{33} \\
X_1 &= -\mathrm{j} \tan(k L_a) \\
X_2 &= +\mathrm{j} \tan(k L_b) \\
F_1 &= T_{41} + X_2 T_{43} - X_1 (T_{21} + X_2 T_{23})
\end{aligned}$$

For the cross flow contraction element (type 12) only, Equations (8.186) – (8.196) should be replaced with the following equations.

$$\begin{aligned}
T_a &= T_{21} + A_1 A_2 \\
T_b &= (T_{23} + B_1 A_2)(\rho c / S_2) \\
T_c &= (T_{41} + A_1 B_2)(\rho c / S_2) \\
T_d &= (T_{43} + B_1 B_2)(S_1 / S_2) \\
A_1 &= (X_1 T_{11} - T_{31}) / F_1 \\
A_2 &= T_{22} + X_2 T_{24} \\
B_1 &= (X_1 T_{13} - T_{33}) / F_1 \\
B_2 &= T_{42} + X_2 T_{44} \\
X_1 &= -\mathrm{j} \tan(k L_a) \\
X_2 &= +\mathrm{j} \tan(k L_b) \\
F_1 &= T_{32} + X_2 T_{34} - X_1 (T_{12} + X_2 T_{14})
\end{aligned}$$

6.5.5 General Notes for all Perforated Tube Muffler Elements

When putting together a muffler system using the available elements, it is important to realise that element types 8 – 15 do not include anything outside the expansion chamber, but include everything else shown on the corresponding figures. For elements 11 and 12, the extent of the expansion chamber that is included is equal to the length of the extension tube. The inlet and discharge tubes adjacent to the muffler element must be included as separate elements in the muffler system. However, these tubes only contribute to the IL, not the TL.

6.5.6 Dual Perforated Tube Muffler Elements (element types 13 & 14)

For element types 13 and 14, similar comments apply as for element type 10, except that there are two perforated tubes. It is assumed that both tubes have the same values of physical lengths, L_{ag} and L_{bg} and that L_{ag} is the physical dimension of the extension on the inlet up to the perforated tube, whereas L_{bg} is the physical dimension of the extension on the discharge up to the perforated tube, as shown in the figure on page 208. No correction values are needed to be input on the ENC GUI. Any adjustments can be made directly by adjusting parameters 7 and 8 (L_{ag} and L_{bg}) on the GUI. The inlet and discharge tube diameters, d_1 and d_3, may be different if necessary for muffler element types 13 and 14. Prior to undertaking the analysis, ENC calculates the acoustic lengths, L_a, L_b and L_c, using:
$L_a = L_{ag} + \delta$; $L_b = L_{bg} + \delta$; $L_c = L - L_{ag} - L_{bg} - 2\delta$,
where $\delta = \ell_0 - \Delta_{1D}$ and ℓ_0 is defined by Equation (8.200) in the textbook.

The perforation length, L_c must be the same for both tubes as shown in the figure on page 208. The Mach number in the expansion chamber for element type 13 is set to zero by ENC, but for type 14, it is calculated, as most of the flow exits from the open end of the inlet tube and enters the open end of the discharge tube.
Thus, $M_2 = M_1[S_1/(S_2 - 2S_1)]$.

For element type 13, No adjustment to tube lengths is made due to flow, as most of the flow is cross flow and its effect on the end tube end correction is not quantifiable. However, the effect is likely to be small.

The 4-pole transmission matrix used by ENC for muffler types 13 and 14 in the tables on pages 209 and 210 and figure on page 208) is a corrected version of Equation (8.185), given by:

$$\begin{bmatrix} p_u \\ S_u u_u \end{bmatrix} = \begin{bmatrix} 1 & M_1\rho c/S_1 \\ M_1 S_1/\rho c & 1 \end{bmatrix} \begin{bmatrix} \mathbf{P} \end{bmatrix} \begin{bmatrix} 1 & M_3\rho c/S_3 \\ M_3 S_3/\rho c & 3 \end{bmatrix}^{-1} \begin{bmatrix} p_d \\ S_u u_d \end{bmatrix}$$

where

$$\begin{bmatrix} \mathbf{P} \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}$$

For muffler element type numbers 13 and 14), the inlet diameter (and corresponding Mach number) can be different to that of the discharge duct. As no mean flow can occur in the chamber for muffler element type 13, the Mach number, M_2, of the chamber is set equal to 0 for all cases. This type of muffler element is not discussed in the textbook. It is discussed in Munjal (2008), where the equations with some errors that have been fixed are reproduced below. The matrix, $[\mathbf{T}]$ discussed in the textbook is now a 6 x 6 matrix (see page 222).

For these muffler element types, Equation (8.167) in the textbook should be replaced with:

$$\begin{bmatrix} -\alpha_1 & -\alpha_3 & 0 & -\alpha_2 & -\alpha_4 & 0 \\ -\alpha_5 & -\alpha_7 & -\alpha_9 & -\alpha_6 & -\alpha_8 & -\alpha_{10} \\ 0 & -\alpha_{11} & -\alpha_{13} & 0 & -\alpha_{12} & -\alpha_{14} \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

Equations (8.168) – (8.174) in the textbook should be replaced with :

$$\alpha_1 = \frac{-\mathrm{j}M_1}{1-M_1^2}\left(\frac{k_a^2+k^2}{k}\right); \quad \alpha_2 = \frac{k_a^2}{1-M_1^2}; \quad \alpha_3 = \frac{\mathrm{j}M_1}{1-M_1^2}\left(\frac{k_a^2-k^2}{k}\right); \quad \alpha_4 = \frac{k^2-k_a^2}{1-M_1^2}$$
$$\alpha_5 = \frac{\mathrm{j}M_2}{1-M_2^2}\left(\frac{k_b^2-k^2}{k}\right); \quad \alpha_6 = \frac{k^2-k_b^2}{1-M_2^2}; \quad \alpha_7 = \frac{-\mathrm{j}M_2}{1-M_2^2}\left(\frac{k_b^2+k_c^2}{k}\right); \quad \alpha_8 = \frac{k_b^2+k_c^2-k^2}{1-M_2^2}$$
$$\alpha_9 = \frac{\mathrm{j}M_2}{1-M_2^2}\left(\frac{k_c^2-k^2}{k}\right); \quad \alpha_{10} = \frac{k^2-k_c^2}{1-M_2^2}; \quad \alpha_{11} = \frac{\mathrm{j}M_3}{1-M_3^2}\left(\frac{k_d^2-k^2}{k}\right); \quad \alpha_{12} = \frac{k^2-k_d^2}{1-M_3^2}$$
$$\alpha_{13} = \frac{-\mathrm{j}M_3}{1-M_3^2}\left(\frac{k_d^2+k^2}{k}\right); \quad \alpha_{14} = \frac{k_d^2}{1-M_3^2}$$

Equation (8.175) in the textbook is replaced with:

$$k_a^2 = k^2 - \frac{\mathrm{j}4k}{d_1(Z_{A1}S_{d1}/(\rho c))}; \quad k_b^2 = k^2 - \frac{\mathrm{j}4kd_1}{(d_2^2-d_1^2-d_3^2)(Z_{A1}S_{d1}/(\rho c))}$$
$$k_c^2 = k^2 - \frac{\mathrm{j}4k}{d_3(Z_{A2}S_{d3}/(\rho c))}; \quad k_d^2 = k^2 - \frac{\mathrm{j}4kd_3}{(d_2^2-d_1^2-d_3^2)(Z_{A2}S_{d3}/(\rho c))}$$

where for zero flow speed in the inlet tube:

$$Z_{A1} = \frac{\rho c}{S_1}\left[\frac{0.006+\mathrm{j}k(t_w+0.75d_h)}{(P_{\text{open}}/100)}\right]$$

and for zero flow speed in the chamber (muffler element 13 only):

$$Z_{A2} = \frac{\rho c}{S_3}\left[\frac{0.006+\mathrm{j}k(t_w+0.75d_h)}{(P_{\text{open}}/100)}\right]$$

For a mean flow condition of Mach number M_1 in the inlet tube and cross flow through the perforations in the perforated tube (muffler element type 13 only):

$$Z_{A1} = \frac{\rho c}{S_d}\left[\frac{0.514d_1M_1+\mathrm{j}k(t_w+0.75d_h)L_cP_{\text{open}}/100}{L_c(P_{\text{open}}/100)^2}\right]$$

For the corresponding discharge tube with a mean Mach number of M_3 (which is equal to M_1 for muffler element type 13)

$$Z_{A3} = \frac{\rho c}{S_d}\left[\frac{0.514d_1M_3+\mathrm{j}k(t_w+0.75d_h)L_cP_{\text{open}}/100}{L_c(P_{\text{open}}/100)^2}\right]$$

For a mean flow condition of Mach number M_1 in the inlet tube and grazing flow along the perforations in the perforated tube (muffler element type 14 only):

$$Z_{A1} = \frac{\rho c}{S_1}\left[\frac{7.337\times10^{-3}\,(1+72.23M_1)+\mathrm{j}\,2.2245\times10^{-5}(1+51\,t_w)(1+204\,d_h)\,f}{(P_{\mathrm{open}}/100)}\right]$$

For the corresponding discharge tube with a mean Mach number of M_3 and grazing flow along the perforations (muffler element type 14 only):

$$Z_{A3} = \frac{\rho c}{S_3}\left[\frac{7.337\times10^{-3}\,(1+72.23M_3)+\mathrm{j}\,2.2245\times10^{-5}(1+51\,t_w)(1+204\,d_h)\,f}{(P_{\mathrm{open}}/100)}\right]$$

For a mean flow condition of Mach number M_2 in the chamber (muffler element type 14 only):

$$Z_{A2} = \frac{\rho c}{S_2}\left[\frac{7.337\times10^{-3}\,(1+72.23M_2)+\mathrm{j}\,2.2245\times10^{-5}(1+51\,t_w)(1+204\,d_h)\,f}{(P_{\mathrm{open}}/100)}\right]$$

For dual perforated tube muffler elements, Equations (8.180) – (8.183) in the textbook should be replaced with the following equations (for $i = 1,\ 6$, $x = L_c$ and eigen values, β_i of the matrix on page 221.).

$$\mathrm{A}_{1,i}(x) = \psi_{4,i}\,\mathrm{e}^{\beta_i x};\quad \mathrm{A}_{2,i}(x) = \psi_{5,i}\,\mathrm{e}^{\beta_i x};\quad \mathrm{A}_{3,i}(x) = \psi_{6,i}\,\mathrm{e}^{\beta_i x}$$
$$\mathrm{A}_{4,i}(x) = \frac{-\psi_{1,i}\,\mathrm{e}^{\beta_i x}}{\mathrm{j}k+M_1\beta_i};\quad \mathrm{A}_{5,i}(x) = \frac{-\,\psi_{2,i}\,\mathrm{e}^{\beta_i x}}{\mathrm{j}k+M_2\beta_i};\quad \mathrm{A}_{6,i}(x) = \frac{-\,\psi_{3,i}\,\mathrm{e}^{\beta_i x}}{\mathrm{j}k+M_3\beta_i}$$

For dual perforated tube muffler elements, Equation (1.184) in the textbook should be replaced with:

$$\begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} & T_{15} & T_{16}\\ T_{21} & T_{22} & T_{23} & T_{24} & T_{25} & T_{26}\\ T_{31} & T_{32} & T_{33} & T_{34} & T_{35} & T_{36}\\ T_{41} & T_{42} & T_{43} & T_{44} & T_{45} & T_{46}\\ T_{51} & T_{52} & T_{53} & T_{54} & T_{55} & T_{56}\\ T_{61} & T_{62} & T_{63} & T_{64} & T_{65} & T_{66} \end{bmatrix} = [\mathbf{A}(0)]\,[\mathbf{A}(L_c)]^{-1}$$

6.5.6.1 3-Duct, Cross-Flow Muffler Element

For muffler element type 13, the Mach number in the chamber, M_2, is set equal to 0 for all cases. It is also necessary to introduce an additional matrix, denoted [**TT**], where

$$\begin{aligned} P_{11} &= TT_{12} + A_3C_3\\ P_{12} &= (TT_{14} + B_3C_3)(\rho c/S_3)\\ P_{21} &= (TT_{32} + A_3D_3)(S_1/\rho c)\\ P_{22} &= (TT_{34} + B_3D_3)(S_1/S_3)\\ A_3 &= (TT_{22}X_2 - TT_{42})/F_2\\ B_3 &= (TT_{24}X_2 - TT_{44})/F_2\\ C_3 &= TT_{11} + X_1TT_{13} \end{aligned}$$

$$
\begin{aligned}
D_3 &= TT_{31} + X_1 TT_{33} \\
TT_{11} &= A_1A_2 + T_{12};\ TT_{12} = B_1A_2 + T_{13};\ TT_{13} = C_1A_2 + T_{15};\ TT_{14} = D_1A_2 + T_{16} \\
TT_{21} &= A_1B_2 + T_{22};\ TT_{22} = B_1B_2 + T_{23};\ TT_{23} = C_1B_2 + T_{25};\ TT_{24} = D_1B_2 + T_{26} \\
TT_{31} &= A_1C_2 + T_{42};\ TT_{32} = B_1C_2 + T_{43};\ TT_{33} = C_1C_2 + T_{45};\ TT_{34} = D_1C_2 + T_{46} \\
TT_{41} &= A_1D_2 + T_{52};\ TT_{42} = B_1D_2 + T_{53};\ TT_{43} = C_1D_2 + T_{55};\ TT_{44} = D_1D_2 + T_{56} \\
A_1 &= (T_{32}X_2 - T_{62}/F_1 \\
A_2 &= T_{11} + X_1T_{14} \\
B_1 &= (T_{33}X_2 - T_{63}/F_1 \\
B_2 &= T_{21} + X_1T_{24} \\
C_1 &= (T_{35}X_2 - T_{65}/F_1 \\
C_2 &= T_{41} + X_1T_{44} \\
D_1 &= (T_{36}X_2 - T_{66}/F_1 \\
D_2 &= T_{51} + X_1T_{54} \\
X_1 &= \mathrm{j}\tan(kL_b(1 - M_3)) \\
X_2 &= -\mathrm{j}\tan(kL_a(1 - M_1)) \\
F_1 &= T_{61} + X_1T_{64} - X_2(T_{31} + X_1T_{34})
\end{aligned}
$$

6.5.6.2 3-Duct, Open-End Muffler Element

For the following analysis for muffler element number 14, the inlet diameter (and corresponding Mach number) need not be the same as that of the discharge duct. Muffler element number 14 is not discussed in the textbook. It is discussed in Munjal (2008), where the equations are reproduced below. The $[\boldsymbol{\alpha}]$ matrix (see page 221) and the [**T**] matrix (see page 222) are the same as for muffler element number 13. For muffler element number 14 it is necessary to introduce additional matrices, denoted [**TT**], [**MAT**, [**TM**], [**X**], [**Y**]].

The 4-pole transmission matrix used by ENC for the 3-duct, open-end muffler element (muffler type 14 in the tables on pages 209 and 210 and figure on page 208) is a corrected version of Equation (8.185), and is given on page 220. The [**P**] matrix to be used in the equation on page 220 is:

$$
[\mathbf{P}] = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} = ([\mathbf{TT_{11}}][\mathbf{X}] + [\mathbf{TT_{12}}])[\mathbf{MAT}] + [\mathbf{TT_{13}}]
$$

where $[\mathbf{MAT}]\mathbf{=}([\mathbf{TT_{21}}][\mathbf{X}]\mathbf{+}[\mathbf{TT_{22}}]\mathbf{-}[\mathbf{Y}][\mathbf{TT_{31}}][\mathbf{X}]\mathbf{+}[\mathbf{TT_{32}}])^{-1}([\mathbf{Y}]([\mathbf{TT_{33}}]\mathbf{-}[\mathbf{TT_{23}}]))$ (Munjal, 2008, p. 818-9, with added bracket correction).

After calculating [**P**], it is necessary to carry out the following adjustments to the individual elements so that the transmission matrix is compatible with Equation (8.185) in the textbook. Thus:

$$
\begin{aligned}
P_{11} &= P_{11} \\
P_{12} &= P_{12}Z_3 \\
P_{21} &= P_{21}/Z_1
\end{aligned}
$$

$$P_{22} = P_{22}(Z_3/Z_1)$$

The reverse flow expansion element transmission matrix, $[\mathbf{X}]$, is (see (Munjal, 2008, p. 811)):

$$[\mathbf{X}] = \begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix}$$

where

$$\begin{aligned} Z_1 =& \rho c/S_1;\ Z_{21} = \rho c/S_{21};\ Z_{23} = \rho c/S_{23};\ Z_3 = \rho c/S_3 \\ X_{11} =& T_a;\ X_{12} = -T_b Z_2;\ X_{21} = T_c/Z_1;\ X_{22} = -T_d Z_2/Z_1 \end{aligned}$$

where $S_{21} = S_2 - S_1$ is the cross-sectional area of the expansion chamber minus the cross-sectional area of the inlet tube, S_1, $S_{23} = S_2 - S_3$ is the cross-sectional area of the expansion chamber minus the cross-sectional area of the discharge tube, S_3 and

$$\begin{bmatrix} T_a & T_b \\ T_c & T_d \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{bmatrix} B_1 & B_2 \\ B_3 & B_4 \end{bmatrix}^{-1}$$

$$\begin{aligned} A_1 &= T_{11}F_{11} + T_{12} + T_{13}F_{21}; & A_2 &= T_{11}F_{12} + T_{14} + T_{13}F_{22} \\ A_3 &= T_{31}F_{11} + T_{32} + T_{33}F_{21}; & A_4 &= T_{31}F_{12} + T_{34} + T_{33}F_{22} \\ B_1 &= T_{21}F_{11} + T_{22} + T_{23}F_{21}; & B_2 &= T_{21}F_{12} + T_{24} + T_{23}F_{22} \\ B_3 &= T_{41}F_{11} + T_{42} + T_{43}F_{21}; & B_4 &= T_{41}F_{12} + T_{44} + T_{43}F_{22} \end{aligned}$$

where the 4×4 T-matrix is defined by Equation (8.184) in the textbook and

$$F_{11} = E_{11};\ F_{12} = -E_{12}/Z_1;\ F_{21} = E_{21}Z_{21};\ F_{22} = -E_{22}Z_{21}/Z_1$$

where $[\mathbf{E}]$ is the 2×2 transfer matrix of the reversal expansion element, which can be calculated using Equation (8.150) in the textbook with $K = (S_1/S_{21})^2$.

The reversal contraction element transmission matrix, $[\mathbf{Y}]$, is (Munjal, 2008, p. 812):

$$[\mathbf{Y}] = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}$$

where $Y_{11} = T_a;\ Y_{12} = T_b Z_3;\ Y_{21} = -T_c/Z_{23};\ Y_{22} = -T_d Z_3/Z_{23}$ and

$$\begin{bmatrix} T_a & T_b \\ T_c & T_d \end{bmatrix} = \begin{bmatrix} C_1 & C_2 \\ C_3 & C_4 \end{bmatrix} \begin{bmatrix} B_1 & B_2 \\ B_3 & B_4 \end{bmatrix}^{-1}$$

where

$$\begin{aligned} [\mathbf{B}] =& [\mathbf{PP}] + [\mathbf{Q}][\mathbf{F}] \\ [\mathbf{C}] =& [\mathbf{R}] + [\mathbf{U}][\mathbf{F}] \end{aligned}$$

where

$$PP_{11} = A_{11};\ PP_{12} = A_{13};\ PP_{21} = A_{31};\ PP_{22} = A_{33}$$
$$Q_{11} = A_{12};\ Q_{12} = A_{14};\ Q_{21} = A_{32};\ Q_{22} = A_{34}$$
$$R_{11} = A_{12};\ R_{12} = A_{23};\ R_{21} = A_{41};\ R_{22} = A_{43}$$
$$U_{11} = A_{22};\ U_{12} = A_{24};\ U_{21} = A_{42};\ U_{22} = A_{44}$$

where $[\mathbf{A}]=[\mathbf{T}]^{-1}$, the 4×4 T-matrix is defined by Equation (8.184) in the textbook and

$$F_{11} = D_{11};\ F_{12} = D_{12}/Z_3;\ F_{21} = -D_{21}Z_{23};\ F_{22} = -D_{22}Z_{23}/Z_3$$

Where $[\mathbf{D}]$ is the 2×2 transfer matrix of the reversal contraction element, which can be calculated using Equation (8.150) in the textbook with $K = 0.5$.

The matrices, $[\mathbf{TT}_{ij}]$ are defined as follows, where the impedance terms in the original reference are removed to make the results compatible with Equation (8.133) in the textbook:

$$[\mathbf{TT_{11}}] = \begin{bmatrix} T_{11} & T_{14} \\ T_{41} & T_{44} \end{bmatrix}$$

$$[\mathbf{TT_{12}}] = \begin{bmatrix} T_{12} & T_{15} \\ T_{42} & T_{45} \end{bmatrix}$$

$$[\mathbf{TT_{13}}] = \begin{bmatrix} T_{13} & T_{16} \\ T_{43} & T_{46} \end{bmatrix}$$

$$[\mathbf{TT_{21}}] = \begin{bmatrix} T_{21} & T_{24} \\ T_{51} & T_{54} \end{bmatrix}$$

$$[\mathbf{TT_{22}}] = \begin{bmatrix} T_{22} & T_{25} \\ T_{52} & T_{55} \end{bmatrix}$$

$$[\mathbf{TT_{23}}] = \begin{bmatrix} T_{23} & T_{26} \\ T_{53} & T_{56} \end{bmatrix}$$

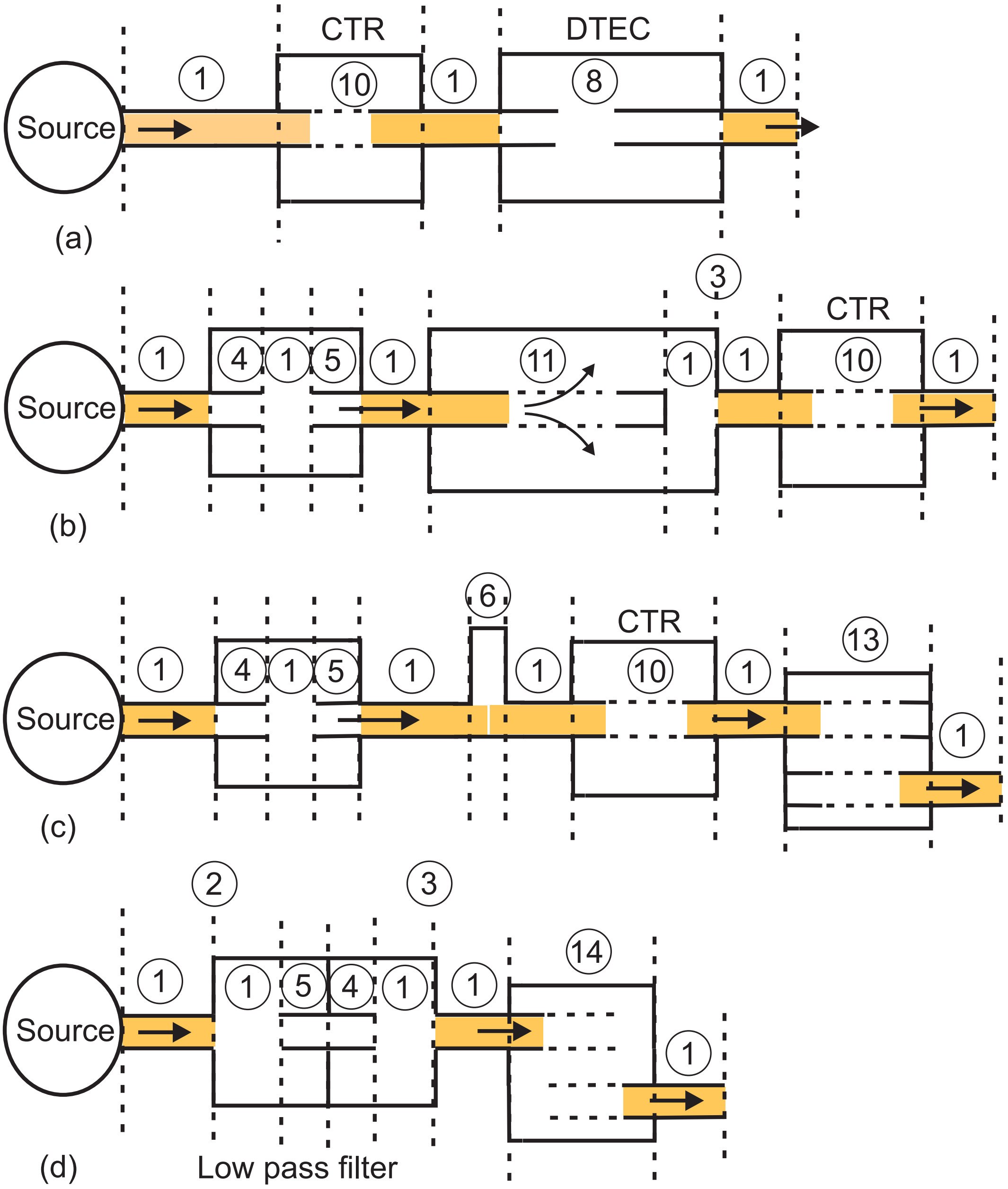
$$[\mathbf{TT_{31}}] = \begin{bmatrix} T_{31} & T_{34} \\ T_{61} & T_{64} \end{bmatrix}$$

$$[\mathbf{TT_{32}}] = \begin{bmatrix} T_{32} & T_{35} \\ T_{62} & T_{65} \end{bmatrix}$$

$$[\mathbf{TT_{33}}] = \begin{bmatrix} T_{33} & T_{36} \\ T_{63} & T_{66} \end{bmatrix}$$

6.5.7 Some Example Muffler Systems

Some examples of muffler systems that can be analysed using the ENC muffler elements illustrated on page 208 are shown in the following figure.



Vertical dashed lines indicate boundaries between individual muffler elements and the numbers in circles indicate which of the muffler elements, illustrated on page 208, is to be used. Note that muffler element types 10–15 do not include the tubes that project into the chamber and these lengths must be added to the inlet and discharge tube lengths respectively. The dashed line on the far right of the figures represents the end of the muffler system where it exhausts to the atmosphere.

All muffler systems should include the pipe connecting the muffler to the sound source and the pipe from the muffler to the exhaust exit, even though these pipes only affect the muffler IL and noise reduction, but do not affect the TL calculations, unless there is a temperature gradient in the pipe. Calculations of muffler IL also require an estimate of the source impedance. ENC will estimate the radiation impedance, which is also required.

When entering a muffler system into ENC, begin with the element closest to the source (element 1) and end with the element that discharges into the atmosphere.

6.5.8 Insertion Loss

To calculate Insertion Loss of a muffler, the source and system end radiation impedance must be calculated. The radiation impedance is calculated by ENC, but the source impedance is often unknown. As a first approximation in the absence of experimental data, the real part of the source impedance is often set as a large number of a few thousand and the imaginary part is set equal to zero. The source impedance is a required input to ENC, so in the absence of data, try using 10^5 for the real part and 0.0 for the imaginary part. Measurement of the source impedance, based on in-duct acoustic pressure measurements, is discussed in the textbook on pages 522–524.

Alternatively, users have the option of selecting the source impedance and/or the termination impedance to be anechoic. A realistic estimate of the possible range in insertion loss values over an extended frequency range may be achieved in practice by undertaking insertion loss (IL) calculations for the two extreme cases of an upstream real impedance of 10^5 MKS Rayls (Pa s/m^3) and an upstream real impedance corresponding to the anechoic condition of the exhaust system upstream of the muffler.

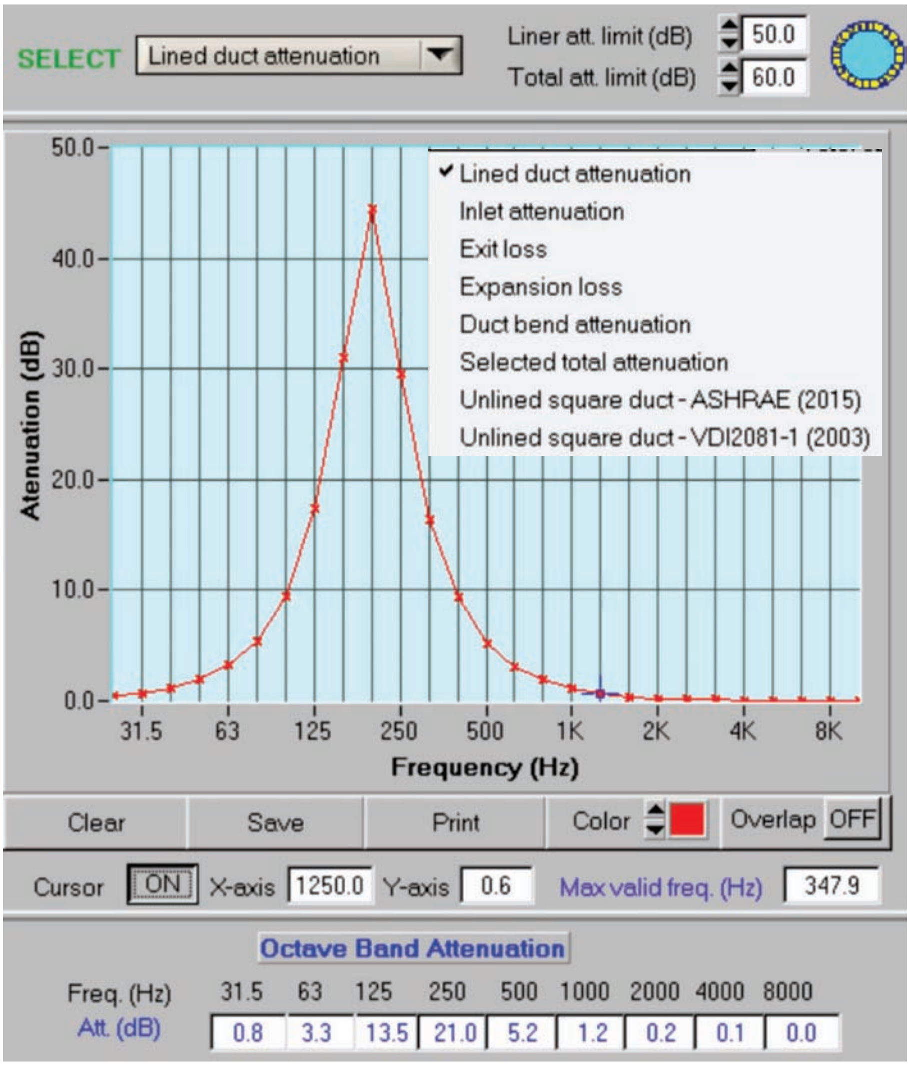
6.6 Dissipative Mufflers (6th edition textbook, pages 524–539)

Dissipative mufflers can be treated as lined ducts. Even mufflers containing splitter elements can be treated as lined ducts. Even if there is no solid septum in the centre of the splitters, a silencer with lining on the walls equal in thickness to half the thickness of the intermediate baffles will perform the same as a silencer with solid septa in the centre of the baffles.

For mufflers with multiple baffles (splitter mufflers), the attenuation is calculated by considering the muffler as a duct of width equal to the distance between splitters and the lining thickness equal to half the splitter thickness. If the splitters and gaps between them are not all the same, then the attenuation for the section of duct between each splitter needs to be calculated and the results for each section combined using (for N sections):

$$IL_{\text{overall}} = -10 \log_{10} \frac{1}{N} \sum_{i=1}^{i=N} 10^{-IL_i/10}$$

Attenuation calculations are plotted on the graph shown below as a function of frequency.

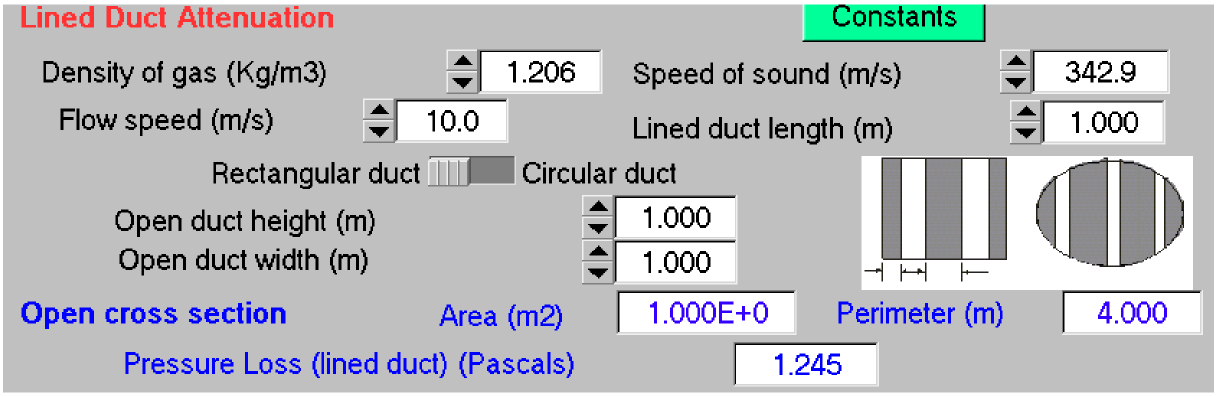


The “Liner att. limit (dB)” and the “Total att. limit(dB)” allow you to set an upper limit on the graph that is caused by flanking due to duct and muffler wall vibrations. Normally this is set to 50 or 60 dB, but in cases where there is good vibration isolation between the muffler section of the duct and the inlet and exit ducts, this limit may be higher.

The “overlap” switch allows multiple curves (use “color” to select color of each) to be plotted on the same set of axes. Note that the values plotted on the graph are energy averages of ten frequencies over a 1/3-octave band of frequencies (see 5^{th} edition textbook, example 5.1, page 243 for averaging method). Beneath the graph, the octave band attenuations (energy average of the appropriate 1/3-octave band values shown in the graph) are presented in a table (see figure on previous page).

To do a lined duct (or splitter silencer) attenuation calculation, the procedure outlined in the 6^{th} edition textbook is followed. The total attenuation consists of an inlet attenuation, liner attenuation, exit attenuation and expansion attenuation. If a silencer is inserted in a duct and there are no splitters (only lining on the duct walls), there may be no inlet or exit correction, provided the dimensions of the airway remain unchanged in going from the inlined duct to the lined duct section.

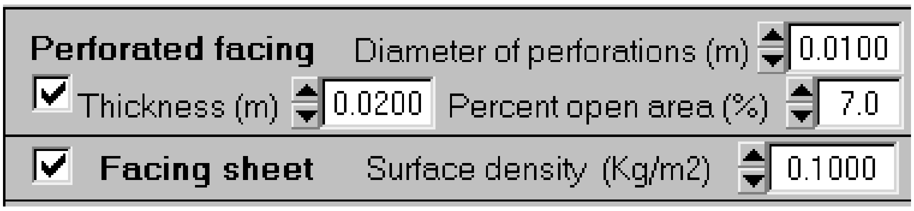
The first step in a silencer insertion loss analysis is to type in the density and speed of sound in the gas in the duct, the flow speed of the gas in the duct, the lined duct length, whether the duct is circular or rectangular in cross section and the cross sectional dimensions (see following figure).



If the duct is circular in cross-section, the diameter is required and if it is rectangular, the height and width of the section is required. Of course, good results can be obtained for ducts of other section shapes by treating them as rectangular or circular ducts of the same cross sectional area. If the other section shape is lined around its entire perimeter, it is best to treat it as a circular duct of the same area. In all cases, the dimensions refer to the open area of duct, and do not include the liner. Note that if the duct is divided by lined baffles (or partitions) as in a typical dissipative muffler, the dimensions required are the open cross sectional dimensions between each baffle, not the overall dimensions. In this case the muffler attenuation is equal to the attenuation through one airway between two of the baffles. Do not add the attenuations for each airway. The software will calculate the open duct cross-sectional area, the perimeter of the open area and the expected pressure drop due to the lined duct. ENC will also calculate the duct cross sectional area, perimeter and pressure loss due to the specified flow speed.

Clicking on the "Constants" button in the above figure allows you to set the speed of sound and gas density for the calculations of the entire window — see Section 0.6.4 in this manual for a full description.

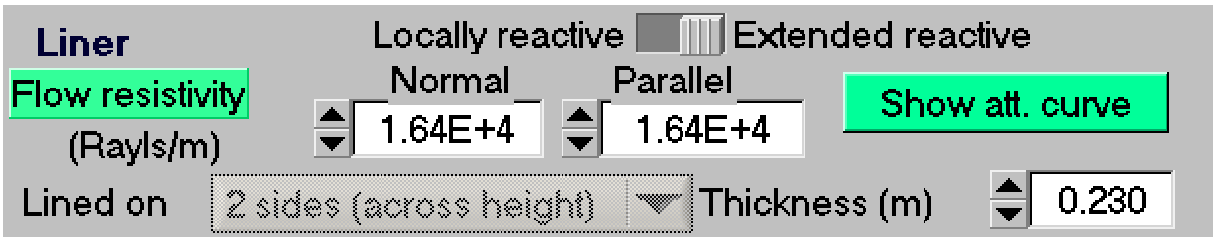
6.6.1 Perforated Facing



In the perforated facing panel, enter details (panel thickness and percent open area) about the liner facing (see figure above). Click on the box on the left side of the "perforated facing" panel to select whether or not there is a perforated panel. If the box is not ticked, the perforated panel details will be "greyed out" and not used in the calculations. Enter also the surface density (mass per square metre — kg/m^2) of any protective impervious membrane such as polyethylene. If there is no membrane, enter 0.0 here. Note that if both the membrane and perforated panel are used together, it is essential that a spacer (e.g. 25 mm mesh) is used to keep the two separated. Otherwise, the attenuations calculated here will be greater than those realised in practice, especially at higher frequencies.

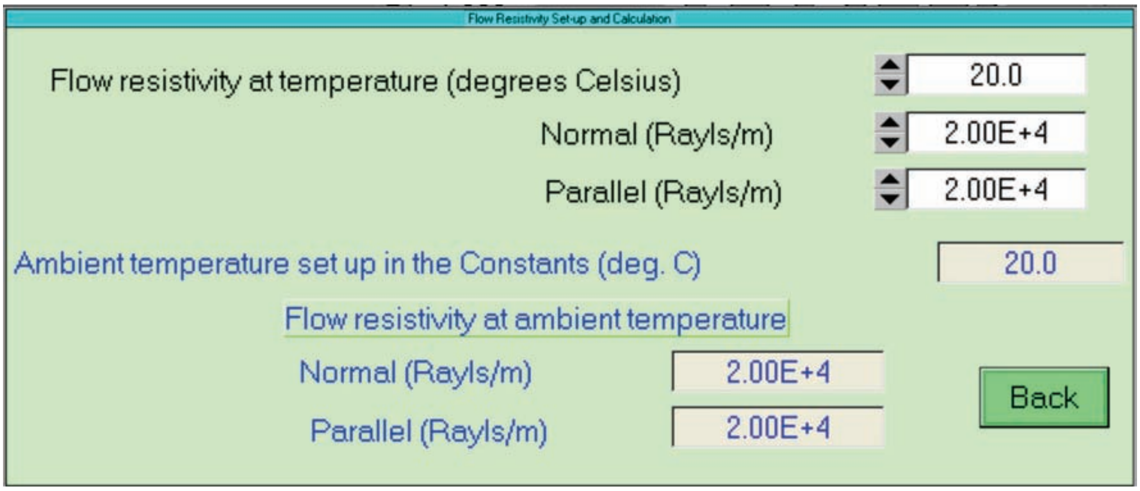
6.6.2 Liner Attenuation (see pages 527–534 in the 6th edition textbook)

In the "Liner" panel (see following figure) enter the number of sides that are lined (rectangular duct only) and the location of the lined side(s) if there are less than 4. Note that "2 sides" refers to two opposite sides lined and you can choose between "across height" or across width". If only two adjacent sides are lined, then you must do two calculations for "1 side" lined and add the two results arithmetically (liner only results). Do not add the total attenuations in each case, only the attenuations for the liner. If three sides are lined, do the calculations for 2 opposite sides and then the remaining side and add the two results (liner attenuation only). For circular ducts, it is assumed that the liner extends the full circumference of the duct. If it does not, then use a square duct of the same cross-sectional area with the equivalent number of sides lined.



Also in the " liner" panel, you may enter the flow resistivity (rayls/m — see pages 783–786 in the 6th edition textbook) of the liner material in the direction normal to the axis of the duct ("normal") and in the direction parallel to the duct axis ("parallel"). Although the analysis is strictly for isotropic materials, good results are obtained for orthotropic materials which make up the majority of fibre glass and rockwool materials.

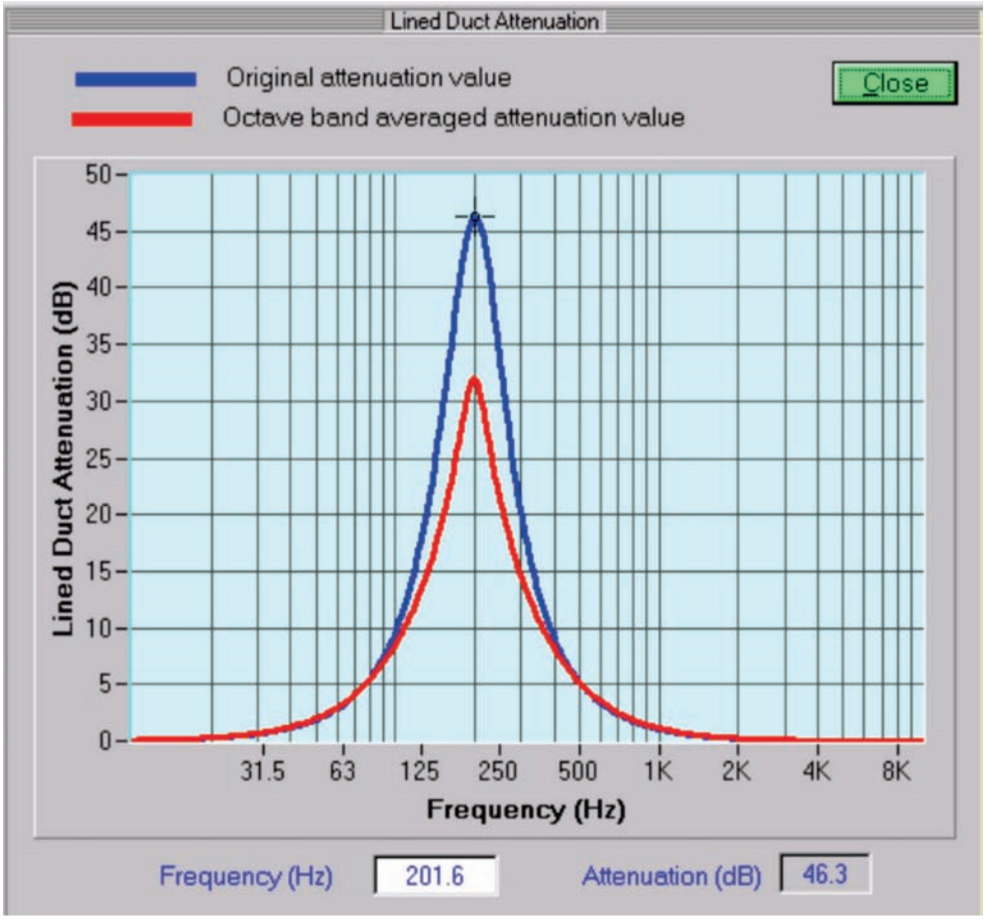
As flow resistivity is a function of the ambient temperature, ENC allows you to enter the flow resistivity at the temperature it was measured (usually 20°C) and then ENC will automatically populate the flow resistivity values in the above figure. To do this click on the green button labelled “flow resistivity” and the pop-up window below will appear. To obtain the correct answer, it is necessary to change the data in the top three data boxes shown in the following figure.



The top three input boxes are for the temperature at which the flow resistivity was measured and the values that were measured. The bottom three boxes are then automatically populated based on the temperature set in the “constants” window. The flow resistivity boxes in the main panel (see previous page) are also automatically populated with the new flow resistivity values and these are used in the liner attenuation calculations.

The switch on the top of the panel on the previous page (locally reactive / extended reactive) is used to select between a liner that has closely spaced solid partitions normal to the duct axis so that sound propagation in the liner parallel to the duct axis is prevented (locally reactive) and a liner that allows axial sound propagation within it (extended reactive). For the locally reactive case, only the normal flow resistivity value is used. For the extended reaction case, the software will only give good results if the flow resistivity in the parallel direction is different from the normal direction by less than a factor of 2.

If the green “Show att. curve” button is clicked, the following figure appears. This figure contains 2 curves: the blue curve represents the single frequency calculated liner attenuations and the red curve represents octave band averaged values where the octave band centre frequency is the frequency corresponding to the current data point being plotted on the graph. This single data point represents an average of all data points in an octave band with this centre frequency. Note that the octave band centre frequencies are not the standard ones – they vary incrementally as the frequency corresponding to the data point being plotted increments.

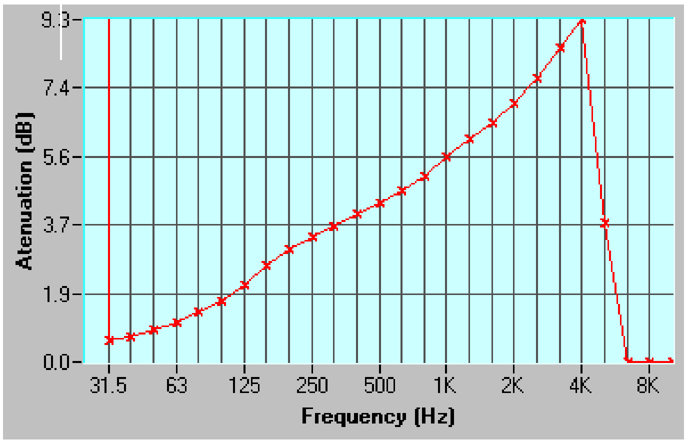


If there is an air space between the back of the liner and the duct wall, you need to add this depth to the liner thickness (within reason — this approximation becomes less reliable as the cavity depth exceeds the liner thickness.).

The attenuation plotted on the curve is the total liner attenuation for the specified length.

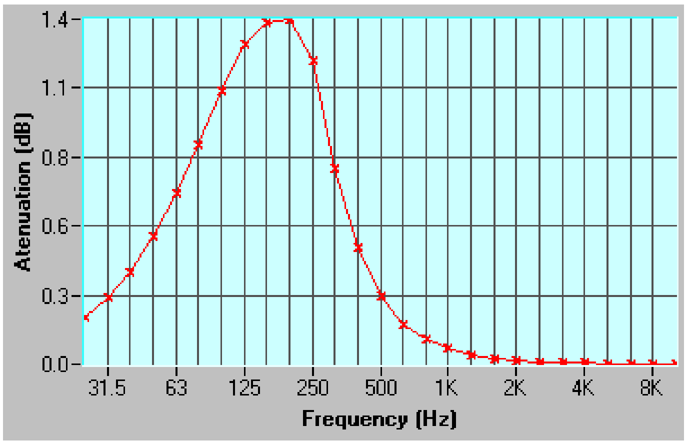
The attenuation due only to the liner is given in the grey box at the right of the panel (see figure at right) for the specified frequency.

Note that ENC calculates the attenuation of the least attenuated duct mode. When that mode is attenuated by more than about 40 dB as may happen in a long lined duct, other propagation modes become important so the amount of attenuation given by ENC will be an overestimate.



The liner attenuation calculation is very complex and sometimes the calculating program converges incorrectly. To guarantee correct results, the software should only be used in the range represented by figures 8.28–8.33, pp. 528–533 in the 6th edition textbook. However, ENC does give good results for many materials and liner thicknesses outside of this range, but care should be taken to identify obviously erroneous results.

If the calculated attenuations exceed 7dB per length of duct equal to half the duct width, then please change the input parameters (flow resistivity or duct size) slightly and re-run the calculation. If the results show an exponential tendency or a step change as shown in the figure at right, then again the software has failed to converge to the correct solution and you should change one of the input parameters by a small amount and try again.

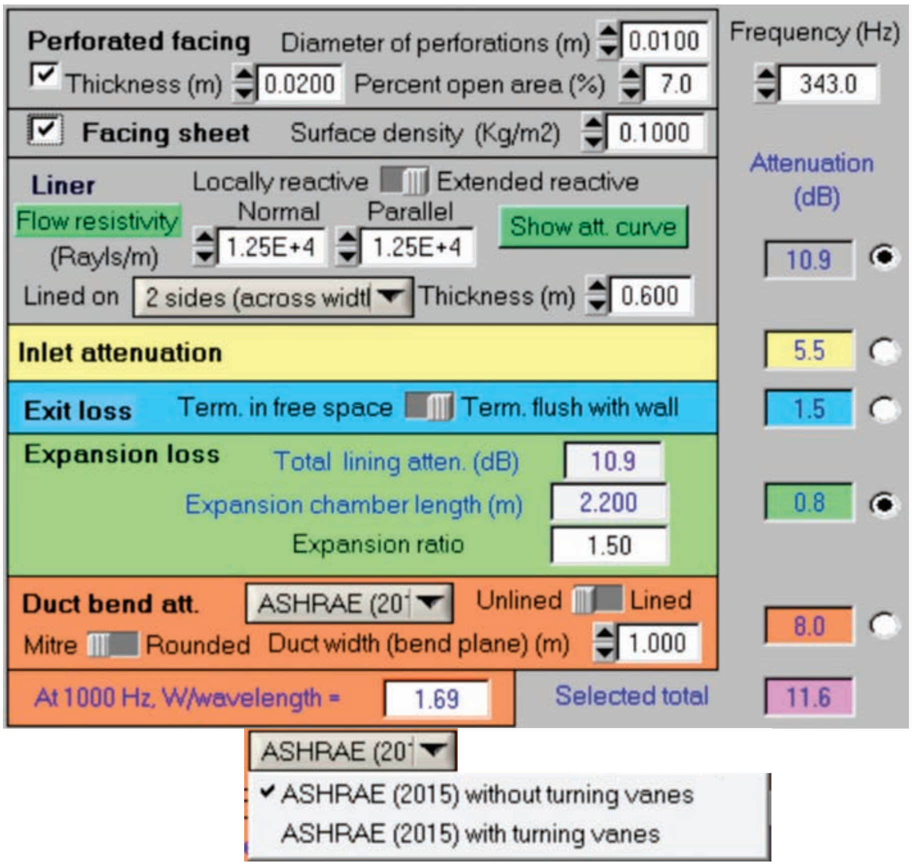


The problem seems to be more prevalent when an impervious membrane or perforated panel (low percent open) is used. The correct curve shape, which indicates that the software tracked the correct modal solution is shown at right.

In calculating the total attenuation of the lined duct (see Figure on the next page), the following quantities need to be calculated and added: liner attenuation (grey colour, discussed above), due to waves entering the inlet over a range of angles (yellow), exit loss due to reflection from the exit (blue — select whether the outlet terminates flush with a wall/ceiling or free space), expansion loss (green) and duct bend attenuation, if one exists (orange). Each quantity can be selected by clicking in the circle to the right of the panel. The numbers in the box next to the circle are the attenuations corresponding to the frequency selected in the box under "Frequency". The "total attenuation" if it is selected for display in the graph and attenuation table is only calculated using the quantities selected (with a dot inside the circle — see following figure). Values are tabulated in octave bands in the table below the graph and may be read from the graph for 1/3-octave bands using the cursor.

If a lined duct includes a rounded bend, add the distance travelled around the outer circumference of the bend to the lined duct length. This additional attenuation due to the distance travelled around the lined bend is not included in the duct bend attenuation calculations.

The bottom line in the orange panel in the following figure refers to the duct width (W) in the plane of the bend divided by the wavelength at 1000 Hz, of sound in the duct.



6.6.3 Inlet Attenuation (see page 538 in the 6th edition textbook)

The attenuation due to sound having to enter a duct (assuming that the incident angle of the sound is random) is calculated here using Figure 8.35, p. 538 in the 6th edition textbook. This is usually only applicable if a muffler is used as an inlet or outlet attenuator for cooling air for an enclosure and not if it is inserted into an existing duct. Note that for a splitter silencer with one or more baffles, the area, S is the cross-sectional area of a single airway and not the entire silencer.

6.6.4 Exit Loss (see 6th edition textbook, page 541–542)

When sound exits from a muffler to free space, there is an exit loss, which can be calculated using Table 8.13, p. 542 in the 6th edition textbook. Again, this is usually only applicable to the addition of a muffler to an enclosure to attenuate sound that is associated with the discharge or inlet of cooling air. If added to an existing duct, the duct will already have exit losses. However, if the muffler cross sectional area is different to that of the existing duct, then the exit loss associated with the muffler will be different and it should be calculated here for both cross-sectional area cases (with and without muffler) and the difference used to calculate the muffler exit loss.

6.6.5 Expansion Loss (see 6th edition textbook, pages 537–539)

When a liner is added to a duct section, sometimes the dimension of the part of the duct containing the liner is increased in the direction normal to the plane of the liner to reduce the pressure drop through the duct system as a result of installing the muffler. In some cases, the dimension change is such that the open area of the inlet duct is the same as in the muffler section. In other cases, it may be less or more. When it is the same, it is not necessary to know the number of baffles in the muffler in order to calculate the effective expansion ratio, R. In all other cases, it is necessary to know the number of baffles as well as the dimensions of the inlet duct as shown in the following equation. If the value of R calculated in the second of the following equations is less than 1, the reciprocal value is entered into the expansion loss sub panel in ENC.

$$R = \begin{cases} \dfrac{2h + 2\ell}{2h} & \text{same total open area in the inlet duct and muffler} \\ \dfrac{(N+1)(2h+2\ell)}{W} & \text{all other cases} \end{cases} \tag{6.2}$$

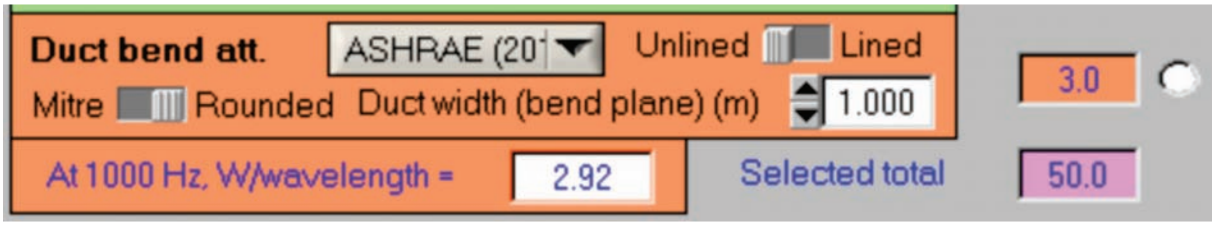
where N is the number of baffles, $2h$ is the air gap between baffles (splitters), 2ℓ is the baffle thickness and W is the width of the inlet duct in a direction normal to the plane of the baffles. Note that the liner thickness, ℓ, on the duct walls is half the baffle thickness. The $+1$ is included in the second two of Equations (6.2) to account for the walls being lined with a liner of half the baffle thickness. If the part of the ductwork containing the baffles has a larger cross-sectional area than the entrance and exit ducts, the expansion loss is calculated by replacing the denominator in Equation (6.2) by the inlet duct width. Once you have estimated the effective expansion, the additional attenuation as a result of this expansion is calculated here using Figure 8.36, p. 539 from the 6th edition textbook. Note that you need to define a liner (see lined duct above) and enter the cross sectional area of the open duct plus liner to be able to use this part. The open duct area is calculated when the liner is specified in the top left of the panel.

If analysing a duct with baffles, the liner thickness to be entered into ENC is half the baffle thickness and it is assumed that the thickness of the liner on the walls parallel to the plane of the baffles is half the baffle thickness.

If analysing a lined duct with no baffles, enter the thickness of the liner in the box labelled “thickness” in the “Liner” section of the GUI.

6.6.6 Duct Bend (see 6th edition textbook, page 540)

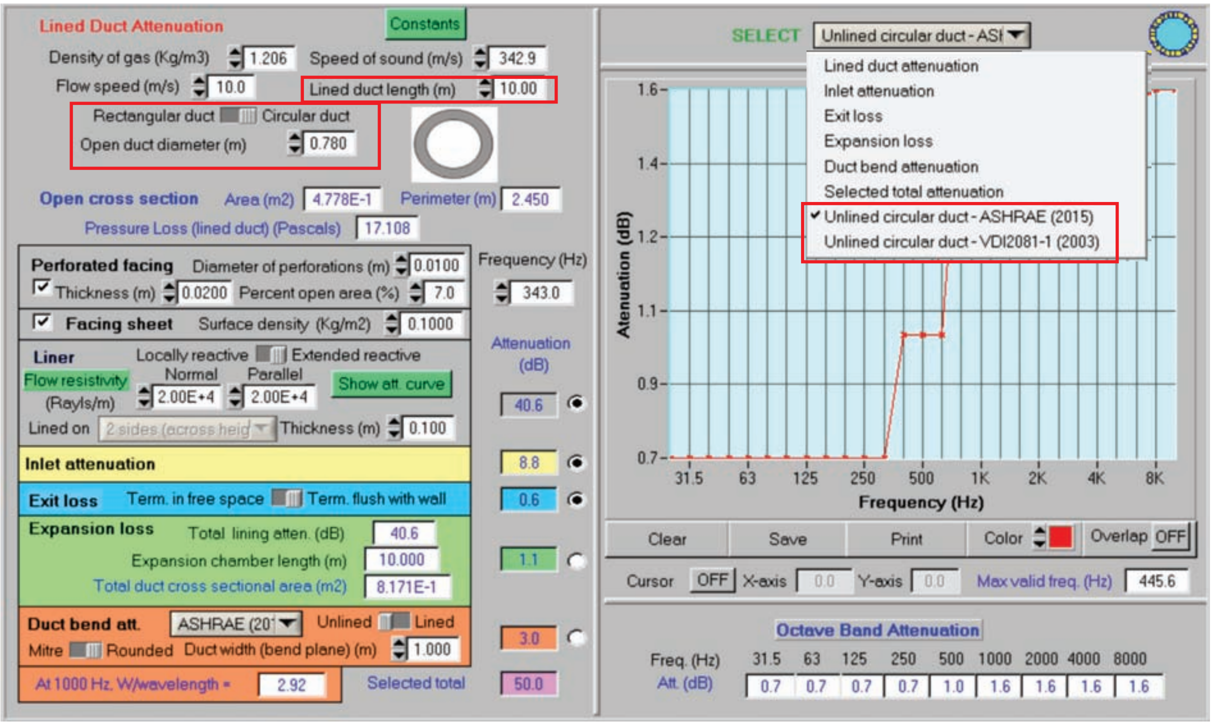
Where a duct bend exists, this section can be used to calculate the attenuation, following Table 8.10 in the 6th edition textbook. Attenuations for duct bends in both a rectangular section duct, where W = width of duct in the plane of the bend, and for a circular section duct, where W = duct diameter, are provided in table 8.10, p. 540 in the 6th edition textbook, where, λ = wavelength (all in metres). The value of W/λ at 1000 Hz is provided for convenience at the bottom of the bend section on the RHS of the GUI. Values at other frequencies, f, can be obtained by multiplying the value at 1000 Hz by $f/1000$.



The attenuation values for a rounded bend applies to lined and unlined bends as well as to rectangular and circular section ducts and the values are sourced from ASHRAE (2015). Any additional attenuation due to a lining of the bend is taken into account by adding the length of travel around the mid section of the bend to the lined straight duct section, when calculating the lined straight duct attenuation.

W/λ	Insertion Loss (dB)				
	Mitred bend, no turning vanes		Mitred bend, with turning vanes		Rounded bend
$W/\lambda < 0.14$	0	0	0	0	0
$0.14 \geq W/\lambda < 0.28$	1	1	1	1	1
$0.28 \geq W/\lambda < 0.55$	5	6	4	4	2
$0.55 \geq W/\lambda < 1.11$	8	11	6	7	3
$1.11 \geq W/\lambda < 2.22$	4	10	4	7	3
$W/\lambda \geq 2.22$	3	10	4	7	3

6.6.7 Unlined Duct Attenuation (see 6th edn. textbook, pp. 540–541)



The attenuation for unlined rectangular and circular section ducts can be obtained by selecting one of the "unlined" options in the graph selection menu on the RHS of the GUI. The corresponding duct type, size and length are selected on the LHS of the GUI near the top of the screen. This is illustrated in the previous figure (note items enclosed in red boxes). There are two options available for calculating the corresponding attenuations. One comes from ASHRAE (2015) and the second comes from VDI2081-1 (2003).

For rectangular section ducts, ENC first calculates an equivalent square section that has the same cross-sectional area. Table 8.11 in the 6th edition textbook is then used to obtain attenuation values. For duct sizes that are between the sizes listed in the table, linear interpolation is used to obtain the corresponding attenuation values. For duct sizes that are smaller than the smallest size in the table, the attenuation values corresponding to the smallest size in the table are used. Similarly, for the ASHRAE calculations for duct sizes that are larger than 1.83 m $\times$ 1.83 m, the attenuation values corresponding a size of 1.83 m $\times$ 1.83 m are used. If the VDI 2081 method is chosen, the upper duct size is 2.44 m $\times$ 2.44 m (not shown in the textbook) and the attenuations for larger duct sizes are set equal to those for the 2.44 m $\times$ 2.44 m duct size.

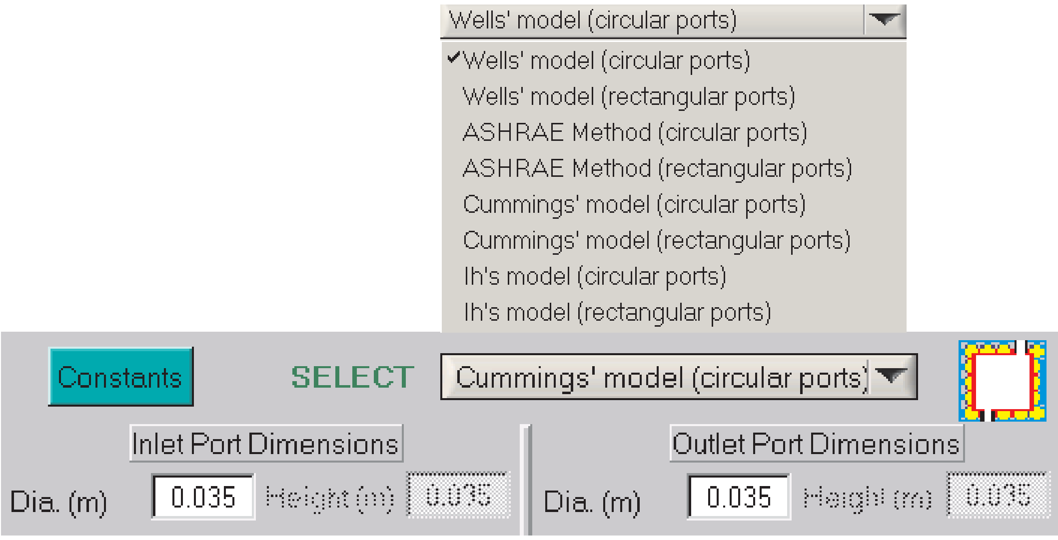
The attenuations for unlined circular section ducts are provided in Table 8.12 in the 6th edition textbook. Each line in the table corresponds to a range of duct sizes from a diameter of 1 mm to 1600 mm. As all diameters between these two limits are covered in the table, there in no need for linear interpolation as was done for the rectangular section ducts. However, for duct sizes greater than the upper diameter limit of 1600 mm, attenuation values corresponding to the 1600 diameter are used. ENC gives the value of W/λ for a frequency of 1000 Hz to assist in relating the graph to Table 8.10 in the textbook. Values of W/λ at higher and lower frequencies may be obtained by multiplying the value at 1000 Hz by frequency/1000.

Results for duct lengths less than 10 m can be confusing as ENC only gives results to the nearest 0.1 dB, so for smaller duct lengths, it is best to use a duct length that is 10 times longer and then divide the result by 10.

Unlined duct attenuation values should be doubled if the duct is externally lined.

6.7 Lined Plenum Chamber (6th edition textbook, pages 556–560)

In some air handling systems a plenum chamber is used to reduce mean pressure fluctuations. There have been a number of models published for calculating the transmission loss of a plenum chamber and these are summarised in the paper, "Comparison of models for predicting the transmission loss of plenum chambers", by Li and Hansen, Applied Acoustics, 66, pages 810–828 (2005). A number of models are discussed in the 6th edition textbook and are available in ENC: the Well's model, the ASHRAE method, Cummings model and Ih's model and the user must first select which model is to be used (see following figure).

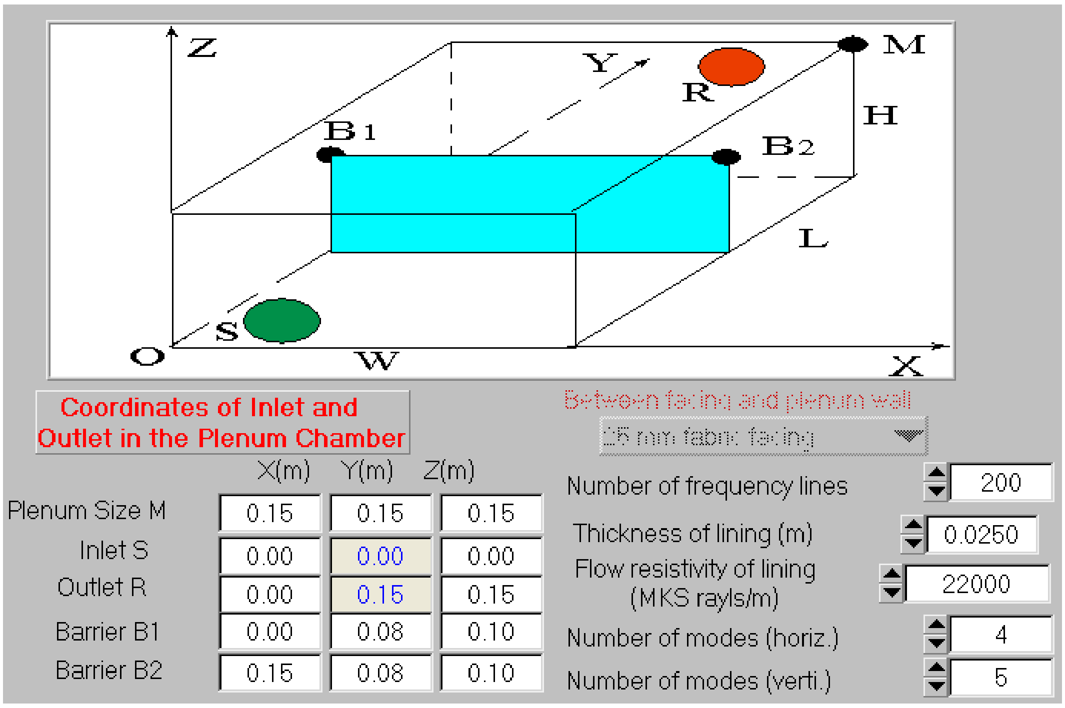


The Wells model is the simplest and least accurate and is only applicable to lined chambers. The ASHRAE method is a modified form of Wells' model that agrees better with experimental data. Ih's model is accurate but only suitable for an unlined chamber. Cummings model is accurate and is intended for lined chambers. However, it also gives accurate results when a thin liner with high flow resistivity (effectively no liner) is used. All models give the option of circular or rectangular ports. However, results for a rectangular port are similar to those for a circular port of the same area. The Cummings model is more accurate than the Wells model over the entire frequency range even though it is based on the so-called Cummings low frequency model (see above reference).

After selecting which model you wish to use (which includes whether the inlet and outlet ports are round or rectangular in cross section) you must enter the cross-sectional dimensions of the inlet and outlet ports.

Next you need to enter the plenum size (which is effectively determined when you enter the coordinate location of "M" — see the following figure). Note that only rectangular section plenums can be analysed here. If you have a cylindrical plenum, then you can only use the Wells model or the ASHRAE method and a square cross section of equivalent area to the actual cylinder cross section.

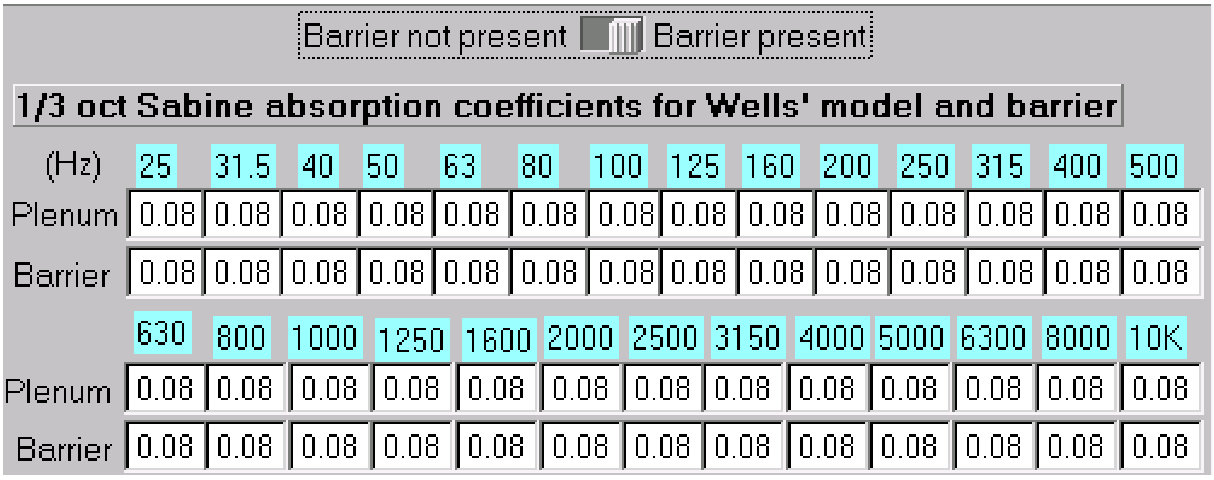
Next you need to enter the x and z coordinates of the inlet and outlet port centres (the y-coordinates are fixed by the size of the plenum chamber which is why they are in blue text) and the coordinates of the top corners of the barrier (if one exists) (see following figure). Note that both the Cummings and Ih models are quite sensitive to the actual locations of the inlet and outlet ports.

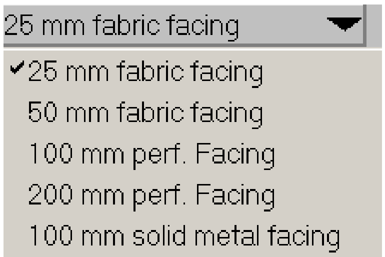


As can be seen from the above figure, for both the Ih and Cummings models, you have the option of adjusting the number of frequency lines. Increasing them will result in longer calculation times but a more accurate 1/3-octave band average, which is plotted on the graph and used to calculate the octave band average in the table. For the Cummings model only, you also have the option of adjusting the number of plenum chamber modes that are used to calculate the response. Increasing the number of modes increases the accuracy at high frequencies but the calculation times can become quite long — up to minutes.

Also for the Cummings model only, you will need to enter the thickness and flow resistivity (Rayls/m) of the acoustical material used to line the plenum chamber. What data are required for particular models can be a bit confusing so to assist you, if data are not required, the place where it is entered is “greyed out”.

For the Wells or ASHRAE models, the 1/3-octave band absorption coefficients of the plenum chamber liner must be entered in the following table. For all models, if a baffle or barrier exists, then move the switch at the top of the table to “Barrier present“ and enter the absorption coefficients of the barrier surface and the plenum chamber. The insertion loss of the barrier is calculated using the “Indoor Barrier” window in Module 5 and the result is added arithmetically to the Insertion Loss of the plenum chamber to get the total insertion loss. Note that in order to calculate the barrier insertion loss, data are needed for the absorption coefficients of the plenum interior, irrespective of the calculation model used, even if it is for Ih’s model with no sound absorbing material in the plenum. With no barrier in place, no sound absorption coefficient data are needed for the Ih or Cummings models and the table is greyed out. For the ASHRAE model, absorption coefficients are only needed for frequencies above that corresponding to the first cut-on mode of the inlet duct — all other cells in the table are “greyed” out to indicate that the absorption data are not needed for those particular frequencies.





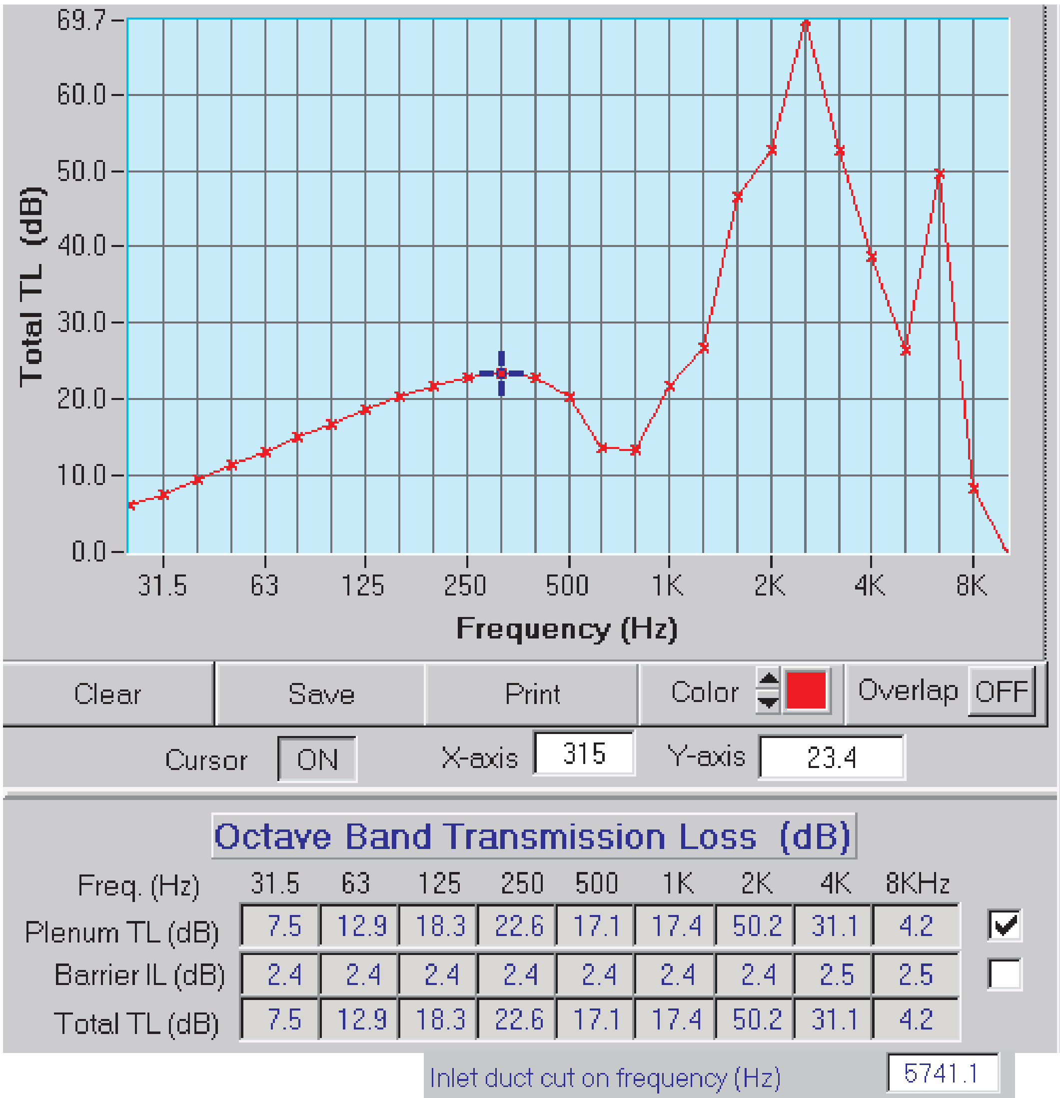
The Ih model is only applicable to an unlined plenum chamber and the latter model uses values of the plenum liner flow resistivity and thickness to calculate the plenum sound absorption effect.

For the ASHRAE method, the calculation of the low frequency TL of the plenum (for frequencies below the first higher order mode cut-on frequency of the inlet duct) requires you to choose what sort of liner the chamber has (see figure at right). For higher frequencies, you need to enter the liner absorption coefficient in the table shown above.

For the ASHRAE method, to avoid discontinuities in the plot, the 500 Hz value in Table 8.19, p. 558 in the 6th edition textbook is also used for frequencies between 500 Hz and the inlet duct cut-on frequency. The 5000 Hz value in Table 8.19, p. 558 in the 6th edition textbook is also used for frequencies greater than 5000 Hz. The 80 Hz value in Table 8.19 in the 6th edition textbook is also used for frequencies lower than 80 Hz. The 50 Hz value in Table 8.20 in the 6th edition textbook is also used for frequencies lower than 50 Hz. However, the validity of doing this has not been verified.

Click on “run” after each change of data — sometimes it may take a short time for the results to be calculated by ENC.

The 1/3-octave band Transmission Loss for the plenum chamber is plotted on the graph shown on the next page and octave band results (which are energy averages of the 1/3-octave band results) are included in the table below the graph (see following figure). Finally the inlet duct cut-on frequency is also shown.



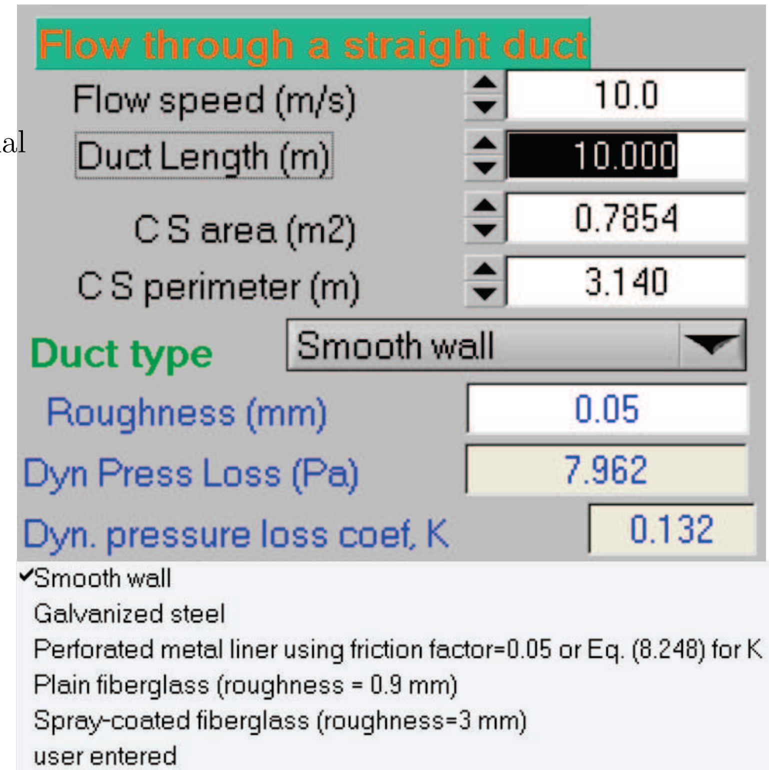
The Transmission Loss calculated here is very close to the insertion loss value, provided that there is some acoustic absorbing material on the interior walls of the chamber or the baffle. The additional transmission loss as a result of placing a baffle (or barrier) in the chamber between the inlet and outlet is simply added arithmetically to the TL of the chamber without a baffle which is difficult to justify theoretically. However, for convenience it is also listed separately in the octave band results table and may be plotted separately or combined with the unbaffled chamber TL simply by clicking on the appropriate empty boxes adjacent to the table (see above figure).

6.8 Pressure Loss (6th edition textbook, pages 541–548)

ENC calculates the dynamic pressure loss resulting from gas flow through straight ducts (Section 6.8.1), rectangular and circular-section silencers (Section 6.8.1.1) as well as various unlined elements making up a duct system that may or may not contain silencers (Section 6.8.2). Note that the total pressure loss through a duct or silencer is the sum of the inlet and exit losses and the loss due to flow through the duct system and/or silencer.

For all pressure loss calculations, you need to establish the required gas properties by clicking on the "constants" button. In a number of cases, there is more than one option for calculating the pressure loss. In these cases, it is probably prudent to select the one that gives the highest pressure loss.

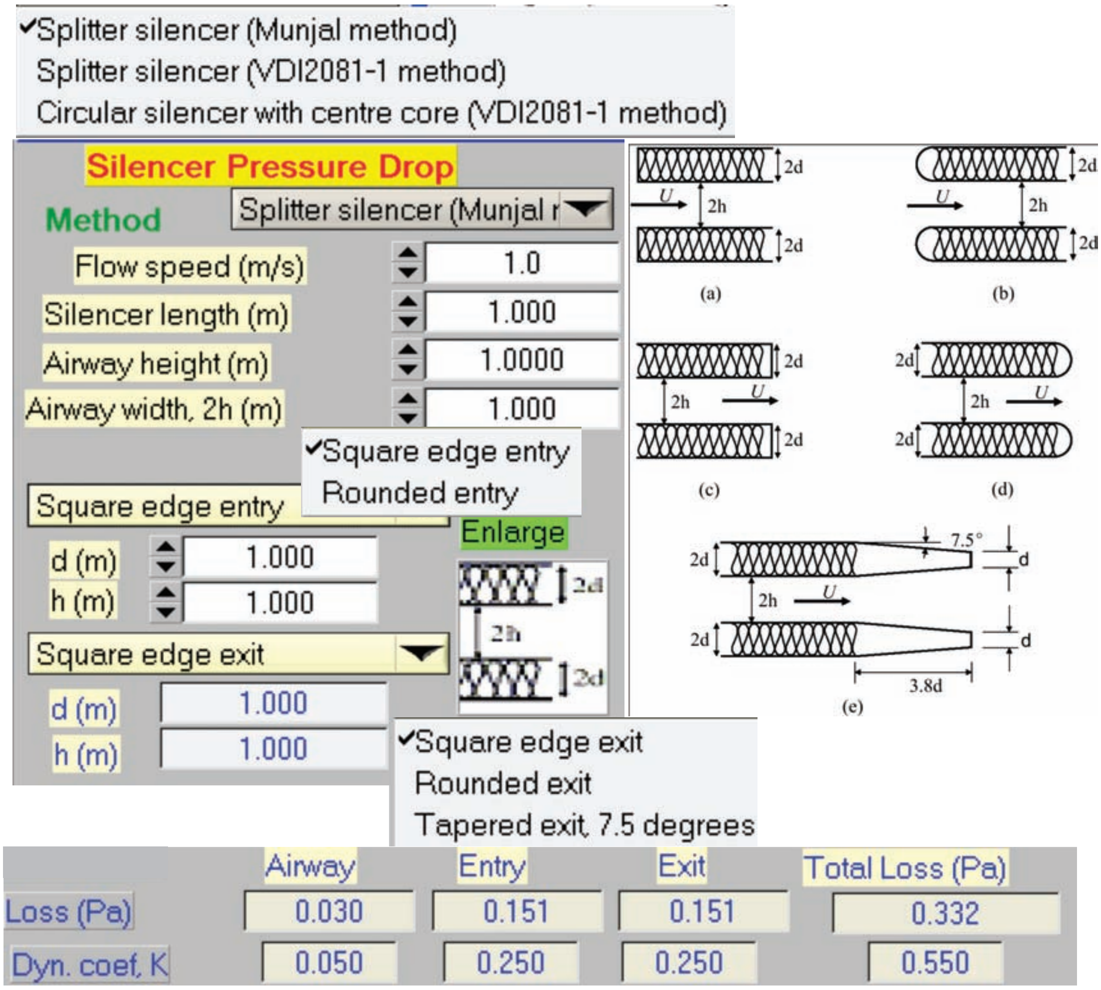
6.8.1 Loss Due to Flow Through a Straight Duct



To calculate the pressure loss in a straight duct, you need to enter the duct length, cross-sectional perimeter, cross-sectional area and flow speed, as shown in the figure at right. You also need to enter the type of wall from the choices shown at right. If you choose "user entered", you will need to enter the roughness in mm. The choice, "Perforated metal liner....", Enters the friction factor (f_m = 0.05) directly into Equations (8.237) and (8.238) in the textbook. The dynamic pressure loss, the duct roughness and the dynamic pressure loss coefficient, K are all output in blue (see figure at right). For all pressure loss calculations, you need to establish the required gas properties by clicking on the "constants" button.

The pressure loss through a straight duct with a perforated metal liner is calculated using Equations (8.237)–(8.242) in the 6$^{\text{th}}$ edition textbook.

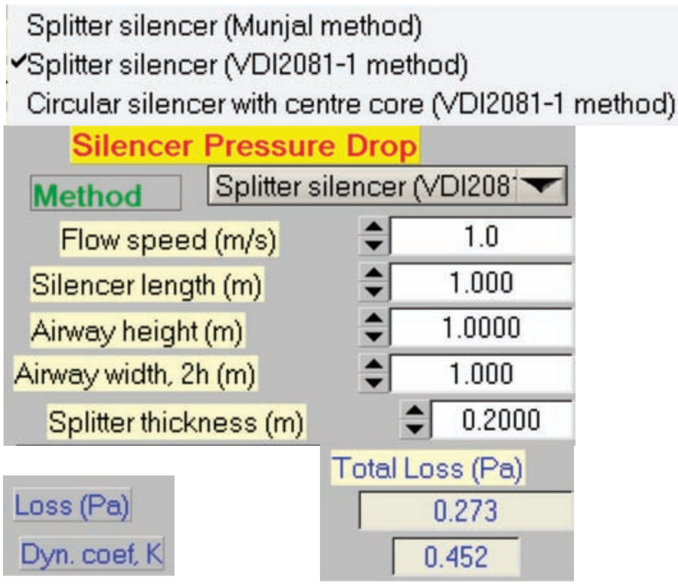
6.8.1.1 Silencer Pressure Drop



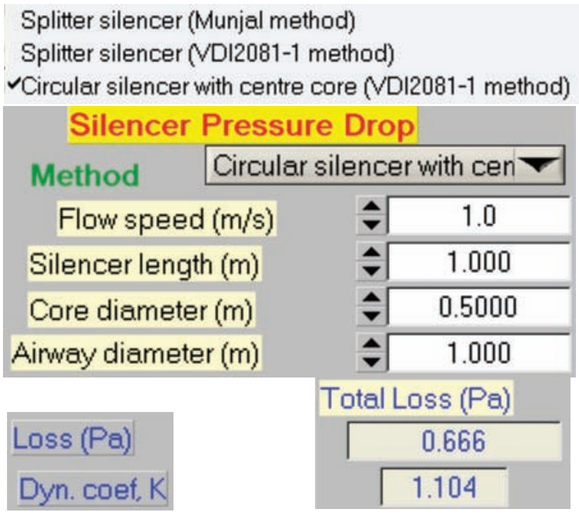
For all silencer calculation methods, it is necessary to select the correct gas properties by clicking on the green “Constants” button. For the rectangular splitter silencer, the pressure loss is the same for multiple splitters as it is for a single splitter. However, for a circular silencer for which the heights of the splitter airways are not all the same, it is necessary to average the pressure losses, although a more conservative approach would be to use the highest loss calculated for all airways.

The Munjal method chosen in the above figure, and used for calculating the pressure drop of splitter silencers, is based on the 2006 Ver and Beranek book, “Noise and Vibration Control”, page 334 and is described in the 6th edition textbook on page 546. The dimensions d and h shown in the figure at right are defined for various types of inlet and outlet conditions. Note that the exit and inlet dimensions must be the same, so it is only possible to enter the inlet cross-sectional dimensions. Diagrams showing the various geometries can be seen by clicking on “Enlarge” and the pictures on the right hand side of the above image are obtained. The required input data are the gas flow speed, the silencer length, and the cross-sectional area and cross-sectional perimeter of the airway between splitters. In addition, the type of entry to and exit from the airway must also be selected. The output, shown in blue text, provides the pressure loss for entry and exit from the silencer as well as the loss due to flow between the splitters (airway) and the total loss (sum of the entry, airway and exit losses).

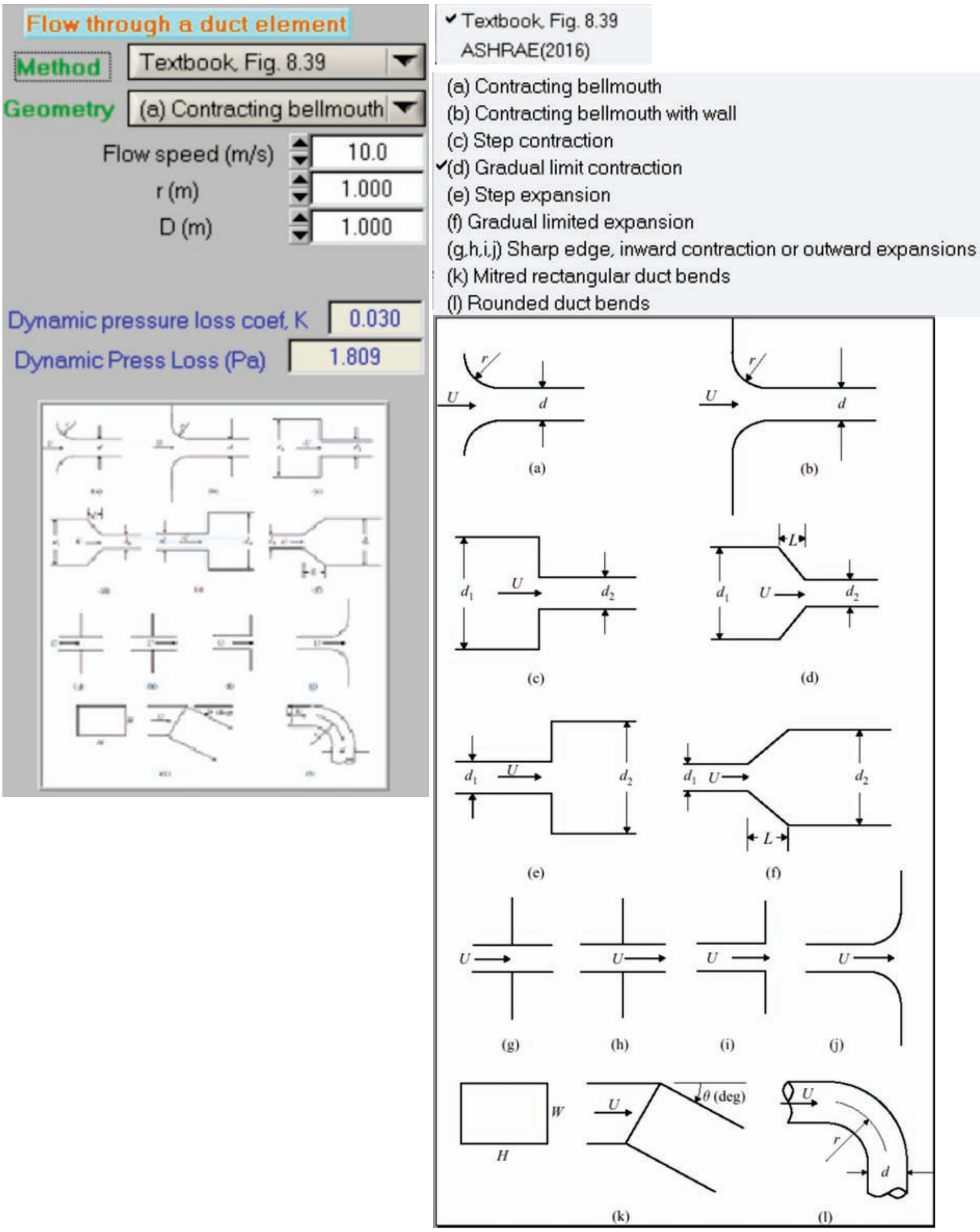
If the VDI method (based on the German standard, VDI2081-1 standard) is chosen, as illustrated in the figure at right, there is no choice for the entry and exit configuration and the total loss is based on the assumption that there is no aerodynamic treatment for the inlet or exit from the airways. The only output available in this case is the total pressure loss, as shown in the figure.



A choice is also available for a circular silencer with a centre pod, for which the total loss is calculated according to the VDI2081-1 standard (see figure below). For this case the required input data are the flow speed, silencer length core diameter and airway diameter. It is assumed that the duct wall is lined for the same length as the centre pod. Again, the only output is the total pressure loss.



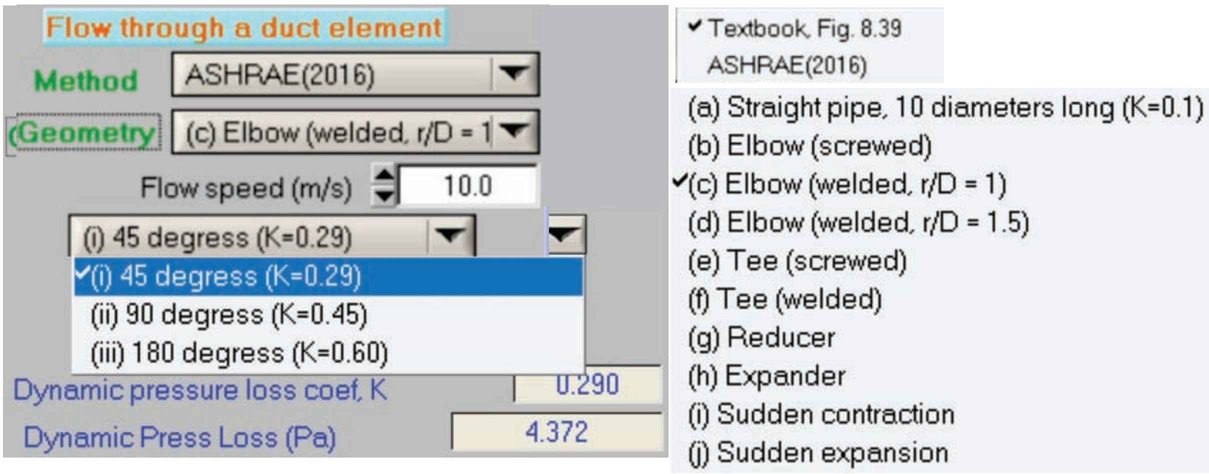
6.8.2 Loss Due to Flow Through a Duct Element



There are two different ways to calculate the pressure loss due to gas flowing through a duct element, as outlined in the 6th edition textbook on pages 544 to 545. Each method is applicable to the duct elements listed. Pictures of the duct elements for the “Textbook

(Fig. 8.39)" method are shown in the low-quality figure above the input data and results. A higher quality picture (see above figure at right) can be obtained by clicking on the low-quality picture. Required input data for the "Textbook (Fig. 8.39)" method include the choice of duct element, the gas flow speed and some dimensions of the duct element shown in the high-quality figure. The pressure loss outputs are given in blue at the bottom of the panel (see figure on the previous page, above left).

For the "ASHRAE(2016)" method (ASHRAE, 2016) the required input data are the flow speed and the selection of the element of interest as shown in the figure below, where the output data are in blue font.



6.9 Flow Generated Noise (6th edition textbook, pages 548–554)

Noise generated by flow through the following elements can be calculated using this part of ENC. Circular ducts lined only on the inside wall are not included as the noise generation is negligible.

- Straight unlined ducts.
- Splitter-type circular or rectangular-section dissipative mufflers.
- Circular mufflers with a centre pod
- 90 degree bend or elbow.
- Pins used to anchor acoustic material to the inside of ducts.
- Grilles used to terminate air conditioning ducts.

Details about each option, and the various choices available for each of the main options, are discussed below. Note that variables that are "greyed out" in ENC are not valid for the particular option that has been chosen. To begin a calculation for any of the options to follow, first click on the "constants" button to enter the gas properties.

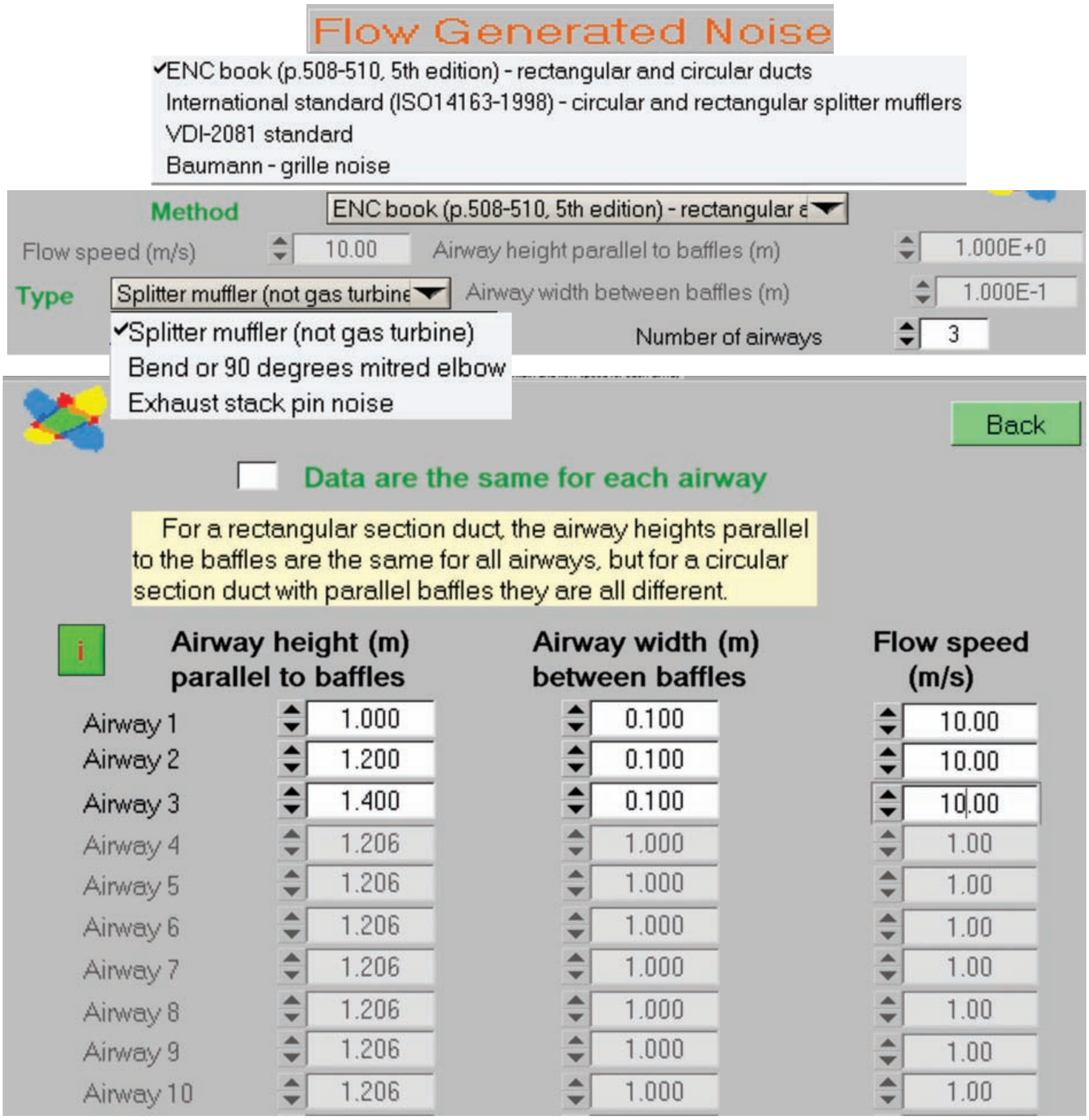
Please note that if a graph has tiny "x" symbols only at octave band centre frequencies and the cursor can only read values at octave band centre frequencies, then care must be taken in obtaining 1/3-octave band values. In cases where the y-axis represents noise reduction or transmission loss, the y-axis value where the curve crosses a 1/3-octave vertical line is likely to be a good approximation of the actual 1/3-octave value if the curve is smoothly increasing or decreasing but not if the curve slope varies greatly with frequency. On the other hand, whenever the y-axis represents sound pressure level or sound power level, it is not possible to interpolate between octave band cursor values to obtain 1/3-octave band values, as each octave band value represents the logarithmic sum of the three 1/3-octave band values that make up the octave band.

There are three options (discussed below in three separate subsections) available for calculating self-noise of dissipative mufflers and other duct system elements: Textbook pp. 548-550, ISO14163-1998 (textbook p.551), VDI2081 (textbook p. 550) and grille noise (textbook, p. 553). Where there is more than one option for the same calculation, it is probably prudent to select the one that gives the highest noise levels.

6.9.1 Textbook

The textbook option has procedures for calculating noise generated by gas flowing in rectangular and circular-section splitter mufflers, or around a 90° bends, as well as exhaust noise resulting from pins supporting acoustic material lining the inside of gas turbine exhaust ducts.

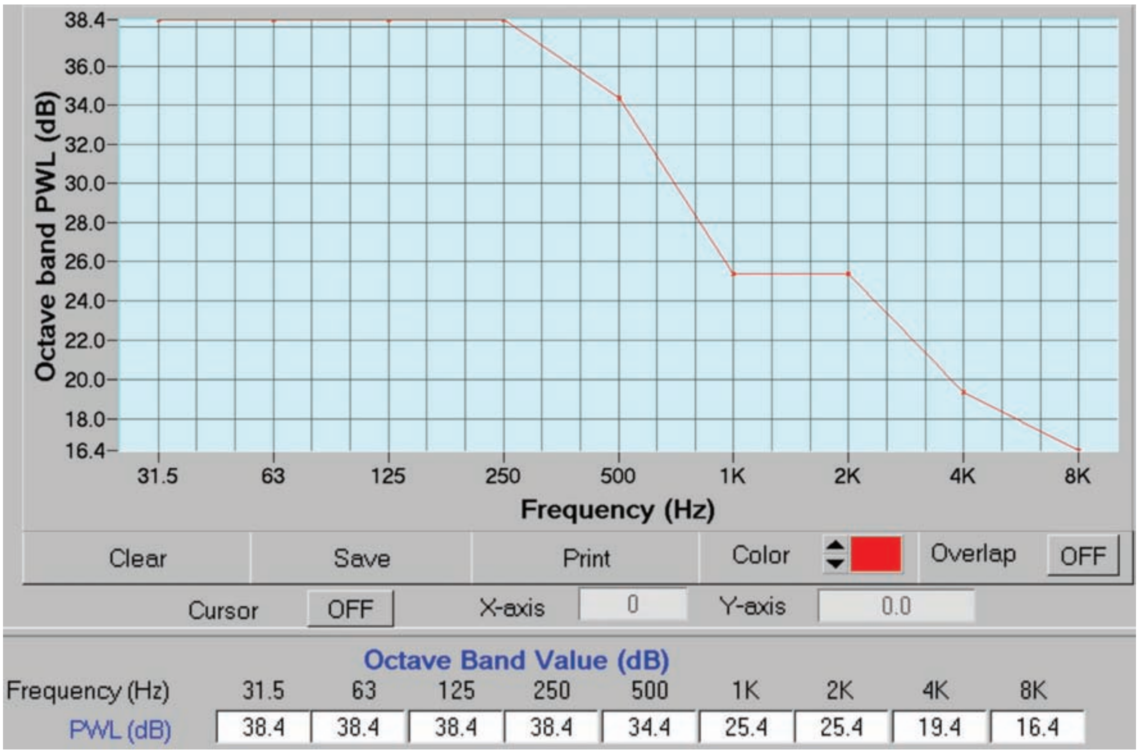
6.9.1.1 Splitter Mufflers



The method that is outlined in the 6th edition textbook on pages 550–552, is applicable to splitter mufflers in air conditioning ducts, or industrial air handling ducts, but not exhaust ducts such as gas turbine exhausts. Gas turbine exhausts are covered in Section 6.9.2 below. The splitter arrangement can also be used for circular-section or oval-section ducts, but the height dimension (and thus noise generating ability, of each airway is not constant across the muffler cross section. (see the figure on the previous page). However, ENC does allow different airway sizes and flow speeds, which allow circular and oval cross-section ducts to be treated.

When the splitter muffler option is selected, the number of airways making up the muffler must be entered. If this number is 1, then the gas flow speed as well as the airway cross-sectional height and width must be entered (greyed out in the figure on the previous page as the number of airways is greater than one). If the number of airways is selected as greater than one, then a pop-up window appears (lower part of the above figure) and the airway gas flow velocity as well as the airway cross-sectional height and width must be entered for each airway. As can be seen in the figure above, there is a box to tick labelled “Data are the same for each airway”. In this case ENC will use the data entered for the first airway for all airways. The self noise for each airway is added logarithmically to obtain the total self-noise generation level.

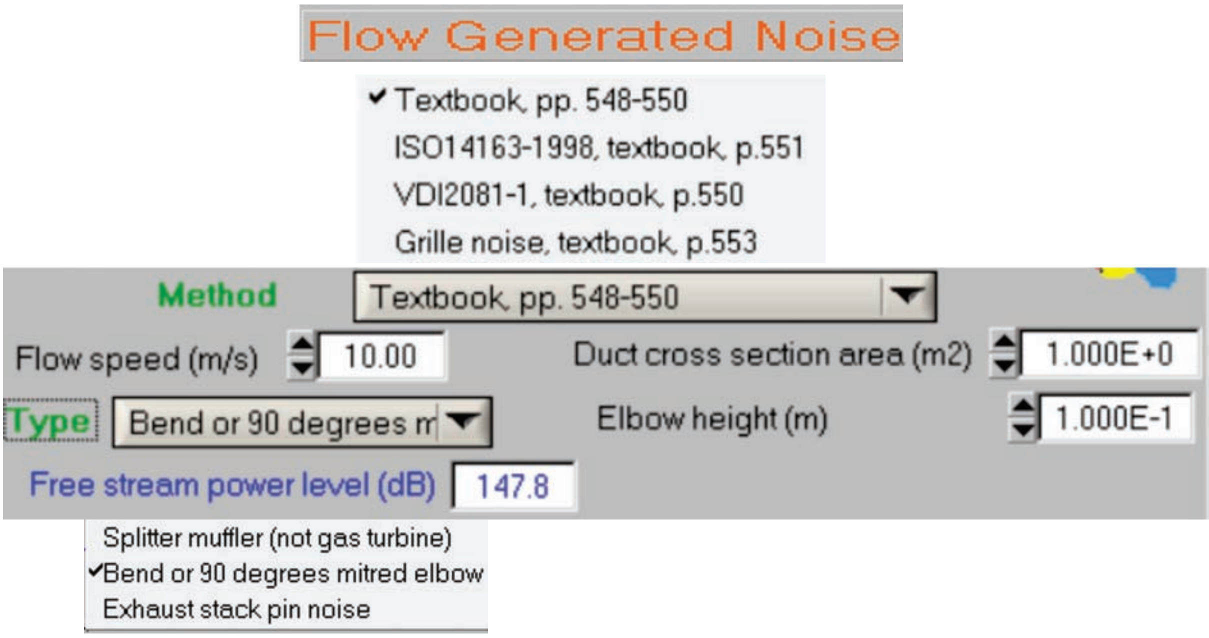
Octave band, in-duct sound power levels generated by the exhaust gas entering, exiting and flowing through the silencer are plotted on a graph (see following figure) and the plotted data as well as the overall sound power level are listed in the table below the graph. Multiple curves for different configurations can be shown simultaneously by clicking on the “Overlap” button. Values can be read from the graph by turning the cursor “ON”.



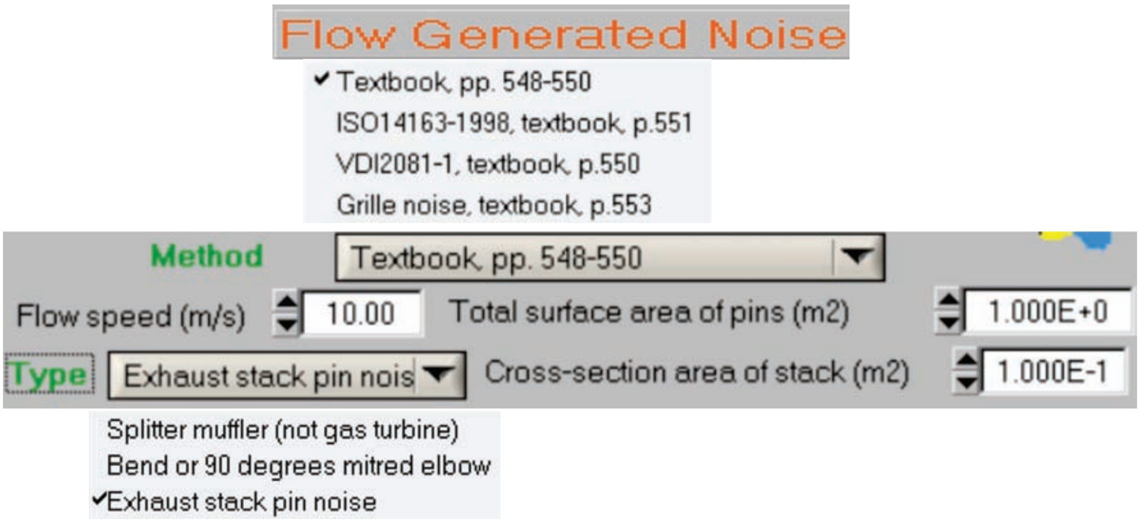
6.9.1.2 Bend or 90 Degree Mitred Elbow

If a bend or 90 degree mitred elbow is chosen, you must enter the flow speed of gas in the duct leading up to the elbow, the duct cross-sectional area and the duct width in the plane of the elbow (or elbow height, H), as shown in the following figure. Note this only applies to sharp 90° bends (see Figure 8.41 in the 6th edition textbook), not rounded bends that are usually found in circular-section pipes.

The output is in graphical and table format as it is for splitter mufflers discussed above. Octave band, in-duct sound power levels are plotted on the graph and, together with the overall sound power level, are listed in the table below the graph. In addition, the free stream power level in dB re 10^{-12} W is provided in blue text above the graph.

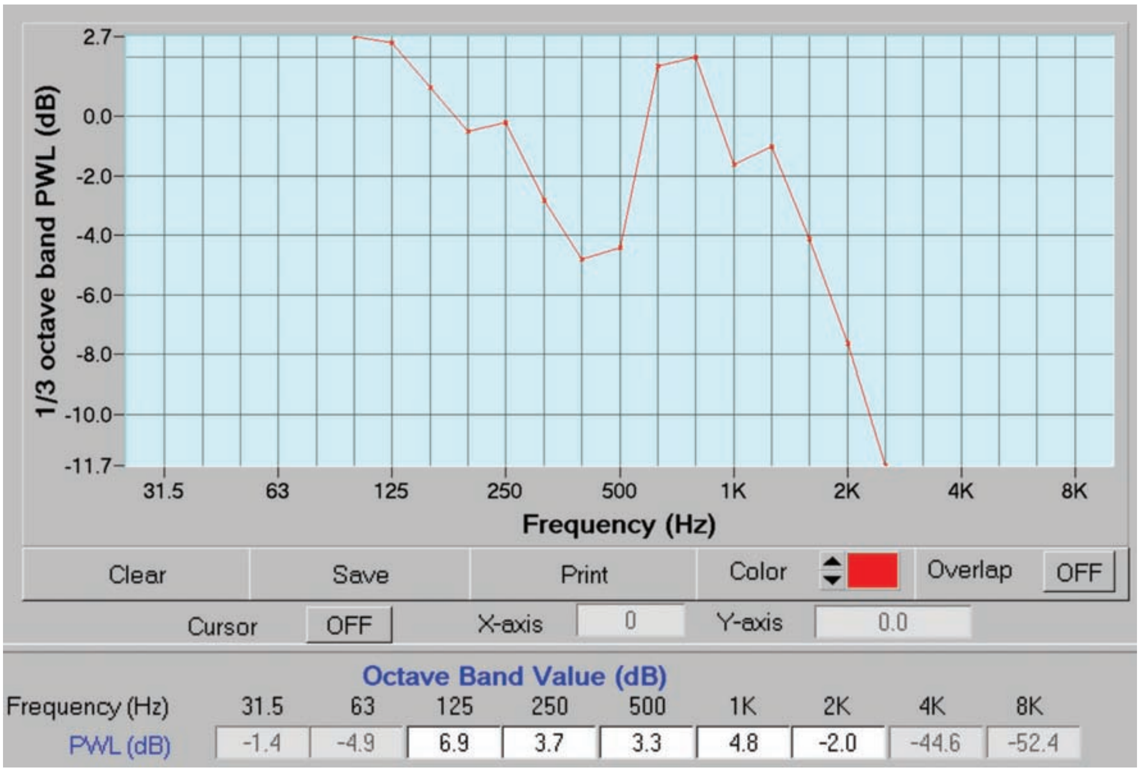


6.9.1.3 Exhaust Stack Pin Noise(6th edition textbook, page 553)



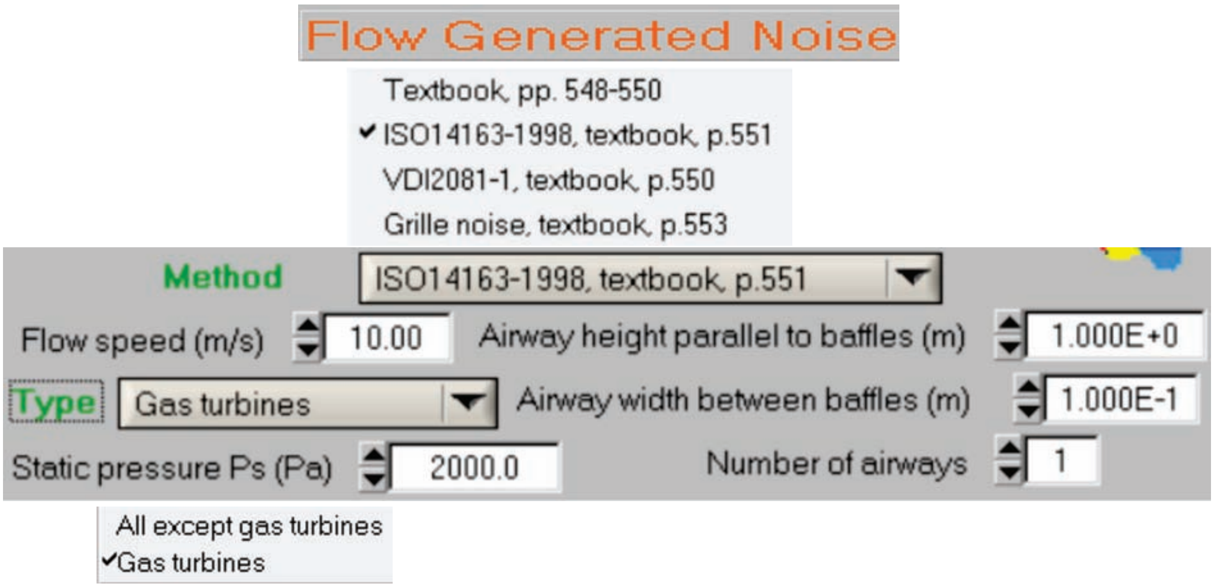
When ducted exhaust systems discharge to the atmosphere, they are often lined internally with sound absorbing porous material to reduce emitted noise. The porous material is fixed to the duct wall with pins and fast moving exhaust gases, such as found in gas turbine exhausts, generate noise as they travel past these pins. This noise can be estimated using the ENC procedure illustrated in the above figure.

1/3-octave band, in-duct sound power levels are plotted on a graph (see following figure) and octave band sound power levels, together with the overall sound power level, are listed in the table below the graph. Multiple curves for different configurations can be shown simultaneously by clicking on the "Overlap" button. Values can be read from the graph by turning the cursor "ON".



6.9.2 ISO14163-1998

6.9.2.1 Splitter Mufflers



The ISO14163 method can only be used for splitter mufflers in circular, oval and rectangular-section ducts. It is outlined on page 551 (Equation (8.251)) of the 6th edition textbook, with a value of 0.02 for the unknown constant, δ (not provided by the standard) and a value of 58 for the unknown constant, B, when the analysis is applied to air conditioning ducts and a value of 68 for B and 0.04 for Δ when applied to a gas turbine noise source (not provided in the standard). For most industrial ducts where the air flow is driven by a fan, choose the "all except gas turbines" option. The ISO14163-1998 is the only option that can be used for gas turbines.

The output is in graphical (octave band sound power levels) and table format (octave and overall sound power levels).

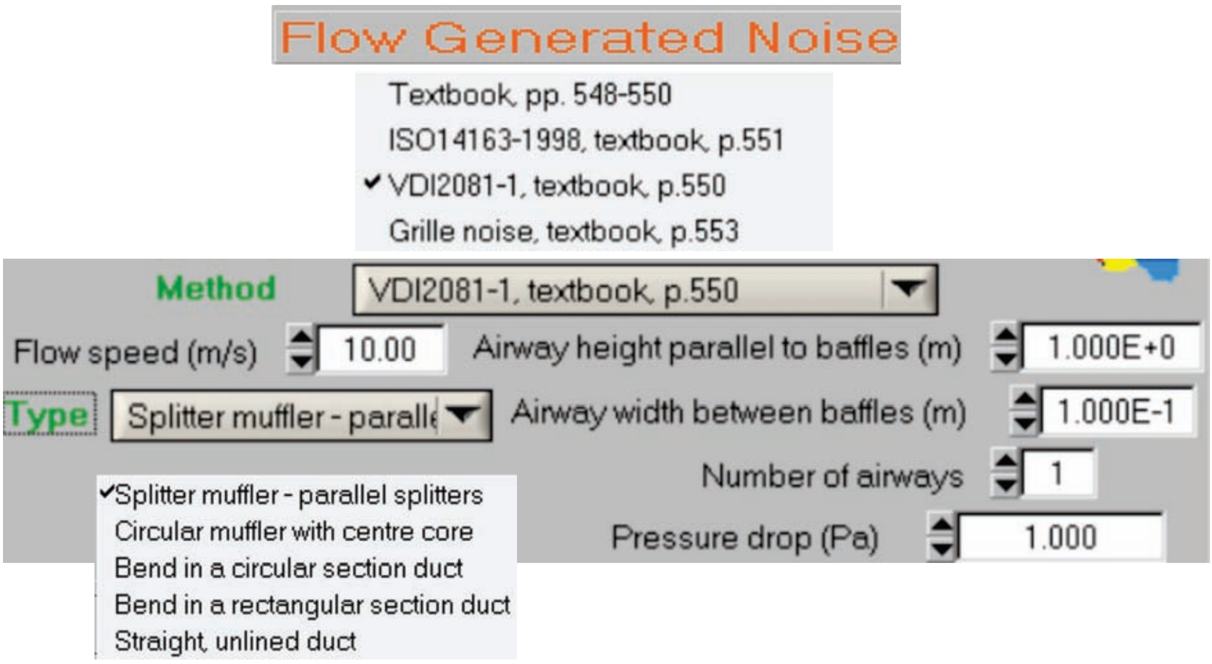
If more than one airway is selected, in this current version, ENC assumes that all airways have identical dimensions and flow speeds and so the self-noise sound power level increases over that for a single airway by by $10 \log 10n$, where n is the number of identical airways.

6.9.3 VDI 2081

The standard, VDI 2081 provides a method for calculating the self noise generation in straight, unlined ducts and in circular mufflers with a centre pod. The same standard also provides an alternative method for calculating self-noise generation in rectangular and circular-section splitter-type mufflers, and 90°bends or elbows.

6.9.3.1 Splitter Mufflers

The VDI2081 method for splitters in circular, oval or rectangular-section ducts is outlined on pages 551–552 (Equations (8.252) and (8.254)) of the 6th edition textbook. The required input data are the airway height in a direction parallel to the baffle surface, the flow speed, the splitter thickness, the number of airways, the pressure drop through the muffler (calculated using the dynamic pressure loss from the left hand part of this page) and the muffler length.

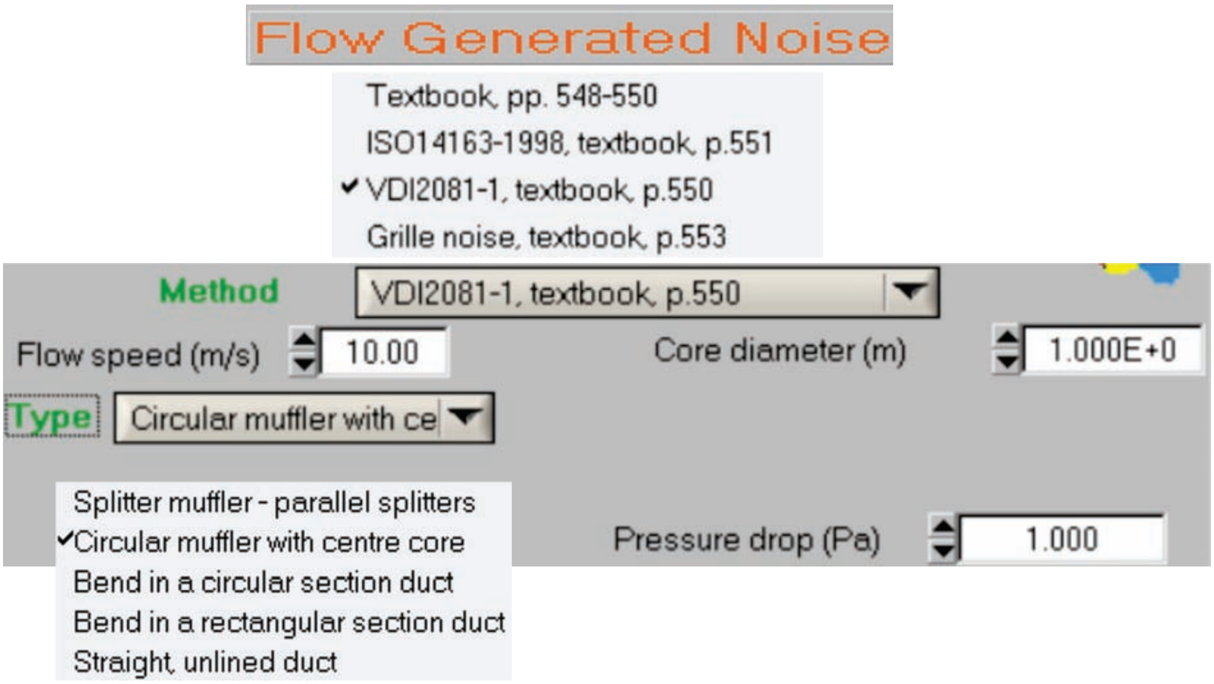


The output is in graphical (octave band sound power levels) and table format (octave and overall sound power levels).

If more than one airway is selected, in this current version, ENC assumes that all airways have identical dimensions and flow speeds and so the self-noise sound power level increases over that for a single airway by by $10 \log 10n$, where n is the number of identical airways.

6.9.3.2 Circular Muffler with Centre Core

The VDI2081 method for circular mufflers with a centre pod (or core) is outlined on page 552 (Equation (8.254)) of the 6th edition textbook.

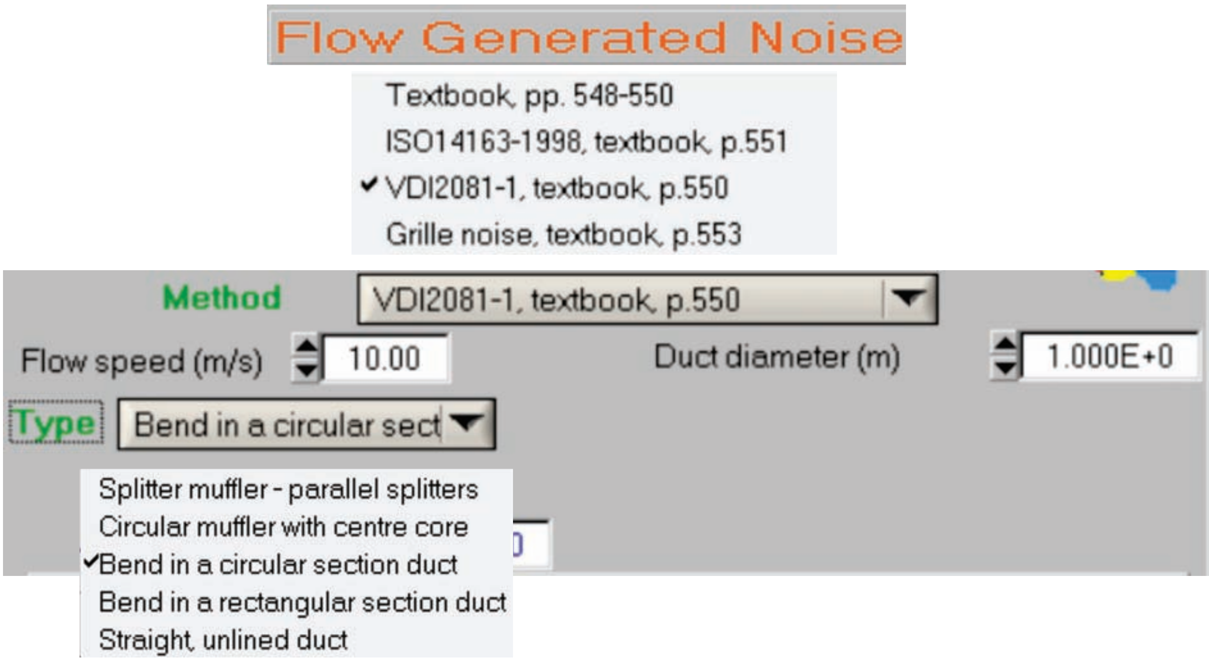


The required input data are the gas flow speed through the muffler, the pressure drop through the muffler (calculated using the dynamic pressure loss from the left hand part of this page) and the centre pod (core) diameter. All dimensions are in metres.

The output is in graphical (octave band sound power levels) and table format (octave and overall sound power levels).

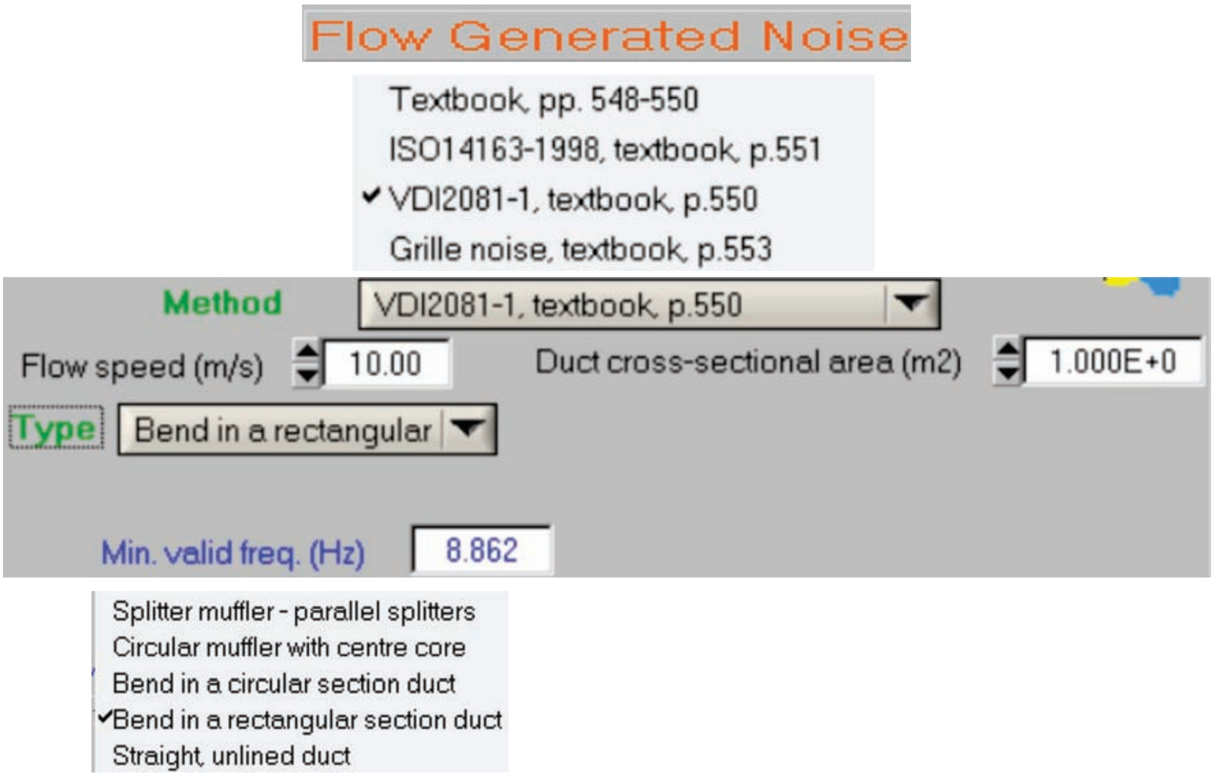
6.9.3.3 90 Degree Bend in a Circular-section Duct

If this option is chosen, you must enter the flow speed of gas in the duct leading up to the bend and the duct diameter, as shown in the following figure. The output is in graphical (1/3-octave band sound power levels) and table format (octave and overall sound power levels).



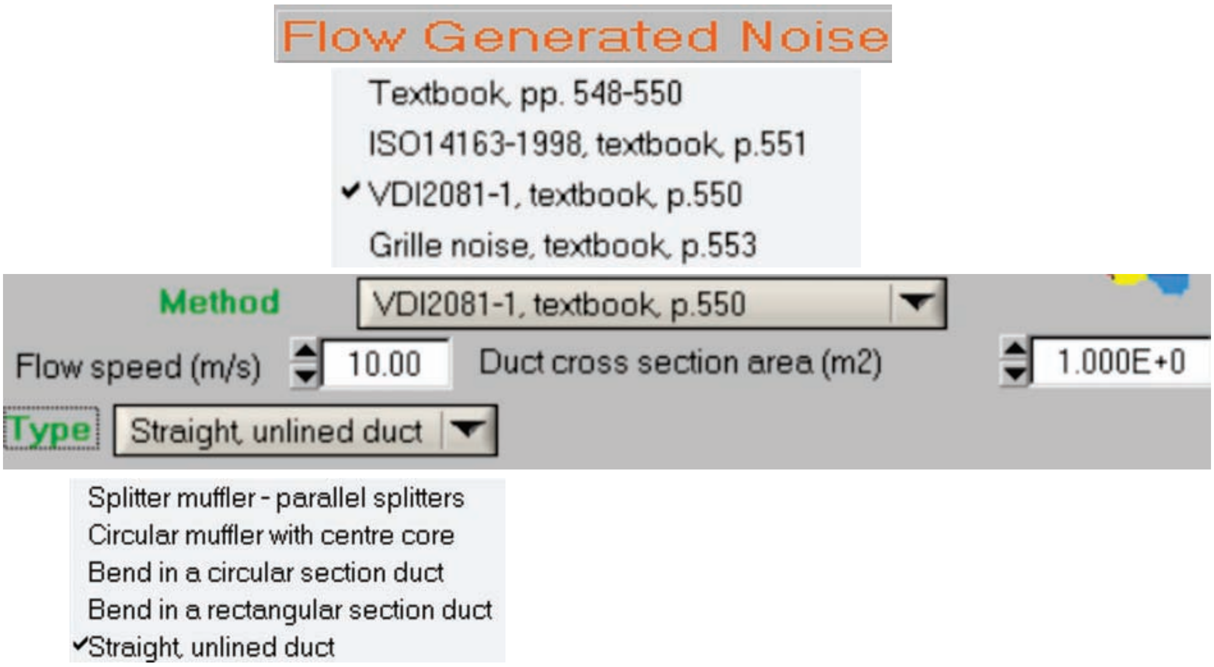
6.9.3.4 90 Degree Bend in a Rectangular-section Duct

If this option is chosen, you must enter the flow speed of gas in the duct leading up to the bend and the duct cross-sectional area, as shown in the following figure. The output is in graphical (1/3-octave band sound power levels) and table format (octave and overall sound power levels).

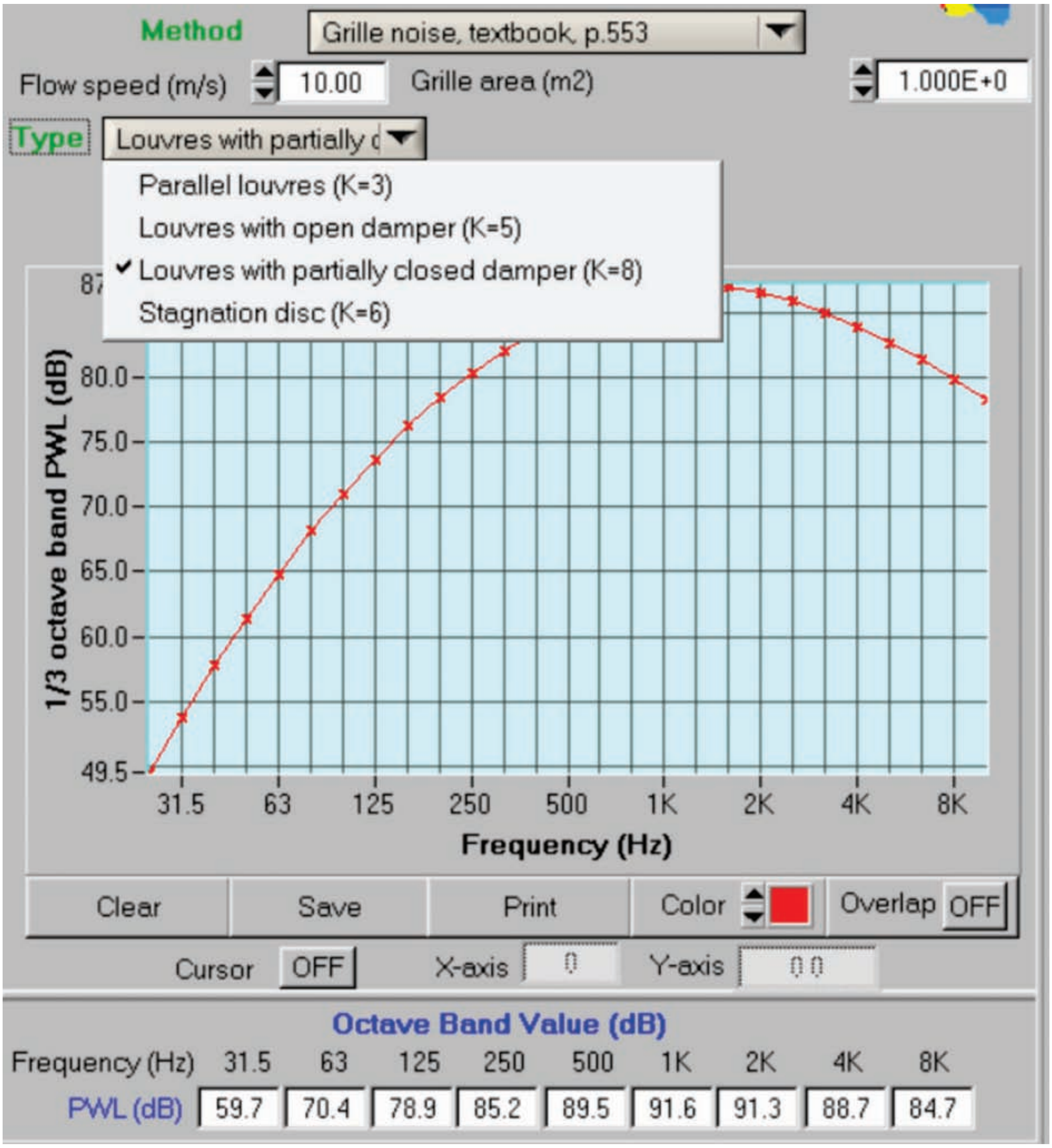


6.9.3.5 Straight, Unlined Duct

If a straight, unlined duct is chosen, then the gas flow speed and duct cross sectional area must be entered. The output is in graphical (octave band sound power levels) and table format (octave and overall sound power levels).



6.10 Grille Noise



This part of ENC calculates the noise generated by grilles placed at the exit of air conditioning ducts. The method is described on pages 552–553 in the 6th edition textbook. To calculate grille noise, you must choose the grille type and enter the air flow speed in the upstream duct and the grille area, as shown in the following figure.

For an air conditioning duct terminated by a grille, the noise is directly proportional to the pressure drop across the grille, which is characterised by the the dynamic pressure loss coefficient, K. Values of K are usually available from the grille manufacturer, but range from 3 for parallel louvres, 5 for louvres with an open damper, 8 for louvres with a partially closed damper and approximately 6 for a stagnation disk outlet. The overall sound power level, L_W, generated by the grille is (Baumann and Coney, 2006, p. 636):

$$L_W = 10 + 10\log_{10}(SK^3U^6) \qquad (\text{dB re } 10^{-12}\text{ W}) \tag{6.3}$$

where S is the grille area and U is the speed of flow in the upstream duct. The 1/3-octave sound power level spectrum levels may be calculated using:

$$L_W(1/3\text{-oct}) = \begin{cases} 10\log_{10}(SK^3U^6) - 12.3\left[\log_{10}(f/f_p)\right]^2; & f \le f_p \\ 10\log_{10}(SK^3U^6) - 11.5\left[\log_{10}(f/f_p)\right]^{1.6}; & f > f_p \end{cases} \qquad (\text{dB re } 10^{-12}\text{ W}) \tag{6.4}$$

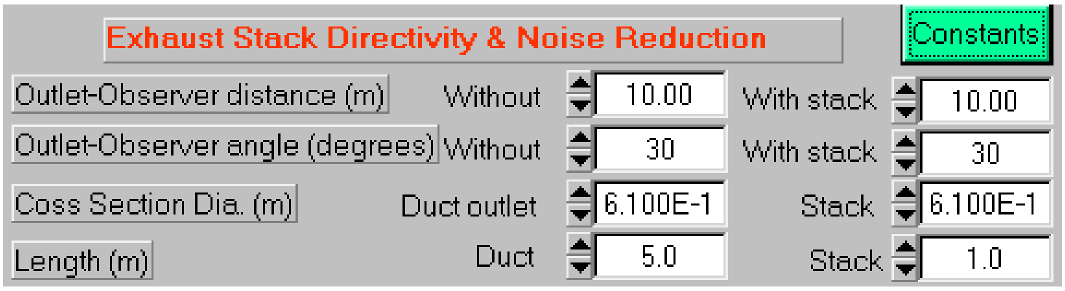
where $f_p = 140U$ is the frequency of maximum noise level and f is the 1/3-octave band centre frequency.

The octave band levels are obtained by logarithmically summing the three 1/3-octave band levels making up the octave band. Octave band levels are then each adjusted by the same number of decibels so that their logarithmic sum is equal to the overall level.

The output is in graphical (1/3-octave band sound power levels) and table format (octave and overall sound power levels).

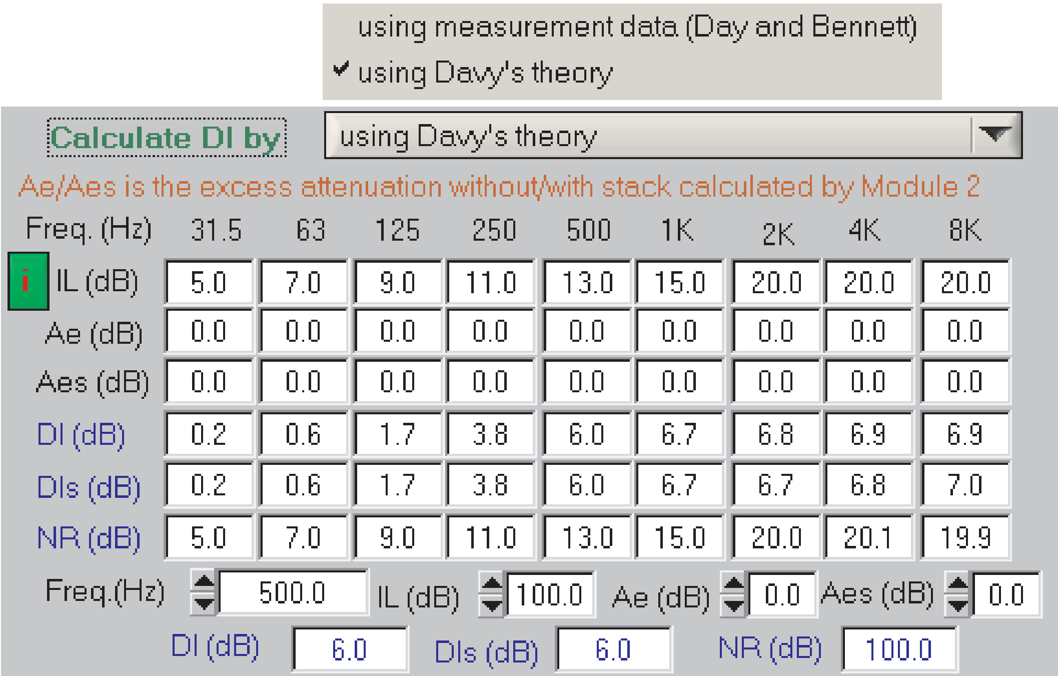
6.11 Exhaust Stack Directivity and Noise Reduction (see 6th edition textbook, pages 561–567)

This section calculates the directivity of an exhaust stack as well as the noise reduction that will occur as a result of installing one, using Figure 8.45, 8.46 or 8.47 on pp. 561–563 in the 6th edition textbook and Equation (8.286). Data that must be entered first include the distance between the outlet and observer, the angle subtended by the observer to the exhaust duct axis, the duct length (from the noise source to the duct exit) with and without the stack in place and the duct exit cross sectional area for the outlet with and without the stack in place (see following figure).



The value of the subtended angle is 90 degrees if the exhaust opening is pointed up and is at the same height as the observer, at some horizontal distance away. The value is 0 degrees if the exhaust duct is pointed directly at the observer.

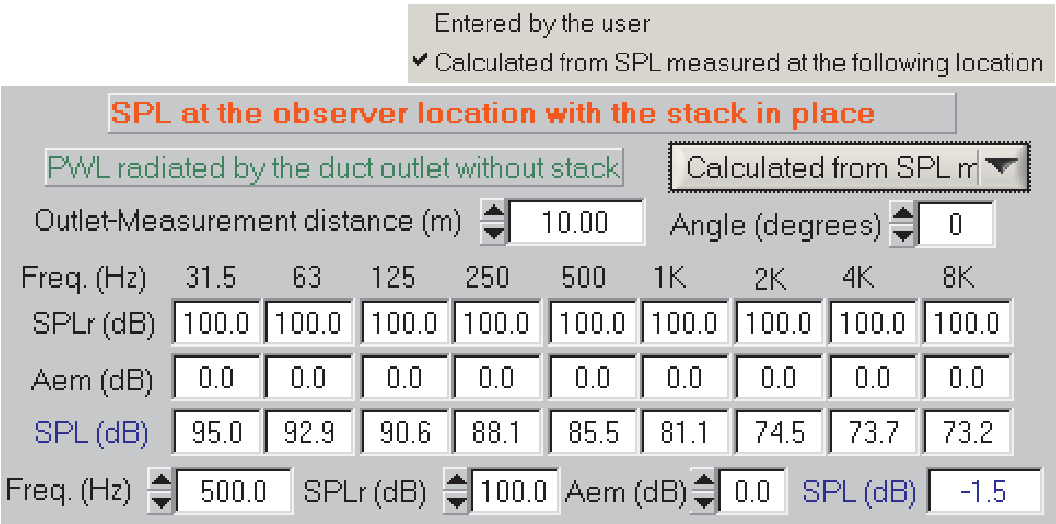
The first line of data to be entered is the table (see following figure) is the octave band insertion loss of the stack itself. That is, the difference in sound pressure level at the duct outlet with and without the stack in place.



If desired, you can also insert the excess attenuation values for sound propagating from the duct opening to the observer with and without the stack in place. These are calculated using module 3. If the excess attenuation is the same with and without the stack in place, you may enter zero for both rows of values. HOWEVER, IF YOU WANT TO CALCULATE THE SOUND PRESSURE LEVEL AT THE OBSERVER USING THE LOWER TABLE ON THIS WINDOW (see following figure), YOU MUST ENTER ACCURATE EXCESS ATTENUATION VALUES HERE AS THEY WILL BE USED IN THE LOWER TABLE CALCULATIONS.

The directivity from the exhaust opening to an observer location is calculated by ENC for the exhaust opening at the top of the stack (DI_s) and for the exhaust opening without the stack (DI). For this calculation, in addition to the data already discussed above, you need to enter the speed of sound in the exhaust gas. There are two estimation schemes from which you can choose for estimating the directivity index of the exhaust stack. The first choice is based on experimental data and encapsulated in Figure 8.46 in the 6th edition textbook. The second is purely theoretical, based on a theory developed by Davy (2010) and included in the 6th edition textbook as Figure 8.47.

Finally, the last line in the table (see following figure) is the noise reduction at the observer due to the installation of the stack. Note that although the directivity information used in the calculations has not been averaged over octave bands, the octave band centre frequency results given are very close to what would be obtained by band averaging.



Clicking on the “Constants” button in the above figure allows you to set the speed of sound and gas density for the calculations of the entire window — see Section 0.6.4 in the manual for a full description.

At the bottom of the table you can use the calculator to calculate results for individual frequencies in addition to the octave band centre frequency results shown in the table. The input data are labelled in black and the calculated data in blue. The table at the bottom of the panel allows you to calculate the sound pressure level at the observer location with the stack in place using Equation (8.287). To do this calculation the sound power radiated by the duct prior to the installation of the stack is required. There are 2 methods ENC can use to determine the sound power level values. Click on the box to the right of the title, “PWL radiated by duct outlet without stack” (see previous figure) to select the method you wish ENC to use.

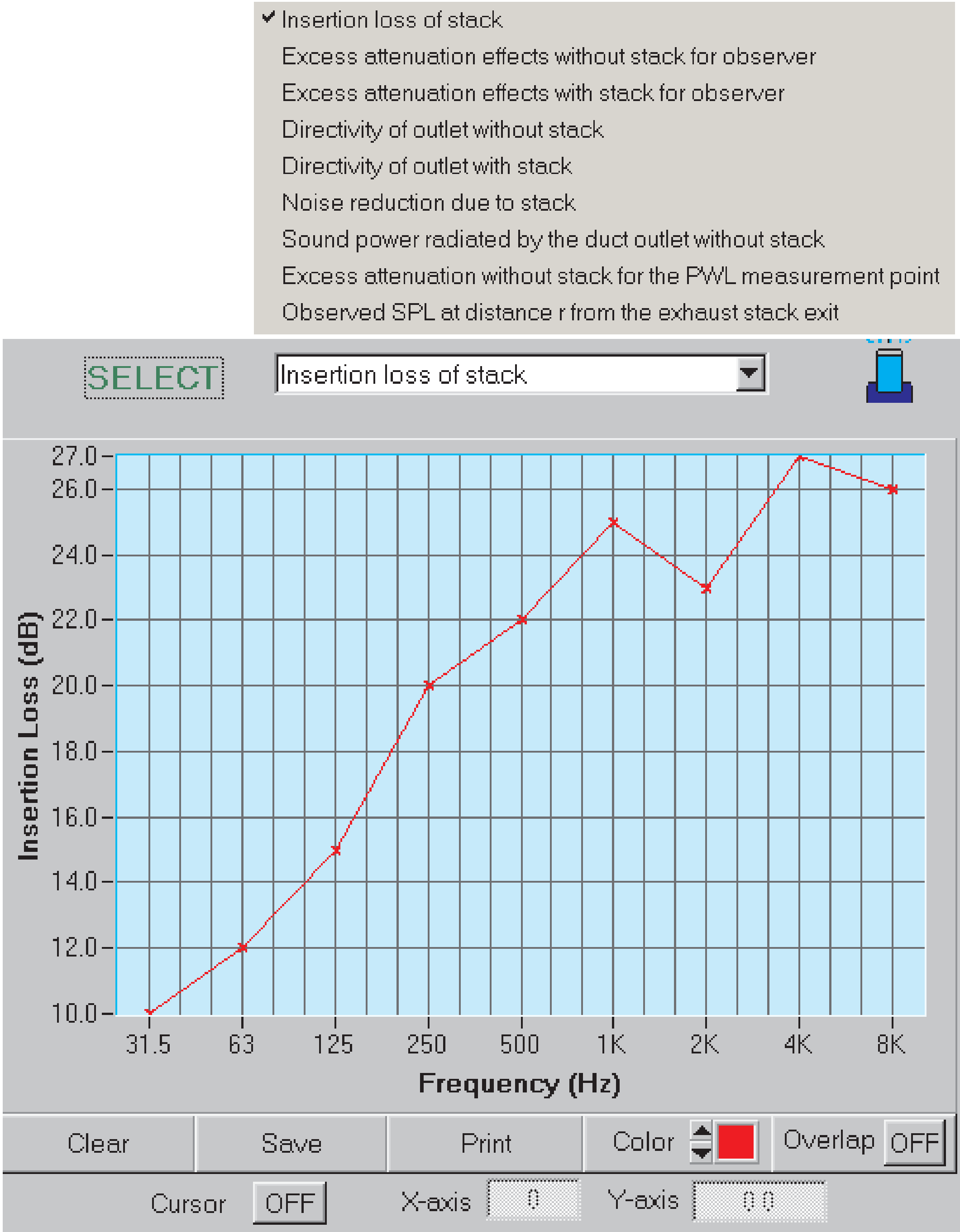
If you select "entered by user", then you must enter the octave band sound power levels in the first line of the table.

If you select the option, "calculated from SPL measured at the following location", ENC will use the measured sound pressure level at some distance, r, from the stack to calculate the radiated sound power using Equation (8.285). For this option you need to enter the distance from the duct outlet that the measurement was made and the angle in degrees subtended to the measurement location from the duct axis. You also need to enter octave band values of excess attenuation, Aem, associated with sound propagation from the duct outlet to the measurement location (calculated using module 3 of ENC). ENC will calculate the directivity associated with this measurement for the duct outlet, include the effect of the excess attenuation and calculate the radiated sound power level for the duct WITHOUT the stack.

As the sound power levels calculated using the information in the first line of the table are for the duct WITHOUT the stack attached, the sound power radiated by the duct WITH the stack attached is determined by ENC by subtracting the insertion loss values entered in the upper table from the sound power levels calculated for the duct without the stack in the lower table. Thus the insertion loss values in the upper table directly affect the SPL values in the lower table. Similarly the insertion loss value entered below the upper table for the single frequency calculation is used for the single frequency calculation under the lower table.

The calculation in the lower table also uses values of excess attenuation (Aes) with the stack in place from the upper table. For the individual frequency calculations, the value of Aes entered below the upper table will be used for the lower table calculations.

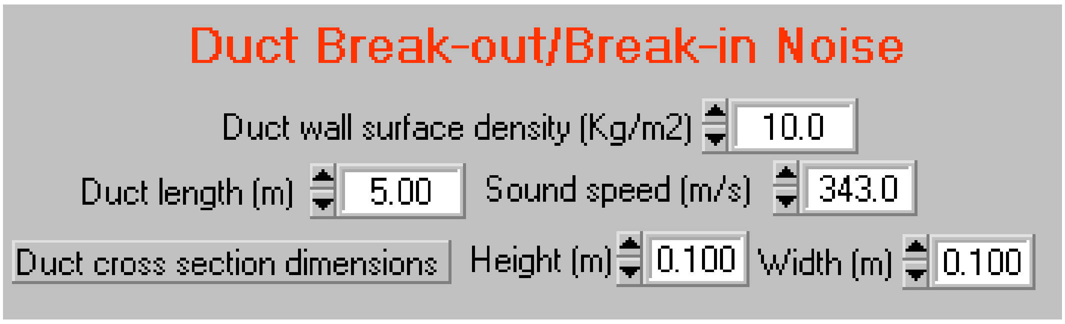
All of the data and results discussed above may be plotted on the graph on the right side of the panel (see figure on next page). The parameter to be plotted is selected by clicking on the selection box above the graph.


Insertion loss of stack
Excess attenuation effects without stack for observer
Excess attenuation effects with stack for observer
Directivity of outlet without stack
Directivity of outlet with stack
Noise reduction due to stack
Sound power radiated by the duct outlet without stack
Excess attenuation without stack for the PWL measurement point
Observed SPL at distance r from the exhaust stack exit
SELECT
Insertion loss of stack
Insertion Loss (dB)
27.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
31.5
63
125
250
500
1K
2K
4K
8K
Frequency (Hz)
Clear
Save
Print
Color
Overlap
OFF
Cursor
OFF
X-axis
Y-axis

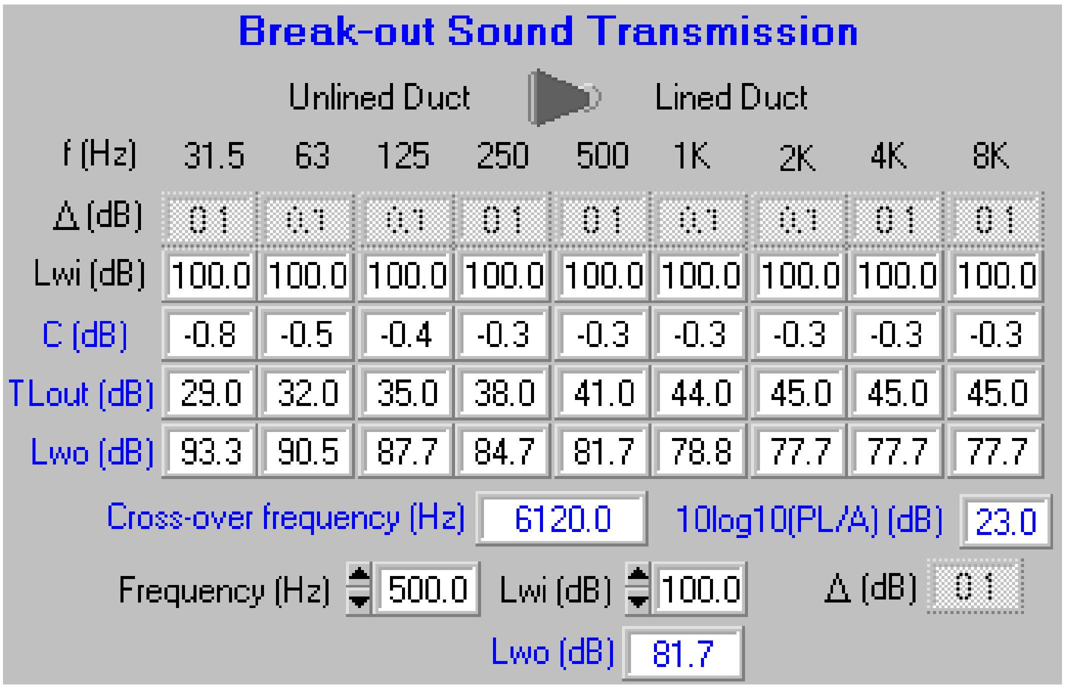
6.12 Duct Break-out/Break-in Noise (6th edition textbook, pages 554–556)

This panel calculates the sound power that may be expected to break out of a duct such as an air conditioning duct, which contains an internal sound field. It will also calculate how much sound power that will break into a duct as a result of an external sound field. The calculations are particularly useful for determining how much noise may be carried by an air conditioning duct from a noisy area (such as a factory or plant room) to a quiet area (such as an office) as well as the importance of fan noise transmission through the duct walls into an office space.

For both break-in and break-out noise, you need to enter the duct wall surface weight (kg/m2), the length of duct over which breakout or break in sound transmission will occur, the speed of sound in the duct and the duct cross section dimensions (see following figure).

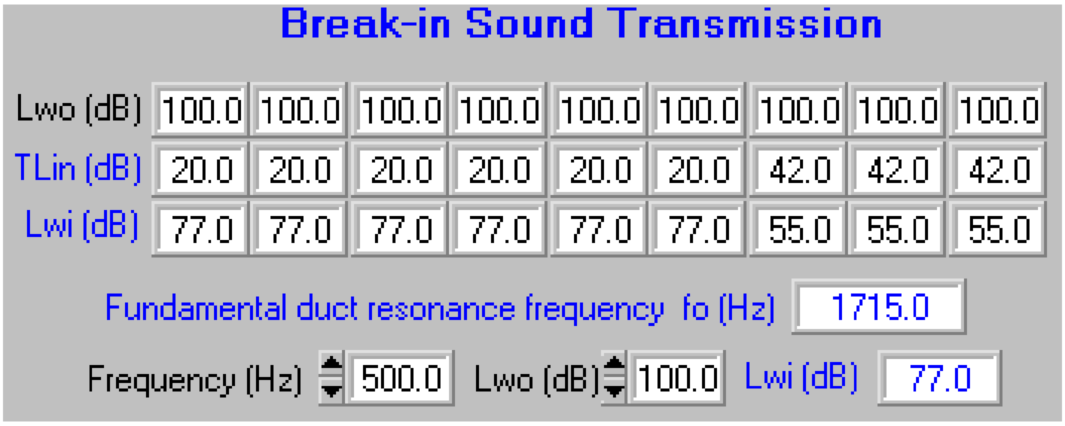


For the break-out section (see following figure), the quantity, Lwi is the sound power propagating down the duct and entering the section from which it will breakout. This must be input by the user in octave bands. The quantity, Lwo is the sound power that will break out of the duct (dB re 10^{-12} W) and this is calculated by ENC using Equation (8.258) in the 6th edition textbook. The quantity, Δ, is the attenuation in dB/m of a lined duct (entered by the user) and the quantity, C, is defined by Equation (8.259) in the 6th edition textbook and TLout is defined by Equations (8.262)–(8.264). Both quantities are calculated by ENC. Below the table are output the cross over frequency (Equation (8.261) in the 6th edition textbook) and the minimum allowed value for TLout (Equation (8.264)). Note that the maximum allowed is 45 dB.

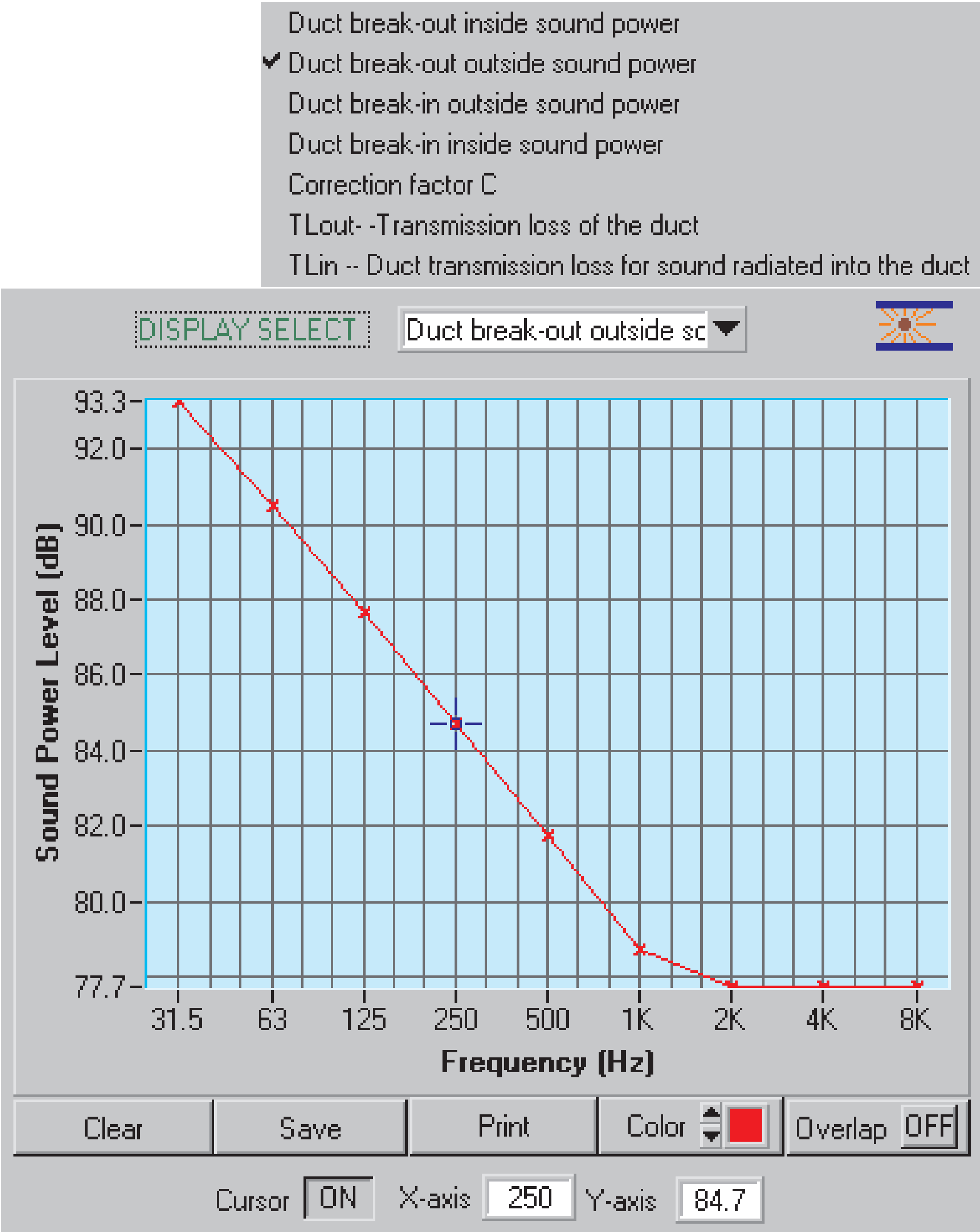


In addition to the octave band values of power in the table, you can also obtain values at specific frequencies by entering the frequency of interest in the box below the table.

For the break-in section (see following figure), the quantity, Lwo is the sound power incident on the duct walls from the external sound field (entered by the user). The quantity, Lwi, is the sound power that will break into the duct (dB re 10^{-12} W) and TLin is the break in sound transmission loss. Both quantities are calculated by ENC. ENC also calculates the fundamental acoustic resonance frequency associated with the duct cross section (line following Equation (8.265) in the 6th edition textbook). Single frequency calculations are also done for the frequency entered in the box below the table.



Any of the outputs calculated by ENC may be plotted. Just select the required quantity from the drop down menu above the graph (see following figure).


Duct break-out inside sound power
Duct break-out outside sound power
Duct break-in outside sound power
Duct break-in inside sound power
Correction factor C
TLout- -Transmission loss of the duct
TLin -- Duct transmission loss for sound radiated into the duct
DISPLAY SELECT
Duct break-out outside sc
93.3
92.0
90.0
88.0
86.0
84.0
82.0
80.0
77.7
Sound Power Level (dB)
31.5
63
125
250
500
1K
2K
4K
8K
Frequency (Hz)
Clear
Save
Print
Color
Overlap
OFF
Cursor
ON
X-axis
250
Y-axis
84.7

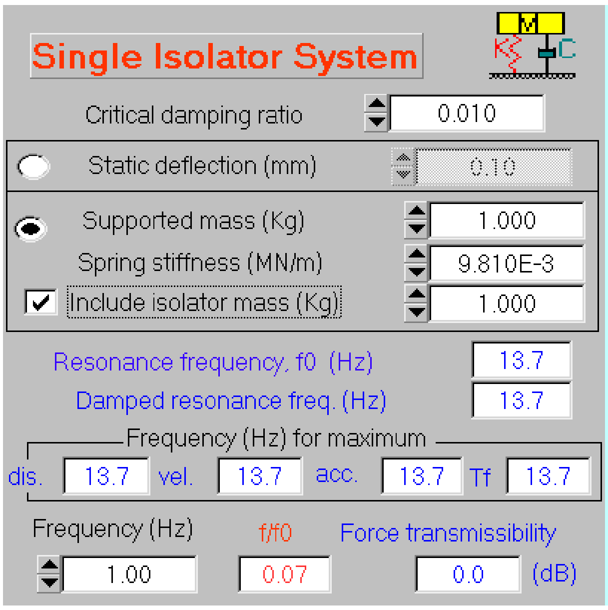
Chapter 7

Vibration Isolation (Module 7)

7.1 Overview

This module carries out the calculations and procedures outlined in Chapter 9 of the 6th edition textbook. Single degree of freedom and multi-degree of freedom systems are both considered in terms of vibration isolation. The effect of flexible foundations on vibration isolation performance, vibration absorbers, damping parameters and units of measurement are also included.

7.2 SDOF System (6th edition textbook, pages 572–579)

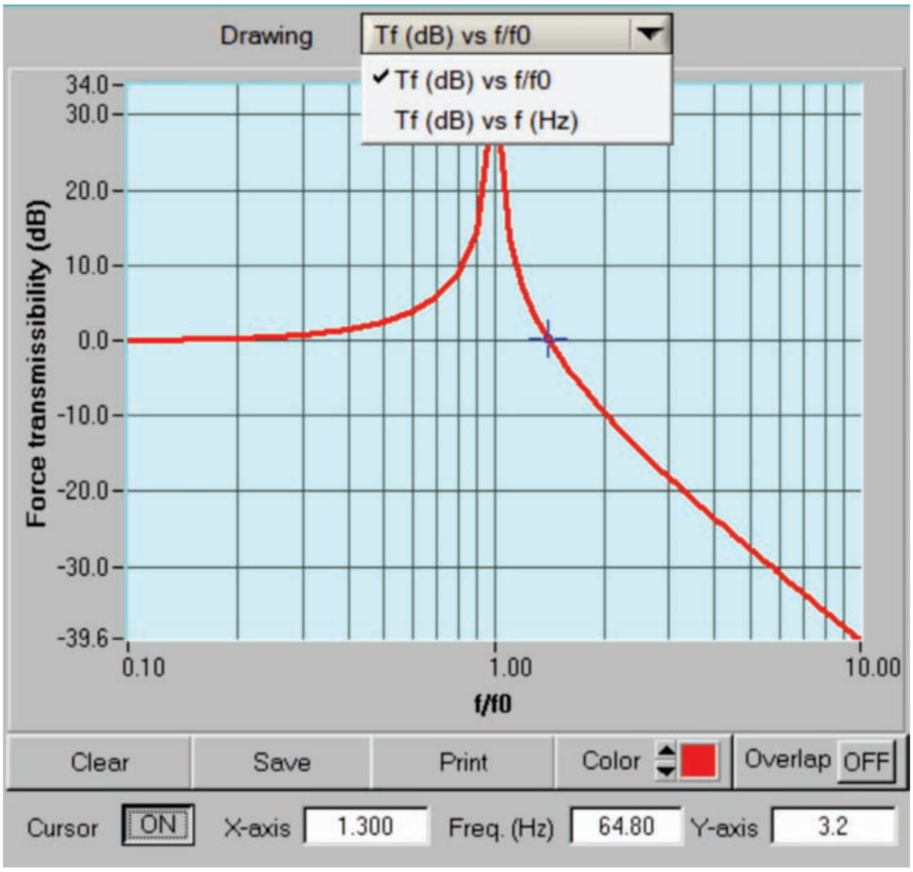


This section calculates the damped natural frequency as well as the frequency corresponding to maximum displacement, velocity, acceleration and transmitted force for a single degree of freedom system using Equations (9.5), (9.6), (9.12), (9.16), (9.18), (9.21) and (9.26) in the 6th edition textbook. The traditional undamped resonance frequency is the same as the frequency corresponding to the maximum velocity. If a coil spring is the isolator, you may choose to include its mass in the calculations to get more accurate results.

You must enter the critical damping ratio and there is a choice of either entering the static deflection of the isolator or its stiffness and the mass that it supports (just click on the appropriate dot). Note that if the spring mass is significant, then 1/3 of the spring mass should be added to the supported mass as the mass quantity to be entered into the software. Also note that for rubber isolators, you need to use the dynamic stiffness value corresponding to the expected amplitude of vibration. The static stiffness value is inappropriate. Note that the units of stiffness are MN/m = 10^6 N/m.

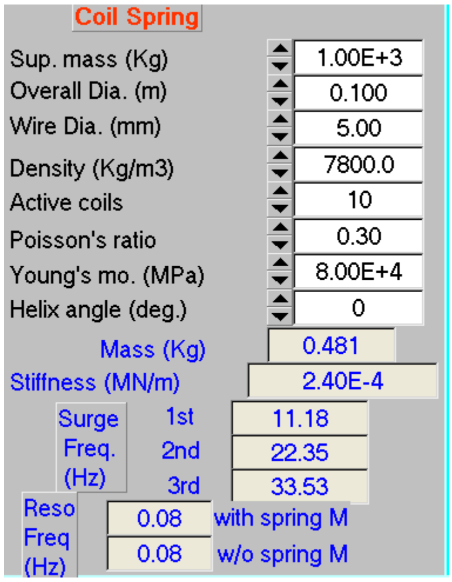
The force transmissibility (T_f) through the spring isolator compared to the situation without the isolator may be calculated for a specific value of the ratio of excitation frequency to undamped resonance frequency, (f/f_0), using the calculator in the module illustrated above at right.

The transmitted force reduction is also plotted as a function of the frequency ratio, f/f_0, in the figure below.



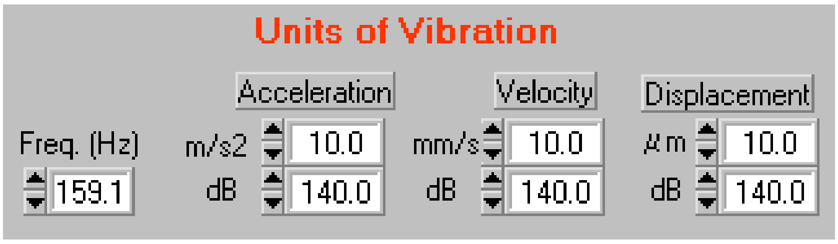
7.2.1 Coil Spring Properties (6th edition textbook, pages 574, 578–579)

ENC will calculate for a coil spring, the spring mass, spring stiffness, the first three surge frequencies of the spring and the mass/spring resonance frequency with and without the spring mass included in the calculations. As can be seen on the figure at right, you need to enter the coil diameter, the wire diameter, the number of active coils, the density of the spring material, Poisson's ratio and Young's modulus of the spring material, the spring helix angle and the mass supported by the spring.



7.3 Units of Vibration (6th edition textbook, pages 602–603)

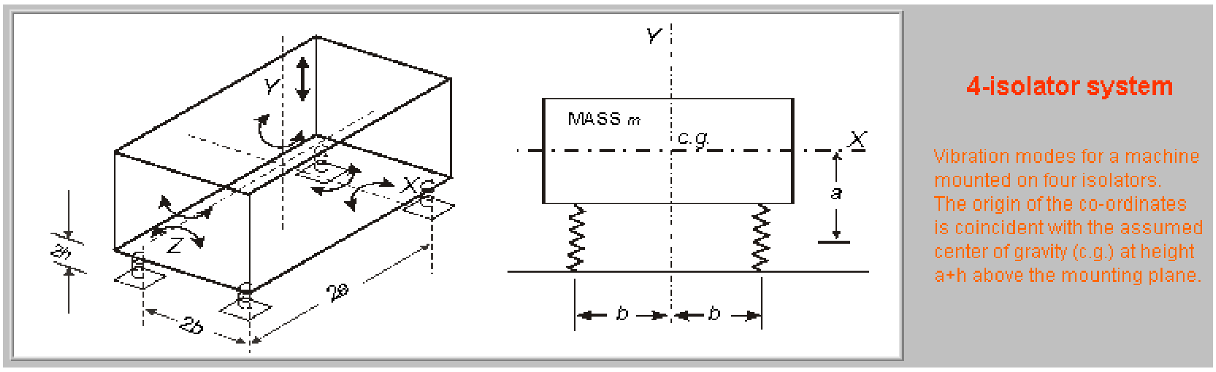
Enter the frequency of interest and any one of acceleration, velocity or displacement (see figure on next page). The software will then calculate the other two and the dB equivalents as well using the reference quantities on page 602 and Equations (9.92)–(9.95) in the 6th edition textbook.



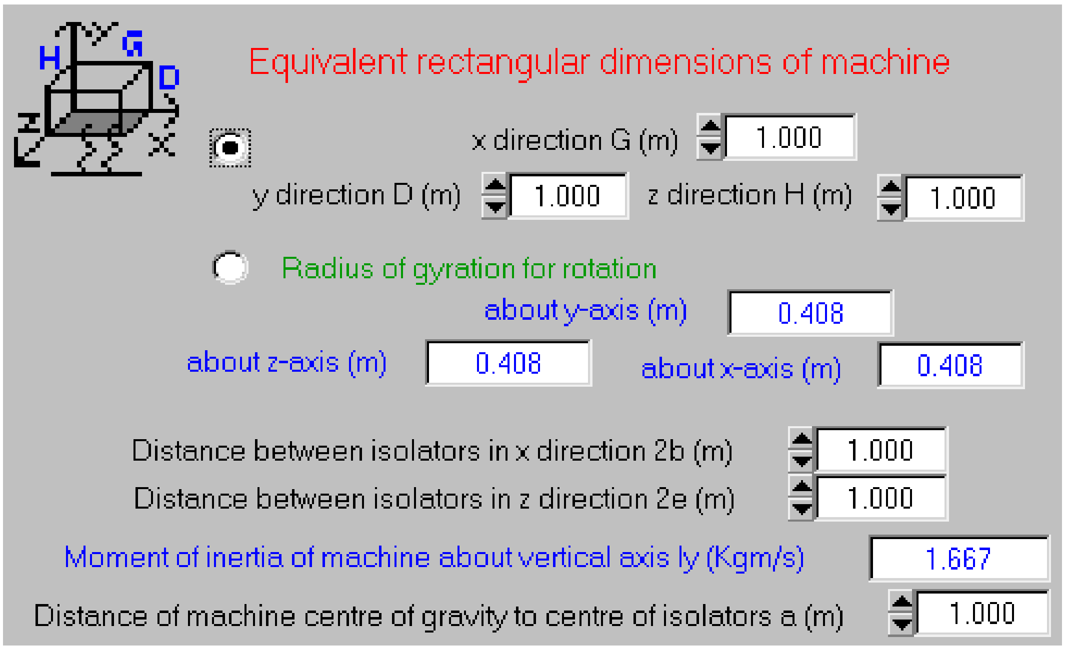
7.4 Damping Measurement (6th edition textbook, pages 606–608)

This part of the module allows you to calculate two of the quantities logarithmic decrement, critical damping ratio and loss factor, given the third one, using Equation (9.98) and Table 9.3, p. 608 in the 6th edition textbook. You can also relate the damping to the 60 dB decay time (T_{60}) of a single degree of freedom system (see Eqs (6.23) and (6.24) in the 6th edition textbook), given its resonance frequency (given in the panel 2 pages back).

7.5 4-Isolator System (6th edition textbook, pages 579–581)

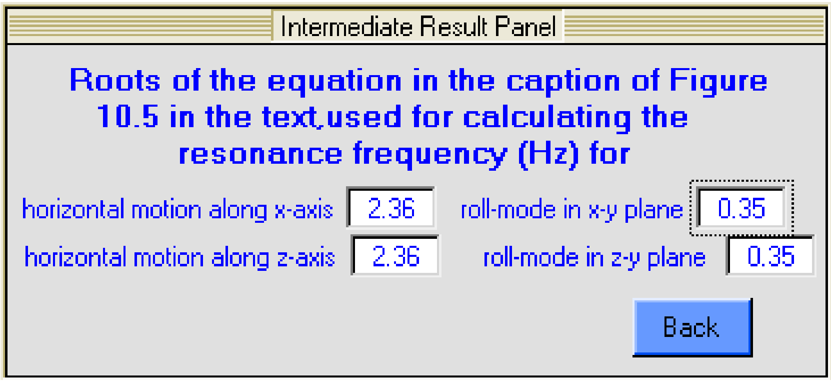


For this system (see following figure), the software will calculate the rotational and translational resonance frequencies using Equations (9.36) and (9.39) and the procedure on page 579 in the 6th edition textbook. You need to enter the mass and geometrical parameters requested (see following figure).



You also need to enter the stiffnesses of the 4 isolators in all three translational directions. Note that if the spring mass is significant, then 1/3 of the spring mass should be added to the supported mass as the mass quantity to be entered into the software. Also note that for rubber isolators, you need to use the dynamic stiffness value corresponding to the expected amplitude of vibration. The static stiffness value is inappropriate. Note that the combined spring stiffness is the one used in the calculations. Note that the units of stiffness are MN/m = 10^6 N/m. You have a choice of entering the radii of gyration about 2 axes or the equivalent rectangular dimensions of the machine (enclose the machine in a rectangular box of the same volume).

The out puts (see above) are all the translational and rotational resonance frequencies for the system. If the spring stiffnesses are different for the 4 isolators, the effective overall stiffness for each direction is calculated by the software for use in the resonance frequency calculations. Note that if necessary, you can check the roots of the equation in the caption of Figure 9.5 in the 6th edition textbook, used to determine the resonance frequencies. This is done by clicking on the “Check Roots” box and the panel shown below appears.



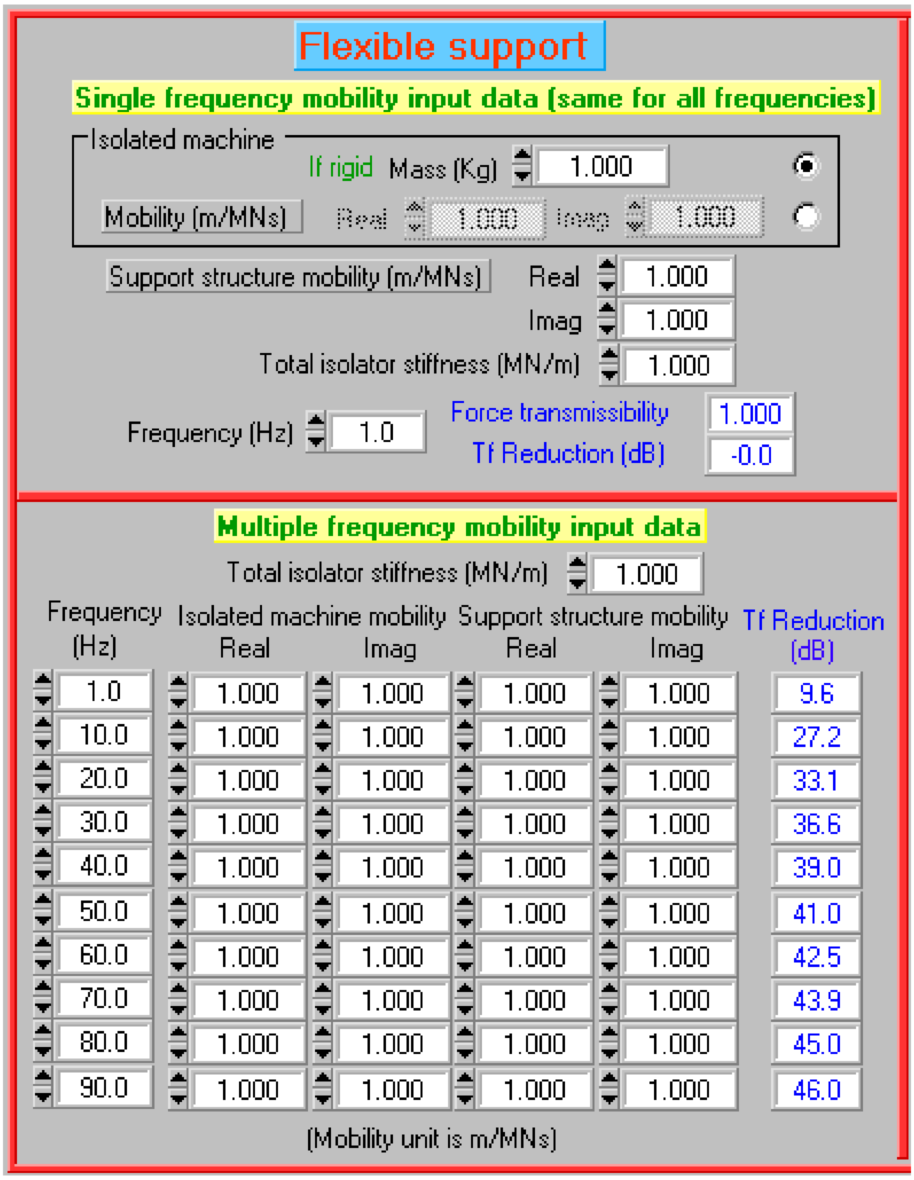
7.6 Flexible Support (6th edition textbook, pages 587–588)

In this part (see figure on the next page), the transmitted force as a function of frequency may be calculated for a flexible machine and support structure, using Equation (9.53) in the 6th edition textbook.

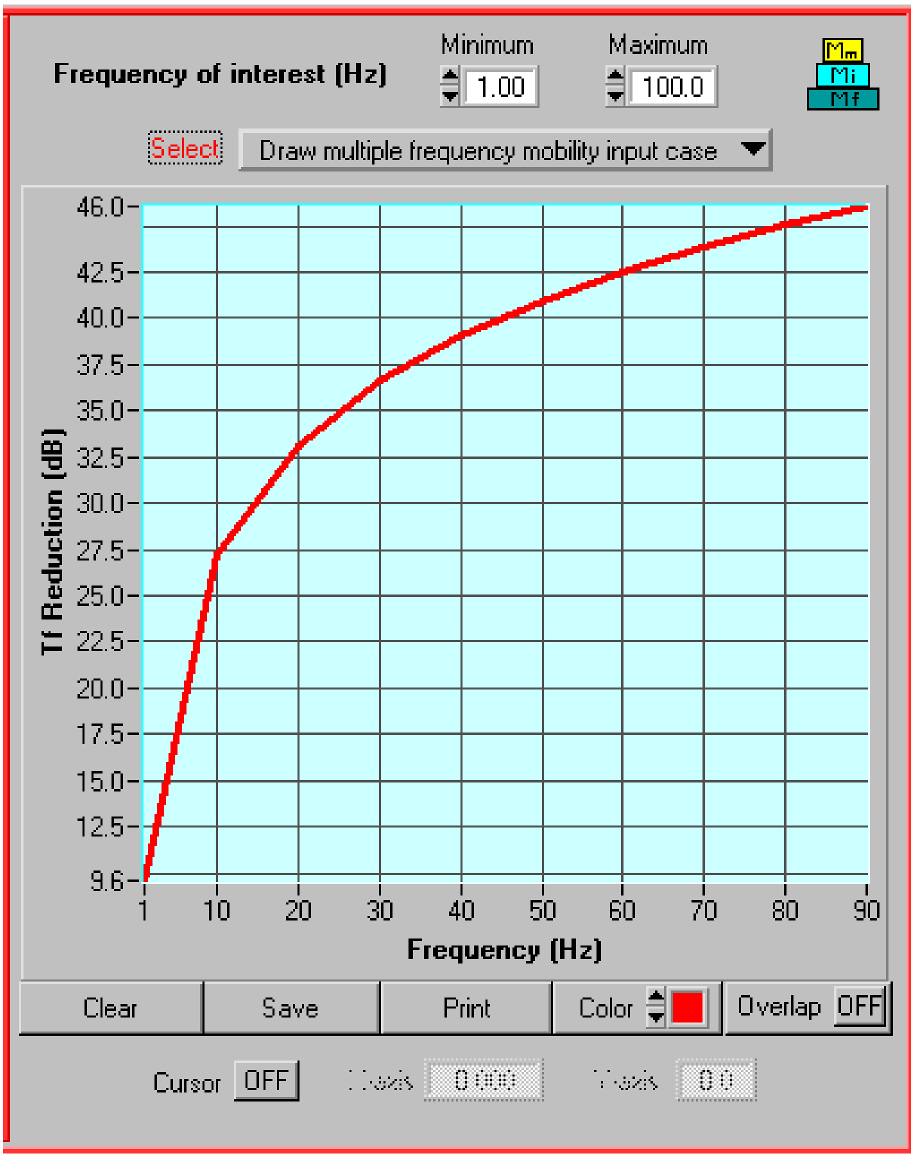
Assuming a rigid isolated mass and a lightweight spring, the mobilities are calculated using Equations (9.54)–(9.56) in the 6th edition textbook.

You may enter single values for the real and imaginary parts of the machine mobility (if the machine is non-rigid) and support structure or you may enter a table of values as a function of frequency. If the machine is relatively stiff, it is sufficient just to enter its mass instead of its mobility.

As can be seen in the following figure, the software calculates the transmitted force reduction (in dB) for any frequency that is specified for the single value mobility data or for the multiple value input data.



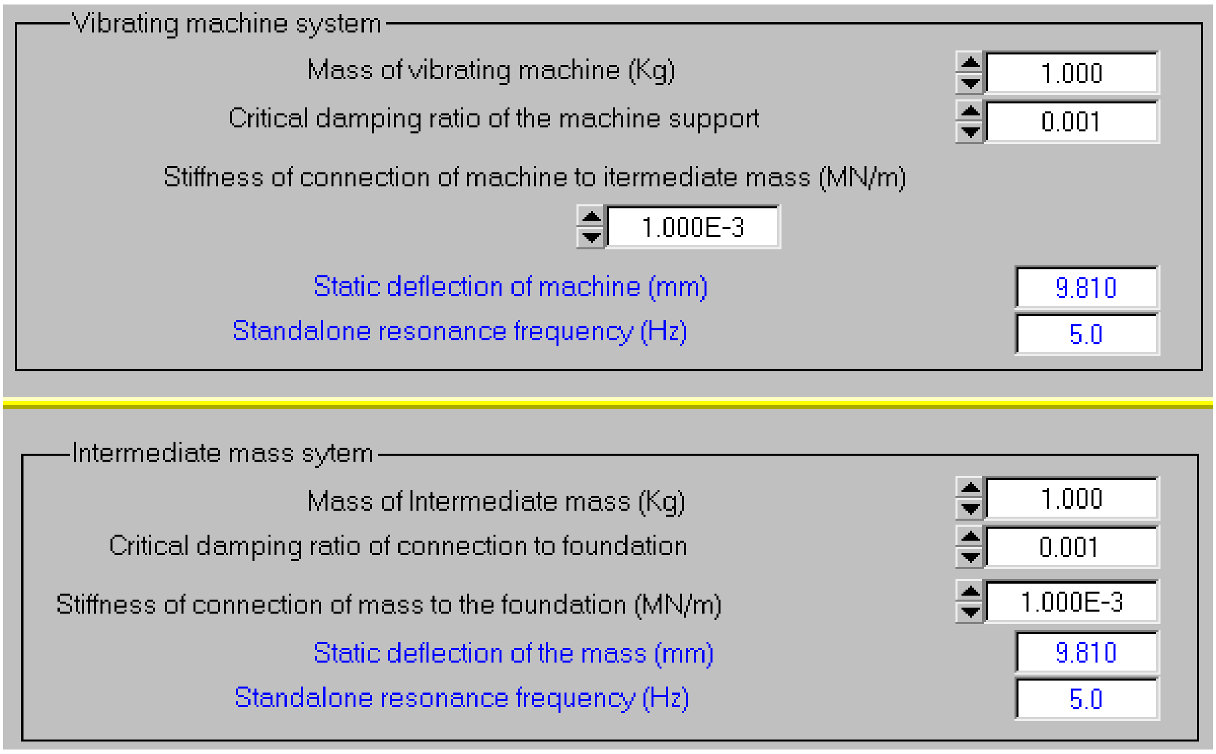
The graph (see following figure) gives a plot of transmitted force reduction as a function of frequency of excitation of the mass representing the machine.



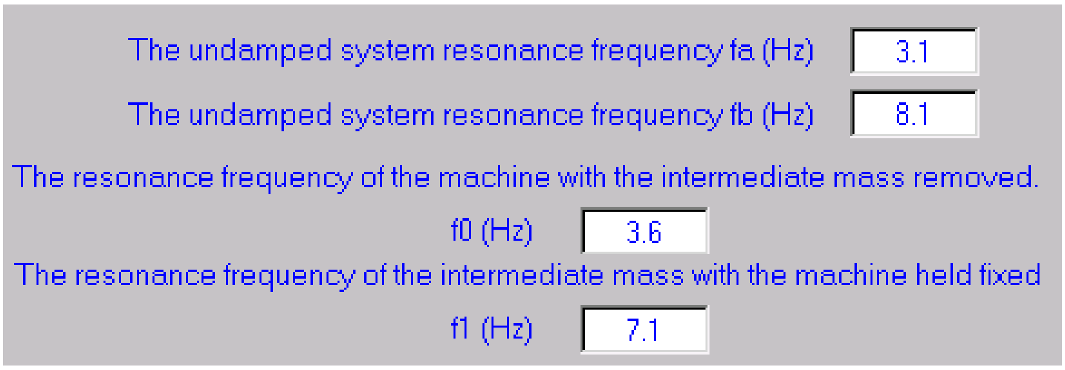
7.7 2-stage Vibration Isolation (6th edition textbook, pages 581–582)

A 2-stage vibration isolator has an intermediate mass placed between the foundation and the equipment to be isolated with spring isolators between the intermediate mass and the foundation and also between the intermediate mass and the equipment to be isolated.

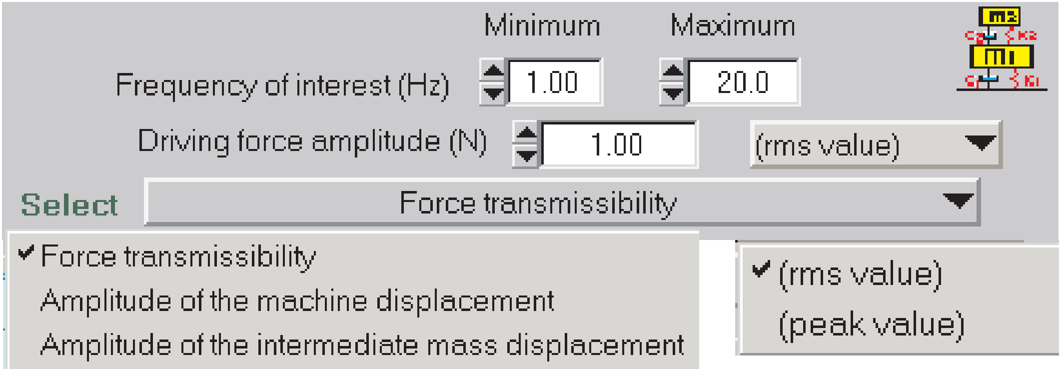
You need to enter the mass of the machine to be isolated, the mass of the intermediate mass, the stiffnesses of the two isolators and the critical damping ratios of the two isolators. ENC will output the static deflection and resonance frequency for each subsystem acting independently (see below), which assumes that the isolators connected to it have their other end connected to a rigid foundation. In addition, for this calculation the intermediate mass is assumed to be disconnected from the machine to be isolated.

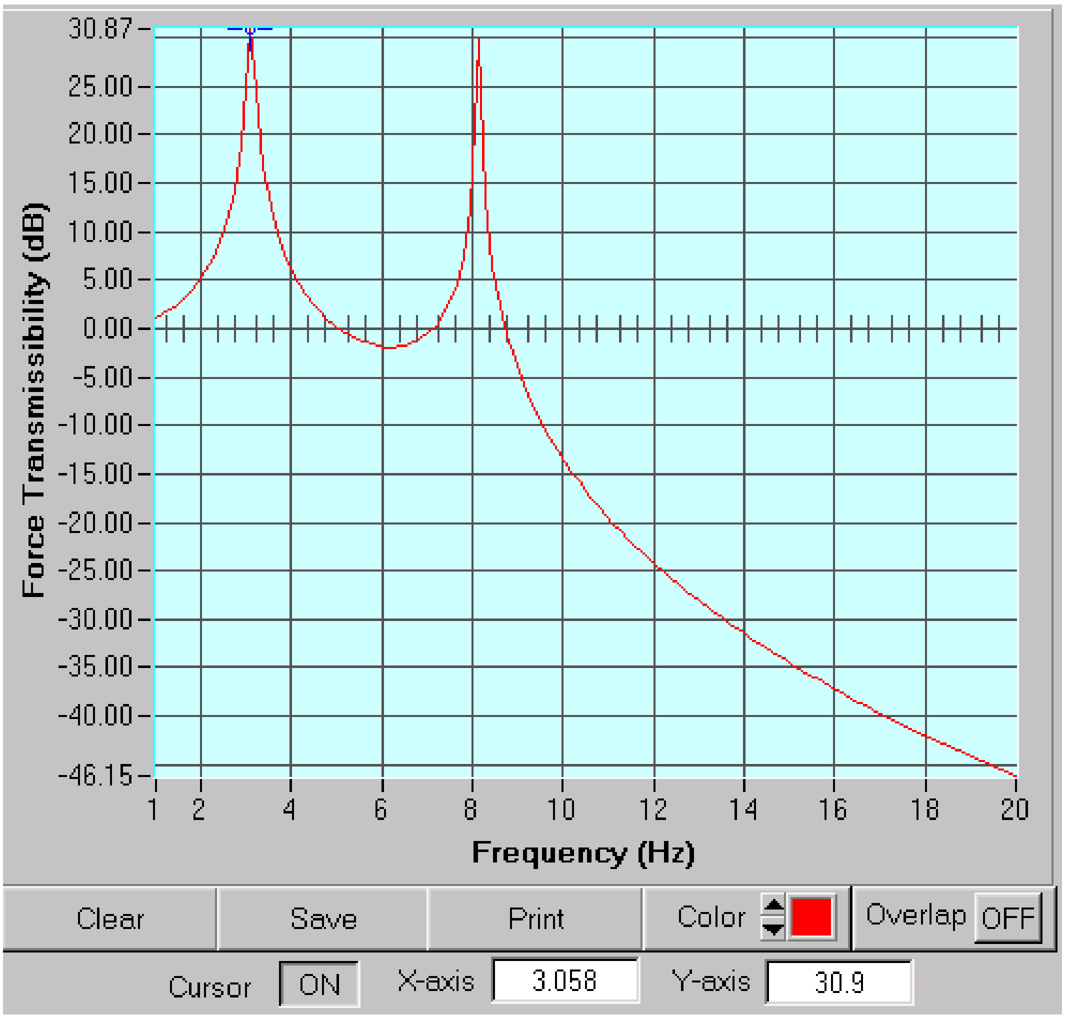


ENC calculates the force transmissibility in dB ($20 \log_{10}[T_F]$) and plots it (see figure on the page after next) and also calculates the two frequencies of maximum transmissibility, f_a and f_b (see following figure) as well as the resonance frequency of the machine with the intermediate mass removed and the resonance frequency of the intermediate mass with the machine held fixed.



You can set up the graph to plot transmissibility or amplitude of the machine or intermediate mass complex displacement (modulus of the complex quantity) for a specified driving force amplitude which you may specify as a peak or RMS quantity (see figure on next page). The displacement is expressed in dB (peak to peak).

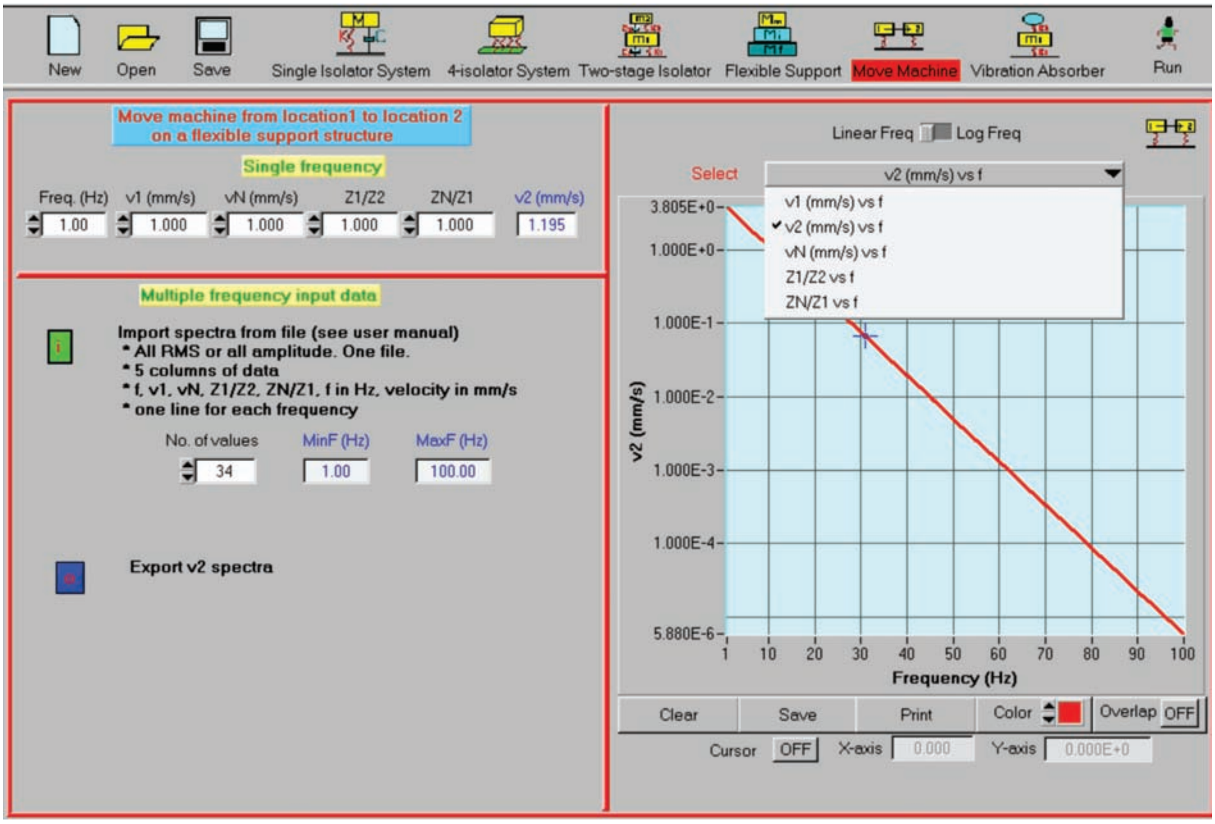

Minimum
Maximum
Frequency of interest (Hz)
1.00
20.0
Driving force amplitude (N)
1.00
(rms value)
Select
Force transmissibility
Force transmissibility
Amplitude of the machine displacement
Amplitude of the intermediate mass displacement
(rms value)
(peak value)


Force Transmissibility (dB)
30.87
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
-40.00
-46.15
1 2 4 6 8 10 12 14 16 18 20
Frequency (Hz)
Clear
Save
Print
Color
Overlap OFF
Cursor ON
X-axis 3.058
Y-axis 30.9

7.8 Moving a Machine on a Flexible Support Structure (See the 6th edition textbook, pages 585–587)

This section allows the calculation of the expected vibration velocity at the foot of a machine when it is moved from location 1 to location 2 on a flexible support structure. Single frequency calculations as well as spectra calculations are possible. For both cases, the output data are the same form as the input data. Thus, if the input velocity data values are RMS quantities, the output data values will also be RMS quantities. However, as all terms in the equation (except velocities v_1, v_N and v_2) are ratios, the only units of importance for the calculations are those for the velocity and these are mm/s.

The input data file is a text file that can be a name of your choosing, but for easy access by ENC, it is most convenient if it is located in the same directory as ENC projects; i.e ENCx.x/projects. The same applies to the output file of velocities at the machine mount at the new location. Each line of the input data file must contain 5 values, separated by a space or tab. In order, these are frequency, f, in Hz, velocity v_1 in mm/s, velocity, v_N in mm/s, Z_1/Z_2 and Z_N/Z_1 (see below for definitions of these quantities). The data file lines should be in order of increasing frequency. That is, the first line in the data file should correspond to the lowest frequency to be considered and the last line must correspond to the highest frequency to be considered. Values in the first column (frequency) should increase as the line number increases. If there is a data line with a frequency less than the previous line, ENC will produce an error. The “No. of values” to enter into the data box in ENC is the actual number of lines in the data file. If the number in the data box is greater than the number of lines in the data file, ENC will produce a warning, but it will still accept the data file and use the number of lines that contain data.



The output from ENC is the velocity at the foot of the machine at the new location. This velocity data, as a function of frequency, may be saved to a file by clicking on the blue button with a red o in the centre.

The required calculation requires the measurement of the following quantities and the existence of a data file that contains them as a function of frequency in the order mentioned on the previous page.

1. Input impedance (Z_1 and Z_2) at structural locations 1 and 2 in the absence of contact of the machine mounting foot with the structure. This can be measured using a shaker and an impedance head or an impact hammer.

2. Velocity, v_1, measured on the machine mount with the machine operating. This can be measured using an accelerometer, with the output, a, converted to velocity, v at frequency, f, using $v = 2\pi f$.

3. Velocity, v_N, measured on the machine mount with the machine operating and a flexible mount of known point impedance, Z_N, placed between the machine mount and the support structure. If it is possible to completely disconnect the machine mount from the support structure and operate the machine, then $Z_N = 0$.

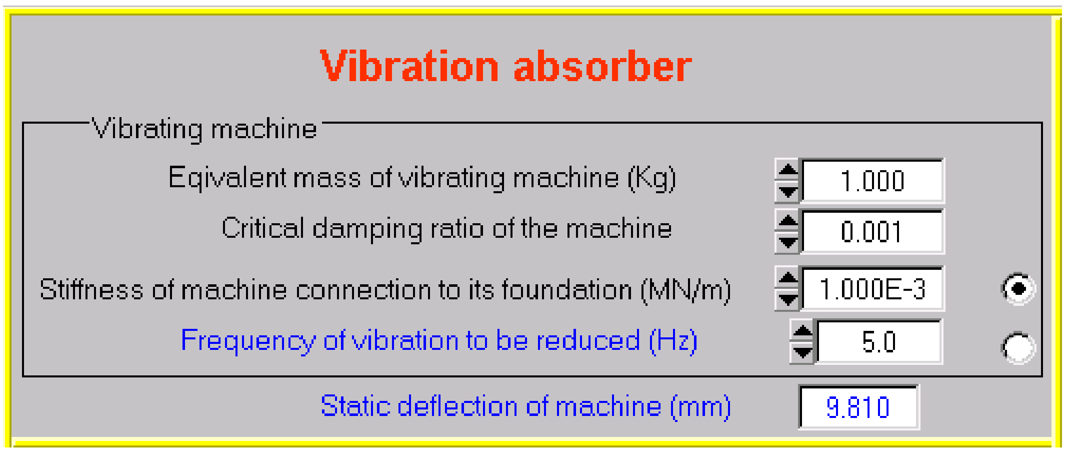
The equation used by ENC (derived from Equation (9.64) in the 6th edition textbook) is:

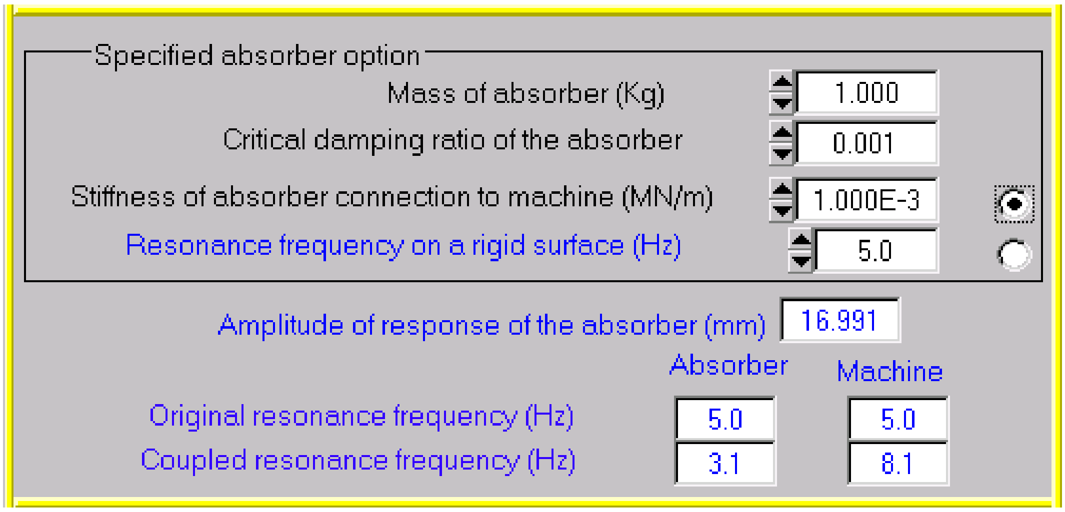
$$v_2 = \frac{v_1(Z_1/Z_2)[(v_N/v_1)(1 - Z_N/Z_1)}{[v_N/v_1 - 1] - (Z_1/Z_2)[(v_N/v_1)(Z_N/Z_1) - 1]}$$

7.9 Vibration Absorber (6th edition textbook, pages 591–595)

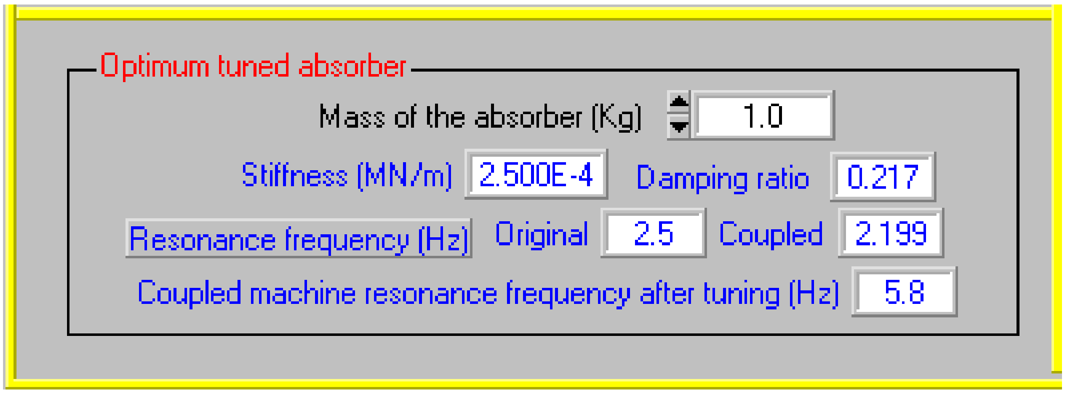
This section allows you to design an optimum vibration absorber (using Equations (9.76)–(9.78) in the 6th edition textbook) to remove the influence of a particular structural or machine response frequency. You can also determine the performance of an absorber of any particular design as described by Equations (9.70) – (9.77) in the 6th edition textbook.

First the mass of the vibrating machine and the damping ratio of the machine support is entered. The stiffness of the vibrating machine support or its resonance frequency (frequency of vibration to be reduced) is then entered (see following figure). After entering the preceding quantities there are two options (specified or optimum absorber — see figures and explanations on the next page).

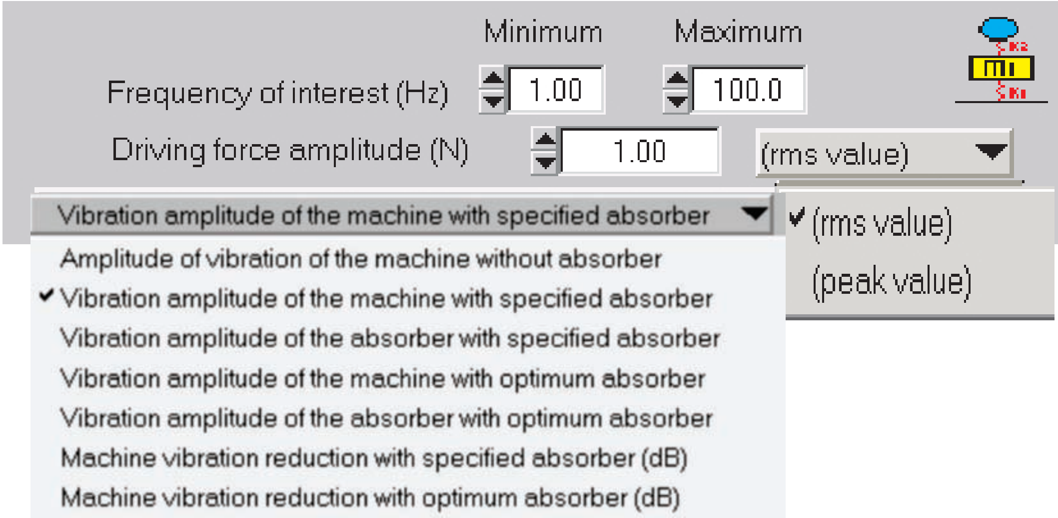


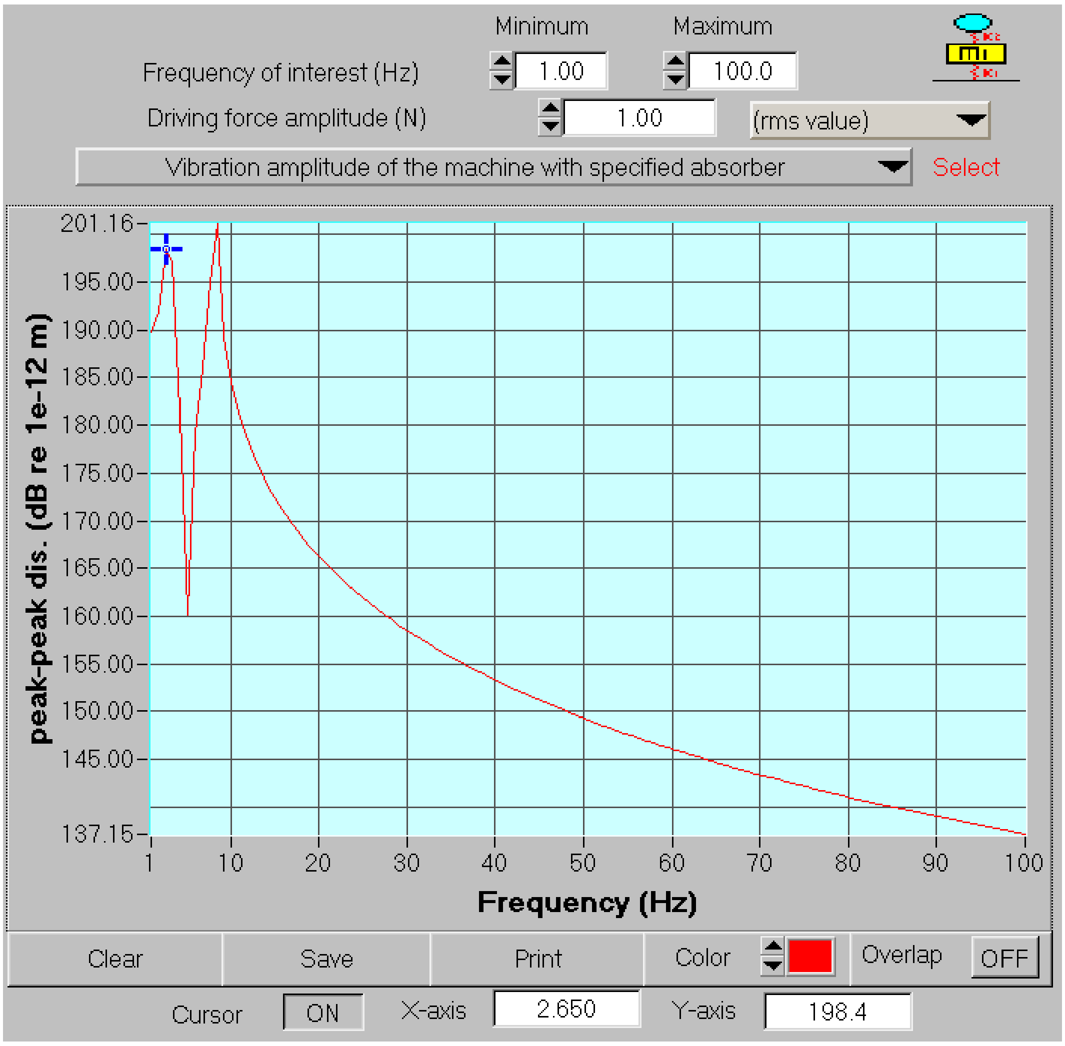


The first option (specified absorber option — see above) calculates the absorber and machine response as a function of frequency for the absorber parameters that are entered. This requires that the absorber mass and critical damping ratio be entered and either the absorber stiffness or its resonance frequency on a hard surface. The program outputs for this option are the two graphs mentioned above, the displacement of the absorber and the original and coupled resonance frequencies of the absorber and machine mass. The second option (optimum absorber — see below) does not require that the absorber stiffness or critical damping ratio are entered. It calculates these quantities for an optimised absorber configuration.



The vibration amplitude (peak to peak, not RMS or peak) of the absorber or mass under control is plotted in the graph on the right side of the panel (see next page). You can choose the frequency range you wish to plot and also enter the peak or rms driving force amplitude (see following figure). You may choose other parameters to plot from the menu (see following figure).


Minimum
Maximum
Frequency of interest (Hz)
1.00
100.0
Driving force amplitude (N)
1.00
(rms value)
Vibration amplitude of the machine with specified absorber
(rms value)
(peak value)
Amplitude of vibration of the machine without absorber
Vibration amplitude of the machine with specified absorber
Vibration amplitude of the absorber with specified absorber
Vibration amplitude of the machine with optimum absorber
Vibration amplitude of the absorber with optimum absorber
Machine vibration reduction with specified absorber (dB)
Machine vibration reduction with optimum absorber (dB)


Minimum
Maximum
Frequency of interest (Hz)
1.00
100.0
Driving force amplitude (N)
1.00
(rms value)
Vibration amplitude of the machine with specified absorber
Select
peak-peak dis. (dB re 1e-12 m)
201.16
195.00
190.00
185.00
180.00
175.00
170.00
165.00
160.00
155.00
150.00
145.00
137.15
1
10
20
30
40
50
60
70
80
90
100
Frequency (Hz)
Clear
Save
Print
Color
Overlap
OFF
Cursor
ON
X-axis
2.650
Y-axis
198.4

Chapter 8

Sound Power of Equipment (Module 8)

8.1 Overview

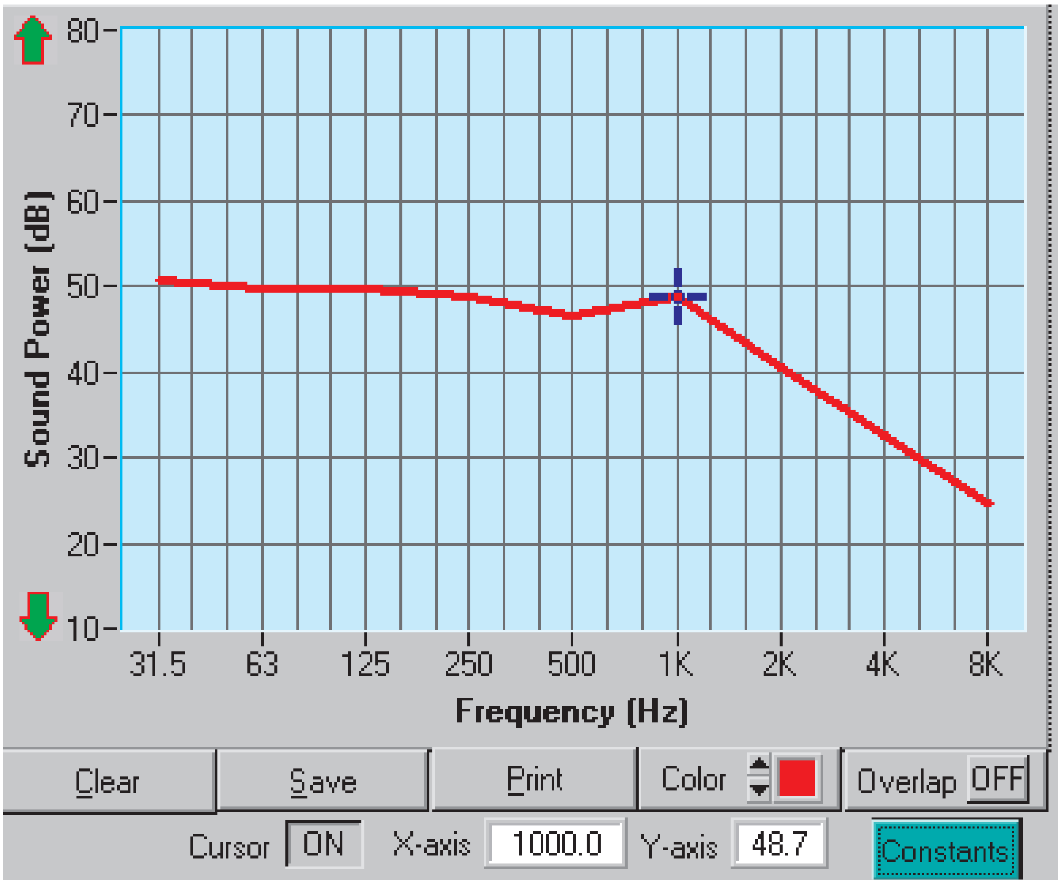
This module is for the calculation of sound power and sound pressure levels of a large number of sound sources, including process equipment and transport vehicles. There are 4 separate windows. The first, "sound power and SPL estimation" is for the calculation of sound power and sound pressure levels of a large number of standard types of equipment. The second, "Road Traffic Noise", is for the estimation of road traffic noise levels using the UK DoT model, CoRTN. The third, "Highway Noise" is for the estimation of traffic noise using the USA, FHWA Traffic Noise Model (TN). The fourth, "Rail Traffic Noise" is for the estimation of train noise using the UK DoT model.

8.2 Sound Power and SPL Estimation

This window is for the calculation of sound power and sound pressure levels of a large number of standard types of equipment. The estimations done here are useful when manufacturer's data are not available, but they are not intended to take the place of measured data — use these calculations only when measured data are impossible to obtain.

The items of equipment considered here are those discussed in Chapter 10 of the 6$^{\text{th}}$ edition textbook. In many parts of the output, "SPL" is used as short notation for "sound pressure level" and "PWL" is used for " sound power level". **N**ote that for calculating PWL from SPL and vice versa, it has been assumed throughout that $\rho c \approx 400$. Clicking on the constants button will simply bring up this message. All calculated sound power or sound pressure level data are displayed in a table and plotted on the right side of the screen. Click on the green arrows to the left of the graph to change the scale on the y-axis and centre the curve on the display.

The data inputs for this module are very self explanatory and are also discussed in detail in the 6$^{\text{th}}$ edition textbook. The quantity plotted corresponds to the line in the table below the plot that has a tick on the square at the right end of the line of data (see next page).

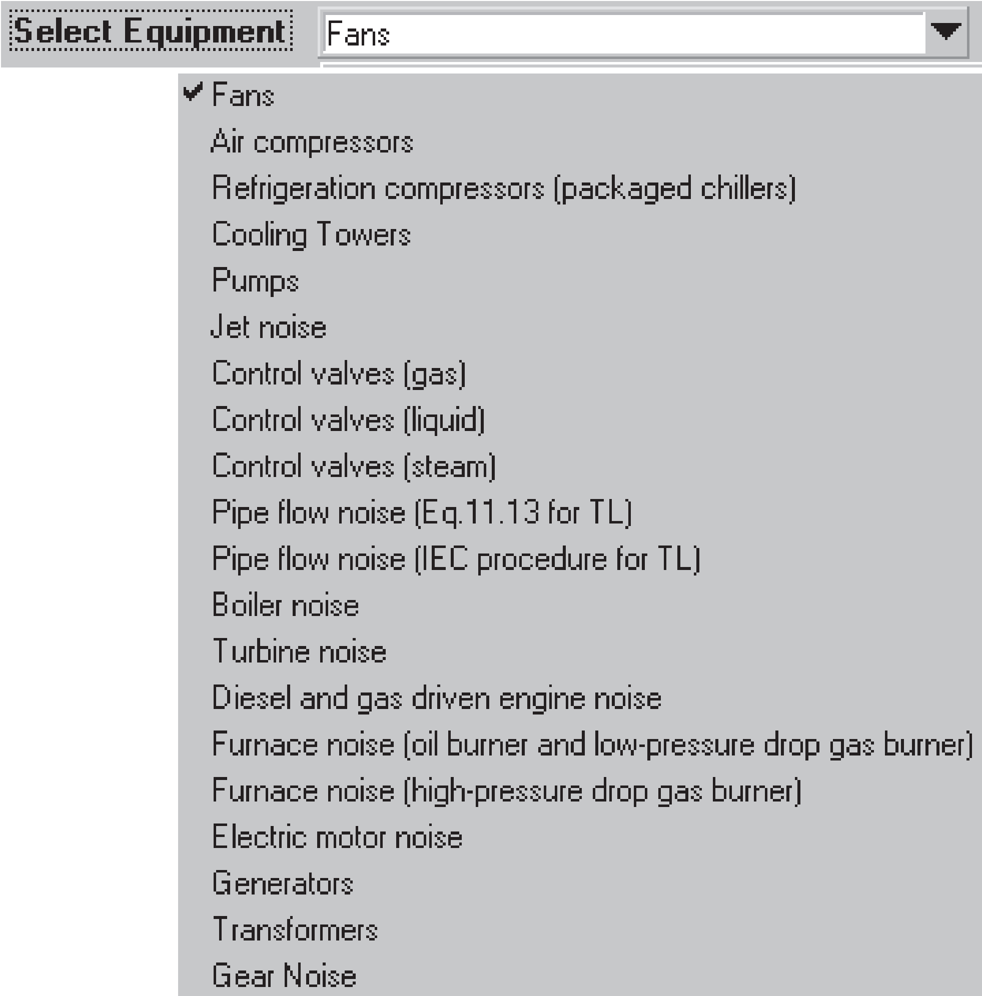


Estimated PWL and SPL

Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	
Internal PWL (dB)	96.1	99.1	102.1	105.1	108.1	111.1	114.4	119.3	123.2	☑
External PWL (dB)	40.1	52.2	64.2	76.1	88.1	100.0	112.1	117.7	118.0	☐
Internal SPL (dB)	117.6	120.6	123.6	126.6	129.6	132.6	135.9	140.8	144.7	☐
SPL 1m (dB)	11.7	23.7	35.7	47.6	59.6	71.6	83.6	89.2	89.5	☐

Note that in many cases, subtracting the octave band corrections listed in the 6$^{\text{th}}$ edition textbook from the overall sound power or sound pressure level often results in octave band values that do not add up to the overall level. ENC slightly adjusts the octave band corrections so that the octave band values exactly add up to the total level calculated by the corresponding equation.

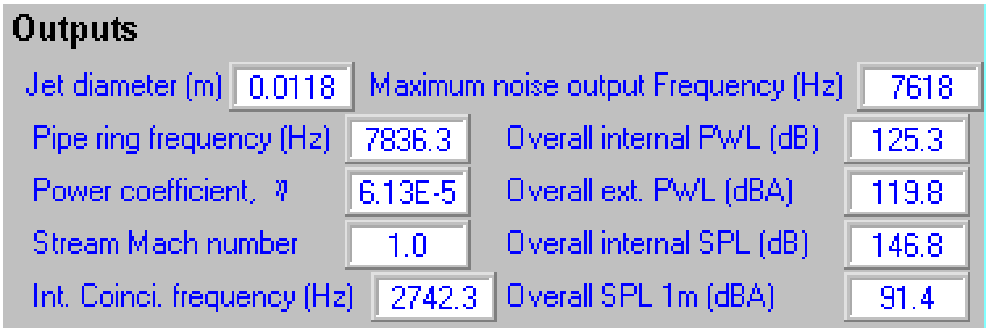
To begin, select the equipment of interest from the menu (see following figure).



For each type of equipment in the menu, there is a sub-menu. Each sub-menu item will be addressed in the following discussion. For each item selected, ENC calculates a number of outputs that are shown in the "output panel" and also tables of sound power or sound pressure levels in octave bands. These latter quantities are also shown graphically.

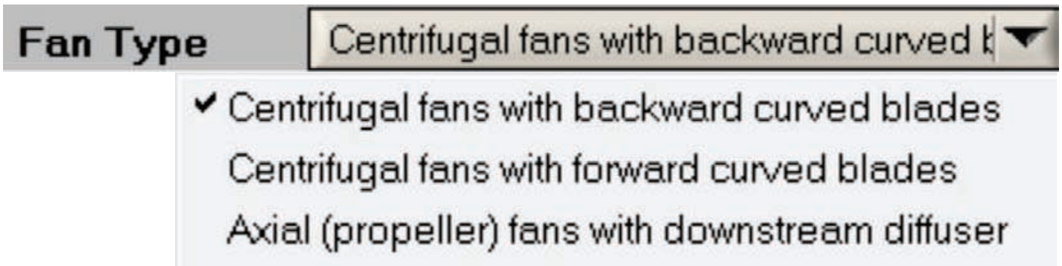
An example output panel for control valves is shown below. All outputs include overall sound power or sound pressure levels, both linear and A-weighted. Octave band values for the same quantities are usually tabulated under the graph on the right of the screen.

Note that in some cases the octave band sound power or sound pressure levels will add up to a little less than the overall level. This is because some energy is present outside of the frequency range of the specified octave bands.



8.2.1 Fans (6th edition textbook, pages 612–615)

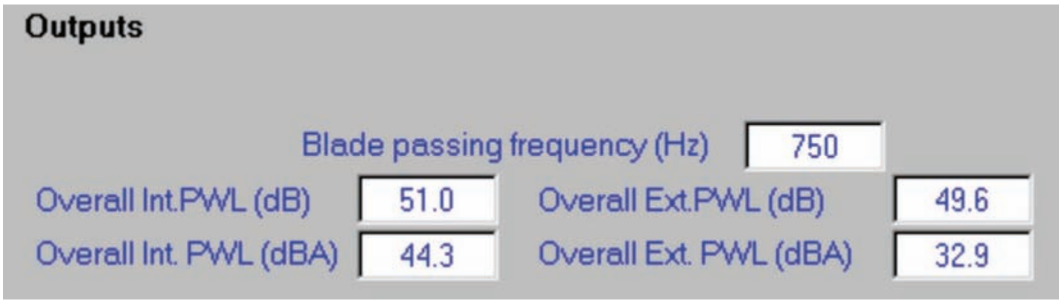
ASHRAE guidelines state that manufacturers' data should be used in all cases. Where such data are unavailable, the German standard, VDI2081-1 (2003) provides guidelines for a limited range of fan types.



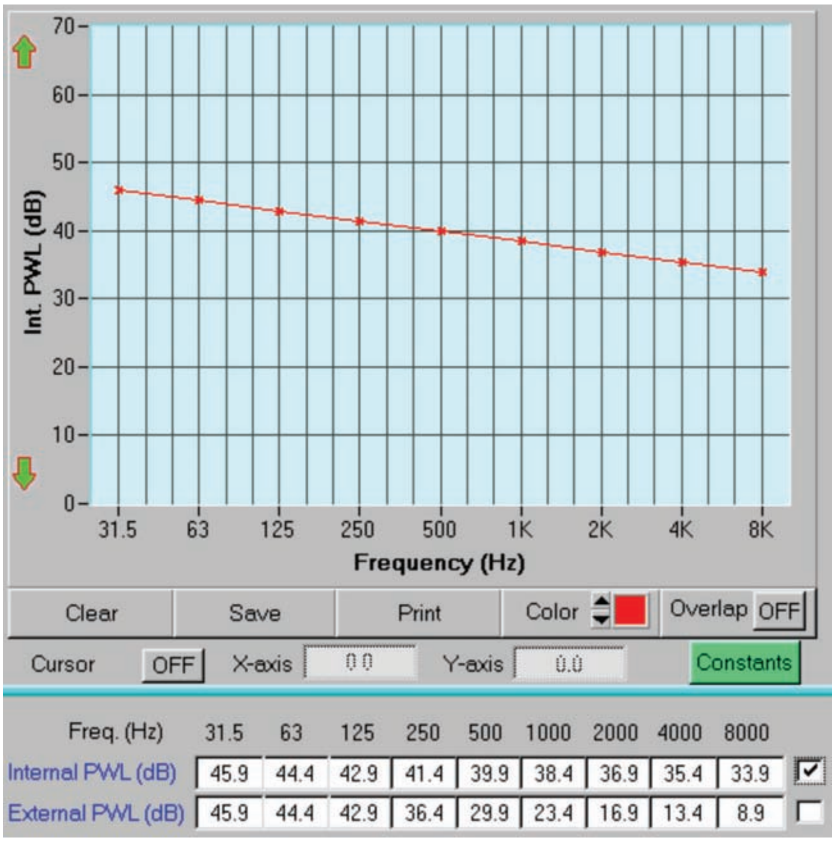
If you wish to proceed, the first step is to choose the type of fan from the list shown above. For all of these fans, ENC uses the equations on page 614 of the 6th edition edition of the textbook to calculate the sound power level in octave bands.

You need to input the volume flow rate, number of fan blades and rotational speed (RPM) and the pressure difference between inlet and outlet for each case to be considered.

For all fan types, ENC will output the blade passing frequency in the output panel as well as the octave band and A-weighted overall sound power levels both within and outside the duct. The sound power and sound pressure levels are output beneath the graph. as shown in the following figure.

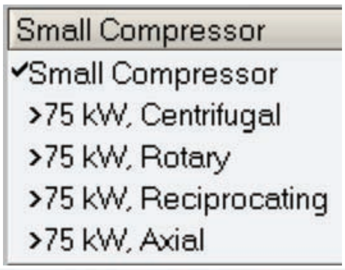


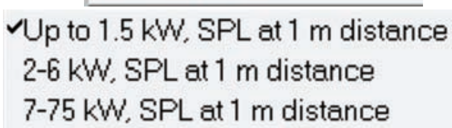
You can plot the external or internal octave band results by clicking the appropriate box below the graph as shown in the following figure.



8.2.2 Air Compressors (6th edition textbook, pages 615–617)

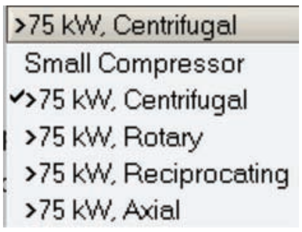
The compressor sub-menu is shown at right.

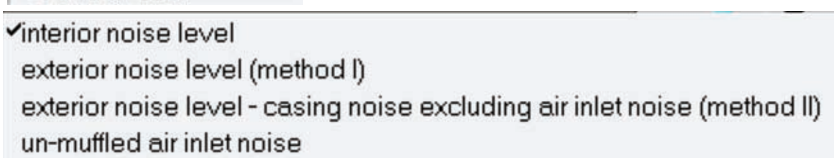




Data for small compressors (the first item on the sub menu shown at right) are obtained from Table 10.4 in the 6th edition textbook. Sound pressure levels at 1 m distance from the compressors are provided in the output panel for various compressor powers (lower part of the figure at right). No input data are needed. However, you must select the compressor size from the menu shown at right.

Output results for the next 4 items in the top sub menu shown at right, which represent the 4 different generic compressors, include the sound pressure inside the pipe at the compressor exit and the exterior noise radiated by the compressor casing and air inlet.

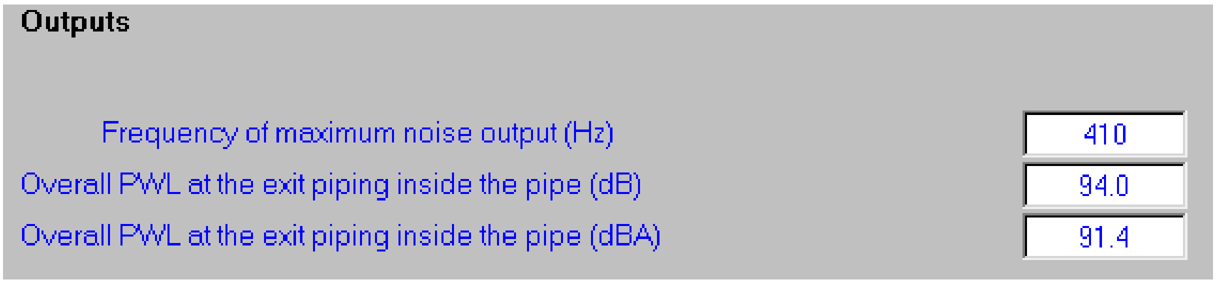




There are two methods that can be used for calculating exterior noise levels. Method I applies to all compressors and uses Equation (10.15) in the 6th edition textbook together with the calculated interior noise level at the exit piping. Method II is based on compressor power and is not available for axial compressors. In addition, for centrifugal compressors the un-muffled air inlet noise may be calculated separately.

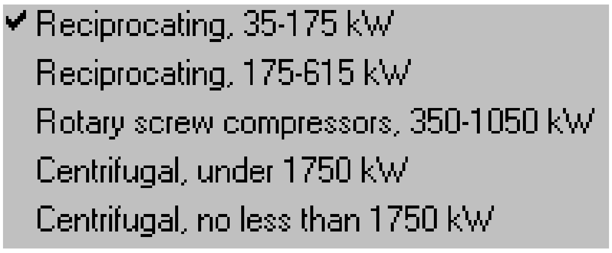
The compressor power in kW is needed as input for all 4 items. For the centrifugal compressor, the impeller tip speed is also needed as an input for some of the calculations. For the rotary and axial compressors, the number of impeller blades and impeller rpm are needed as input in addition to the power. For the reciprocating compressor, the number of cylinders and crankshaft rpm are needed as input.

In addition to the octave band sound power levels, the outputs (see following figure) for these three items include the frequency of maximum noise level. The equations used for these calculations are (10.5)–(10.14) in the 6th edition textbook. Note that when the octave band levels do not add up to the overall level calculated according to Equation (10.7), the octave band levels are corrected by ENC so that they add up to the overall level.



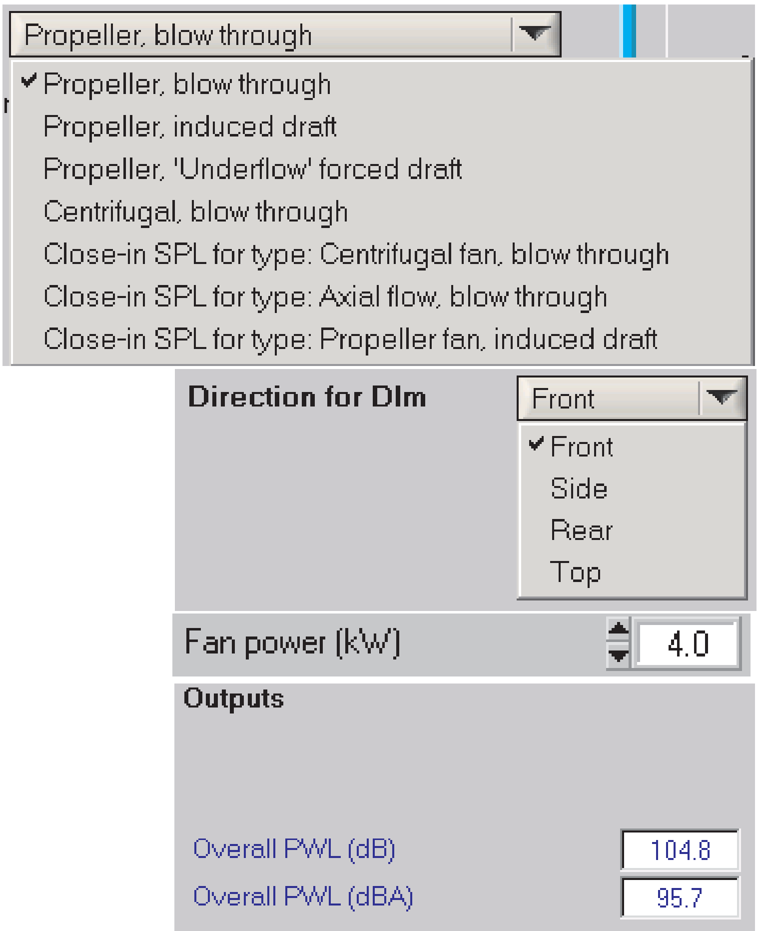
8.2.3 Refrigeration Compressors (6th edition textbook pages 617–618)

No input data are required for the 5 types of compressor listed at right. ENC uses Table 10.6 to calculate the sound pressure levels in octave bands as well as overall linear and A-weighted at 1 m.



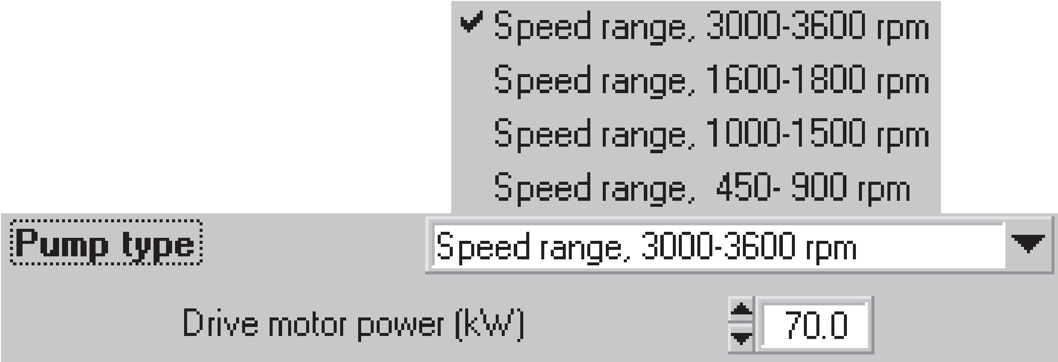
8.2.4 Cooling Towers (6^{th} edition textbook, pages 618–620)

There are four types of cooling tower from which to choose as indicated by the first four lines of the pop-up menu shown at right (three propeller types and one centrifugal type). For each one, the fan power and direction of interest (front, rear, side or top) needs to be specified also using the menu shown at right. The output consists of three lines under the graph. One line corresponds to the overall sound power levels in octave bands, the second line represents A-weighted values and the third line is a list of directivity indices corresponding to the direction of radiation chosen (ie front, side, rear or top (see Table 10.9 in the 6^{th} edition textbook). The appropriate directivity index must be added to the sound pressure level calculated using the sound power level in the first line and the excess attenuation effects calculated using module 3. Note that the octave band corrections given in the 6^{th} edition textbook are slightly reduced by ENC to ensure that they add up to the overall levels calculated using Equations (10.19) to (10.20) in the 6^{th} edition textbook. Note that overall linear and A-weighted levels are shown on the bottom left panel.



If any of the three “close in” options are chosen, ENC will give the sound pressure level at 1 m for the intake and discharge of the cooling tower using Table 10.10 in the 6^{th} edition textbook. The “Direction for DIm” menu disappears as it is no longer relevant. Corresponding octave band levels are listed for each case beneath the graph and the tick box indicates whether the intake (In) or discharge (Dis) is plotted. Note that for these cases, the total levels in the bottom left panel are sound pressure levels at 1 m.

8.2.5 Pumps (6th edition textbook, page 621)



As shown in the figure above, the only input data needed are the speed range and pump drive motor power. ENC uses Tables 10.11 and 10.12 in the 6th edition textbook to calculate the sound pressure levels at 1 m from the pump and these are output beneath the graph in octave bands. ENC also calculates and displays overall linear and A-weighted levels.

8.2.6 Jet Noise (6th edition textbook, pages 621–624)

For this calculation you need to input the data listed on the GUI. The ratio of specific heats, γ, and the molecular weight, M_W (kg/mole) of the gas in the jet can be obtained from the popup window that appears when clicking on the constants button. ENC calculates the jet density, ρ_j, temperature, T_j speed of sound, c_j, jet Mach number, M_j and Mach number, M_0, based on the speed of sound, c_0 in the ambient medium surrounding the jet, using the gas properties as well as the static pressure, P_u and static temperature, T_u of the gas upstream of the jet nozzle and the assumption that the jet is isentropic. If the upstream gas is flowing at speed, U_u, the equations require the total upstream pressure, P_{uT} and total upstream temperature, T_{uT}. The total upstream pressure and temperature are:

$$P_{uT} = P_u \left(1 + \frac{(\gamma - 1)M_u^2}{2}\right)^{\gamma/(\gamma-1)} \quad ; \quad T_{uT} = T_u + \frac{U_u^2(\gamma - 1)M_W}{2\gamma R}$$

where the upstream Mach number, $M_u = U_u/c_u$ and $c_u = \sqrt{\frac{\gamma R T_u}{M_W}}$.

Thus:

$$c_0 = \sqrt{\frac{\gamma R T_0}{M_W}}; \quad T_j = T_{uT}\left(\frac{P_0}{P_{uT}}\right)^{(\gamma-1)/\gamma} \quad ; \quad \rho_j = \frac{P_0 M_W}{R T_j}; \quad c_j = \sqrt{\frac{\gamma R T_j}{M_W}}$$

where P_0 (Pa) and T_0 (K) are the static ambient pressure and static ambient temperature respectively, in the gas surrounding the nozzle exit, R is the universal gas constant (8.314 J mol^{-1} K^{-1}) and M_W is the gas molecular weight (kg/mole).

The static temperature, T_j (K), of the jet can also be written as:

$$T_j = T_{uT}\left(1 + \frac{(\gamma - 1)M_j^2}{2}\right)^{-1}$$

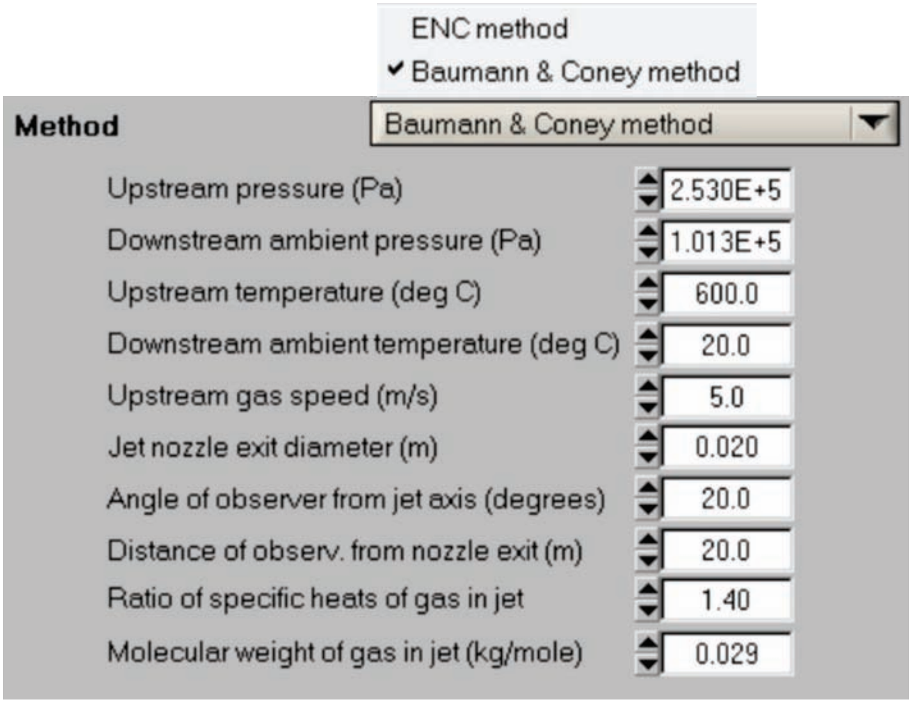
where the fully expanded jet Mach number is:

$$M_j = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_{uT}}{P_0}\right)^{(\gamma-1)/\gamma} - 1\right]}$$

Three Mach numbers are needed in the following calculations. For unchoked jets, these are $M_0 = U_j/c_0$; $M_j = U_j/c_j$; $M_c = 0.62M_0$. For choked jets, the equations for M_0 and M_j remain the same but the equation for M_c becomes $M_c = U_c/c_j$, where $U_c = \dfrac{U_j}{1 + M_j^{-1}}$. The required speeds of sound, c_0 and c_j from previous equations are also required, as is the fully expanded jet speed, U_j, given by:

$$U_j = \sqrt{\frac{2\gamma R T_{uT}}{M_W(\gamma - 1)}\left[1 - \left(\frac{P_0}{P_{uT}}\right)^{(\gamma-1)/\gamma}\right]}$$

The calculations are valid for both choked and unchoked jets. There is a choice of two calculation methods: the 6th edition textbook and the Baumann & Coney method (Baumann and Coney, 2006, pp. 616–623).

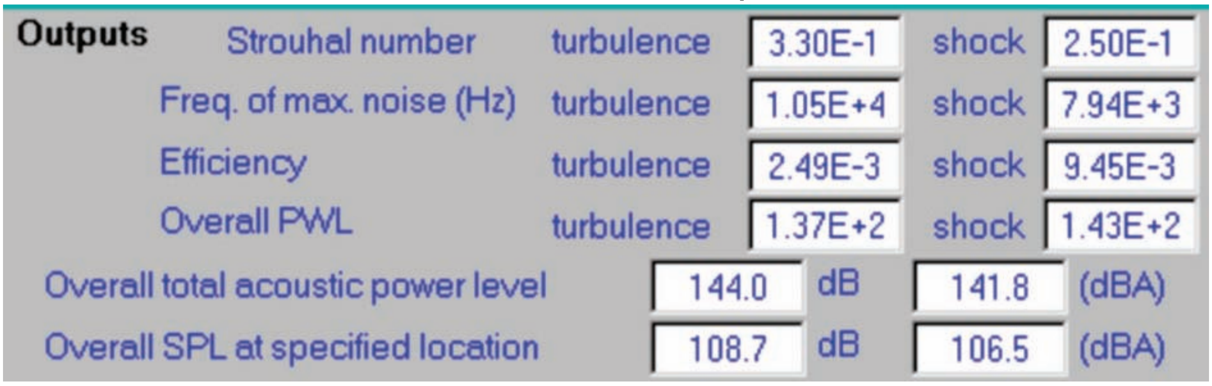


For both calculation methods, there are two components that make up the total noise. The first is jet mixing noise, often referred to as turbulence noise and the second is shock noise. For subsonic jets, there is no shock noise, only turbulence noise. For sonic and supersonic jets, both types on noise exist and must be calculated separately. The resulting sound pressures for each noise type are added logarithmically to give the total sound pressure levels and the same applies to sound power levels. The peak frequency of each type of noise is calculated using the Strouhal number that characterises the gas flow exiting the nozzle and Equation (10.26). The Strouhal number is then used to calculate the frequency corresponding to the peak in the spectrum Equation (10.26) in the 6th edition textbook (see Figure 10.3 in the textbook), allowing the 1/3-octave and octave band levels over the entire spectrum to be calculated. For the ENC method, previous versions used a Strouhal number of 0.2 but this is a bit low, especially for subsonic flow at the nozzle exit. In version 6.6 of ENC and later versions, various Strouhal numbers are used, depending on the nozzle exit Mach number and which calculation method is chosen.

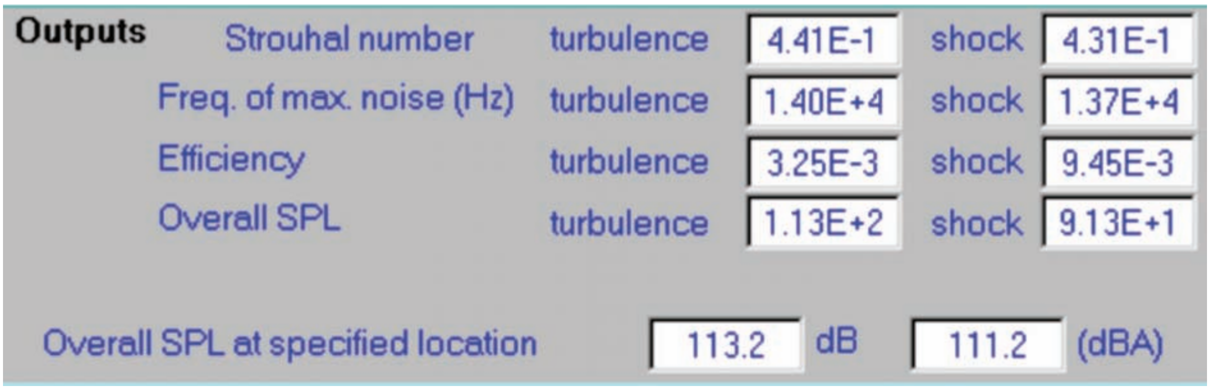
The density and temperature of the ambient gas refer to the gas that surrounds the jet but is not part of it (usually air).

In addition to the octave band sound pressure level at a specified distance and the octave band sound power level (which are also plotted), ENC provides other outputs as illustrated below. If there is a value of 0.00E+0 in the boxes adjacent to the "shock" label, it means that the jet flow is subsonic, so there is no shock noise contribution. The output types for the ENC method differ slightly from those for the Baumann & Coney method because the latter method does not provide a procedure for estimating sound power levels due to the shock mechanism when the flow of the jet is supersonic.

ENC method output



Baumann & Coney method output



8.2.6.1 ENC Method

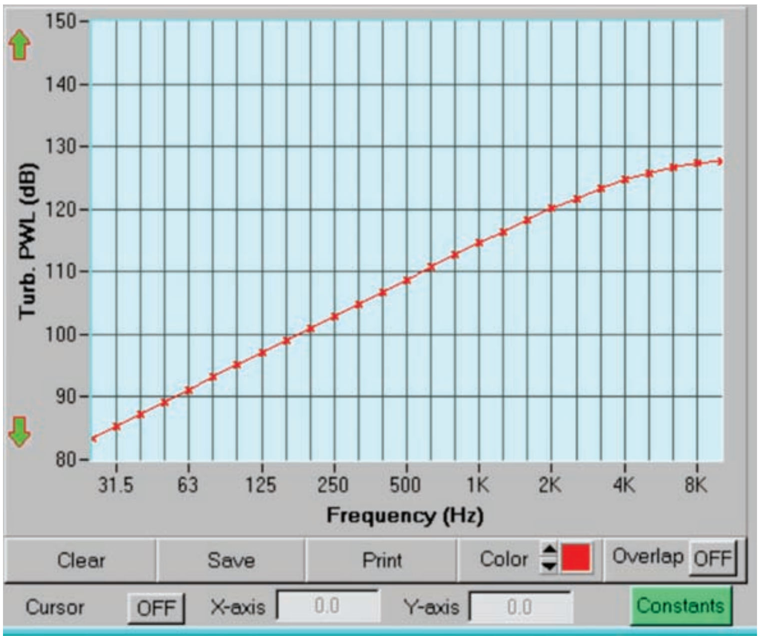
For the ENC method, the outputs are calculated using Equations (10.21)–(10.26), Figures 10.2 and 10.3, and Table 10.13 in the 6th edition textbook. Note that ENC includes the quantity $10\log_{10}[\rho c/400]$ on the right hand side of Equation (10.25) in the 6th edition textbook. The peak frequency of the turbulence noise is calculated using Equation (10.26) in the 6th edition textbook, where U is the jet exit velocity, U_j, defined in the equation on page 287. For jet Mach numbers (M_j), of less than 0.3, a Strouhal number of 0.37 is used for calculating the turbulence noise contribution and for Mach numbers greater than 0.3, a Strouhal number of 0.33 is used. For calculating the peak frequency of shock noise, a Strouhal number of 0.25 is used for calculating the turbulence noise contribution.

For the ENC method, the same equations are used for the turbulence noise calculations as used for the shock noise calculations for a choked jet, except for the acoustic efficiency. For turbulence noise (both choked and unchoked jets), the acoustical efficiency, η, is given by Equation (10.23) in the textbook and for shock noise (choked jet only), the acoustical efficiency is calculated using Figure 10.2 in the textbook.

For choked jets, the total sound pressure level is the logarithmic sum of that for the turbulence noise and that for the shock noise. For unchoked jets the total sound pressure and sound power levels are only those due to turbulence noise.

In the ENC method, the spectral shape of Figure 10.3 in the textbook is used for both shock and turbulence noise, although this is likely to lead to some errors when the jet is choked (see Baumann and Coney method in the next section).

In addition to the outputs shown on the previous page, octave and one-third octave band outputs are provided as shown in the following figure.



Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
Turb. PWL (dB)	90.4	96.3	102.1	107.9	113.8	119.6	125.0	129.5	132.0
Shock PWL (dBA)	96.2	102.0	107.9	113.7	119.6	125.4	130.8	135.2	137.8
Total PWL (dB)	97.2	103.1	108.9	114.7	120.6	126.4	131.8	136.3	138.8
Total PWL (dBA)	60.5	78.8	94.1	106.9	117.9	126.5	133.0	137.1	137.6
Total SPL (dB)	61.9	67.8	73.6	79.4	85.3	91.1	96.5	101.0	103.5
Total SPL (dBA)	25.2	43.4	58.7	71.6	82.6	91.2	97.7	101.8	102.3

8.2.6.2 Baumann & Coney method

Turbulence Noise

For the Baumann & Coney method, the outputs are calculated using the equations on pages 617–623 in Baumann and Coney (2006). Equation (10.23) for a subsonic jet in the textbook is replaced with (Baumann and Coney, 2006, Eq.(15.8)):

$$\eta = K_a \frac{(\rho_j/\rho_0)^{w-1} M_0^{4.5}}{(1 - M_c^2)^2}$$

Where $K_a = 4 \times 10^{-5}$, $M_0 = U_j/c_0$, U_j is the fully expanded jet velocity, c_0 is the speed of sound in ambient gas surrounding the jet, ρ_j is the density of the fully expanded jet, $M_c = 0.62 M_0$ and w is (Baumann and Coney, 2006):

$$w = \frac{3M_0^{3.5}}{0.6 + M_0^{3.5}} - 1$$

The peak frequency of the turbulence noise is calculated using Equation (10.26) in the 6$^{\text{th}}$ edition textbook, where U is the jet exit velocity, U_j. The equation is repeated on pafe 291. The Strouhal number corresponding to the peak noise frequency for mixing noise is estimated using the following table. For choked or unchoked jets, the fully expanded jet velocity, U_j is given by the equation on page 287. For an unchoked jet, the convection velocity, U_c is given by, $U_c = 0.62 U_j$.

Table 8.1 Values of subsonic jet Strouhal number, (N_s), as a function of angle from the jet axis for various temperature ratio values where T_j is the temperature (in K) of the jet at the exit (see equation on page 286 and T_0 is the ambient temperature in the gas surrounding the jet, K. See Table 15.1 in (Baumann and Coney, 2006, pp.620).

T_j/T_0	$\theta = 50°$	$\theta = 60°$	$\theta = 70°$	$\theta = 80°$	$\theta \geq 90°$
1	0.7	0.8	0.8	1.0	0.9
2	0.5	0.4	0.6	0.5	0.6
3	0.3	0.4	0.4	0.4	0.5

Equations (10.21), (10.22) and (10.24) in the textbook are then used to calculate the turbulence contribution to the overall sound power for turbulence noise. Jet acoustical efficiency and sound power are not used in the calculations for shock sound pressure levels with the Baumann & Coney method. However, it is possible to estimate the sound power spectrum by using the sound pressure spectrum shape corresponding to an angle of 90° to the jet axis and this is done by ENC.

The overall sound pressure level produced by a subsonic (unchoked) jet at an angle of 90° to the jet axis, at distance r (m) from the jet nozzle exit is:

$$L_p(90°)_{\text{overall}} = 139.5 + 10\log_{10}(A/r^2) + 10\log_{10}\left[\left(\frac{p_0}{1.013 \times 10^5}\right)^2 \left(\frac{\rho_j}{\rho_0}\right)^w\right] + 10\log_{10}\left[\frac{M_0^{7.5}}{1 - 0.1M_0^{2.5} + 0.015M_0^{4.5}}\right]$$

where $A = (\pi/4)d_j^2$, d_j = nozzle exit diameter, ρ_j = density of fully expanded jet.

The overall sound pressure level produced by a subsonic jet at an angle of $\theta°$ to the jet axis is:

$$L_p(\theta°)_{\text{overall}} = L_p(90°)_{\text{overall}} - 30\log_{10}\left[1 - \frac{M_c\cos\theta}{(1+M_c^5)^{1/5}}\right] - 1.67\log_{10}\left[1 + \frac{1}{10^{(40.56-\theta')} + 4\times10^{-6}}\right]$$

where $\theta' = 0.26(180-\theta)M_j^{0.1}$, degrees.

The peak frequency, f_p, for turbulence noise (which is the only noise component for unchoked jets) is:

$$f_p = \frac{N_s U_j}{d_j} \quad \text{(Hz)}$$

The 1/3-octave band levels for turbulence noise are calculated using Figure 10.3 in Baumann and Coney (2006), which, for $x = \log_{10}(f/f_p)$ may be described as:
1/3-octave level = overall level $+a + bx + cx^2 + dx^3 + ex^4 + fx^5 - 10$ dB,
where

$$\begin{aligned}a &= 3.1952E-02\\ b &= -4.0799E-01\\ c &= -8.5725E+00\\ d &= 2.4133E+00\\ e &= 5.5791E-01\\ f &= -4.7047E-01\end{aligned}$$

The 1/3-octave levels are then added logarithmically to give octave band levels as well as the overall level.

Shock Noise (caused by choked flow with a converging nozzle)
The peak frequency for shock noise (which occurs in addition to turbulence noise in choked jets) is (Baumann and Coney, 2006, page 623)):

$$f_p = \frac{0.9U_c}{d_j\beta(1+M_c\cos\theta)} \quad \text{(Hz)}$$

where the minus sign in the denominator in the reference is an error and has been changed to a "+" sign here. The corresponding Strouhal number is calculated using f_p calculated in the preceding equation and the equation on page 291 for the peak noise frequency for turbulence noise.

In the preceding equation, θ (degrees) is the angle between the jet axis and an observer located downstream of the jet, d_j is the nozzle exit diameter and for a choked jet, U_c is the jet convection velocity and the convection Mach number is $M_c = U_c/c_j$. For choked jets:

$$U_c = \sqrt{\frac{2\gamma R T_{uT}}{M_W(\gamma+1)}}$$

However, Baumann and Coney (2006) suggest that a good approximation is, $U_c = 0.7U_j$. A more accurate version of this approximation is $U_c = \dfrac{U_j}{1 + M_j^{-1}}$ and this is what is used by ENC. U_j andM_j are defined on page 287. In the peak frequency equation, β is defined as $\beta = \sqrt{M_j^2 - 1}$.

The overall sound pressure level due to the shock noise component of a choked jet is approximately independent of direction (according to (Baumann and Coney, 2006, page 622)) and is:

$$L_{p,\text{overall}} = C_0 + 10\log_{10}\left(\frac{\beta^n A}{r^2}\right)$$

where $n = 4$ if $\beta < 1$,
$n = 1$ if $\beta \geq 1$ and $T_{uT}/T_0 < 1.1$;
$n = 2$ if $\beta \geq 1$ and $T_{uT}/T_0 \geq 1.1$
T_{uT} is the upstream gas total temperature (K) and T_0 is the temperature of the medium at the jet nozzle exit.

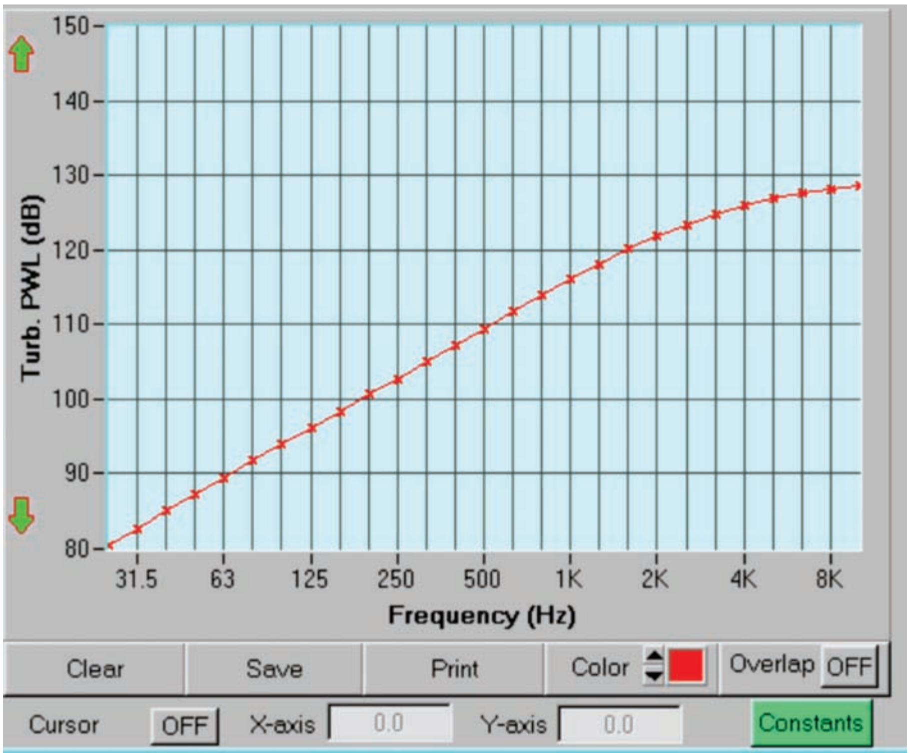
The 1/3-octave band SPL is:

$$\begin{aligned} L_{p,1/3\text{-octave}} =& 143.5 + 10\log_{10}\left(\frac{\beta^n A}{r^2}\right) - 16.13\log_{10}\left[\frac{5.163}{\sigma^{2.55}} + 0.096\sigma^{0.74}\right] \\ &+ 10\log_{10}\left\{1 + \frac{17.27}{N_{sh}}\sum_{i=0}^{N_{sh}-1}\left[(C(\sigma))^{i^2}\sum_{j=1}^{N_{sh}-i-1}\frac{\cos(\sigma q_{ij})\sin(0.1158\sigma q_{ij})}{\sigma q_{ij}}\right]\right\} \end{aligned}$$

where $C(\sigma) = 0.8 - 0.2\log_{10}(2.239/\sigma^{0.2146} + 0.0987\sigma^{2.75})$
$\sigma = 6.91\beta d_n f/c$ (c is speed of sound in medium surrounding jet),
$N_{sh} = 8$ (number of shocks)
$q_{ij} = (1.7ic/U)\{1 + 0.06[j + 0.5(i + 1)]\}[1 - 0.7(u/c)\cos\theta]$
n is defined above. However, if $T_j/T_0 < 1.1$, the prediction should be reduced by 2 dB.

The choked flow sound pressure level and the turbulence sound pressure level are added logarithmically in ENC to produce the total sound pressure level in each octave band for choked flow.

Results for octave band calculations are provided in the table on the RHS of the window and 1/3-octave band data are plotted on the graph shown on page 293. The plot limits on the y-axis can be adjusted using the adjacent green arrows. The quantity that appears on the graph is the one corresponding to the line in the table in the figure on page 293 that has a tick in the box on the RHS of the line.



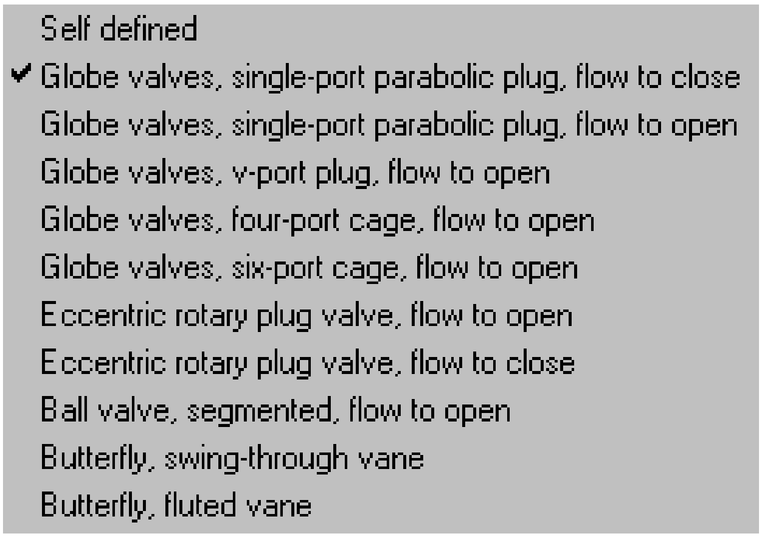
Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	
Turb. PWL (dB)	87.8	94.6	101.2	107.9	114.6	121.2	126.8	130.8	132.9	☑
Turb. SPL (dB)	62.7	69.4	76.1	82.7	89.4	96.0	101.7	105.6	107.8	☐
Shock SPL (dB)	-9.9	2.5	14.9	27.2	39.7	52.0	64.4	76.3	85.7	☐
Total SPL (dB)	62.7	69.4	76.1	82.7	89.4	96.0	101.7	105.7	107.8	☐
Total SPL (dBA)	26.1	45.2	61.3	75.0	86.8	96.2	102.9	106.5	106.6	☐

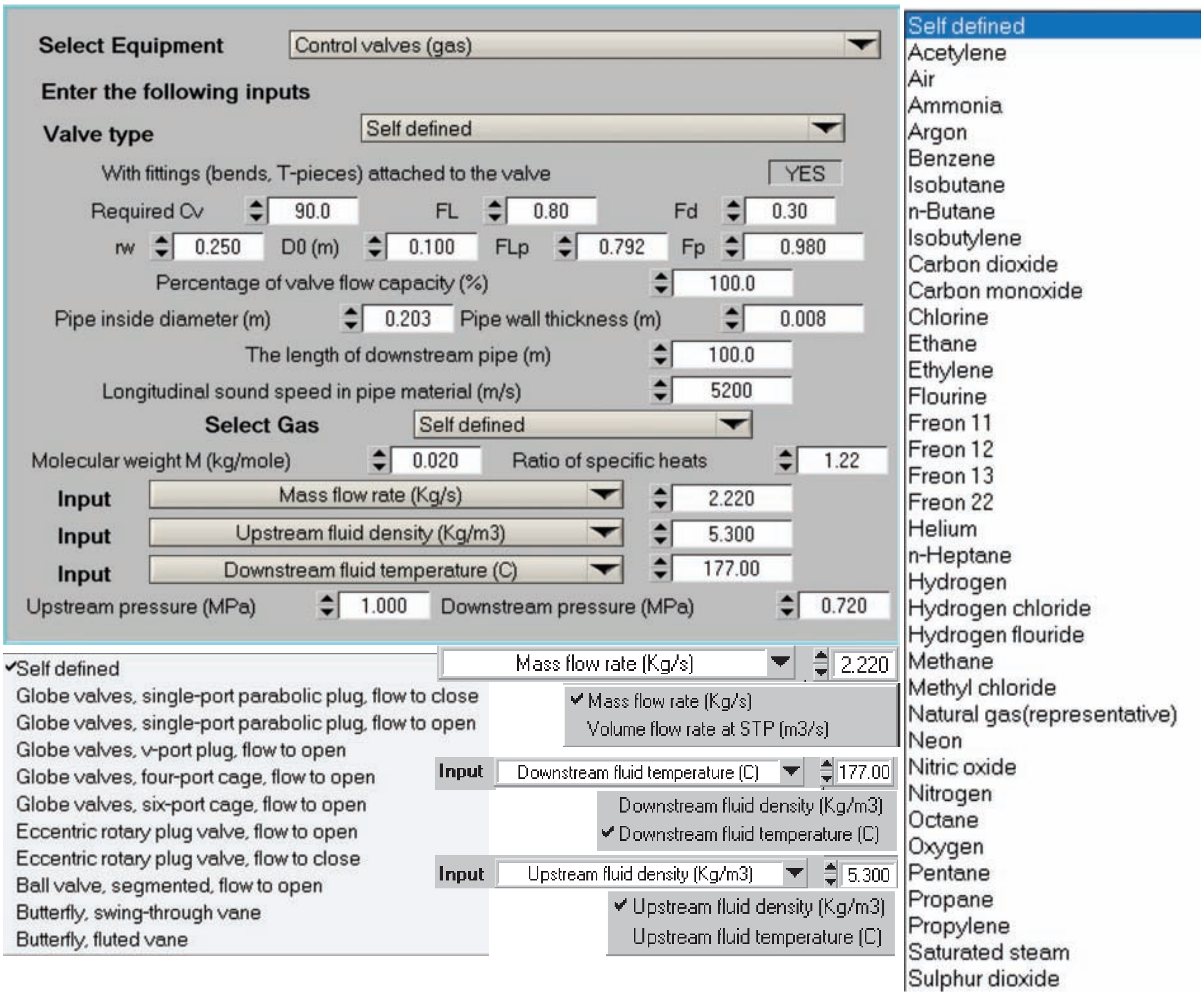
8.2.7 Control Valves (Gases) (6$^{\text{th}}$ edition textbook, pages 624–634)

The 6$^{\text{th}}$ edition textbook and ENC use the IEC 60534/8/3 (2000) International standard formulation. Note that ENC provides means to calculate the sound power in and sound pressure radiated by the downstream piping attached to the valve. Radiation from the valve body or upstream piping is considered to be negligible according to the IEC standard.

The calculations are only valid for steel or steel alloy pipes so it is recommended that users use 5200 m/s for the longitudinal sound speed in the pipe wall.

You may choose the type of valve from the list at right or decide to define all properties yourself. Choosing a particular type of valve will fix the quantities labelled “required Cv”, “FL”, “Fd” and “rw”. These quantities are, respectively, the valve flow coefficient, the valve pressure recovery factor, the valve style modifier coefficient and the ratio of acoustic power propagated downstream of the valve to the total acoustic power generated by the valve. If you wish to change any of these fixed values, just select “user defined” after selecting the particular valve type. The quantities FLp and Fp in the second line are used in the form FLp/Fp to replace FL when fittings are attached to the valve. These quantities are usually obtained from the valve manufacturer. You can specify “YES” or “NO” for fittings being attached (see following figure).





The quantity D0 is the valve discharge diameter in metres. The "percentage of valve flow capacity" is the ratio of flow through the valve to maximum rated flow through the valve expressed as a percentage. The "pipe inside diameter" and "pipe wall thickness" are for the downstream piping. The quantity, C_v, is the number of US gallons of water that will flow through the valve in 1 minute. The quantities, F_L, F_{LP}, F_d, F_P and r_w are valve characteristics available from the valve manufacturer or from Table 10.14 in the textbook. You are also asked to enter the length of downstream piping of interest and the longitudinal wave speed in the material (see module 1). You can select your gas type from a list of 37 gases, including steam or you can specify the gas as "self defined". If you select the gas type, ENC will automatically enter the gas molecular weight and ratio of specific heats. You can use the "CONSTANTS" setup window (in the tools menu) to calculate the gas density and speed of sound given the pressure and temperature.

Following selection of the gas type, there are three inputs required, and for each input, there is a choice of two parameters to input. Only one of each choice is required (see above figure). The final two inputs required are the valve upstream and downstream pressures in MPa.

The outputs provided by ENC are quite extensive and are shown in the following figure.

Outputs Regime I	Overall TL 56.9	Downstream Mach Nr.	0.2
Jet diameter (m)	0.1328	Freq. of max. internal SPL, fp (Hz)	675
Pipe ring freq., fr (Hz)	7836.3	Overall internal PWL (dB)	125.3
Power coefficient, η	6.13E-5	Overall ext. PWL (dBA)	113.5
Mach number, Mv or Mj	1.0	Overall internal SPL (dB)	146.8
Int. Coinci. freq., f0 (Hz)	2742.3	Overall SPL 1m (dBA)	85.2

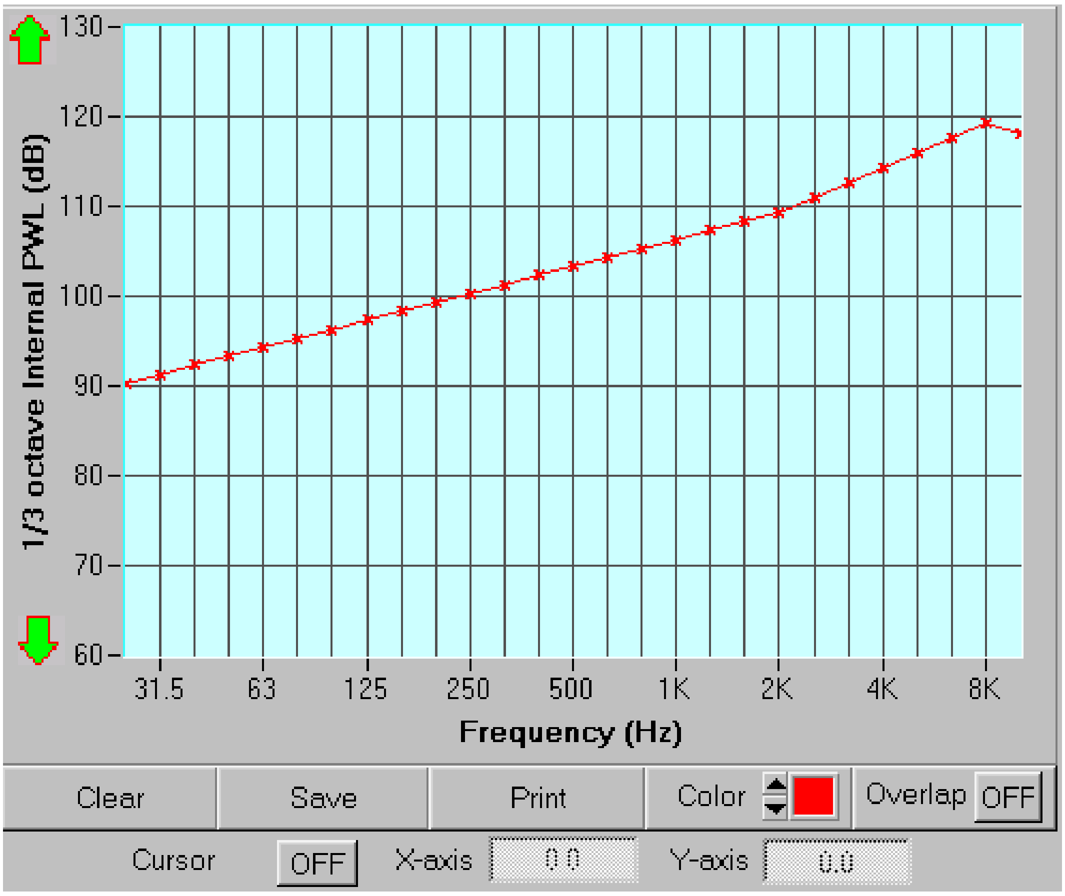
All of the outputs (including sound power and sound pressure levels) refer to the piping downstream of the valve. The jet diameter is the diameter of the jet in the vena contracta in the valve. The "int. Coinci frequency (Hz)" is the internal coincidence frequency of the downstream pipe. The flow regime (from regimes I to IV) is indicated for the valve being analysed.

In addition to the outputs illustrated above, ENC provides 1/3-octave band plots and tables of octave band values for the following quantities:

- Internal sound power level (downstream piping only — upstream not important))
- external sound power level
- external sound pressure level at 1m from the pipe wall (downstream piping only)
- pipe wall transmission loss

As for all items discussed in this section, the line corresponding to the ticked box (see following figure) is plotted on the graph (see figure on next page). However, in this case, 1/3-octave instead of octave band results are plotted so the numbers on the graph (which may be read using the cursor) do not necessarily agree with the numbers in the table.

Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	
Internal PWL (dB)	96.1	99.1	102.1	105.1	108.1	111.1	114.4	119.3	123.2	☑
External PWL (dB)	38.4	50.4	62.4	74.3	86.3	98.3	110.3	115.9	116.2	☐
Internal SPL (dB)	117.6	120.6	123.6	126.6	129.6	132.6	135.9	140.8	144.7	☐
SPL @ 1m (dB)	9.9	22.0	34.0	45.8	57.9	69.8	81.9	87.4	87.7	☐
Pipe wall TL (dB)	103.3	94.3	85.3	76.4	67.4	58.4	49.7	48.3	52.0	☐



The pipe wall Transmission Loss is calculated using the following procedure.

1. Calculate internal overall unweighted sound power (watts) using Equations (10.22), (10.27) and Table 10.14 in the 6^{th} edition textbook.

2. Calculate internal overall unweighted sound pressure using Equation (10.40) in the 6^{th} edition textbook

3. Get the spectrum of unweighted internal sound pressure levels using pages 629–631 in the 6^{th} edition textbook.

4. Calculate the unweighted sound power level inside the pipe from the result in 1 above using $10 \log_{10}(W_a/W_{\text{ref}})$.

5. Calculate the spectrum shape of unweighted internal sound power levels using the same procedure as used for the sound pressure level spectrum.

6. Calculate the overall pipe TL using the IEC method — see page 632 in the 6^{th} edn. textbook).

7. Calculate the overall external A-weighted sound pressure level using Equations (10.65) to (10.67) in the 6^{th} edition textbook. (Note that the TL used in these equations should really be called a TL adjustment. It is not really a TL as it relates the A-weighted external sound pressure level to the unweighted external sound

pressure level. And it's an adjustment that can only be used in this equation for valve noise).

8. Calculate the overall external A-weighted radiated sound power using Equation (10.65) in the 6th edition textbook.

9. Calculate the unweighted spectrum band levels for both sound pressure level and sound power level using Equations (10.66) to (10.68) in the 6th edition textbook.

10. Adjust the spectrum levels (by the same number of dB in each band) so that when they are A-weighted and summed logarithmically they produce the same overall A-weighted levels as calculated in items 8 and 9 above.

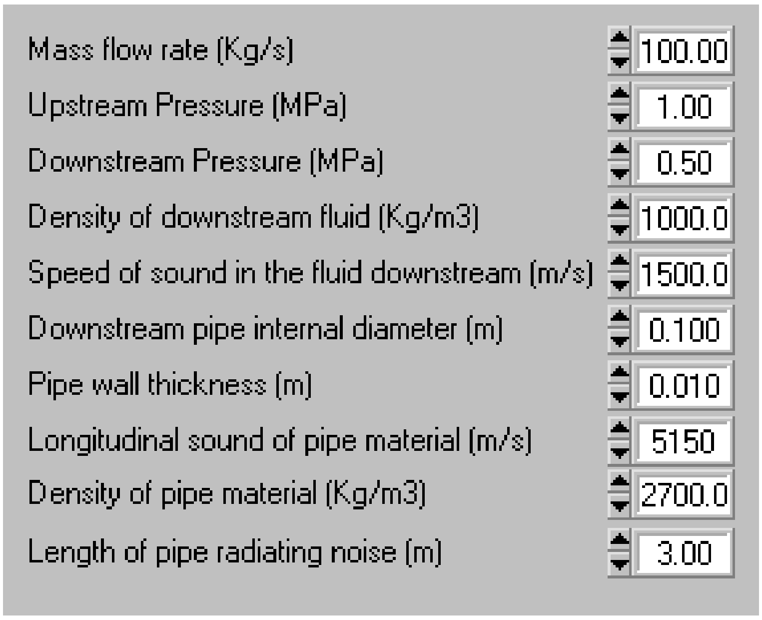
11. The 1/3-octave band pipe TL is the difference between the internal and external band sound pressure levels.

12. Octave band sound pressure and sound power levels are obtained by logarithmically summing the three 1/3-octave components and the octave band TL is found by logarithmically averaging the three 1/3-octave components.

8.2.7.1 Valves with Multihole Trim

This calculation follows a similar procedure to that described above, except that two additional items of data are needed: AH which is the cross-sectional area of one of the passages and LH which is the passage length (with the assumption that all passages are the same length). The number of passages is not needed as it is included in the calculation of F_d, which should be provided by the valve manufacturer and which is an input to ENC.

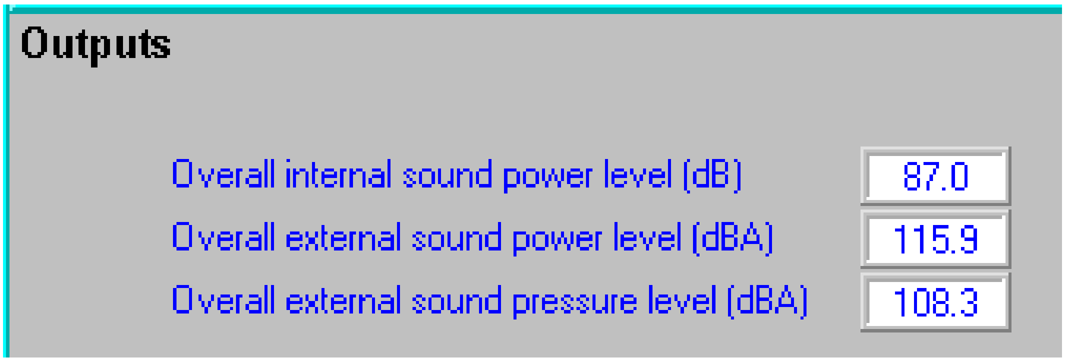
8.2.8 Control Valves (Liquid, IEC60534-8-4, 1994) (5th edition textbook, pages 590–591)

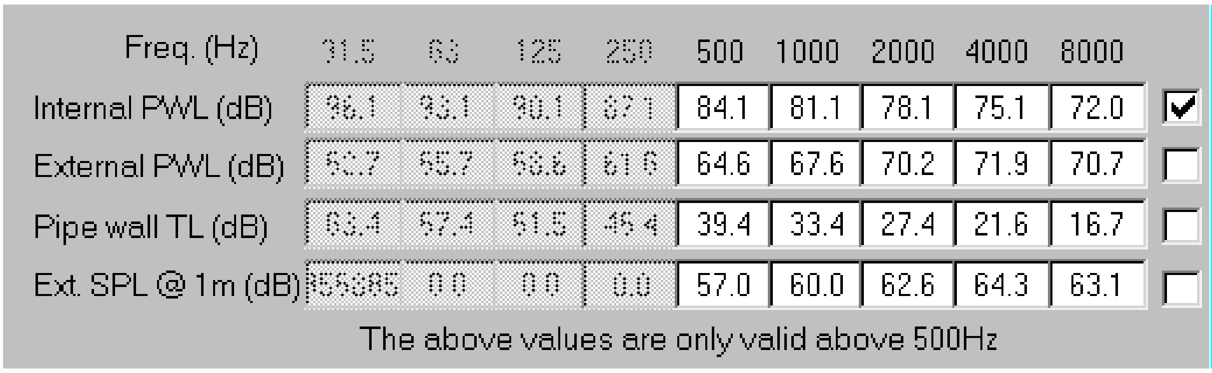


This panel follows the procedures outlined in the international standard, IEC60534-8-4 (1994 edition). If the procedure in the 2015 standard is needed, then see the next section. For the procedure in the 1994 standard, the input data required by ENC are shown in the table at right. Note that all calculations are for noise radiation from the downstream piping. The amount radiated from the upstream piping or the valve is considered negligible.

The calculations are only valid for steel or steel alloy pipes so it is recommended that users use 5200 m/s for the longitudinal sound speed in the pipe wall and 7850 kg/m^3 for the density of the pipe material.

The outputs that are provided by ENC for the downstream piping are shown in the following two figures.



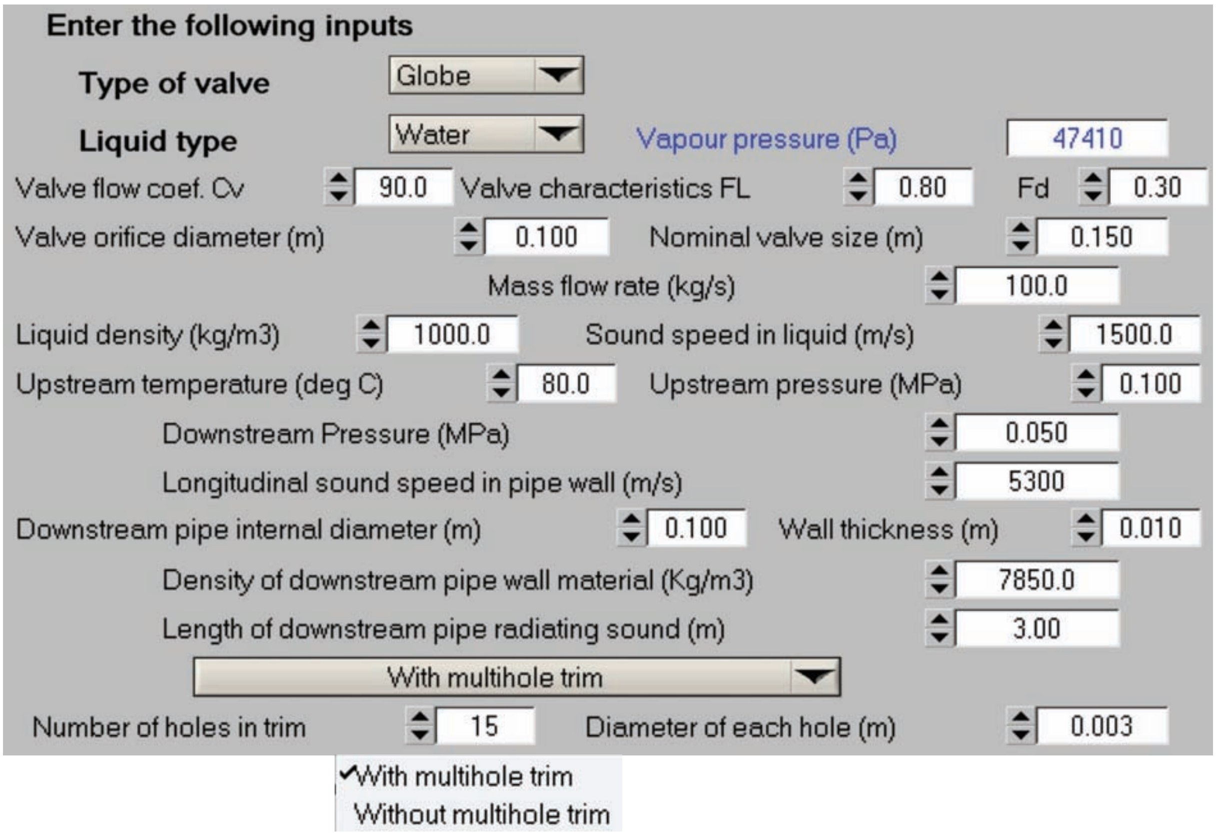


The "TL" quantity refers to the Transmission Loss of the downstream piping, calculated according to the standard. The line in the table below that has a ticked box to its right is plotted in the graph as illustrated at the beginning of this chapter. Note that numbers in boxes below 500 Hz are "greyed out" as the IEC procedure is not valid at these frequencies.

8.2.9 Control Valves (Liquid, IEC60534-8-4, 2015 edition)

The following prediction procedure is outlined in the 6th edition textbook, pages 635–637 and follows IEC 60534-8-4 (2015) The required input data are shown in the following figure. Noise resulting from reflections, loose parts or resonances is not taken into account here. Noise generated by multi-stage valves can be calculated using procedures in IEC 60534-8-4 (2015).

In the input data, the quantity, C_v, is the number of US gallons of water that will flow through the valve in 1 minute. The quantities, F_L, F_{LP}, F_d and F_P are valve characteristics available from the valve manufacturer or from Table 10.14 in the textbook. You are also asked to enter the length of downstream piping that is radiating sound and the longitudinal wave speed in the material (see module 1). You can select the type of valve as "globe" or "other" and the type of liquid as "water" or "other". If water is selected as

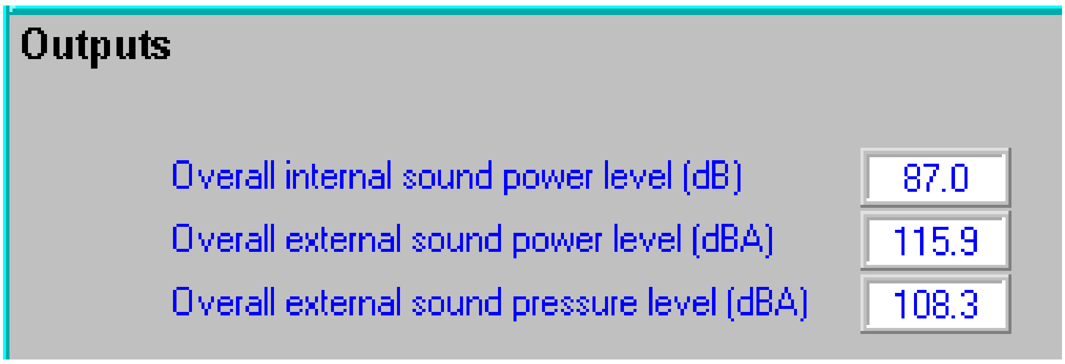


the liquid, ENC calculates the vapour pressure based on the temperature of the water in the inlet pipe. If a different vapour pressure is needed, then select "other" as the liquid, even if it is water.

The calculations are only valid for steel or steel alloy pipes so it is recommended that you use 5400 m/s for the longitudinal sound speed in the pipe wall and 7850 kg/m^3 for the density of the pipe material.

There is also an option at the lower part of the window to specify a valve with cage installed on its outlet with a multi-hole trim. In this case the number of holes and the diameter of each must be entered. For holes that are non-circular in cross section, the equivalent diameter, d is used , where $d = \sqrt{4A/\pi}$, where A is the cross-sectional area of a single hole.

The outputs that are provided by ENC for the downstream piping are shown in the following two figures.



Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	
Internal PWL (dB)	96.1	93.1	90.1	87.1	84.1	81.1	78.1	75.1	72.0	☑
External PWL (dB)	52.7	55.7	58.6	61.6	64.6	67.6	70.2	71.9	70.7	☐
Pipe wall TL (dB)	63.4	57.4	51.5	45.4	39.4	33.4	27.4	21.6	16.7	☐
Ext. SPL @ 1m (dB)	55685	0.0	0.0	0.0	57.0	60.0	62.6	64.3	63.1	☐

The above values are only valid above 500Hz

The "TL" quantity refers to the Transmission Loss of the downstream piping, calculated according to the standard. The line in the above table that has a ticked box to its right is plotted in the graph as illustrated at the beginning of this chapter.

The theory for this procedure is not provided in the textbook, so it is outlined here.

The pressure ratio, X_{Fz}, at which cavitation can be acoustically detected for an inlet pressure, P_1, of 6×10^5 Pa, is defined as:

$$X_{Fz} = \begin{cases} 0.9\left(1 + 3F_d\sqrt{\dfrac{C_v}{1.17F_L}}\right)^{-0.5} & \text{; for all except valves with multihole trims} \\ (4.5 + 1650 N_0 d_H^2/F_L)^{-0.5} & \text{; for valves with multihole trims} \end{cases} \tag{8.1}$$

where N_0 is the number of holes in the trim and d_H is the diameter of each hole. For holes with a non-circular cross section, use $d_H = \sqrt{4A_H/\pi}$, where A_H is the cross sectional area of the hole. To account for inlet pressures different to 6×10^5 Pa, the quantity, X_{Fz} is replaced in calculations by X_{Fzp1}, defined as:

$$X_{Fzp1} = X_{Fz}\left(\frac{6 \times 10^5}{P_1}\right)^{0.125} \tag{8.2}$$

The differential pressure, ΔP_c, is:

$$\Delta P_c = \text{smaller of} \begin{cases} (P_1 - P_2) \\ F_L^2(P_1 - P_{va}) \end{cases} \quad \text{(Pa)} \tag{8.3}$$

where P_1 is the upstream pressure, P_2 is the downstream pressure, F_L is the valve pressure recovery factor (see page 627 in the textbook) and P_{va} is the vapour pressure for the liquid in the pipe. For water, the vapour pressure may be calculated using the Arden Buck equation:

$$P_{va} = 611.21 \exp\left[\frac{18.678 - T_1/234.5}{T_1/(T_1 + 257.14)}\right] \quad \text{(Pa)} \tag{8.4}$$

where T_1 is the temperature of the water in °C.

The acoustic power, W_a, generated by liquid passing through a control valve is (IEC 60534-8-4, 2015):

$$W_a = \eta W_m = \frac{\eta \dot{m} \Delta P_c}{\rho_f} \quad \text{(W)} \tag{8.5}$$

where ρ_f is the density of the liquid and $\dot{m}$ is the mass flow rate. The efficiency factor, η, is different for turbulent flow and cavitating flow and may be calculated using the following equations.
For **turbulent flow**, $X_F \leq X_{Fzp1}$ and $\eta = \eta_{\text{turb}}$, where:

$$X_F = (P_1 - P_2)/(P_1 - P_{va}) \tag{8.6}$$

and

$$\eta_{\text{turb}} = 10^A \left(\frac{U_v}{c_f}\right) \tag{8.7}$$

where $A = -4.6$ for globe valves, $A = -4.3$ for other valve types, c_f is the speed of sound in the liquid and U_v is the speed of the flow through the vena contractor, given by:

$$U_v = \frac{1}{F_L}\sqrt{\frac{2\Delta P_c}{\rho_f}} \qquad \text{(m/s)} \tag{8.8}$$

For **cavitating flow**, $X_{Fzp1} < X_F < 1$ and $\eta = \eta_{\text{turb}} + \eta_{\text{cav}}$, where

$$\eta_{\text{cav}} = 0.32\eta_{\text{turb}}\left(\frac{P_1 - P_2}{\Delta P_c X_{Fzp1}}\right)^{0.5} \mathrm{e}^{5X_{Fzp1}}\left(\frac{1 - X_{Fzp1}}{1 - X_F}\right)^{0.5}\left(\frac{X_F}{X_{Fzp1}}\right)^5 (X_F - X_{Fzp1})^{1.5} \tag{8.9}$$

The overall internal sound pressure level, L_{pi}, downstream of the control valve is calculated using:

$$L_{pi} = 10\log_{10}\left[\frac{3.18 \times 10^9 W_a \rho_f c_f}{d_i^2}\right] \qquad \text{(dB re 20 µPa)} \tag{8.10}$$

The internal sound pressure level for the 1/3-octave band with a centre frequency, f, is different for turbulent and cavitating flow.

For **turbulent flow**:

$$L_{pi}(f) = L_{pi} + \Delta(f, \text{turb}) \qquad \text{(dB re 20 µPa)} \tag{8.11}$$

where

$$\Delta(f, \text{turb}) = -8 - 10\log_{10}\left[\frac{1}{4}\left(\frac{f}{f_{p,\text{turb}}}\right)^3 + \left(\frac{f_{p,\text{turb}}}{f}\right)\right] \qquad \text{(dB)} \tag{8.12}$$

and

$$f_{p,\text{turb}} = \left(\frac{U_v}{d_j}\right)\left(\frac{0.036F_L^2 C_v f_d^{0.75}}{1.17X_{Fzp1}^{1.5} D d_0}\right)(P_1 - P_{va})^{-0.57} \qquad \text{(Hz)} \tag{8.13}$$

where D is the nominal valve size (m), d_0 is the valve orifice diameter (m), U_v is defined in Equation (8.8) and d_j is the jet diameter given by:

$$d_j = 4.6 \times 10^{-3} F_d \sqrt{C_v F_L} \qquad \text{(m)} \tag{8.14}$$

For **cavitating flow**:

$$L_{pi}(f) = L_{pi} + 10\log_{10}\left(\frac{\eta_{\text{turb}}}{\eta_{\text{turb}} + \eta_{\text{cav}}}10^{\Delta(f,\text{turb})/10} + \frac{\eta_{\text{cav}}}{\eta_{\text{turb}} + \eta_{\text{cav}}}10^{\Delta(f,\text{cav})/10}\right) \tag{8.15}$$

where

$$\Delta(f, \mathrm{cav}) = -9 - 10\log_{10}\left[\frac{1}{4}\left(\frac{f}{f_{p,\mathrm{cav}}}\right)^{1.5} + \left(\frac{f_{p,\mathrm{cav}}}{f}\right)^{1.5}\right] \qquad \text{(dB)} \tag{8.16}$$

$$f_{p,\mathrm{cav}} = 6 f_{p,\mathrm{turb}}\left(\frac{1 - X_F}{1 - X_{Fzp1}}\right)^2 \left(\frac{X_{Fzp1}}{X_F}\right)^{2.5} \qquad \text{(Hz)} \tag{8.17}$$

The TL for the 1/3-octave band with centre frequency, f, is:

$$\mathrm{TL} = 10 + 10\log_{10}\left(\frac{c_L \rho_m t}{\rho c d_i}\right) + 20\log_{10}\left[\left(\frac{f_r}{f}\right)\left(\frac{f}{f_r}\right)^{1.5}\right] \qquad \text{(dB)} \tag{8.18}$$

where ρ and c are, respectively, the density and speed of sound in the gas external to the pipe (usually air).

The sound pressure level outside of the pipe and adjacent to the pipe for the 1/3-octave band with centre frequency, f, is:

$$L_{pe}(f) = L_{pi}(f) - \mathrm{TL} \qquad \text{(dB re 20 µPa)} \tag{8.19}$$

and the sound power level radiated by a pipe of length, ℓ_p, is:

$$L_W(f) = L_{pe}(f) + 10\log_{10}(d_i + 2t) + 10\log_{10}\ell_p + 5 \qquad \text{(dB re } 10^{-12}\text{ W)} \tag{8.20}$$

The external sound pressure level at 1 m from the pipe wall is:

$$L_{pe,\mathrm{1m}}(f) = L_{pe}(f) - 10\log_{10}\left(\frac{d_i + 2t + 2}{d_i + 2t}\right) \qquad \text{(dB re 20 µPa)} \tag{8.21}$$

Overall sound power and sound pressure levels may be obtained by logarithmically summing the 1/3-octave band levels. A-weighted overall levels are obtained by first adding the appropriate A-weighting, from Table 2.3, p. 82 in the 6th edition textbook, to each 1/3-octave band and logarithmically adding the 1/3-octave A-weighted levels.

8.2.10 Control Valves (Steam) (6th edition textbook, page 634)

As steam is a gas, the calculation procedures are the same as for "Control Valves (Gas)" discussed a few pages previously, except when the calculated acoustical efficiency factor, $\eta < 0.005$. In this case, the calculated sound pressure and sound power levels are increased by 3 dB to reflect what is measured for steam valves.

In ENC, the calculation in the bottom right panel for the SPL at 1 m (dB) is a copy of Table 10.15 in the 6th edition textbook, which is provided as an alternative estimate if you do not wish to use the more complicated calculations due to lack of input data. This table is the same for all steam valves and is based on many field measurements with light thermal wrapping around the outlet pipe.

8.2.11 Pipe Flow Noise (turbulent flow noise source), Baumann method

External sound pressure levels in an octave band with a centre frequency of f, at a distance of 1 m from the pipe wall, for a pipe carrying gases in a turbulent flow condition, may be calculated using (Baumann and Coney, 2006, p. 631):

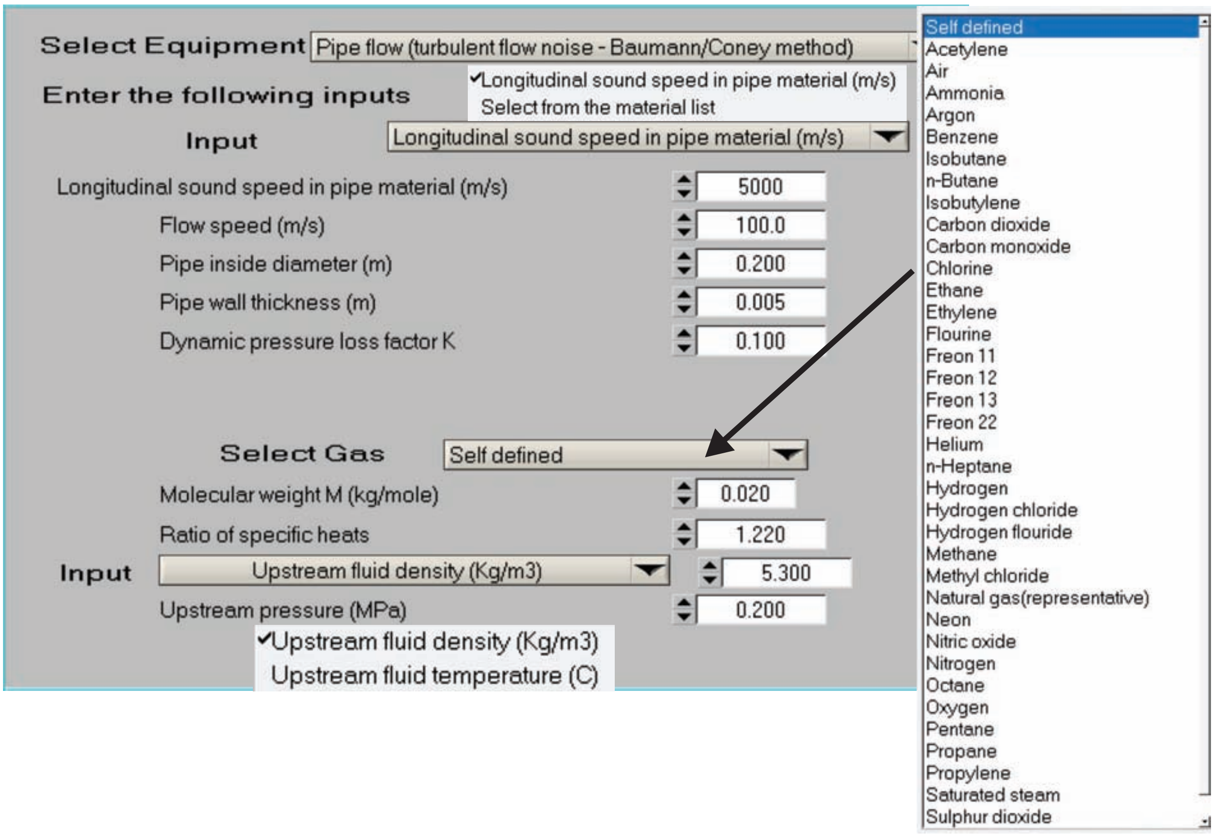
$$L_p = -3.5 + 40\log_{10} U + 20\log_{10}\rho + 20\log_{10} K - 10\log_{10}\left[\frac{t}{d_i}\left(1 + \frac{1.83}{d_i}\right)\right] - 5\log_{10}\left[\frac{f}{f_r}\left(1 - \frac{f}{f_r}\right)\right] + \Delta L \tag{8.22}$$

where U is the gas flow speed, ρ is the density of the gas inside the pipe, t is the pipe wall thickness, d_i is the pipe inside diameter, f_r is the pipe ring frequency $= c_L/[\pi(d_i+t)]$, K is the friction loss in a length, L, of pipe equal to $10d_i$ (use $K = 0.1$ for a smooth-wall pipe and Equations (8.237) and (8.238) in the 6th edn textbook (with $L = 10d_i$) for a pipe with a perforated sheet metal liner) and:

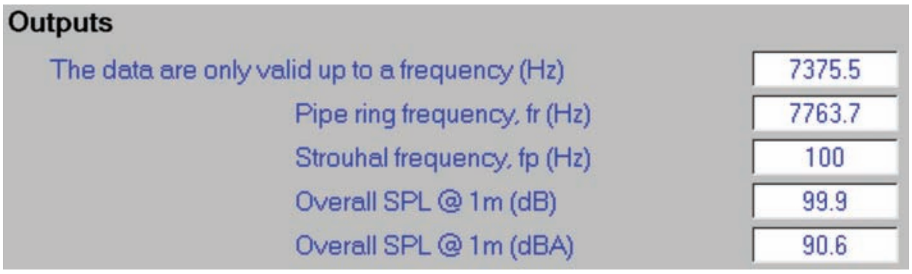
$$\Delta L = \begin{cases} 10.4 + 11.4\log_{10}(f/f_p); & f/f_p < 0.5 \\ 7; & 0.5 \le (f/f_p) < 5 \\ 14 - 10\log_{10}(f/f_p); & 5 \le (f/f_p) < 12 \\ 41.9 - 36.1\log_{10}(f/f_p); & (f/f_p) \ge 12 \end{cases} \tag{8.23}$$

where $f_p = 0.2U/d_i$ is the peak noise level frequency corresponding to a Strouhal number of 0.2. If pipe fittings such as elbows are included in the 10 m pipe section used to calculate K due to friction, then the K factors due to these fittings can be determined using Figure 8.39 in the 6th edn textbook and these are added to the value of K for friction losses in the straight section pipe, 10 m long (often approximated as $K = 0.1$).

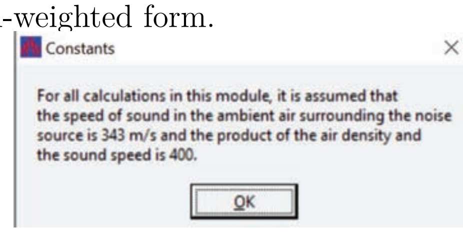
The above calculation is only valid up to a frequency of $0.95f_r$.



To use this method in ENC, the required input data are shown in the figure above. For the gas flowing in the pipe, you can either enter the molecular weight and ratio of specific heats or you can select the gas from a drop down list as shown in the figure. The other required inputs are the absolute pressure in the pipe and either the density of the gas or its temperature.



The outputs (see figure at right) provided in the left hand panel are the pipe ring frequency, the maximum valid frequency for the results, the frequency at which the noise is loudest and the overall sound pressure level at 1 m in dB and dBA. Octave band data are plotted in the following figure for data below $0.95f_r$. You may choose whether to plot the results in A-weighted or un-weighted form.

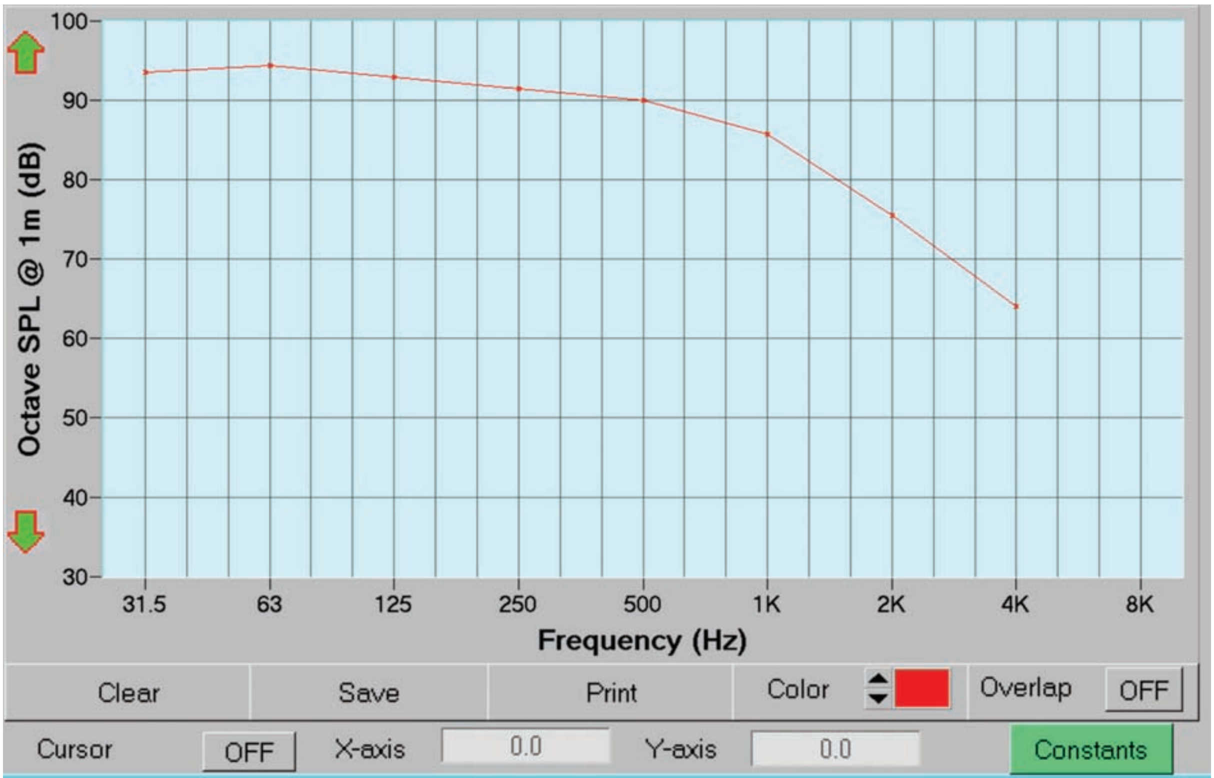


If you click on the green button, labelled “Constants”, the message at right appears. This means that the analysis assumes that the gas external to the pipe is air at atmospheric pressure and 20°C.

8.2.12 Pipe Flow Noise (valve noise source)

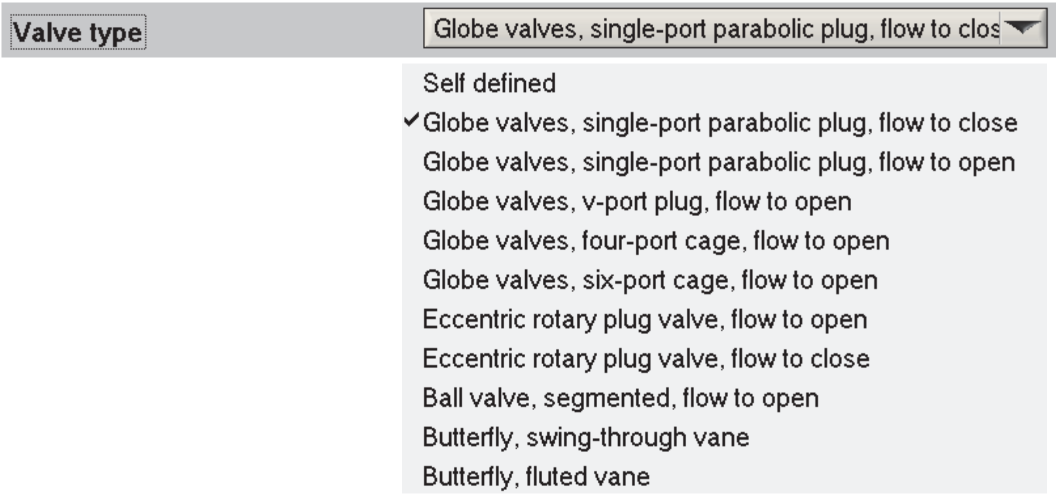
The internal sound power and sound pressure levels are calculated as for valve noise and the calculation for the radiated noise then follows the steps below.

1. Calculate the pipe ring frequency.
2. Calculate the TL in 1/3-octave bands using Equation (8) from 1994 version of the standard, IEC60534-8-4 or Eqs. (22) to (24) of the 2015 version of the same standard.
3. Calculate the external sound pressure level adjacent to the pipe wall in 1/3-octave bands by subtracting the band TL from the internal band sound pressure level.
4. Calculate the sound pressure level (in 1/3-octave bands) external to the pipe and 1 m from the pipe wall using Equation (10.90) in the 6th edition textbook modified for 1/3-octave band level calculation.
5. Calculate the externally radiated unweighted sound power level in 1/3-octave bands in the 6th edition textbook modified for1/3-octave band level calculation.
6. Calculate the octave band and overall unweighted and A-weighted external sound power levels and sound pressure levels at 1 m from the pipe wall using the 1/3-octave band levels calculated in item 3.

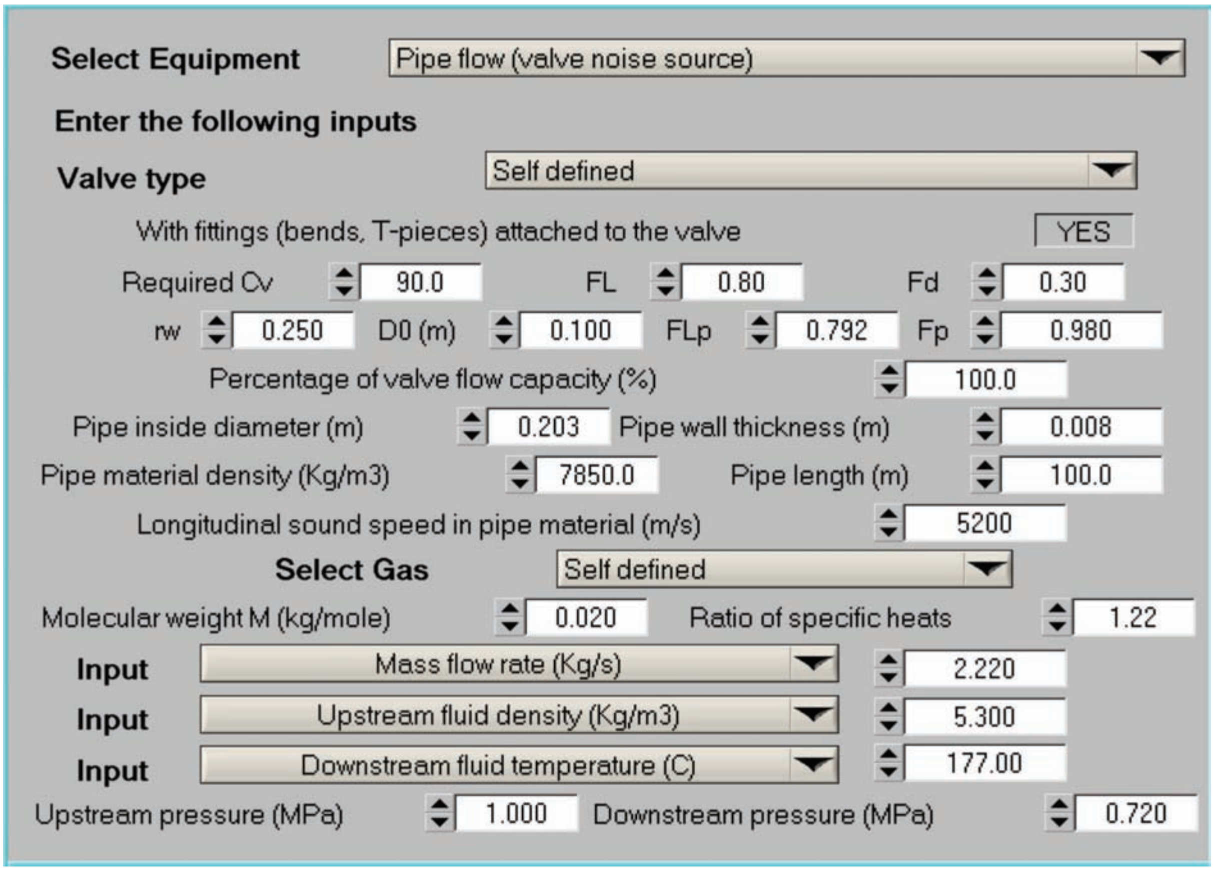


Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000
SPL @ 1m (dB)	93.6	94.4	92.9	91.5	90.1	85.7	75.5	64.0	0.0
SPL @ 1m (dBA)	54.2	68.2	76.8	82.9	86.9	85.7	76.7	65.0	-1.1

To use ENC, you must first choose the valve type as shown in the following figure.



The required input data are shown in the following figure.



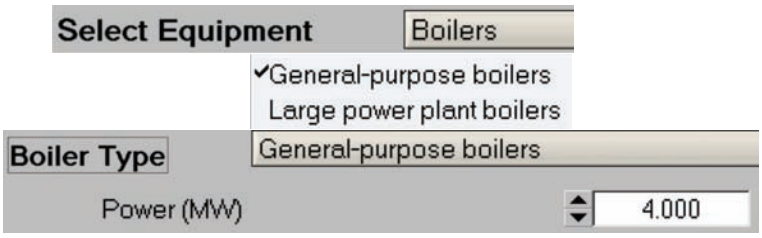
The output data are shown in the following two figures.

Outputs	Regime I	Downstream Mach Nr.	0.2
Jet diameter (m)	0.0118	Freq. of max. internal SPL, fp (Hz)	7618
Pipe ring freq., fr (Hz)	8149.7	Overall internal PWL (dB)	125.3
Power coefficient, η	6.13E-5	Overall ext. PWL (dBA)	118.5
Mach number, Mv or Mj	1.0	Overall internal SPL (dB)	146.8
Int. Coinci. freq., f0 (Hz)	2852.0	Overall SPL 1m (dBA)	90.2

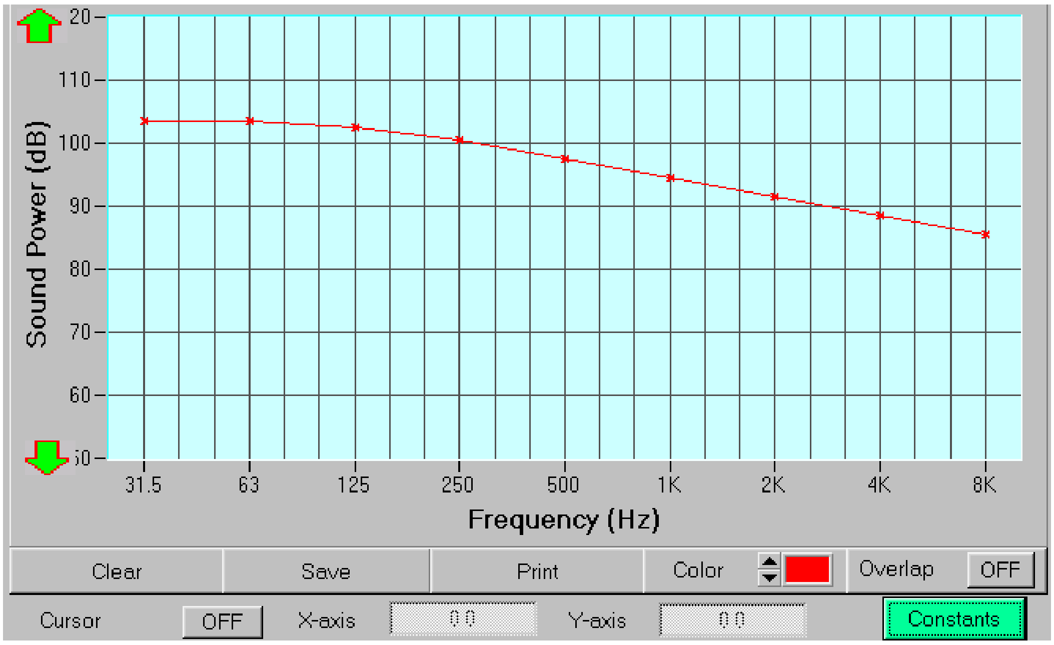
Freq. (Hz)	31.5	63	125	250	500	1000	2000	4000	8000	
Internal PWL (dB)	96.5	99.5	102.5	105.5	108.5	111.5	115.3	120.3	122.4	✔
External PWL (dB)	49.5	58.5	67.5	76.5	85.5	94.4	104.1	113.7	116.9	☐
Internal SPL (dB)	118.0	121.0	124.0	127.0	130.0	133.0	136.8	141.8	143.9	☐
SPL @ 1m (dB)	21.2	30.2	39.2	48.2	57.2	66.1	75.8	85.4	88.6	☐
Pipe wall TL (dB)	87.0	81.0	75.0	69.1	63.0	57.1	51.4	46.7	45.3	☐

As for all items discussed in this chapter, the quantity corresponding to the ticked box is plotted in the figure above the octave band table. However, in this case, 1/3-octave instead of octave band results are plotted so the 1/3-octave band numbers on the graph (which may be read using the cursor) do not necessarily agree with the octave band numbers in the table, as the octave band result in the table is the logarithmic sum of the values in the three 1/3-octave bands that make up the particular octave band. Click on the green arrows next to the graph to make the curve visible.

8.2.13 Boilers (6th edition textbook, pages 638–639)

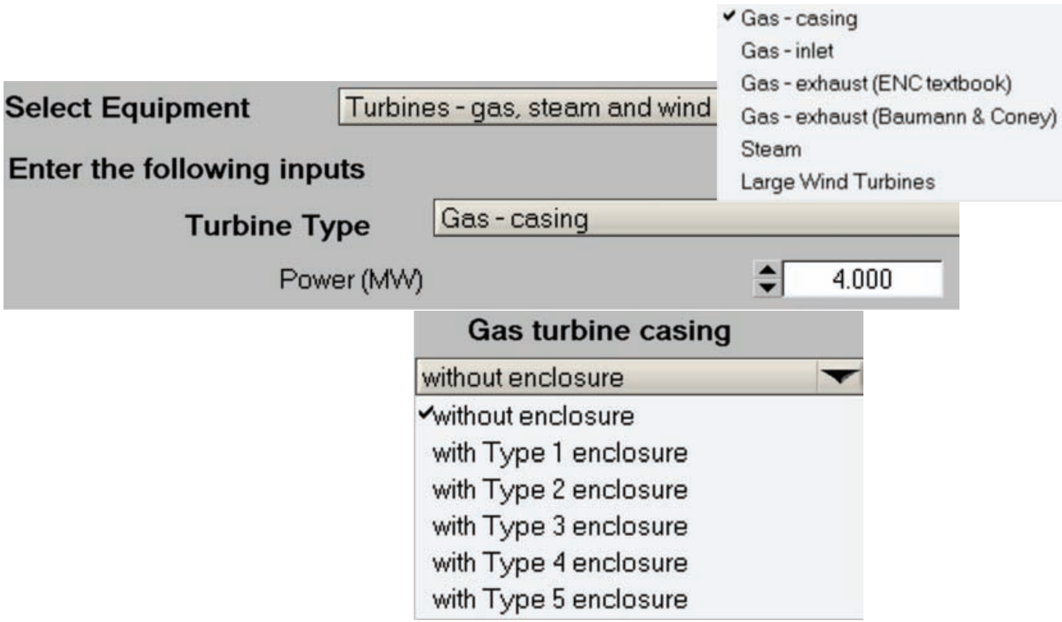


Boiler noise is calculated using Equation (10.94) for general-purpose boilers and Equation (10.95) for large power plant boilers. You need to choose the type of boiler (from the two buttons) and enter the boiler power in MW. ENC outputs the overall boiler sound power level and the octave band sound power levels calculated using Table 10.16 in the 6th edition textbook. The octave band levels are plotted on the graph shown in the following figure.



8.2.14 Turbines (Gas, Steam and Wind) (6th edition textbook, pages 639–640, 649–650)

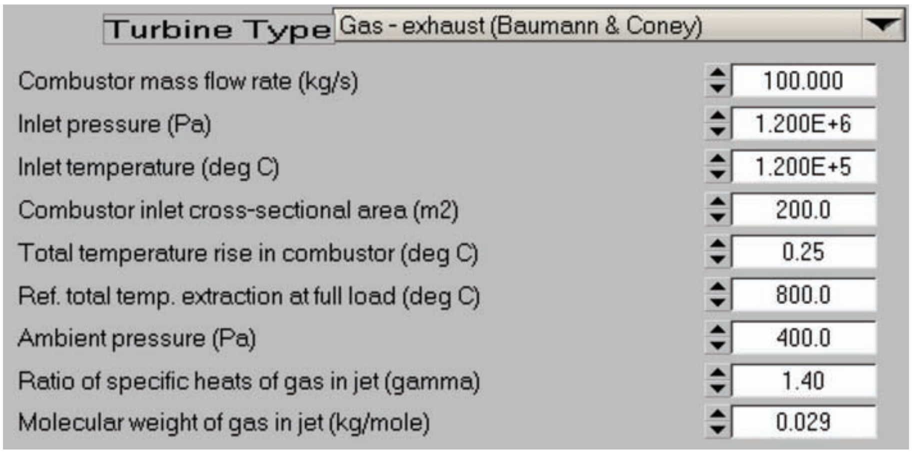
The turbine type and noise source are selected first (see figure below).



8.2.14.1 Gas and Steam Turbines

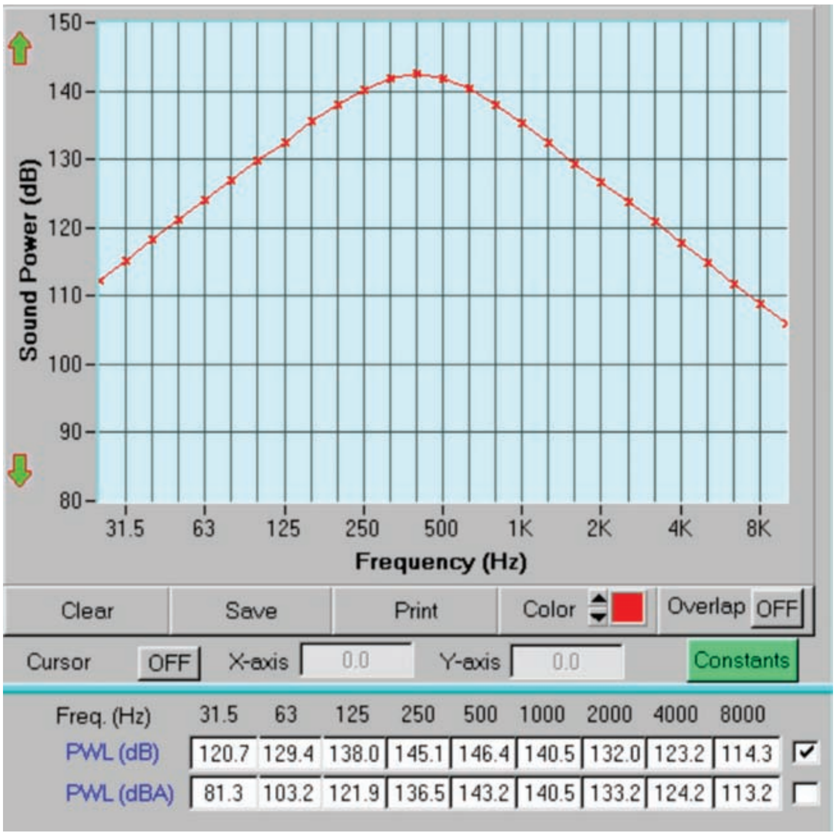
Gas turbine overall radiated sound power levels are calculated using Equations (10.96), (10.97) and (10.98) for noise radiated by the casing, inlet and exhaust (ENC textbook) respectively. For steam turbines, the total sound power level radiated by all parts is calculated using Equation (10.99) in the 6th edition textbook. The octave band sound power levels for both gas and steam turbines are calculated from the overall levels using Table 10.17. ENC outputs the overall turbine sound power level (in dB linear and dB(A)) and the octave band sound power levels calculated using Table 10.17, and allows for turbine casing enclosures (see above figure) when calculating casing sound power radiation, as in Table 10.18 in the 6th edition textbook. The octave band levels are plotted on the graph. Note that for the inlet and casing noise, the octave band levels do not add up to the overall level — in fact they add up to a larger number. This is because of the presence of intense tones for which the octave band containing them is not predictable. So a conservative approach has been to assume that they occur in all octave bands above 250 Hz and make the octave band corrections accordingly. The unfortunate result is that the octave band noise levels then add up to more than the overall level. However this is probably preferable to under predicting the noise in some octave bands.

An alternative method is available for calculating the sound power radiated by a gas turbine exhaust in 1/3-octave bands, octave bands and overall sound power level (un-weighted and A-weighted). This is the option labelled, “Gas – exhaust (Baumann & Coney)”, which is discussed in (Baumann and Coney, 2006). This method is more accurate that the method used in the option labelled “Gas – exhaust (ENC textbook)”, but it requires additional input data as illustrated in the following figure. It is necessary to use the constants popup page to obtain the last two items in the list on the GUI.

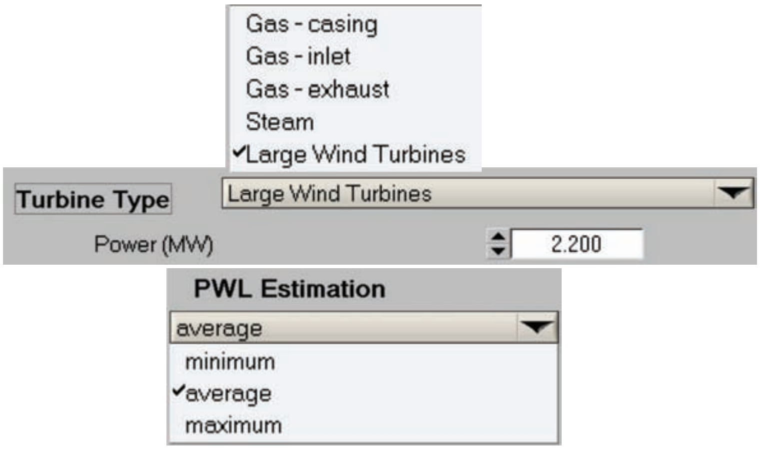


Most gas turbine exhausts point in the vertical direction, which means that sound levels in a horizontal direction from the exhaust may be lower than expected and this directivity effect may be calculated in ENC Module 6, “Ex. stack”. However, in downwind conditions, especially at low frequencies, sound levels in the far field of the exhaust may be greater than expected (Cazzolato et al., 2024).

A typical graph and Table of octave band sound power levels for a gas turbine exhaust calculated using the Baumann & Coney method are illustrated in the following figure.



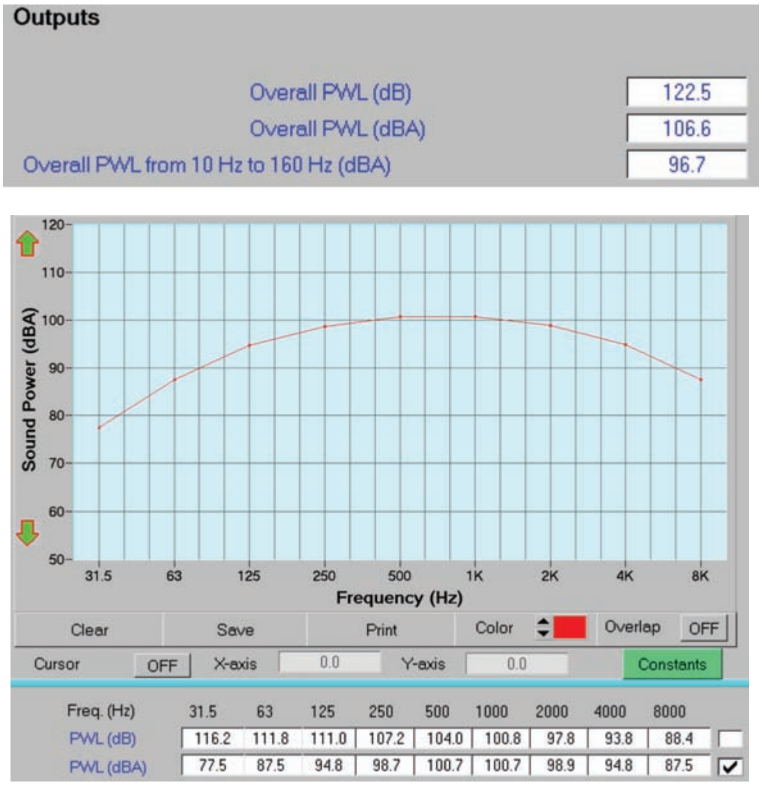
8.2.14.2 Wind Turbines



Wind turbine overall A-weighted sound power radiation levels can be calculated using corrected equations (10.118) and (10.119) in the textbook, for turbine powers greater than 200 kW. ENC also provides minima and maxima (see above figure) sound power levels, representing a range that describes a particular turbine type with a 95% confidence level.

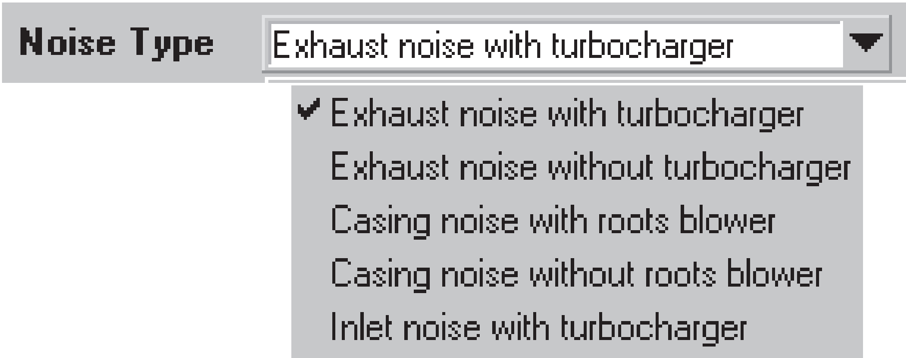
The range of values represented by the difference between maximum and minimum values are illustrated by error bars in Figure 10.6 in the textbook (which has since been updated according to Søndergaard (2013)).

The outputs provided by ENC in the left hand panel are shown in the following figure.



8.2.15 Diesel and Gas Driven Engines (6th edition textbook, pages 640–643)

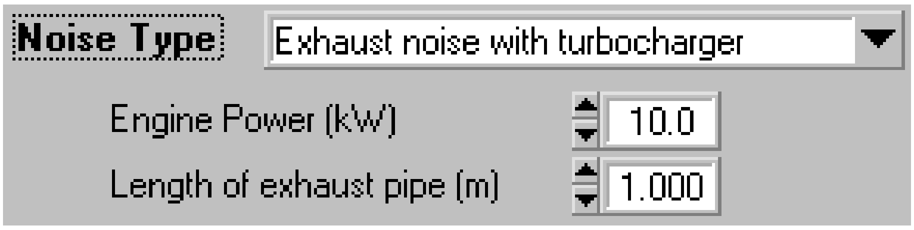
The noise radiated by this equipment is divided into three components: exhaust, casing and inlet. Each component is treated separately by ENC and the component of interest is selected from the “noise type” menu shown below.



For all noise types, the overall sound power levels are calculated by ENC as well as the octave band sound power levels. The latter are adjusted slightly so that they add up to the overall level (logarithmic addition) and are plotted on the graph.

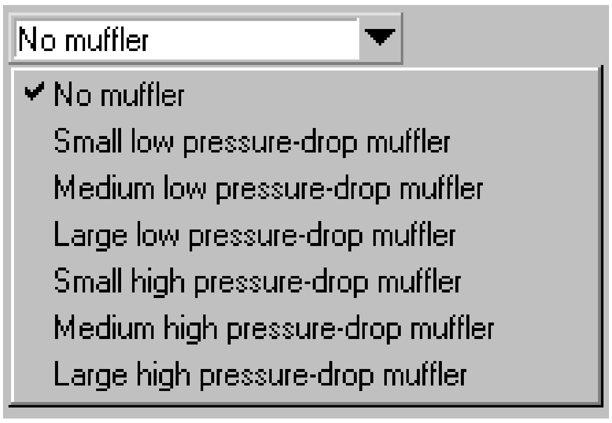
8.2.15.1 Exhaust Noise (6th edition textbook, page 641)

If the “ exhaust noise” option is chosen (with or without the turbocharger), the input data required are those shown below.



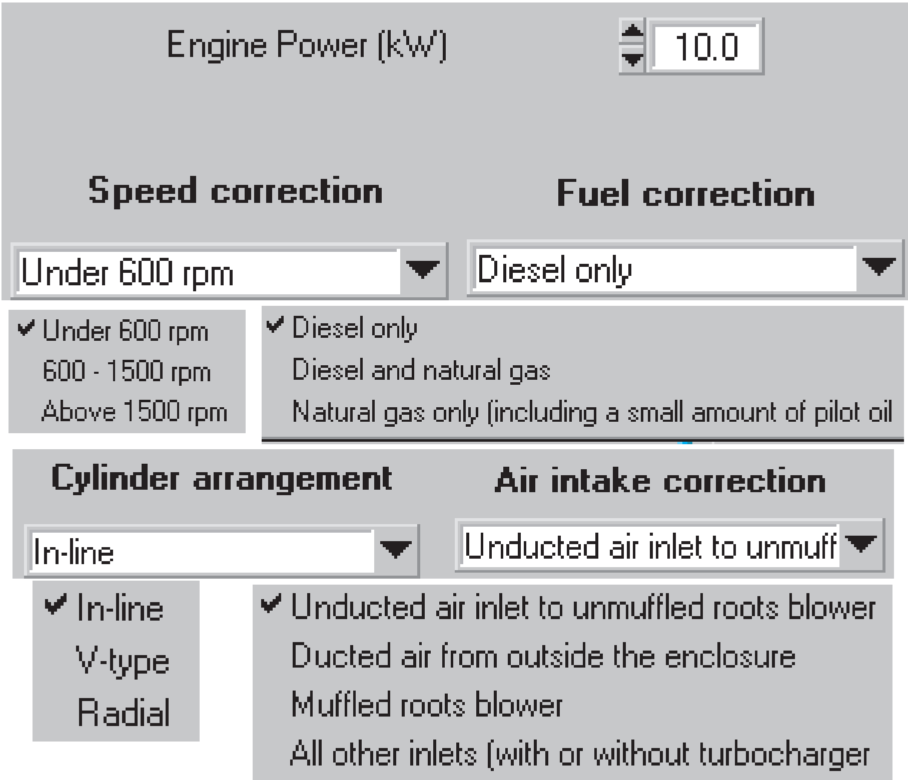
In addition, the type of muffler used can be specified using the menu illustrated at right.

The outputs generated by this panel are calculated using Equation (10.100) and Tables 10.19 and 10.20 in the 6th edition textbook.



8.2.15.2 Casing Noise (6th edition textbook, pages 641–642)

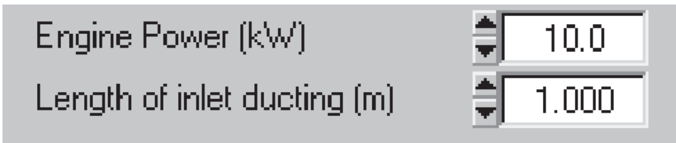
If the casing noise option (with or without the roots blower) is chosen, the required input data are shown below.



As can be seen you are provided with a selection for each of four input parameters. ENC uses Equation (10.101) and Tables 10.21 and 10.22 in the 6th edition textbook to do the calculations.

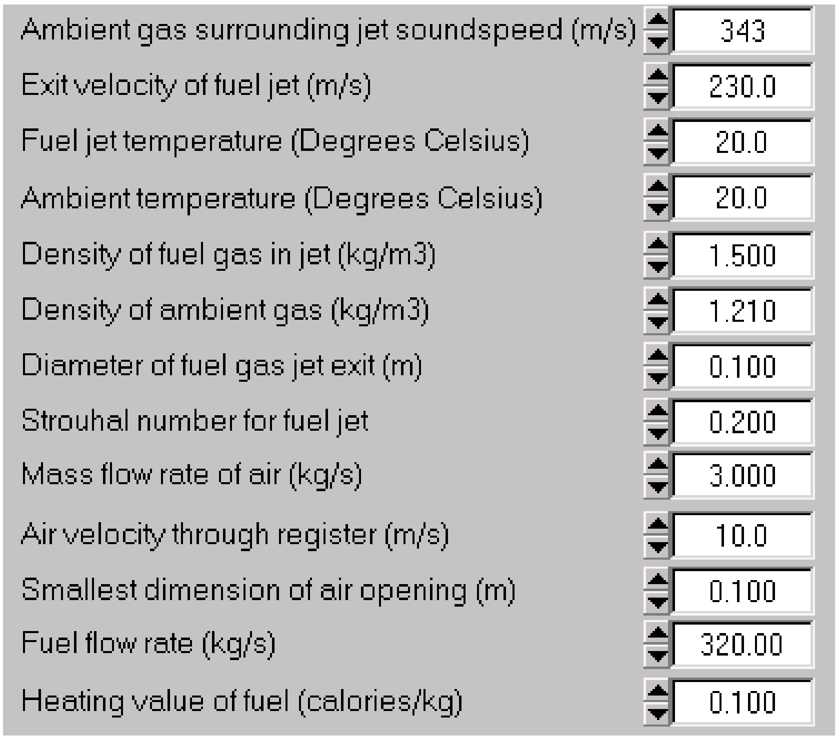
8.2.15.3 Inlet Noise (6th edition textbook, pages 642–643)

If the inlet noise option is chosen, the required input data are shown at right.



Equation (10.102) and Table 10.23 are used by ENC to provide the outputs.

8.2.16 Furnaces (pages 643–644 in the 6th edition textbook)



There are two types of furnace included in the equipment list. The first category includes oil burners and low pressure drop gas burners and the second category includes high pressure gas burners.

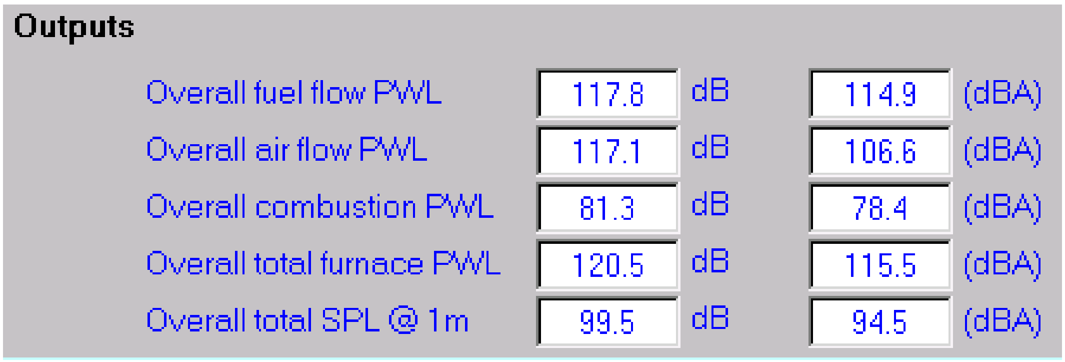
For the oil burner, the input data shown in the upper figure at right are needed.

For the low pressure gas burner, the input data shown in the lower figure at right are needed.

The sound power of the primary and secondary air in both cases is calculated using Equations (10.103) and Equation (10.104) in the 6th edition textbook. For the **o**il burner, fuel flow noise is negligible, whereas for the **l**ow pressure drop gas burner, (less than 100 kPa), the fuel flow noise is calculated using Equations (10.21)–(10.26) in the 6th edition textbook. The Strouhal number requested for the input applies to the fuel jet. The air jet Strouhal number is set at 1.0 whereas the fuel gas Strouhal number may be entered by the user and is usually set equal to 0.2 in the absence of better information. The density and temperature of the ambient gas refer to the gas that surrounds the jet but is not part of it (usually air). The density and temperature of the "gas in jet" refer to the fuel gas upstream of the nozzle exit. Octave band levels are calculated from the overall level by following the procedure described on page 644 of the 6th edition textbook and then adjusted (same number of dB per octave band) so that they add up to the overall level calculated using Equation (1.98), page 36 in the 6th edition textbook.

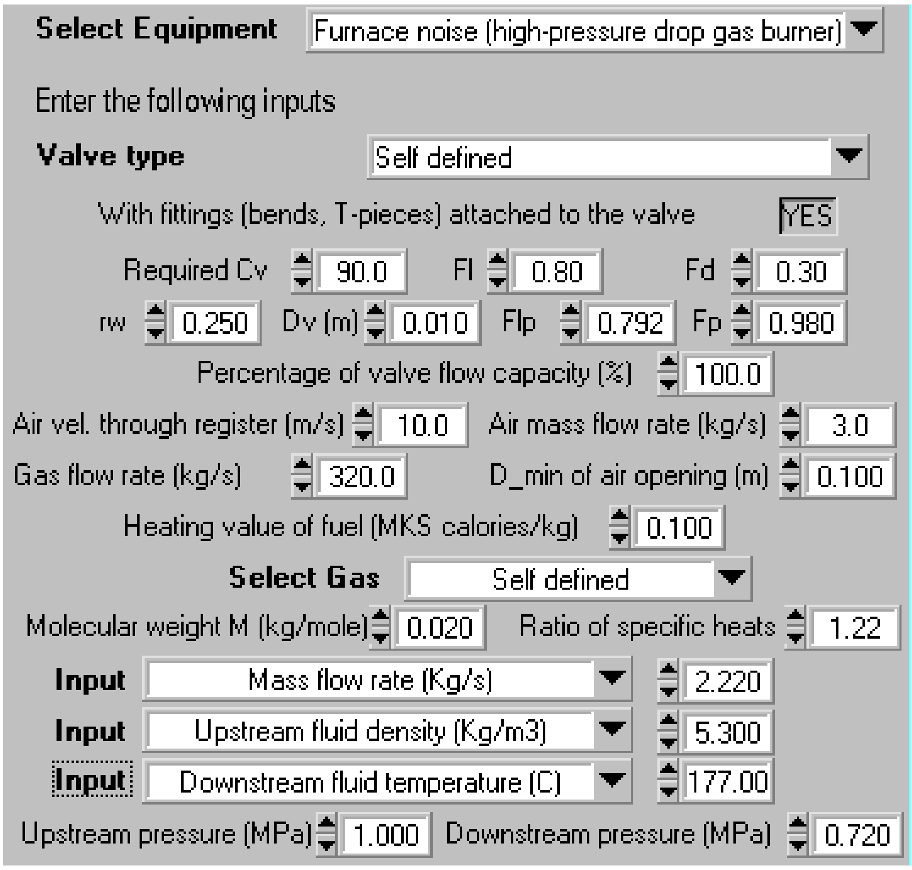
The sound power of combustion noise is calculated using Equation (10.106) in the 6th edition textbook. The octave band values are calculated as described on page 643 of the 6th edition textbook.

ENC outputs the overall sound power levels (both linear and dBA) for air flow noise, fuel flow noise and combustion noise as well as the overall levels arising from all sources combined (see following figure).

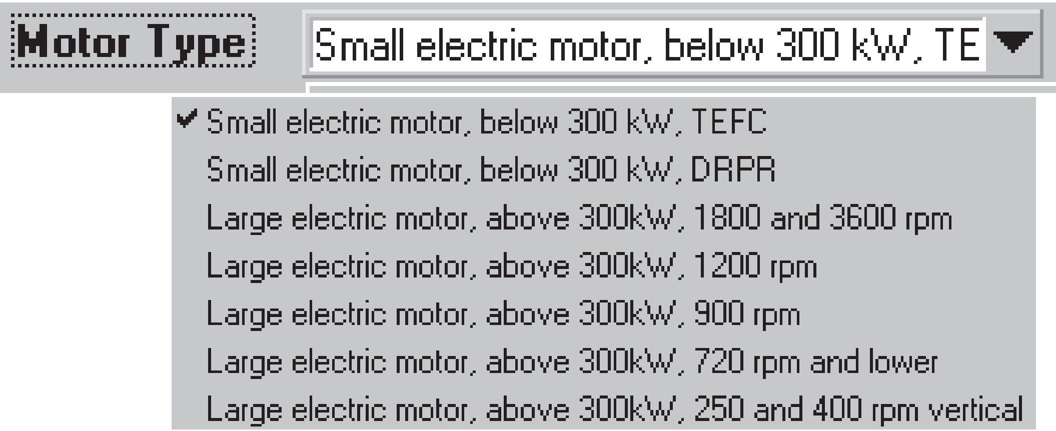


Octave band levels for each case except the last case (SPL at 1m) are provided in a table below the graph. The spectrum shape for the SPL at 1m is the same as the overall PWL and the levels at all frequencies are 9 dB lower for the SPL at 1 m.

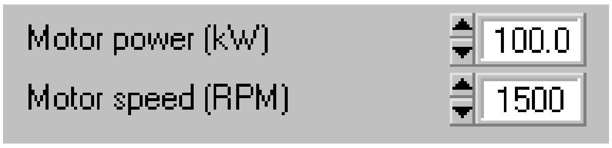
For **h**igh pressure drop gas burners, the calculations are the same as above, except for the fuel flow noise which must be calculated in the same way as for valve noise (using the IEC standard procedure). This is why there are many more parameters to enter than for the low pressure drop fuel flow (see following figure). You should refer to the discussion on valve noise for explanations of the parameters. The outputs are the same as for the low pressure drop burners.



8.2.17 Electric Motors (6th edition textbook, pages 644–645)



First of all you need to select the type of electric motor from the menu shown above. In addition, the motor power and speed needs to be entered (see figure at right).

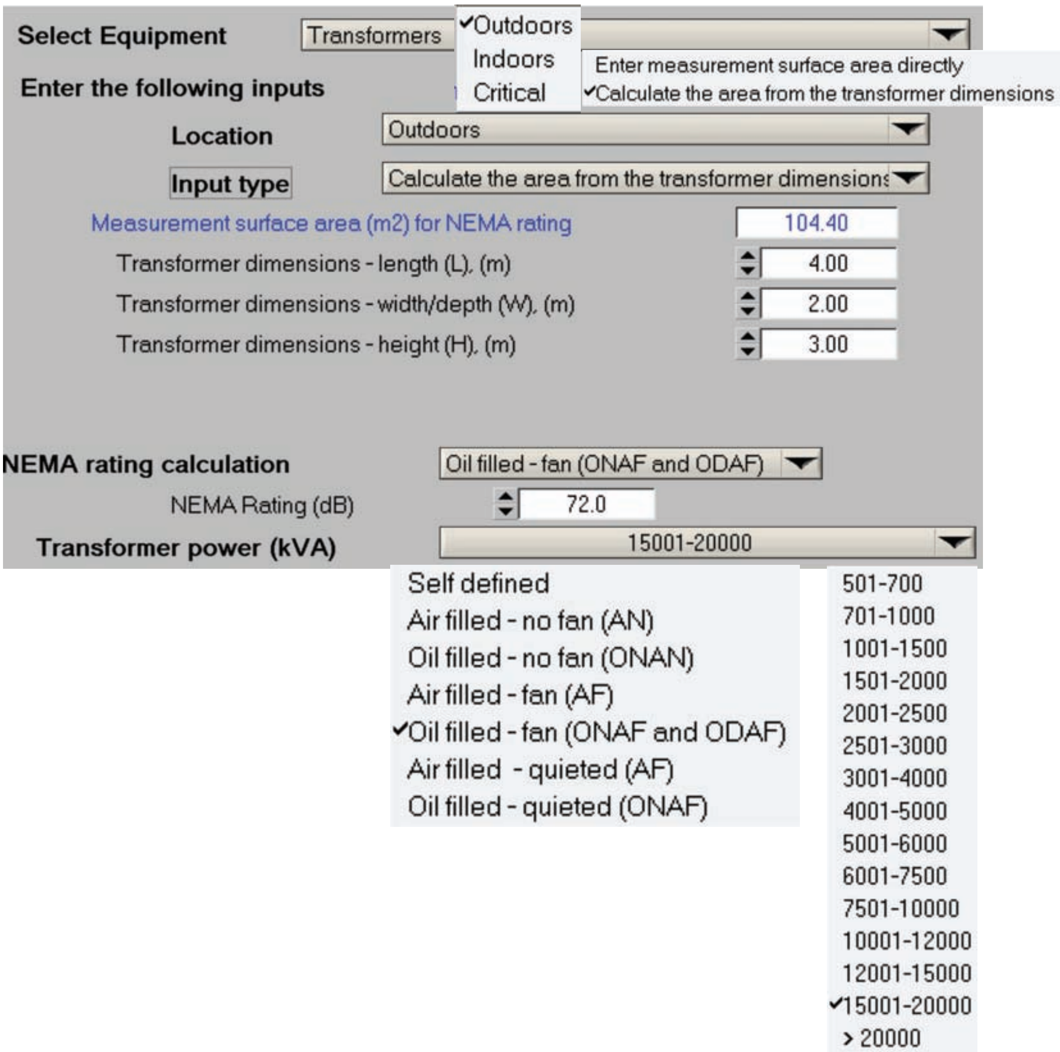


ENC uses Equations (10.107) & (10.108) and Tables 10.24 & 10.25 in the 6th edition textbook to calculate the sound pressure level at 1 m (overall and in octave bands). The octave band sound pressure levels are adjusted slightly so that they add up to the overall level (Equations (10.107) and (10.108)) and they are also plotted on the graph. Note that ENC includes the quantity, $10\log_{10}[\rho c/400]$, on the right hand side of Equations (10.107) and (10.108).

8.2.18 Generators (6th edition textbook, page 645)

For this equipment, only two input data items are needed (see figure at right). ENC uses Equation (10.109) and Table 10.26 to calculate the overall and octave band sound power levels. The octave band levels are plotted on the graph.

8.2.19 Transformers (6th edition textbook, pages 646–649)



First select the intended transformer location (outdoors, indoors or critical – see above figure). The location choice results in different corrections for obtaining the octave band sound power levels from the overall A-weighted sound power level.

Next, select whether the area of the measurement surface area used to calculate the NEMA rating is to be calculated from transformer dimensions (length, width and height) or if the measurement surface area is to be entered directly.

Next, select the type of transformer for calculating the maximum acceptable NEMA rating (A-weighted overall audible sound level). In this menu, "AN" means air cooled by natural convection for an air-filled transformer, AF means air cooled by fan-forced convection for an air-filled transformer, "ONAN" means oil cooling by natural convection and radiation and air cooling by natural convection, ONAF means oil cooling by natural convection and radiation and air cooling by fan-forced convection, "ODAF" means directed oil flow for cooling and air cooling by fan-forced convection and "OFAF" means forced (via a pump) oil flow for cooling and air cooling by fan-forced convection. OFAF transformers have similar maximum acceptable NEMA ratings to ONAF and ODAF transformers.

Note that air filled transformer powers do not exceed 1000 kVA and oil filled transformers usually have powers greater than 500 kVA.

If at all possible, you should use the "user defined" option for the NEMA rating and then enter the NEMA rating supplied by the transformer manufacturer. In this case, care must be taken to ensure that the measurement surface area entered above is the same as the one used to obtain the NEMA rating.

If you select the option of a transformer power greater than 20000 kVA, then a box will appear where you can enter the actual power in kVA (see figure below).

This is the maximum acceptable NEMA value so in some cases a lower value may be available from the transformer manufacturer.

Next select the area, S (m^2), of the measurement surface (different to the area used in ENC version 5.3 and earlier versions). The measurement surface area is the area of the measurement surface used to obtain the NEMA A-weighted audible sound level rating, N_R. This is typically a surface located 2 m from a horizontal contour made by a tight string placed around the transformer tank and touching the tank or its protrusions in various places. For transformers with a tank height, h, less than 1.2 m, the contour height is half the tank height above the ground. For transformers with a tank height, h, greater than 1.2 m, two measurement contours are used, one at a height of 1/3 of the tank height and one at a height of 2/3 of the tank height. The area, S, to be used in ENC is given by $S = 1.25\ell_m h$ m where ℓ_m is the length of the measurement contour and the top surface area is taken into account by the factor of 1.25. the length, ℓ_m, may be approximated as $\ell_m = 2L + 2W + 16$, where L is the length of the transformer tank and W is its width.

ENC then uses the following equation to calculate the un-weighted (or linear) octave band sound power levels, L_W, which are added together logarithmically to obtain the overall un-weighted as well as the A-weighted sound power level. Un-weighted or A-weighted sound power levels are plotted on the graph.

$$L_W = N_R + 10\log_{10} S + C(f)$$

where f is the octave band centre frequency and values for $C(f)$ are provided in the following table.

Table 8.2 Values of the correction factor, $C(f)$, for transformer noise

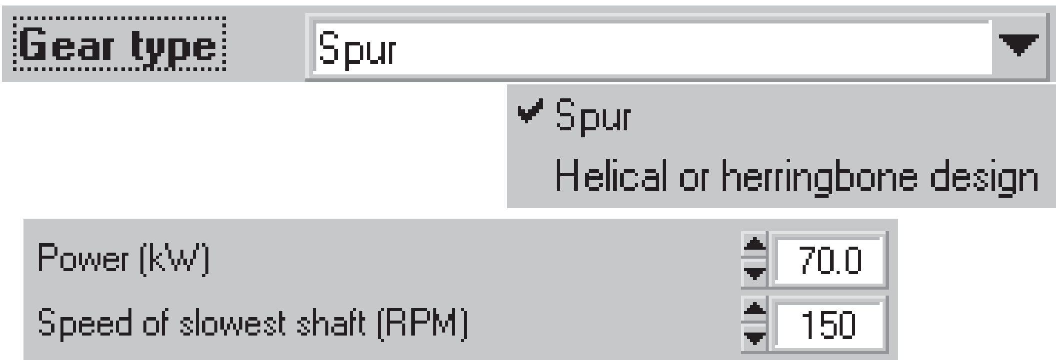
Octave band centre frequency (Hz)	Octave band corrections (dB)		
	Location 1[a]	Location 2[b]	Location 3[c]
31.5	−3.4	−3.4	−3.4
63	2.6	5.6	5.6
125	4.6	10.6	10.6
250	−0.4	5.6	9.6
500	−0.4	5.6	9.6
1000	−6.4	−3.4	3.6
2000	−11.4	−11.4	−1.4
4000	−16.4	−16.4	−6.4
8000	−23.4	−23.4	−13.4

[a]Outdoors, or indoors in a large mechanical room with a large amount of mechanical equipment.

[b]Indoors in small rooms, or large rooms with only a small amount of other equipment.

[c]Any critical location where a problem would result if the transformer should become noisy above its NEMA rating, following installation.

8.2.20 Gears (6th edition textbook, page 646)



First you need to select the type of gear mesh (only two buttons) and then specify the power being transmitted and the rpm of the slowest wheel in the mesh (see figure above). ENC then uses Equation (10.110) in the 6th edition textbook and the procedure explained in the following lines in the 6th edition textbook to calculate the octave band sound pressure levels at 1 m from the gearbox and these levels are also plotted on the graph. Note that ENC includes the quantity $10\log_{10}[\rho c/400]$ on the right hand side of Equation (10.110).

8.3 Transportation Noise (6th edition textbook, pages 650–682)

ENC calculates noise due to road and rail traffic. However, calculation of aircraft noise is a very complex procedure and ENC does not calculate any aircraft noise. Specialised software should be used for this.

Traffic noise is calculated using 2 models. The first is CoRTN, developed in the UK by the Department of Transport and the second is TNM, developed in the USA by the Federal Highway Administration (FHWA). Train noise is calculated using the UK model developed by the Department of Transport.

8.3.1 Road Traffic Noise — EU CNOSSOS Model (6th edition textbook, pages 650–662)

This window calculates the sound power of road traffic noise, where the source is deemed to be located 0.5 m above the road beneath the centre of a particular vehicle and in the centre of the traffic lane. Five different source types are considered as listed below.

1. Light (passenger cars, caravans, trailers, delivery vans $\leq$ 3.5 metric tons).
2. Medium-heavy (buses with 2 axles, mini-buses, motor-homes, delivery vans $\geq$ 3.5 metric tons).
3. Heavy (buses with 3 or more axles, semi-trailers).

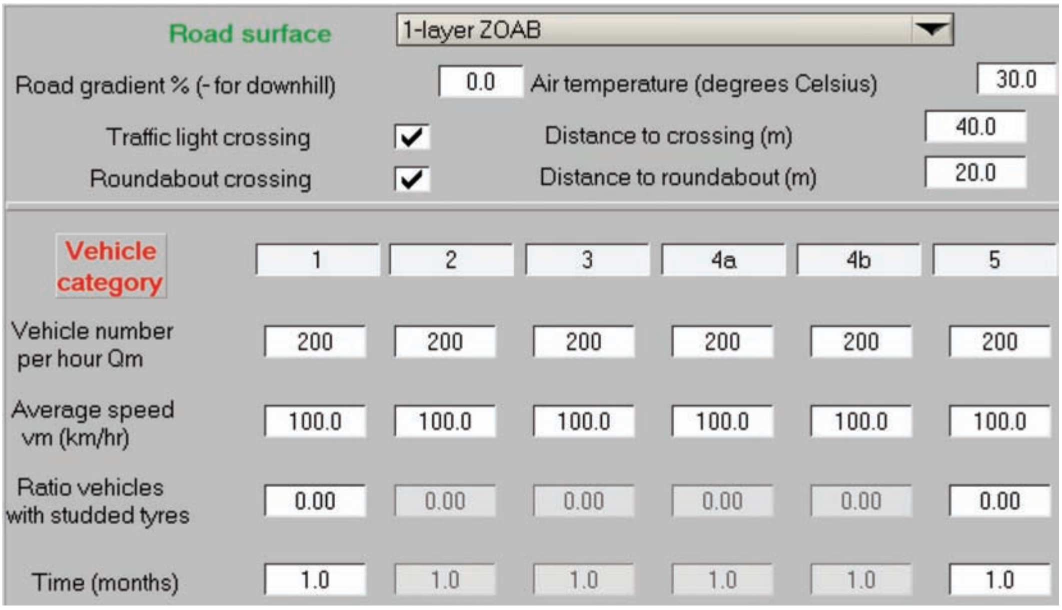
4a. Powered two-wheelers (mopeds, tricycles $<$ 50 cc).

4b. Powered two-wheelers (motorcycles, tricycles $>$ 50 cc).

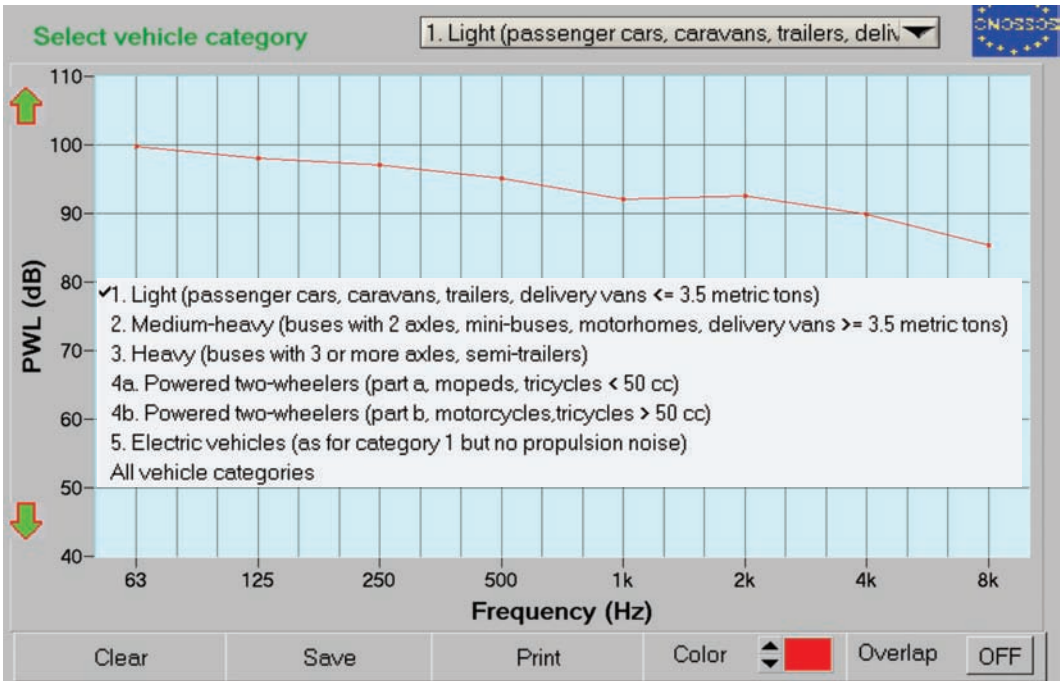
5. Electric vehicles

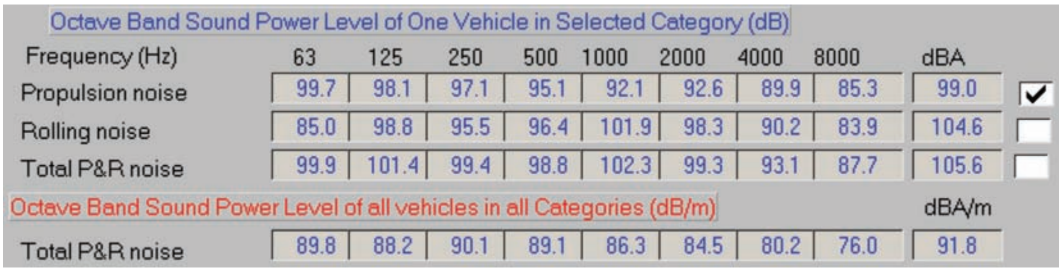
The source is then treated as an incoherent line source and the radiated sound power level per metre is calculated using Equation (10.120) in the textbook. ENC propagation models in Module 3 may then be used to calculate environmental noise levels. The first term on the RHS of Equation (10.120) in the textbook is made up of propulsion noise and rolling noise components, each of which is calculated by ENC from the input data.

Various road parameters and vehicle parameters affect the generated sound power and it is up to the user to enter parameters such as vehicle speed and road surface type as illustrated in the following figure. All of these parameters are discussed in the 6th edition textbook.



The output includes the octave band and overall A-weighted sound power of one vehicle in the selected vehicle category (1, 2, 3, 4a, 4b and 5). The vehicle category is selected from the menu on the top right of the page as shown on the following figure. The data that is plotted corresponds to the selected vehicle category and also the data corresponding to the box that is ticked in the figure following the figure with the graph.



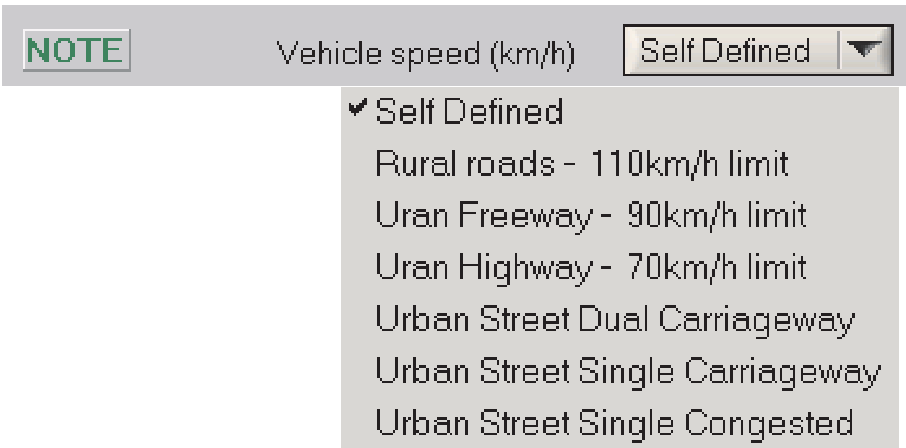


The data in the first 3 rows in the previous figure correspond to the sound power generated by a single vehicle in the category selected above the graph. The bottom row of numbers correspond to the total sound power per metre of road length radiated by a line source consisting of contributions from all categories of vehicles. The sound power radiated by a length of road, L metres long is obtained by adding $10 \log_{10} L$ to the overall A-weighted sound power level and the the octave band levels as well.

Line source data can be used in Module 3 to calculate sound pressure levels in community locations near highways.

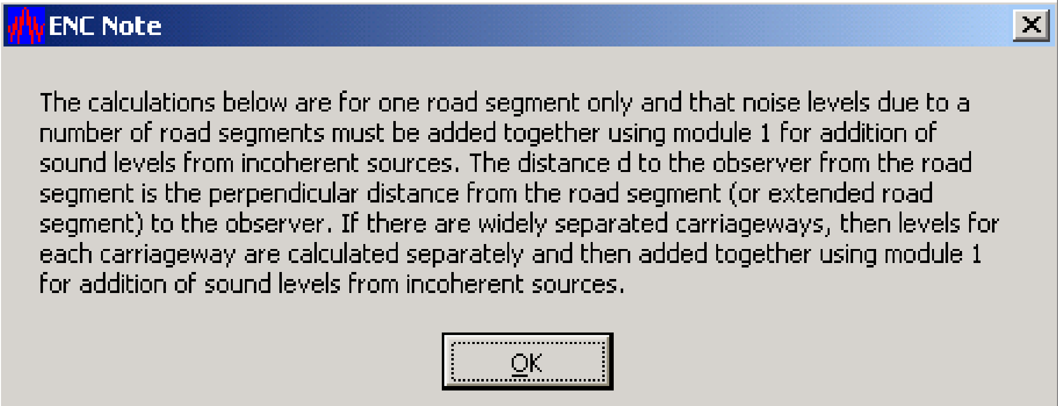
8.3.2 Traffic noise — CoRTN (6th edition textbook, pages 656–660)

This window calculates L_{10} noise levels averaged over 1 hour intervals and over 18 hours, using the UK Dept. of Transport CoRTN model. The noise levels are calculated using a base level proportional to traffic volume with corrections added to account for the percentage of heavy vehicles, the road gradient, the type and condition of the road surface, the ground type, the distance to the observer, the angle of view and the presence of any barriers. In the 6th edition textbook, the corrections due to ground and distance are lumped together, but in ENC they are treated separately as they are in the published CoRTN model. Note that the road must be divided into segments and the sound levels at the observer calculated for each segment using this ENC window. The overall noise level at any particular observer location is then found by adding the individual contributions together using module 1 of ENC.

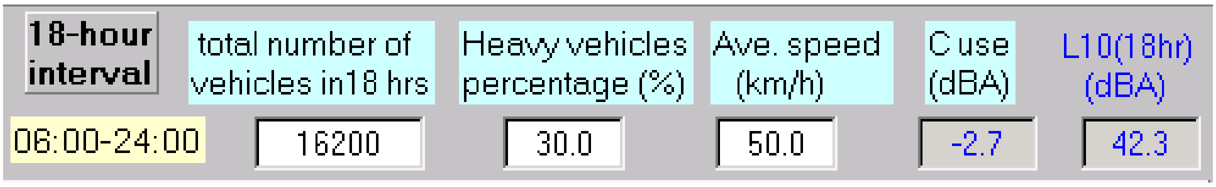


To begin, decide on whether you will be defining the average vehicle speed or whether you would prefer to enter the road type and then have ENC determine the average vehicle speed according to the CoRTN model (see figure above).

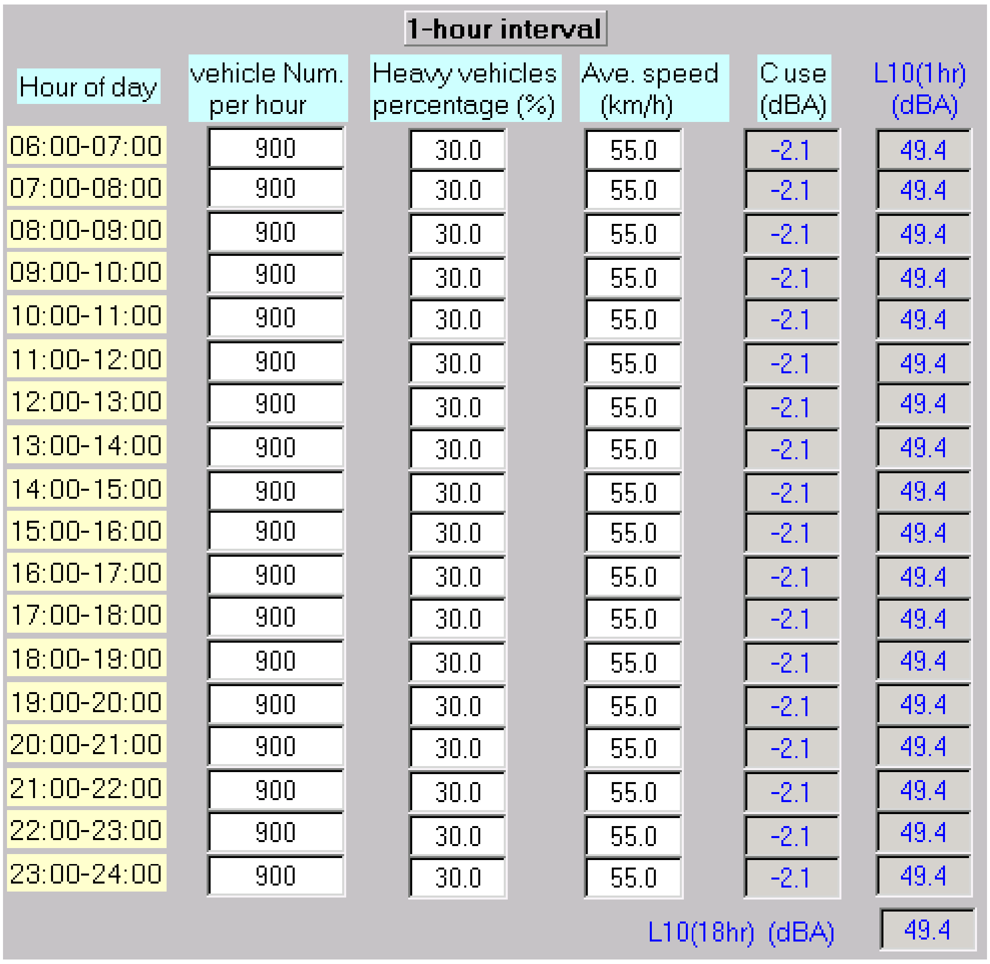
If you left click on "NOTE", the explanatory note below will appear.



Next, decide on whether single hour or 18-hour L_{10} noise levels need to be calculated. Enter the total number of vehicles if you want to calculate the 18-hour L_{10} noise levels (see figure below).



Enter the number of vehicles per hour for each hourly interval if you want to calculate the single hourly L_{10} noise levels (see following figure).



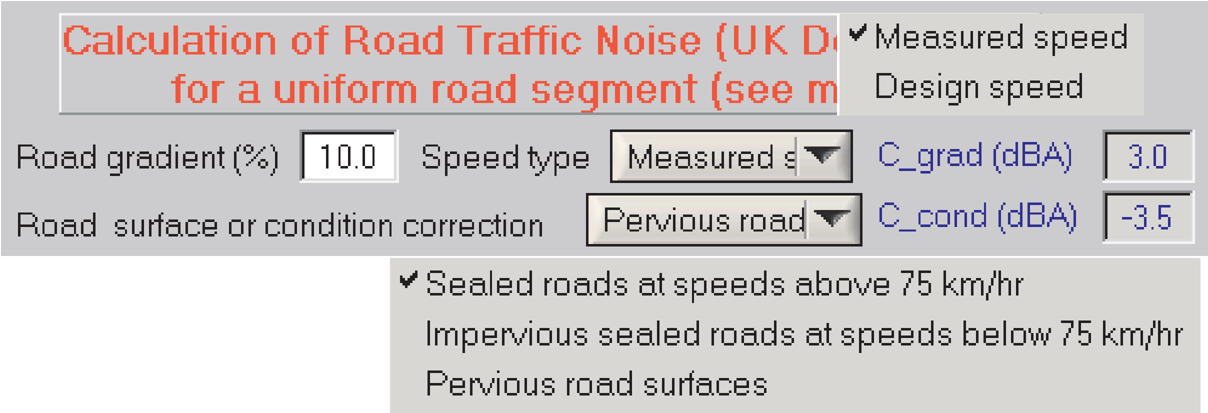
1-hour interval

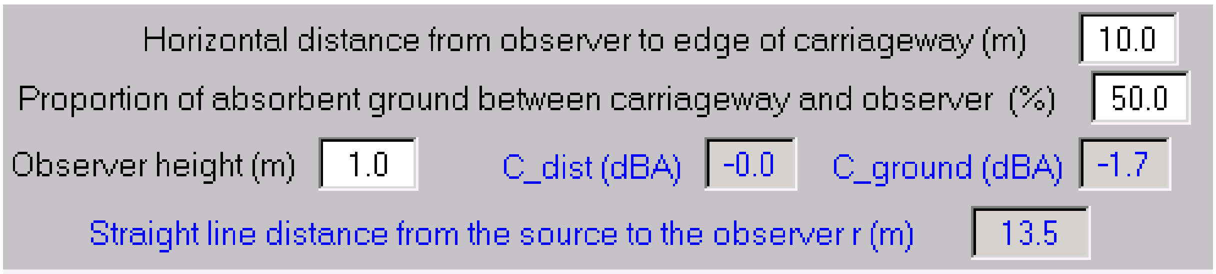
Hour of day	vehicle Num. per hour	Heavy vehicles percentage (%)	Ave. speed (km/h)	C use (dBA)	L10(1hr) (dBA)
06:00-07:00	900	30.0	55.0	-2.1	49.4
07:00-08:00	900	30.0	55.0	-2.1	49.4
08:00-09:00	900	30.0	55.0	-2.1	49.4
09:00-10:00	900	30.0	55.0	-2.1	49.4
10:00-11:00	900	30.0	55.0	-2.1	49.4
11:00-12:00	900	30.0	55.0	-2.1	49.4
12:00-13:00	900	30.0	55.0	-2.1	49.4
13:00-14:00	900	30.0	55.0	-2.1	49.4
14:00-15:00	900	30.0	55.0	-2.1	49.4
15:00-16:00	900	30.0	55.0	-2.1	49.4
16:00-17:00	900	30.0	55.0	-2.1	49.4
17:00-18:00	900	30.0	55.0	-2.1	49.4
18:00-19:00	900	30.0	55.0	-2.1	49.4
19:00-20:00	900	30.0	55.0	-2.1	49.4
20:00-21:00	900	30.0	55.0	-2.1	49.4
21:00-22:00	900	30.0	55.0	-2.1	49.4
22:00-23:00	900	30.0	55.0	-2.1	49.4
23:00-24:00	900	30.0	55.0	-2.1	49.4
				L10(18hr) (dBA)	49.4

Enter the percentage of heavy vehicles in the locations shown in the preceding two figures. ENC uses this to calculate C_{use}. Note that the 18-hour L_{10} noise level can also be calculated from the single hourly L_{10} noise levels (see bottom of preceding figure). The calculation is done by taking the logarithmic average of the single hourly values and for the same number of vehicles is slightly different to the 18-hour value calculated in the upper figure.

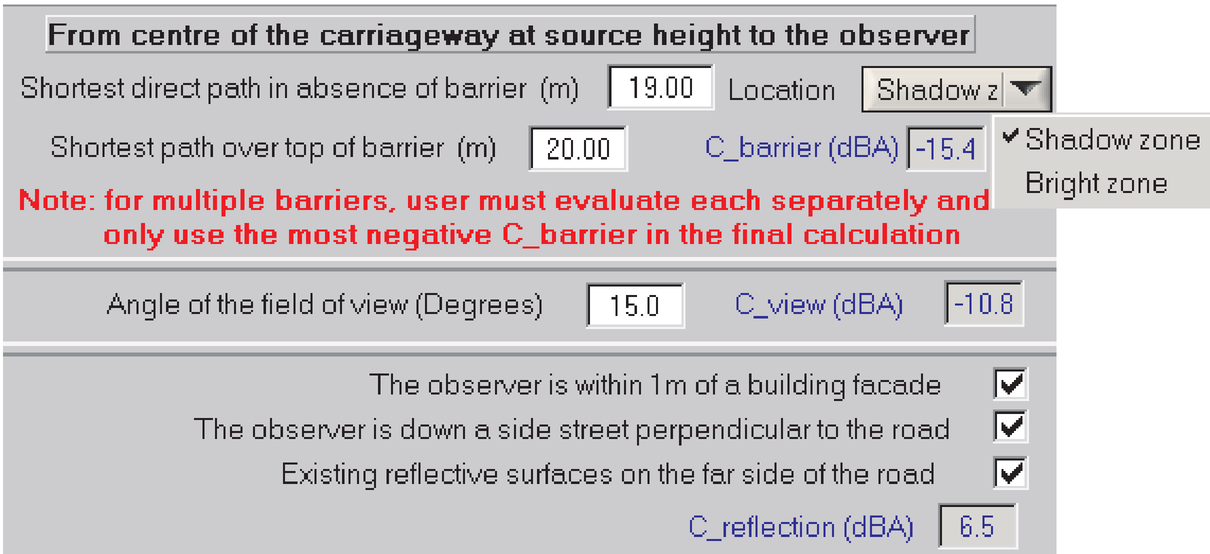
The A-weighted L_{10} noise levels are calculated using Equations (10.135) and (10.136) in the 6$^{\text{th}}$ edition textbook. These equations use the data in the previous tables plus some additional correction factors to account for the effects of road gradient, C_{grad}, the type and condition of the road surface, C_{cond} , the ground type, C_{ground} , the distance to the observer, C_{dist} , the angle of view, C_{view}, the presence of any barriers, C_{barrier} , and reflection effects, $C_{\text{reflection}}$. The calculation of each of these is done as shown on the following four figures.

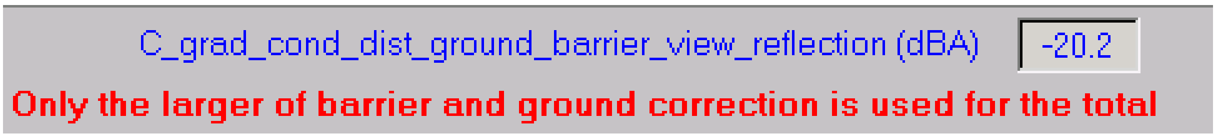
In the panel illustrated in the following figure, the measured speed would correspond to the "self defined" selection for the panels on page 323. Following the approach of CoRTN, which is slightly different to the 6$^{\text{th}}$ edition textbook, the distance correction is separated from the ground correction (see second figure on the next page). Note that the distance entered by the user is the perpendicular distance from the observer to the road segment (or extended road segment).





Corrections for barriers, field of view subtended by the road segment to the observer and reflections are calculated using the panels illustrated in the following two figures.



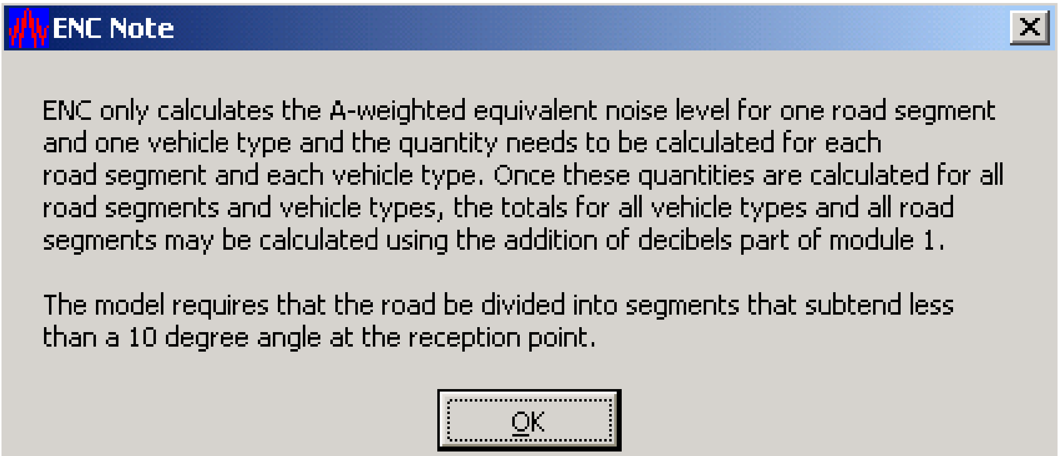


The total correction due to all the effects mentioned above is calculated by arithmetically summing them all, except that only the larger of the ground correction and barrier correction is used.

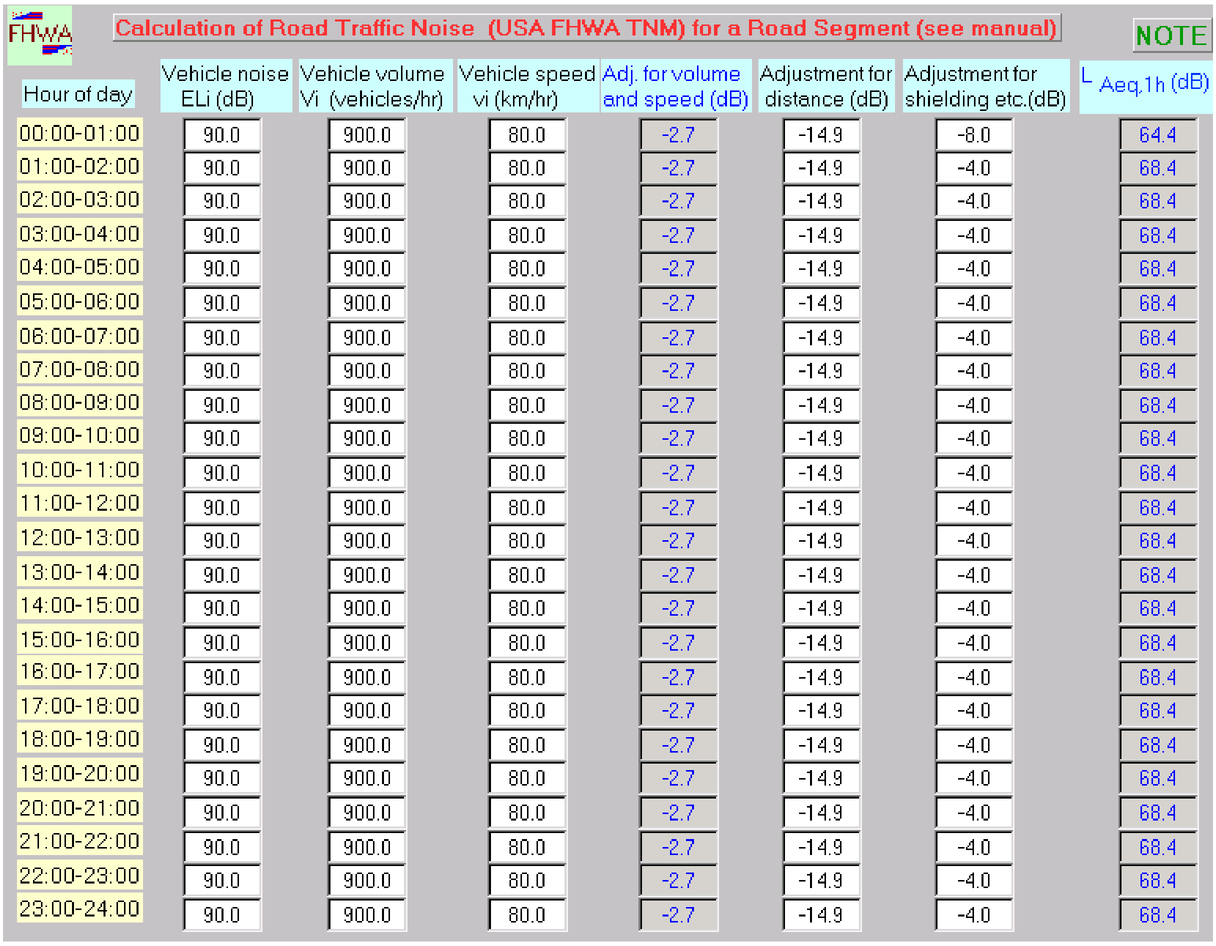
If there are widely separated carriageways, the levels for each carriageway are calculated separately and then added together using module 1.

8.3.3 Road Traffic Noise — FHWA-TNM Model (6th edition textbook, pages 660–661)

This window calculates road traffic noise according to the USA FHWA Traffic Noise Model (TNM). The user must enter the vehicle emission level, which is the maximum sound pressure level measured during a pass-by test at the nominated speed (also entered by the user) at a perpendicular distance of 15 m from the centre line of the traffic lane (or centre of the vehicle). There is a large data base of emission levels for a large number of vehicle types and operating conditions available from FHWA. Note that as for CoRTN, the noise level must be calculated for each lane of traffic and each vehicle type and the results combined logarithmically using module 1. The road must also be divided into segments that subtend no more than 10 degrees at the observer. Please click on "NOTE" near the top of the screen and read it before starting (see following figure).



The required input data are shown in black font in the following figure. After entering the vehicle noise emission level for the particular vehicle type being considered, enter the number of vehicles of this type for each hourly interval listed in the following table. Then enter the vehicle average speed for each hourly interval (many values will not vary from one hour to the next). The adjustment for shielding and ground effects as described by the FHWA model is complex and not followed explicitly by ENC. Instead, the user may use module 3 for these calculations and enter the overall ground and barrier correction in the column labelled "adjustment for shielding etc."

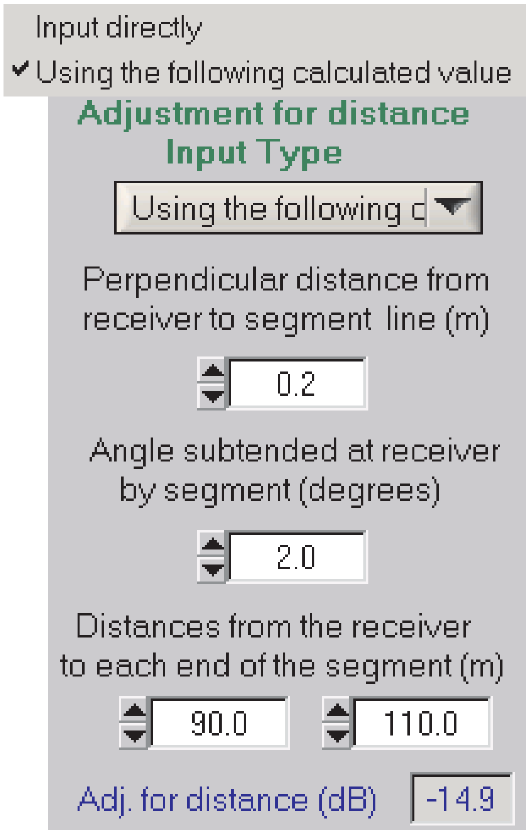


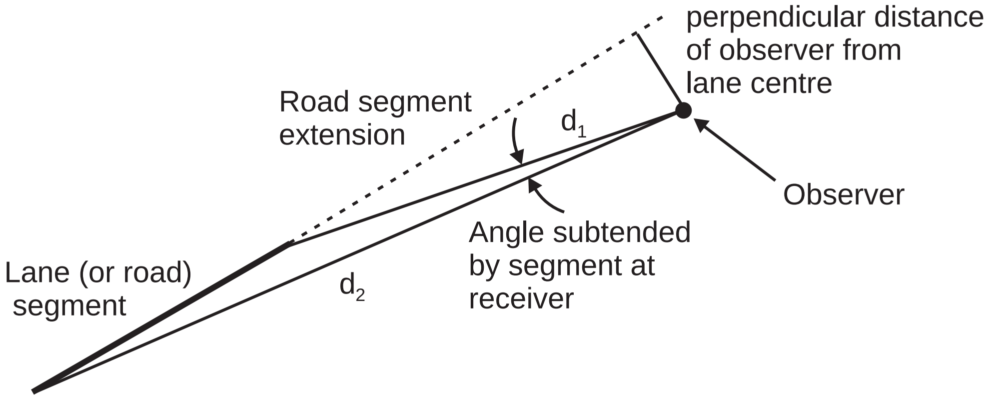
Calculation of Road Traffic Noise (USA FHWA TNM) for a Road Segment (see manual)

Hour of day	Vehicle noise ELi (dB)	Vehicle volume Vi (vehicles/hr)	Vehicle speed vi (km/hr)	Adj. for volume and speed (dB)	Adjustment for distance (dB)	Adjustment for shielding etc.(dB)	L Aeq,1h (dB)
00:00-01:00	90.0	900.0	80.0	-2.7	-14.9	-8.0	64.4
01:00-02:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
02:00-03:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
03:00-04:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
04:00-05:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
05:00-06:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
06:00-07:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
07:00-08:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
08:00-09:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
09:00-10:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
10:00-11:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
11:00-12:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
12:00-13:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
13:00-14:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
14:00-15:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
15:00-16:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
16:00-17:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
17:00-18:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
18:00-19:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
19:00-20:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
20:00-21:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
21:00-22:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
22:00-23:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4
23:00-24:00	90.0	900.0	80.0	-2.7	-14.9	-4.0	68.4

The adjustment for distance can be entered directly or calculated using the panel on the right hand side of the window. If this is the case, then the "input directly option must be selected. If the other option, "use the following calculated value" is selected, then the value, Adj. for distance (dB) calculated in the panel at right is automatically entered by ENC into the column in the left panel labelled, "Adjustment for distance". Note that the lower half of the panel at right is greyed out unless the perpendicular distance of the observer is less than 0.3 m and the subtended angle is less than 20 degrees.

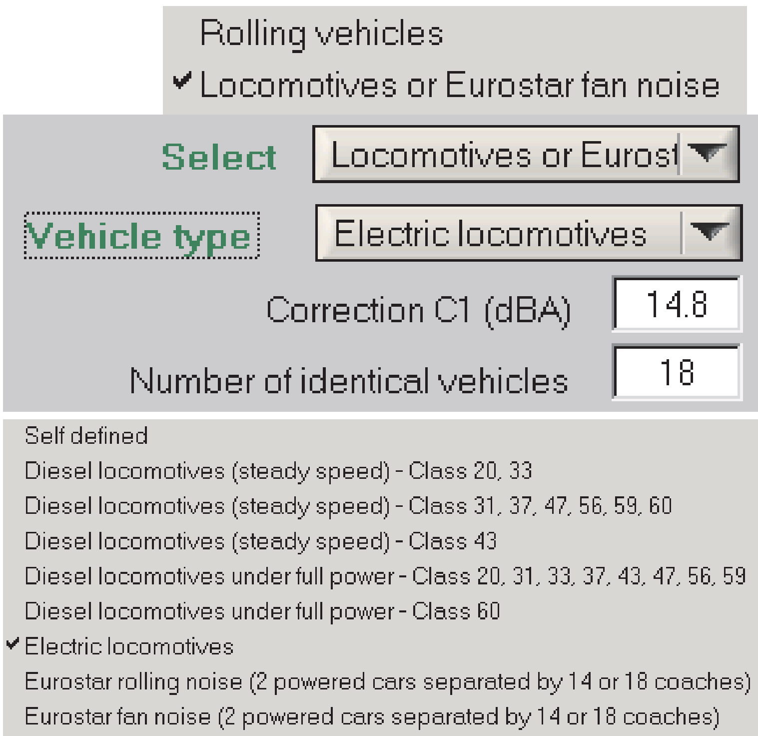
The quantities, "perpendicular distance from observer to segment line", "angle subtended at observer by segment" and "distances from the observer to each end of the segment are defined in the figure on the next page. The latter two quantities are defined by d_1 and d_2 on the figure.





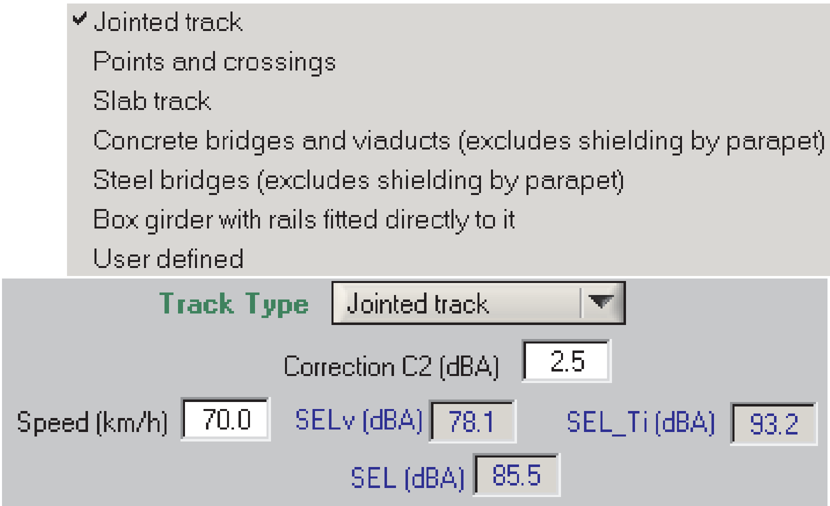
8.3.4 Rail Traffic noise — UK DoT (6th edition textbook, pages 662–667)

This window calculates 6-hour and 18-hour equivalent noise levels at an observer location generated by a segment of railway track with a train running on it. The observer location must be at a normal distance greater than 10 m from the track segment (or its extension). The track segments are selected so that the noise variation at the observer location from one end of the track segment to another does not vary by more than 2 dB. Once the noise levels at the observer location due to each train type on each track segment have been calculated, they are added logarithmically using the procedures in module 1 of ENC.



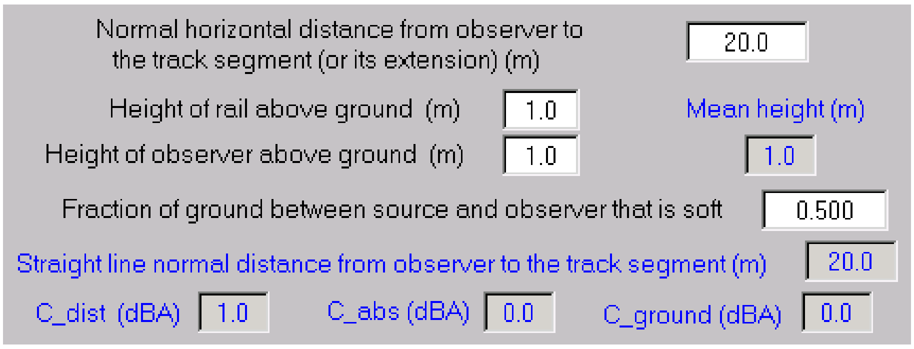
The first step is to divide the track into reasonable segments that satisfy the <2 dB noise level variation. Next is to select the type of train or rolling stock for which noise levels are to be calculated. This is done by clicking on the two items shown in the figure at right and selecting an item from each drop down menu. ENC calculates the correction term, C_1, for train type, based on your two selections and Table 10.46 in the textbook. If “self defined” is selected in the lower drop down menu, then you must enter your own value for C_1.

Next, you must enter the number of vehicles of this type in each train that passes by (see figure at right above).



The next step is to enter the track type (see figure at right) and ENC will calculate the correction C_2 for track type. If the "self defined" option is chosen from the drop down menu, you will need to enter your own value of C_2. For either case, you must enter the speed of the train in km/hour.

With the vehicle data entered as described above, ENC can calculate values for sound exposure level (SEL) of a single vehicle (SEL_v or SELv in ENC), defined by Equations (10.178)–(10.180) in the 6th edition textbook. SEL is defined on page 84 in the 6th edition textbook. SEL_{Ti} (or SEL_Ti in ENC) for each vehicle type is then calculated using Equation (10.178) together with the number of vehicles of this type entered by the user. Note that this quantity has also been corrected for the track type by adding the correction, C_2, from Table 10.47 in the 6th edition textbook. Note also that this result is for only one vehicle type and one track segment. The quantity SEL (dBA) is calculated by adding the total of all the correction terms calculated in the left hand panel to SEL_Ti.The total of all the correction terms is the quantity in the bottom left panel.

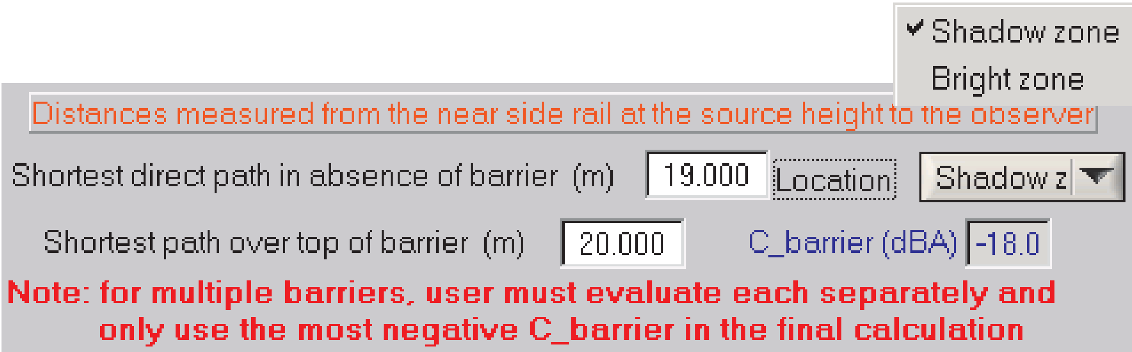


As illustrated in the figure at right, you must enter the normal horizontal distance from the track segment (or its extension if necessary) to the observer, the height of the track above the ground between the track and observer and the height of the observer above the ground. Finally enter the percentage of soft ground between the track segment and observer. ENC will then calculate the straight line normal distance from the track to the observer. Note that this distance is different for diesel locomotives as the effective source height in this case is 4 m above the track. ENC will also calculate the corresponding three correction terms indicated in blue text.

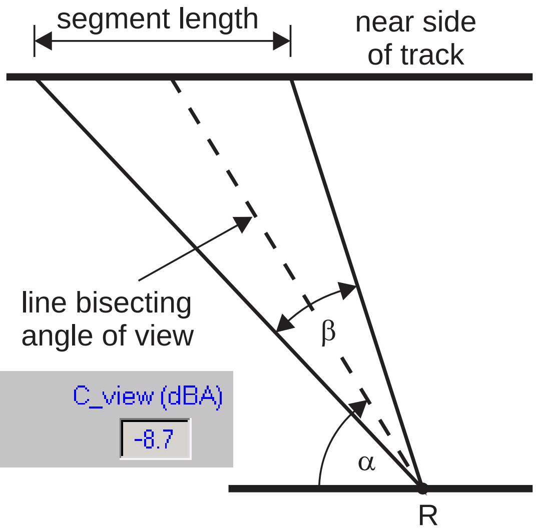
Calculation of the above-mentioned correction terms requires you to enter the required data in the left hand panel. These correction terms account for the effects of air absorption, C_{abs}, the ground type, C_{ground} , the distance to the observer, C_{dist} , the angle of view, C_{view}, the presence of any barriers, $C_{barrier}$, and reflection effects, $C_{reflection}$. In addition there is a correction to account for the presence of ballast to support the railway sleepers, C_{others}, which applies to all segments of the track except the one closest to the observer. The calculation of each of these is done as shown on the figures on the next page. The first panel (shown on the next page) calculates the corrections due to distance from the track (near side), the correction due to air absorption and the correction due to the ground.

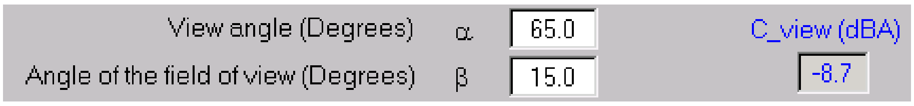
In the figure on the previous page, note that all distances from the observer are to the rail on the **N**EAR side of the track. Note that normal distances are to the track segment where possible, or its extension when the line from the observer to the track segment cannot meet the track at 90 degrees.

The next correction term is that for any barriers or buildings between the observer and track segment. This is a much simpler procedure than we use in module 3 and as such is not very accurate. The distances requested are all referenced to the near side rail.

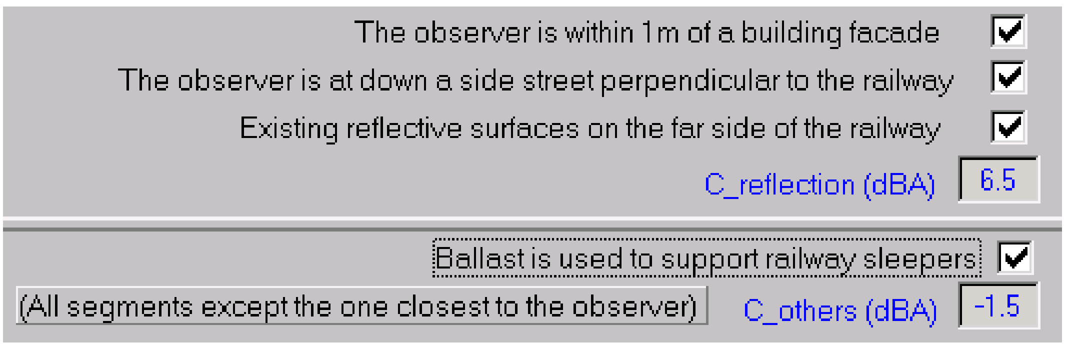


The next correction term is to account for the view angle, α, and the field of view, β, defined in the figure at right where R is the observer.





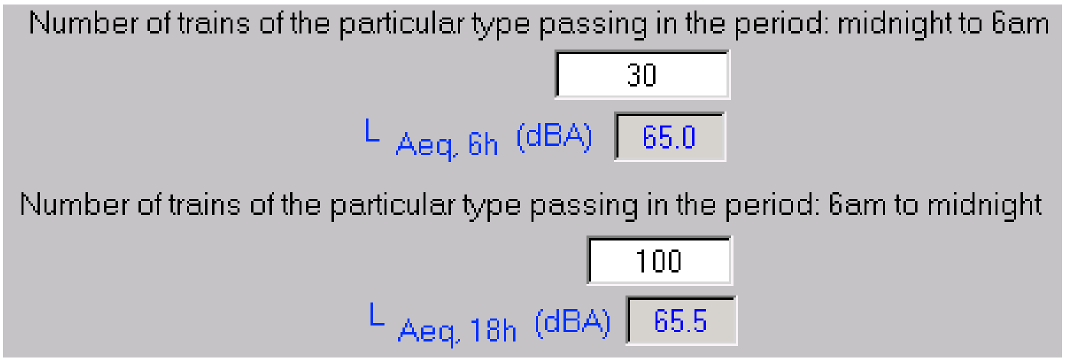
The corrections due to reflections and ballast supporting the track sleepers are calculated next and all that you need to do is click on the appropriate boxes (see following figure).



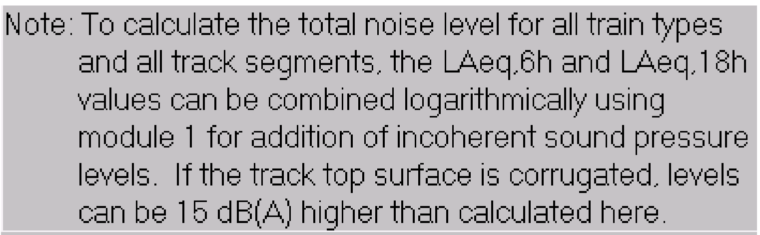
ENC then combines all the correction terms into a single number as shown in the following figure.

ENC will then calculate the overall SEL for that particular track segment and vehicle type, taking into account all of the correction terms as well as the number of vehicles of that type. The overall SEL for a particular train and track segment is calculated by combining logarithmically the SEL values for each vehicle type. This can be done by opening another ENC window and using module 1. The overall SEL for all of the track segments is also calculated by combining the overall values for each track segment (including all vehicle types making up the train) using module 1.

If you enter the number of trains that pass by in a particular period (see figure below), ENC calculates the night-time and day-time $L_{Aeq,6h}$ and $L_{Aeq,18h}$, respectively for the particular vehicle type and track segment.



To get the overall noise levels, it is necessary to repeat the calculations for all vehicle types and all track segments and add the results together. Each train may also have to be treated separately as the number and type of vehicles may vary from train to train. This just makes the procedure more tedious, but the end result is still obtained by combining all of the individual results together using module 1. Please read the note in ENC which is reproduced below.



Chapter 9

Statistical Energy Analysis (SEA) (Module 9)

Here, instructions are provided for running the SEA module in ENC. Background theory is limited in the textbook so it is expanded in Appendix A of this manual.

This module consists of 3 pages (see figure below). **These pages must be filled out and run sequentially.** This is because page 2 uses information entered in page 1 and page 3 uses information entered in pages 1 and 2.

Note that before you exit any page to move on to the next one it is essential that you do the following

1. Click on “save” to save the page in case you wish to go back to it to change something.
2. Remember that when saving a page it is essential that you type the full file name in the filename box and do not click on an existing file and change 1 or more characters as this will result in overwriting of the file whose name you chose without using the new filename. Unfortunately this is a bug in the programming shell which is beyond our control.
3. Click on “RUN” to allow all the data you have written on the page to be written to a file that will be used by a subsequent page.

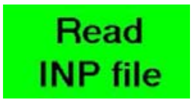
Please note that for the SEA analysis in this module to provide reliable results, at least 3 (and preferably 6) resonant modes in the frequency band are required for each subsystem that is part of the analysis. The number of modes can be calculated by multiplying the chosen bandwidth (= upper band limit − lower band limit in Hz) by the modal density (modes/Hz, calculated when executing the analysis by clicking on “run” on the “SEA calculation results” page).

For the calculation of coupling loss factors involving plates, it is assumed that the wave fields are dominated by normal incidence components so that use of the normal incidence transmission coefficient to calculate the CLF is sufficiently accurate, especially considering the general accuracy limitations of the SEA method.

9.1 Subsystem Input Data

This page is accessed by clicking on the “Subsystem input data” button at the top of the screen. This is where physical data for all subsystems that make up the overall system must be entered.

The “Subsystem input data” page must be completed before moving on to the “Coupling loss factor input data” page and the “SEA calculation results” page. If ENC crashes, it is likely that a valid number has not been entered in one of the data lines. ENC does not check the validity of all subsystem input data and these are the first items to check if ENC produces unexpected results. However, ENC will produce a list of the more commonly encountered data input errors on the SEA calculation results page. ENC will also reproduce the input data for each subsystem (as well as calculated data, including subsystem mean square velocities or sound pressures) on the “SEA calculation results” page.

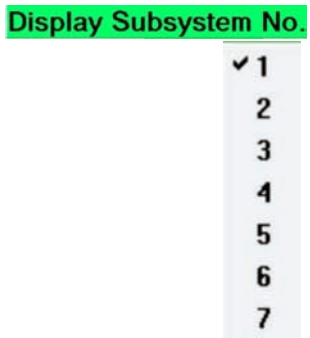


Clicking on the green “Read INP file” button on the top left of the page (illustrated at right) allows you to read in the input file that was recorded when you last clicked on the “RUN” button. This input file has the file name, “fullSEA.inp” and can be modified using a text editor such as notepad. The line number shown in ENC refers to the line number in the input file. The line number in the input file is not shown so to find the relevant number it is necessary to count down from the first line. The lines with multiple data entries have one entry for each subsystem entered by the user. The order of the data in a line reflects the order of the display subsystem numbers in ENC.

When beginning analysis, the first step is to enter a value in the “Number of subsystems” data box (see following figure), which represents the total number of subsystems that make up the system to be analysed. In this version of ENC, the maximum allowed number of subsystems is 50. Then you must enter the analysis frequency. Note that the bandwidth (octave or 1/3-octave) is not chosen on this page but may be chosen on the “SEA calculation results” page. Next, the density and sound speed in the gaseous medium surrounding the entire system are entered. These latter two quantities can be populated automatically by using the “constants” button.

The next step is to draw a diagram of your entire system, numbering each subsystem within it, usually beginning with the subsystem with an input force and then sequentially numbering subsystems (beginning with 1) in the sequence in which the force is transmitted (although any numbering should work, provided it begins with 1).

Best results are achieved if the subsystems are numbered so that subsystems connected together are numbered sequentially as much as possible so that the largest terms in the coupling matrix are as close to the diagonal as possible, thus resulting in a more accurate matrix inversion.



The "Display Subsystem No." shown on the menu at right is selected in order to enter details of the subsystem number on your diagram corresponding to the selected display number. Then you must choose the subsystem type corresponding to that number from the list, which appears when you click on the yellow box and which is reproduced in the table on the next page. The subsystem list shown in the table shows the 25 available subsystem types in the same order in which they appear in ENC. However, the type numbers in the left hand column of the table are not sequential and these are the numbers that will appear in the data file created by ENC which you can change using a text editor. The data file created by ENC is saved in the enc6.0 directory created when you install ENC and the file has the name, "fullSEA.INP". Note that the first 5 lines of the data file each contain one data entry corresponding, respectively, to the analysis frequency, number of subsystems, density of gas surrounding the entire system, speed of sound in the gas surrounding the entire subsystem, and the subsystem type (chosen from the menu reproduced on the next page).

Both infinite and semi-infinite subsystems are defined. Infinite subsystems are used when the application of external excitation is well away from the subsystem boundary (beam ends or plate edges). For subsystems not subjected to external excitation, the subsystem types are usually semi-infinite, so that should be the type generally chosen. However, for subsystems not subjected to external excitation, the choice is not important, as it only affects the calculation of coupling loss factors and ENC will choose the most appropriate option to use in all cases.

For corrugated plates with bending waves, the plate orientation when joined to other subsystems is important. If the join is along the edge with the profile shape, then the chosen subsystem type should be 21 (wave propagation parallel to corrugations). If the join is on the edge at 90 degrees to the profile shape, the chosen subsystem type should be 22 (wave propagation across the corrugations). Any other join location should use subsystem type 11 for which the bending wave speed is the geometric average of the wave speed corresponding to subsystem type 21 and the wave speed corresponding to subsystem type 22.

Note that there is a maximum allowable dimension for isotropic plate subsystems, given by $L < \dfrac{c_{g,B}}{2\pi f\eta}$, where $c_{g,B}$ is the bending wave group velocity ($= 2c_B$, where c_B is the bending wave speed), f is frequency and η is the internal damping of the plate. ENC outputs the maximum permitted dimension for each isotropic plate in the system to assist you to check that the analysis is valid.

Generally the "semi-infinite" option is chosen. However, for cases where external forces are applied away from the edge of a subsystem, the "infinite" option should be used. For junctions where two or more subsystems are connected, ENC will automatically use the correct option, irrespective of which option is entered on this page.

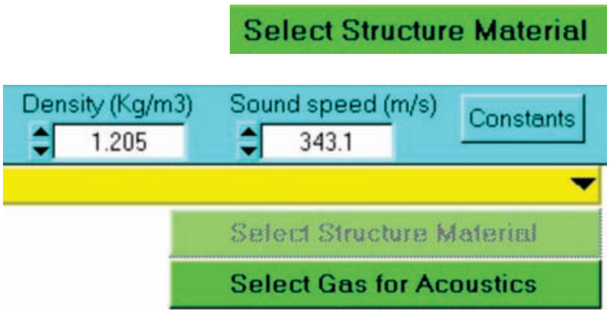
When you choose a subsystem type corresponding to a particular subsystem ID number, you will notice that various lines of input data are greyed out so that data cannot be entered. This is because the type of data to be entered is dependent on the subsystem type that is chosen. A typical table (different for each subsystem type) is illustrated on page 290. Note that the data lines are numbered from 6 to 29 to make it easier to reference

Table 9.1 Subsystem type IDs and corresponding definitions

ID number	Description
1	Beam, infinite - axial waves
2	Beam, semi-infinite - axial waves
3	Beam, infinite - torsional waves
4	Beam, semi-infinite - torsional waves
5	Beam, infinite - bending waves
6	Beam, semi-infinite - bending waves
7	Isotropic plate, infinite, in-plane compressional waves
8	Isotropic plate, semi-infinite, in-plane compressional waves
9	Isotropic plate, infinite - bending waves
10	Isotropic plate, semi-infinite, bending waves
19	Corrugated plate, infinite, in-plane compressional waves
20	Corrugated plate, semi-infinite, in-plane compressional waves
11	Corrugated plate, infinite, bending waves
21	Corrugated plate, semi-infinite in stiffest direction, bending waves
22	Corrugated plate, semi-infinite in least stiff direction, bending waves
23	Sandwich plate, infinite, in-plane compressional waves
24	Sandwich plate, semi-infinite, in-plane compressional waves
12	Sandwich plate, infinite, bending waves
25	Sandwich plate, semi-infinite, bending waves
13	Thin-walled, circular-section cylinder, bending waves
14	1-D acoustic duct, infinite
15	1-D acoustic duct, semi-infinite
16	3-D acoustic space
17	Cavity wall space between 2 partitions
18	User entered subsystem (total mass (kg), impedance, loss factor, modal density (modes/Hz))

them in the following descriptions, and these numbers are also the line numbers in the data file prepared by ENC for use in the final calculation stage carried out on the page, “SEA calculation results”.

6	Material density (kg/m^3)	7800.0
7	Young's modulus (Pa)	2.07E+9
8	Poisson's ratio	0.3
9	No data to be entered by user	1.00E-5
10	No data to be entered by user	1.00E-5
11	Plate perimeter (m)	1.0
12	Plate thickness (m)	0.003
13	Plate plan area (m^2)	1.0
14	No data to be entered by user	Clarkson method
15	Resonant radiation into free space, rad. eff. option	0-User entered resonant radiation efficiency
16	Modal density calculation method	1-Using theoretical analysis
17	Mass calculation method	2-Calculated from system density and dimensions
18	Enter 1 for a rectangular and 2 for a circular plate	1
19	Loss factor calculation method	1-User entered loss factor
20	Radiation loss calculation method	0-Already included in subsystem loss factor
21	No data to be entered by user	1-Sinusoidal profile
22	Forced radiation efficiency calc. method (acoustic exc.)	4-User entered radiation efficiency
23	Point force impedance calculation method	2-Theoretical formulae
24	Point moment impedance calculation method	1-User entered impedance values
25	External Excitation	0-No external excitation
26	No data to be entered by user	1.00
27	No data to be entered by user	1.00
28	No data to be entered by user	1.00E-1
29	Plate or wall aspect ratio (>=1)	1.00



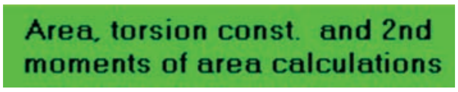
All quantifiable units are MKS units.

Material properties for structural systems can be entered manually or can be entered by selecting from the material list, which appears when you click on the “”Select Structure Material” button shown at right. Similarly, properties of acoustic subsystems can be entered manually or by clicking on the “Select Gas for Acoustics” button. The “constants” button near the top right of the page is used to select the gas that surrounds the entire subsystem, thus allowing different gases to be inside enclosed subsystem spaces within the system.

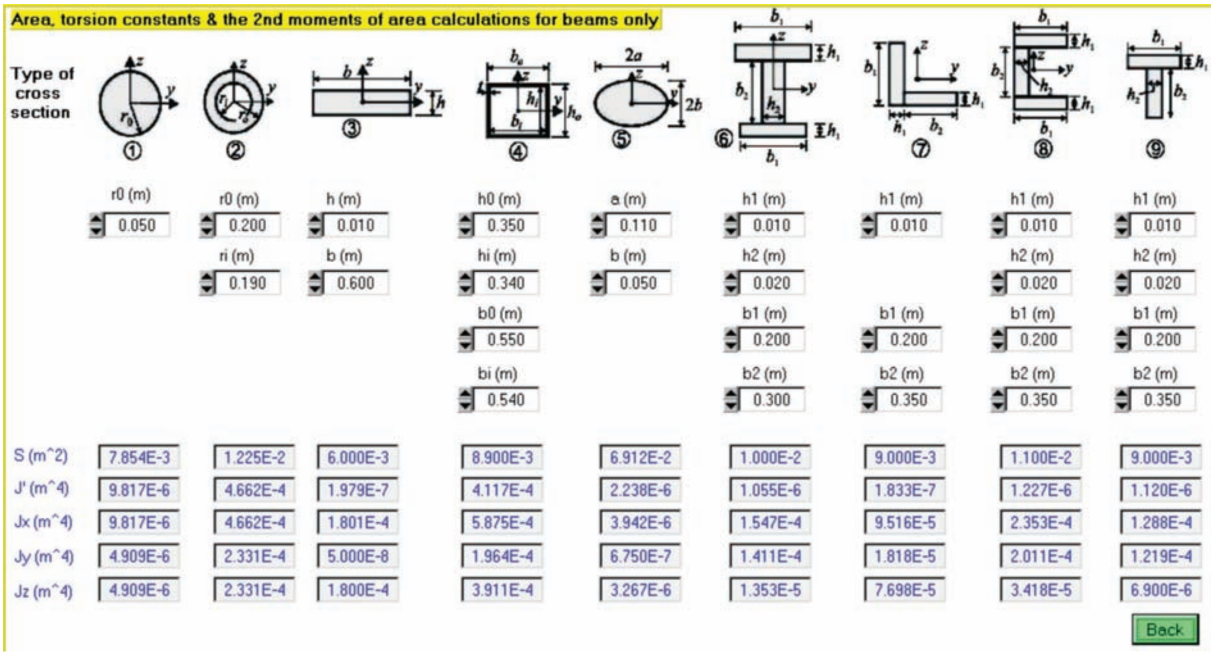
Data **lines 6 and 7** shown in the above figure are self-explanatory and will not be discussed further.

Data **line 8** is Poisson’s ratio for structural subsystems and for sandwich plates it is Poisson’s ratio for the two skins. Data **line 8** is the area averaged mean normal incidence absorption coefficient for the two ends of of a 1-D tube (subsystem types 14 and 15, used only if the subsystem is excited by an external reverberant field, option 6 in line 25). For subsystem type 16, data **line 8** is the Sabine absorption coefficient for the 3-D space.

Not all cells in the ENC table shown above require data. If a cell is not relevant to the particular subsystem ID, it is greyed out. Also, some cells that are not greyed out request different data for different subsystems. Examples are **lines 9 and 10**, which contain data for beams that are different to data for corrugated or sandwich plates. For isotropic plates and acoustic subsystems, these data are greyed out. For corrugated plates, these lines contain, respectively, the plate bending stiffness in the stiffest direction and the plate length parallel to the corrugations. The bending stiffness does not need to be entered for sinusoidally corrugated plates (selected in data line 14), as it is calculated by ENC. For a non-sinusoidal corrugation profile, the bending stiffness can be calculated using the single panel option in Module 5. The shape must be approximated using straight lines. Click on the green button labelled “More properties for orthotropic panel” to enter the profile. The bending stiffness value will appear in the yellow panel next to the corrugation profile sketch and is labelled “1st bending stiffness”. For sandwich plates, data **lines 9 and 10** contain the thicknesses of the two skins.



For beams, **lines 9 and 10** contain, respectively, the beam torsion constant, J', and the second moment of area, J, which may be calculated for a range of beam cross-sectional shapes by clicking on the button shown at right, which produces the popup shown below (only available for beam and plate subsystems). For the particular cross section of interest, you should enter the dimensions requested in the boxes in the column below the figure showing the cross section that describes the beam under consideration. The calculations in blue font in the last 5 rows of the table apply to the figure immediately above each particular column. S is the cross-sectional area of the section in the figure, J′ is the torsion constant for a beam with a cross-section shown in the figure, Jx is the second moment of area for twisting about an axis perpendicular to the page and Jx and Jz are, respectively, the second moments of area for bending about the x and z axes shown in the figures. Even though the second moment of area is only required for bending wave calculations in beams, it must also be entered for axial wave-type beam subsystems as it is needed in the coupling loss calculations using the “Cremer, Maidanik or other” option for the CLF calculation method.

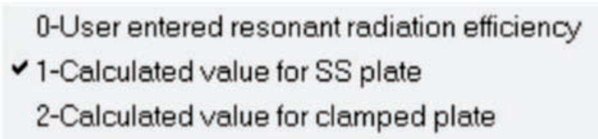


Data **lines 11 and 12** are self explanatory. The plate plan area in data **line 13** is the area taken up by a plate when it is laid on a flat surface and thus it excludes any additional area due to corrugations

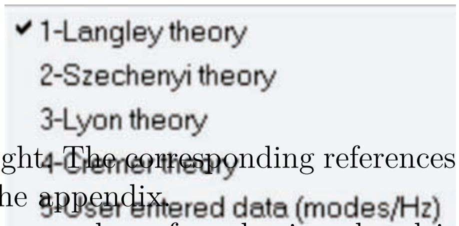
Line numbers 14, 15, 16, 17, 19, 20, 22, 23, 24 and 25 in the input data table all require you to choose a calculation method from a popup window for each subsystem and the corresponding input data for the particular calculation option is entered adjacent to the box containing the chosen option. The pop-up windows are illustrated in the following figures adjacent to where the relevant data are discussed and are generally self-explanatory.

The menu for input **line 14** is only applicable to subsystems 11, 12, 19, 20, 21, 22, 23, 24, 25. For the corrugated plate subsystems, it offers users a choice of corrugation profile: "sinusoidal" or "other". For the sandwich plate subsystems (12, 23, 24 and 25), **line 14** allows the user to enter the method to be used for the stiffness calculation of a sandwich plate. The plate stiffness is required for calculating the plate impedance (used for CLF estimations) and the plate modal density. These options are described in Table A.14 in the appendix.

The menu for the resonant radiation efficiency option (**line 15**) is shown at right for a plate. Note that "SS" means that the plate edges are simply supported (the usual assumption). The calculated values are obtained using Maidanik's theory, corrected according to Crocker Crocker and Price (1969a) and Leppington et al. (1982). For a cylinder, only two options are offered (user entered data or calculated for a simply supported cylinder, where the simple support is achieved using shear diaphragms at each end). The cylinder radiation efficiency for mechanical excitation is calculated according to Szechenyi (1971).



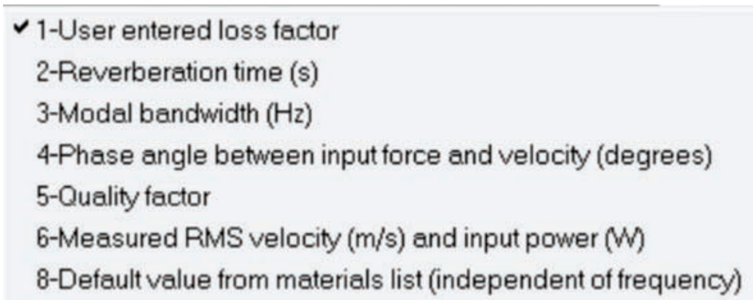
The menu for the modal density calculation (**line 16**) for beams, plates and acoustic systems only has two options: "Using theoretical analysis" and "User entered data". The options for a cylinder are shown at right. The corresponding references and equations are provided in Tables A.12 to A.15 in the appendix.



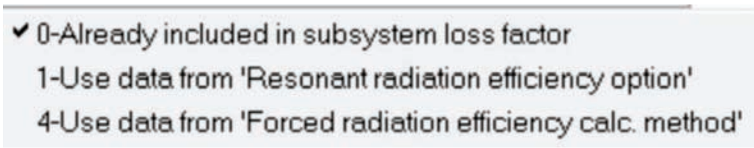
Note that ENC will produce an error message if the number of modes in a band is less than 2. If it is less than 0.1, ENC sets it equal to 0.1 to prevent the program crashing and then prints out a further error message.

The menu for the mass calculation method (**line 17**) has two self explanatory choices. In **line 18**, there is a choice of rectangular or circular/cylindrical, which applies to a plate or room shape. Note that only circular plates can be used as partitions separating cylindrical rooms and rectangular plates can only be used as partitions separating rectangular rooms.

The options for the Damping loss factor calculation method (**line 19**) are shown at right. The various methods for calculating subsystem loss factors are explained in the appendix, Section A.6. Note that choice 7, which is not shown in the figure, applies only to subsystem 16, and is the same as option 6 shown at right, except that



"RMS velocity (m/s)" is replaced with "RMS sound pressure (Pa)". Also for subsystems 16 and 17, choice 8 is replaced with "9-From room Sabine absorption coefficient".

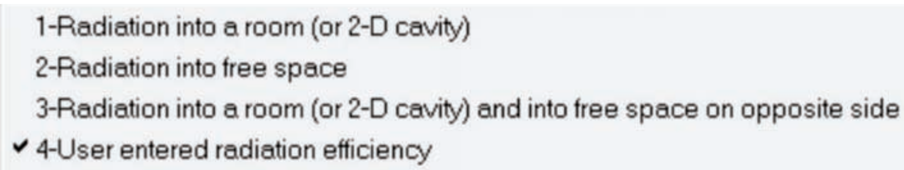


Radiation loss is only calculated for plates and cylinders. The options for the radiation loss calculation method (**line 20**) are shown in the figure at right. The radiation loss may already be included in the damping loss factor of **line 19** if the loss factor was measured on a similar plate using methods 2 to 6 in **line 19**. In that case the first option in **line 20** is selected. Otherwise, if the loss factor was determined using either option 1 or 8 in **line 19** (and zero is not selected for the radiation loss calculation method in **line** 20), the radiation loss is added to the damping loss by ENC. The radiation loss for a plate or cylinder radiating to free space depends on whether the plate is excited by a diffuse acoustic field (forced excitation) or by vibration (resonant excitation). This is why the options provide a choice for calculating the radiation efficiency, which is needed for the radiation loss calculation (see the appendix, Section A.6). The radiation loss factor calculation procedures may be found in the sections in the Appendix, listed below.

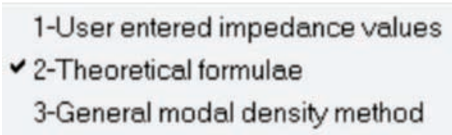
1. Option 2 is for resonant radiation from a plate or cylinder (excitation by a vibration source) and is described in Section A.6.1.1.

2. Option 3 is for forced radiation from a plate (excitation by a sound field) and is described in Section A.6.2.1.

Data **line 21** is only used for the corrugated plate subsystems 11, 19, 20, 21 and 22 that have a sinusoidal profile. The datum is the peak to trough height of the corrugations in a sinusoidally corrugated plate. Even though it is not greyed out for the "other profile" choice in **line 14**, it is only used for the "sinusoidal profile" choice.

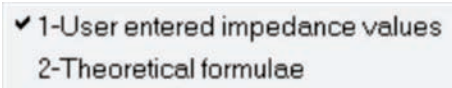


In data input **line 22**, there are five choices for the forced radiation efficiency calculation method, as explained in Section A.6.2.1 in Appendix A (see figure at right on the previous page). Choose item 1 if the plate is radiating into a 3-D room and the opposite side is not radiating into free space. Choose item 2 if the plate is radiating into free space from one side and the other side is not radiating into an enclosed space (such as a plate separating two acoustic spaces). Choose item 3 if the plate is radiating into a 3-D room on one side and free space on the other side. Choose item 4 to enter a radiation efficiency value manually. Choose item 5 if the plate is between two 1-D pipes that only have plane waves propagating. Note that for sound radiation into an enclosed space, with the exception of option 4, ENC will choose the appropriate radiation efficiency to use, based on the calculation model chosen on the "Coupling loss factor input data" page for Junction types 31–34.



There are three choices for determining the point or line force impedance and these are selectable from the data input **line 23** (see figure at right). These impedances are used for determining the subsystem input power due to an excitation source that is external to the system being analysed. The option, "General modal density method" in the point force impedance calculation method popup menu is for situations where a reasonably simple expression is not available for the point force impedance for an infinite system. In this case, the real point force impedance may be estimated from the modal density, as explained in Section A.4 in Appendix A. Note that this choice should only be used if the external excitation type specified in **line 25** is a point force or point velocity. If any other excitation type is chosen in **line 25**, ENC will automatically change the option choice in **line 23** to the second one.

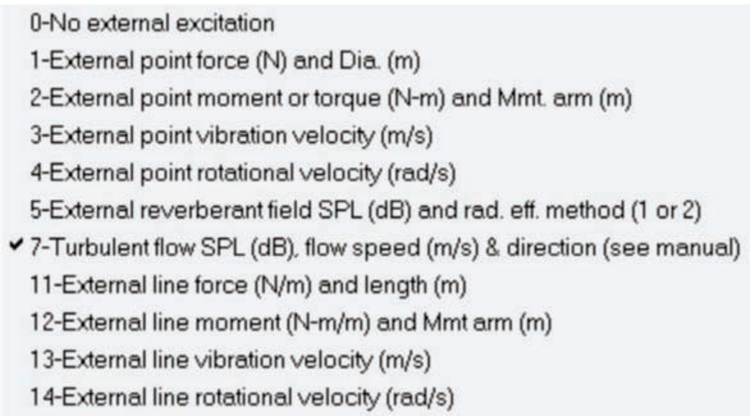
Note that impedances used to determine coupling loss factors are all calculated using subsystem input data. Any user entered impedance data in lines 23 and 24 are only used to calculate external input powers due to external forces or moments. The option of using user entered impedances for coupling loss factor estimations is not available; instead, there is an option for user entered coupling loss factors for any selected junction.



There are two choices for determining the point or line moment impedance and these are selectable from the data input **line 24** (see figure at right). These impedances are only used for determining the subsystem input power due to an excitation source that is external to the system being analysed. Impedances used for calculating coupling loss factors are all calculated from first principles as explained in the preceding paragraph.

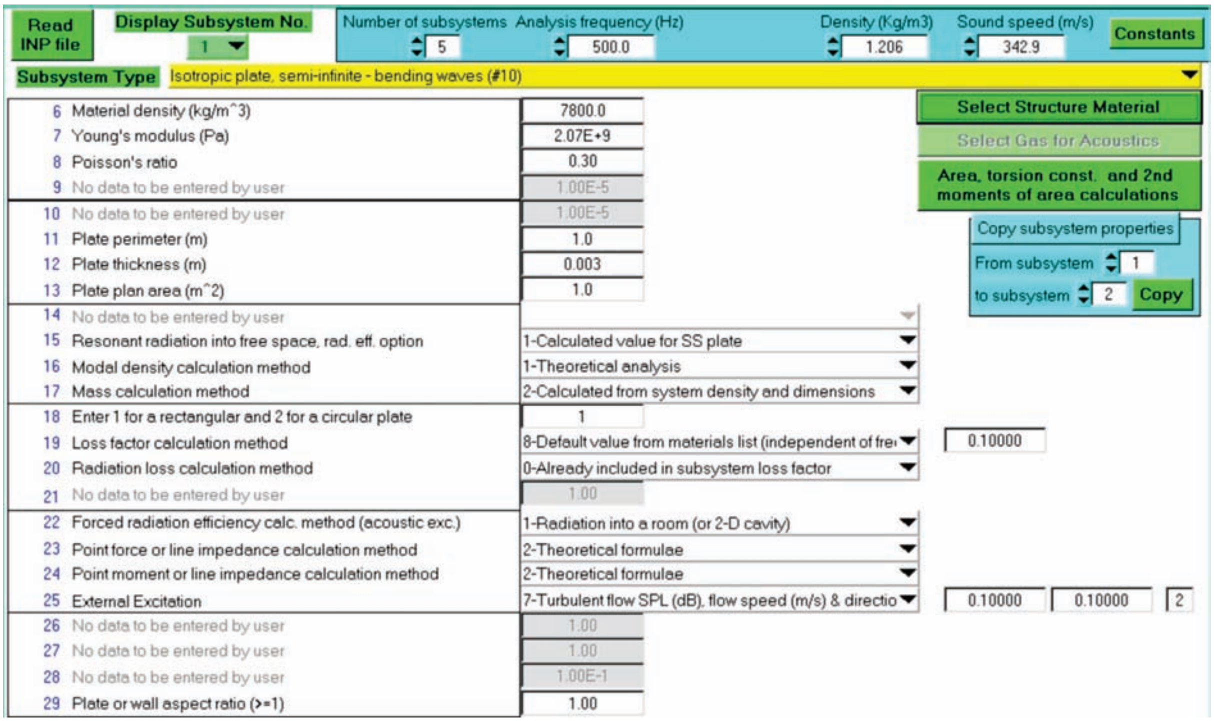
Table 9.2 Excitation type IDs, descriptions and subsystems that each applies to

ID number	Description	Applicable subsystems
0	No external excitation	1–25
1	External RMS point force (N) [and diameter (m)]	1, 2, 5, 6, [7–12], 13, [19–25]
2	External point moment or torque (N-m) [and moment arm (m)]	3–6, [9–12], [21, 22, 25]
3	External RMS point vibration velocity (m/s) [and diameter (m)]	1, 2, 5, 6, [7–12], 13, [19–25]
4	External RMS point rotational velocity (rad/s) [and moment arm (m)]	3–6, [9–12], [21, 22, 25]
5	External reverberant field SPL (dB) [and radiation efficiency method (1 or 2)]	[9-12], 15, [21, 22, 25]
6	Internally generated reverberant field SPL (dB)	14–16
7	Turbulent flow SPL (dB), flow speed (m/s) and direction (1 or 2)	9–12, 21, 22, 25
9	Ext. RMS point force (N), beam width (m) and attached plate subsystem number	5, 6
10	Plane internal source, m.s. vel. (mm^2/s^2), area (m^2), location (0,1,2 or 3)	16
11	External RMS line force (N/m)	7–13, 19–25
12	External RMS line moment (N-m/m)	9–12, 21, 22, 25
13	External RMS line vibration velocity (m/s)	7–13, 19–25
14	External RMS line rotational velocity (rad/s)	9–12, 21, 22, 25



In data **line 25** (see above table), there are 14 options for the external excitation type. Of course, not all excitation types are appropriate for all subsystem types. An external excitation is that caused by an acoustic or vibration source that is external to the system being analysed. The excitation ID numbers, descriptions and subsystems that they each apply to are listed in the following table. Note that for excitation types 1–5, in column 2, the second data item is enclosed in square brackets, as it only applies to subsystem type numbers enclosed in square brackets in column 3.

When clicking on an excitation type, zero, one, two or three additional data boxes appear adjacent to the excitation type data box. An example of choosing an excitation type in **line 25** that requires three additional data boxes is shown in the following figure. Note that the data boxes are in order so that the left most box refers to the first item (before the first comma) in the description box on the left, etc.



In an alternative presentation, the following table shows a list of subsystems with the excitation types applicable to each listed in the third column.

Table 9.3 External excitation types corresponding to the various subsystem types

Subsystem ID number	Subsystem description	Excitation type number
1	Beam, infinite - axial waves	0, 1, 3
2	Beam, semi-infinite - axial waves	0, 1, 3
3	Beam, infinite - torsional waves	0, 2, 4
4	Beam, semi-infinite - torsional waves	0, 2, 4
5	Beam, infinite - bending waves	0–4, 9
6	Beam, semi-infinite - bending waves	0–4, 9
7	Isotropic plate, infinite, in-plane comp. waves	0, 1, 3, 11, 13
8	Isotropic plate, semi-infinite, in-plane comp. waves	0, 1, 3, 11, 13
9	Isotropic plate, infinite - bending waves	0–5, 7, 11–14
10	Isotropic plate, semi-infinite, bending waves	0–5, 7, 11–14
19	Corrugated plate, infinite, in-plane comp. waves	0, 1, 3, 11, 13
20	Corrugated plate, semi-infinite, in-plane comp. waves	0, 1, 3, 11, 13
11	Corrugated plate, infinite, bending waves	0–5, 7, 11–14
21	Corrugated plate, semi-infinite, stiffest dir., bending	0–5, 7, 11–14
22	Corrugated plate, semi-infinite, least stiff dir., bending	0–5, 7, 11–14
23	Sandwich plate, infinite, in-plane comp. waves	0, 1, 3, 11, 13
24	Sandwich plate, semi-infinite, in-plane comp. waves	0, 1, 3, 11, 13
12	Sandwich plate, infinite, bending waves	0–5, 7, 11–14
25	Sandwich plate, semi-infinite, bending waves	0–5, 7, 11–14
13	Thin-walled, circular-section cylinder, bending waves	0, 1, 3
14	1-D acoustic duct, infinite	0, 6
15	1-D acoustic duct, semi-infinite	0, 5, 6
16	3-D acoustic space	0, 6, 10
17	Cavity wall space between 2 partitions	0
18	User entered subsystem	0–4

The required input data for each of the external excitation options listed in the table on page 295 are now explained.

Excitation type 1 requires as input, the applied RMS point force, which may be applied normal to the beam axis or plate to generate bending waves or parallel to the beam axis or parallel to the plane of the plate to generate longitudinal waves. For forces applied to plates, the diameter of the applied force is also required. If the shape of the applied force is non-circular, then the required input is the diameter of a circle of the same area as the applied force. If the force diameter is unknown, use 0.01 m.

Excitation type 2 requires as input, the applied RMS torque for beams or the applied RMS point moment for plates. For plates, the moment arm (distance between the two forces generating the moment) is also required.

Excitation type 3 requires as input, the structural RMS velocity at the point of application of the applied force. For forces applied to plates, the diameter of the applied force is also required.

Excitation type 4 requires as input, the RMS rotational velocity at the point of application of the torque (beams) or moment (plates). For plates, the moment arm (distance between the two forces generating the moment that results in the rotational velocity) is also required. If the moment arm is unknown, use 0.01 m.

Excitation type 5 for plate subsystems, requires as input, the reverberant field sound pressure level (dB re 20 µPa) exciting the plate and the plate radiation efficiency calculation method. For the radiation efficiency calculation method, 1 is entered for the method according to Lyon and DeJong (1995) and 2 for the method according to Fahy (1969). The equations used with each of these methods are provided in the appendix. For the 1-D duct subsystem 15, the reverberant field sound pressure level (dB re 20 µPa) adjacent to the duct opening only is required. The sound pressure level is converted to mean square pressure and then used with Equation (A.18) in the appendix to calculate the power input the the 1-D duct.

Excitation type 6 allows the sound power input to a 1-D (subsystems 14 and 15), 2-D (subsystem 17) or 3-D (subsystem 16) enclosed space to be calculated based on the reverberant field sound pressure level and the space average absorption coefficient, which is entered in data line 8. For 2-D and 3-D enclosures, this is the Sabine absorption coefficient, while for a 1-D enclosure, such as a tube, it is the average normal incidence absorption coefficient of the ends of the tube (see equations (A.22) to (A.24) in the Appendix). Note that if the absorption coefficient for any space type is greater than about 0.5, this type of data input cannot be used, as the sound field is no longer dominated by the reverberant field. The required input is the reverberant field sound pressure level. For subsystem types 16 and 17, the surface averaged Sabine absorption coefficient entered on Line 8 is also used. For the 1-D duct of subsystem types 14 and 15, the normal incidence absorption coefficient (which is the average of the two duct ends) from line 8 is used. Note that the reverberant sound pressure level in the room at the end of the SEA analysis will usually be lower than the reverberant sound pressure level entered here as some of the energy leaks into attached substructures. In most cases, it may be preferable to use excitation type 8.

Excitation type 7 applies to flat plates, which may be isotropic, corrugated or sandwich. The first data box requires the Turbulent flow SPL (dB re 20 µPa), the second box requires the flow speed (m/s) and the third data box requires either 1 or 2 to be inserted. A value of 1 corresponds to flow parallel with the longest side of an isotropic or sandwich rectangular plate and a value of 2 corresponds to flow parallel with the shortest side. For circular isotropic or sandwich plates, either 1 or 2 may be inserted. For a corrugated plate, a value of 1 corresponds to flow parallel to the corrugations and a value of 2 corresponds to flow across the corrugations.

Excitation type 8 allows an external sound power input for subsystems 14, 15, 16 and 17. The sound power is entered in dB re 10^{-12} Watts.

Excitation type 9 corresponds to a point force excitation of bending waves in a beam attached along its length to the surface of a plate. The first data box requires the RMS point force (N) applied to the beam well away from its ends. The second data box requires the width of the beam surface attached to the plate and the third data box requires the subsystem number of the plate to which the beam is attached.

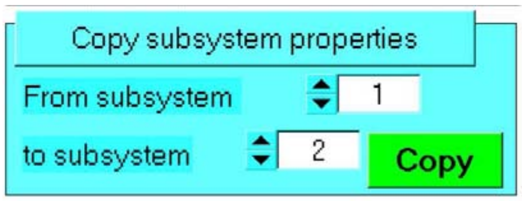
Excitation type 10 corresponds to a excitation of a 3-D space by a plane source. The first data box requires the mean square velocity of the plate (mm^2/s^2). The second data box requires the area of the plane source and the third data box requires the number of plane reflecting room surfaces adjacent to the plane source to be entered (0, 1, 2 or 3). Do not include any absorptive room surfaces when counting the number of reflective room surfaces adjacent to the sound source. The input sound power is calculated by ENC using equation (A.19) in the Appendix.

Excitation type 11 is only applicable to plates and requires as input, the applied RMS line force, which may be applied normal to the plate to generate bending waves or parallel to the plane of the plate to generate longitudinal waves.

Excitation type 12 is only applicable to plates and requires as input, the applied RMS line moment, which can only generate bending waves.

Excitation type 13 is only applicable to plates and requires as input, the RMS structural velocity at the point of application of the applied force.

Excitation type 14 requires as input, the RMS rotational velocity at the point of application of the line moment (plates).



If a subsystem is exactly the same as one that has been previously selected, there is no need to enter all the data again. You can simply copy data from the existing subsystem to the new subsystem by using the "copy subsystem properties" box illustrated at right.

A list of the subsystem input data is provided in the file, "Subsysdat.txt", which can be found in the directory on your computer where ENC has been installed (eg d:
enc6). The first line contains the number of subsystems (=N). Each of the next N lines contain the subsystem ID number, the subsystem type number and a description of the subsystem type. The next lines contain the input data used to define each subsystem. All data (one line for each item of data) are then listed for each subsystem, beginning with subsystem ID number = 1. Each data line contains the data value, the subsystem ID number to which it applies and the subsystem type number followed by a description of the data value. Each group of data corresponding to a particular subsystem ends with a value of zero for the data item and a value of 100 for the subsystem type (which is meaningless).

9.2 Coupling Loss Factor Input Data

This page is accessed by clicking on the by clicking on the "Coupling loss factor input data" button at the top of the screen. Before entering any data on this page, it is necessary to complete entering data on the "Subsystem input data" page and then click on "Run" on that page. The "Coupling loss factor input data" page is where data corresponding to all connections (joints or junctions) between subsystems must be entered. This page must be completed before moving on to the "SEA calculation results" page. If ENC crashes, it is likely that a valid number has not been entered in one of the data lines. ENC does check most of the data input on this page for validity, and does produce error flags for many of the more obvious errors. However, it is wise to check the data input on this page after checking the data input on the "Subsystem input data" page if ENC produces unexpected results. ENC will produce a list of the more commonly encountered data input errors on the SEA calculation results page.

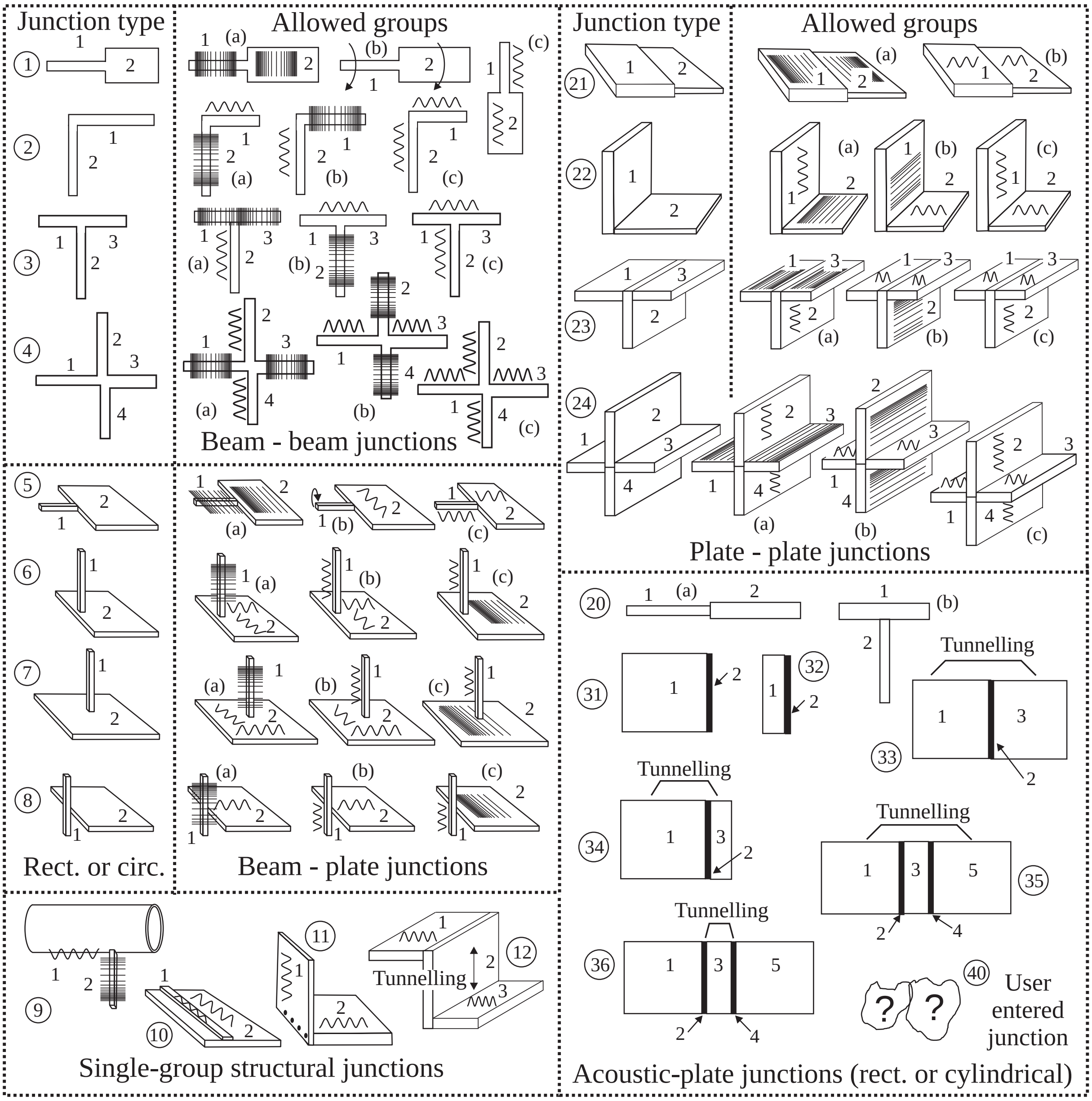
When calculating transmission coefficients (used to calculate CLFs) for structural connections, the sum of impedances of all subsystems connected at the junction and representing the same type and orthogonal direction of motion must be used (see the impedance sum in Equation (A.159). It is important to note that impedances representing different orthogonal directions of motion cannot be summed together in that equation. This is why some groups for the same junction may look similar but are included as they represent junction motion in a different orthogonal direction (see for example junction types 2, 3, 4, 22, 23 and 24, where groups (a) and (b) look similar but represent junction motion in orthogonal directions. It is very important that the same physical subsystems have the same ID number in all groups of a particular junction, even though they may be represented in different subsystems (which have different wave types, as only one wave type is permitted for any subsystem).

When there is transmission between structural bending waves, energy transmission occurs due to two types of motion: vertical motion normal to the direction of wave propagation and rotational motion. CLFs for each type of motion must be added together to obtain the junction CLF (Lyon and DeJong, 1995, p. 191). This can also be achieved by adding transmission coefficients associated with each type of motion to obtain a single transmission coefficient to use in the CLF calculation. If this results in a total transmission coefficient greater than 1, ENC sets it equal to 1.

If the vibro-acoustic system to be analysed includes a double wall separating two acoustic spaces, both the η_{24} and the η_{15} coupling loss factors must be calculated.

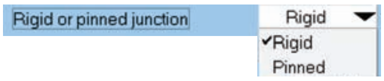
Clicking on the green "Read INP file" button on the top left of the page (illustrated at right) allows you to read in the input file that was recorded when you last clicked on the "Run" button. This input file has the file name, "fullSEAcoupl.inp" and can be modified using a text editor such as notepad. This input file has descriptions of the data at the end of each line to assist you to modify the file without having to generate a new file using the ENC GUI. The order of the data reflects the order of the junction numbers in ENC and for each junction number, it reflects the order of the data shown on the GUI. The three input files, "fullSEA.inp", "fullSEAcoupl.inp" are used by ENC module 9, page 3 ("SEA calculation results" and "SEApage5.INP") to produce the output for this module.

Junctions are divided into various types with type numbers ranging from 1 to 40 (although not all numbers between these limits are used). When clicking on the "Junction type ID" data box, a list of type numbers is displayed and you need to choose one of these. All possible choices are shown in the following figure. Each junction type has between one and six groups associated with it and these are also shown in the following figure.

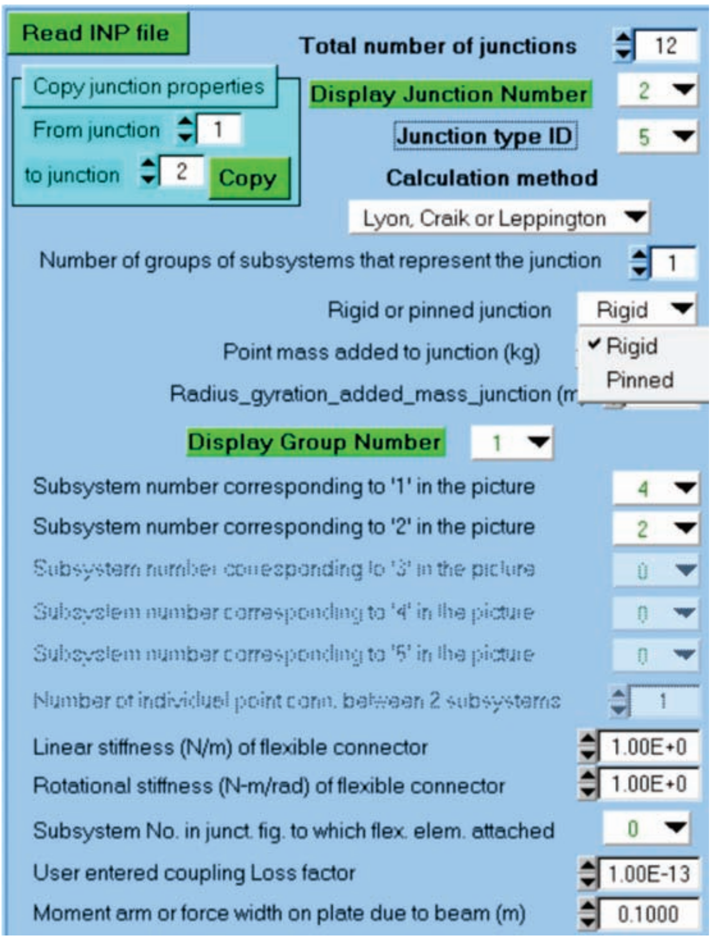


On the figure, sinusoidal lines represent bending waves and a series of straight lines represent longitudinal waves. A curved arrow represents torsional waves. You can choose to use between one and the maximum number of groups for which to enter data. Note that groups are separated by at least one different subsystem type and thus are represented by different junctions and coupling loss factors. Only one set of subsystems is allowed for each group. Junction types 6 and 7 have twice as many groups as appear on the figure, as beams may be connected to the plate on both sides. ENC will not allow you to choose more groups than are allowed for the particular junction type. When entering data for groups within a single junction type ID, it is necessary that the same physical subsystem is connected at the same location in the junction for each group. The idea of the different groups is to allow different wave types (represented by different subsystems) to be included for the same junction. This condition does not apply exactly for junction type IDs 6 and 7, as each group can be repeated with a different beam on the opposite side of the plate.

ENC version 6.3 onwards allows the option of a pinned structural junction as well as the more usual rigid junction assumption for each listed structural junction and the user must make the choice between a rigid or pinned junction for each junction (see figure at right).



For pinned connections, only translational motion of the junction is possible, which means that only wave transmission that involves translational motion in the same direction between two subsystems is possible. Bending waves can transmit energy across a junction if the incident and transmitted energy are both travelling in the same direction. This is because bending waves are characterised by both translational and rotational motion, so even though the rotational motion cannot be transmitted across a pinned junction, translational motion can be transmitted. However, if the bending waves in one of the subsystems attached to the junction are travelling at 90 degrees to bending waves in another subsystem attached to the same junction, there will be no energy transmission across the junction between these two subsystems via bending waves. This is because the translational motion in one of the systems is at 90 degrees to the translational motion in the other and thus no coupling will occur. However, the bending wave energy associated with translational motion of the incident bending wave can be transmitted as a longitudinal wave if incident on a 90 degree pinned junction.



Longitudinal waves can only be transmitted across a pinned or rigid junction if the direction of propagation of the longitudinal waves in one of the subsystems has a component of motion in the same direction as the direction of wave propagation in the second attached subsystem. A pinned connection option will be available in ENC version 6.3.

ENC takes into account both rotational and translational junction motion in the transmission of bending waves. The transmission coefficients for each type of motion are calculated separately, then added together prior to calculating the corresponding CLF.

When entering data on this page, the first step is to enter a value in the "**Total number of junctions**" data box (see figure at right), which represents the total number of junctions between subsystems that make up the system to be analysed.

In this version of ENC, the maximum allowed number of junctions is 50. Next, the **Display Junction Number** is entered. This is the junction number identified on your system illustration (that you should develop prior to using this module) and the junction that is defined by all data on the remainder of the page.

Note that where a downward pointing arrow is shown in a data box, the value to be entered into the box must be selected from the list that appears when clicking anywhere in the box.

Although, it may appear to be relatively simple to select a "**Junction type ID**" number from the illustrations in the figure on page 301, there are two aspects that require consideration, so that the correct choice of junction ID is made.

1. **Tunnelling – Structural Non-Resonant Transmission of Bending Waves** This phenomenon is described in Appendix A and most often occurs when a plate is connected at right angles to a second plate which, in turn, is connected at right angles to a third plate. The third plate is in a plane that is parallel to the plane of the first plate. Bending waves in the first plate do not excite longitudinal resonances in the second plate but are nevertheless transmitted to the third plate via the tunnelling mechanism. This is implemented in practice using a coupling loss factor between plates 1 and 3 for junction type 12. This factor will be different to that calculated for the same plates connected end to end as in Junction type ID=21(b). This is because, the energy for junction type ID=12 is transmitted via translational motion normal to the plane of the plates (as for Junction type ID=22(a) or 22(b)) at the plate ends whereas for junction type 21(b), the energy is primarily transmitted via rotational motion of the plate ends.

2. **Tunnelling – Acoustic Non-Resonant Transmission between Rooms** SEA usually only considers resonant transmission from one subsystem to another, but in some cases, non-resonant transmission is important and this needs to be included by appropriate selection of the coupling loss factor ID. One example is transmission from one room to another via a central partition. In this case there is resonant transmission from the source room to the partition and also from the partition to the receiving room. However, there is also non-resonant transmission from the source room to the receiving room (via the forced response of the partition) and this is taken into account using a non-resonant coupling loss factor between the two rooms. Each resonant or non-resonant transmission path is characterised by an individual junction. Non-resonant transmission is taken into account in junction types 33–36 and for these junction types, only non-resonant transmission is calculated to find the CLF for transmission between the lowest and highest subsystem numbers shown on the picture on the GUI. As an example, to account for both resonant and non-resonant transmission from one room to another via a double wall partition as illustrated for junction types 35 or 36, it is necessary to separately calculate the CLFs for the cases shown in the following two tables.

Table 9.4 Coupling loss factors needed to characterise transmission from one acoustic space to another via a double-wall partition (junction type 35)

CLF index to calculate	Junction description	Junction type number
1,2	Room to partition (resonant)	31
2,3	Partition to cavity (resonant)	32
3,4	cavity to partition (resonant)	32
4,5	Partition to room (resonant)	31
1,3	Room to cavity (tunnelling, forced)	34
3,5	Cavity to room (tunnelling, forced)	34
1,5	Room to room (tunnelling, forced)	35

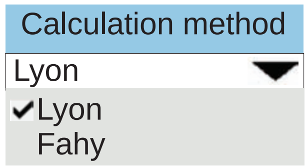
Table 9.5 Coupling loss factors needed to characterise transmission from one acoustic space to another via a double-wall partition (junction type 36)

CLF index to calculate	Junction description	Junction type number
1,2	Room to partition (resonant)	31
2,3	Partition to cavity (resonant)	32
3,4	cavity to partition (resonant)	32
4,5	Partition to room (resonant)	31
2,4	Partition to partition (tunnelling, forced)	36
1,5	Room to room (tunnelling, forced)	35

If junction type 36 is used, the non-resonant transmission (tunnelling) from room 1 to cavity 3 is not calculated. This will result in the sound pressure level in cavity 3 being lower than expected and in some cases, much lower. If the sound pressure level in the cavity is required, then junction type 36 should not be be used and the CLFs listed in the first of the preceding tables should all be included as separate junctions and the corresponding coupling loss factors are then included in the system A-matrix.

Note that the tunnelling is an additional non-resonant transmission path between two subsystems not adjacent to one another. However, the resonant transmission paths between all subsystems adjacent to one another and connected must still all be included in the total number of junctions and in the coupling loss factor calculations.

Referring to the figure on page 302, after entering the "**Display Junction Number**" (from your personal system diagram), the next option to enter is "**Junction type ID**", which may be determined from the figure on page 301, which is a duplicate of the figure on the ENC GUI. The required number is identified in the figure and then selected from the list that appears when you click on the space inside the "**Junction type ID**" box.



The next step is to choose the "**Calculation method**" to be used for the coupling loss factor calculations (see figure at right). In ENC version 6.2 onwards, this option only applies to junction types 31–35. For all other junction types, the method used follows that described in Lyon and DeJong (1995).

For "Junction type" IDs 31–35, there are either two calculation method options (for junction ID types 31, 33 and 35) or three options (for junction ID types 32 and 34).

The options for junction type 31 refer to the model used to estimate the radiation efficiency for a panel (plate) radiating into an enclosed 3-D space (Lyon or Fahy). Each of these models is described on page 343 in this manual. If the enclosure or narrow cavity is a 1-D space such as found for a partition in a 1-D duct, the same 1-D radiation efficiency model is used for all options (see page 345 in this manual).

The options for junction type 32 are for calculating the radiation efficiency for sound radiated by a panel into a narrow cavity (see this manual, page 344). The three options are based on the models published by Maidanik, Leppington and Craik, respectively. The same options are available for junction type 34. Even though junction type 34 is for non-resonant transmission, the panel radiation efficiency for sound radiating into the cavity is required, as described on page 387 of this manual.

The two options for junction types 33 and 35 are different from the two options for junction type 21. This is because junction types 33 and 35 are only for forced response between the two acoustic spaces (1 and 3 for junction type 33 and 1 and 5 for junction type 35) outside of the single or double wall, respectively. For this calculation there is a choice between the Norton and Craik method or the Leppington method (see this manual, page 387).

For junction type 36, there is only one calculation method available and this is described on page 392 of this manual. Junction type 36 requires the stud number, bending stiffness and length, whereas use of junction type 35 requires the stud mass and number. The use of the stud parameters is part of the discussion on pages 390 to 393 in this user manual. For circular panels, the studs are all of different lengths. In this case, the stud mass to enter into ENC is the total mass of all studs divided by the number of studs. Similarly, the length of one stud is the total length of all studs divided by the number of studs. The stud stiffness is a function of the stud cross-sectional profile and material and therefore is not a function of stud length. For a staggered stud configuration, the number of studs is the only number connected to one panel.

The ID=36 procedure is used to calculate coupling loss factors for one of the non-resonant transmission paths (η_{24}) from room 1 to room 5 (and vice versa). This path is used in place of (not as well as) the path characterised by η_{13} and η_{35}. Thus, to use the η_{24} path, we use Equations (A.264), (A.266) and (A.267), where $\tau_{13} \times \tau_{35}$ in Equation (A.266) is replaced with τ_{24}. It is up to the user of ENC to decide which combination to use for calculating non-resonant transmission. One choice involves using junction type IDs 34 (twice) and 35, while the other choice involves using junction type IDs 35 and 36. The latter choice is necessary if the effect of stud stiffness is to be included. Both approaches take into account the total number of studs in the cavity, with junction type 35 using the stud mass and junction type 36 using the stud stiffness.

Although the coupling loss factors for junction types 33–36 are only for the forced response components of the energy transmission, the transmission loss values provided on the output page and in the file, TLOSS.txt, include the resonant transmission calculated using junction types 31 and 32.

As a check, the double wall transmission loss may also be calculated from the ratio of the SEA results for the mean squared sound pressure in the source room, $\langle p_S^2 \rangle$ to that in the receiver room $\langle p_R^2 \rangle$ using:

$$\mathrm{TL} = 10\log_{10}\left(\frac{\langle p_S^2 \rangle}{\langle p_R^2 \rangle}\right) + 10\log_{10}\left(\frac{A}{S_R\bar{\alpha}_R}\right) \tag{9.1}$$

where A is the area of one side of the partition and $S_R\bar{\alpha}_R$ is the receiver room absorption. However, this calculation assumes that there is no contribution to the sound levels due to transmission through walls other than the common partition between the two rooms. This validity of this assumption depends on each individual situation.

The next step is to choose "**the number of groups of subsystems that represent the junction**". Referring to the figure on page 301, it can be seen that Junction types 1–7, and 21–24 are characterised by two or more possible groups. It is not necessary to use all groups in a junction but if a particular junction type is selected, then a number of 1 or greater must appear in this data box. ENC will automatically indicate if the number is too large. For all junction types, except for types 5 and 6, the allowed number of groups is one of each type indicated in the figure on page 301. Except for junctions 6 and 7, only one of each group may be used for any particular junction. ENC will recognise the group being selected by the first subsystem type entered below the "Display group number" box, which is why the group does not have to be identified explicitly. For junction types 6 and 7, a maximum of two groups for each group type are allowed, to enable a beam to be attached on both sides of the plate. Note that for junctions that show different group types, ENC will identify which type corresponds to each group by using the subsystem type that corresponds to the subsystem numbers in the picture (see three paragraphs below).

The next step is to choose whether the junction is rigid or pinned (see page 302 for a discussion of these options). This choice is only available for structural junctions 1–9, 12 and 21–24.

The next step is to enter the "**Point mass added to junction (kg)**" for junction types 1–9 or the "**Length of line connection (m)**" for junction types 12 and 21–24. This line is greyed out for other junction types. If no mass is added to the junction for junction types 1–9, enter 0.0 here. For junction types 12 and 21–24, enter the "Length of line connection (m)".

The next step is to enter the radius of gyration of the added mass (only for junction types 1–8). This value is used in the calculation of coupling loss factors for bending wave transmission.

The next step is to enter a value for the "**Display Group Number**", which all the data in cells below this box will apply to. Each number is linked to any one of the groups assigned to this Junction Type ID. ENC will work out which group in the picture is relevant based on the subsystems allocated to the numbers 1–5 for the junction shown in the ENC picture. However, for all groups, the same physical subsystem (which could have more than 1 subsystem ID number in the subsystem input data page, corresponding to different wave types) must have the same subsystem ID number (1–5) in the picture shown on the ENC coupling loss input data page.

The next step is to select the subsystem number that is to go in the "**subsystem number...**" data boxes that are not greyed out and which are immediately below the "Display Group Number" label. The number of data boxes requiring a subsystem number that must be filled out varies from 2 to 5 and depends on how many subsystems are numbered on the corresponding figure shown on the junction type illustrations on page 301. The list of subsystems to choose from for these data boxes correspond to the display subsystem numbers used for the "Subsystem input data" page. The display subsystem list appears when you click on a data box. In the **first data box**, enter the display subsystem number corresponding to the subsystem labelled "1" in the figure that corresponds to the junction type ID on page 301. All junction types require this. In the **second data box** enter the display subsystem number corresponding to the subsystem labelled "2" in the figure that corresponds to the junction type on page 301. All junction types require this. In the **third data box** enter the display subsystem number corresponding to the subsystem labelled "3" in the figure that corresponds to the junction type on page 301. This is only needed for junction ID types 3, 4, 12, 23, 24, 33, 34, 35 and 36. In the **fourth data box**, enter the display subsystem number corresponding to the subsystem labelled "4" in the figure that corresponds to the junction type on page 301. This is only needed for junction ID types 4, 24, 35 and 36. In the **fifth data box**, enter the display subsystem number corresponding to the subsystem labelled "5" in the figure that corresponds to the junction type on page 301. This is only needed for junction ID types 35 and 36.

The next step is for **junction types 11 and 36** only, and is greyed out for all other junction types). For junction type 11, the value to enter is the **number of individual point connections** between the two plates making up the junction. Note that this junction type **cannot be used for corrugated or sandwich plates** (subsystem types 11, 12, 19–25). For junction type 36, the value to enter is the number of studs in the double wall cavity.

The next step is to enter the **linear and/or rotational stiffness** of any flexible connection between the two subsystems making up a group in a structural junction. If no flexible connection exists, these values are left as zero. For beam-beam junctions and beam-plate junctions, the linear stiffness units are N/m and the rotational stiffness units are N-m/m. For plate-plate junctions, the linear stiffness units are N/m/m (Nm^{-2}) and the units for rotational stiffness are N-m/m/m (Nm^{-1}). This option is only available for junction types 1–12, 21–24. However, for junction types 9–12, only linear stiffnesses are appropriate and used by ENC. For junctions showing only bending wave transmission (sinusoid symbol), both linear and rotational stiffnesses are required, as although the transmission between bending waves is the result of rotational motion of the junction, some energy is lost due to the translational motion associated with the incident bending wave. This is accounted for in ENC. For junctions showing at least one subsystem with longitudinal waves (parallel straight lines symbol), only the linear stiffness of the flexible element is required, as transmission between longitudinal and bending waves is the result of translational (not rotational) motion of the junction caused by the incident bending wave. If there is no flexible connection, enter 0.0 (the default value) in the data box. For junction types 31 to 36, which involve acoustical spaces, the rotational stiffness line is greyed out but the "Linear stiffness" line is renamed to "**Area of wall radiating into or separating rooms (m^2)**". This value corresponds to the area of panel radiating acoustic energy into the room. The usual case is for this value to be the full area of the actual panel, but sometimes not the entire panel is radiating into the room of interest, such as when a smaller room is mounted on a larger floor or when there are several rooms on the same floor. If this value is left as zero or is less than 10^{-6}, the full panel area of the specified panel in the junction under consideration will be used.

The next step is to enter the **subsystem number in the junction figure** (see page 301) to which flexible element is attached. This number ranges from 0 to 4, depending on which junction type is selected. The value of 0 is used for cases where there is no flexible element.

Next, the **coupling loss factor** (CLF) is entered if this user-entered value is to be used for this group instead of the value calculated by ENC using the information in the above data boxes. If a calculated CLF is to be used, enter 0.0 (or a number less than 10^{-11}) in this box. ENC assumes that for each group, the entered value corresponds to the coupling loss factor, η_{ij}, where i is the subsystem ID number corresponding to the smallest number shown in the relevant junction picture and j is the subsystem ID number corresponding to the largest number shown in the picture (except for junction 36 – see next paragraph). For junction groups that contain more than two subsystems in the picture, coupling loss factors for the additional subsystem combinations are calculated from the entered value using ratios of corresponding calculated impedance values. If the user entered coupling loss factor is between two subsystems in a junction group that has more than one type or direction of motion (such as junctions 3(b), 4(a), 4(b), 23(b), 24(a) and 24(b), the calculation of the CLF corresponding to bending-longitudinal wave transmission (which is represented by a different type of junction motion) is a bit more complex. In this case, only the part of the user entered coupling loss factor that is associated with translational motion in the same direction as the longitudinal wave travel is used to calculate corresponding CLF. For example, in Junction 3(b) and 23(b), the user entered value for η_{13} includes both the translational and rotational junction motions. However, only the translational part can transmit energy to subsystem 2. As an example, referring to junction 3(b), the fraction of the user entered η_{13} to use for η_{12} is the ratio of the theoretical transmission coefficients $(\tau_{12}/(\tau_{13})$, where τ_{13} is the sum of the translational and rotational transmission coefficients for the transmission of bending waves.

For beams attached to plates via point connections, (junction types 5–8), the **Moment arm or force width on plate due to beam (m)** is required. For junction group 5(a), the width of the beam parallel to the plane of the plate surface should be entered. For junction group 5(b), the length of the diagonal across the beam cross-section should be entered, For junction group 5(c) the plate thickness is used so no need to enter a value here. No value is needed here for junction groups 6(a), 7(a), 8(a) and 8(b). For junction groups 6(b), 6(c), 7(b), 7(c) and 8(c) the beam cross-sectional dimension in the direction normal to the axis about which the applied force or moment causes the beam to bend or in the propagation direction of the produced bending or longitudinal wave, is required.

9.2.1 Junction Types 31–36

Junctions 31–36 are those that represent transmission of energy between two acoustic spaces and between an acoustic space and a plate-like structure. The acoustic spaces may be 1-D, 2-D or 3-D in nature. An example of a 1-D space is a pipe in which only wave propagation in a direction along the pipe axis is possible. The calculation of radiation efficiencies, for any plate-like structure separating one 1-D space from another 1-D space, is done assuming that the sound field in normally incident on the plate. The radiation efficiencies so calculated are used to determine coupling loss factors as explained in Appendix A.

An example of a 2-D space is the space between the two partitions of a double wall structure (see pictures on page 301 of junction types 34, 35 and 36). As can be seen, it is acceptable for a partition to separate two 3-D spaces (see picture of junction type 33) or a 3-D space and a 2-D space (see pictures of junction types 34–36). However, if space 1, 3 or 5 in any of the pictures of junction types 31–36 is a 1-D space, then all other spaces in a particular picture will be treated as a 1-D space with wave propagation in a direction normal to any partition. A space may be treated as 1-D if its cross-sectional dimensions (in the same plane as any partition) are sufficiently small that no cross modes can exist. This means that the cross-sectional dimensions must be smaller than half of a wavelength at all frequencies of interest (not usually the case).

When building up a system model involving transmission between acoustic spaces where tunnelling is involved (see pictures of junction types 33–36), it is important to add separate junctions that account for resonant transmission. As an example, if part of a subsystem looks like junction 35, it is necessary to enter into ENC a separate junction for each of the junction types shown in the top table on page 304 so that ENC calculates all the coupling loss factors needed for the analysis.

Junction type 32 is not an available option for the 1-D acoustic case as there are no acoustic modes present to couple with the modes on the plate. However, Junction types 31, 33–36 may also be used for 1-D acoustic fields, provided that 1-D assumptions apply to all acoustic spaces shown in the pictures on page 301. For 1-D acoustic fields, it is assumed that sound waves exciting any partition are normally incident on the partition.

If there is a double wall between two acoustic spaces, both the η_{24} and the η_{15} coupling loss factors must be calculated. For the 1-D double wall case, there can be no resonant transmission between partitions 2 and 4 or between the acoustic space 3 and partitions 2 or 4. Thus the lines corresponding to coupling loss factor indices, 2,3 3,4 and 2,4 in the tables on page 304 are deleted for the 1-D case. See Appendix A for a full description of the two methods.

If it is desirable to include sound absorbing material in the double wall cavity, it will be necessary to take this into account by selecting “9-From room sabine absorption coeff.” in the “19 Loss factor calculation method” line on the subsystem input data page for the acoustic space between the two wall panels. Then a value between 0.5 and 1.0 should be entered in the corresponding data box. If studs are used in the double wall, then the number and stiffness of the studs is selected on the coupling type 36 input data page and the mass of a single stud is selected on the coupling type 35 input data page.

The junction configurations that can be used by ENC are illustrated in the figure on page 301. Details of each junction type as well as explanations and options for calculating the coupling loss factor for each type and for each group for junctions with multiple types, are provided in Section A.8 in Appendix A.

9.3 Calculation of Subsystem Energies

These calculations are done in the SEA results page. First, the modal densities (modes/rad/sec), input powers (watts) and coupling loss factors are calculated. Then, the following equation is solved for subsystem modal energies, E_i/n_i, by matrix inversion using LU factorisation.

$$\omega \begin{bmatrix} (\eta_1 + \sum\limits_{\substack{i=1\\i\neq 1}}^{m} \eta_{1i})n_1 & (-\eta_{12}n_1) & \cdots & (-\eta_{1m}n_1) \\ (-\eta_{21}n_2) & (\eta_2 + \sum\limits_{\substack{i=1\\i\neq 2}}^{m} \eta_{2i})n_2 & \cdots & (-\eta_{2m}n_2) \\ \vdots & \vdots & \ddots & \vdots \\ (-\eta_{m1}n_m) & \cdots & \cdots & (\eta_m + \sum\limits_{\substack{i=1\\i\neq m}}^{m} \eta_{mi})n_m \end{bmatrix} \begin{bmatrix} E_1/n_1 \\ E_2/n_2 \\ \vdots \\ E_m/n_m \end{bmatrix} = \begin{bmatrix} \Pi_1 \\ \Pi_2 \\ \vdots \\ \Pi_m \end{bmatrix} \tag{9.2}$$

The mean square vibration velocity, $\langle u^2 \rangle_{St\Delta}$, of a structural subsystem, i, is related to its total energy, E_i, by:

$$\langle u^2 \rangle_{St\Delta} = E_i/M \qquad (\mathrm{m^2/s^2}) \tag{9.3}$$

where M is the total mass of the subsystem and the subscript, $St\Delta$, indicates that the average is over space, S, time, t, and frequency band, Δ.

The mean square sound pressure, $\langle p_i^2 \rangle_{St\Delta}$, in an acoustic subsystem, i, (such as an enclosure) is related to its total energy, E_i, by:

$$\langle p_i^2 \rangle_{St\Delta} = E_i \rho c^2 / V_i \quad (\mathrm{Pa^2}) \tag{9.4}$$

where V_i is the enclosure volume. The average sound pressure level, $L_{p,i}$, in the enclosure for the 1/3-octave or octave band being considered is then:

$$L_{p,i} = 10 \log_{10} \langle p_i^2 \rangle_{St\Delta} + 94 \qquad (\text{dB re } 20\,\mu\text{Pa}) \tag{9.5}$$

In addition to the subsystem total energy, it is of interest to calculate the subsystem modal energy so that the major power transmission paths can be identified. Subsystems with relatively low modal energies may be ignored as transmission pathways. The modal energy of subsystem, i, is given by $E_i/(n_i \times \Delta f)$, where the frequency units used in the modal density, n_i must be the same as used in the bandwidth, Δf. Note that in most cases E_i/n_i is referred to as the modal energy of subsystem, i, but this is not physically accurate. However, including the bandwidth in the equation is not necessary for comparing the relative modal energies in the subsystems making up the overall system. nevertheless, ENC does include the bandwidth in the modal energy results provided so they represent actual energy per mode (Joules).

9.4 Radiation Efficiencies

The radiation efficiency of a plate subsystem is used to calculate the CLFs for transmission into a room or wall cavity. It may also be used to calculate the sound power radiated to free space by the vibrating plate, once the mean square vibration velocity, $\{v^2\}$ is known (calculated in this module by ENC). The radiated sound power may be calculated using the following expression.

$$W = \rho c S \sigma \{v^2\}$$

where σ is the radiation efficiency and S is the plate area. The radiation efficiency for this calculation for a plate excited resonantly (or mechanically) is determined using Maidanik's theory (Maidanik, 1962), corrected according to Crocker and Price (1969a) and Leppington et al. (1982) (see Section A.6.1.1). If the plate is excited by an acoustic field (forced vibration) and radiating to free space, the radiation efficiency must be calculated according to Davy (2009) (see Section A.6.2.1).

However, radiation efficiencies are also used to calculate coupling loss factors for plates radiating into acoustic spaces and for this application there are a number of methods provided in the literature for calculating the radiation efficiency. If the radiation is into a 3D space, two options are available for calculating the radiation efficiency (see Section A.6.2.1). If the radiation is into a 2D cavity, there are also two possible and different options for calculating the radiation efficiency (see Section A.6.2.2).

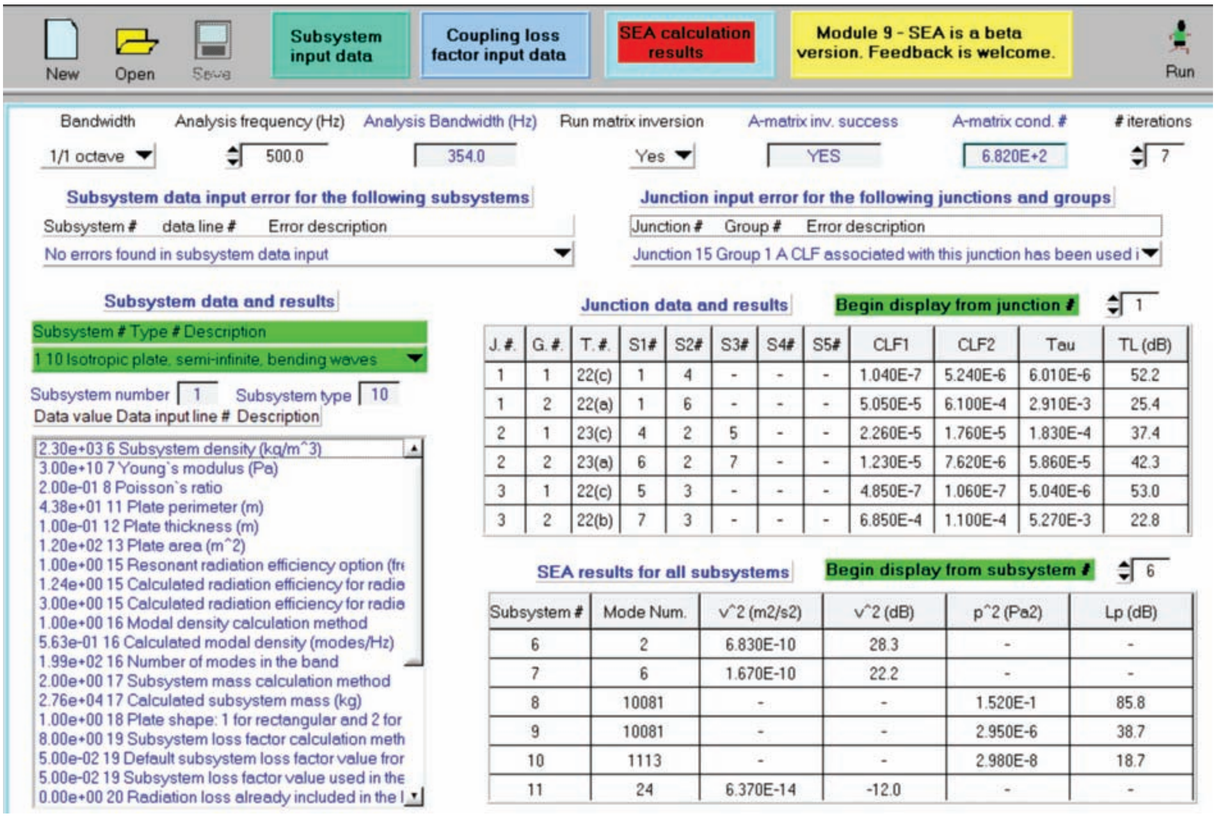
The various radiation efficiency calculation methods and situations in which each may be used are summarised in the following table.

Table 9.6 Radiation efficiency calculation methods for various plate excitation and location situations

Situation	Subsection reference in Appendix	Relevant references
Resonant (mechanical) excitation	A.6.1.1	Maidanik (1962) Crocker and Price (1969a) Leppington et al. (1982)
Forced (acoustic) excitation	A.6.2.1	Davy (2009)
Resonant or forced excitation	A.6.2.1	Lyon and DeJong (1995, p. 199) Fahy (1969)
Resonant or forced excitation	A.6.2.2	Craik (2003) Cremer et al. (1988, p. 533) Leppington et al. (1982, p. 269)
All excitation types 1-D space	A.6.2.3	Davy (2009)

Data for each type of radiation efficiency as well as the sound power (in watts) for each plate subsystem (as if it were radiating to free space) is provided in the ENC output file, SEAresults.txt.

9.5 Available Results



In addition to providing subsystem mean square velocities or sound pressure levels, ENC can provide a range of intermediate results if required. These results are available as text files that can be imported into a spreadsheet program such as excel, with column separations identified by a tab.

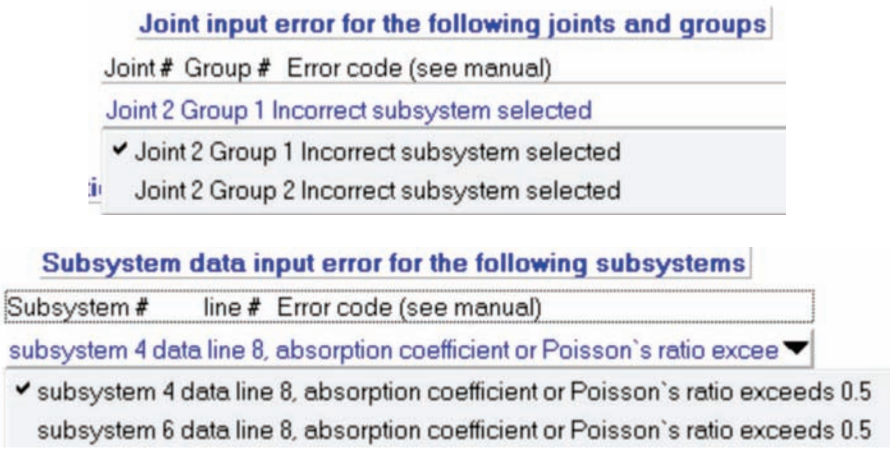
The results provided on the ENC GUI are shown in the figure on the previous page and the various sections are discussed separately in the following paragraphs.

The “A-matrix inversion success” shown in the second most right hand box in the top row of the GUI indicates whether the matrix inversion necessary to obtain a valid result was successful. If there is an “N” in this box none of the mean square velocity or sound pressure results are valid.

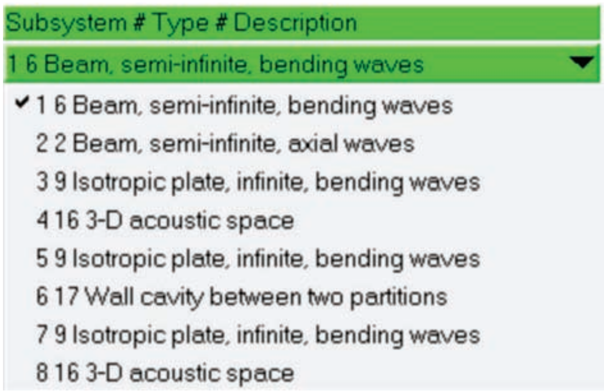
The A-matrix condition number indicates the accuracy that may be expected for the results, where the exponent (or power of ten) value in this number indicates the number of significant figures that are lost during the matrix inversion process. In ENC, the matrix inversion is implemented with double precision so the expected accuracy is 15 significant figures. So it can be seen that the condition number would have to be very large to be a problem (something like 10^{10}). ENC also uses LU decomposition prior to matrix inversion to optimise the order of the rows in the A-matrix so that the condition number is as small as possible.

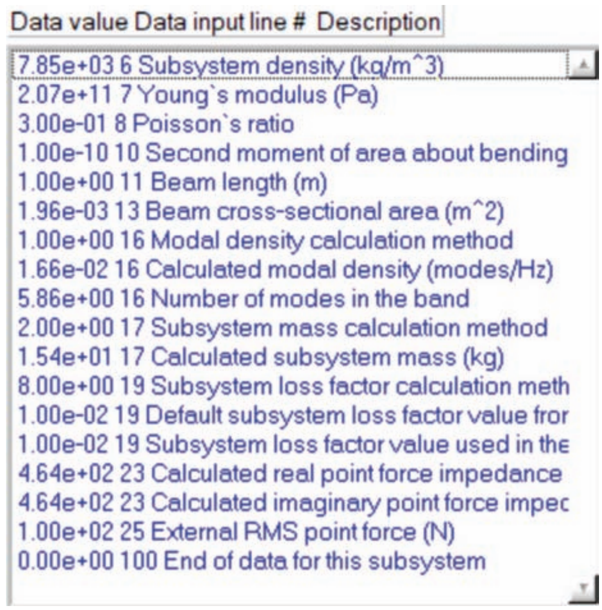
The box titled “# iterations has a value between 1 and 10. The greater the number of iterations, the more accurate will be the result. However, 3 or 4 iterations are usually sufficient. With each iteration the loss factor of each subsystem is increased slightly to account for energy loss via coupling to other subsystems. The amount to add is calculated as described in (Lyon and DeJong, 1995, p. 217).

The two tables below the next row of titles (see figure at right) list the errors in the data input by users that have been found by the ENC checking routine for the subsystems and junctions. Note that these errors are those that are most commonly expected and are not guaranteed to cover even most situations that may be encountered by careless data entry. If you see results that do not make sense, please carefully check your input data.



When clicking on a particular subsystem in the subsystem list on the LHS of the GUI (see figure at right), a pop-up page will appear with the input data and results for that subsystem. The first number in a line in the table is the data value. Even if the data value is an integer number input or a choice selected by the user on the GUI, its numerical value is expressed in this table as a real number of the form 0.xxxE+xx (eg 0.123E+02). If the data description in blue font is truncated, the full description may be read by double clicking on the relevant line.





Junction data including coupling loss factors, transmission coefficients and transmission loss values as well as which subsystems are participating in each junction, are provided in the upper table on the right-hand side of the GUI (see figure on page 315). The titles of the first 3 columns are “junction number”, “Group number” (see figure on the coupling loss factor input data page in ENC), and “junction type”. Note the box labelled “Begin display from junction #”. As there is only room for 6 junctions on the GUI and ENC allows up to 50 junctions, the number in this box enables you to begin the display at any junction number and see the data for the next 6 junctions (including the one in the data box).

Junction data and results   Begin display from junction # 1

J. #.	G. #.	T. #.	S1#	S2#	S3#	S4#	S5#	CLF1	CLF2	Tau	TL (dB)
1	1	22(c)	1	4	-	-	-	1.040E-7	5.240E-6	6.010E-6	52.2
1	2	22(a)	1	6	-	-	-	5.050E-5	6.100E-4	2.910E-3	25.4
2	1	23(c)	4	2	5	-	-	2.260E-5	1.760E-5	1.830E-4	37.4
2	2	23(a)	6	2	7	-	-	1.230E-5	7.620E-6	5.860E-5	42.3
3	1	22(c)	5	3	-	-	-	4.850E-7	1.060E-7	5.040E-6	53.0
3	2	22(b)	7	3	-	-	-	6.850E-4	1.100E-4	5.270E-3	22.8

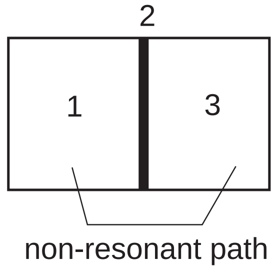
The columns labelled S1# to S5# show the subsystem ID numbers that correspond to the labels on the figure on the coupling loss factor input data page GUI. Each junction is characterised by 2 coupling loss factors, CLF1 and CLF2, one for each of the two directions of power transmission. For example, CLF1 for junction number 5 would be η_{12}, while CLF2 would be η_{21} and CLF1 for junction number 35 would be η_{15}, while CLF2 would be η_{51}. The one exception to the rule is for junction 36, where CLF1 is η_{24}, while CLF2 is η_{42} (see the figure on page 301, where the two calculated CLFs are between the subsystems connected by tunnelling). Values in the column labelled, "Tau", represent transmission coefficients and these are calculated for all junctions between structural element pairs or acoustic element pairs, but not between an acoustic and structural element pair. Transmission Loss (TL) values for structural junctions are a measure of the transmitted vibrational energy, while for acoustic spaces, they represent the usual measure of acoustic energy transmission. A text file of the data in this table is in the directory on your computer where ENC has been installed (eg d: enc6) and is named "Junctiondat.txt". Note that a dash for the value of coupling loss factor (CLF) η_{ij}, means that no energy is transmitted between subsystems i and j. Similarly, a dash for TL means that there is no transmission of energy via the junction in question and the actual TL is theoretically infinite. However in the file, "Junctiondat.txt", the dash for "Tau" is replaced with 0.0 and the dash for "TL(dB)" is replaced with 500.

9.5.1 Transmission Loss between Acoustic Spaces

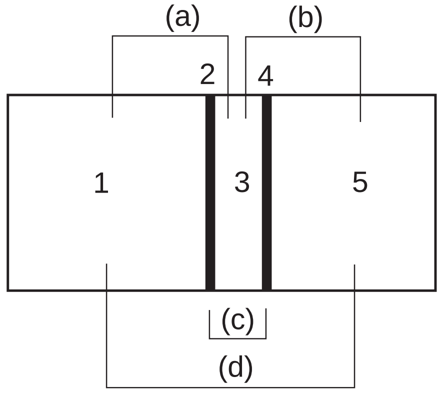
The transmission of energy from one acoustic space to another via a partition between the two spaces can be quantified using Transmission Loss or TL. In ENC, the TL is calculated from the ratio of the mean squared sound pressure in the acoustic space from which the noise originates, $\langle p_S^2 \rangle$, to that in the acoustic space (receiver space) where the noise is transmitted to, $\langle p_R^2 \rangle$, using:

$$\mathrm{TL} = 10\log_{10}\left(\frac{\langle p_S^2\rangle}{\langle p_R^2\rangle}\right) + 10\log_{10}\left(\frac{A}{S_R\bar{\alpha}_R}\right) \tag{9.6}$$

where A is the area of one side of the partition and $S_R\bar{\alpha}_R$ is the receiver space absorption.



For acoustic spaces separated by a single partition, the energy transmission has a resonant and a non-resonant component. The transmission coefficient for the resonant component, $(\tau_{12} \times \tau_{23})$, is added to that for the non-resonant component, τ_{13} to give the total transmission coefficient, τ.
The transmission loss is then: $\text{TL} = -10 \log_{10} \tau$.



For calculating the **TL of a double wall construction**, there are 3 different approaches suggested in the literature and all give slightly different results. All approaches use the same resonant transmission paths and each of these paths must be represented in ENC by a separate junction. The difference lies in how non-resonant transmission is treated. Referring to the figure at right, the resonant transmission paths between subsystem 1 and subsystem 5 are represented by the 4 junctions characterised by the loss factors, η_{12}, η_{23}, η_{34} and η_{45}, respectively. These junction types, as identified in the figure on page 301, are 31 (between subsystems 1 and 2), 32 (between subsystems 2 and 3), 32 (between subsystems 3 and 4) and 31 (between subsystems 4 and 5), respectively. The non-resonant transmission paths are shown on the figure at right as (a), (b), (c), and (d). One approach to obtain the overall non-resonant transmission coefficient is to multiply τ_a with τ_b and add the result to τ_d. In ENC, this is achieved by defining a junction of type 34 (between subsystems 1 and 3), a second junction of type 34 (between subsystems 3 and 5) and a third junction of type 35 (between subsystems 1 and 5). A second approach to obtain the overall non-resonant transmission coefficient is to add τ_c and τ_d. In ENC, this is achieved by defining a junction of type 36 (between subsystems 2 and 4), and a second junction of type 35 (between subsystems 1 and 5). A third approach, which may involve some double counting, is to use all paths mentioned in approaches one and two. In ENC, this requires defining a junction of type 34 (between subsystems 1 and 3), a second junction of type 34 (between subsystems 3 and 5), a third junction of type 35 (between subsystems 1 and 5) and a fourth junction of type 36 (between subsystems 2 and 4). The TL between acoustic spaces 1 and 5 is then calculated from the ratio of the mean squared sound pressure in the source room, $\langle p_S^2 \rangle$ to that in the receiver room $\langle p_R^2 \rangle$ using:

$$\text{TL} = 10 \log_{10} \left(\frac{\langle p_S^2 \rangle}{\langle p_R^2 \rangle} \right) + 10 \log_{10} \left(\frac{A}{S_R \bar{\alpha}_R} \right) \tag{9.7}$$

where A is the area of one side of the partition and $S_R \bar{\alpha}_R$ is the receiver room absorption.

It should be noted that sound absorbing material in the acoustic space between the wall panels not only adds damping to the acoustic space entered in the data box of item 19 on the subsystem input data page), but it may also add damping to the wall panels. ENC accounts for the acoustic damping automatically, but not so with the panel damping. The amount of panel damping to add depends on the type of contact (adhesive, pins, compression or just touching) and the magnitude of the bare panel loss factor. The smaller the bare panel loss factor, the greater will be the effect of the sound absorbing material. In practice, we may expect the TL increase due to cavity sound absorption to be between 2 and 4 dB at frequencies above the critical frequency of the panel most affected. The increase in damping for a lightly damped bare panel may be estimated as the amount that increases the TL in this range.

The TL output provided by ENC for junction types 33, 34 and 35 includes both resonant and non-resonant transmission. TL results for all other junctions only include either resonant or non-resonant transmission, depending on the type of transmission defined in the appendix for that particular junction. Thus, the TL for junction type 36 is the transmission loss due to non-resonant transmission across the cavity between the two partition leaves making up the double wall.

The "TL results" for junction types 31 and 32 represent the effective radiation efficiency of the radiating panel, as TL between a vibrating structure and acoustic space is meaningless. A negative "TL value" for either of these junction types means that the radiation efficiency of the panel is greater than 1.

9.5.2 Additional Results

Additional results (see figure on page 317), such as number of modes in the frequency band, mean square velocities and mean square sound pressures (with their decibel levels), are provided in a table for all subsystems on the RHS of the GUI. Note the box labelled "Begin display from junction #". As there is only room for 6 subsystems on the GUI and ENC allows up to 50 subsystems, the number in this box enables you to begin the display at any subsystem number and see the data for the next 6 subsystems (including the one in the data box). A text file of the data in this table is in the directory on your computer where ENC has been installed (eg d:/enc6) and is named "SEAresults.txt".

SEA results for all subsystems   Begin display from subsystem #   6

Subsystem #	Mode Num.	v^2 (m2/s2)	v^2 (dB)	p^2 (Pa2)	Lp (dB)
6	2	6.830E-10	28.3	-	-
7	6	1.670E-10	22.2	-	-
8	10081	-	-	1.520E-1	85.8
9	10081	-	-	2.950E-6	38.7
10	1113	-	-	2.980E-8	18.7
11	24	6.370E-14	-12.0	-	-

For users interested in junction transmission loss values, ENC produces a file called TLOSS.txt that can be found in the folder, enc6.x (enc6.3 for version 6.3), which is the directory where ENC was installed.

Appendix A

SEA (Module 9) Background Theory

A.1 Introduction and Approximations

In this appendix, we outline the theory that underpins the brief descriptions of how to use ENC in Chapter 9 of this manual. The purpose of using this SEA module is to calculate vibration and sound levels in structures made up of well defined elements called subsystems. Energies in these subsystems are characterised by mean square vibration velocities in structural elements and mean square sound pressures in acoustic elements. These quantities are calculated from the external input powers acting on each subsystem, which may be sound pressures (for acoustic subsystems) or forces (for structural subsystems). Calculations are also required to obtain subsystem input impedances, modal densities and internal damping for each structural element as well as the coupling loss factors that characterise the transmission of energy between adjacent subsystems. Note that a subsystem for the purposes of SEA contains only a single wave type on a single structural element. Different wave types are included by adding a subsystem for each wave type. The procedure for calculating subsystem energies and corresponding mean square velocities and sound pressures in each subsystem is described in Section A.9. Prior to that section, are sections detailing how to calculate the quantities required for calculating subsystem energies. The energy input to the system by one or more excitation forces or sound fields is equal to the total energy in the system (consisting of all of the subsystems) plus that lost due to damping and sound radiation. The energy is assumed to be equally distributed among all vibration modes, so that each mode of a subsystem or system of connected subsystems has equal modal energy. For a given subsystem, the total vibratory power flowing into it is equal to the power dissipated by the subsystem plus the power flowing out of it. Energy is also dissipated at junctions between adjacent structural subsystems. By setting up appropriate matrix equations, the modal energy in each part of the structure can be determined and this modal energy is directly related to the area, time and band averaged mean square vibration velocity of a structural subsystem or the area, time and band averaged mean square sound pressure in an acoustic subsystem. The vibration velocity levels of structural subsystems together with their radiation efficiencies can be used to estimate the sound power radiated by a particular subsystem.

It is important to remember that SEA is an approximate analysis, intended to provide the user with a guide as to expected vibration and acoustic levels in a connected structure subjected to external excitation sources. SEA is most effective in predicting changes on vibration and/or acoustic levels as a result of structural changes. Many analytical papers have been written about the energy flow between coupled structures and it is clear that an accurate analysis is complex, impractical to program for structural systems containing many elements and beyond what is intended by ENC. The most important approximations, uncertainties, assumptions and information regarding some of the calculations undertaken in the analysis performed by ENC are listed below.

1. The power flow between two coupled systems is proportional to the difference in average modal energies in the two subsystems, which means that it is assumed that the systems are only weakly coupled. Weak coupling applies if the subsystem loss factor is much greater (at least a factor of 3) than coupling loss factors between the the subsystem in question and other connected subsystems.

2. The number of acoustic or vibration modes in the frequency band of interest must be more than three for all subsystems. Fewer modes results in less accurate results.

3. The modal overlap should also be greater than 1, so subsystems with greater internal damping (higher loss factors) require fewer modes for the same accuracy.

4. The loss of energy due to dissipation at junctions between subsystems is assumed to be included in subsystem damping loss factors.

5. Loss of energy due to acoustic radiation from plate-like subsystems can be significant and is calculated by ENC and added to the subsystem loss factor if that subsystem is exposed to free space.

6. For plate-like subsystems, the plate thickness must be less than the plate bending wavelength/6. This may not apply to sandwich plates.

7. The dimensions of any subsystem for a particular wave type must not exceed $c_g/(2\pi f\eta)$, where c_g is the group wave speed, f is the excitation frequency (Hz) and η is the internal loss factor for the subsystem.

8. As the impedance of plates is a function of mass/unit area and stiffness, similar expressions can be used for isotropic, corrugated and sandwich plates.

9. For the calculation of coupling loss factors involving plates, it is assumed that the wave fields are dominated by normal incidence components so that use of the normal incidence transmission coefficient to calculate the CLF is sufficiently accurate, especially considering the general accuracy limitations of the SEA method.

10. The longitudinal wavespeed in a corrugated panel is same as for an isotropic panel.

11. The longitudinal wavespeed in sandwich panel same as in skins.

12. For calculating the point force impedance for junction 5(a) for a sandwich plate, m is the mass/unit area of skins. Then we use the same expression as for a non-sandwich plate.

13. For calculating the point force impedance for junction 5(b) for a sandwich plate, it is a bending moment input so we can use the same equation as for part 5(c).

14. The moment equation for the plate impedance can be split into real and imaginary parts by multiplying the numerator and denominator by the complex conjugate of the denominator. The result of one example is shown below.
$$\frac{5.3\omega m}{k_{Bp}^4}\left[1 - 1.46\mathrm{j}\log_{\mathrm{e}}(0.89k_{Bp}r)\right]^{-1} = \frac{5.3\omega m(1 + \mathrm{j}1.46\log_{\mathrm{e}}(0.89k_{Bp}r)}{k_{Bp}^4[1 + (1.46\log_{\mathrm{e}}(0.89k_{Bp}r))^2]}$$

15. For junction type ID = 10, the beam bending motion is solely in a direction normal to the plate surface.

16. Junction type ID = 11 is only valid for isotropic plates, not for corrugated or sandwich plates.

17. For junction types 6 and 7 only, beams can be on both sides of plate so the point impedance sum used in the CLF calculations must include both beams but only count the plate once. We cannot mix different wave types on different sides of plate. However, wave types for junction types (b) and (c) are the same, so the impedance sum in these cases must include bending waves from all beams.

18. Rotational stiffnesses are needed for junction types 1 (b), 1(c), 2(b), 3(c), 4(b), 5(b), 5(c), 6(b), 6(c), 7(b), 8, 21(b), 22(a), 22(b), 23(c), 24(b) if there is a flexible element in the junction.

19. Linear stiffnesses are needed for junction types 1(a), 2(a), 3(a), 3(b), 4(a), 5(a), 6(a), 7(a), 9, 21(b), 22, 23(a), 23(b), 24(a) if there is a flexible element in the junction.

20. For line impedances, ρ_mh has been replaced by m, mass/unit area, which allows incorporation of corrugated and sandwich plates.

21. The isotropic plate analysis is only valid for thin plates or thin skins on sandwich plates. Thin is defined as $h \leq 0.8c_s/f$.

22. For corrugated plates, if a sinusoidal profile specified, ENC will calculate the stiffness in the stiffest direction and ignore the user entered stiffness in data input line 9 on the “Subsystem input data page.

23. If point masses on a junction and/or junction flexibility are to be taken into account, we can only use the “Lyon, Craik or Leppington” CLF calculation method, which involves calculating the point force or moment impedances of the subsystems making up the junction.

A.2 SEA Concepts

For a satisfactory outcome from an SEA analysis, it is necessary to consider frequency-band-averaged data, using at least 1/3-octave bandwidths, and preferably octave bandwidths. It is recommended that there should be at least three modes resonant in the frequency band being considered for each subsystem involved in the analysis, and the modal overlap (see chapter 6 in the 6th edition textbook) should be at least unity and even higher if possible. A modal overlap factor greater than unity will reduce the variance of the estimated response, but it is not a requirement for the successful application of SEA (Shorter and Langley, 2005; Lyon, 1995). For further discussion on this topic, readers should refer to Mace (2003); Renji (2004); Wang and Lai (2005).

One of the concepts behind SEA is that interconnected systems transfer vibro-acoustic energy between them and the total energy in the system must always be fully accounted for. Consider two generic vibro-acoustic systems as shown in Figure A.1, which have a mechanism to transfer energy between them. Examples of a vibro-acoustic system could be a vibrating panel, or an enclosure such as a room.

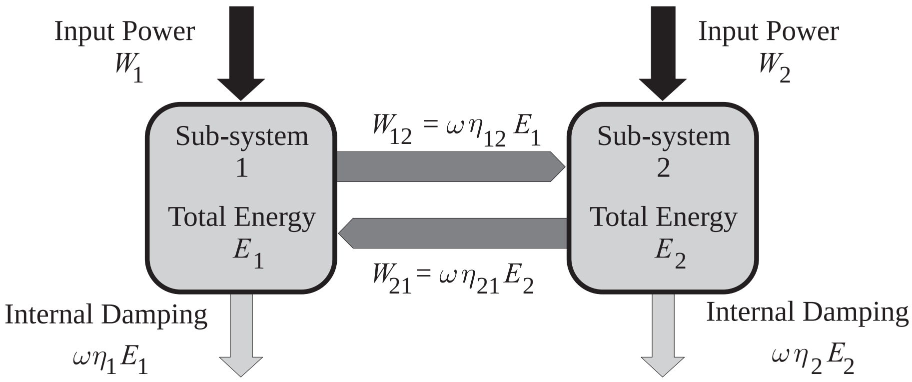


Figure A.1 Two vibro-acoustic systems that are connected and have power flowing into (or out of) them.

Imagine that a system boundary is drawn around subsystem 1 in Figure A.1. An equation describing the energy balance of subsystem 1 is:

$$W_1 + W_{21} = \omega\eta_1 E_1 + W_{12} \tag{A.1}$$

where W_1 is the external input power entering subsystem 1, W_{21} is the power coming from subsystem 2 into subsystem 1, $\omega\eta_1 E_1$ is the power dissipated in subsystem 1 by damping mechanisms, η_1 is the dissipative or damping loss factor (DLF) in subsystem 1, ω (radians/sec) is the centre frequency of the band, E_1 (joules) is the total energy in subsystem 1, W_{12} is the power (watts) that leaves subsystem 1 and goes into subsystem 2. The left-hand side of Equation (A.1) is the power entering the subsystem, and the right-hand side is the power that is lost by the subsystem by damping and power transferred to a connected subsystem. Equation (A.1) can be re-arranged to give:

$$W_1 = [\omega\eta_1 E_1] + [\omega\eta_{12} E_1] - [\omega\eta_{21} E_2] \tag{A.2}$$

where $W_{12} = [\omega\eta_{12}E_1]$, $W_{21} = [\omega\eta_{21}E_2]$, η_{12} is the coupling loss factor from subsystem 1 to subsystem 2 and η_{21} is the coupling loss factor from subsystem 2 to subsystem 1. The coupling loss factor (CLF) is a ratio of the energy that is transferred from one subsystem to another, which varies with frequency, and can be determined theoretically, numerically using finite element analysis, or experimentally. The determination of CLFs is discussed in detail in Section A.8. The difference between DLFs and CLFs is that the former is a measure of energy lost by a subsystem due to dissipation within the subsystem and the latter is a measure of the energy transferred to another system across a common boundary.

A complex vibro-acoustic system modelled using the SEA framework can be thought of as a network of subsystems, where power flows in and out, and energy is stored within the systems. Altering the (CLFs) or DLFs of the system has the effect of re-routing the power distribution throughout the network.

Consider the general case of k interconnected subsystems, where $\eta_{i,j}$ represents the coupling loss factor for power transmission between subsystem i and subsystem j, η_i represents the internal damping loss for subsystem, i, n_i represents the modal density, in modes/radian/sec for subsystem, i, W_i represents the external power injected into subsystem i and E_i represents the steady state energy in subsystem i. A system of energy balance equations from Equation (A.2) can be formed and put into a matrix equation as:

$$\omega \begin{bmatrix} (\eta_1 + \sum_{i\neq 1}^{k} \eta_{1i})n_1 & (-\eta_{12}n_1) & \cdots & (-\eta_{1k}n_1) \\ (-\eta_{21}n_2) & (\eta_2 + \sum_{i\neq 2}^{k} \eta_{2i})n_2 & \cdots & (-\eta_{2k}n_2) \\ \vdots & \vdots & \ddots & \vdots \\ (-\eta_{k1}n_k) & \cdots & \cdots & (\eta_k + \sum_{i\neq k}^{k} \eta_{ki})n_k \end{bmatrix} \begin{bmatrix} E_1/n_1 \\ E_2/n_2 \\ \vdots \\ E_k/n_k \end{bmatrix} = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_k \end{bmatrix} \tag{A.3}$$

or in short form as:

$$\omega[\mathbf{C}][\mathbf{E}/\mathbf{n}] = [\mathbf{W}] \tag{A.4}$$

where $[\mathbf{C}]$ is the $(k \times k)$ matrix consisting of combinations of CLFs, DLFs and modal densities as indicated in Equation (A.3), $[\mathbf{E}/\mathbf{n}]$ is the $(k \times 1)$ vector proportional to the modal energies within each subsystem and $[\mathbf{W}]$ is the $(k \times 1)$ vector of input powers to each subsystem. The input power to each subsystem is known (from measurements or from the problem description) and hence the energy, $[\mathbf{E}/\mathbf{n}]$, within each system can be calculated by pre-multiplying each side of the equation by the inverse of $\omega[\mathbf{C}]$:

$$[\mathbf{E}/\mathbf{n}] = \frac{1}{\omega}[\mathbf{C}]^{-1}[\mathbf{W}] \tag{A.5}$$

Determination of subsystem input powers, DLFs, modal densities and CLFs is discussed in Sections A.5, A.6, A.7 and A.8, to follow. The use of mean square vibration velocities to calculate the sound power radiated by a structural subsystem is discussed in Section A.3.

A.3 Subsystem Responses

Following the evaluation of Equation (A.276) and calculation of the energies in each subsystem, the usual practice is to determine the mean square vibration velocity or the mean square acoustic pressure response of all or some subsystems. For structural subsystems the mean square velocity, $\langle v^2\rangle_{St\Delta}$, of the subsystem is:

$$\langle v^2\rangle_{St\Delta} = E/M \tag{A.6}$$

where E is the energy in the subsystem, and M is the total mass of the subsystem. For a structural subsystem with a surface (usually plane) of area, S_S, the band-averaged radiated sound power, $W_{\Delta S}$, is calculated using:

$$W_{\Delta S} = S_S \rho c \sigma_{\Delta S} \langle v^2\rangle_{St\Delta} \tag{A.7}$$

The subscript, Δ, denotes frequency band average, and $\sigma_{\Delta S}$ is the band-averaged radiation efficiency for the structure. ENC only considers sound radiation from plate-like structures, where the radiation efficiency for resonant response (mechanical excitation) is discussed in Section A.6.1.1 and for a plate excited by an acoustic field (forced response), the radiation efficiency is discussed in Section A.6.2.1.

For a thick plate ($h > 0.3c_B/f$), the radiation efficiency for excitation by a vibration field is (Vér, 2006, p. 511):

$$\sigma = \begin{cases} 0.45\sqrt{Pf/c}; & f \le (f_c + 5c/P) \\ 1; & f >> (f_c + 5c/P) \end{cases} \tag{A.8}$$

In the preceding equations, the quantities P and S_p are the panel perimeter and area, respectively. The panel is assumed to be isotropic of uniform thickness, h, and characterised by longitudinal wave speed, c_L. For steel and aluminium panels, c_L takes the value of about 5400 m/s, while for wood, the value lies between 3800 and 4500 m/s. Values of c_L for other materials can be found from the material selection list in Module 5 (double click on the green heading, “Layer 1”).

For acoustic subsystems the space, time and band averaged square pressure is:

$$\langle p^2\rangle_{St\Delta} = E\rho c^2/V \tag{A.9}$$

Analysis of vibro-acoustic problems using SEA can be conducted using commercial or free SEA software or they can be analysed using MATLAB or spreadsheet software packages such as Microsoft Excel or OpenOffice Calc.

A.4 Subsystem Input Impedances

Input Impedances are used to calculate the input power resulting from a point or line force or an incident acoustic field, as will become apparent in Section A.5. They are also used to calculate coupling loss factors (see Section A.8). Point, line and area impedances for various structural and acoustic subsystems are provided in Tables A.1 to A.6.

Although there is not a separate page for calculating subsystem point, line and area impedances, these quantities are used in the Input Power page as well as the Coupling Loss Factor page and are discussed separately here.

Point moment impedances are reduced by a factor of 2 for each pinned boundary, compared to the case where there is an unpinned boundary; and the beam moment impedance is reduced by a factor of 4 at an end that is free to rotate and translate, compared to the case of an infinitely long beam (Lyon and DeJong, 1995, p. 201). This can be seen in Table A.1 in the equation for the impedance of a point force applied normal to the axis of a thin, infinite beam, compared with the equation for a point force applied normal to the axis of a thin, semi-infinite beam, which differs by a factor of 4.

To estimate structural input powers arising from externally applied point forces, we need to know the structural point force impedance at the point of application of the force or the point moment impedance at the point of application of the moment. The space and frequency averaged point impedance of a finite system is well approximated by the point impedance of the equivalent infinite system. The infinite system impedance is used to calculate the externally acting input force or moment in situations where the input force or moment is applied at distances that are at least 1/4 of a wavelength from a structural boundary. The same applies for junction impedances used to calculate coupling loss factors (Lyon and DeJong, 1995, p. 201). For cases for which the junction or location of an applied external force is less than 1/4 of a wavelength from a structural boundary, the resulting semi-infinite impedance values can be derived from the corresponding infinite impedance values by reducing the infinite impedance value by a factor of 2 for each degree of freedom (DOF) that is unrestrained. Thus, for a free beam end, the factor is 2 for torsional or axial excitation or transmission (as these only involve the one displacement or rotational DOF) and 4 for bending wave excitation and transmission (as this involves a displacement and a rotational DOF).

For structures for which there is no analytical expression for the equivalent infinite system impedance, the frequency and space-averaged, real part of the point force impedance may be found from the average modal density over the bandwidth under consideration using (Lyon and DeJong, 1995, p. 200):

$$\langle \mathrm{Re}\{Z_F\}\rangle_{S,\Delta} = \frac{2M}{\pi n(\omega)} \tag{A.10}$$

where M is the total mass of the subsystem and $n(\omega)$ is the modal density.

For a 3D acoustic space the frequency and space-averaged point resistance is:

$$\langle \mathrm{Re}\{Z_A\}\rangle_{S,\Delta} = \frac{\pi n(\omega)\rho c^2}{2V} \approx \frac{\pi \rho f^2}{c} \tag{A.11}$$

where V is the volume of the acoustic space.

For beams excited axially or torsionally or plates excited in bending, the imaginary part of the point impedance is equal to 0. For beams in bending, the imaginary part is equal to the real part. For in plane excitation of plates, the imaginary impedance is a function of the area over which the force acts. For this case, the imaginary impedance is set equal to zero if the area over which the force acts is unknown.

Line impedances are needed to calculate coupling loss factors for plates connected at their edges (see Lyon and DeJong, 1995, p. 202).

Area impedances are needed for calculating coupling loss factors for plates radiating into a room or into free space. They are also needed the calculate the external input power if the external forcing function is an acoustic field. The area impedance of an acoustic space is ρc. The area impedance of a plate is $\mathrm{j}2\pi f \rho_m h_p$ (Lyon and DeJong, 1995, p. 202), where h is the plate thickness, S is the plate cross-sectional area, $k_B = 2\pi/\lambda_B$, $\lambda_B = c_B/f$, c_B is the bending wave speed and c_L is the longitudinal wave speed.

The area impedance (reciprocal of admittance) for an acoustic space is $Z_{F\infty}^{\text{area}} = \rho c$ (Lyon and DeJong, 1995, p. 202).

The coupling loss factor formulation requires a real impedance for the calculation of the transmission coefficient. This is realised in practice by using the magnitude of the impedance in place of the real impedance when and only when the real impedance is zero.

Table A.1 Summary of point impedance formulae, $Z_{F\infty}$ and $Z_{T\infty}$, for isotropic thin beams excited by a point force or point torque (or moment), respectively (Cremer et al., 2005, p. 273, 288) and (Lyon and DeJong, 1995, p. 201-202), where variables are defined following Table A.6

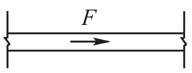
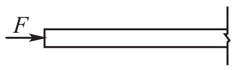
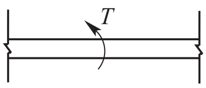
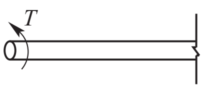
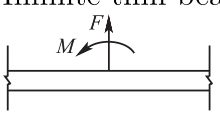
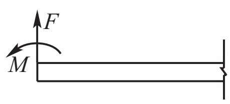
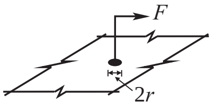
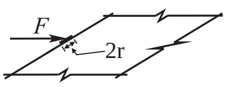
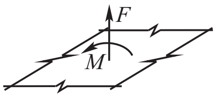
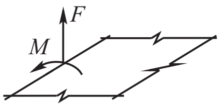
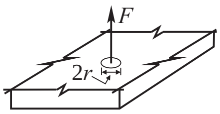
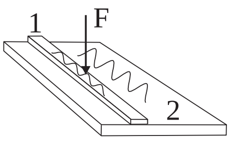
Wave type	Structural element	$Z_{F\infty}$	$Z_{T\infty}$ or $Z_{M\infty}$
Longitudinal	Infinite thin beam 	$2S_b\sqrt{E\rho_m} = 2\rho_m S_b c_{LII}$	—
Longitudinal	Semi-infinite thin beam 	$S_b\sqrt{E\rho_m} = \rho_m S_b c_{LII}$	—
Torsional	Infinite shaft 	—	$2J_x\sqrt{G\rho_m(J'/J_x)} = 2\rho_m J_x c_T$
Torsional	Semi-infinite shaft 	—	$J_x\sqrt{G\rho_m(J'/J_x)} = \rho_m J_x c_T$
Bending	Infinite thin beam 	$2\rho_m S_b c_B(1+\mathrm{j})$	$2\rho_m S_b c_B(1-\mathrm{j})/k_B^2$
Bending	Semi-infinite thin beam 	$\frac{1}{2}\rho_m S_b c_B(1+\mathrm{j})$	$\frac{1}{2}\rho_m S_b c_B(1-\mathrm{j})/k_B^2$

Table A.2 Summary of point impedance formulae, $Z_{F\infty}$ and $Z_{M\infty}$, for thin plates excited by a point force or a point moment (Cremer et al., 2005, p. 275, 288), (Lyon and DeJong, 1995, p. 201, 202) and (Vér, 2006, pp. 498, 499), where variables are defined following Table A.6

Wave type	Structural element	$Z_{F\infty}$	$Z_{M\infty}$
In-plane	Infinite, thin isotropic plate 	$8\pi m f r^2 \left(1 - \frac{\mathrm{j}c_{LI}}{2\pi f r}\right)$	—
In-plane	Semi-infinite, thin isotropic plate 	$4\pi m f r^2 \left(1 - \frac{\mathrm{j}c_{LI}}{2\pi f r}\right)$	—
Bending	Infinite, thin isotropic plate 	$8\omega m/k_{Bp}^2$ $= 2.3 m c_{LI} h$ $= 8 m \kappa_p c_{LI}$	$\frac{16\omega m}{k_{Bp}^4}\left[1 - \frac{4\mathrm{j}}{\pi}\log_{\mathrm{e}}(0.89 k_{Bp} r)\right]^{-1}$
Bending	Semi-infinite, thin isotropic plate 	$3.5\omega m/k_{Bp}^2$ $= m c_{LI} h$	$\frac{5.3\omega m}{k_{Bp}^4}\left[1 - 1.46\mathrm{j}\log_{\mathrm{e}}(0.89 k_{Bp} r)\right]^{-1}$
Bending*	Infinite, thick isotropic plate ($h > 0.8c_s/f$) 	$\frac{Gc_s}{\omega^2}\left\{\frac{0.063}{H^2} + \frac{1}{8}\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left(\frac{0.001}{H^{1.3}} + \frac{0.06\pi c_s}{r\omega}\right)\right\}^{-1}$ Assumes that Poisson's ratio, $\nu = 0.3$	—
Bending	Beam bonded to isotropic plate 	$\begin{cases} \frac{(1-\mathrm{j})k'}{4\rho'_s\omega}; & S_b < (\lambda_{Bb}/6)^2 \\ 2(1+\mathrm{j})\rho_m S_b c_{Bb}; & S_b \geq (\lambda_{Bb}/6)^2 \end{cases}$ where $\rho'_s = \rho_m S_b + 2\rho_m h_p/k_{Bp}$ $k' = (\rho'_s/B)^{1/4}\omega^{1/2}A$ $A = 1 - \mathrm{j}\rho_m h_p/(2\rho'_s k_{Bp})$ $B = Eh_b^3 b/3$	—

*The thick plate point force impedance equation for a semi-infinite plate can be assumed to be approximately 1/2 of the impedance for an infinite thick plate.

Table A.3 Summary of point impedance formulae, $Z_{F\infty}$ and $Z_{M\infty}$, for corrugated and sandwich plates excited by a point force or a point moment, derived from Equations in Table A.2, where variables are defined following Table A.6

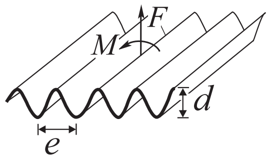
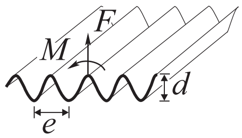
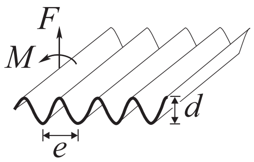
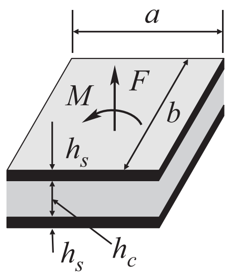
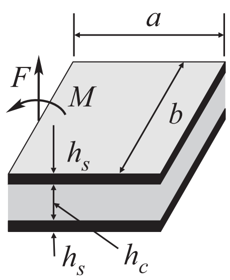
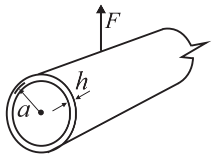
Wave type	Structural element	$Z_{F\infty}$	$Z_{M\infty}$
Bending	Infinite, corrugated plate 	$8[m^2 B_a B_b]^{1/4}$ $\lambda_B >> e$	$\dfrac{16\omega m}{k_{Bp}^4}\left[1 - \dfrac{4\mathrm{j}}{\pi}\log_\mathrm{e}(0.89k_{Bp}r)\right]^{-1}$ $k_B = \left(\dfrac{\omega^4 m^2}{B_a B_b}\right)^{1/8}$
Bending stiffest	Semi-infinite, corrugated plate 	$3.5\sqrt{mB_a}$ $\lambda_B >> e$ $B_a = \max(B_a, B_b)$	$\dfrac{5.3\omega m}{k_{Bp}^4}\left[1 - 1.46\mathrm{j}\log_\mathrm{e}(0.89k_{Bp}r)\right]^{-1}$ $k_B = \left(\omega^2 m/B_a\right)^{1/4}$;
Bending least stiff	Semi-infinite, corrugated plate 	$3.5\sqrt{mB_b}$ $\lambda_B >> e$ $B_b = \min(B_a, B_b)$	$\dfrac{5.3\omega m}{k_{Bp}^4}\left[1 - 1.46\mathrm{j}\log_\mathrm{e}(0.89k_{Bp}r)\right]^{-1}$ $k_B = \left(\omega^2 m/B_b\right)^{1/4}$;
Bending	Infinite, honeycomb core sandwich plate (3 freq. regions) 	$8\sqrt{B_i m_i}$	$\dfrac{16\omega m_i}{k_{Bp}^4}\left[1 - \dfrac{4\mathrm{j}}{\pi}\log_\mathrm{e}(0.89k_{Bp}r)\right]^{-1}$ $k_B = \left(\omega^2 m_i/B_i\right)^{1/4}$;
Bending	Semi-infinite, honeycomb core sandwich plate (3 freq. regions) 	$3.5\sqrt{B_i m_i}$	$\dfrac{5.3\omega m_i}{k_{Bp}^4}\left[1 - 1.46\mathrm{j}\log_\mathrm{e}(0.89k_{Bp}r)\right]^{-1}$ $k_B = \left(\omega^2 m_i/B_i\right)^{1/4}$;

Table A.4 Summary of point impedance formulae, $Z_{F\infty}$, for isotropic thin cylinders excited by a point force (Vér, 2006; Cremer et al., 2005), where $k_B = \omega/c_B$, with other variables are defined following Table A.6

Wave type	Structural element	$Z_{F\infty}$ (Cremer et al., 2005, p. 270, 272)	$Z_{F\infty}$ (Vér, 2006, p. 500)
Bending	Infinite, thin tube 	$\begin{cases} 2.3c_{LI}\rho_m h^2; \\ (f/f_r > 2) \\ \dfrac{2\pi a\rho_m h\sqrt{\omega c_{LI} a/\sqrt{2}}}{(1-\mathrm{j})}; \\ (f/f_r < 0.77h/a) \\ \dfrac{2.3c_{LI}\rho_m h^2}{0.66}\sqrt{\dfrac{f_r}{f}}; \\ (0.77h/a < f/f_r < 0.6) \end{cases}$	$\begin{cases} 2.3c_{LI}\rho_m h^2; \\ (f/f_r > 1.5) \\ 2.3c_{LI}\rho_m h^2 (f_r/f)^{2/3}; \\ (f/f_r < 0.7) \end{cases}$

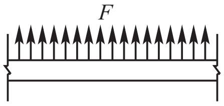
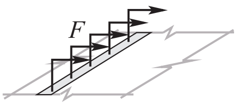
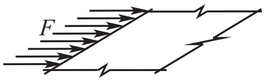
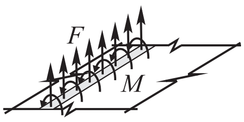
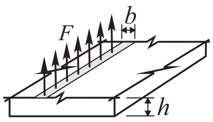
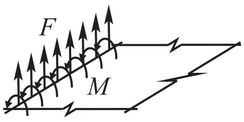
For beams excited axially or torsionally or plates excited in bending, the imaginary part of the point impedance is equal to 0. For beams in bending, the imaginary part is equal to the real part. For in plane excitation of plates, the imaginary impedance is a function of the area over which the force acts. For this case, the imaginary impedance is set equal to zero if the area over which the force acts is unknown.

Line impedances are needed to calculate coupling loss factors for plates connected at their edges (see Lyon and DeJong, 1995, p. 202).

Area impedances are needed for calculating coupling loss factors for plates radiating into a room or into free space. They are also needed the calculate the external input power if the external forcing function is an acoustic field. The area impedance of an acoustic space is ρc. The area impedance of a plate is $\mathrm{j}2\pi f\rho_m h$ (Lyon and DeJong, 1995, p. 202), where h is the plate thickness and ρ_m is the plate density.

The area impedance (reciprocal of admittance) for an acoustic space is $Z_{F\infty}^{\text{area}} = \rho c$ (Lyon and DeJong, 1995, p. 202).

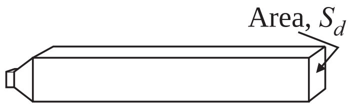
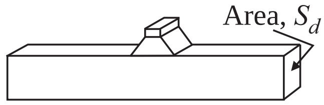
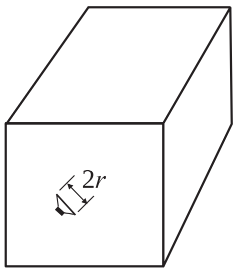
Table A.5 Summary of line impedance formulae, $Z^{\text{line}}_{F\infty}$ and $Z^{\text{line}}_{M\infty}$, for beams and isotropic thin plates[1] excited by a line force or moment, respectively (Lyon and DeJong, 1995, p. 201-202), where $k_B = \omega/c_B$ and all variables are those for the plate, defined following Table A.6

Wave type	Structural element	$Z^{\text{line}}_{F\infty}$	$Z^{\text{line}}_{M\infty}$
Bending	Infinite thin beam 	$\mathrm{j}2\pi f \rho_m S_b$	
Longit-udinal	Infinite thin plate 	$2h\sqrt{E\rho_m}$ $= 2\rho_m h c_{LI}$	—
Longit-udinal	Semi-infinite thin plate 	$h\sqrt{E\rho_m}$ $= \rho_m h c_{LI}$	—
Bending	Infinite thin isotropic plate 	$2\rho_m h c_B(1+\mathrm{j})$	$2\rho_m h c_B(1-\mathrm{j})/k^2_{Bp}$
Bending[2]	Infinite thick isotropic plate ($h > 0.8c_s/f$) 	$\frac{G}{\omega}\left\{\frac{1}{8H^{3/2}} + 0.31\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left[\frac{-1}{8H^{3/2}} + 0.16\log_\mathrm{e}\left(\frac{2\pi c_s}{b\,\omega}\right)\right]\right\}^{-1}$ Assumes that Poisson's ratio, $\nu = 0.3$	—
Bending	Semi-infinite, thin isotropic plate 	$\frac{1}{2}\rho_m h c_B(1+\mathrm{j})$	$\frac{1}{2}\rho_m h c_B(1-\mathrm{j})/k^2_{Bp}$

[1]The same equations can be used for corrugated and sandwich plates, provided that the corresponding values of c_B from Table A.14 are used and the mass per unit area, m from Table A.14 is used in place of $\rho_m h$ for bending waves. For the two longitudinal plate wave examples applied to sandwich plates, the thickness h, is the mean thickness of the two skins and E and ρ_m are Young's modulus and density of the skin material.

[2]The thick plate line force impedance equation for a semi-infinite plate can be assumed to be approximately 1/4 of the impedance for an infinite thick plate.

Table A.6 Summary of point acoustic impedance formulae $Z_A = p/(S_d u_0)$ for a 1-D duct (plane wave propagation) and a 3-D acoustic space

Acoustic space type	Illustration	Z_A
Semi-infinite 1-D duct		$\rho c/S_d$
Infinite 1-D duct		$2\rho c/S_d$
3-D acoustic space. For a source mounted in a wall, the impedance is multiplied by 2, for a source at the junction of two walls, the impedance is multiplied by 4 and for a source mounted in a room corner, the impedance is multiplied by 8.		$\dfrac{\pi\rho f^2}{c}\left(1+\dfrac{2\mathrm{j}}{2kr}\right)$ Source more than 1/4 wavelength from a room surface.

The variables in Tables A.1 to A.6 are defined as follows:

a = cylinder radius (inner radius plus half the wall thickness) or radius of circular beam (m);

b = width of the beam cross section in a direction parallel to the plane of the plate;

B = bending stiffness = EJ_y for a beam and $\dfrac{Eh^3}{12(1-\nu^2)}$ for an isotropic plate (kg m^2 s^{-2});

B_a = bending stiffness for wave travel parallel to the corrugations of a corrugated plate (see Equation (7.10) and Figure 7.4 in the 5th edn textbook. ENC calculates this in Module 5, single wall, orthotropic page by clicking on "More Properties for Orthotropic panel" (kg m^2 s^{-2});

B_b = bending stiffness for wave travel across the corrugations of a corrugated plate = $\dfrac{Eh^3}{12(1-\nu^2)}$ (kg m^2 s^{-2});

B_i = bending stiffness of a sandwich plate for excitation frequency, i (see Table A.15 for its calculation) (kg m^2 s^{-2});

c = speed of sound in the gas in a 3-D acoustic space or 1-D duct (m s^{-1});

c_B = bending wave speed ($= \omega/k_B$) (m s^{-1});

$c_{LII} = \sqrt{E/\rho_m}$ = longitudinal wave speed for a beam or "plane-stress" longitudinal wavespeed for a thin-walled cylinder (used for modal density calculations) (m s^{-1});

$c_{LI} = \sqrt{E/[\rho_m(1-\nu^2)]}$ = longitudinal wave speed for a plate or thin-walled cylinder (m s^{-1});

c_s = shear wave speed ($= \sqrt{G/\rho_m}$) (m s^{-1});

c_T = torsional wave speed (m s^{-1});

d = peak to trough height of the corrugation profile for a thin corrugated plate (m);

e = distance from one peak to the next along a corrugation profile for a thin corrugated plate (m);

E = Young's modulus of elasticity for the beam or plate material (kg m^{-1} s^{-2});

f $(= \omega/(2\pi))$ = excitation frequency (Hz);

$f_r = c_{LI}/(2\pi a)$ = ring frequency (Hz);

G = shear modulus of the beam or plate material $= E/[2(1+\nu)]$ (kg m^{-1} s^{-2});

h = plate or thin-walled cylinder thickness (m);

h_b = depth of the beam cross section in a direction normal to the plane of the plate;

$H = \omega h/(2c_s)$;

J_x = polar second moment of area of the beam cross section about the longitudinal x-axis (sometimes referred to as the polar area moment of inertia) $= \pi d^4/32$ for a circular-section solid shaft, where d is the shaft diameter; and $= bh(b^2 + h^2)/12$ for a rectangular section shaft of cross-sectional dimensions $b \times h$, (m^4);

J_y = second moment of area of the beam cross section about the lateral x-axis (sometimes referred to as the area moment of inertia) $= \pi d^4/16$ for a circular-section solid shaft, where d is the shaft diameter; and $= bh^3/12$ for a rectangular section shaft of cross-sectional dimensions $b \times h$, where the b dimension is parallel to the x-axis, (m^4);

J' = torsion constant for the beam cross-section (equal to the polar second moment of area, J_x, for circular section beams) (m^4);

k = wavenumber in the gas in a 3-D acoustic space or 1-D duct (m^{-2});

k_B = beam bending wavenumber $= [\rho_m S_b \omega^2/(EJ_y)]^{1/4}$ for a beam;

k_{Bp} = isotropic plate bending wavenumber $= (\omega^2 m/B)^{1/4} = \left[\dfrac{12\omega^2 m(1-\nu^2)}{Eh^3}\right]^{1/4}$ (m^{-2});

k_s = shear wavenumber $= \sqrt{\dfrac{\rho_m \omega^2}{G}}$ (m^{-2});

m = effective mass per unit plan area of the plate ($= \rho_m h$ for a flat plate) (kg m^{-2});

m_i = mass per unit area of a honeycomb sandwich plate for frequency region, i (kg m^{-2}) (see Table A.14);

$2r$ = diameter of the excitation footprint on a plate, or moment arm, or distance between the two forces used to generate a moment on a plate, or diameter of a circular acoustic source or for a square acoustic source, $2r \approx \sqrt{A}$ (m), where A is the area of the source (m^2);

S_b = cross-sectional area of the 1-D beam (m^2);

S_p = Area of the 2-D plate (m^2);

S_d = cross-sectional area of the 1-D duct (m^2);

$\kappa_p = \sqrt{J_y/S_p} = h/\sqrt{12}$ = radius of gyration of plate section for bending, where J_y and S_p are the second moment of area and area, respectively, of the plate cross section (m);

λ_{bb} = bending wavelength in a beam;

ν = Poisson's ratio for the plate material;

ρ = density of the gas in a 3-D acoustic space or 1-D duct (kg m^{-3});

ρ_m = density of the beam, plate or cylinder material (kg m^{-3});

$\omega = 2\pi f$ = excitation frequency (radians/sec)

The coupling loss factor formulation requires a real impedance for the calculation of the transmission coefficient. This is realised in practice by using the magnitude of the impedance in place of the real impedance when and only when the real impedance is zero.

When the end of a circular beam of radius, a, is attached to a plate and the beam bending wave motion applies a bending moment to the plate, the moment arm, $2r$, is effectively the dimension of the beam cross section in the direction of the motion ($r = a$). If the moment is distributed over an area that is smaller than the plate thickness, then the imaginary part of the moment impedance is (Cremer et al., 2005, p. 275):

$$\mathrm{Im}\{Z_M\} \approx \frac{8Gr^3}{3\omega(1-\nu)} \tag{A.12}$$

where G is the shear modulus and ν is Poisson's ratio.

For a point excitation with a force, F, uniformly distributed over a small circular area of diameter D, the point force impedance for a thick plate is (Cremer et al., 2005, p. 267):

$$\mathrm{Im}\{Z_F\} \approx \frac{G}{\omega k_s}\left[\frac{0.063}{H^2} + \frac{1}{8}\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left(\frac{0.001}{H^{1.3}} + \frac{0.12\pi}{k_s D}\right)\right]^{-1} \tag{A.13}$$

For a line excitation with a force per unit length F' , uniformly distributed over a narrow strip of width, b, the line force impedance is (Cremer et al., 2005, p. 267):

$$\mathrm{Im}\{Z_F\} \approx \frac{G}{\omega}\left\{\frac{1}{8H^{1.5}} + 0.31\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left[\frac{-1}{8H^{1.5}} + 0.16\log_\mathrm{e}\left(\frac{2\pi}{k_s b}\right)\right]\right\}^{-1} \tag{A.14}$$

where G is the shear modulus, $k_s = \sqrt{\dfrac{\rho_m \omega^2}{G}}$ is the shear wavenumber, Poisson's ratio is assumed to be 0.3, $H = k_s h/2$ and h is the plate thickness.

Note that the torsional wave speed, c_T, in rectangular section beams of dimensions $h \times b$, is less than the wave speed, c_T, for circular beams (Cremer et al., 2005, p. 47). This is because beam sections that are not circularly symmetric, warp when twisted so that the torsion constant is no longer the same as the polar second moment of area of the cross section. The torsional wave speed is given by:

$$c_T = \sqrt{\frac{GJ'}{I'_x}} = \sqrt{\frac{GJ'}{\rho_m J_x}} \tag{A.15}$$

where J' is the torsion constant for the section, $I'_x = \rho_m J_x$ is the polar mass moment of inertia per unit length of the section for rotation about the x-axis and the subscript, x, refers to the axis normal to plane of the beam cross-section and passing through the centroid of the cross section. Values for J' and J_x for various beam cross sections are provided in Tables A.7, A.8 and A.9. The cross-sectional axes, y and z are defined so that y is the horizontal axis and z is the vertical axis.

Table A.7 Torsion constants, J' and second moments of area, J_y and J_z, for beams. The polar second moment of area is given by, $J_x = J_y + J_z$ and the polar mass moment of inertia per unit length, I'_x is obtained by multiplying J_x by the material density, ρ_m.

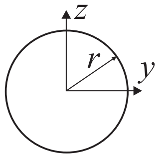
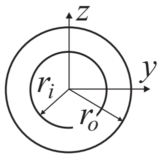
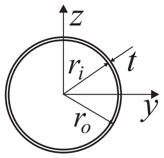
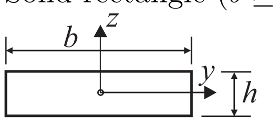
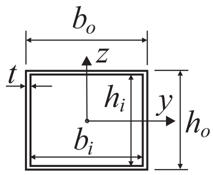
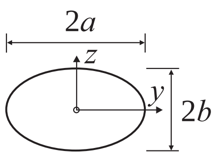
Cross-sectional shape	Torsion constant, J'	Second moment of area, J_y	Second moment of area, J_z
Solid circle 	$\dfrac{\pi r^4}{2}$	$\dfrac{\pi r^4}{4}$	$\dfrac{\pi r^4}{4}$
Hollow circle, $m = r_i/r_o$ 	$\dfrac{\pi}{2}(r_o^4 - r_i^4)$	$\dfrac{\pi}{4}(r_o^4 - r_i^4)$	$\dfrac{\pi}{4}(r_o^4 - r_i^4)$
Thin-wall circle 	$\pi r^3 t$ $r \approx r_o \approx r_i$ and $t << r$	$\pi r^3 t/2$ $r \approx r_o \approx r_i$ and $t << r$	$\pi r^3 t/2$ $r \approx r_o \approx r_i$ and $t << r$
Solid rectangle ($b \geq h$) 	$bh^3 \left[\dfrac{1}{3} - 0.21\dfrac{h}{b}\left(1 - \dfrac{h^4}{12b^4}\right)\right]$	$\dfrac{bh^3}{12}$	$\dfrac{hb^3}{12}$
Thin-wall rectangle 	$2tb^2h^2/(b+h)$ $h \approx h_i \approx h_o$ $b \approx b_i \approx b_o$ $t << b$ and $t << h$	$\dfrac{b_o h_o^3 - b_i h_i^3}{12}$	$\dfrac{b_o^3 h_o - b_i^3 h_i}{12}$
Solid ellipse 	$\dfrac{\pi a^3 b^3}{a^2 + b^2}$	$\dfrac{\pi a b^3}{4}$	$\dfrac{\pi a^3 b}{4}$

Table A.8 Approximate torsion constants, J' and second moments of area, J_y and J_z, for beams with sections consisting of rectangular components. The polar second moment of area is given by, $J_x = J_y + J_z$ and the polar mass moment of inertia per unit length, I'_x is obtained by multiplying J_x by the material density, ρ_m.

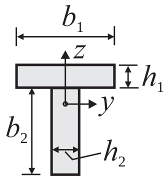
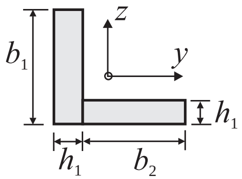
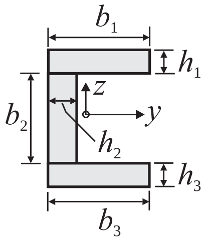
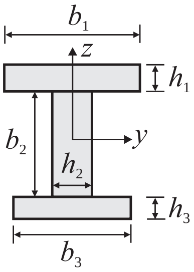
Shape of cross section	Torsion constant, J'	Second moment of area, J_y	Second moment of area, J_z
T-beam 	$\frac{1.12}{3}\sum_{i=1}^{2} b_i h_i^3$	$\frac{h_2 y^3 + b_1(b_2+h_1-y)^3 - (b_1-h_2)(b_2-y)^3}{3}$ where $y = (b_2+h_1) - \frac{(b_2+h_1)^2 h_2 + h_1^2(b_1-h_2)}{2(b_1h_1+b_2h_2)}$	$\frac{b_1^3 h_1}{12} + \frac{b_2 h_2^3}{12}$
Angle beam 	$\frac{1}{3}\sum_{i=1}^{2} b_i h_i^3$	$\frac{h_1 y^3 + (b_2+h_1)(b_1-y)^3 - b_2(b_1-y-h_1)^3}{3}$ where $y = b_1 - \frac{h_1(2b_1-2h_1+b_2-h_1)+(b_1-h_1)^2}{2(b_1-h_1)+2(b_2+h_1)}$	$\frac{h_1 z^3 + b_1(b_2+h_1-z)^3 - (b_1-h_1)(b_2-z)^3}{3}$ where $z = (b_2+h_1) - \frac{h_1(2b_2+b_1)+b_2^2}{2(b_2+b_1)}$
Channel section 	$\frac{1.15}{3}\sum_{i=1}^{3} b_i h_i^3$ $b_3 = b_1$ and $h_3 = h_1$	$\frac{b_1(b_2+2h_1)^3 - b_2^3(b_1-h_2)}{12}$	$\frac{2h_1b_1^3 + b_2h_2^3}{3} - x^2(2b_1h_1+b_2h_2)$ where $x = \frac{2b_1^2h_1 + b_2h_2^2}{2b_1(b_2+2h_1) - 2b_2(b_1-h_2)}$

Table A.9 Approximate torsion constants, J' and second moments of area, J_y and J_z, for an I-section beam. The polar second moment of area is given by, $J_x = J_y + J_z$ and the polar mass moment of inertia, I_x is obtained by multiplying J_x by the material density, ρ_m.

Shape of cross section	Torsion constant, J'	Second moment of area, J_y	Second moment of area, J_z
I-beam 	$\frac{1.13}{3}\sum_{i=1}^{3} b_i h_i^3$ $b_3 = b_1$ and $h_3 = h_1$	$\frac{b_1(2h_1+b_2)^3 - b_2^3(b_1-h_2)}{12}$	$\frac{2h_1b_1^3 + b_2h_2^3}{12}$

A.5 Subsystem External Input Power

Structural systems. The impedance presented to a point excitation source is not simply the point impedance of the substructure. It also depends on the point impedance of any other substructures connected to the substructure to which the external force is applied. In these cases, it may be preferable to estimate the input power using a measurement (or estimate) of the in situ reverberation time of the substructure to which the force is applied and the space, frequency and time-averaged, squared velocity, $\langle v^2 \rangle_{S,\Delta,t}$, over the substructure. Thus, the input power is given by (Hopkins and Robinson, 2014):

$$\Pi_{\text{in}} = \omega \eta M \langle v^2 \rangle_{S,\Delta,t} \tag{A.16}$$

where $\omega = 2\pi f$, M is the subsystem mass and η is the subsystem loss factor, determined using the subsystem reverberation time or one of the other methods described in Section A.6.

The frequency-averaged, subsystem input power can also be obtained from the real part of the equivalent infinite system point input impedance at the point of application of the force or moment using:

$$\Pi_{\text{in}} = \frac{1}{2}\text{Re}\{\hat{F}^* \hat{v}\} = \langle F^2 \rangle_{\Delta,t} \text{Re}\{Y_{F,\infty}\} = \langle v^2 \rangle_{\Delta,t} \text{Re}\{Z_{F,\infty}\} \quad \text{(watts)} \tag{A.17}$$

where $F = \hat{F}\text{e}^{\text{j}\omega t}$, $v = \hat{v}\text{e}^{\text{j}\omega t}$, and $Z_{F,\infty}$ and $Y_{F,\infty}$ are the point impedance and point admittance, respectively, at the point on the structure where the force is applied. The structural input admittance is the reciprocal of the input impedance.

For moment excitation, the moment impedances and mobilities of the structure are used and the force, F, is replaced with the moment, M, and the velocity, v, at the point of application of the force, is replaced with the angular velocity, $\dot{\theta}$.

Acoustic systems. For acoustic systems for which the external input acoustic pressure, p, has a constant spectral amplitude over the band, the acoustic power input, Π_{in}, can be expressed in terms of the acoustic impedance, Z_A, presented to the sound source as (Lyon and DeJong, 1995, p. 207):

$$\Pi_{\text{in}} = \langle pv \rangle = \frac{\langle p^2 \rangle}{\text{Re}\{Z_A\}} \quad \text{(watts)} \tag{A.18}$$

For acoustic systems for which the external input acoustic volume velocity, v, has a constant spectral amplitude over the band, the acoustic power input, $\Pi_{\rm in}$, is (Lyon and DeJong, 1995, p. 207):

$$\Pi_{\rm in} = \langle v^2 \rangle {\rm Re}\{Z_A\} \qquad \text{(watts)} \tag{A.19}$$

Equation (A.19) can be used to calculate the sound power input to a 3-D space as a result of a plane source (simulated by a loudspeaker backed by a small, air-tight enclosure) placed within it. The radiation impedance is doubled for each enclosure wall that is adjacent to it. Thus, for a sound source in a room corner, the radiation impedance will be a factor of 8 greater than it would be for a source in the centre of the space. Only the mean square velocity of the plane sound source and the source area are required in addition to the impedance in order to calculate the radiated sound power. The mean square velocity, $\langle v^2 \rangle$, of the loudspeaker diaphragm can be determined using a microphone placed in the air-tight enclosure to measure the sound pressure, and the following Equation (derived from equation (8.41) in the 5th edition textbook).

$$\langle v^2 \rangle = \langle p^2 \rangle \left(\frac{2\pi f V}{\rho c^2} \right)^2 \tag{A.20}$$

where V is the volume of the small enclosure and $\langle p^2 \rangle$ is the mean square sound pressure, derived from the sound pressure level of the sound field in the enclosure. Note that provided the loudspeaker enclosure is sufficiently small compared to a wavelength of sound at the frequency of interest, the sound pressure in the enclosure may be considered to be uniform. For higher frequencies, it may be necessary to use a laser doppler velocimeter to determine the mean square velocity of the loudspeaker diaphragm.

For a diffuse pressure field (mean square pressure, $\langle p^2 \rangle$) exciting a plate, and for the case of the modal energy in the plate being much less than that in the acoustic space providing the diffuse pressure field, the input power from the room to the plate is (Lyon and DeJong, 1995, p. 208):

$$\Pi_{\rm in} = \frac{2\pi^2 \langle p^2 \rangle n_p(\omega)}{\rho_m h k^2} \sigma_{\rm rad} \qquad \text{(watts)} \tag{A.21}$$

where $n_p(\omega)$ is the plate modal density, ρ_m is the plate material density, h is the plate thickness, k is the wavenumber and $\sigma_{\rm rad}$ is the plate radiation efficiency. Instead of using Equation (A.21), it is often preferable to model the input power as power applied to the acoustic space by a sound source, such that the reverberant mean square pressure so generated will be incident on the plate. In this case, the power input to the acoustic space can then be calculated directly from the reverberant field sound pressure, $\langle p^2 \rangle$, using:

$$\Pi_{\rm in} = \frac{\langle p^2 \rangle S \bar{\alpha}}{4\rho c(1-\bar{\alpha})} \qquad \text{(watts)} \tag{A.22}$$

where S is the total area of the room walls, floor and ceiling, and $\bar{\alpha}$ is the room Sabine absorption coefficient.

For a 2-D space, such as the cavity in a double wall partition, the power input to the acoustic space can be calculated using:

$$\Pi_{\rm in} = \frac{\langle p^2 \rangle S \bar{\alpha}}{\pi\rho c(1-\bar{\alpha})} \qquad \text{(watts)} \tag{A.23}$$

and for a 1-D space, such as a tube:

$$\Pi_{\rm in} = \frac{\langle p^2 \rangle S \alpha_n}{2\rho c(1-\alpha_n)} \qquad \text{(watts)} \tag{A.24}$$

where α_n is the normal incidence absorption coefficient averaged over the two ends of the tube.

For a vibrating plate (of area S_p with a mean square vibration velocity, $\langle v^2 \rangle$) exciting a diffuse sound pressure field in a room, where the modal energy in the plate is much greater than the modal energy in the room, the input power is (Lyon and DeJong, 1995, p. 207):

$$\Pi_{\text{in}} = \langle v^2 \rangle \rho c S_p \sigma_{\text{rad}} \qquad \text{(watts)} \tag{A.25}$$

For excitation of a plate by a turbulent boundary layer having a mean square pressure of $\langle p^2_{\text{TBL}} \rangle$, averaged over the frequency band, the input power is (Lyon and DeJong, 1995, p. 208):

$$\Pi_{\text{in}} = \begin{cases} \dfrac{0.75 S_p \langle p^2_{\text{TBL}} \rangle U}{\pi^2 f \rho_m h c_B} & \text{(watts)} \quad (c_B < 0.75U) \\[2ex] \dfrac{S_p \langle p^2_{\text{TBL}} \rangle}{2\pi f \rho_m h} \left(\dfrac{0.75U}{c_B} \right)^3 \left[\dfrac{a_1}{6} + a_2 \left(\dfrac{0.75U}{2\pi f L} \right)^2 \right] & \text{(watts)} \quad (c_B > 0.75U) \end{cases} \tag{A.26}$$

where c_B is the plate bending wave speed, U is the free stream speed in the fluid, S_p is the plate surface area and L is the plate length in the direction of flow. The constants, a_1 and a_2 depend on the plate mode shapes and details of the flow. In ENC, they are set equal to 1 for flow over a flat plate or flow parallel to the corrugations for a corrugated plate. For flow across the corrugations of a corrugated plate the constants are set equal to 3.

A.6 Subsystem Damping Loss Factors

The subsystem damping loss factor is a measure of the rate of energy flowing out of a system due to dissipation mechanisms, as opposed to the coupling loss factor which is a measure of the energy flowing out across the boundary into another subsystem. There are a number of different ways for determining subsystem damping loss factors and these are summarised in Table A.10. More details are provided in (Hansen, 2018, Sect. 6.6).

The damping loss factor (DLF) of a structural subsystem comprises three damping mechanisms that act independently of each other. These are the structural loss factor of the material, $\eta_{j,s}$, the damping that occurs at the junction between one subsystem and another, $\eta_{j,\text{junct}}$, and the energy loss caused by acoustic radiation damping, $\eta_{j,\text{rad}}$ (Norton and Karczub (2003), p. 407). Hence, the DLF is given by the sum of these three loss factors as:

$$\eta_j = \eta_{j,s} + \eta_{j,\text{junct}} + \eta_{j,\text{rad}}$$

When two subsystems are rigidly connected, it is assumed that the DLF of the junction is less than the structural loss factor of the material, $\eta_{j,\text{junct}} < \eta_{j,s}$. When the connection between subsystems is not rigid, the energy loss that occurs at the junction can provide a significant amount of damping (Lyon and DeJong (1995), p. 167), and depends upon the arrangement of the junction in the system under investigation. Good estimates of the subsystem damping factors are important as these damping factors have a strong influence on the calculated subsystem response values.

Appendix C in the textbook lists values of internal DLFs for various materials, which are likely values of loss factor for a panel installed in a building, and represents a combination of the material internal loss factor, the support loss factor and the sound radiation loss factor. The lower limits of the values in the textbook are suitable for the structural loss factor of the material, $\eta_{j,s}$. The higher limit of the internal loss factor, which accounts for the three damping mechanisms, should be used with caution, as the support loss factor, or junction loss factor, $\eta_{j,\text{junct}}$, may not be appropriate for the system under investigation. More accurate response estimates using SEA will be obtained if DLF values can be determined from experimental measurements or from published results of the junction configuration under investigation. Lyon and DeJong (1995, Chapter 9) and Norton and Karczub (2003, p. 412) describe experimental methods for measuring DLFs.

Damping loss factors should be measured with the subsystem disconnected from other subsystems, but a small amount should be added to account for any dissipation losses through junctions with other subsystems. The damping loss due to sound radiation can be included in the subsystem damping loss factor except for the case where radiation is into a separate subsystem such as a room, in which case it is the coupling loss factor or the radiation loss factor. The radiation loss factor is estimated from the substructure radiation efficiency, σ. For a vibrating plate, the radiation efficiency and hence the radiation loss factor depends on whether the plate is excited mechanically (resonant response) or by an incident sound field (forced or non-resonant response). The radiation loss factors for a plate excited by an incident vibration field or an incident sound field or a cylinder excited by an incident vibration field are discussed in the following three subsections. Note that in most cases measured loss factors for subsystems include the loss factor due to acoustic radiation. Thus in cases where the plate or cylinder subsystem is radiating into another subsystem, such as a room, the coupling loss factor associated with this radiation, and used in an SEA model, should be subtracted from the measured internal loss factor of the plate.

Using Equations (6.24) and (6.75) in the textbook, the loss factor for an enclosure is:

$$\eta = \frac{2.2}{fT_{60}} = \frac{2.2cS\bar{\alpha}}{55.25fV} = \frac{2.2 \times 2\pi}{55.25}\frac{cS\bar{\alpha}}{\omega V} = \frac{cS\bar{\alpha}}{4\omega V} = \frac{cS\bar{\alpha}}{8\pi fV}.$$

For a 1-D diffuse sound field in a duct, the mean square sound pressure, $\langle p^2 \rangle$, at any time, t, after the sound source is turned off is, $\langle p^2 \rangle = \langle p_0^2 \rangle e^{-c\bar{\alpha}t/L}$, where $\bar{\alpha}$ is the fraction of energy absorbed by each wall, L is the distance between opposite walls (length of a 1-D room) and $\langle p_0^2 \rangle$ is the steady state mean square sound pressure before the sound is turned off. Following the procedure for a 3-D sound field on page 330 of the textbook, we obtain the following for the reverberation time in the 1-D duct of length, L.

$T_{60} = 13.82L/c\bar{\alpha}$, which gives: $\quad \eta = \dfrac{2.2}{fT_{60}} = \dfrac{2.2c\bar{\alpha}}{13.82Lf} = \dfrac{c\bar{\alpha}}{2\pi fL}.$

A.6.1 Radiation Damping Loss

The radiation damping loss factor, η_{rad}, for a vibrating plate of mass/unit area, m, is ((Fahy, 1982, p. 177) and (Lyon and DeJong, 1995, p. 199)):

$$\eta_{\text{rad}} = \frac{\rho c \sigma}{\omega m} \tag{A.27}$$

where σ is the plate radiation efficiency. The calculation of the radiation efficiency depends on whether the plate is excited by a vibration field or diffuse acoustic field and whether it is radiating into free space, an enclosed space such as a room or a cavity such as that between two walls in a double wall construction. The calculation of each type of radiation efficiency is discussed in the following subsections. Experimental data showing radiation efficiencies greater than 3 have not been published, so when calculated values exceed 3 in ENC, they are set equal to 3.

Equation (A.27) may also be used for a cylinder excited by a vibration source, with the corresponding radiation efficiency calculated as described in Section A.6.2.4.

Table A.10 Relationship of loss factor, η, to various other measures of damping

Damping measure	Symbol	Units	$\eta =$
Loss factor	η	—	η
Quality factor	Q	—	$1/Q$
Critical damping ratio	ζ	—	$\dfrac{2\zeta}{\sqrt{1-\zeta^2}}$
Reverberation time (60 dB)	T_{60}	sec	$\dfrac{2.2}{fT_{60}}$
Decay rate	DR	dB/sec	$\dfrac{\text{DR}}{27.3f}$
Wave attenuation	γ	nepers	$\dfrac{c_g\gamma}{\pi f}$
Logarithmic decrement	δ	—	δ/π
Phase angle by which strain lags force	ϵ	radians	$\tan\epsilon$
Modal bandwidth	Δf	Hz	$\dfrac{\Delta f}{f}$
Imaginary part of modulus of elasticity, $(E_r + \mathrm{j}E_i)$	E_i	Pa	E_i/E_r
Sabine absorption coefficient	$\bar{\alpha}$	—	$\dfrac{cS\bar{\alpha}}{8\pi fV}$

Radiation efficiencies calculated by ENC for plates excited by acoustic or vibration fields and radiating into an enclosed space, a narrow cavity or free space may also be used with the SEA estimates of average vibration velocity to calculate radiated sound powers.

A.6.1.1 Plate Radiation to Free Space - Vibration Excitation, Maidanik (1962); Leppington et al. (1982)

Isotropic Plates

The radiation efficiency for simply supported, rectangular, flat panels of dimensions $\ell_1 \times \ell_2$, with $\ell_1 \leq \ell_2$ may be calculated using the procedure illustrated by Equation (A.28), where the radiation efficiency is a function of the ratio of the excitation frequency, f to the panel critical frequency, f_c (see textbook, Chapter 7) and fundamental resonance frequency, $f_{1,1}$ (see textbook, Chapter7).

$$\sigma = \begin{cases} \dfrac{4S_p}{c^2} f^2; & f < f_{1,1} \quad \text{(Vér, 2006)} \\ \left(\dfrac{2c^2}{f_c^2 S_p}\delta_1 + \dfrac{Pc}{f_c S_p}\delta_2\right)\gamma; & 2f_{1,1} < f < xf_c \quad \begin{array}{l}\text{(Maidanik (1962)}\\ \text{corrected according to}\\ \text{Crocker and Price (1969b),}\\ \text{rewritten as in}\\ \text{Bies et al. (2024))}\end{array} \\ 0.5\sqrt{2\pi f \ell_1/c}; & f = f_c \quad \text{(Leppington et al., 1982)} \\ \sqrt{\ell_1 f_c/c} + \sqrt{\ell_2 f_c/c}; & f = f_c \quad \text{Maidanik (1962)} \\ (1 - f_c/f)^{-1/2}; & f >> f_c \quad \begin{array}{l}\text{(Maidanik (1962) and}\\ \text{Leppington et al. (1982))}\end{array} \end{cases} \tag{A.28}$$

where x is a value between 0.7 and 0.99. In ENC, x is set equal to 0.99. For circular plates the same equations are applicable, with ℓ_1 and ℓ_2 replaced by $1.8a$, where a is the plate radius.

$$\delta_1 = \begin{cases} \dfrac{4}{\pi^4} \dfrac{(1 - 2\xi_c^2)}{\xi_c(1 - \xi_c^2)^{1/2}}; & f < f_c/2 \\ 0; & f > f_c/2 \end{cases} \tag{A.29}$$

$$\delta_2 = \frac{1}{4\pi^2}\left[\frac{(1 - \xi_c^2)\log_e\left(\dfrac{1 + \xi_c}{1 - \xi_c}\right) + 2\xi_c}{(1 - \xi_c^2)^{3/2}}\right] \tag{A.30}$$

and where

$$\xi_c = (f/f_c)^{1/2} \tag{A.31}$$

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{B}{m}} \tag{A.32}$$

For a simply supported isotropic rectangular plate $f_{1,1} = \dfrac{\pi}{2}\sqrt{\dfrac{B}{m}}\left[\dfrac{1}{\ell_1^2} + \dfrac{1}{\ell_2^2}\right]$ (A.33)

For a simply supported orthotropic rectangular plate $f_{1,1} = \dfrac{\pi}{2m^{1/2}}\left[\dfrac{B_a}{\ell_1^4} + \dfrac{B_b}{\ell_2^4} + \dfrac{2B_{ab}}{\ell_1^2\ell_2^2}\right]^{1/2}$ (A.34)

where $B_{ab} = 0.5(B_a\nu + B_b\nu + Gh^3/3)$.

For a simply supported orthotropic circular plate $f_{1,1} = \dfrac{4.977}{2\pi a^2}\sqrt{\dfrac{\sqrt{B_a B_b}}{m}}$ (A.35)

In the preceding equations, the quantities m, P and S_p are the plate mass per unit area (kg/m^2), perimeter (m) and area (m^2), respectively and B is the bending stiffness per unit width, with the subscripts a and b representing the directions of maximum and minimum stiffness. For a simply supported flat plate (rectangular or circular):

$$B = Eh^3/(12(1 - \nu^2)) \tag{A.36}$$

where E is Young's modulus, ν is Poisson's ratio for the plate material and h is the plate thickness (m).

The calculation of the stiffness of a corrugated plate for bending about an axis at right angles to the corrugations is discussed in the 6th edition textbook on pages 403–404.

For simply supported plates, γ takes the value of 1 while for clamped edge plates γ takes the value 2. All other conditions lie between these extremes.

Leppington et al. (1982) showed that the term containing δ_1 in Equation (A.28) is invalid and should be omitted for all frequencies and this is done in ENC, although the the value calculated using the corrected Maidanik equations is also available in the output.

It can be seen from the preceding equations that there are gaps in the predictions between the lowest panel resonance and twice this frequency, as well as on either side of the critical frequency, although there is an estimate at exactly the critical frequency. The first mentioned gap is filled by linear interpolation between the $\log_{10}(\sigma)$ values corresponding to $\log_{10}(f_{1,1})$ and $\log_{10}(2f_{1,1})$. For the gap above the critical frequency, Equation (A.28) defines valid values of frequency to be such that $f >> f_c$, although "$>>$" is not defined. Similarly for frequencies below f_c, the upper valid value of f is that frequency, f, corresponding to the quantity, $k\ell_1[(f_c/f)^{1/2} - 1]$, no longer being "large" (Leppington et al., 1982), where "large" is undefined. Thus, any values of σ higher than the value corresponding to $f = f_c$ are set equal to the value of σ at $f = f_c$. These approximations are sufficiently accurate for the purposes of SEA and for any sound power calculations. An upper practical limit of $\sigma = 3$ is also set in ENC, as experimentally measured flat panel radiation efficiencies above this value have not been reported in the literature.

For plates supported at the edge and on intermediate battens (or studs), the perimeter, P, in Equation (A.28) is the overall length of the plate perimeter plus twice the length of all the studs. The area, S_p, is the area of the entire plate.

Note that for square, clamped-edge plates, the fundamental resonance frequency is 1.83 times that calculated using Equation (A.35). For plates with aspect ratios of 1.5, 2, 3, 6, 8 and 10 the factors are 1.89, 1.99, 2.11, 2.23, 2.25 and 2.26, respectively.

The radiation efficiency for excitation of a thick plate ($h > 0.3c_B/f$) by a vibration field is (Vér, 2006, p. 511):

$$\sigma = \begin{cases} 0.45\sqrt{Pf/c}; & f \le (f_c + 5c/P) \\ 1; & f >> (f_c + 5c/P) \end{cases} \tag{A.37}$$

This equation is used in ENC for sound radiation by thick plates excited by a vibration field. The radiation efficiency can also be used with module 2 - Sound Power to calculate the sound power radiated to free space by a plate-like element of a system, once this SEA module has been used to determine the mean square surface velocity.

For a circular plate, the preceding equations may be used but the plate dimensions are replaced with

$$\ell_1 = \ell_2 = 1.8a \tag{A.38}$$

where a is the plate radius.

The preceding analysis can also be used to find approximate radiation efficiency values for corrugated and sandwich plates.

Corrugated and Orthotropic Plates

For corrugated plates, the critical frequency is dependent on the direction of incidence of the incident sound field with respect to the plane of the plate surface. Due to the different stiffness along the corrugations compared to that across the corrugations, the critical frequency will depend on the angle of the incident wave. For the purpose of calculating radiated sound power an approximate estimate of the radiation efficiency is needed that takes into account sound radiation in all directions. Thus, in the absence of measured data, ENC obtains an approximate estimation of a plate radiation efficiency for a corrugated plate by using the previous analysis for an isotropic plate. However, for the corrugated plate, the critical frequency, f_c, is calculated using Equation (A.32) with a bending stiffness, B, corresponding to the geometric average of the bending stiffness corresponding to the direction of maximum plate stiffness and the bending stiffness corresponding to the direction of minimum plate stiffness. For a corrugated plate, the mass per unit area and the bending stiffness along the corrugations (the larger stiffness) must be entered by the user. This bending stiffness and mass/unit plan area can be calculated by ENC in the module 5, single wall, orthotropic panel page by clicking on the "More Properties for Orthotropic Panel" button and drawing the panel cross-sectional profile, then clicking on the "back" button followed by the "run" button. The bending stiffness corresponding to wave travel across the corrugations is the same as for an isotropic plate of the same thickness.

Of course, if the user has better estimates, then those values should be inserted in the data boxes that come up when "User entered data" is selected for the "Resonant radiation efficiency option" and the "Forced radiation into free space, rad. eff. option".

Sandwich Plates

There are two options for calculating bending stiffnesses for sandwich plates. The first, (Yoerkie et al., 1983, pp. 105-107), assumes that the two skins have the same thickness as well as being made of the same material. The second, (Clarkson and Ranky, 1983), allows the two skins to have different thicknesses, although the material is assumed to be the same. Sandwich plates can be treated in the same way as isotropic plates, except that the bending stiffness used to calculate the effective critical frequency to be used in the equations is frequency dependent. The bending stiffnesses, mass/unit area and critical frequencies are calculated in ENC using the following equations for frequency, $f_i = \omega_i/(2\pi)$.

$m = 2\rho_s h_s + \rho_c h_c$ is the total plate mass/unit area.

B_i is the bending stiffness corresponding to excitation frequency, f_i, given by:

$B_i = B_1$ for $\omega < \omega_1$

$B_i = B_2$ for $\omega_1 \leq \omega \leq \omega_2$

$B_i = B_3$ for $\omega > \omega_2$

$$\omega_1 = \frac{G_c h_c}{\sqrt{mB_1}}; \quad B_1 = \frac{E_s h_s (h_s + h_c)^2}{2(1-\nu_s^2)}$$

$$\omega_2 = \frac{G_c h_c}{\sqrt{mB_3}}; \quad B_2 = \frac{G_c^2 h_c^2}{4m\omega^2}; \quad B_3 = \frac{E_s h_s^3}{12(1-\nu_s^2)}$$

$$f_{ci} = \frac{c^2}{2\pi}\sqrt{m_i B_i}$$

A.6.2 Plate Radiation to Free Space Resulting From Diffuse Sound Field Excitation

For this case, which applies to isotropic, orthotropic and sandwich plates, ENC estimates the plate radiation efficiency using (Davy, 2009):

$$\sigma = \log_e\left(\frac{1+\sqrt{1+q^2}}{F+\sqrt{F^2+q^2}}\right) + \frac{1}{\alpha}\log_e\left(\frac{H+\sqrt{H^2+q^2}}{F+\sqrt{F^2+q^2}}\right) \tag{A.39}$$

where

$H = 1.0/[0.67\sqrt{2ka/\pi} - 0.124]$

$q = \dfrac{\pi}{2k^2a^2}$

$F = 1.3\sqrt{\dfrac{\pi}{2ka}} = \dfrac{1.3H}{\sqrt{2}}$

$a = 4S_p/P$, where S_p is the plate area and P is the plate perimeter.

$\alpha = (H/F) - 1$
If $\alpha = 0$, the second term on the RHS of Equation (A.39) is replaced with $F/\sqrt{H^2 + q^2}$.

For plates excited by an incident wave at an angle, ϕ, to the normal to the plate surface, the radiation efficiency is (Davy, 2009):

$$\sigma(\phi) = \begin{cases} \dfrac{1}{\sqrt{(g^2+q^2)}} & F \le |g| \le 1 \\ \dfrac{1}{\sqrt{(H-\alpha g)^2 + q^2}} & 0 \le |g| < F \end{cases} \tag{A.40}$$

where $g = \cos\phi$. These equations are used in ENC to calculate the radiation efficiency of a plate acting as a partition in a 1-D duct, where $\phi = 0.0$.

An alternative equation (not used in current versions of ENC), to estimate the radiation efficiency for excitation of a square plate by a plane wave incident at an angle, ϕ (degrees), to the normal to the plate surface is (Vér, 2006, p. 511):

$$\sigma(\phi) = \begin{cases} \min\begin{cases} 0.5 \times (0.8)^{\phi/90}(k/2)\sqrt{S_p}; \\ 1/\cos\phi; \end{cases} & 0.1\lambda^2 < S_p < 0.4\lambda^2 \\ \min\begin{cases} (0.5)^{\phi/90}\sqrt{(k/2)\sqrt{S_p}}; \\ 1/\cos\phi; \end{cases} & S_p \ge 0.4\lambda^2 \end{cases} \tag{A.41}$$

Another expression (not used by ENC) for the radiation efficiency corresponding to diffuse field excitation of a square plate is (Vér, 2006, p. 511):

$$\sigma = 0.5[0.2 + \log_e(k\sqrt{S_p})]; \quad \text{for } k\sqrt{S_p} > 1 \tag{A.42}$$

The above two equations are also likely to apply to rectangular plates, provided that the aspect ratio is not too great and provided that $\sqrt{S_p}$ is replaced with $4S_p/P$, where P is the plate perimeter. However, neither of the above two equations are used in current versions of ENC and are provided here for information only.

A.6.2.1 Plate Radiation to an Enclosure or Room for Vibration or Acoustic Excitation

For the calculation method choice of "Lyon, Craik or Leppington" on the "Coupling loss factor input data" page in ENC, the expression used for the radiation efficiency of a flat plate radiating into a room is (Lyon and DeJong, 1995, p. 199):

$$\begin{aligned} \sigma &= \frac{2Pk^2}{\pi S_p k_{Bp}^3\left(1 + \dfrac{\pi k^2}{2k_{Bp}^2}\right)} + \left[\left(\frac{k_{Bp}^2}{k^2} - 1\right)^2\left(\frac{\pi k_{Bp}^4}{k^4} + 1\right)^2 + \frac{2\pi}{k_{Bp}\sqrt{S_p}}\right]^{-1} \\ &= \frac{2P(f/f_c)^{3/2}}{\pi k S_p\left(1 + \dfrac{\pi f}{2f_c}\right)} + \left[\Big[(f_c/f) - 1\Big]^2\Big[\pi(f_c/f)^2 + 1\Big]^2 + \frac{2\pi(f/f_c)^{1/2}}{k\sqrt{S_p}}\right]^{-1} \end{aligned} \tag{A.43a,b}$$

where the plate bending wavenumber, $k_{Bp} = \left[\frac{12\omega^2\rho_m(1-\nu^2)}{Eh^2}\right]^{1/4} = \left[\frac{12\omega^2}{c_{LI}^2 h^2}\right]^{1/4} = \omega/c_{Bp}$ and the wavenumber in air, $k = 2\pi/\lambda$.

For the calculation method choice of “Cremer, Maidanik or other” on the “Coupling loss factor input data” page in ENC, the expression used for the radiation efficiency, σ, of a rectangular plate, of dimensions $a \times b$ and thickness, h, for resonant radiation into a cavity (with the plate mounted in one wall of the cavity) is (Fahy, 1969):

$$\sigma = \begin{cases} \dfrac{64hc_L(a+b)}{\pi^5 cab}\left[\dfrac{\sin^{-1}(f/f_c)^{1/2}}{1-(f/f_c)} + \tan\left[\sin^{-1}(f/f_c)^{1/2}\right]\right]; & 2f_{1,1} < f < 0.9f_c \\ 0.51(1-f_c/f)^{-1/2}; & f > 1.1f_c \end{cases} \tag{A.44}$$

This expression is also used by ENC for a circular plate by replacing $(a+b)$ in the numerator with half the plate perimeter, $P/2$, and ab in the denominator with the plate area, S.

The analysis in this section is also used by ENC for corrugated and sandwich plates. The only quantity that requires separate calculation is the plate bending wave number k_{Bp}, which is given by:

$$k_{Bp} = (2\pi f)^{1/2}\left(\frac{m}{B}\right)^{1/4} \tag{A.45}$$

The mass/unit area, m and bending stiffness, B, to be used in Equation (A.243) for corrugated and sandwich plates are estimated in the same way as described in Section A.6.1.1.

A.6.2.2 Plate Radiation to a Narrow Cavity for Vibration or Acoustic Excitation

As the cavity is defined as a space between parallel walls where the spacing is much less than a wavelength, the bending wavelength in the wall will be the same as that in air so the radiation efficiency in this case will have the same form as the expression for the radiation efficiency at coincidence, regardless of whether the excitation is vibration or acoustic. In fact, Craik (2003) uses the expression derived in Cremer et al. (1988, p. 533) for a point excited rectangular plate, which is:

$$\sigma = 0.45\sqrt{fP/c} \tag{A.46}$$

where P is the perimeter of the plate. This is also a good approximation for circular plates.

Leppington et al. (1982, p. 269) undertook a detailed analysis that took into account the plate aspect ratio and obtained the following expression:

$$\sigma = 0.5\sqrt{2\pi f\ell_1/c} \tag{A.47}$$

where the plate dimensions satisfy $\ell_1 \leq \ell_2$. For a square plate, where $\ell_1 = \ell_2$, Equation (A.47) results in values that are approximately 39% higher than those calculated using Equation (A.46). Equation (A.46) with $\ell_1 \leq \ell_2$ and $\ell_1 = a\pi/2$ is also a good approximation for a circular plate of radius, a.

Equation (A.46) gives results that are approximately 55% lower for a square plate (with an even greater difference for plates with large aspect ratios) than given by the earlier expression derived by Maidanik (1962) (repeated below), whereas (A.47) gives a result that is 37% lower.

$$\sigma = \sqrt{\frac{\ell_1 f_c}{c}} + \sqrt{\frac{\ell_2 f_c}{c}} \tag{A.48}$$

ENC provides the option of using the Craik, Leppington or Maidanik formulation. The analysis in this section is also used by ENC for corrugated and sandwich plates.

A.6.2.3 Plate Radiation into a 1-D space

This section is concerned with plates separating 1-D spaces so that wave propagation is along the axis of the 1-D space and normal to any plate acting as a partition between 1-D spaces. This situation is included in coupling types 31–35 when the acoustic space is represented by subsystem type 14 or 15. In this situation, waves are incident and radiated by the plate in a direction normal to the plate surface and the resulting radiation efficiency can be calculated using Equation (A.40) from Davy (2009) to give:

$$\sigma(\phi = 0) = \begin{cases} \dfrac{1}{\sqrt{(1+q^2)}} & F \leq 1 \\[2ex] \dfrac{1}{\sqrt{(H-\alpha)^2 + q^2}} & F > 1 \end{cases} \tag{A.49}$$

where

$H = 1.0/[0.67\sqrt{2ka/\pi} - 0.124]$

$q = \dfrac{\pi}{2k^2a^2}$

$F = 1.3\sqrt{\dfrac{\pi}{2ka}} = \dfrac{1.3H}{\sqrt{2}}$

$a = 4S_p/P$, where S_p is the plate area and P is the plate perimeter.

$k = 2\pi/\lambda =$ wavenumber

$\alpha = (H/F) - 1$

If $\alpha = 0$, the second term on the RHS of Equation (A.239) is replaced with $F/\sqrt{H^2 + q^2}$.

A.6.2.4 Cylinder - Radiation to Free Space

The radiation loss factor for mechanical excitation (resonant) is (Lyon and DeJong, 1995, p. 199):

$$\eta_{\text{rad}} = \frac{\rho c S \sigma}{\omega M_s} = \frac{\rho c \sigma}{\omega \rho_m h} \tag{A.50}$$

where $S = 2\pi a L h \rho_m$ is the cylinder surface area, a is the cylinder radius, h is the cylinder wall thickness, L is the cylinder length, ρ_m is the cylinder material density and $M_s = \rho_m S h$ is the total mass of the cylinder wall. The cylinder radiation efficiency, σ, for resonant (mechanical) excitation, is Szechenyi (1971):

$$\sigma = \begin{cases} \dfrac{\sqrt{3}}{7.2}\left(\dfrac{f}{f_r}\right)^{0.5}\left(\dfrac{f}{f_c}\right); & 0.5f_r < f < 0.8f_r \\[2ex] \dfrac{\sqrt{3}}{5}\dfrac{f}{f_c}; & f < 0.5f_r \end{cases} \tag{A.51}$$

where $f_r = c_{LI}/(2\pi a)$ is the ring frequency, c_{LI} is the longitudinal wave speed in the cylinder wall (same as in a plate of the same thickness as the wall), a is the radius of curvature of the cylinder and f_c is the critical frequency (same as for a plate with the same thickness as the wall).

Richards (1979) provide a different expression for the radiation efficiency of a cylinder vibrating in bending.

$$\sigma = \begin{cases} 1.55(k_d a)^2 ka; & 0 < k_d a < 0.9 \\ \dfrac{ka}{k_d a}; & k_d a > 0.9 \end{cases} \quad \text{(A.52)}$$

where $k_d^2 = k^2 - k_B^2$ and $k_B = 2\pi f/c_B$.

A.6.2.5 Summary of Radiation Efficiencies Calculated by ENC

Radiation Efficiencies are calculated by ENC for all of the above-mentioned excitation situations. As well as radiation efficiencies, radiated sound powers for each case are calculated. The cases discussed are listed in the following table. Results are provided for all subsystems, with one line for each radiation efficiency type and with the data values in the same order as the display subsystem numbers on the subsystem input data page. Where subsystems are not plates or cylinders subject to bending wave motion, the radiation efficiency value is set equal to 0.0.

Table A.11 Cases for which radiation efficiencies and radiated sound power values are provided by ENC

Case Number	Description
1	Diffuse field radiation into enclosure, mechanical or acoustic excitation (Lyon)
2	Diffuse field radiation into enclosure, mechanical or acoustic excitation (Fahy)
3	Diffuse-field acoustic excitation (forced) and radiation to free space (Davy)
4	Plane wave acoustic excitation (forced) and radiation to free space or 1-D space (Davy)
5	Mechanical excitation (resonant) and radiation to free space (Maidanik)
6	Mechanical excitation (resonant) and radiation to free space (Leppington)
7	Diffuse field radiation into narrow cavity such as a double wall cavity (Maidanik)
8	Diffuse field radiation into narrow cavity such as a double wall cavity (Leppington)
9	Diffuse field radiation into narrow cavity such as a double wall cavity (Craik)

A.7 Subsystem Modal Density

When the boundary impedance is random, averaged modal densities for 2-D and 3-D systems are, respectively:

$$n(\omega)_{\text{2-D}} = \frac{kS}{2\pi c_g} \quad \text{and} \quad n(\omega)_{\text{3-D}} = \frac{kV}{2\pi^2 c_g} \tag{A.53}$$

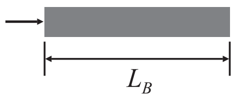
where k is the wavenumber of the wave being analysed.

Modal density tables are provided in the following pages (Hansen, 2018, p. 277–279) and (Cremer et al., 2005, p. 302).

Table A.12 Modal densities, $n(\omega)$, of 1-D subsystems

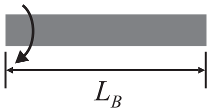
Beam excited axially

$$n(\omega) = \frac{L_B}{\pi c_g}; \qquad \text{where } c_g = c_{LII} = \sqrt{\frac{E}{\rho_m}}$$



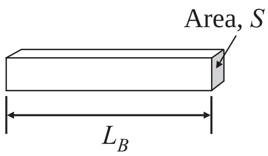
Beam excited torsionally

$$n(\omega) = \frac{L_B}{\pi c_g}; \qquad \text{where } c_g = c_T = \sqrt{\frac{G}{\rho_m}}$$



Beam in bending

$$n(\omega) = \frac{L_B}{\pi c_g}; \qquad \text{where } c_g = 2c_B = 2\left[\frac{EJ_y\omega^2}{\rho_m S}\right]^{1/4}$$



1-D duct excited acoustically

$$n(\omega) = \frac{L}{\pi c}$$

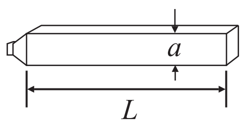
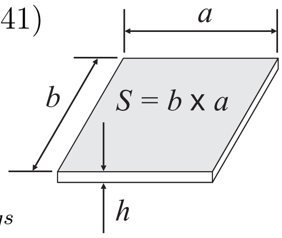


Table A.13 Modal densities, $n(\omega)$, of 2-D subsystems

Finite isotropic plate, bending modes
(incl. shear effects) (Lyon and DeJong, 1995, p. 141)

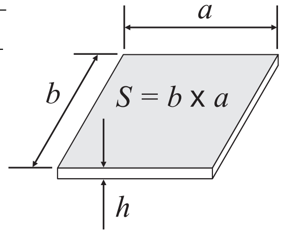
$$n(\omega) = \frac{S\omega}{2\pi}\left[\frac{1}{c_{gB}c_B} + \frac{1}{c_{gs}c_s}\right] = \frac{S\omega}{4\pi}\left[\frac{1}{c_B^2} + \frac{2}{c_s^2}\right]$$

where $c_{gB} = 2c_B = 2\left(\frac{B\omega^2}{m}\right)^{1/4}$ and $c_s = \sqrt{\frac{G}{\rho}} = c_{gs}$



Finite isotropic plate, in-plane compressional modes

$$n(\omega) = \frac{S\omega}{2\pi c_{gL}c_{LI}};\ \text{where } c_{gL} = c_{LI} = \sqrt{\frac{E}{\rho_m(1-\nu^2)}}$$



Finite isotropic plate, in-plane shear modes

$$n(\omega) = \frac{S\omega}{2\pi c_{gs}c_s};\qquad \text{where } c_{gs} = c_s = \sqrt{\frac{G}{\rho_m}} \text{ and}$$

$$G = \frac{E}{2(1+\nu)}$$

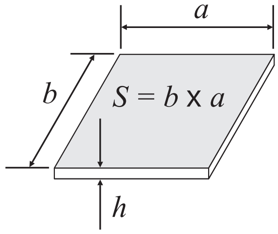


Table A.14 Modal densities, $n(\omega)$, of sandwich and corrugated plates

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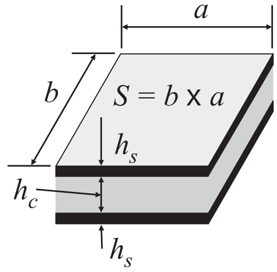
Finite honeycomb-core sandwich plate, (bending modes, frequency regions 1 and 3); shear wave modes, frequency region 2)
(Yoerkie et al., 1983, pp. 105–108)



$$n_i(\omega) = \frac{S_p}{4\pi}\sqrt{\frac{m_i}{B_i}}; \quad i = 1 \text{ or } 3; \; n_2(\omega) = \frac{S\omega_2 m_2}{2\pi G_c h_c}$$

$$m_1 = m_2 = 2\rho_s h_s + \rho_c h_c; \; m_3 = \rho_s h_s + \rho_c h_c/6$$

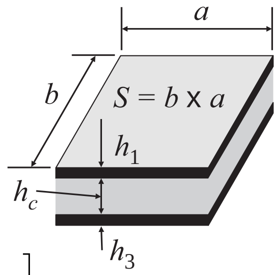
$$n(\omega) = n_1(\omega) \text{ for } \omega < \omega_1$$
$$n(\omega) = n_2(\omega) \text{ for } \omega_1 \le \omega \le \omega_2$$
$$n(\omega) = n_3(\omega) \text{ for } \omega > \omega_2$$

$$\omega_1 = \frac{G_c h_c}{\sqrt{m_1 B_1}}; \quad B_1 = \frac{E_s h_s (h_s + h_c)^2}{2(1-\nu_s^2)}; \quad \omega_2 = \frac{G_c h_c}{\sqrt{m_3 B_3}}; \quad B_2 = \frac{G_c^2 h_c^2}{\omega^2 m_2}$$

$$B_3 = E_s h_s^3/[12(1-\nu_s^2)]$$

$$c_{B1} = \omega^{1/2}\left(B_1/m_1\right)^{1/4}; \quad c_{s2} = \sqrt{G_c h_c/m_2}; \quad c_{B3} = \omega^{1/2}\left(B_3/(\rho_s h_s + \rho_c h_c/6)\right)^{1/4}$$

Finite honeycomb-core sandwich plate
(Clarkson and Ranky, 1983)



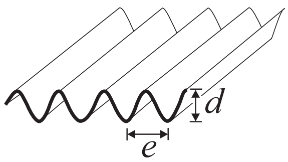
$$n(\omega) = \frac{abm\omega}{4\pi g B_L}\left\{1 + \left[m\omega^2 + 2g^2 B_L(1-\nu^2)\right] \times \left[m^2\omega^4 + 4m\omega^2 g^2 B_L (1-\nu^2)\right]^{-1/2}\right\}$$

$$B_L = d^2\left[\frac{E_1 h_1 E_3 h_3}{E_1 h_1 + E_3 h_3}\right]; \; g = \frac{\sqrt{G_{cx} G_{cy}}}{h_c}\left[\frac{1}{E_1 h_1} + \frac{1}{E_3 h_3}\right]$$

$$m = \rho_1 h_1 + \rho_3 h_3 + \rho_c h_c; \; d = h_c + 0.5(h_1 + h_3)$$

Finite corrugated plate, bending modes

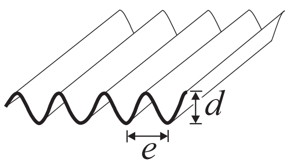
(Clarkson and Pope, 1983) $c_{LI} = \sqrt{\dfrac{E}{\rho_m(1-\nu^2)}}$



$$n(\omega) = \frac{0.93S}{2\pi c_{LI}}\left[\frac{S_y}{h^2 I_y}\right]^{1/4}; \; I_y = B(1-\nu^2)/E$$

B is calculated using Equation (7.10) in the textbook.
For a sinusoidally corrugated plate, $I_y = 0.13hd^2$ (Garifullin et al., 2021) where d is the peak to trough height of the corrugation.

Finite corrugated plate, bending modes
(Lyon and DeJong, 1995, p. 141)



$$n(\omega) = \frac{S\omega}{4\pi c_{B1} c_{B2}}$$

where $c_{B1} = \left(\dfrac{B\omega^2}{m}\right)^{1/4} = \left(\dfrac{\omega^2 E h^3}{12m(1-\nu^2)}\right)^{1/4}$

and c_{B2} can be calculated using Equations (7.1) and (7.10) in the textbook.

Table A.15 Modal densities, $n(\omega)$, of 3-D structures. (See also Section A.7.3 below.)

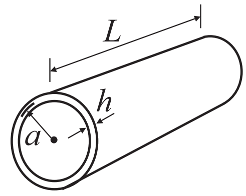
Thin-walled cylinder (Lyon and DeJong, 1995, p. 143)

$$n(\omega) = \frac{N(f_u) - N(f_\ell)}{2\pi\Delta f}; \ \left(\begin{array}{l}\Delta f = f_u - f_\ell; \\ f_u, \ f_\ell \text{ are the band upper and lower frequency limits.}\end{array}\right)$$

$$N(f) = \frac{L\sqrt{3}}{h}\left(\frac{f}{f_r}\right)\left\{1 + \left[\frac{\pi/2}{(f/f_r)^{1/2} + 0.5(f/f_r)^{3.5}}\right]^4\right\}^{-1/4}; f_r = \left(\frac{1}{2\pi a}\right)\sqrt{\frac{E}{(\rho_m(1-\nu^2))}}$$

Thin-walled cylinder (Cremer et al., 2005, p. 302)

$$n(\omega) \approx \begin{cases} \dfrac{1.25La}{hc_{LII}}\left(\dfrac{f}{f_1}\right)^{1/2}; & (f/f_1 \le 1); \quad c_{LII} = \sqrt{E/\rho_m} \\ \dfrac{\sqrt{3}La}{c_{LII}h}; & (f/f_1 > 1); \quad f_1 = c_{LII}/(2\pi a) \end{cases}$$



Thin-walled cylinder[1,2]

(Szechenyi (1971), with Eq. 10c corrected according to their Fig. 6(a))

$$n(\omega) \approx \begin{cases} \dfrac{2.5S_c}{\pi^2 hc_{LII}}\left(\dfrac{f}{f_1}\right)^{1/2}; \quad f_1 = c_{LII}/(2\pi a) & (f/f_1 \le 0.48) \\ \dfrac{3.6S_c}{\pi^2 hc_{LII}}\left(\dfrac{f}{f_1}\right) & (0.48 < f/f_1 \le 0.83) \\ \dfrac{S_c}{\pi^2 hc_{LII}}\left\{2 + \dfrac{0.596}{F - 1/F}\left[F\cos\left(\dfrac{1.745f_1^2}{F^2f^2}\right) - \dfrac{1}{F}\cos\left(\dfrac{1.745F^2f_1^2}{f^2}\right)\right]\right\}; & (f/f_1 > 0.83) \end{cases}$$

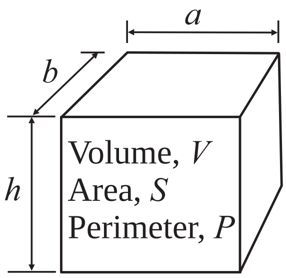
[1]This expression is closest to the exact analysis of Langley (1994)

[2]The results of Szechenyi (1971) are for resonance frequency density (resonance frequencies/Hz) but as there are two possible modes for each resonance frequency, their result has been multiplied by 2 and divided by 2π here to obtain modal density expressed as modes/rad s^{-1} (see Clarkson (1981), with their definition of c_L requiring a change to $c_{LII} = \sqrt{E/\rho_m}$, as pointed out by Langley (1994)).

Table A.16 Modal densities, $n(\omega)$, of 2-D and 3-D acoustic spaces. (See also Section A.7.3 below.)

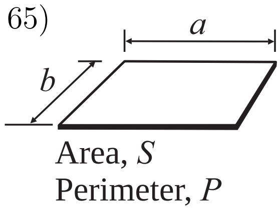
3-D rectangular room (see textbook p. 323)

$$n(\omega) = \frac{V\omega^2}{2\pi^2 c^3} + \frac{S\omega}{8\pi c^2} + \frac{P}{16\pi c}$$



2-D rectangular cavity (Yoerkie et al., 1983, p. 65)

$$n(\omega) = \frac{S\omega}{4\pi c^2} + \frac{P}{2\pi c}$$

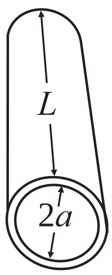


Cylindrical room (Garret, 2020, p. 643)

$$n(\omega) = \frac{V\omega^2}{2\pi^2 c^3} + \frac{S\omega}{8\pi c^2} + \frac{P}{16\pi c}$$

$V = \pi a^2 L \quad S = 2\pi a(a + L),$

$P = 4\pi a + 4L$



Variables not defined following Table A.6 are defined below.

c_g is the group wave speed, which is different for different wave types and different for plates and beams;

$c_{LII} = \sqrt{E/\rho_m}$ is the longitudinal wavespeed for a rod or beam, or the "plane-stress" longitudinal wavespeed for a thin cylinder (m s^{-1});

$c_{LI} = \sqrt{E/[\rho_m(1-\nu^2)]}$ is the longitudinal wavespeed for an isotropic plate (m s^{-1});

$c_L = \sqrt{E(1-\nu)/[\rho_m(1+\nu)(1-2\nu)]}$ is the pure longitudinal wavespeed for a 3-D solid;

E_s is Young's modulus of elasticity for the skin material of the sandwich plate (kg m^{-1} s^{-2});

$f_1 = c_{LII}/(2\pi a)$ is the "plane-stress" ring frequency (Hz) (Langley, 1994);

$F = 1.414$ for octave band analysis and 1.122 for 1/3-octave bands;

G_c is the shear modulus for the core of the sandwich plate where the modulus is identical in the x- and y-directions (kg m^{-1} s^{-2});

G_{cx} is the shear modulus for the core of the sandwich plate in the x-direction (kg m^{-1} s^{-2});

G_{cy} is the shear modulus for the core of the sandwich plate in the y-direction (kg m^{-1} s^{-2});

$I_y = 0.13hd^2$ is the max. 2nd moment of area per unit width about the corrugated plate cross sect. (m^3) where h is the sheet thickness (m) and d is the peak to trough distance (m);

L is the length of beam, duct or cylinder (m);

m is the mass per unit area (kg/m^2);

P is the perimeter of a plate edge ($= 2(a+b)$) or a 2-D room ($= 2(a+b)$) or a 3-D room ($= 4(a+b+h)$) or a cylinder ($= 4(\pi a + L)$) (m);

S is the interior surface area of a 2-D cavity ($= 2ab$), a 3-D room ($= 2(ab+ah+bh)$) or a cylinder ($= 2\pi a(a+L)$) (m^2);

S_c is the surface area of a cylinder (excluding end caps) ($2\pi aL$) (m^2);

S_y is the area of a corrugated plate that includes the component due to the corrugations (m^2);

λ_B is the bending wavelength in a plate (m);

ν_s is Poisson's ratio for the skin material of the sandwich plate;

ρ_s is the density of the outside skins of a sandwich plate (kg m^{-3})

ρ_c is the density of the core of a sandwich plate (kg m^{-3})

A.7.1 Sandwich Plate Modal Densities for Longitudinal Waves

Sandwich plates considered by ENC are honeycomb structures sandwiched between two thin skins, usually made from aluminium or carbon fibre. For the purposes of SEA analysis undertaken in ENC, the modal density for longitudinal waves (subsystem type numbers 23 and 24) is considered to be the modal density in the thin skins, as the honeycomb structure is not considered to significantly contribute to the longitudinal wave modal density of the construction, as it does not contribute significantly to the longitudinal stiffness.

A.7.2 Corrugated Plate Modal Densities for Longitudinal Waves

Longitudinal waves in corrugated plates are considered by ENC to behave similarly to longitudinal waves in flat plates, so the same equations as used for flat plates are used for calculating the wave speed and modal density.

A.7.3 Thin Cylinder Modal Density (Bending Modes)

Although the modal density calculation for a thin cylinder is complex, it can be calculated with the use of tables (Langley, 1994) and then calculating the mode count, $N(f_\ell)$ and $N(f_u)$, up to the beginning and ending frequencies of the frequency band of interest, using:

$$N_i(f) = \frac{S}{2}\left(\frac{\rho_m h}{D}\right)^{1/2} f_r\, \gamma_i(\Omega); \quad i = 1, 2 \qquad \text{(A.54)}$$

where S is the cylinder surface area $= 2\pi aL$, L is the cylinder length, ρ_m is the density of the cylinder wall material, h is the cylinder wall thickness, $D = \dfrac{Eh^3}{12(1-\nu^2)}$, f_r is the plane-stress ring frequency given by $f_r = \dfrac{1}{2\pi a}\sqrt{\dfrac{E}{\rho_m}}$, a is the cylinder radius, $\Omega = f/f_r$, the total mode count, $N(f) = N_1(f) + N_2(f)$. Values of $\gamma_1(\Omega)$ and $\gamma_2(\Omega)$ (see Equation (A.54)) are listed in the following tables as a function of Ω.

Table A.17 Values of $\gamma_1(\Omega)$

Ω	0	1	2	3	4	5	6	7	8	9
0.0	0.0000	0.0004	0.0011	0.002	0.0031	0.0043	0.0056	0.0071	0.0087	0.0103
0.1	0.0121	0.014	0.0159	0.018	0.0201	0.0223	0.0246	0.027	0.0294	0.032
0.2	0.0345	0.0372	0.0399	0.0427	0.0456	0.0485	0.0515	0.0545	0.0576	0.0608
0.3	0.064	0.0673	0.0706	0.074	0.0775	0.081	0.0846	0.0882	0.0919	0.0956
0.4	0.0994	0.1032	0.1071	0.1111	0.1151	0.1192	0.1233	0.1274	0.1316	0.1359
0.5	0.1402	0.1446	0.149	0.1535	0.158	0.1626	0.1672	0.1719	0.1766	0.1813
0.6	0.1862	0.191	0.1959	0.2009	0.2059	0.211	0.2161	0.2213	0.2265	0.2318
0.7	0.2371	0.2424	0.2478	0.2533	0.2588	0.2644	0.27	0.2756	0.2814	0.2871
0.8	0.2929	0.2988	0.3047	0.3107	0.3167	0.3227	0.3288	0.335	0.3412	0.3475
0.9	0.3538	0.3602	0.3666	0.3731	0.3796	0.3862	0.3928	0.3995	0.4062	0.413
1	0.4199	0.4268	0.4338	0.4408	0.4479	0.455	0.4622	0.4694	0.4768	0.4841
1.1	0.4916	0.4991	0.5066	0.5142	0.5219	0.5297	0.5375	0.5454	0.5534	0.5614
1.2	0.5695	0.5776	0.5859	0.5942	0.6026	0.6111	0.6197	0.6283	0.637	0.6459
1.3	0.6548	0.6638	0.6729	0.6822	0.6915	0.701	0.7106	0.7204	0.7303	0.7404
1.4	0.7508	0.7614	0.7726	0.7839	0.7952	0.8065	0.8177	0.8289	0.8401	0.8512
1.5	0.8624	0.8735	0.8846	0.8957	0.9067	0.9178	0.9288	0.9398	0.9508	0.9618
1.6	0.9727	0.9837	0.9946	1.0055	1.0164	1.0273	1.0382	1.049	1.0599	1.0707
1.7	1.0815	1.0923	1.1031	1.1139	1.1247	1.1354	1.1462	1.1569	1.1676	1.1784
1.8	1.1891	1.1998	1.2105	1.2211	1.2318	1.2425	1.2531	1.2638	1.2744	1.285
1.9	1.2957	1.3063	1.3169	1.3275	1.3381	1.3487	1.3592	1.3698	1.3804	1.3909
2	1.4015	1.412	1.4225	1.4331	1.4436	1.4541	1.4646	1.4751	1.4856	1.4961
2.1	1.5066	1.5171	1.5276	1.5381	1.5485	1.559	1.5695	1.5799	1.5904	1.6008
2.2	1.6113	1.6217	1.6321	1.6426	1.653	1.6634	1.6738	1.6842	1.6946	1.705
2.3	1.7154	1.7258	1.7362	1.7466	1.757	1.7674	1.7777	1.7881	1.7985	1.8088
2.4	1.8192	1.8296	1.8399	1.8503	1.8606	1.871	1.8813	1.8917	1.902	1.9123
2.5	1.9227	1.933	1.9433	1.9536	1.964	1.9743	1.9846	1.9949	2.0052	2.0155
2.6	2.0258	2.0361	2.0464	2.0567	2.067	2.0773	2.0876	2.0979	2.1082	2.1184
2.7	2.1287	2.139	2.1493	2.1595	2.1698	2.1801	2.1903	2.2006	2.2109	2.2211
2.8	2.2314	2.2416	2.2519	2.2622	2.2724	2.2827	2.2929	2.3031	2.3134	2.3236
2.9	2.3339	2.3441	2.3543	2.3646	2.3748	2.385	2.3953	2.4055	2.4157	2.426
3	2.4362	2.4464	2.4566	2.4668	2.4771	2.4873	2.4975	2.5077	2.5179	2.5281
3.1	2.5383	2.5485	2.5587	2.5689	2.5791	2.5893	2.5995	2.6097	2.6199	2.6301
3.2	2.6403	2.6505	2.6607	2.6709	2.6811	2.6913	2.7015	2.7116	2.7218	2.732
3.3	2.7422	2.7524	2.7626	2.7727	2.7829	2.7931	2.8033	2.8134	2.8236	2.8338
3.4	2.844	2.8541	2.8643	2.8745	2.8846	2.8948	2.905	2.9151	2.9253	2.9354
3.5	2.9456	2.9558	2.9659	2.9761	2.9862	2.9964	3.0066	3.0167	3.0269	3.037
3.6	3.0472	3.0573	3.0675	3.0776	3.0878	3.0979	3.1081	3.1182	3.1283	3.1385
3.7	3.1486	3.1588	3.1689	3.1791	3.1892	3.1993	3.2095	3.2196	3.2297	3.2399
3.8	3.25	3.2602	3.2703	3.2804	3.2906	3.3007	3.3108	3.3209	3.3311	3.3412
3.9	3.3513	3.3615	3.3716	3.3817	3.3918	3.402	3.4121	3.4222	3.4323	3.4425
4	3.4526	3.4627	3.4728	3.4829	3.4931	3.5032	3.5133	3.5234	3.5335	3.5436
> 4.09	$\gamma_1(\Omega) \approx \Omega - 0.5464$									

Table A.18 Values of $\gamma_2(\Omega)$

Ω	0	1	2	3	4	5	6	7	8	9
0.0	0.0000	0.0002	0.0005	0.0009	0.0014	0.002	0.0026	0.0033	0.0041	0.0049
0.1	0.0057	0.0066	0.0076	0.0086	0.0096	0.0107	0.0118	0.013	0.0142	0.0154
0.2	0.0167	0.018	0.0194	0.0208	0.0222	0.0237	0.0253	0.0268	0.0284	0.03
0.3	0.0317	0.0334	0.0352	0.037	0.0388	0.0407	0.0426	0.0445	0.0465	0.0486
0.4	0.0506	0.0527	0.0549	0.0571	0.0593	0.0616	0.0639	0.0663	0.0687	0.0712
0.5	0.0737	0.0762	0.0788	0.0814	0.0841	0.0869	0.0897	0.0925	0.0954	0.0983
0.6	0.1013	0.1044	0.1075	0.1107	0.1139	0.1172	0.1205	0.124	0.1274	0.131
0.7	0.1346	0.1383	0.1421	0.1459	0.1499	0.1539	0.158	0.1622	0.1665	0.1709
0.8	0.1754	0.18	0.1847	0.1895	0.1945	0.1996	0.2048	0.2103	0.2158	0.2216
0.9	0.2276	0.2338	0.2402	0.2469	0.254	0.2614	0.2693	0.2777	0.2869	0.2973
1	0.3108	0.3244	0.3348	0.3441	0.3526	0.3605	0.3679	0.375	0.3817	0.3882
1.1	0.3943	0.4003	0.406	0.4115	0.4167	0.4218	0.4268	0.4315	0.4361	0.4405
1.2	0.4448	0.4489	0.4529	0.4567	0.4604	0.464	0.4674	0.4707	0.4738	0.4768
1.3	0.4796	0.4823	0.4849	0.4873	0.4895	0.4916	0.4935	0.4952	0.4968	0.4981
1.4	0.4991	0.4999	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
> 1.49	$\gamma_2(\Omega) = 0.5$									

The modal density, $n(f)$, for a 1/3-octave or octave frequency band centred on f is calculated using:

$$n(f) = \frac{N(f_u) - N(f_\ell)}{\Delta f} \tag{A.55}$$

where $\Delta f = 0.2316f$ for a 1/3-octave bandwidth and $\Delta f = 0.7071f$ for an octave bandwidth. This analysis only provides approximate results (see Finnveden (1997)), but is acceptable for SEA analysis averaged over 1/3-octave or octave bands.

Lyon and DeJong (1995) use the following approximate expression for the mode count, which is a curve fit over the frequency range, together with Equation (A.55) to calculate the modal density:

$$N(f) = \frac{L\sqrt{12}}{2h}\left(\frac{f}{f_r}\right)\left\{1 + \left[\frac{\pi/2}{(f/f_r)^{1/2} + 0.5(f/f_r)^{3.5}}\right]^4\right\}^{-1/4} \tag{A.56}$$

A.8 Coupling Loss Factors (CLFs)

ENC can handle a number of different connections between various subsystem types. Each connection will be described in a separate section to follow. When considering subsystems, all wave types could be included so a simple beam would have 10 possible coupling loss factors when connected to another beam at right angles at their ends. Of course, 5 of these can be derived from the other 5 using modal densities and others may not be important contributors to energy transmission. We could also look at coupling between different waves on the same subsystem as a result of reflection from the junction, but this form of coupling is not included in ENC as it is usually ignored in practical SEA analysis, as the error in treating different waves as separate and uncoupled is acceptable and within the accuracy expected from an SEA analysis (Lyon and

DeJong, 1995, p. 191). It is important to remember that for a particular structural element, each wave type is considered to be a separate subsystem.

When entering coupling loss data into ENC, it is vitally important that the correct subsystem ID numbers are used. For example, in the pictures below, the subsystem ID that corresponds to the subsystem identified as "1" in the following figures is entered in ENC in the column identified as "Subsystem ID corresponding to subsystem 1 in the figure in the manual". The same applies to the next 4 columns. If the junction in question can be characterised by only 2 subsystems, then enter 0 in the next three columns.

CLF calculations often require the calculation of the transmission coefficient of the junction under consideration and this is a function of the real part of the infinite impedances of the attached subsystems. In cases where the real part of zero but the imaginary part is not, the CLF formulation works if the magnitude of the imaginary part is used instead (Lyon and DeJong, 1995, p. 202). Note that transmission coefficients must satisfy reciprocity so that $\tau_{ij} = \tau_{ji}$, where i and j represent the ID numbers of the connected subsystems for which the transmission coefficient applies.

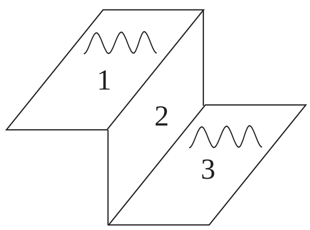
Note that the admittance of a stiffness $Y = \mathrm{j}\omega/k$. If it is a torsional stiffness, the torsional admittance is, $Y = \mathrm{j}\omega/k_{\mathrm{tors}}$, where k_{tors} is the torsional stiffness (N-m/rad).

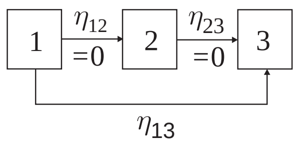
The net power flow from system 1 to subsystem 2, $\Pi_{12} = \omega(\eta_{12}E_1 - \eta_{21}E_2)$ (Lyon and DeJong, 1995, p. 181), which is a function of the coupling loss factor between subsystems 1 and 2. Note that the coupling loss factor, η_{21}, for power flow from system 2 to system 1 can be calculated from the coupling loss factor, η_{12}, for power flow from system 1 to system 2 using:

$$\begin{cases} \eta_{21} = \eta_{12}(n_1/n_2) & \text{for 1-D systems} \\ \eta_{21} = \eta_{12}(n_1 c_1/(n_2 c_2)) & \text{for 2-D systems} \\ \eta_{21} = \eta_{12}(n_1 c_1^2/(n_2 c_2^2)) & \text{for 3-D systems} \end{cases} \tag{A.57}$$

where n_1 and n_2 are the modal densities of systems 1 and 2, while c_1 and c_2 are the phase speeds of the waves in systems 1 and 2, respectively.

A.8.1 Tunnelling Phenomena





SEA usually only considers resonant transmission from one subsystem to another, but in some cases, non-resonant transmission, or "tunnelling" is important. This phenomenon describes the transmission of energy from one subsystem (1) to another subsystem (3) via non resonant response in a connecting subsystem (2). Sometimes, this non-resonant connection may be the only connection between systems 1 and 3. At other times, there may be additional resonant connections between systems 1 and 2 as well as between systems 2 and 3.

An example of the former is three plates connected at right angles with plate 1 parallel to plate 3 and perpendicular to plate 2 as shown in the figure above at right. In this case, the resonance frequencies of in-plane modes of plate 2 are much higher than those of bending modes in plates 1 and 3. Thus the low-frequency bending modes of plate 1 couple with the low-frequency modes of plate 3 via forced in-plane motion of plate 2. An example of the latter is the coupling between two rooms via a partitioning wall. In this case, there is both resonant and non-resonant transmission via the wall and the representation is illustrated in the figure at right. Each resonant or non-resonant transmission path is characterised by an individual coupling loss factor and each individual coupling loss factor results in one more row and column in the C-matrix of Equation (A.275). This particular example is treated separately in Sections A.8.6.3 to A.8.6.3.

A.8.2 User Entered Coupling Loss Factors

If a calculated CLF is not to be used, a value of 0.0 (or a number less than 10^{-11}) is entered in the box with this label on the "Coupling loss factor input data" page. ENC assumes that for each group, the entered value corresponds to the coupling loss factor, η_{ij}, where i is the subsystem ID number corresponding to the smallest number shown in the relevant junction picture and j is the subsystem ID number corresponding to the largest number shown in the picture (except for junction 36 – see paragraph after next). For junction groups that contain more than two subsystems in the picture, coupling loss factors for the additional subsystem combinations are calculated from the entered value using ratios of corresponding calculated impedance values. If the user entered coupling loss factor is between two subsystems in a junction group that has more than one type or direction of motion (such as junctions 3(b), 4(a), 4(b), 23(b), 24(a) and 24(b), the calculation of the CLF corresponding to bending-longitudinal wave transmission (which is represented by a different type of junction motion) is a bit more complex. In this case, only the part of the user entered coupling loss factor that is associated with translational motion in the same direction as the longitudinal wave travel is used to calculate corresponding CLF. For example, in Junction 3(b) and 23(b), the user entered value for η_{13} includes both the translational and rotational junction motions. However, only the translational part can transmit energy to subsystem 2. As an example, referring to junction 3(b), the fraction of the user entered η_{13} to use for η_{12} is the ratio of the theoretical transmission coefficients $(\tau_{12}/(\tau_{13})$, where τ_{13} is the sum of the translational and rotational transmission coefficients for the transmission of bending waves.

Note that if there is a double wall, both the η_{24} and the η_{15} coupling loss factors must be calculated and the η_{15} coupling loss factor must be calculated before the η_{24} coupling loss factor. That is, the junction number corresponding to η_{15} must be smaller than the junction number (on the coupling loss factor input data page) corresponding to η_{24}. If this is not the case, ENC will produce an error message that will be on the "SEA calculation Results" page.

Junction type ID=36 requires special treatment in the way data are entered. For this junction, the coupling loss factor that must be entered is η_{24}. If there is a double wall, both the η_{24} and the η_{15} coupling loss factors must be calculated and the η_{15} coupling loss factor must be calculated before the η_{24} coupling loss factor. That is, the junction number corresponding to η_{15} must be smaller than the junction number (on the coupling loss factor input data page) corresponding to η_{24}.

A.8.3 Coupling Loss Factors for Structural Point Connections

Where two substructures are connected at a point junction, the coupling loss factor is given by (Lyon and DeJong, 1995, p. 188):

$$\eta_{12}^{\text{point}} = \frac{\beta_{\text{corr}}}{2\pi f n_1(f)} \frac{2\tau_{12,\infty}}{(2-\tau_{12,\infty})} \tag{A.58}$$

where $n_1(f) = 2\pi n_1(\omega)$ and:

$$\beta_{\text{corr}} = \left\{1 + \left[\frac{1}{2\pi[\beta_{1,\text{net}} + \beta_{2,\text{net}}]}\right]^8\right\}^{-1/4} = \left\{1 + \left[\frac{1}{2\pi f[\eta_{1,\text{net}} n_1(f) + \eta_{2,\text{net}} n_2(f)]}\right]^8\right\}^{-1/4} \tag{A.59}$$

where $n_i(f)$ is the modal density for subsystem i and $\eta_{i,\mathrm{net}}$ is the damping loss factor for subsystem i, plus some fraction of the loss due to coupling with other systems. The quantity, $\beta_{i,\mathrm{net}}$ is equal to the reciprocal of the (i,i) diagonal term in the inverse of the C-matrix of Equation (A.276) (Lyon and DeJong, 1995, p. 217). Thus, $\beta_{i,\mathrm{net}}$ for $i = 1, N$, where N is the number of subsystems in the analysis, can be found by iteration, beginning with a value of one or two (corresponding to $\beta_{\mathrm{corr}} \approx 1$). The new C-matrix and its inverse are then found and the resulting diagonal values of the new inverse are used to estimate new values of $\beta_{i,\mathrm{net}}$, which are then used to find a new C-matrix. The number of iterations to use can be set by the user, but the more iterations used, the longer will be the processing time. Generally 3 or 4 iterations are sufficient.

The correction factor, $2/(2 - \tau_{12,\infty})$, included in Equation (A.58) as proposed by (Lyon and DeJong, 1995, p. 188), to account for the reflected wave having less energy than the incident wave at a junction, was shown by Craik (1997) to be unjustified, so it will not be included in the analysis to follow. For a junction consisting of N subsystems, the transmission coefficient between junction i an junction j is::

$$\tau_{ij,\infty} = \frac{4q\mathrm{Re}\{Z_{i,\infty}\}\mathrm{Re}\{Z_{j,\infty}\}}{\left|\sum\limits_{k=1}^{N} Z_{k,\infty}\right|^2} \tag{A.60}$$

where q is the number of points at which subsystems i and j are connected, N is the number of subsystems connected at the junction (including source and receiving subsystems) and $\mathrm{Re}\{Z_\infty\}$ is the real part of the point impedance for the equivalent infinite system (see Tables A.1 to A.4). Ignoring the correction, $2/(2 - \tau_{12,\infty})$, as explained above, Equation (A.59) becomes the more familiar expression:

$$\eta_{ij}^{\mathrm{point}} = \frac{\beta_{\mathrm{corr}}\tau_{ij,\infty}}{2\pi f n_i(f)} \tag{A.61}$$

where $fn_i(f) = \omega n_i(\omega)$ and β_{corr} is found by iteration as explained on page 357.

The impedances in Equation (A.60) are moment impedances when bending or torsional waves are being transmitted and/or received. For longitudinal waves transmitted and/or received, point force expressions are used. If beams are connected at right angles at their ends, then semi-infinite moment impedances are used if the bending wave motion is in the plane of the two beams and semi-infinite force impedances are used if the bending wave motion is perpendicular to the plane of the two beams. Note that any end connected element is described by a semi-infinite impedance for the coupling loss factor calculation. If one beam is connected at its end to the centre of another beam, the appropriate (force or moment) semi-infinite impedance is used for the end-connected beam and the appropriate infinite impedance is used for the centre connected beam.

Another consideration is whether the junction connection is rigid or pinned. If it is pinned, no rotational motion can be transmitted through the junction. This means that only the portion of bending wave motion that involves translational motion normal to the direction of wave propagation can be transmitted. Thus, for pinned junctions, bending waves in the source beam can only produce longitudinal waves in a receiver beam around a 90 degree junction (such as for two beams connected at right angles). The translational motion associated with bending wave propagation can also result in the transmission of bending waves across an in-line junction where wave propagation is in the same direction for both subsystems. The same conclusions also apply to plate connections. For longitudinal waves, only motion in the direction of wave propagation is transmitted through the junction to a significant extent for both rigid and pinned junctions.

Thus, longitudinal waves cannot be transmitted around a 90 degree bend. This result applies to plates as well as beams (Cremer et al., 1988, p.361).

If a mass, m_a, is part of a point junction, such as between beams, its effect can be included by adding its inertial impedance, $\mathrm{j}2\pi f m_a$, to the term inside the modulus lines in the denominator of Equation (A.60). If a subsystem, i, is connected to the junction via a stiffness element of stiffness, k_i, the subsystem impedance, $Z'_{F,i,\infty}$, to be used in Equation (A.60) in place of $Z_{i,\infty}$ is (Lyon and DeJong, 1995, p. 191):

$$Z'_{i,\infty} = \left(\frac{\mathrm{j}\omega}{k_i} + \frac{1}{Z_{i,\infty}} \right)^{-1} \tag{A.62}$$

If bending waves that result in both translational and rotational motion are incident on a junction, it is sufficiently accurate to add the transmission coefficients for translational and rotational motion together to obtain a net transmission coefficient (Lyon and DeJong, 1995, p. 191). It is important that the impedance sum used to calculate the transmission coefficient (see Equation (A.60)) includes all subsystems connected at the junction that have a wave type that can contribute to the rotational or translational motion under consideration.

Note that Equations (A.60) and (A.62) also apply to rotational motion if the impedances used are all moment impedances.

In summary, for each structural point connection between two subsystems, the following junction properties must be specified.

1. type of connection (rigid or pinned)
2. type of source element (beam, plate, 3-D solid)
3. type of receiver element (beam, plate, 3-D solid)
4. type of wave incident (this will correspond to a unique subsystem)
5. type of wave transmitted (this will correspond to a unique subsystem)

For a 1-D acoustic system, a junction has a common pressure, so that acoustic admittances (reciprocal of acoustic impedances, see table A.6), $Y_{F,\infty}$, add at the junction (Lyon and DeJong, 1995, p. 191). As pressure is a scalar quantity, the acoustic impedances of all 1-D acoustic subsystems connected at the junction will contribute to the impedance sum. Thus, for a junction consisting of N subsystems, the transmission coefficient between junction i an junction j is:

$$\tau_{ij,\infty} = \frac{4\mathrm{Re}\{Y_{F,i,\infty}\}\mathrm{Re}\{Y_{F,j,\infty}\}}{\left| \sum\limits_{k=1}^{N} Y_{F,k,\infty} \right|^2} \tag{A.63}$$

If more than two subsystems are connected, then the impedances (force or moment as appropriate), corresponding the relevant type and direction of junction motion, for the other connected subsystems are also needed to allow use of Equation (A.60). Generally the connection of more than two subsystems involves the same physical junction but with different wave types either incident or transmitted. Each type of junction motion requires a different junction ID. The one exception is for the 1D duct system that allows many physically different ducts to be connected at the same junction, with all ducts having the same longitudinal wave type. As the wave Thus junctions are identified by a single integer number and the wave types for the same junction are identified by a letter (a, b or c) following the junction number.

For all junctions involving point connections, Equations (A.60) and (A.61) are used and the only unknowns are the impedances to be used. For beams connected at their ends or plates connected at their edges, semi-infinite impedances are used and for beams or plates connected more than one quarter of a wavelength from the beam end or plate edge, infinite impedances are used.

In the following subsections, the following quantities are used:

k_B = bending wavenumber $=[\rho_m S\omega^2/(EJ_y)]^{1/4}$ for a beam.

$$k_B = \left[\frac{12\omega^2 m(1-\nu^2)}{Eh^3}\right]^{1/4} \text{ for a plate.}$$

c_B = bending wave speed ($= \omega/k_B = c_g/2$);

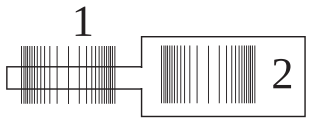
c_s = shear wave speed ($= \sqrt{G/\rho_m} = c_g$);

c_L = longitudinal wave speed ($=\sqrt{E/\rho_m} = c_g$ for a beam and

$c_L = \sqrt{E/[\rho_m(1-\nu^2)]} = c_g$ for a plate or thin-walled cylinder);

k_s = shear wavenumber $= \sqrt{\dfrac{\rho_m\omega^2}{G}}$

A.8.3.1 Beam-Beam, End to End In-line, Axial-Axial (ID=1a)



This junction type can transmit energy whether pinned or rigid, with consideration of only lateral junction motion in the horizontal direction. The same results apply to both pinned and rigid junctions. The impedances to use in Equation (A.60) are force impedances for a semi-infinite beam subject to longitudinal motion:

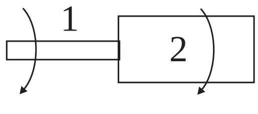
$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1}S_1c_{LII,1} \tag{A.64}$$

$$Z_{F,2,\infty} = S_2\sqrt{E_2\rho_{m2}} = \rho_{m2}S_2c_{LII,2} \tag{A.65}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors.

The same equations are used for both "Calculation method" choices provided on the ENC GUI.

A.8.3.2 Beam-Beam, End to End In-line, Torsional-Torsional (ID=1b)



This junction type can only transmit energy if it is rigid, with consideration of only rotational junction motion around the beam axis. The impedances to use in Equation (A.60) are torsional impedances for a semi-infinite shaft:

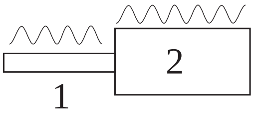
$$Z_{T,1,\infty} = J_{x1}\sqrt{G_1\rho_{m1}(J_1'/J_{x1})} = \rho_{m1}J_{x1}c_{T1} \tag{A.66}$$

$$Z_{T,2,\infty} = J_{x2}\sqrt{G_2\rho_{m2}(J_2'/J_{x2})} = \rho_{m2}J_{x2}c_{T2} \tag{A.67}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors.

The same equations are used for both "Calculation method" choices provided on the ENC GUI.

A.8.3.3 Beam - Beam, End to End In-line, Bending-Bending (ID=1c)



This junction type can transmit energy whether rigid or pinned, with consideration of lateral vertical motion and rotational junction motion around an axis perpendicular to the beam axis. This is because bending waves are associated with motion in a direction normal to their propagation direction as well as rotational motion. The impedances to use in Equation (A.60) are both force and moment impedances for a semi-infinite beam:

$$Z_{F,1,\infty} = \frac{1}{2}\rho_{m1} S_1 c_{B,1}(1+\mathrm{j}) \tag{A.68}$$

$$Z_{F,2,\infty} = \frac{1}{2}\rho_{m2} S_2 c_{B,2}(1+\mathrm{j}) \tag{A.69}$$

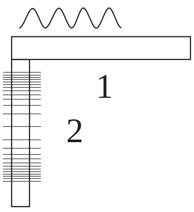
$$Z_{M,1,\infty} = \frac{1}{2}\rho_{m1} S_1 c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.70}$$

$$Z_{M,2,\infty} = \frac{1}{2}\rho_{m2} S_2 c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \tag{A.71}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors. The coupling loss factor for translational motion must be added to that for rotational motion, but each is calculated separately: one using force impedances and force impedance sums and the other using moment impedances and moment impedance sums.

A.8.3.4 Beam - Beam, End to End 90-deg, Bending-Longitudinal (ID=2a)

This junction type can transmit energy whether pinned or rigid, with consideration of only translational junction motion parallel to beam 2 axis. The same results apply to both pinned and rigid junctions. The impedances to use in Equation (A.60) are force impedances for a semi-infinite beam:



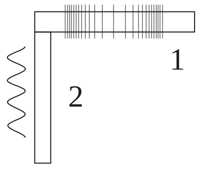
$$Z_{F,1,\infty} = \frac{1}{2}\rho_{m1} S_1 c_{B,1}(1+\mathrm{j}) \tag{A.72}$$

$$Z_{F,2,\infty} = S_2\sqrt{E_2\rho_{m2}} = \rho_{m2} S_2 c_{LII,2} \tag{A.73}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors.

A.8.3.5 Beam - Beam, End to End 90-deg, Longitudinal-Bending (ID=2b)

This junction type can transmit energy whether pinned or rigid, with consideration of only translational junction motion parallel to beam 1 axis. The same results apply to both pinned and rigid junctions. The impedances to use in Equation (A.60) are force impedances for a semi-infinite beam:

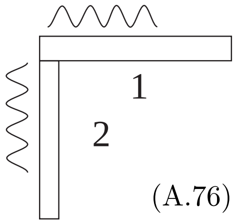


$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1} S_1 c_{LII,1} \tag{A.74}$$

$$Z_{F,2,\infty} = \frac{1}{2}\rho_{m2} S_2 c_{B,2}(1+\mathrm{j}) \tag{A.75}$$

These impedances are used together with Equations (A.61) and (A.60) to calculate the corresponding coupling loss factors.

A.8.3.6 Beam - Beam, End to End 90-deg, Longitudinal-Bending (ID=2c)



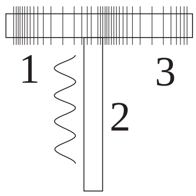
This junction type can only transmit energy if it is rigid, with consideration of only rotational junction motion, parallel to an axis perpendicular to the page and passing through the junction. The impedances to use in Equation (A.60) are moment impedances for bending waves on a semi-infinite beam:

$$Z_{M,1,\infty} = \frac{1}{2}\rho_{m1}S_1 c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.76}$$

$$Z_{M,2,\infty} = \frac{1}{2}\rho_{m2}S_2 c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \tag{A.77}$$

These impedances are used together with Equations (A.61) and (A.60) to calculate the corresponding coupling loss factors.

A.8.3.7 Beam 90 deg T-junction, Axial-Bending-Axial (ID=3a)



This junction type can transmit energy whether pinned or rigid, with consideration of only translational junction motion parallel to beam 1 axis. The same results apply to both pinned and rigid junctions. The impedances to use in Equation (A.60) for beams 1 and 3 are longitudinal force impedances for a semi-infinite beam and for beam 2, they are bending force impedances for a semi-infinite beam. Thus:

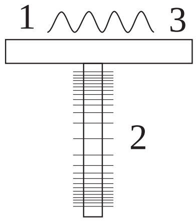
$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1}S_1 c_{LII,1} \tag{A.78}$$

$$Z_{F,2,\infty} = 0.5\rho_{m2}S_2 c_{B,2}(1+\mathrm{j}) \tag{A.79}$$

$$Z_{F,3,\infty} = S_3\sqrt{E_3\rho_{m3}} = \rho_{m3}S_3 c_{LII,3} \tag{A.80}$$

These impedances are used together with Equations (A.61) and (A.60) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{23} and η_{32}.

A.8.3.8 Beam 90 degree T-junction, Bending-Axial-Bending (ID=3b)



This junction type can transmit energy whether pinned or rigid, with consideration of translational junction motion parallel to the beam 2 axis as well as rotational motion, about an axis perpendicular to the page and passing through the junction. The transmission of energy from beam 1 to beam 2 and beam 3 to beam 2 (and vice versa) is a result of only translational junction motion in a direction parallel to the axis of beam 2. The bending wave transmission from beam 1 to 3 involves the addition of 2 coupling loss factors, both of which are associated with bending wave transmission. One CLF is the result of the transmission of rotational motion about an axis perpendicular to the page and passing through the junction and the other CLF is a result of translational motion of the junction in a vertical direction, which is perpendicular to the direction of bending wave propagation between beams 1 and 3. For pinned junctions, rotational motion is not transmitted.

The transmission coefficients as a result of translational motion of the junction are τ_{12}, τ_{23} and the translational motion contribution to τ_{13}. The impedances used to calculate these transmission coefficients using Equation (A.60), are longitudinal force impedances for a semi-infinite beam for beam 2 and for beams 1 and 3, they are bending force impedances for an semi-infinite beam.

$$Z_{F,1,\infty} = 0.5\rho_{m1}S_1 c_{B,1}(1+\mathrm{j}) \tag{A.81}$$

$$Z_{F,2,\infty} = S_2\sqrt{E_2\rho_{m2}} = \rho_{m2}S_2c_{LII,2} \quad \text{(A.82)}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3}S_3c_{B,3}(1+\mathrm{j}) \quad \text{(A.83)}$$

To calculate the contribution of the rotational motion of the junction (rigid type only) to τ_{13}, moment impedances of all connected subsystems are needed in the impedance sum of Equation (A.60). The relevant impedances are:

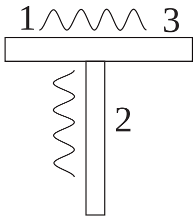
$$Z_{M,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \quad \text{(A.84)}$$

$$Z_{M,2,\infty} = 0.5\rho_{m2}S_1c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \quad \text{(A.85)}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}S_3c_{B,3}(1-\mathrm{j})/k_{B,3}^2 \quad \text{(A.86)}$$

The force and moment impedances in the above equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{23} and η_{32}.

A.8.3.9 Beam - Beam 90 deg T-junction, Bending-Bending-Bending (ID=3c)



This junction type can transmit energy whether rigid or pinned, with consideration of vertical translational junction motion as well as rotational junction motion, parallel to an axis perpendicular to the page and passing through the junction. If pinned, there is only energy transmission between beams 1 and 3, as a result of translational motion of the junction in the vertical direction. However, there is no energy transmission between beams 1 and 2 nor between beams 2 and 3 so the contributions to both τ_{12} and τ_{23} are zero for translational motion of the junction. In the impedance sum of Equation (A.60), used for finding the translational component of τ_{13}, the impedances to use are semi-infinite bending wave force impedances for beams 1 and 3 and the semi-infinite longitudinal impedance for beam 2 (see below).

$$Z_{F,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1+\mathrm{j}) \quad \text{(A.87)}$$

$$Z_{F,2,\infty} = \rho_{m2}S_2c_{LII,2} \quad \text{(A.88)}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3}S_3c_{B,3}(1+\mathrm{j}) \quad \text{(A.89)}$$

For a rigid junction, energy is transmitted between all subsystem pair combinations as a result of rotational motion of the junction about an axis perpendicular to the page and passing through the junction. The impedances to use in Equation (A.60) are moment impedances for a semi-infinite beam (see below).

$$Z_{M,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \quad \text{(A.90)}$$

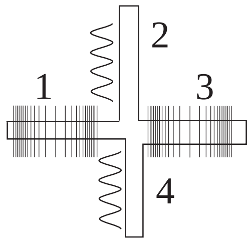
$$Z_{M,2,\infty} = 0.5\rho_{m2}S_2c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \quad \text{(A.91)}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}S_3c_{B,3}(1-\mathrm{j})/k_{B,3}^2 \quad \text{(A.92)}$$

For calculating τ_{13}, the contribution due to rotational motion of the junction must be added to the contribution due to translational motion of the junction.

The impedances calculated using the above equations are used together with Equations (A.61) and (A.60) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{23} and η_{32}.

A.8.3.10 Four Beams Connected at Right Angles, Longitudinal-Bending-Longitudinal-Bending (ID=4a)



This junction type can transmit energy whether rigid or pinned. If pinned, there can be no transmission from beam 2 to beam 4 via rotational motion of the junction. Thus, for the pinned junction, all transmissions between beams, including between beam 2 and beam 4, will be a result of translational motion of the junction in the horizontal direction. The impedances to use for a pinned junction in Equation (A.60) for subsystems 2 and 4 are bending force impedances for a semi-infinite beam and for subsystems 1 and 3 we use longitudinal force impedances. For rigid junctions, there will be additional transmission between beams 2 and 4 due to rotational motion of the junction about an axis perpendicular to the page and passing through the junction. The impedances to use for a rigid junction in Equation (A.60) for calculating the transmission coefficients are the same force impedances as used for a pinned junction, with an additional transmission coefficient between beams 2 and 4 as a result of transmission of rotational motion, which must be added to the one calculated for translational motion of the junction. To calculate this transmission coefficient, τ_{24b}, we use bending moment impedances for all four beams in the impedance sum of Equation (A.60). The impedances that are to be used are:

$$Z_{F,1,\infty} = \rho_{m1} S_1 c_{LII,1} \tag{A.93}$$

$$Z_{F,2,\infty} = 0.5\rho_{m2} S_2 c_{B,2}(1 + \mathrm{j}) \tag{A.94}$$

$$Z_{F,3,\infty} = \rho_{m3} S_3 c_{LII,3} \tag{A.95}$$

$$Z_{F,4,\infty} = 0.5\rho_{m4} S_4 c_{B,4}(1 + \mathrm{j}) \tag{A.96}$$

$$Z_{M,1,\infty} = 0.5\rho_{m1} S_1 c_{B,1}(1 - \mathrm{j})/k_{B,1}^2 \tag{A.97}$$

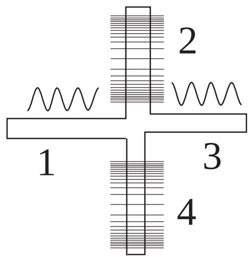
$$Z_{M,2,\infty} = 0.5\rho_{m2} S_2 c_{B,2}(1 - \mathrm{j})/k_{B,2}^2 \tag{A.98}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3} S_3 c_{B,3}(1 - \mathrm{j})/k_{B,3}^2 \tag{A.99}$$

$$Z_{M,4,\infty} = 0.5\rho_{m4} S_3 c_{B,4}(1 - \mathrm{j})/k_{B,4}^2 \tag{A.100}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{14}, η_{41}, η_{23}, η_{32}, η_{24}, η_{42}, η_{34} and η_{43}.

A.8.3.11 Four Beams Connected at Right Angles, Bending-Longitudinal-Bending-Longitudinal(ID=4b)



This junction type can transmit energy whether rigid or pinned. If pinned, there can be no transmission from beam 2 to beam 4 via rotational motion of the junction. Thus, for the pinned junction, all transmissions between beams, including between beam 1 and beam 3, will be a result of translational motion of the junction in the horizontal direction. The impedances to use for a pinned junction in Equation (A.60) for subsystems 1 and 3 are bending force impedances for a semi-infinite beam and for subsystems 2 and 4 we use longitudinal force impedances. For rigid junctions, there will be additional transmission between beams 1 and 3 due to rotational motion of the junction about an axis perpendicular to the page and passing through the junction. The impedances to use in Equation (A.60) for calculating the transmission coefficients for a rigid junction are the same force impedances as used for a pinned junction, with an additional transmission coefficient between beams 1 and 3 as a result of transmission of rotational motion, which must be added to the one calculated for translational motion of the junction. To calculate this transmission coefficient, τ_{13b} we use bending moment impedances for all four beams in the impedance sum of Equation (A.60). The impedances that are to be used are:

$$Z_{F,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1+\mathrm{j}) \tag{A.101}$$

$$Z_{F,2,\infty} = \rho_{m2}S_2c_{LII,2} \tag{A.102}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3}S_3c_{B,3}(1+\mathrm{j}) \tag{A.103}$$

$$Z_{F,4,\infty} = \rho_{m4}S_4c_{LII,4} \tag{A.104}$$

$$Z_{M,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.105}$$

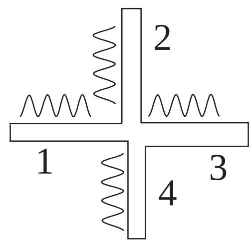
$$Z_{M,2,\infty} = 0.5\rho_{m2}S_2c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \tag{A.106}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}S_3c_{B,3}(1-\mathrm{j})/k_{B,3}^2 \tag{A.107}$$

$$Z_{M,4,\infty} = 0.5\rho_{m4}S_3c_{B,4}(1-\mathrm{j})/k_{B,4}^2 \tag{A.108}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{14}, η_{41}, η_{23}, η_{32}, η_{24}, η_{42}, η_{34} and η_{43}.

A.8.3.12 Four Beams Connected at Right Angles, Bending-Bending-Bending-Bending (ID=4c)



This junction type can transmit energy whether pinned or rigid. In both cases energy can be transmitted between beams via translational motion of the junction. However, rotational energy can be transmitted between the various beams only if the junction is rigid. Note that translational energy cannot be transmitted between beams 1 and 2, 1 and 4, 2 and 3, as well as 3 and 4, as each of the two subsystems making up these pairs do not generate translational motion in the same direction.

For the transmission of energy via translational forces in the horizontal direction (for the calculation of τ_{24}), the impedances to use in Equation (A.60) for subsystems 2 and 4 are bending force impedances for a semi-infinite beam and for subsystems 1 and 3 we use longitudinal force impedances. For the transmission of energy via translational forces in the vertical direction (for the calculation of τ_{13}), the impedances to use in Equation (A.60) for subsystems 1 and 3 are bending force impedances for a semi-infinite beam and for subsystems 2 and 4 we use longitudinal force impedances. Note tat in each case, the impedance sum contains 4 impedances.

For the calculation of the rotational transmission coefficient components of all subsystem pairs, the moment impedances of all four beams are used. The impedances to use for horizontal translational motion of the junction are:

$$Z_{F,1,\infty} = \rho_{m1}S_1c_{LII,1} \tag{A.109}$$

$$Z_{F,2,\infty} = 0.5\rho_{m2}S_2c_{B,2}(1+\mathrm{j}) \tag{A.110}$$

$$Z_{F,3,\infty} = \rho_{m3}S_3c_{LII,3} \tag{A.111}$$

$$Z_{F,4,\infty} = 0.5\rho_{m4}S_4c_{B,4}(1+\mathrm{j}) \tag{A.112}$$

The impedances to use for vertical translational motion of the junction are:

$$Z_{F,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1+\mathrm{j}) \tag{A.113}$$

$$Z_{F,2,\infty} = \rho_{m2} S_2 c_{LII,2} \quad \text{(A.114)}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3} S_3 c_{3,4}(1+\mathrm{j}) \quad \text{(A.115)}$$

$$Z_{F,4,\infty} = \rho_{m4} S_4 c_{LII,4} \quad \text{(A.116)}$$

The moment impedances to use for rotational motion transmission are:

$$Z_{M,1,\infty} = 0.5\rho_{m1} S_1 c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \quad \text{(A.117)}$$

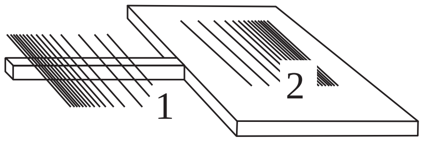
$$Z_{M,2,\infty} = 0.5\rho_{m2} S_2 c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \quad \text{(A.118)}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3} S_3 c_{B,3}(1-\mathrm{j})/k_{B,3}^2 \quad \text{(A.119)}$$

$$Z_{M,4,\infty} = 0.5\rho_{m4} S_3 c_{B,4}(1-\mathrm{j})/k_{B,4}^2 \quad \text{(A.120)}$$

These impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{14}, η_{41}, η_{23}, η_{32}, η_{24}, η_{42}, η_{34} and η_{43}.

A.8.3.13 Beam - Plate, End of Beam Attached to Plate Edge, Axial-Longitudinal (ID=5a)



This junction type can transmit energy whether pinned or rigid. Energy is transmitted through the junction by horizontal junction motion. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to longitudinal motion and for the receiver plate the impedance is the force impedance of a semi-infinite plate subject to in-plane motion:

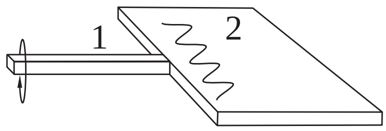
$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1} S_1 c_{LII,1} \quad \text{(A.121)}$$

$$Z_{F,2,\infty} = 4\pi m_{s2} f r^2 \left(1 - \frac{\mathrm{j}c_{LI,2}}{2\pi f r}\right) \quad \text{(A.122)}$$

where $2r$ is the width of the beam cross section that is attached to the plate edge (in the direction parallel to the plate edge) and S_1 is the beam cross sectional area. For corrugated plates, m_{s2} is the mass per unit plan area and for sandwich plates, m_{s2} is the mass per unit area of the skin attached to the beam (mass per unit area of both skins if the beam is attached to both) and $c_{LI,2}$ is the longitudinal wave speed in the skin attached to the beam. In practice, for sandwich plates, the analysis is only valid if the beam is attached to both skins.

The preceding impedances are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.14 Beam - Plate, End of Beam Attached to Plate Edge, Torsional-Bending (ID=5b)



This junction type can only transmit energy if it is rigid. Energy is transmitted through the junction by rotational motion. The impedance to use in Equation (A.60) for the source beam is the moment impedance for a semi-infinite beam subject to twisting motion and for the receiver plate the impedance is the moment impedance of a semi-infinite plate subject to bending motion:

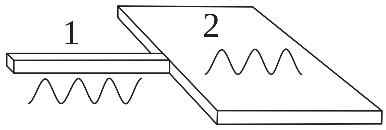
$$Z_{M,1,\infty} = 2\rho_{m1} J_x c_T \quad \text{(A.123)}$$

$$Z_{M,2,\infty} = \frac{5.3\omega m_{s2}}{k_{B,2}^4}\left(1 - 1.46\mathrm{j}\log_{\mathrm{e}}(0.89k_{B,2}r)\right)^{-1} \tag{A.124}$$

where $2r = \sqrt{ab}$, where a and b are the beam cross-sectional dimensions. For corrugated plates, m_{s2} is the mass per unit plan area. For sandwich plates, $c_{LI,2}$ is the longitudinal wave speed in the skin attached to the beam, m_{s2} is the effective mass per unit area and $c_{B,2}$ is the bending wave speed in the composite panel. These latter quantities depend on the frequency region under consideration and are defined in Table A.14. In practice, for sandwich plates, the analysis is valid only if the beam is attached to both skins.

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.15 Beam - Plate, End of Beam Attached to Plate Edge, Bending-Bending (ID=5c)



This junction type can transmit energy whether pinned or rigid. The bending wave is associated with translational motion normal to the beam surface and rotational motion about an axis parallel to the plate edge and passing through the junction. The impedance to use in Equation (A.60) for the transmission of rotational motion is the moment impedance for a semi-infinite beam subject to bending motion and for the receiver plate, the impedance is the moment impedance of a semi-infinite plate subject to bending motion. For the transmission of the translational motion, the force impedances are needed. The needed impedances are listed below.

$$Z_{F,1,\infty} = 0.5\rho_{m1}S_1c_{B,1}(1+\mathrm{j}) \tag{A.125}$$

$$Z_{F,2,\infty} = 3.5\sqrt{B_2m_{s2}} = 3.5\omega m/k_B^2 \tag{A.126}$$

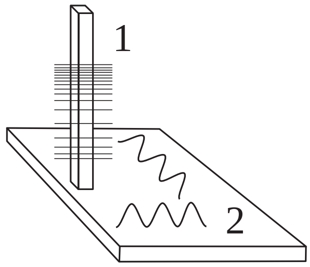
$$Z_{M,1,\infty} = \frac{1}{2}\rho_{m1}S_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.127}$$

$$Z_{M,2,\infty} = \frac{5.3\omega m_{s2}}{k_{B,2}^4}\left(1 - 1.46\mathrm{j}\log_{\mathrm{e}}(0.89k_{B,2}r)\right)^{-1} \tag{A.128}$$

where B_2 is the bending stiffness of the plate per unit width, $2r$ is the depth of the beam cross section that is attached to the plate edge (in the direction normal to the plate surface). For corrugated plates, m_{s2} is the mass per unit plan area. For sandwich plates, $c_{LI,2}$ is the longitudinal wave speed in the skins, m_{s2} is the effective mass per unit area and $c_{B,2}$ is the bending wave speed in the composite panel. These latter quantities depend on the frequency region under consideration and are defined in Table A.14. For sandwich plates, it is assumed that beam is attached to both skins. For corrugated plates, the width of the beam must span at least 2 peaks in the corrugation profile and the beam depth must be at least the peak to trough height of the profile.

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.16 Beam - Plate, End of Beam Attached to Plate Surface Near Edge, Axial-Bending (ID=6a)



This junction type can transmit energy whether pinned or rigid. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to longitudinal motion and for the receiver plate the impedance is the force impedance of a semi-infinite plate subject to bending motion:

$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1}S_1c_{LII,1} \tag{A.129}$$

$$Z_{F,2,\infty} = 3.5\sqrt{B_2m_{s2}} = 3.5\omega m_{s2}/k_B^2 \tag{A.130}$$

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

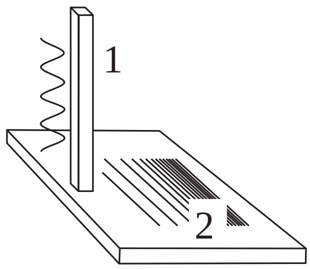
If the plate thickness, $h > c_s/f$, where c_s is the shear wave speed, the impedance, $Z_{F,2,\infty}$, assuming Poisson's ratio, $\nu \approx 0.3$, is:

$$Z_{F,2,\infty} = \frac{Gc_s}{2\omega^2}\left\{\frac{0.063}{H^2} + \frac{1}{8}\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left(\frac{0.001}{H^{1.3}} + \frac{0.06\pi c_s}{r\omega}\right)\right\}^{-1} \tag{A.131}$$

where $H = \omega h_2/(2c_{s2}) = \pi f h_2/c_{s2}$, h_2 is the total plate thickness and $2r_1$ = diameter of attached beam or for a beam with a rectangular cross section, $2r_1 = \sqrt{S_1}$. For thick flat and corrugated plates, $G_2 = E_2/[2(1+\nu_2)]$ is the shear modulus, $c_{s2} = \sqrt{G_2/\rho_{m2}}$ is the shear wave speed and h_2 is the plate thickness.

For thick sandwich plates, $c_{s2} = \sqrt{G_2h_{c2}/(2m_{sf2} + \rho_{c2}h_{c2})}$ is the shear wave speed, h_{c2} is the thickness of the sandwich plate core, G_2 is the shear modulus of the panel, m_{sf2} is the mass per unit area of one of the face sheets and ρ_{c2} is the density of the core (Yoerkie et al., 1983).

A.8.3.17 Beam - Plate, End of Beam Attached to Plate Surface Near Edge, Bending-Longitudinal, Bending in Beam in a Direction Normal to Plate Edge (ID=6b)



This junction type can transmit energy whether it is rigid or pinned. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to bending motion and for the receiver plate the impedance is the force impedance of a semi-infinite plate subject to lateral motion:

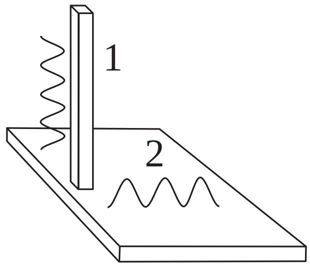
$$Z_{F,1,\infty} = \frac{1}{2}\rho_{m1}S_1c_{B,1}(1+\mathrm{j}) \tag{A.132}$$

$$Z_{F,2,\infty} = 4\pi m_{s2}fr^2\left(1 - \frac{\mathrm{j}c_{LI,2}}{2\pi fr}\right) \tag{A.133}$$

where $2r$ is the width of the beam cross section that is attached to the plate edge (in the direction parallel to the plate edge) and S_1 is the beam cross sectional area. For corrugated plates, m_{s2} is the mass per unit plan area and for sandwich plates, m_{s2} is the mass per unit area of the skin attached to the beam. Also, for sandwich plates, $c_{LI,2}$ is the longitudinal wave speed in the plate attached to the beam.

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.18 Beam - Plate, End of Beam Attached to Plate Surface Near Edge, Bending-Bending, Bending in Beam in a Direction Normal to Plate Edge (ID=6c)



This junction type can only transmit energy if it is rigid. The impedance to use in Equation (A.60) for the source beam is the moment impedance for a semi-infinite beam subject to bending motion and for the receiver plate the impedance is the moment impedance of a semi-infinite plate subject to bending motion:

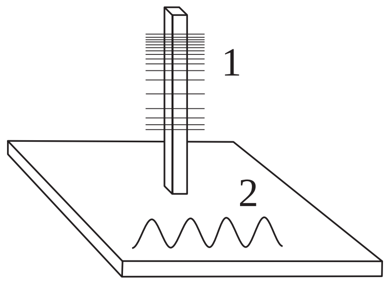
$$Z_{M,1,\infty} = \frac{1}{2}\rho_{m1} S_1 c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \qquad \text{(A.134)}$$

$$Z_{M,2,\infty} = \frac{5.3\omega m_{s2}}{k_{B,2}^4}\left(1-1.46\mathrm{j}\log_{\mathrm{e}}(0.89 k_{B,2} r)\right)^{-1} \qquad \text{(A.135)}$$

where $2r$ is the depth of the beam cross section that is attached to the plate edge (in the direction normal to the axis about which the plate is caused to bend or parallel to the direction of bending wave propagation).

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.19 Beam - Plate, End of Beam Attached to Plate Surface Away From Edge, Axial-Bending (ID=7a)



This junction type can transmit energy whether pinned or rigid. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to longitudinal motion and for the receiver plate the impedance is the force impedance of an infinite plate subject to bending motion:

$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1} S_1 c_{LII,1} \qquad \text{(A.136)}$$

$$Z_{F,2,\infty} = 8\sqrt{B_2 m_{s2}} = 8\omega m/k_B^2 \qquad \text{(A.137)}$$

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

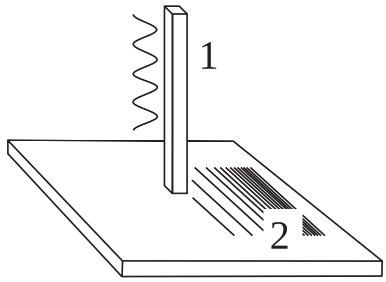
If the plate thickness, $h > c_s/f$, where c_s is the shear wave speed, the impedance, $Z_{F,2,\infty}$, assuming Poisson's ratio, $\nu \approx 0.3$, is:

$$Z_{F,2,\infty} = \frac{G_2 c_{s2}}{\omega^2}\left\{\frac{0.063}{H^2} + \frac{1}{8}\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left(\frac{0.001}{H^{1.3}} + \frac{0.06\pi c_s}{r_1\omega}\right)\right\}^{-1} \qquad \text{(A.138)}$$

where $H = \omega h_2/(2c_{s2}) = \pi f h_2/c_{s2}$, h_2 is the total plate thickness and $2r_1$ = diameter of attached beam or for a beam with a rectangular cross section, $2r_1 = \sqrt{S_1}$. For thick flat and corrugated plates, $G_2 = E_2/[2(1+\nu_2)]$ is the shear modulus, $c_{s2} = \sqrt{G_2/\rho_{m2}}$ is the shear wave speed and h_2 is the plate thickness.

For thick sandwich plates, $c_{s2} = \sqrt{G_2 h_{c2}/(2m_{sf2} + \rho_{c2} h_{c2})}$ is the shear wave speed, h_{c2} is the thickness of the sandwich plate core, G_2 is the shear modulus of the panel, m_{sf2} is the mass per unit area of one of the face sheets and ρ_{c2} is the density of the core (Yoerkie et al., 1983).

A.8.3.20 Beam - Plate, End of Beam Attached to Plate Surface Away From Edge, Bending-Longitudinal (ID=7b)



This junction type can transmit energy whether pinned or rigid. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to longitudinal motion and for the receiver plate the impedance is the force impedance of an infinite plate subject to bending motion:

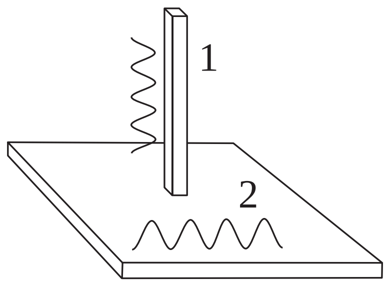
$$Z_{F,1,\infty} = \frac{1}{2}\rho_{m1} S_1 c_{B,1}(1 + \mathrm{j}) \tag{A.139}$$

$$Z_{F,2,\infty} = 8\pi m_{s2} f r^2 \left(1 - \frac{\mathrm{j} c_{LI,2}}{2\pi f r}\right) \tag{A.140}$$

where $2r$ is the width of the beam cross section that is attached to the plate edge (in the direction parallel to the plate edge) and S_1 is the beam cross sectional area. For corrugated plates, m_{s2} is the mass per unit plan area and for sandwich plates, m_{s2} is the mass per unit area of the skin attached to the beam. Also, for sandwich plates, $c_{LI,2}$ is the longitudinal wave speed in the skin attached to the beam.

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.21 Beam - Plate, End of Beam Attached to Plate Surface Away From Edge, Bending-Bending (ID=7c)



This junction type can only transmit energy if it is rigid. The impedance to use in Equation (A.60) for the source beam is the moment impedance for a semi-infinite beam subject to bending motion and for the receiver plate the impedance is the moment impedance of an infinite plate subject to bending motion:

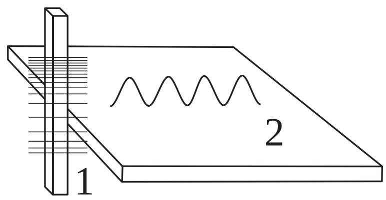
$$Z_{M,1,\infty} = \frac{1}{2}\rho_{m1} S_1 c_{B,1}(1 - \mathrm{j})/k_{B,1}^2 \tag{A.141}$$

$$Z_{M,2,\infty} = \frac{16\omega m_{s2}}{k_{B,2}^4}\left(1 - \frac{4\mathrm{j}}{\pi}\log_\mathrm{e}(0.89 k_{B,2} r)\right)^{-1} \tag{A.142}$$

where $2r$ is the width of the beam cross section that is attached to the plate edge (in the direction of the applied force).

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.22 Beam - Plate, Centre Side of Beam Attached to Plate Edge and Beam Perpendicular to the Plate Edge, Axial-Bending (ID=8a)



For axial motion in the beam, this junction type can transmit energy whether pinned or rigid. The same results are obtained for both junction types. The impedance to use in Equation (A.60) for the source beam is the force impedance for an infinite beam subject to longitudinal motion and for the receiver plate the impedance is the force impedance of a semi-infinite plate subject to bending motion:

$$Z_{F,1,\infty} = 2S_1\sqrt{E_1\rho_{m1}} = 2\rho_{m1}S_1c_{LII,1} \tag{A.143}$$

$$Z_{F,2,\infty} = 3.5\sqrt{B_2m_{s2}} = 3.5\omega m/k_B^2 \tag{A.144}$$

If the plate thickness, $h > c_s/f$, where c_s is the shear wave speed, the impedance, $Z_{F,2,\infty}$, assuming Poisson's ratio, $\nu \approx 0.3$, is:

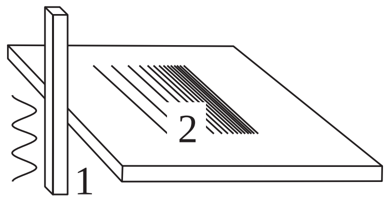
$$Z_{F,2,\infty} = \frac{Gc_s}{2\omega^2}\left\{\frac{0.063}{H^2} + \frac{1}{8}\left(\frac{H}{H+1.6}\right)^2 + \mathrm{j}\left(\frac{0.001}{H^{1.3}} + \frac{0.06\pi c_s}{r\omega}\right)\right\}^{-1} \tag{A.145}$$

where $H = \omega h_2/(2c_{s2}) = \pi f h_2/c_{s2}$, h_2 is the total plate thickness and $2r_1$ = diameter of attached beam or for a beam with a rectangular cross section, $2r_1 = \sqrt{S_1}$. For thick flat and corrugated plates, $G_2 = E_2/[2(1+\nu_2)]$ is the shear modulus, $c_{s2} = \sqrt{G_2/\rho_{m2}}$ is the shear wave speed and h_2 is the plate thickness.
For thick sandwich plates, $c_{s2} = \sqrt{G_2h_{c2}/(2m_{sf2} + \rho_{c2}h_{c2})}$ is the shear wave speed, h_{c2} is the thickness of the sandwich plate core, G_2 is the shear modulus of the panel, m_{sf2} is the mass per unit area of one of the face sheets and ρ_{c2} is the density of the core (Yoerkie et al., 1983).

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.23 Beam - Plate, Centre Side of Beam Attached to Plate Edge and Beam Perpendicular to the Plate Edge, Bending-Longitudinal (ID=8b)

This junction type can transmit energy whether it is rigid or pinned. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to bending motion and for the receiver plate the impedance is the force impedance of a semi-infinite plate subject to lateral motion:



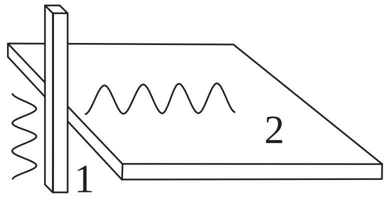
$$Z_{F,1,\infty} = 2\rho_{m1}S_1c_{B,1}(1+\mathrm{j}) \tag{A.146}$$

$$Z_{F,2,\infty} = 4\pi m_{s2}fr^2\left(1 - \frac{\mathrm{j}c_{LI,2}}{2\pi fr}\right) \tag{A.147}$$

where $2r$ is the width of the beam cross section that is attached to the plate edge (in the direction parallel to the plate edge) and S_1 is the beam cross sectional area. For corrugated plates, m_{s2} is the mass per unit plan area and for sandwich plates, m_{s2} is the mass per unit area of the skin attached to the beam. Also, for sandwich plates, $c_{LI,2}$ is the longitudinal wave speed in the plate attached to the beam.

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.24 Beam - Plate, Centre Side of Beam Attached to Plate Edge and Beam Perpendicular to the Plate Edge, Bending-Bending (ID=8c)



For bending motion in the beam, this junction type can can only transmit energy if it is rigid. The impedances to use in Equation (A.60) for the source beam are bending moment impedances for an infinite beam and for the receiver plate, they are bending moment impedances for a semi-infinite plate. Thus:

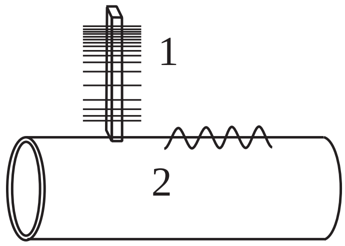
$$Z_{M,1,\infty} = 2\rho_{m1} S_1 c_{B,1}(1 - \mathrm{j})/k_{B,1}^2 \tag{A.148}$$

$$Z_{M,2,\infty} = \frac{5.3\omega m_{s2}}{k_{B,2}^4}\left(1 - 1.46\log_\mathrm{e}(0.89 k_{B,2} r)\right)^{-1} \tag{A.149}$$

where $2r$ is equal to the plate thickness.

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.25 Beam - Cylinder, End of Beam Attached to Cylinder Surface Away From Edge, Axial-Bending (ID=9)



This junction type can transmit energy whether pinned or rigid. The same results apply to both pinned and rigid junctions. The impedance to use in Equation (A.60) for the source beam is the force impedance for a semi-infinite beam subject to longitudinal motion and for the receiver cylinder, the impedance is the force impedance of an infinite cylinder subject to bending motion:

$$Z_{F,1,\infty} = S_1\sqrt{E_1\rho_{m1}} = \rho_{m1} S_1 c_{LII,1} \tag{A.150}$$

$$Z_{F,2,\infty} = \begin{cases} 2.3 c_{LI,2}\rho_{m2} h_2^2; & (f/f_r > 2) \\ \dfrac{2\pi a_2 \rho_{m2} h_2 \sqrt{\omega c_{LI,2} a_2/\sqrt{2}}}{(1 - \mathrm{j})}; & (f/f_r < 0.77 h_2/a_2) \\ \dfrac{2.3 c_{LI,2}\rho_{m2} h_2^2}{0.66}\sqrt{\dfrac{f_r}{f}}; & (0.77 h_2/a_2 < f/f_r < 0.6) \end{cases} \tag{A.151}$$

where a_2 is the cylinder radius and h_2 is the wall thickness (see 6th edition textbook, page 710).

The impedances defined by the preceding equations are used together with Equations (A.60) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}.

A.8.3.26 Beam Bonded Lengthwise to a Plate (ID=10)

See Section A.8.5, subsection A.8.5.1.

A.8.3.27 Plates Connected at Right Angles Using Bolts or Screws (ID=11)

See Section A.8.5, subsection A.8.5.8.

A.8.3.28 Tunnelling From One Plate to Another Parallel Plate (ID=12)

See Section A.8.5, subsection A.8.5.4.

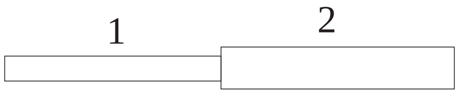
A.8.4 Coupling Loss Factors for Acoustic Point Connections

For a 1-D acoustic system, a junction has a common pressure, so that acoustic admittances (reciprocal of acoustic impedances), $Y_{F,\infty}$, add at the junction. Thus, for a number, N, of 1-D acoustic systems connected at a single point, the transmission coefficient is:

$$\tau_{12} = \frac{4\mathrm{Re}\{Y_{F,1}\}\mathrm{Re}\{Y_{F,2}\}}{\left|\sum\limits_{m=1}^{N} Y_{F,m}\right|^2} \tag{A.152}$$

Note that this model is appropriate for plane waves and higher order modes. although the accuracy improves at frequencies above the cut-on of the first higher order mode.

A.8.4.1 Acoustic Duct - Acoustic Duct, End to End (ID=20a)

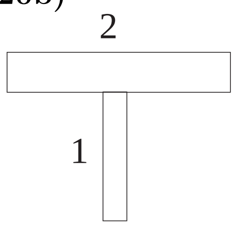


For two 1-D acoustic ducts (any cross-sectional shape), joined end to end, the acoustic admittances, for energy transmission dominated by plane waves:

$$Y_{F,1} = \frac{S_1}{\rho c}; \qquad Y_{F,2} = \frac{S_2}{\rho c} \tag{A.153a,b}$$

The admittances defined by the preceding equations are used together with Equations (A.152) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}. This approach is only valid in the frequency range where plane wave propagation dominates the energy transmission, which is in the frequency range below twice the cut-on of the first cross mode (see textbook, pages 534-535).

A.8.4.2 Acoustic Duct - Acoustic Duct, End to Middle (ID=20b)



For two 1-D acoustic ducts (any cross-sectional shape), joined at 90 degrees (not necessarily in the centre of duct 2) as shown in the figure, the acoustic admittances, for energy transmission dominated by plane waves:

$$Y_{F,1} = \frac{S_1}{\rho c}; \qquad Y_{F,2} = \frac{S_2}{2\rho c} \tag{A.154a,b}$$

Note the division by a factor of 2 in the admittance for duct 2, which has a junction well away from its ends.

The admittances defined by the preceding equations are used together with Equations (A.152) and (A.61) to calculate the corresponding coupling loss factors, η_{12} and η_{21}. This approach is only valid in the frequency range where plane wave propagation dominates the energy transmission, which is in the frequency range below twice the cut-on of the first cross mode (see textbook, pages 534-535).

A.8.5 Coupling Loss Factors for Structural Line Connections

When two substructures are connected along a line of length, L, and it is assumed that the sound field is uniformly distributed over the incidence angle, the average coupling loss factor (CLF), averaged over all angles of incidence, is (Lyon and DeJong, 1995, p.193):

$$\langle\eta_{12}^{\mathrm{line}}\rangle_\theta = \frac{c_{g,1}L\beta_{\mathrm{corr}}}{4\pi f S_1}\langle\tau_{12,\infty}^{\mathrm{line}}(\theta)\cos\theta\rangle_\theta = \frac{c_{g,1}L\beta_{\mathrm{corr}}}{4\pi f S_1}\frac{2}{\pi}\int\limits_0^{\pi/2}\tau_{12,\infty}^{\mathrm{line}}(\theta)\cos\theta\,\mathrm{d}\theta \tag{A.155a,b}$$

where $\langle \tau_{12}^{\text{line}} \cos(\theta) \rangle_\theta = \frac{2}{\pi} \int_0^{\pi/2} \tau_{12}^{\text{line}}(\theta) \cos\theta \, \mathrm{d}\theta$, S_1 is the area of the source structure (usually a plate) and c_g is the group wave speed for the particular wave type being considered. For longitudinal waves, $c_g = c_L I$, and for bending waves, $c_g = 2c_B$. Shear waves are neglected in this analysis due to their likely insignificant contribution to normal vibration levels and sound transmission.

In practice, to keep SEA analysis tractable, it is usually assumed that most of the incident energy is normal to the junction, so that the CLF for power transmission from subsystem 1 to subsystem 2 for an incident sound field is (Lyon and DeJong, 1995, p.193):

$$\langle \eta_{12}^{\text{line}} \rangle_\theta \approx \eta_{12}^{\text{line}}(0) = \frac{\beta_{\text{corr}} c_{g,1} L}{4\pi f S_1} \tau_{12,\infty}^{\text{line}}(0) \tag{A.156}$$

where $c_g/S_1 = k_1/n_1(f)$, the correction term, $2/[2 - \tau_{12,\infty}^{\text{line}}(0)]$ has been omitted as advised by Craik (2003) and the correction, β_{corr}, to allow for the effect of coupling with other subsystems is found by iteration, as explained on page 357.

For line connection cases, Equation (A.156) will be used by ENC when the Lyon method is chosen, due to the difficulty in evaluating the integral in Equation (A.155) and the lack of certainty about the direction from which most of the energy is coming. In any case, the normal incidence transmission coefficient is a good approximation and will give conservative results (that is, it will slightly overestimate coupling loss factors and energy transmission).

An exception is the transmission between two plates at right angles, for which an evaluation of the integral is available (Lyon and DeJong, 1995, p.194-5) and this is used by ENC for this one case. For this case, Equation (A.155) can be rewritten in terms of the normal incidence transmission coefficient, $\tau_{12,\infty}^{\text{line}}(0)$, for an infinitely extending structure, as:

$$\langle \eta_{12}^{\text{line}} \rangle_\theta = \frac{\beta_{\text{corr}} k_1 L}{4\pi f n_1(f)} \frac{2}{\pi} \int_0^{\pi/2} \tau_{12,\infty}^{\text{line}}(\theta) \cos(\theta) \mathrm{d}\theta = \frac{\beta_{\text{corr}} I_{12}^{\text{line}} \tau_{12,\infty}^{\text{line}}(0)}{2\pi f n_1(f)} \tag{A.157}$$

where

$$I_{12}^{\text{line}} \tau_{12,\infty}^{\text{line}}(0) = \frac{k_1 L}{\pi} \int_0^{\pi/2} \tau_{12,\infty}^{\text{line}}(\theta) \cos(\theta) \mathrm{d}\theta \tag{A.158}$$

where:

$$\tau_{12,\infty}^{\text{line}}(0) = \tau_{12,\infty}^{\text{line}}(0) = \frac{4\mathrm{Re}\{Z_{F,1,\infty}^{\text{line}}\}\mathrm{Re}\{Z_{F,2,\infty}^{\text{line}}\}}{\left| \sum_{m=1}^{N} Z_{F,m,\infty}^{\text{line}} \right|^2} \tag{A.159}$$

where there are N plates connected at the junction. The impedances, $Z_{F,1,\infty}^{\text{line}}$ and $Z_{F,2,\infty}^{\text{line}}$ are line impedances that depend on the connecting structure type. The quantity, I_{12}^{line}, is determined by the integral over angle for the wave type and incident angle range (see Equation A.157 and (Lyon and DeJong, 1995, p. 194)). The quantity, β_{corr}, is found by iteration, as explained on page 357.

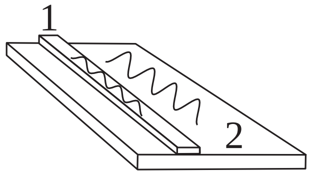
For two plates connected at right angles (Lyon and DeJong, 1995, p. 195):

$$I_{12}^{\text{line}} = \frac{L}{4} \left(\frac{k_1^4 k_2^4}{k_1^4 + k_2^4} \right)^{1/4} \tag{A.160}$$

where k_1 and k_2 are the bending wavenumbers in the two plates.

When there is transmission between bending waves in one subsystem and waves in another connected subsystem, the type of impedance to use (force or moment) will depend on what junction motion is common to both connected subsystems. Junction motions are common if they are either rotational about the same axis or translational in the same orthogonal direction. When bending waves are transmitted in the same direction as the incident waves, two transmission coefficients must be calculated (and added together) when the Lyon approach is used. One is for the transmission of energy resulting from translational motion of the junction normal to the direction of wave propagation and one is for the transmission of energy resulting from rotational motion of the junction. In the latter case, the force impedances in Equation (A.159) are replaced with moment impedances. However, when the transmitted bending waves are travelling in a direction at 90 degrees to the incident waves, only rotational junction motion is common. The above discussion will become clearer when individual junction types are considered in the following pages.

A.8.5.1 Single-Beam-Stiffened Plate (ID=10)



The junction type is rigid only. There is only one calculation method for this junction, as described below. The line impedances to use in Equation (A.159) are listed below.

The line impedance for the beam is (Lyon and DeJong, 1995, p. 202):

$$Z_b^{\text{line}} = \text{j}2\pi f \rho_b S_b \tag{A.161}$$

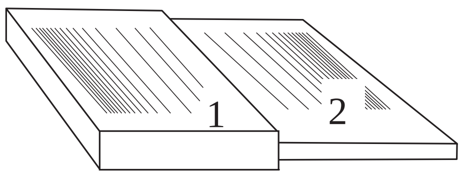
Equation (A.159) for the transmission coefficient requires the real part of Z_b^{line}, which is zero. However, in this case, the SEA formulation works if the real part is set equal to the magnitude, $2\pi f \rho_b S_b$ in the numerator of Equation (A.159) (Lyon and DeJong, 1995, p. 202).

The line impedance for the plate is:

$$Z_p^{\text{line}} = 2m_p c_{Bp}(1+\text{j}) \tag{A.162}$$

To calculate the coupling loss factor, the normal incidence transmission coefficient, calculated using Equations (A.159), (A.161) and (A.162) is used in Equation (A.156), where $c_{g,1} = 2c_{Bb}$ and β_{corr} is found by iteration, as explained on page 357.

A.8.5.2 Plate - Plate, Edge to Edge, 180-deg, Longitudinal-Longitudinal (ID=21a)



This junction type can transmit energy whether rigid or pinned and the longitudinal wave motion in the plate is normal to the plate edge connection. Both rigid and pinned junctions give the same results. The impedance to use in Equation (A.159) for the source and receiver plates is the longitudinal force impedance for a semi-infinite plate.

$$Z_{F,1,\infty}^{\text{line}} = m_1 c_{LI,1} \tag{A.163}$$

$$Z_{F,2,\infty}^{\text{line}} = m_2 c_{LI,2} \tag{A.164}$$

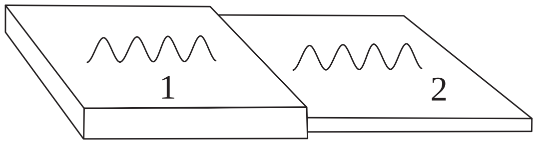
The transmission coefficient for normally incident longitudinal waves at the junction is calculated using the above equations and Equation (A.159).

The coupling loss factor is given by Equation (A.156):

$$\eta_{12}^{\text{line}} \approx \frac{\beta_{\text{corr}} c_{g,1} L \tau_{12}^{\text{line}}(0)}{4\pi f S_1} \tag{A.165}$$

where L is the length of the joined edge, β_{corr} is found by iteration, as explained on page 356, and $c_{g,1} = c_{LI,1}$.

A.8.5.3 Plate - Plate, Edge to Edge, 180-deg, Bending-Bending (ID=21b)



This junction type can transmit energy whether rigid or pinned. If pinned, the bending wave energy can only be transmitted by translational junction motion normal to the plate edge. If the junction is rigid, energy is transmitted by both rotational and translational motion of the junction. Transmission coefficients for each type of junction motion must be summed to obtain an overall coupling loss factor for the junction.

For energy transmission via rotational junction motion, the impedance to use in Equation (A.159) for the the source and receiver plates is the force impedance of a semi-infinite plate subject to bending wave incidence:

$$Z^{\text{line}}_{F,1,\infty} = 0.5 m_1 c_{B,1}(1 + \text{j}) \tag{A.166}$$

$$Z^{\text{line}}_{F,2,\infty} = 0.5 m_2 c_{B,2}(1 + \text{j}) \tag{A.167}$$

For energy transmission via rotational junction motion, the impedance to use in Equation (A.159) for the the source and receiver plates is the moment impedance of a semi-infinite plate subject to bending motion:

$$Z^{\text{line}}_{M,1,\infty} = 0.5 m_1 c_{B,1}(1 - \text{j})/k^2_{B,1} \tag{A.168}$$

$$Z^{\text{line}}_{M,2,\infty} = 0.5 m_2 c_{B,2}(1 - \text{j})/k^2_{B,2} \tag{A.169}$$

where m_1 and m_2 are the masses per unit area of subsystems 1 and 2, respectively.

The transmission coefficient for normally incident bending waves at the junction is calculated using the above equations and Equation (A.159), where the subscript, F, is for translational motion of the junction and for rotational motion, the subscript F replaced with the subscript M.

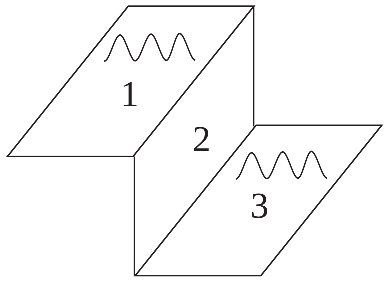
The transmission coefficient due to translational motion and that due to rotational motion must be added together to obtain an overall transmission coefficient, $\tau^{\text{line}}_{12}(0) = \tau^{\text{line}}_{21}(0)$, for the junction.

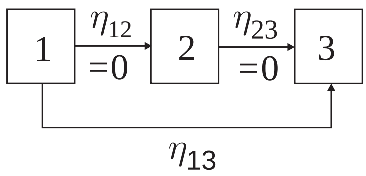
The coupling loss factor is given by Equation (A.155a) (rearranged below):

$$\eta_{12} \approx \frac{\beta_{\text{corr}} c_{g,1} L \tau^{\text{line}}_{12}(0)}{4\pi f S_1} \tag{A.170}$$

where L is the length of the joined edge, β_{corr} is found by iteration, as explained on page 356, and $c_{g,i} = 2c_{B,i}$.

A.8.5.4 Plate - Plate, Edge to Edge, 90-deg, Bending-Longitudinal-bending (ID=12)





In this case, if the two plates are of similar thickness, the higher frequency longitudinal modes in plate 2 will not couple with the low frequency modes on plate 1, so there will be little resonant transmission energy. However, if plate 2 with longitudinal waves is joined to plate 3 on the opposite edge to plate 1 (see figure at right), and the plane of plate 3 is parallel to plate 1, there will be transmission of energy from bending waves in plate 1 to bending waves in plate 3 via in-plane motion of plate 2 (see Section A.8.1 for a discussion of this tunnelling phenomenon). The in-plane motion of plate 2 results in vertical translational motion of the junctions at each of its ends. This form of coupling is taken into account via a coupling loss factor, η_{13}. As only translational and not rotational motion is transmitted, the required impedances are just the translational impedances, given by the following equations. The same results are obtained in this case for both pinned and rigid junction connections.

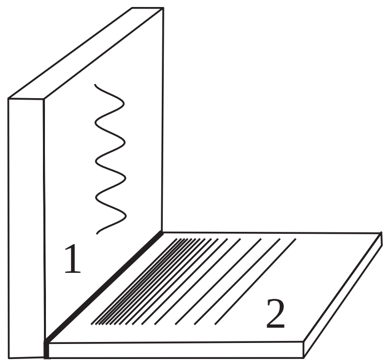
$$Z^{\text{line}}_{F,1,\infty} = 0.5 m_1 c_{B,1}(1 + \text{j}) \tag{A.171}$$

$$Z^{\text{line}}_{F,2,\infty} = 0.5 m_2 c_{B,2}(1 + \text{j}) \tag{A.172}$$

where m_1 and m_2 are the masses per unit area of subsystems 1 and 2, respectively.

The impedances defined by the preceding equations are used together with Equations (A.156) and (A.159) to calculate the corresponding coupling loss factors, η_{13} and η_{31}, where $c_{g,i} = 2c_{B,i}$ and $N = 2$.

A.8.5.5 Plate - Plate, Edge to Edge, 90-deg, Bending-Longitudinal, line connection (ID=22a)



Energy is transmitted through this junction by only translational motion of the junction. Thus the same results are obtained for both pinned and rigid junctions.

The coupling loss factor is given by Equation (A.170), repeated below as:

$$\eta^{\text{line}}_{12} \approx \frac{\beta_{\text{corr}} c_{g,1} L \tau^{\text{line}}_{12,\infty}(0)}{4\pi f S_1} \tag{A.173}$$

where i and j are the plate identifying numbers, $c_{g,1} = 2c_{B,1}$, β_{corr} is found by iteration, as explained on page 356 and

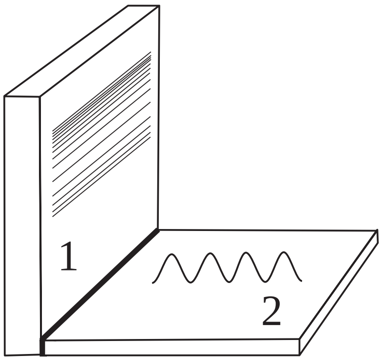
$$\tau^{\text{line}}_{12,\infty}(0) = \tau^{\text{line}}_{21,\infty}(0) = \frac{4\text{Re}\{Z^{\text{line}}_{F,1,\infty}\}\text{Re}\{Z^{\text{line}}_{F,2,\infty}\}}{\left|\sum\limits_{i=1}^{2} Z^{\text{line}}_{F,i,\infty}\right|^2} \tag{A.174}$$

and where:

$$Z^{\text{line}}_{F,1,\infty} = 0.5 m_1 c_{B_1}(1 + \text{j}) \tag{A.175}$$

$$Z^{\text{line}}_{F,2,\infty} = m_2 c_{LI,2} \tag{A.176}$$

A.8.5.6 Plate - Plate, Edge to Edge, 90-deg, Bending-Longitudinal, line connection (ID=22b)



Energy is transmitted through this junction by only translational motion of the junction. Thus the same results are obtained for both pinned and rigid junctions.

The coupling loss factor is given by Equation (A.170), repeated below as:

$$\eta_{ij}^{\text{line}} \approx \frac{c_{g,i} L \tau_{ij,\infty}^{\text{line}}(0)}{4\pi f S_i} \tag{A.177}$$

where i and j are the plate identifying numbers, β_{corr} is found by iteration, as explained on page 356 and $c_{g,i} = 2c_{B,i}$ for bending waves and $c_{g,i} = c_{LI,i}$ for longitudinal waves.

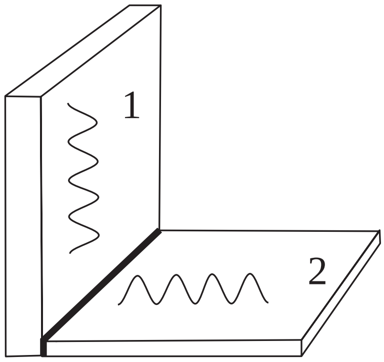
$$\tau_{ji,\infty}^{\text{line}}(0) = \tau_{ij,\infty}^{\text{line}}(0) = \frac{4\text{Re}\{Z_{F,i,\infty}^{\text{line}}\}\text{Re}\{Z_{F,j,\infty}^{\text{line}}\}}{\left|\sum_{m=1}^{2} Z_{F,m,\infty}^{\text{line}}\right|^2} \tag{A.178}$$

and where:

$$Z_{F,2,\infty}^{\text{line}} = 0.5 m_2 c_{B_2}(1+\text{j}) \tag{A.179}$$

$$Z_{F,1,\infty}^{\text{line}} = m_1 c_{LI,1} \tag{A.180}$$

A.8.5.7 Plate - Plate, Edge to Edge, 90-deg, Bending-Bending, line connection (ID=22c)



As the plates are connected at right angles, bending wave energy can only be transmitted by rotational motion of the junction.

The coupling loss factor for a line connection according to (Lyon and DeJong, 1995, p. 194) is (see Equation (A.157), corrected according to Craik (2003)):

$$\eta_{12}^{\text{line}} \approx \frac{1}{2\pi f n_1(f)} \beta_{\text{corr}} I_{12}^{\text{line}} \tau_{12,\infty}^{\text{line}}(0) \tag{A.181}$$

where

$$\tau_{12,\infty}^{\text{line}}(0) = \tau_{21,\infty}^{\text{line}}(0) = \frac{4\text{Re}\{Z_{M,1,\infty}^{\text{line}}\}\text{Re}\{Z_{M,2,\infty}^{\text{line}}\}}{\left|\sum_{i=1}^{2} Z_{M,i,\infty}^{\text{line}}\right|^2} \tag{A.182}$$

where there are N plates connected at the junction and where:

$$Z_{M,1,\infty}^{\text{line}} = 0.5 m_1 c_{B,1}(1-\text{j})/k_{B,1}^2 \tag{A.183}$$

$$Z_{M,2,\infty}^{\text{line}} = 0.5 m_2 c_{B,2}(1-\text{j})/k_{B,2}^2 \tag{A.184}$$

where $2r$ is the depth of the beam cross section that is attached to the plate edge (in the direction normal to the plate edge and in the direction of the applied force).

For plates connected at right angles, β_{corr} is found by iteration, as explained on page 357, and:

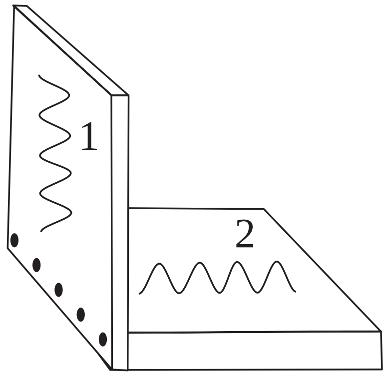
$$I_{12}^{\text{line}} = \frac{L}{4}\left(\frac{k_{B,1}^4 k_{B,2}^4}{k_{B,1}^4 + k_{B,2}^4}\right)^{1/4} \tag{A.185}$$

A.8.5.8 Plate - Plate, Edge to Edge, 90-deg, Bending-Bending, Point-Line Connection (ID=11)

No procedure for this situation is provided by Lyon and DeJong (1995).

An alternative procedure, (Panuszka et al. (2005), Norton and Karczub (2003, p. 418)) is outlined below.

If the plates are connected by N bolts (N point connections) :

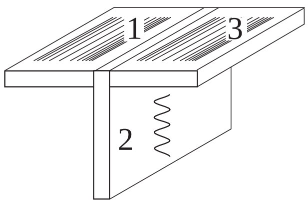


$$\eta_{12} = \begin{cases} \dfrac{4Nh_1 c_{LI,1}(\rho_{m1}h_1^3c_{LI,1}^2)(\rho_{m2}h_2^3c_{LI,2}^2)}{\sqrt{3}\omega S_1(\rho_{m1}h_1^3c_{LI,1}^2+\rho_{m2}h_2^3c_{LI,2}^2)^2}; & \lambda_b < \ell \\ \dfrac{c_{B,1}L\langle\tau_{12,\infty}^{\text{line}}\rangle_\theta}{2\pi f S_1}; & \lambda_b \geq \ell \end{cases} \tag{A.186}$$

where λ_b is the longest plate bending wavelength of the two connected plates, S_1 is the area of plate 1, ℓ is the distance between the points, L is the total length of the line connection and $\tau_{12,\infty}^{\text{line}}$ is the same as for a line connection in junction ID 22b above. Note that for this 2-D system, $\eta_{21} = \eta_{12}(n_1c_1/(n_2c_2))$, where n_1 and n_2 are the modal densities of plates 1 and 2, respectively, $c_1 = c_{B,1}$ and $c_2 = c_{B,2}$.

A.8.5.9 T-Junction Plate (1) - Plate(2) - Plate(3), Longitudinal-Bending-Longitudinal (ID=23a)

ENC assumes that the line connection spans the full width of plates 1 and 3.



This junction type can transmit energy whether pinned or rigid. The same results apply to both pinned and rigid junctions as energy is only transmitted by horizontal translational motion of the junction. For calculating the transmission coefficients, the impedances to use in Equation (A.159) for plates 1 and 3 are longitudinal force impedances for a semi-infinite plate and for plate 2, they are bending force impedances for a semi-infinite plate. Thus:

$$Z_{F,1,\infty} = h_1\sqrt{E_1\rho_{m1}} = \rho_{m1}h_1c_{LI,1} = m_1c_{LI,1} \tag{A.187}$$

$$Z_{F,2,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1+\mathrm{j}) = 0.5m_2c_{B,2}(1+\mathrm{j}) \tag{A.188}$$

$$Z_{F,3,\infty} = h_3\sqrt{E_3\rho_{m3}} = \rho_{m3}h_3c_{LI,3} = m_3c_{LI,3} \tag{A.189}$$

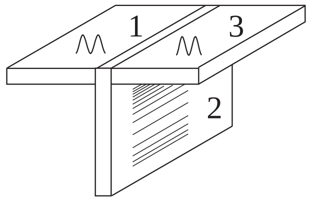
The corresponding coupling loss factors are then calculated using:

$$\langle\eta_{ij}^{\text{line}}\rangle_\theta \approx \eta_{ij}^{\text{line}}(0) = \frac{\beta_{\text{corr}}c_{g,i}L}{4\pi f S_i}\tau_{ij,\infty}^{\text{line}}(0) \tag{A.190}$$

where i and j are the plate identifying numbers, β_{corr} is defined on page 356 and $c_{g,i} = 2c_{B,i}$ for bending waves and $c_{g,i} = c_{LI,i}$ for longitudinal waves.

$$\tau_{ij,\infty}^{\text{line}}(0) = \tau_{ji,\infty}^{\text{line}}(0) = \frac{4\text{Re}\{Z_{F,i,\infty}^{\text{line}}\}\text{Re}\{Z_{F,j,\infty}^{\text{line}}\}}{\left|\sum\limits_{m=1}^{2} Z_{F,m,\infty}^{\text{line}}\right|^2} \tag{A.191}$$

A.8.5.10 T-Junction Plate (1) - Plate(2) - Plate(3), Bending-Longitudinal-Bending (ID=23b)



ENC assumes that the line connection spans the full width of plates 1 and 3.

This junction type can transmit energy whether pinned or rigid, with consideration of translational junction motion in the vertical direction, as well as rotational motion about an axis perpendicular to the page and passing through the junction. The transmission of energy from plate 1 to plate 2 and plate 3 to plate 2 (and vice versa) is a result of only translational junction motion in a vertical direction. The bending wave transmission from plate 1 to 3 involves the addition of 2 coupling loss factors, both of which are associated with bending wave transmission. One CLF is the result of the transmission of rotational motion about an axis perpendicular to the page and passing through the junction and the other CLF is a result of translational motion of the junction in a vertical direction, which is perpendicular to the direction of bending wave propagation between plates 1 and 3. For pinned junctions, rotational motion is not transmitted.

The transmission coefficients as a result of translational motion of the junction are τ_{12}, τ_{23} and the translational motion contribution to τ_{13}. The impedances used to calculate these transmission coefficients using Equation (A.159), are longitudinal force impedances for a semi-infinite plate for plate 2 and for plates 1 and 3, they are bending force impedances for an semi-infinite plate.

$$Z_{F,1,\infty} = 0.5\rho_{m1}h_1c_{B,1}(1+\mathrm{j}) = 0.5m_1c_{B,1}(1+\mathrm{j}) \tag{A.192}$$

$$Z_{F,2,\infty} = h_2\sqrt{E_2\rho_{m2}} = \rho_{m2}h_2c_{LI2} = m_2c_{LI2} \tag{A.193}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3}h_3c_{B,3}(1+\mathrm{j}) = 0.5m_3c_{B,3}(1+\mathrm{j}) \tag{A.194}$$

To calculate the contribution of the rotational motion of the junction (rigid type only) to τ_{13}, moment impedances of all connected subsystems are needed in the impedance sum of Equation (A.159). The relevant impedances are:

$$Z_{M,1,\infty} = 0.5\rho_{m1}h_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 = 0.5m_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.195}$$

$$Z_{M,2,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1-\mathrm{j})k_{B,2}^2 = 0.5m_2c_{B,2}(1-\mathrm{j})k_{B,2}^2 \tag{A.196}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}h_3c_{B,3}(1-\mathrm{j})k_{B,3}^2 = 0.5m_3c_{B,3}(1-\mathrm{j})k_{B,3}^2 \tag{A.197}$$

The corresponding coupling loss factors are then calculated using:

$$\langle\eta_{ij}^{\text{line}}\rangle_\theta \approx \eta_{ij}^{\text{line}}(0) = \frac{\beta_{\text{corr}}c_{g,i}L}{4\pi f S_i}\tau_{ij,\infty}^{\text{line}}(0) \tag{A.198}$$

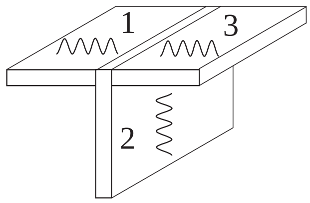
where i and j are the plate identifying numbers, β_{corr} is defined on page 356 and $c_{g,i} = 2c_{B,i}$ for bending waves and $c_{g,i} = c_{LI,i}$ for longitudinal waves. The transmission coefficient for translational junction motion is:

$$\tau_{ij,\infty}^{\text{line}}(0) = \tau_{ji,\infty}^{\text{line}}(0) = \frac{4\mathrm{Re}\{Z_{F,i,\infty}^{\text{line}}\}\mathrm{Re}\{Z_{F,j,\infty}^{\text{line}}\}}{\left|\sum\limits_{m=1}^{2} Z_{F,m,\infty}^{\text{line}}\right|^2} \tag{A.199}$$

and for rotational junction motion, the transmission coefficient contribution to the total $\tau^{\text{line}}_{31,\infty}(0)$ is:

$$\tau^{\text{line}}_{13,\infty}(0) = \tau^{\text{line}}_{31,\infty}(0) = \frac{4\text{Re}\{Z^{\text{line}}_{M,i,\infty}\}\text{Re}\{Z^{\text{line}}_{M,j,\infty}\}}{\left|\sum_{m=1}^{2} Z^{\text{line}}_{M,m,\infty}\right|^2} \tag{A.200}$$

A.8.5.11 T-Junction Plate (1) - Plate(2) - Plate(3), Bending-Bending-Bending (ID=23c)



ENC assumes that the line connection spans the full width of plates 1 and 3.

This junction type can transmit energy whether pinned or rigid, with consideration of vertical translational junction motion as well as rotational junction motion, parallel to an axis perpendicular to the page and passing through the junction. If pinned, there is only energy transmission between plates 1 and 3, as a result of translational motion of the junction in the vertical direction. However, there is no energy transmission between plates 1 and 2 nor between plates 2 and 3 so the contributions to both τ_{12} and τ_{23} are zero for translational motion of the junction. In the impedance sum for translational motion, the translational impedances to use in the sum of Equation (A.159) are semi-infinite bending wave force impedances for plates 1 and 3 and the semi-infinite longitudinal impedance for plate 2 (see below).

$$Z_{F,1,\infty} = 0.5\rho_{m1}h_1c_{B,1}(1+\text{j}) = 0.5m_1c_{B,1}(1+\text{j}) \tag{A.201}$$

$$Z_{F,2,\infty} = \rho_{m2}h_2c_{LI,2} = m_2c_{LII,2} \tag{A.202}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3}h_3c_{B,3}(1+\text{j}) = 0.5m_3c_{B,3}(1+\text{j}) \tag{A.203}$$

For a rigid junction, energy is transmitted by both translational motion between subsystems 1 and 3 and by rotational motion for all subsystem pair combinations. Thus the CLF for each type of motion must be determined and then added together to obtain the overall CLF for the junction. The impedances to use in Equation (A.159) for translational motion are those from Equations (A.201), (A.202) and (A.203) above, and the impedances to use for rotational motion are:

$$Z_{M,1,\infty} = 0.5\rho_{m1}h_1c_{B,1}(1-\text{j})/k^2_{B,1} = 0.5m_1c_{B,1}(1-\text{j})/k^2_{B,1} \tag{A.204}$$

$$Z_{M,2,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1-\text{j})k^2_{B,2} = 0.5m_2c_{B,2}(1-\text{j})k^2_{B,2} \tag{A.205}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}h_3c_{B,3}(1-\text{j})k^2_{B,3} = 0.5m_3c_{B,3}(1-\text{j})k^2_{B,3} \tag{A.206}$$

For calculating τ_{13}, the contribution due to rotational motion of the junction must be added to the contribution due to translational motion of the junction.

The corresponding coupling loss factors are then calculated using:

$$\langle\eta^{\text{line}}_{ij}\rangle_\theta \approx \eta^{\text{line}}_{ij}(0) = \frac{\beta_{\text{corr}}c_{g,i}L}{4\pi f S_i}\tau^{\text{line}}_{ij,\infty}(0) \tag{A.207}$$

where i and j are the plate identifying numbers, β_{corr} is defined on page 356 and $c_{g,i} = 2c_{B,i}$ for bending waves and $c_{g,i} = c_{LI,i}$ for longitudinal waves.

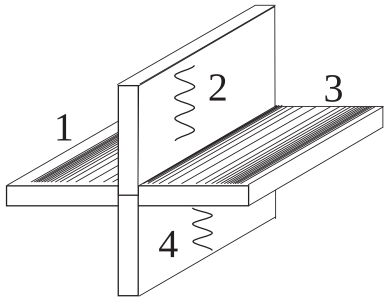
For translational force transmission:

$$\tau_{ij,\infty}^{\text{line}}(0) = \tau_{ji,\infty}^{\text{line}}(0) = \frac{4\text{Re}\{Z_{F,i,\infty}^{\text{line}}\}\text{Re}\{Z_{F,j,\infty}^{\text{line}}\}}{\left|\sum_{m=1}^{2} Z_{F,m,\infty}^{\text{line}}\right|^2} \tag{A.208}$$

and for rotational moment transmission:

$$\tau_{ij,\infty}^{\text{line}}(0) = \tau_{ji,\infty}^{\text{line}}(0) = \frac{4\text{Re}\{Z_{M,i,\infty}^{\text{line}}\}\text{Re}\{Z_{M,j,\infty}^{\text{line}}\}}{\left|\sum_{m=1}^{2} Z_{M,m,\infty}^{\text{line}}\right|^2} \tag{A.209}$$

A.8.5.12 Four Plates, Edge-Connected at Right Angles, Longitudinal-Bending-Longitudinal-Bending (ID=24a)



This junction type can be pinned or rigid. In both cases energy can be transmitted between plates via translational motion of the junction. However, rotational energy can be transmitted between plates 2 and 4 only if the junction is rigid.

It is assumed that the line connection spans the full width of all plates.

For the transmission of energy via translational forces in the horizontal direction, the impedances to use in Equation (A.208) for subsystems 2 and 4 are translational horizontal bending force impedances for a semi-infinite plate and for subsystems 1 and 3 we use translational horizontal force impedances for a semi-infinite plate:

$$Z_{F,1,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1+\text{j}) = 0.5m_2c_{B,2}(1+\text{j}) \tag{A.210}$$

$$Z_{F,2,\infty} = \rho_{m1}h_1c_{LI,1} = m_1c_{LI,1} \tag{A.211}$$

$$Z_{F,3,\infty} = 0.5\rho_{m4}h_4c_{B,4}(1+\text{j}) = 0.5m_4c_{B,4}(1+\text{j}) \tag{A.212}$$

$$Z_{F,4,\infty} = \rho_{m3}h_3c_{LI,3} = m_3c_{LI,3} \tag{A.213}$$

For the transmission of rotational forces between subsystems 2 and 4, it is necessary to use moment impedances in Equation (A.209) and the impedance sum must include the sum of moment impedances for all four subsystems. The moment impedances are:

$$Z_{M,1,\infty} = 0.5\rho_{m1}h_1c_{B,1}(1-\text{j})/k_{B,1}^2 = 0.5m_1c_{B,1}(1-\text{j})/k_{B,1}^2 \tag{A.214}$$

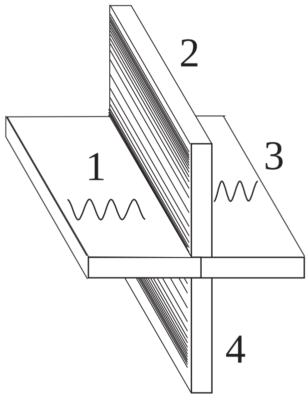
$$Z_{M,2,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1-\text{j})/k_{B,2}^2 = 0.5m_2c_{B,2}(1-\text{j})/k_{B,2}^2 \tag{A.215}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}h_3c_{B,3}(1-\text{j})/k_{B,3}^2 = 0.5m_3c_{B,3}(1-\text{j})/k_{B,3}^2 \tag{A.216}$$

$$Z_{M,4,\infty} = 0.5\rho_{m4}h_4c_{B,4}(1-\text{j})/k_{B,4}^2 = 0.5m_4c_{B,4}(1-\text{j})/k_{B,4}^2 \tag{A.217}$$

These impedances are used together with Equations (A.207), (A.208) and (A.209) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{14}, η_{41}, η_{23}, η_{32}, η_{24}, η_{42}, η_{34} and η_{43}.

A.8.5.13 Four Plates, Edge-Connected at Right Angles, Bending-Longitudinal-Bending-Longitudinal (ID=24b)



This junction type can transmit energy whether pinned or rigid. In both cases energy can be transmitted between plates via translational motion of the junction. However, rotational energy can be transmitted between plates 1 and 3 only if the junction is rigid.

It is assumed that the line connection spans the full width of all plates.

For the transmission of energy via translational forces in the horizontal direction, the impedances to use in Equation (A.208) for subsystems 2 and 4 are translational vertical bending force impedances for a semi-infinite plate and for subsystems 1 and 3 we use translational vertical force impedances for a semi-infinite plate:

$$Z_{F,1,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1+\mathrm{j}) = 0.5m_2c_{B,2}(1+\mathrm{j}) \tag{A.218}$$

$$Z_{F,2,\infty} = \rho_{m1}h_1c_{LI,1} = m_1c_{LI,1} \tag{A.219}$$

$$Z_{F,3,\infty} = 0.5\rho_{m4}h_4c_{B,4}(1+\mathrm{j}) = 0.5m_4c_{B,4}(1+\mathrm{j}) \tag{A.220}$$

$$Z_{F,4,\infty} = \rho_{m3}h_3c_{LI,3} = m_3c_{LI,3} \tag{A.221}$$

For the transmission of rotational forces between subsystems 1 and 3, it is necessary to use moment impedances in Equation (A.209) and the impedance sum must include the sum of moment impedances for all four subsystems. The moment impedances are:

$$Z_{M,1,\infty} = 0.5\rho_{m1}h_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 = 0.5m_1c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.222}$$

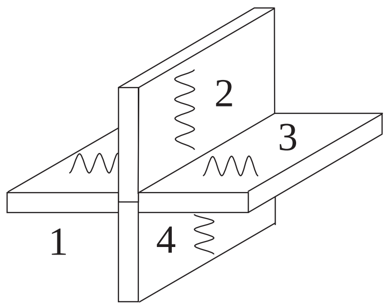
$$Z_{M,2,\infty} = 0.5\rho_{m2}h_2c_{B,2}(1-\mathrm{j})/k_{B,2}^2 = 0.5m_2c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \tag{A.223}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3}h_3c_{B,3}(1-\mathrm{j})/k_{B,3}^2 = 0.5m_3c_{B,3}(1-\mathrm{j})/k_{B,3}^2 \tag{A.224}$$

$$Z_{M,4,\infty} = 0.5\rho_{m4}h_4c_{B,4}(1-\mathrm{j})/k_{B,4}^2 = 0.5m_4c_{B,4}(1-\mathrm{j})/k_{B,4}^2 \tag{A.225}$$

These impedances are used together with Equations (A.207), (A.208) and (A.209) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{14}, η_{41}, η_{23}, η_{32}, η_{24}, η_{42}, η_{34} and η_{43}.

A.8.5.14 Four Plates, Edge-Connected at Right Angles, Bending-Bending-Bending-Bending (ID=24c)



This junction type can transmit energy whether pinned or rigid. In both cases energy can be transmitted between plates via translational motion of the junction. However, rotational energy can be transmitted between the various plates only if the junction is rigid. Note that translational energy cannot be transmitted between plates 1 and 2, 1 and 4, 2 and 3, as well as 3 and 4, as each of the two subsystems making up these pairs do not generate translational motion in the same direction.

It is assumed that the line connection spans the full width of all plates.

For the transmission of energy via translational forces in the horizontal direction (for the calculation of τ_{24}), the impedances to use in Equation (A.208) for subsystems 2 and 4 are bending force impedances for a semi-infinite plate and for subsystems 1 and 3 we use longitudinal force impedances. For the transmission of energy via translational forces in the vertical direction (for the calculation of τ_{13}), the impedances to use in Equation (A.208) for subsystems 1 and 3 are bending force impedances for a semi-infinite plate and for subsystems 2 and 4 we use longitudinal force impedances. For the calculation of the rotational transmission coefficient components of all subsystem pairs, the moment impedances of all four plates are used. The impedances to use for horizontal translational motion of the junction are:

$$Z_{F,1,\infty} = \rho_{m1} h_1 c_{LI,1} = m_1 c_{LI,1} \tag{A.226}$$

$$Z_{F,2,\infty} = 0.5\rho_{m2} h_2 c_{B,2}(1+\mathrm{j}) = 0.5 m_2 c_{B,2}(1+\mathrm{j}) \tag{A.227}$$

$$Z_{F,3,\infty} = \rho_{m3} h_3 c_{LI,3} = m_2 c_{LI,3} \tag{A.228}$$

$$Z_{F,4,\infty} = 0.5\rho_{m4} h_4 c_{B,4}(1+\mathrm{j}) = 0.5 m_4 c_{B,4}(1+\mathrm{j}) \tag{A.229}$$

The impedances to use for vertical translational motion of the junction are:

$$Z_{F,1,\infty} = 0.5\rho_{m1} h_1 c_{B,1}(1+\mathrm{j}) = 0.5 m_1 c_{B,1}(1+\mathrm{j}) \tag{A.230}$$

$$Z_{F,2,\infty} = \rho_{m2} h_2 c_{LI,2} = m_2 c_{LI,2} \tag{A.231}$$

$$Z_{F,3,\infty} = 0.5\rho_{m3} h_3 c_{B,3}(1+\mathrm{j}) = 0.5 m_2 c_{B,3}(1+\mathrm{j}) \tag{A.232}$$

$$Z_{F,4,\infty} = \rho_{m4} h_4 c_{LI,4} = m_4 c_{LI,4} \tag{A.233}$$

The moment impedances to use for rotational motion transmission are:

$$Z_{M,1,\infty} = 0.5\rho_{m1} h_1 c_{B,1}(1-\mathrm{j})/k_{B,1}^2 = 0.5 m_1 c_{B,1}(1-\mathrm{j})/k_{B,1}^2 \tag{A.234}$$

$$Z_{M,2,\infty} = 0.5\rho_{m2} h_2 c_{B,2}(1-\mathrm{j})/k_{B,2}^2 = 0.5 m_2 c_{B,2}(1-\mathrm{j})/k_{B,2}^2 \tag{A.235}$$

$$Z_{M,3,\infty} = 0.5\rho_{m3} h_3 c_{B,3}(1-\mathrm{j})/k_{B,3}^2 = 0.5 m_3 c_{B,3}(1-\mathrm{j})/k_{B,3}^2 \tag{A.236}$$

$$Z_{M,4,\infty} = 0.5\rho_{m4} h_4 c_{B,4}(1-\mathrm{j})/k_{B,4}^2 = 0.5 m_4 c_{B,4}(1-\mathrm{j})/k_{B,4}^2 \tag{A.237}$$

These impedances are used together with Equations (A.207). (A.208) and (A.209) to calculate the corresponding coupling loss factors, η_{12}, η_{21}, η_{13}, η_{31}, η_{14}, η_{41}, η_{23}, η_{32}, η_{24}, η_{42}, η_{34} and η_{43}.

A.8.6 Coupling Loss Factors for Area Connections

In this section we will consider the transmission of energy from resonant modes on a plate to resonant modes in a room or 2-D cavity. We will also consider the forced transmission of non resonant energy between two acoustic spaces (1 and 3) separated by a partition, 2. In both cases the transmission is a result of vibration of a finite-size panel. In the latter case, the transmission from room 1 to room 3 via partition 2 consists of resonant transmission from one room to the partition and from the partition to the second room, as well as non-resonant transmission from room 1 to room 3 via partition 2. For the example of a single-panel partition between two rooms, this requires the evaluation of η_{21} and η_{23} using junction type 31 and the evaluation of η_{13} using junction type 33 as described below.

The coupling loss factor, η_{12} can be calculated from η_{21} using Equation (A.57), repeated below:

$$\eta_{12} = \eta_{21}(n_2 c_{B2}^2/(n_1 c_1^2)) \tag{A.238}$$

where n_1 and n_2 are the modal densities of subsystems 1 and 2, c_{B2} is the bending wave speed in panel 2 and c_1 is the wave speed in the cavity air space.

In some cases it is of interest to be able to calculate the sound power radiated by a panel in the overall system being analysed. The radiated sound power will depend on the space-average vibration level on the plate in the frequency band of interest and the plate radiation efficiency, σ. This latter quantity depends on how the plate is excited as well as the frequency of excitation.

If the plate is excited by a reverberant sound field, the radiation efficiency for radiation into free space is:

$$\sigma = \log_e\left(\frac{1+\sqrt{1+q^2}}{F+\sqrt{F^2+q^2}}\right) + \frac{1}{\alpha}\log_e\left(\frac{H+\sqrt{H^2+q^2}}{F+\sqrt{F^2+q^2}}\right) \tag{A.239}$$

where $H = 1.0/[0.67\sqrt{(}2ka/\pi) - 0.124]$ $q = \dfrac{\pi}{2k^2a^2}$

$F = 1.3\sqrt{\dfrac{\pi}{2ka}} = \dfrac{1.3H}{\sqrt{2}}$

$a = 2S_p/P$, where S_p is the plate area and P is the plate perimeter.

$\alpha = (H/F) - 1$

If $\alpha = 0$, the second term on the RHS of Equation (A.239) is replaced with $F/\sqrt{H^2+q^2}$.

Equations (A.243) and (A.239) apply to both rectangular and circular plates.

For plates excited by an incident wave at an angle, ϕ, to the normal to the plate surface, instead of a diffuse sound field, the radiation efficiency is (Davy, 2009):

$$\sigma(\phi) = \begin{cases} \dfrac{1}{\sqrt{(g^2+q^2)}} & F \le |g| \le 1 \\ \dfrac{1}{\sqrt{(H-\alpha g)^2+q^2}} & 0 \le |g| < F \end{cases} \tag{A.240}$$

where $g = \cos\phi$. This option (with $\phi = 0$) is used in ENC to calculate the sound power radiated by a 1-D duct terminated by a plate as well as the coupling loss factor for transmission through a plate in a 1-D duct system (coupling types 31, 33 and 35).

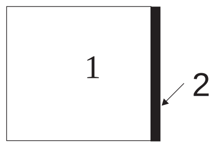
If the plate is excited mechanically so that it responds resonantly, the radiation efficiency is given by Equation (A.28).

ENC calculates the free space radiated sound power (in watts) for both resonant and forced plate responses for all plates in the system, even though some may not be radiating to free space. The radiated sound power, W is calculated using:

$$W = \rho c S_2 \sigma \langle v^2 \rangle_{S,t} \tag{A.241}$$

The calculated values are labelled and output in the text file fullSEA.OUT for all plate subsystems. For non-plate subsystems, the output values are zero.

A.8.6.1 Plate - Radiation into a Room (ID=31)



The coupling loss factor for resonant transmission between a plate (2) and a room (1) is (Fahy, 1982, p. 177):

$$\eta_{21} = \frac{\rho c \sigma}{\omega \rho_m h} \tag{A.242}$$

where the plate (2) has an area, S_p, perimeter, P, thickness, h, and density, ρ_m. Both rectangular and cylindrical rooms can be used in ENC. The plate radiation efficiency, σ, for resonant transmission into a 3-D enclosure is (Lyon and DeJong, 1995, p. 199):

$$\begin{aligned}\sigma &= \frac{2Pk^2}{\pi S_p k_{Bp}^3\left(1+\dfrac{\pi k^2}{2k_{Bp}^2}\right)} + \left[\left(\frac{k_{Bp}^2}{k^2}-1\right)^2\left(\frac{\pi k_{Bp}^4}{k^4}+1\right)^2+\frac{2\pi}{k_{Bp}\sqrt{S_p}}\right]^{-1} \\ &= \frac{2P(f/f_c)^{3/2}}{\pi k S_p\left(1+\dfrac{\pi f}{2f_c}\right)} + \left[\Big[(f_c/f)-1\Big]^2\Big[\pi(f_c/f)^2+1\Big]^2+\frac{2\pi(f/f_c)^{1/2}}{k\sqrt{S_p}}\right]^{-1}\end{aligned} \quad \text{(A.243a,b)}$$

where the plate bending wavenumber, $k_{Bp} = \left[\dfrac{12\omega^2\rho_m(1-\nu^2)}{Eh^2}\right]^{1/4} = \left[\dfrac{12\omega^2}{c_L^2h^2}\right]^{1/4} = \omega/c_{Bp}$ and the wavenumber in air, $k = 2\pi/\lambda$.

An alternative radiation efficiency calculation method for radiation into a 3-D enclosure is provided by Fahy (1969). This method is used by ENC if the calculation method option of "Cremer, Maidanik or other" is chosen on the "coupling loss factor data input" page in ENC For a rectangular plate, of dimensions $a \times b$ and thickness, h, the radiation efficiency, σ, is:

$$\sigma = \begin{cases} \dfrac{64hc_L(a+b)}{\pi^5 cab}\left[\dfrac{\sin^{-1}(f/f_c)^{1/2}}{1-(f/f_c)}+\tan\left[\sin^{-1}(f/f_c)^{1/2}\right]\right]; & 2f_{1,1} < f < 0.9f_c \\ 0.51(1-f_c/f)^{-1/2}; & f > 1.1f_c \end{cases} \quad \text{(A.244)}$$

Note that this expression also apples to a circular plate if $(a+b)$ in the numerator is replaced with half the plate perimeter, $P/2$, and ab in the denominator is replaced with the plate area, S.

If the enclosure is a 1-D subsystem type 15, the radiation efficiency is calculated for a 1-D wave in the acoustic system (see Equation (A.49), (Davy, 2009), with $\phi = 0$).

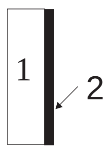
The coupling loss factor, η_{12}, for excitation of a plate (2) by the sound field (1) in a room is related to the coupling loss factor, η_{21}, for radiation by the plate into a room by:

$$\eta_{12} = \eta_{21}(n_2c_{B2}^2/(n_1c_1^2)) \quad \text{(A.245)}$$

where n_1 is the modal density of the room and n_2 is the modal density of the plate.

For the purposes of data input into ENC, for this junction, the cavity subsystem ID number is entered into the system 1 column and the plate subsystem ID number is entered into the system 2 column in the data input table in the coupling loss data page. Zero is entered into the system 3, 4 and system 5 columns.

A.8.6.2 Plate - Radiation into a Narrow Cavity (ID=32)



The coupling loss factor for resonant transmission between a plate (2) and a narrow cavity (1) is represented by the same equation as for ID=31, but with a different radiation efficiency:

$$\eta_{21} = \frac{\rho c\sigma_2}{\omega\rho_m h} \quad \text{(A.246)}$$

where the plate (2) has an area, S_p, perimeter, P, thickness, h, and density, ρ_m. The radiation efficiency of the partition is then given by the same expression as for the radiation efficiency at coincidence (due to the same wave speeds in the panel and in air), with the coincidence frequency replaced by the actual frequency (Craik, 2003). The radiation efficiency of the partition, is thus given by (Craik, 2003):

$$\sigma_2 = 0.45\sqrt{P_2f/c} \quad \text{(A.247)}$$

where P_2 is the perimeter of the partition between the cavity wall and the room. That is, it is given by, $P_2 = 2(L_x + L_y)$ where L_x and L_y are the dimensions of the face of the cavity. If the cavity, 3, is divided into smaller spaces using ribs (connecting the front and back walls), similar to the studs that would be used in a double wall construction, then the perimeter, P_3, must be increased by twice the total length of all partitions connected to the leaf, the volume V_3 is the total volume of all cavities between studs and the coupling loss factor represents the entire cavity 3, not just 1 cell between 2 ribs. Equation (A.247) is one of several that have appeared in the literature. However, it is not the most commonly used.

An alternative radiation efficiency equation (also based on a coincidence frequency equation), which is more commonly used is (Maidanik, 1962):

$$\sigma_2 = \sqrt{\frac{L_x f}{c}} + \sqrt{\frac{L_y f}{c}} \tag{A.248}$$

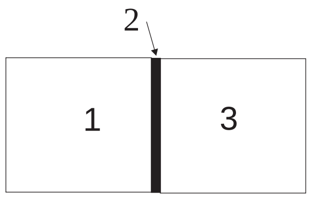
If it is a 1-D space such as a duct that is attached to the partition, rather than a 3-D space, the above equations are still used by ENC to calculate the radiation efficiency.

If studs between the panels exist, the lengths must be added to either L_x or L_y, depending on which dimension they are parallel to. Equation (A.248) gives a result that is approximately a factor of 2 greater than the result calculated using Equation (A.247). In ENC, Equation (A.247) is used as there is more support for it in the literature.

The coupling loss factor, η_{12}, for excitation of a plate (2) by the sound field (1) in a cavity is related to the coupling loss factor, η_{21}, for radiation by the plate into a cavity by Equation (A.245).

For the purposes of data input into ENC, for this junction, the cavity subsystem ID number is entered into the system 1 column and the plate subsystem ID number is entered into the system 2 column in the data input table in the coupling loss data page. Zero is entered into the system 3, 4 and system 5 columns.

A.8.6.3 Room - Room (non-resonant transmission)



Room - Room, Separated by a single leaf partition (ID=33) (Crocker and Price, 1969a)

The energy transmission between two rooms (which can be 1-D or 3-D spaces via a common, single-leaf partition consists of both resonant and non-resonant transmission. The calculation for ID=33, undertaken in this section, is only for non-resonant transmission from room 1 to room 3, characterised by the coupling loss factor, η_{13} and which is another example of the tunnelling phenomenon. Thus for the calculation of this CLF (η_{13}), the approach for the transmission between 1-D spaces is the same as for 3-D spaces. However, the calculation of the overall transmission loss between spaces 1 and 3 does make use of the radiation efficiency, which is calculated differently for a 1-D system (see section s:platenorm).

For the purposes of data input into ENC, for this junction, the lowest cavity subsystem ID number is entered into the system 1 column, the plate subsystem ID number is entered into the system 2 column and the highest cavity subsystem ID number is entered into the system 3 column in the data input table in the coupling loss data page. Zero is entered into the system 4 and 5 columns. The coupling loss factors for resonant transmission (η_{12}, η_{21}, η_{23} and η_{32}) are calculated separately using separate junction numbers in ENC and the procedure corresponding to ID=31, in Section A.8.6.1.

The coupling loss factor, η_{13}, (ID=33) for non-resonant transmission between 2 rooms (subsystems 1 and 3) separated by a single-leaf partition (subsystem 2) is a function of the mass-law transmission coefficient, τ_2 (Norton and Karczub, 2003, p. 420):

$$\eta_{13} = \frac{\tau_2 S_p c_1}{8\pi f V_1} \tag{A.249}$$

where V_1 is the volume of room 1, c_1 is the speed of sound in room 1, S_p is the surface area of the partition and the transmission coefficient for non-resonant transmission, τ_2, is given by (Norton and Karczub, 2003, p. 420):

$$\tau_2 = \begin{cases} \pi \left\{ \dfrac{\pi^9 (\rho_m h)^2}{2^{13}\rho^2 S_p} \left[1 - \left(\dfrac{10 f}{f_c} \right)^2 \right] + 1 + \left(\dfrac{\pi f \rho_m h}{\rho c} \right)^2 \right\}^{-1}; & f_{1,1} < f < f_c/2 \\ \pi \left[1 + \left(\dfrac{\pi f \rho_m h}{\rho c} \right)^2 \right]^{-1}; & f \geq f_c/2 \end{cases} \tag{A.250}$$

where h is the partition thickness, ρ_m is the partition density and the π term preceding the bracket is introduced to convert the normal incidence transmission coefficient to a random incidence coefficient (Craik, 2003). The "1+" addition has been made for completeness, although it has little effect for practical structures (Bies et al., 2024, p. 380).

An alternative and more accurate (for frequencies above $f_c/4$) (Equation (3.12) in Leppington et al. (1987)) and (Hopkins, 2007, pp. 425) for calculating the non-resonant transmission coefficient for frequencies below $0.95 f_c$ is:

$$\begin{aligned} \tau_2 = \left(\frac{2\rho}{\rho_m h k (1 - \mu^{-2})} \right)^2 \Bigg\{ & \log_e (k\sqrt{S_p}) + 0.16 - U(L_x/L_y) \\ & + \frac{1}{4\mu^3} \Big[(2\mu - 1)(\mu + 1)^2 \log_e(\mu - 1) \\ & + (2\mu + 1)(\mu - 1)^2 \log_e(\mu + 1) - 4\mu - 8\mu^3 \log_e(\sqrt{\mu}) \Big] \Bigg\} \end{aligned} \tag{A.251}$$

where $\mu = f_c/f$ and the function, $U(L_x/L_y)$, which is difficult to evaluate as it involves an integral, is close to zero for plate aspect ratios (long side/short side) less than three (Hopkins, 2007, pp. 426). This equation is used by ENC for frequencies below $0.95 f_c$. Above this frequency, sound transmission is dominated by resonant transmission (see Equation (A.258)) and the calculations in this section are not used and ENC sets the coupling loss factor for non resonant transmission, $\eta_{13} = \eta_{31} = 0$.

Both of the above equations agree to within less 1 dB for frequencies less than $f_c/4$ and within 3 dB for frequencies less than $f_c/2$.

If one is interested in calculating transmission loss for comparison with experiments, the overall transmission loss may be calculated from the total (resonant + non-resonant) transmission coefficient, $\tau_{\text{tot}} = \tau_{\text{res}} + \tau_2$, using:

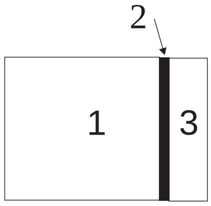
$$\text{TL} = -10 \log_{10}(\tau_{\text{res}} + \tau_2) = -10 \log_{10} \tau_{\text{tot}} \tag{A.252}$$

Resonant transmission is taken into account by by considering the partition as a separate subsystem and using resonant coupling loss factors, η_{12}, η_{21}, η_{23} and η_{32}, which can be calculated as for ID=31 in Section A.8.6.1. Thus two separate junctions must be included in the data entry to account for resonant transmission (with a junction ID=31). For the purposes of coupling loss input data entry in ENC calculations for the ID=31 case, the partition ID is 1 and the room ID is 2 for both cases.

The transmission coefficient for resonant transmission is given by (Hopkins, 2007, p. 420):

$$\tau_{\text{res}} = \frac{\eta_{12}\eta_{23}V_1 S_3 \bar{\alpha_3}}{\eta_2\eta_3 V_3 S_2} \tag{A.253}$$

where $S_3\bar{\alpha_3}$ is the absorption area in room 3 (receiver room). Coupling loss factors are calculated using Equations (A.242) and (A.245), with the radiation efficiency given by Equation (A.243).



Cavity - Room, Separated by a single leaf partition (ID=34) (Craik, 2003)

The energy transmission between a narrow cavity (such as found in a double leaf partition) to a room via a common, single-leaf, partition consists of both resonant and non-resonant transmission. In this section, the coupling loss factor for non-resonant transmission only is calculated.

For the calculation of this CLF (η_{13}), the approach used by ENC for the transmission from a 1-D space to a cavity is same as for transmission from a 3-D space into a cavity. This calculation does require use of a radiation efficiency and the equations for this calculation are the same as those used in the calculations for coupling type 32.

As for all 3-D acoustic spaces, the shape of the space may be rectangular or cylindrical. The coupling loss factors, η_{12} and η_{21}, corresponding to resonant transmission to and from the partition 2 and room 1 are calculated separately using the procedure for ID=31 in Section A.8.6.1. The coupling loss factors, η_{23} and η_{32}, corresponding to resonant transmission to and from the partition 2 to cavity 3 are calculated separately using the procedure for ID=32 in Section A.8.6.2. For these resonance transmission coupling loss factor calculations, both must be entered into ENC as two additional and separate junctions. For the purposes of coupling loss input data entry in ENC calculations for calculating the above coupling loss factors using the procedure for ID=31, partition 2 subsystem ID number number is entered into the system 2 column and the room 1 subsystem ID number is entered into the system 1 column. For use of the procedure for ID=32, partition 2 subsystem ID number number is entered into the system 2 column and the cavity 3 subsystem ID number is entered into the system 1 column. for both cases of transmission between the room and partition and between the partition and cavity.

For the ID=34 calculation outlined here (non-resonant transmission between room 1 and narrow cavity 3, which is another example of the tunnelling phenomenon), the room subsystem ID number is entered into the system 1 column, the plate subsystem ID number is entered into the system 2 column and the cavity subsystem ID number is entered into the system 3 column in the data input table in the coupling loss data page. Zero is entered into the system 4 and 5 columns.

Room 3 is a narrow cavity, such as used in a double wall partition. Thus, the non-resonant coupling loss factor, η_{13}, is calculated more accurately using the procedure in this section than is achieved by treating it like the ID=33 situation. This is done by considering that the sound field in the cavity is mainly incident at grazing incidence, resulting in the wave speed in the partition being equal to the wave speed in air. This new calculation procedure is outlined below and is identified by a coupling ID=34. The following expression is used to calculate the coupling loss factor for non-resonant transmission (Craik, 2003) between room 1 and cavity 3.

$$\eta_{31} = \frac{\rho^2 c^3 S_2 \sigma_2}{\omega^3 \rho_{m2}^2 h_2^2 V_3} \tag{A.254}$$

where V_3 is the volume of the cavity, ρ_{m2} is the density of the partition material, h_2 is the thickness of the partition separating the wall cavity from the room, $\omega = 2\pi f$, S_2 is the total area of the partition separating the room from the cavity. The radiation efficiency of the partition is then given by the same expression as for the radiation efficiency at coincidence (due to the same wave speeds in the panel and in air), with the coincidence frequency replaced by the actual frequency (Craik, 2003). The radiation efficiency of the partition, is then given by (Craik, 2003):

$$\sigma_2 = 0.45\sqrt{P_2 f/c} \tag{A.255}$$

where P_2 is the perimeter of the partition between the cavity wall and the room. That is, it is given by, $P_2 = 2(L_x + L_y)$ where L_x and L_y are the dimensions of the face of the cavity. If the cavity, 3, is divided into smaller spaces using ribs (connecting the front and back walls), similar to the studs that would be used in a double wall construction, then the volume V_3 is the total volume of all cavities between studs and the coupling loss factor represents the entire cavity 3, not just 1 cell between 2 ribs. Equation (A.255) is one of several that have appeared in the literature but it is NOT the one used in ENC.

An alternative radiation efficiency equation (also based on a coincidence frequency equation), which is more commonly used, is (Maidanik, 1962):

$$\sigma_2 = \sqrt{\frac{L_x f}{c}} + \sqrt{\frac{L_y f}{c}} \tag{A.256}$$

Equation (A.256) gives a result that is approximately a factor of 2 greater than the result calculated using Equation (A.255).

Equation (A.256), derived in Maidanik (1962), is the most commonly cited reference for the radiation efficiency of a baffled rectangular panel at the coincidence frequency and it also appears in (Cremer et al., 2005, p, 499). The alternative Equation (A.255) used by Craik (2003), and also presented in (Cremer et al., 1988, p. 533) is a slight modification of the expression for a baffled beam, which is derived by Lyon and Maidanik (1962). This latter expression agrees numerically with that provided by Leppington et al. (1982) for a baffled rectangular panel, but the numerical values are a factor of 2 less than the values obtained using the expression in Maidanik (1962) and (Cremer et al., 2005, p, 499). ENC uses the approach embodied in Equation (A.255). However, above 0.95 times the critical frequency, where resonant transmission dominates, ENC sets the coupling loss factor for non resonant transmission, $\eta_{13} = 0$.

For the purposes of data input into ENC, for this junction, the room subsystem ID number is entered into the system 1 column, the plate subsystem ID number is entered into the system 2 column and the cavity subsystem ID number is entered into the system 3 column in the data input table in the coupling loss data page. Zero is entered into the system 4 column. Only the non-resonant coupling loss factor between the room and cavity is calculated here. The two coupling loss factors for resonant transmission to and from the plate are calculated separately using the Junction ID=31 above.

The transmission coefficient for non-resonant transmission corresponding to Equation (A.254) for η_{31} is:

$$\tau_{31} = \tau_{13} = \frac{8\pi\eta_{31} f V_1}{c S_2} \tag{A.257}$$

The transmission coefficient for resonant transmission is given by (Hopkins, 2007, p. 420):

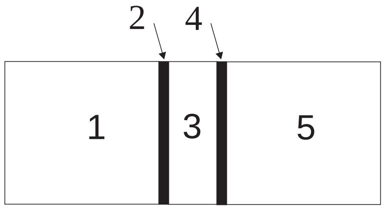
$$\tau_{\text{res}} = \frac{\eta_{12}\eta_{23} V_1 S_3 \bar{\alpha_3}}{\eta_2 \eta_3 V_3 S_2} \tag{A.258}$$

where $S_3\bar{\alpha_3}$ is the absorption area in room 3 (receiver room). Coupling loss factors are calculated using Equations (A.242) and (A.245), with the radiation efficiency given by Equation (A.243).

The overall transmission loss (TL) is thus:

$$\mathrm{TL} = -10\log_{10}(\tau_{31} + \tau_{\mathrm{res}}) \tag{A.259}$$

Separated by a double leaf partition (ID=35) – (Craik, 2003; Díaz-Cereceda et al., 2013)



The transmission of energy from room 1 to room 5 consists of the resonant transmission path and the non-resonant transmission paths, characterised by the following coupling loss factors, which must all be included in the calculation. This section is concerned with calculation of the coupling loss factor corresponding to non-resonant transmission between room 1 and room 5, which is another example of the tunnelling phenomenon discussed in Section A.8.1.

1. η_{12} and η_{21} (resonant transmission, calculated as for ID=31)
2. η_{23} and η_{32} (resonant transmission, calculated as for ID=32)
3. η_{34} and η_{43} (resonant transmission, calculated as for ID=32)
4. η_{45} and η_{54} (resonant transmission, calculated as for ID=31)
5. η_{13} and η_{31} (non-resonant transmission, calculated as for ID=34)
6. η_{35} and η_{53} (non-resonant transmission, calculated as for ID=34)
7. η_{15} and η_{51} (non-resonant transmission, calculated as for ID=35 - this section)

The ID=31 procedure (with the systems numbered as for the ID=31 procedure) must be used to calculate coupling loss factors for resonant transmission from the room to the adjacent partitions (ie from subsystem 1 to 2 (and vice versa) and from subsystem 4 to 5 (and vice versa)). The ID=32 procedure is used to calculate resonant transmission from partition 2 to cavity 3 (and vice versa) and cavity 3 to partition 4 (and vice versa). For this case, the cavity volume used is the entire volume of open space between the two leaves making up the partition, the partition area is the total area of one face of one of the two leaves making up the partition partition and the perimeter is the partition perimeter of one leaf of the partition plus twice the length of the studs (or ribs) connecting the the two leaves of the partition.

Use ID=34 to calculate coupling loss factors for non-resonant transmission from room 1 to cavity 3 (and vice versa) (tunnelling) and from room 5 to cavity 3 (and vice versa). For a cavity with ribs (or studs), the cavity volume to be used for this ID=34 calculation is the total volume between the two partitions and the partition area is the total area of one face. However, the cavity the perimeter is the partition perimeter plus twice the length of the studs (or ribs) connecting the the two leaves of the partition. For the purposes of coupling loss input data entry in ENC calculations for ID=34, the room ID is 1, the cavity ID is 3 and the partition ID is 2.

Use ID=35 in this section to calculate coupling loss factors for non-resonant transmission from room 1 to room 5 (and vice versa). For the purposes of coupling loss input data entry in ENC calculations, the room 1 ID is 1 and the room 5 ID is 5, the partition 2 ID is 2, the partition 4 ID is 4 and the cavity 3 ID is 3.

The non-resonant connection between the two rooms, defined using η_{15}, requires treating the double wall as a single connection that approximately follows mass-law based on the total mass of the partition. The coupling loss factor, η_{15} is:

$$\eta_{15} = \frac{cS_p\tau_{15}}{4\omega V_1} \tag{A.260}$$

where τ_{15} is:

$$\tau_{15} = \begin{cases} \pi \left\{ \dfrac{\pi^9(\rho_{m3}h_3 + \rho_{m4}h_4)^2}{2^{13}\rho^2 S_p} \left[1 - \left(\dfrac{10f}{f_c}\right)^2\right] + 1 + \right. \quad \text{(A.261)} \\ \left. \quad + \left(\dfrac{\pi f(\rho_{m3}h_3 + \rho_{m4}h_4)}{\rho c}\right)^2 \right\}^{-1}; \quad f_{1,1} < f < f_c/2 \\ \pi \left[1 + \left(\dfrac{\pi f(\rho_{m3}h_3 + \rho_{m4}h_4)}{\rho c}\right)^2\right]^{-1}; \quad f \geq f_c/2 \quad \text{(A.262)} \end{cases}$$

An alternative expression that is based on Equation (A.251) introduced for ID=33 is:

$$\begin{aligned} \tau_{15} = \left(\frac{2\rho}{(\rho_{m3}h_3 + \rho_{m4}h_4)k(1-\mu^{-2})}\right)^2 & \left\{ \log_e(k\sqrt{S}) + 0.16 - U(L_x/L_y) \right. \\ & + \frac{1}{4\mu^3}\Big[(2\mu - 1)(\mu + 1)^2 \log_e(\mu - 1) \\ & \left. + (2\mu + 1)(\mu - 1)^2 \log_e(\mu + 1) - 4\mu - 8\mu^3 \log_e(\sqrt{\mu})\Big]\right\} \end{aligned} \tag{A.263}$$

where $\mu = f_c/f$ and f_c is the lower critical frequency of panels 2 and 4 and the equation is valid for frequencies below $0.95f_c$. Above this frequency transmission is dominated by resonant transmission.

An alternative approach would be to calculate separately the non-resonant transmission coefficients, τ_2 and τ_4 of partition leaves 2 and 4 respectively, using Equation (A.250) or Equation (A.251) and then calculate $\tau_{15} = \tau_2\tau_4$.

The overall double-panel transmission loss is given by:

$$\text{TL} = -10\log_{10}(\tau_{\text{res}} + \tau_{\text{non-res1}} + \tau_{\text{non-res2}}) \tag{A.264}$$

The total transmission coefficient for resonant transmission is derived using Equation (A.258) to give:

$$\tau_{\text{res}} = \frac{\eta_{12}\eta_{23}V_1S_3\bar{\alpha_3}}{\eta_2\eta_3V_3S_2} \times \frac{\eta_{34}\eta_{45}V_3S_5\bar{\alpha_5}}{\eta_4\eta_5V_5S_4} \tag{A.265}$$

The transmission coefficient for non-resonant transmission along the first path is:

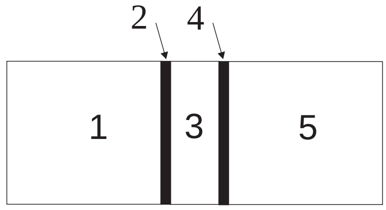
$$\tau_{\text{non-res1}} = \tau_{13} \times \tau_{35} \tag{A.266}$$

The transmission coefficient for non-resonant transmission along the second path is:

$$\tau_{\text{non-res2}} = \tau_{15} \tag{A.267}$$

If the panel is circular, the stud mass value to enter is the total mass of studs divided bu the number of studs.

Alternative for two rooms separated by a double leaf partition (ID=36) – (Craik, 2003; Díaz-Cereceda et al., 2013)



There is an alternative way of looking at the non-resonant transmission between the two rooms separated by a double wall partition consisting of two solid leaves with a cavity in between (Díaz-Cereceda et al., 2013). Instead of modelling the leaves as connections between the rooms and cavity in the double wall (thus calculating η_{13}, η_{31}, η_{53} and η_{35}), the cavity is modelled as a connection between the two leaves. In this case, it is assumed that there is non-resonant transmission between the two leaves of the double wall via the cavity (coupling loss factors, η_{24} and η_{42}), and also between the two rooms via the double wall acting as a single-leaf partition controlled by mass law (coupling loss factor, η_{15} and η_{51}). In this approach coupling loss factors η_{13} and η_{35} are replaced with coupling loss factor, η_{24}, which is calculated here as case ID=36. The coupling loss factor, η_{24}, is broken into 2 parts for the purposes of the calculation: η_{24a} for non resonant airborne transmission via the air in the cavity and η_{24s} for non-resonant structural transmission via the studs connecting the two leaves.

Then the coupling loss factor, $\eta_{24} = \eta_{24a} + \eta_{24s}$. In summary, the coupling loss factors that must be calculated (and their case ID for the calculations) using this alternative approach are listed below, with the loss factors, η_{24} and η_{42} calculated as described in this section.

1. η_{12} and η_{21} (resonant transmission, calculated as for ID=31)
2. η_{23} and η_{32} (resonant transmission, calculated as for ID=32)
3. η_{34} and η_{43} (resonant transmission, calculated as for ID=32)
4. η_{45} and η_{54} (resonant transmission, calculated as for ID=31)
5. η_{24} and η_{42} (non-resonant transmission, calculated as for ID=36 - this section)
6. η_{15} and η_{51} (non-resonant transmission, calculated as for ID=35)

The ID=36 procedure is used to calculate coupling loss factor, $\eta_{24} = \eta_{24a} + \eta_{24s}$ for non-resonant transmission from partition 2 to partition 4 (and vice versa).

η_{24a} may be calculated using:

$$\eta_{24a} = \frac{\mathrm{Re}\{Y_4\}}{2\pi f M_2 |Y_2 + Y_4 + Y_a|^2} \tag{A.268}$$

$$Y_i = \frac{1}{\sqrt{D_i \rho_{mi} h_i}}; \quad (i = 2 \text{ or } 4) \tag{A.269}$$

$$Y_a = \frac{\mathrm{j} 2\pi f d_3}{\rho c^2 S_3} \tag{A.270}$$

$$D_i = \frac{E_i h_i^3}{12(1-\nu_i^2)}; \quad (i = 2 \text{ or } 4) \tag{A.271}$$

where M_2 is the mass of panel 2, E_i, h_i ρ_{mi} and ν_i are Young's modulus, thickness, density and Poisson's ratio respectively, for leaf, i, S_3 is the surface area of one side of the partition (S_2 or S_4) and d_3 is the cavity depth (distance between the two leaves).

The coupling loss factor, η_{24s}, due to non-resonant transmission via the studs connecting the two leaves can be calculated by modelling the studs as line springs with a stiffness, K.

For wooden studs the stiffness of each stud can be taken as $K_L = 10^{10}$ N/m. For other stud types, the stiffness can be calculated in the double wall (Davy method) page in ENC, Module 5, where the stiffness is the reciprocal of the compliance given by ENC. Thus, the non-resonant transmission coefficient for transmission via the studs is (Díaz-Cereceda et al., 2013):

$$\eta_{24s} = \frac{n\mathrm{Re}\{Y_4/L_y\}}{2\pi f M_2 |Y_2/L_y + Y_4/L_y + Y_s/L_y|^2} \tag{A.272}$$

where n is the number of studs, M_2 is the mass of panel 2, L_y is the length of each stud and $Y_s = \mathrm{j}\omega/K$. The mobilities, Y_2 and Y_4 are:

$$Y_i = \frac{1}{2(1+\mathrm{j})\rho_{mi} h_i c_{B,i} (f/f_{c,i})^{1/2}}; \quad (i = 2 \text{ or } 4) \tag{A.273}$$

The overall coupling loss factor, η_{24}, due to the combined non-resonant transmission by the air and non-resonant transmission via the studs is:

$$\eta_{24} = \eta_{24a} + \eta_{24s} \tag{A.274}$$

The ID=36 procedure is used to calculate coupling loss factors for one of the non-resonant transmission paths (η_{24}) from room 1 to room 5 (and vice versa). This path is used in place of (not as well as) the path characterised by η_{13} and η_{35}. Thus, to use the η_{24} path, we use Equations (A.264), (A.266) and (A.267), where $\tau_{13} \times \tau_{35}$ in Equation (A.266) is replaced with τ_{24}. It is up to the user of ENC to decide which combination to use for calculating non-resonant transmission. One choice involves using junction type IDs 34 (twice) and 35, while the other choice involves using junction type IDs 35 and 36. The latter choice is necessary if the effect of stud stiffness is to be included. Both approaches take into account the total number of studs in the cavity, with junction type 35 using the stud mass and junction type 36 using the stud stiffness.

In ENC, the double wall transmission loss is calculated by taking into account all transmission paths listed on page 392.

A.9 Calculation of Subsystem Energies

These calculations are done in the SEA results page. First, the following equation is solved for total subsystem energies, E_i, by matrix inversion using LU factorisation.

$$\omega \begin{bmatrix} (\eta_1 + \sum\limits_{\substack{i=1\\i\neq 1}}^{m} \eta_{1i}) n_1 & (-\eta_{12} n_1) & \cdots & (-\eta_{1m} n_1) \\ (-\eta_{21} n_2) & (\eta_2 + \sum\limits_{\substack{i=1\\i\neq 2}}^{m} \eta_{2i}) n_2 & \cdots & (-\eta_{2m} n_2) \\ \vdots & \vdots & \ddots & \vdots \\ (-\eta_{m1} n_m) & \cdots & \cdots & (\eta_m + \sum\limits_{\substack{i=1\\i\neq m}}^{m} \eta_{mi}) n_m \end{bmatrix} \begin{bmatrix} E_1/n_1 \\ E_2/n_2 \\ \vdots \\ E_m/n_m \end{bmatrix} = \begin{bmatrix} \Pi_1 \\ \Pi_2 \\ \vdots \\ \Pi_m \end{bmatrix} \tag{A.275}$$

or in short form as:

$$\omega[\mathbf{A}][\mathbf{E}/\mathbf{n}] = [\mathbf{W}] \tag{A.276}$$

where [**A**] is the $(k \times k)$ matrix (**called the A-matrix**) consisting of combinations of CLFs, DLFs and modal densities as indicated in Equation (A.3), [**E/n**] is the $(k \times 1)$ vector of the modal energies within each subsystem and [**W**] is the $(k \times 1)$ vector of input powers to each subsystem. The input power to each subsystem is known (from measurements or from the problem description) and hence the total energy, E_i, in each subsystem, i, can be calculated by multiplying the modal energy (E_i/n_i) by the subsystem modal density, $n_i(\omega)$ (modes/radian/sec), where the modal energies in each subsystem, [**E/n**], are calculated using:

$$[\mathbf{E}/\mathbf{n}] = \frac{1}{\omega}[\mathbf{C}]^{-1}[\mathbf{W}] \tag{A.277}$$

The mean square vibration velocity, $\langle u^2 \rangle_{St\Delta}$, of a structural subsystem, i, is related to its total energy, E_i, by:

$$\langle u_i^2 \rangle_{St\Delta} = E_i/M_i \qquad (\mathrm{m}^2/\mathrm{s}^2) \tag{A.278}$$

where M_i is the total mass of the subsystem and the subscript, $St\Delta$, indicates that the average is over space, S, time, t, and frequency band, Δ.

Note that the modal densities in Equation (A.275) may be expressed as modes/Hz or modes/rad/sec. The resulting total system energies, E_i will be the same for both cases. The actual modal energy (or energy per mode) for subsystem, i, is defined as the total subsystem energy for subsystem, i, divided by the number of modes in the band, where the number of modes is equal to the modal density multiplied by the bandwidth. If the modal density is in modes/Hz, then the bandwidth must be expressed in Hz and similarly, if the modal density is in modes/rad/sec, then the bandwidth must be expressed in rad/sec. Thus, the modal energy is the same for both cases. As one is usually only interested in the relative modal energies of the subsystems, the bandwidth is often not used in the calculation and this sometimes leads to confusion as to what is meant by E_i/n_i. In most cases practitioners use the modal density as modes/rad/sec and refer to E_i/n_i as the modal energy. However, in ENC, we use the actual modal energy $(E_i/(n_i \times \Delta f)$ in the output, where consistent units are used for frequency in the modal density, n_i and in the bandwidth, Δf. Thus, the same results are obtained regardless of whether frequency is expressed as Hz or rad/sec.

The mean square sound pressure, $\langle p_i^2 \rangle_{St\Delta}$, in an acoustic subsystem, i, (such as an enclosure) is related to its total energy, E_i, by:

$$\langle p_i^2 \rangle_{St\Delta} = E_i \rho c^2 / V_i \qquad (\mathrm{Pa}^2) \tag{A.279}$$

where V_i is the enclosure volume. The average sound pressure level, $L_{p,i}$, in the enclosure for the 1/3-octave or octave band being considered is then:

$$L_{p,i} = 10 \log_{10} \langle p_i^2 \rangle_{St\Delta} + 94 \qquad (\text{dB re } 20\,\mu\text{Pa}) \tag{A.280}$$

In addition to the subsystem total energy, E_i, it is of interest to calculate the subsystem modal energy levels so that the major power transmission paths can be identified. Subsystems with low modal energies may be ignored as transmission pathways. The modal energy of subsystem, i, is given by E_i/n_i, where the modal density, n_i is in modes/rad/sec.

Appendix B

Errata and Additions for Engineering Noise Control, 6th edn.

p32, Equation (1.87), remove “eq” at the end of the equation.

p36, Equation (1.101), the subscripts “60,1 60,1 and 60,1” should be “60,1 60,2 and 60,3”, respectively.

p.43, Line above Equation (1.113), Change “These” to “For 1/3-octave bands, these”.

p.43, in order to be consistent with more commonly used base-10 filters, change Equation (1.115) to

$$\Delta f = f_{C(\text{exact})} \times (10^{3/20N} - 10^{-3/20N}) = \begin{cases} 0.230768 f_{C(\text{exact})}; & \text{for 1/3-octave bands} \\ 0.704592 f_{C(\text{exact})}; & \text{for octave bands} \end{cases}$$

p.43, 3 lines from bottom of page, change “(707 – 353) = 354” to “(708 – 355) = 353”.

p.43, Bottom line, change “354” to “353”.

p127, 2 lines below Equation (2.112), change (2.114) to (2.112).

p254, LHS of Equation (5.25), change $\langle p^2 \rangle_{d_{SR}}$ to $\langle p_t^2 \rangle_{d_{SR}}$.

p257, LHS of Equation (5.49), change $\langle p^2 \rangle_t$ to $\dfrac{\langle p_t^2 \rangle_{d_{SR}}}{\langle p^2 \rangle_{1\text{m}}}$.

p257, beginning 4 lines under Equation (5.49), delete the following sentence. “ The modulus of the spherical wave reflection coefficient, $|Q|$ and the phase angle, α_s, represent the complex conjugate of Q', which, in turn, is defined by Equation (5.23) and the following text.”

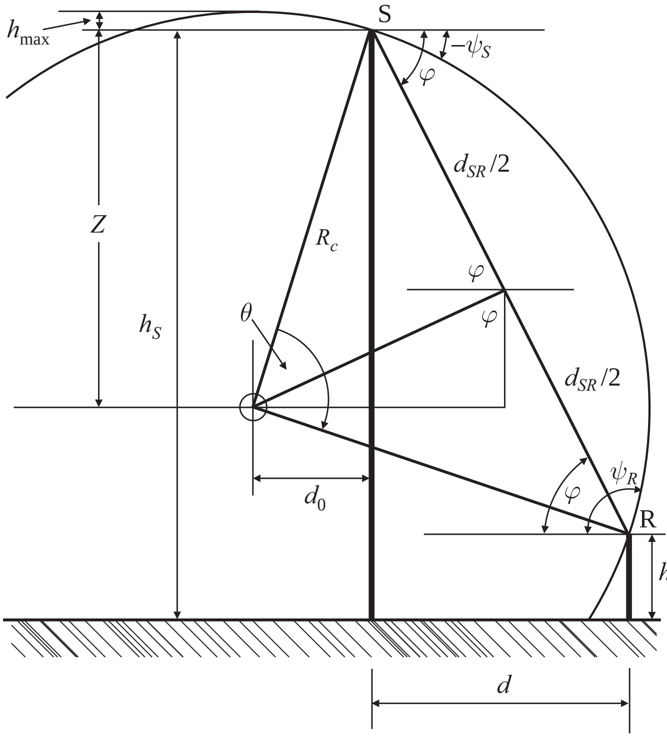
p262, 3 lines above Section 5.3.3, in order to be consistent with more commonly used base-10 filters, replace $2^{1/2b} - 2^{-1/2b}$ with $10^{3/20b} - 10^{-3/20b}$.

p262, line immediately above Section 5.3.3, change 0.23156 to 0.230768 and change 0.7071 to 0.704592.

p264, 2 lines above Equation (5.70), remove "Equation (5.25)," and in 1 line above Equation (5.70), add "(see Equation (5.25))" after "waves".

p272, first line after Equation (5.83), after "where " add "$B_m = U_0/\log_e[(z_r/z_0) + 1]$, A_m is defined in Equation (5.76d) and ".

p276, replace Figure 5.9 with the following, showing a different definition of Z.



p277, second line from the top, add "is" after "it" at the end of the line.

p280, first line following Figure 5.11 caption, after "(5.102)", add "with z_i^2 replaced with $(z_i - \tilde{z})^2$."

p281, Equation (5.117) only applies to flat ground. For sloping ground, we need to calculate a new launch angle for the reflected ray relative to the horizontal. To do this, we use Equation (5.108) to calculate the incidence angle relative to the local ground plane. Then we subtract this angle (which should be greater than $\pi/2$) from π. We then add twice the ground slope to the result (taking the sign of the slope into account) to get the reflected ray launch angle (relative to the horizontal). If the launch angle is greater than $\pi/2$, no reflected ray exists that will arrive at the receiver.

p285, In Equation (5.127) change $\partial c/\partial z$ to $\mathrm{d}c/\mathrm{d}z$ in two places.

p286, last line, change the first ψ_{S2} to ψ_{R2}.

p287, first line, change the first ψ_{S2} to ψ_{R2}.

p325, 2 lines above Equation (5.230), change 1– –8 to 1 – 8.

p329, Following the end of the third line from the top, for clarification, we may write "The excess attenuation term, A_{ref} for reflection from a vertical surface (which may be added arithmetically to the RHS of Equation (5.219)) may be written as:

$$A_{\mathrm{ref}} = -10\log_{10}\left[1 + \left(\frac{d_{SR}}{r_S + r_R}\right)^2 (1-\alpha_r)10^{\mathrm{DI}_r/10}\right] \qquad \text{(dB)}$$

where d_{SR} is the straight-line distance from the source to the receiver and $r_S + r_R$ is the distance from source to receiver around the diffraction edge."

p331, last paragraph, second line add "(see Section 5.7.1.7)" at the end of the first sentence and remove the next two sentences. In the first line, change A_r to A_{ref}.

p331, Equation (5.243), change A_r to A_{ref}.

p334, 4 lines above equation (5.259), change Equation (5.253) to Equation (5.254).

p334, Line under Equation (5.260), change "inverse" to "reciprocal".

p337, Equation(5.267), the second and third lines should be multiplied by -1.

p338, First dot point, it is not straightforward to adapt Equation (5.156) to this situation. It is better to use the following equations to find the coordinates of the image source, imaged across the mean ground plane. Consistent with the analysis on page 333, the x-coordinate is the horizontal coordinate in the direction from source to receiver and the z-coordinate is the height above an arbitrary datum. The x and z coordinates of the source are denoted x_{SE} and z_{SE}, respectively and those of the receiver are x_{RE} and z_{RE}.

The image source coordinates are denoted x'_{SE} and z'_{SE}, where
$x'_{SE} = [2(x_{SE} + az_{SE} - ab)/(a^2+1)] - x_{SE}$
$z'_{SE} = [2a(x_{SE} + az_{SE} - ab)/(a^2+1)] + 2b - z_{SE}$
where a and b are defined on page 333. The image receiver coordinates are found in a similar way, by replacing the subscript, S with R in the above equations.

p339, 6$^{\mathrm{th}}$ line from the top, replace "Section 5.1.7.2" with "Sections 5.1.7.2, 5.1.7.3 and 5.1.7.4".

p339, 3rd black dot point see p338 comment.

p339, 4$^{\mathrm{th}}$ line above equation (5.274), change "Equation (1.11.3) to "Equation (1.98)".

p340, Section 5.7.2, Remove the sentence beginning on the 8th line under the heading and replace the remainder of the section with: "The excess attenuation, A_r, due to reflection from a vertical surface is:

$$A_{\mathrm{ref}} = -10\log_{10}\left[1 + \left(\frac{d_{SR}}{r_S + r_R}\right)^2 (1-\alpha_r)\right] \qquad \text{(dB)}$$

where d_{SR} is the straight-line distance from source to receiver and $r_S + r_R$ is the distance from source to receiver around the diffraction edge."

p424, 4 lines under section 7.2.6.1 heading, replace "0.23156" with "0.230768".

p426, Equation (7.65), LHS should be ω_0 OR RHS should be divided by 2π (see page 281 in the reference).

p427, 3 lines under Equation (7.72), replace "0.23156" with "0.230768" and replace "0.7071" with "0.704592".

p500, 6 lines from the top of the page, a is the radius of the expansion chamber and k is the wavenumber.

p508, line above Eq (8.140), change "Eq. 13" to "Eq. 11".

p508, Replace Equation (8.141) with the following equation and replace the definitions of Z_{A1} and Z_{An} below the equation with $Z_{A1} = \rho c/S_u$ and $Z_{An} = \rho c/S_d$.

$$\mathrm{TL} = 10\log_{10}\left[\left\{\frac{1+M_n}{1+M_1}\right\}^2 \left(\frac{1}{4}\right)\left(\frac{Z_{A1}}{Z_{An}}\right)\left|T_{11} + \frac{T_{12}}{Z_{A1}} + Z_{An}T_{21} + \frac{Z_{An}T_{22}}{Z_{A1}}\right|^2\right]$$

p511, Figure 8.18, remove the S_{duct} labels and in the caption, remove "where $S_2 = S_3 - S_1$".

p512, Figure 8.19 caption, add "where $S_2 = |S_3 - S_1|$" to the end of the caption.

p512, Figure 8.19(a), interchange S_1 and S_3.

p515, multiply the RHS of Equation (8.162) by $(1-M^2)$ when flow of Mach number M is present.

p517, multiply the RHS of Equation (8.168) by -1.

p519, Equation (8.185), remove ρc from the left and right hand sides of the equation (makes the equation compatible with Equation (8.133)).

p519, Equation (8.187), multiply the right hand side by the characteristic impedance, $(\rho c/S_1)$ and in Equation (8.188), divide the right hand side by the characteristic impedance, $(\rho c/S_1)$.
When there is flow through the muffler (M_1 non zero and $M_2 = 0$), the transfer matrix of Equation (8.185) must be replaced by (Munjal (2014), p. 126):

$$\begin{bmatrix} 1 & M_1\rho c/S_1 \\ M_1 S_1/\rho c & 1 \end{bmatrix}\begin{bmatrix} T_a & T_b \\ T_c & T_d \end{bmatrix}$$

p519, Add the following after the first line following Equation (8.196).
The lengths, L_a, L_b and L_c used in Equations on pages 518 and 519 are the optimal acoustic lengths and are calculated from the chamber length, L, using the following equations (see Equations (11), (17), (18) and (19) in Ramya and Munjal, "Improved tuning of the extended concentric tube resonator for wide-band transmission loss", Noise Control Engineering Journal, 62(4), 252–263).

$$L_a = (L/2) - \Delta_{1D}$$

$$L_b = (L/4) - \Delta_{1D}$$
$$L_c = (L/4) + 2\Delta_{1D}$$

where

$$\Delta_{1D} = 10^{-5}\left[1 - 4.278\,(P_{\text{open}}/100)^{-0.5454}\right]\left[1 + 59.89t_w^{0.6891}\right] \times \left[1 - 306.61d_1^{0.497}\right][1 + 75.98d_h]\left[1 - 1.124(d_2/d_1)^{-2.95}\right] \times \left[1 + 1.623 \times 10^{-4}L^{-3.197}\right]$$

Note that Equations (8.197) to (8.200) in the textbook are used to calculate the geometric lengths corresponding to the optimal acoustic lengths.

p519, Equation (8.200), second line, replace d with $d_1$and multiply the RHS by $(1 - M^2)$ when flow of Mach number M is present.

p521, Equation (8.206) is the transmission matrix corresponding to particle (not volume) velocity. To convert this matrix to one compatible with volume velocity, divide T_{12} by πa^2 and multiply T_{21} by πa^2. The resulting volume velocity transmission matrix can then be used with the volume velocity based transmission matrices corresponding to other muffler elements to calculate the IL and TL of a muffler system.

p542, Additional information for perforated pipes. The friction factor is:
$f_m = 0.0304 + 0.15 \times P_{\text{open}}/100$ (DOI: 10.13140/RG.2.1.3426.5043).

p621, Line following Equation (10.22), add “fully expanded” before the word, “jet”.

p621, 2 lines above Equation (10.23), replace”flowing gas” with “fully expanded jet” and add “fully expanded” before the word, “jet”.

p621, 2 lines following Equation (10.23), replace “stream” with “fully expanded jet”.

p621, last line, add “fully expanded” before the word, “jet”.

p622, 5, 8 and 11 lines from the top, add “for air” after “1.89” and note for other gases, the critical ratio is defined as $[(\gamma + 1)/2]^{\gamma/(\gamma-1)}$.

p622, Figure 10.2 caption, add “air” before “jets”.

p623, line following Figure 10.3, replace “jet diameter” with “nozzle exit diameter”.

p711, Table 11.5, first row, change “1-D duct” to Semi-infinite 1-D duct” and change the equation to $\rho c/S_d$. Note that the impedance shown in the text is for an infinite duct excited internally well away from the ends.

p717, Table 11.7, In the “finite honeycomb-core sandwich panel” section, in the expression for $n_2(\omega)$, change G to G_c.

p.721, Equation (11.91a), change to $\eta_{12}^{\text{line}} = \dfrac{c_{g1} L \beta_{\text{corr}}}{2\omega S_1} \langle \tau_{12,\infty}^{\text{line}}(\theta) \cos\theta \rangle_\theta$.

p726, 3 lines under equation (12.1), replace "0.23156" with "0.230768".

p812, line immediately below Equation (E.3), change r_i/r_1 to r_1/r_i.

p812, Equation (E.7), change d to d_{SR}.

p812, Equation (E.8), replace the part including and following the $\approx$ symbol with $= 2\pi f \Delta t$.

p812, 2 lines under Equation (E.8), replace "horizontal separation distance" with "length of non-reflected ray path".

p813, Equation (E.10), following "$h_S/10$", add "≈ 0.1", following "$h_R/10$", add "≈ 0.1" and change "d" to "d_{SR}".

p813, Equation (E.12), change "d" to "d_{SR}".

p813, 2 lines under Equation (E.13), change "d is the horizontal" to "d_{SR} is the".

p855, Porter reference, the first sentence should be "The bellhop manual and user's guide."

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