Example Problems in Engineering Noise Control, 2nd Edn.

A companion to "Engineering Noise Control"

Colin H. Hansen
Department of Mechanical Engineering
University of Adelaide
South Australia 5005
AUSTRALIA

FAX: +61-8-8303-4367
e-mail:chansen@mecheng.adelaide.edu.au

Published by Colin H Hansen, Adelaide, South Australia

 A catalogue record for this book is available from the Australian National Library.

Published by Colin H Hansen

ISBN 0-9751704-1-4

This version updated May 2, 2006

Contents

Preface

This book of problems in acoustics and noise control is intended as a companion for the 3rd edition of the book, "Engineering Noise Control" by David A. Bies and Colin H. Hansen, and covers chapters 1 to 10 and 12 in that text, with the problems arranged in the order in which the material appears in the textbook. Some of the problems are formulated to illustrate the physics underlying the acoustical concepts and others are based on actual practical problems. Many of the problems and associated solutions extend the discussion in the text and illustrate the more difficult concepts by example, thus acting as a valuable source and understanding for the consultant and student alike. Most of the problems are also suitable as exercises in graduate courses or 4th year undergraduate courses which use "Engineering Noise Control" as a text.

A very detailed 300-page book of solutions is also available from the author. The solutions to the problems consistently reference appropriate tables, figures, equations and page numbers in the 3rd edition of the text to enable the reader to understand the concepts on which the solutions are based.

C.H.H. September, 2003
e-mail:chansen@mecheng.adelaide.edu.au

Acknowledgments

The author would like to thank the many people (too numerous to mention) who were responsible for providing ideas for problems. The author would also like to thank his undergraduate and graduate students who provided an excellent opportunity for fine tuning the solutions to the problems in this book.

Finally, the author would like to express his deep appreciation to his family, particularly his wife Susan and daughters Kristy and Laura for their patience and support during the long nights and weekends needed to assemble the problems and solutions in a form suitable for publication.

This book is dedicated
to Susan,
to Kristy
and to Laura.

1

Problems in Fundamentals

Unless otherwise stated assume an air temperature of 20°C corresponding to an air density of 1.206kg/m^3 and a speed of sound of 343m/s.

1.1 You are responsible for a large factory containing many items of noisy equipment. You have been informed that some of your employees are suffering from severe hearing loss and you have also received threats of legal action from members of the surrounding community because of excessive noise made by your facility. List the steps (in order) that you would take to quantify and rectify the problem.

1.2 (a) Verify from fundamental principles that the speed of sound in Helium is 1/0.34 times that in air. Helium has a molecular weight of 4g/mole and it is a monatomic gas for which the average number of excited degrees of freedom is 3. Thus the ratio of specific heats $\gamma = (3+2)/3$. Air has a molecular weight of 29 g/mole.

(b) Explain why taking a mouthful of helium from a balloon makes you speak with a high pitched voice.

1.3 Given the first order approximation that $c_{wet} = (1+0.16h)c_{dry}$, calculate the speed, c, of sound in air at 30°C with a relative humidity of 95%. The quantity, h, is the fraction of total molecules which are H_2O. Vapour pressure of water at 30°C is 4240Pa and h = (vapour pressure/total pressure) × (%relative humidity/100). Assume the total pressure is atmospheric (101.4 kPa)

1.4 A reciprocating compressor installation is suffering piping joint failures due to excessive fluid pulsations at the compressor discharge. Prior to designing pulsation dampeners (see Ch 9), it is necessary to calculate the speed of sound in the compressed gas and this must

include the gas flow speed.
Assume a gas discharge pressure of 8MPa, a temperature of 120°C, a pipe diameter of 0.1m, a gas flow rate of 250,000m^3 per day measured at 15°C and atmospheric pressure, ratio of specific heats of 1.4 and a molecular weight of 29 grams per mole. Calculate the

(a) gas mass flow (kg/s)

(b) density of gas in the discharge pipe

(c) gas flow speed in the discharge pipe (m/s)

(d) speed of sound in the gas relative to the pipe and in the direction of gas flow.

1.5 What is the speed of sound in a gasoline engine cylinder just after combustion when the pressure is 200 times atmospheric pressure and the temperature is 1000°C? The ratio of specific heats of the gas mixture is 1.35 and the gas density is 1.4kg/m^3 at 0°C and atmospheric pressure.

1.6 Using the Universal Gas Law, calculate the temperature fluctuations in a plane sound wave characterised by an Intensity Level of 95dB re 10^{-12}W/m^2. Assume an adiabatic process for which PV^γ = Const.

1.7 Show, using the Universal Gas Law, that the value of ρc of air is equal to 400 at sea level and at a temperature of 40°C.

1.8 Calculate the fundamental longitudinal acoustical resonance frequency of a 100mm diameter pipe, 4 metres long and open at one end and closed at the other.

1.9 In a tail pipe following a muffler, there is a strong resonance at 250 Hz at a particular engine speed. This is the lowest resonance frequency of the tail pipe.

(a) If the tail pipe is 1.2 m long, what is the average exhaust gas temperature in the tail pipe in °C? Assume the tail pipe to be effectively open at each end. The molecular weight of the exhaust gas is 0.035 kg/mole and the ratio of specific heats is 1.4.

(b) What is the density of the exhaust gas at this temperature? State any assumptions that you make.

1.10 There is a low-frequency resonance instability in a furnace and as an engineer, you need to track down its source. You are also interested in the acoustic power generated at higher frequencies. The molecular weight of the exhaust gases is 0.035 kg/mole, the ratio of specific heats is 1.4, the pressure in the furnace is atmospheric and the temperature in the furnace is 1600°C.

(c) Calculate the speed of sound in the furnace

(b) Calculate the density of the gas in the furnace

(c) Calculate the wavelength of sound corresponding the frequency of instability if this frequency is 40 Hz. Comment on what one of the furnace dimensions might be to produce this resonance instability. [Hint: treat it like a closed end tube with the resonance being the lowest tube resonance.

(d) If the average sound pressure level measured in the furnace at distances further from the wall than half a wavelength is 120 dB in the 500 Hz octave band, what is the sound power level in watts generated by the burner in this frequency band? Assume that the furnace is a cylinder of 4 m diameter and assume an average Sabine sound absorption coefficient for the internal surfaces of the furnace of 0.02 in the 500 Hz band. State any other assumptions you make.

(e) If a second burner with a sound power level of twice the original burner were added to the furnace (and the original burner remained as well), what would be the resulting reverberant field sound level in the furnace and away from the furnace walls in the 500 Hz octave band.

1.11 The speed of sound waves propagating through a liquid is modified by the presence of gas bubbles.

(a) Derive an expression for the speed of sound for a proportion x of gas in the liquid. Assume adiabatic compression for the gas.

[**Hint**: Calculate the effective bulk modulus of the liquid containing the gas by calculating the change in volume of the gas and change in volume of the liquid for a given change in pressure. (Use the gas law for the gas component). Then calculate the effective density of the mixture of terms of x.]

(b) Show that as $x \to 1$, the expression for the speed of sound approaches that for a gas and as $x \to 0$ the expression approaches that for a liquid.

1.12 Using equations 1.6, 1.7 and 1.40c, derive equations 1.43 and 1.72 and show that the spherical wave intensity is the same as the plane wave intensity.

1.13 Given that the acoustic pressure at distance r from a small source, radius r_0, and surface velocity amplitude $U = U_0 e^{j\omega t}$ is of the form:

$$p = \frac{A}{r} e^{j\omega(t - r/c)}$$

(a) Find an expression for the particle velocity at any arbitrary distance from the source.

(b) show that the constant A is given by:

$$A = j\omega r_0^2 \rho U_0$$

(c) Find the acoustic power radiated by this source at 100Hz if $U_0 = 2$m/s and $r_0 = 5$cm.

1.14 Show that the particle velocity amplitude at distance r from a point monopole in a free field is

$$|u| = \frac{|p|}{\rho c} \left| 1 - \frac{j}{kr} \right|$$

for a single frequency $(\omega = kc)$. (Begin with the spherical wave solution to the wave equation.) At what kr value is the velocity amplitude twice $|p|/\rho c$?

1.15 The rms velocity fluctuation in a plane acoustic wave is given as 0.2m/s. Find the sound pressure level L_p (dB),

(a) in air using $p_{ref} = 20\,\mu\text{Pa}$,

(b) in water using $p_{ref} = 1\,\mu\text{Pa}$.

Briefly discuss whether non-linear effects might be important in each case. What other phenomena might occur in (b), and under what conditions?

1.16 (a) Calculate the sound pressure level (dB re 1μPa) of an acoustic disturbance in water, at 150kPa static pressure, at which the instantaneous total pressure becomes negative.

(b) What is the acoustic particle velocity amplitude if the disturbance is a plane wave.

(c) What is the acoustic particle velocity amplitude if the disturbance is a point source, 1m from the measurement location and the frequency is 1000Hz.

1.17 (a) A point monopole in a free field produces a sound pressure level at 1m of 110dB re 20μPa. What is the sound pressure level at 10m?

(b) Show that the particle velocity amplitude is:

$$\frac{|p|}{\rho c}\left|1 - \frac{\mathrm{j}}{kr}\right|$$

for a monopole operating at a single frequency, and evaluate this for the two positions in (a), given the frequency is 100Hz and the fluid is air. Start with the potential function harmonic solution of the wave equation for spherical waves.

1.18 The acoustic pressure of a harmonic spherical wave may be written as:

$$p(r, t) = \frac{A}{r}\mathrm{e}^{\mathrm{j}(\omega t - kr)}$$

(a) Derive an expression for the radial acoustic particle velocity.

(b) Derive an expression for the specific acoustic impedance at a distance r from a monopole source.

(c) At what distance (in wavelengths) from the sound source is the modulus of the specific acoustic impedance half that for a plane wave.

1.19 A small spherical sound source is radiating 1 watt of single frequency (1000Hz) sound power into free space. Calculate the following at a distance of 0.3m.
(a) r.m.s. sound pressure
(b) sound pressure level
(c) r.m.s. particle velocity
(d) phase between pressure and particle velocity (what leads what?)
(e) mean active sound intensity
(f) reactive sound intensity amplitude
(g) sound intensity level
(h) If the source also radiated 1 watt of acoustic power at 1500Hz simultaneously with the 1000Hz signal, what would be the total r.m.s. sound pressure?

1.20 Given that the sound pressure levels in the 1/3 octave bands of 200Hz, 250Hz and 315Hz are 78dB, 73dB and 80dB respectively, what is the 250Hz octave band sound pressure level?

1.21 Three omnidirectional, uncorrelated acoustic sources *A*, *B* and *C* are to be placed at three corners of a square with 10m sides. Independent calibration tests on these sources showed that they produced the following amounts of acoustic power.

Source A	10 watts
Source B	20 watts
Source C	15 watts

(a) Calculate the sound pressure level (dB re 20μPa) at the remaining corner (opposite B) of the 10 metre square (i.e. position *D*), assuming that *D* is in the far field of *A*, *B* and *C*.

(b) Calculate the <u>direction</u> of the resultant intensity vector at *D*.

(c) Explain physically the meaning of sound intensity and show why more than one microphone is necessary for its measurement except in the far free field of a source where the acoustic pressure and particle velocity are in phase.

(d) What is the advantage of sound intensity measurements over sound pressure measurements for the determination of the sound power of noisy equipment.

1.22 Write out definitions (words only) of the following terms

(a) Specific acoustic impedance
(b) characteristic impedance
(c) interference
(d) phase speed
(e) sound power
(f) particle velocity

1.23 What is implied about the octave and 1/3 octave band level variation with band centre frequency for a noise with a flat spectrum level? Spectrum level is the level in a frequency band 1Hz wide.

1.24 The sound pressure level measured at three locations around a machine is used to estimate the sound power level of a particular machine. The sound pressure levels measured at the three locations in the factory with the machine running in the **1/3 OCTAVE** bands 400Hz, 500Hz and 630Hz are 98, 102, and 96 dB respectively and with the machine turned off the levels are 95, 98 and 94 respectively.

(a) Calculate the L_{eq} for the 500Hz **OCTAVE BAND** for the machine only with no background noise influence.

(b) If an enclosure were placed around the machine that resulted in noise reductions of 15dB, 20 dB, and 23dB in the three 1/3 octave bands respectively, what would be the expected noise reduction for a uniform noise spectrum in the 500 octave band?

1.25 Two identical speakers driven by a pure tone signal through the same amplifier channel each produce 85dB at a microphone location equally distant from both speakers. What would be the sound pressure level if both speakers operated together? What would it be if a 45 degree phase shift were introduced in one channel?

1.26 Two coherent pure tone sound sources are 30° out of phase. What is the total sound pressure level at 10m if the sound level due to each source by itself is 85dB? What would you predict if the sources were 180° out of phase? What would you measure in practice? Why?

1.27 (a) Two signals $A\cos \omega t$, $A\cos(\omega t + \varphi)$ represent pressures at P caused by two separate sources. Using the same notation, what are (i) the amplitudes of the separate pressures at P; (ii) their rms values; (iii) the phase difference in radians between them?

(b) Derive an expression for the rms value of the combined pressure in question (a) above. Hence find the difference in sound pressure level, ΔL (dB), between the combined pressure at P and the pressure due to either source alone. Evaluate ΔL for a phase difference of 60°.

1.28 (a) Assume that the sound pressure as a result of a narrow band of noise arriving at a receiver from the same source but along two different paths may be described by equation 1.90 in the text. Write an expression for the phase difference between the two signals as a function of the centre frequency of the band of noise and the path length difference.

(b) What is the sound pressure at the receiver when the path length difference is 0.5 wavelengths and 1.0 wavelength?

(c) If the path difference is at least one wavelength or greater and the bandwidth is wide enough for the two signals to each contain all phases, then the phase difference between the two signals will be essentially random. Show that the limiting form of equation 1.90 in the text for this case corresponds to the expression for incoherent addition.

1.29 Two signals adding incoherently produce a level at the receiver of 75dB re 20µPa. When one (referred to as "first") is removed a level of 69dB results. If the other signal were removed and the first presented by itself what would be the resulting level?

1.30 Two large natural gas pumps are housed in a shed near an occupied small wood framed dwelling. The pumps are driven individually by electric motors operating at the same speed, but the phase between them, though fixed while they are running, is essentially random, being dependent on the order in which they are started and the time lapse between starting the second following the first. The pumps are started and stopped at frequent intervals. Occupants of the dwelling complain of occasional vibration which causes dishes, pictures on the walls, etc. to rattle enough to disturb their sleep. Each pump produces a 15Hz fundamental frequency and resonances at about this frequency can be expected to be excited in the dwelling. A sound pressure level of about 60dB re 20µPa would be just sufficient to produce the effects causing the complaints.

(a) Explain the possible acoustic phenomenon and suggest a strategy for noise control.

(b) Suggest appropriate measurements to verify your theory.

1.31 The specifications for an item of woodworking machinery state that the time averaged noise level at the operator's position is less than 95dB(A). When the machine is operating, the noise level measured at the operator's position is 97dB(A). When the machine is turned off, the noise level measured at the operator's position is 94dB(A). All measurements are averages taken during a typical working day using a statistical noise meter. Is the machine in compliance with specifications?

1.32 Near the operator of a noisy machine in a noisy factory the sound level in the 500Hz octave band is measured as 95dB. With the machine turned off, the level is 91dB at the same location. What is the noise level due to the machine alone?

1.33 A barrier exists between a source and receiver and results in a sound pressure level at the receiver of 60dB(A). There are four sound wave paths over the top of the barrier with corresponding noise reductions of 8, 13, 13 and 8dB(A) respectively. There are two paths around each end of the barrier with noise reductions of 18 and 12dB(A) respectively. What would the receiver sound level be if the barrier were removed and if the noise reduction of a ground reflected wave is 5dB(A)?

1.34 (a) When the phase difference between two signals is random the signals are incoherent, in which case square pressures add. If the level at a receiver is 75dB re 20μPa and it is composed of a signal which has travelled over line-of-sight from the source and a second signal which has been once reflected from the ground with a 5dB loss, assuming incoherent addition what would be the level at the receiver if the reflected signal were absent?

(b) If an obstacle is placed on the line-of-sight between the source and receiver, sound will reach the receiver by diffracting around the obstacle. Sound reaches a receiver by three paths. Over path **A** it suffers 4dB loss on reflection from the ground and 7dB loss on diffracting over the obstacle. Over path **B** it suffers 5dB loss due to diffraction and 5dB on reflection from the ground. Over path **C** (with no ground reflections) it suffers a 4dB loss due to diffraction. Assuming incoherent addition and that the situation is initially as in part (a) (with the reflected wave included) what will the sound pressure level be at the receiver after the placement of the obstacle?

(c) Alternatively if phase is not random, destructive interference may occur between the direct and reflected signals at the position of the receiver. For the case of two coherent signals (one of which has been reflected from the ground with a 5dB loss) the level at the receiver is 65dB re 20μPa. When an obstacle (the same as in part b) is placed between the noise source and receiver, the level at the receiver increases to 70dB and the waves diffracting around it may be considered to combine incoherently (random phase). What was the sound reducing effect (in dB) of the destructive interference prior to placement of the obstacle.

1.35 A harmonic plane wave travelling in the positive x-direction interferes with another plane wave travelling in the negative x-direction. The modulus of the sound pressure in the negative going wave is one quarter of that of the positive going wave and the two waves are in phase at $x = 0$. Derive an expression for the net active acoustic intensity in terms of the amplitude of the positive going wave. What would the active intensity have been if the two waves had the same amplitude?

1.36 Consider a tube of circular cross-section, 50mm in diameter and 1m long, driven at one end by a loudspeaker which at low frequencies (for which the wavelength is large compared to the speaker diameter) may be modelled as a rigid piston. The tube at the opposite end to the speaker is terminated by a long tapered wedge of porous material such that reflected sound is insignificant and the end simulates an infinite tube.

(a) Over what frequency range will the tube conduct only plane waves?

(b) If the amplitude of motion of the loudspeaker cone is 0.1mm at a frequency of 500Hz, what is the acoustic power introduced into the tube?

(c) If the power introduced into the tube is to be kept constant as the frequency is varied, how should the amplitude of the speaker cone vary over the plane wave of operation of the device?

1.37 Assume that at a point $x = 0$, the sound pressure in a one dimensional plane wave (such as a wave in a tube) made up of two single frequency waves, ω_1 and ω_2, is given as a function of time by:

$$p(0, t) = 5e^{j\omega_1 t} + 3e^{j\omega_2 t}$$

where $\omega_1 = 500$ rad/sec and $\omega_2 = 200$ rad/sec.

(a) What are the particle velocity and particle displacement as a function of time at $x = 5$m.

(b) What are the r.m.s. values of these two quantities?

(c) What is the active sound intensity?

(d) What is the amplitude of the reactive sound intensity?

(e) Recalculate your answers to (c) and (d) if a wave travelling to the left were added to the existing wave travelling to the right if the sound pressure associated with the left travelling wave is:

$$p_L(0, t) = 4e^{j500t} + 2e^{j200t}$$

1.38 The complex pressure amplitude produced by a plane wave travelling in a semi-infinite, hard-walled duct having $e^{j\omega t}$ time dependence can be described by $\bar{p}(x) = e^{-jkx}$ where A is a real constant and x is the distance from the sound source located at the end of the tube.

(a) Derive an expression for the complex acoustic particle velocity.

(b) Explain the difference between particle velocity and sound speed.

(c) Derive an expression for the specific acoustic impedance at any location x in the tube.

(d) Derive an expression for the specific acoustic impedance corresponding to the tube being terminated rigidly instead of infinitely.

1.39 A loudspeaker introduces sound into one end of a small diameter (compared to a wavelength) tube of length L and diameter d. The loudspeaker is at axial coordinate location $x = 0$ and the other end of the tube is rigid and at $x = -L$.

(a) Write expressions for the acoustic velocity potential, acoustic pressure and acoustic particle velocity in terms of one real unknown constant A , the tube length L, location x along the tube and angular excitation frequency, ω.

(b) Evaluate the constant A in terms of the velocity amplitude U_0 of the speaker diaphragm, assuming it to be a rigid piston.

(c) Rewrite the expressions of part (a) for acoustic pressure and particle velocity in terms of U_0 and use the results to write an expression for the real and imaginary parts of the acoustic intensity as a function of axial location x along the tube.

(d) Give a physical interpretation of the results obtained in (c) above.

1.40 A loudspeaker is placed at one end ($x = 0$) of a tube of cross-sectional area of S = 10cm^2, and at the other end (x = 0.3m) a second loudspeaker is placed. The first loudspeaker is driven to produce a single frequency wave and the resulting sound field in the tube is sampled with a microphone. The sound field has a pressure maximum of 100dB re 20μPa at x = 0.03m, 0.15m and 0.27m. The sound field has a pressure minimum of 96.5dB re 20μPa at x = 0.09m and 0.21m. Find

(a) frequency of the sound wave in the tube

(b) volume velocity of the first loudspeaker

(c) Mechanical impedance of the second loudspeaker.

[**Hint:** Write an expression for the total sound pressure in the tube in terms of a left and right travelling wave. Include a phase angle, θ in the wave which is reflected from the second speaker. The mechanical impedance is Sp/u. Let A be the amplitude of the right travelling incident wave (on the second loudspeaker) and let B be the amplitude of the left travelling reflected wave.]

1.41 An impedance tube with a speaker at one end and a sample of acoustic material at the other end is used to determine the sound absorbing properties of acoustic material as described in Appendix C of the text. The measurement involves determining the difference between the maximum and minimum values of the acoustic standing wave set up in the tube. The standing wave results from the interference of two waves travelling in the tube in opposite directions. As it turns out, multiple reflections from each end of the tube result in more than one wave travelling in each direction. However, this does not affect the measurement because it can be shown that any number of acoustic waves travelling in a single direction may be represented as a single travelling wave.

(a) Show that this conclusion is correct mathematically for two waves of different amplitudes and the same frequency and

(b) for two waves of the same amplitude but different frequencies (assuming only plane waves propagating).

(c) What phenomenon is observed if the two waves of part (b) are very close in frequency?

1.42 (a) Write expressions for the plane wave acoustic pressure and particle velocity at any location in the tube of problem 1.41 in terms of the complex pressure amplitude P_0 and complex particle velocity amplitude U_0 at the surface of the acoustic material and show that the specific acoustic impedance at any point in the tube is given by:

$$Z = \frac{\rho c}{S}\left[\frac{j\rho c U_0 \sin(kx) - P_0 \cos(kx)}{\rho c U_0 \cos(kx) - jP_0 \sin(kx)}\right]$$

where x is the distance along the tube from the material sample which is mounted at the left end of the tube at $x = 0$ and S is the tube cross-sectional area.

(b) How would the expression in (a) above for the impedance differ if the tube were open at the left end and the sample was placed at the right end at $x = 0$. Show that the two expressions are equivalent when evaluated at the open end of the tube (assuming a tube length of L.)

1.43 (a) For the tube shown in the figure below, calculate the specific acoustic impedance looking into the left end of the tube at 100Hz if the reflection coefficient of the surface of the sample at the right end of the tube is 0.5 + 0.5j. The higher order mode cut-on frequency of the tube is 200Hz and the temperature of the air in the tube is 20°C. In your analysis, let the surface of the sample be the origin of the coordinate system.

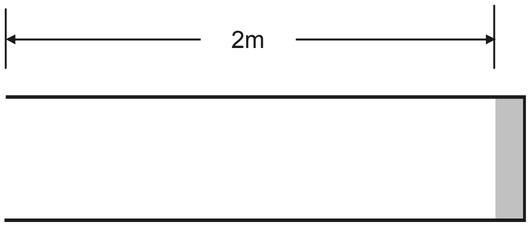
(b) Calculate the sound absorption coefficient of the sample.

1.44 The maximum and minimum sound pressure levels measured in an impedance tube at 250Hz are 95dB and 80dB respectively. The distance from the face of the sample to the nearest pressure minimum is 0.2m. Calculate the following:

(a) the normal incidence absorption coefficient of the sample at 250Hz

(b) the normal specific acoustic impedance of the sample at 250Hz

(c) the random incidence absorption coefficient of the sample at 250Hz (see Appendix C, in text book)



(d) the sound intensity in the tube.

1.45 A loudspeaker backed by a small enclosure, radiating low frequency sound into a circular cross section tube terminated in an impedance $Z_0 = R_0 + jX_0$, produces a constant local particle velocity amplitude U_L at its surface.

(a) Derive an expression for the sound power transmitted down the tube in terms of R_0, X_0 and U_L.

(b) If $R_0 = 0$, what is the transmitted power?

(c) If all losses, including propagation losses and losses at the termination are negligible, what is the impedance presented to the loudspeaker? What does this suggest about the power generated?

(d) In case (a) what is the phase between the pressure and particle velocity at the pressure maxima in the resulting acoustic pressure field in the tube?

(e) Show that when $R_0 = \rho c$ the magnitude of the amplitude reflection coefficient is given by:

$$|R_p| = X_0 [4\rho^2 c^2 + X_0^2]^{-1/2}$$

1.46 A small diameter tube with a loudspeaker mounted at one end may be used to measure the normal incidence absorption coefficient α_n of a sample of material mounted at the other end. The quantity α_n is defined as the ratio of the energy absorbed by the sample to that incident upon it. The energy reflection coefficient, $|R_p|^2$, is simply $1 - \alpha_n$.

(a) For single frequency sound, use the solution to the wave equation to derive an expression for the total sound pressure amplitude as a function of axial location x in the tube, real amplitude A, of the incident wave and the pressure amplitude reflection coefficient, R, of the sample. Let the sample surface be at $x = 0$ and the loudspeaker be at $x = L$. Assume a phase shift of θ between the waves incident and reflected from the sample.

(b) Show that the ratio of maximum to minimum pressure in the tube is $(A+B)/(A-B)$ where A is the real amplitude of the wave incident on the sample and B is the real amplitude of the wave reflected by the sample.

(c) Derive an expression for the energy reflection coefficient $|R_p|^2$ in terms of the decibel difference L_0 between the maximum and minimum pressures in the tube.

(d) Show that the normal incidence absorption coefficient,
$$\alpha_n = 1 - \left[\frac{10^{L_0/20} - 1}{10^{L_0/20} + 1}\right]^2 .$$

(e) Derive an expression (in terms of the complex amplitude reflection coefficient R) for the normal specific acoustic impedance of the sample.

1.47 (a) Show that the general expression for the specific acoustic impedance in a tube, looking towards one end at distance, L, from that end, which is terminated in an impedance Z_L, is given by:

$$Z = \rho c \left[\frac{Z_L/\rho c + \mathrm{j}\tan kL}{1 + \mathrm{j}(Z_L/\rho c)\tan kL}\right]$$

(b) Show that the pressure reflection coefficient is zero when the terminating specific acoustic impedance = ρc.
Hint: Let the termination impedance Z_L be at $x = 0$

(c) For a tube of cross-sectional area, S_T, with a termination of a solid plate containing a small hole of cross sectional area S_H and effective length ℓ, derive an expression for the pressure reflection coefficient, R. [**Hint:** see equation 9.14 in the text and use the condition of continuity of acoustic pressure and acoustic volume velocity (acoustic particle velocity × cross sectional area) at the hole].

(d) Consider now the condition of air blowing across the hole on the outside of the tube at a speed of Mach number M, where M is much less than 1. Acoustically, this condition is similar to the condition of flow through the hole in the direction of sound propagation. Using equation 9.8 in the text and the condition of continuity of acoustic pressure and acoustic volume velocity at the hole, derive an expression for the impedance in the tube at $x = 0$, looking towards the plate with hole.

(e) Show that when the ratio, S_H/S_T is equal to M (and M is small), at low frequencies and small hole diameters, the plate with hole will act as a good absorber of sound and specify the condition, fd_H for this to be true, where d_H is the hole diameter and f is the frequency of sound in the tube. [**Hint:** Use equations 9.15 and 9.17 in the text].

(f) Show that in the limit of small L and long wavelengths that the impedance of a tube with blocked ends corresponds to a stiffness and that of an open ended tube corresponds to a lumped mass. Derive expressions for each quantity.

(g) If an acoustic source has an internal impedance Z_0 and it is to be used to drive a load of acoustic impedance Z_0 through a tube , is there an optimum tube length for maximum sound power into the load at a given frequency and if so, what is the optimum length? [**Hint:** maximum power will be transmitted into a load when the source impedance is equal to the load impedance.]

(h) What does the result of (g) suggest about the frequency response of a system in which sound is conducted by means of a tube from a source to your ear? How might the frequency response be smoothed out?

(i) Explain why the sound power radiated by a speaker into an open ended tube varies more strongly with frequency at low frequencies than at high frequencies.

1.48 A loudspeaker mounted in one end of a uniform, 150mm diameter tube, open at the opposite end, is modelled as a rigid piston of infinite internal impedance, driven at a fixed amplitude at 250Hz. The radiation impedance of the open end of the tube (mounted in a large baffle) of diameter $2a$ may be approximated as:

$$Z_r = (\rho c \pi a^2)[(ka)^2/2 + \mathrm{j}0.8ka]$$

Qualitatively describe why the sound power output of the loudspeaker depends on the tube length and find the length of tube which will maximise the power output.

1.49 (a) Describe how a standing wave tube is used to determine the normal specific acoustic impedance of a solid. Derive the appropriate equations as part of your answer.

(b) Results of a measurement in a standing wave tube were: SWR = 4.2, maximum sound pressure level = 70dB and 1st minimum in standing wave = 0.4 wavelengths from the surface of the sample.

(i) What is the normal specific acoustic impedance of the material
(ii) What is the normal incidence sound power reflection coefficient of the material?
(iii) What is the absorption coefficient of the material?
(iv) What is the sound intensity at the surface of the material? If the tube is rigid walled, will this vary along the tube? Explain your answer.
(v) How far apart would successive minima be in the standing wave if the frequency were 200Hz?

1.50 (a) Demonstrate mathematically that the sound intensity is independent of distance in an impedance tube terminated by a test sample of arbitrary specific acoustic impedance, assuming no losses in propagation along the tube.

[**Hint**: The sound field is made up of two plane waves travelling in opposite directions.]

(b) Explain why the sound intensity in such a tube cannot be determined from a single microphone output.

(c) Explain how in principle two identical microphones can be used to measure the intensity in the tube.

1.51 The plane wave reflection coefficient for normally incident waves reflected from a plane surface of specific acoustic impedance Z_s is given by:

$$R_p = \frac{Z_s - \rho c}{Z_s + \rho c}$$

(a) Show that the absorption coefficient (fraction of incident energy absorbed and equal to ($\alpha = 1 - |R_p|^2$)) of the surface is given by:

$$\alpha = \frac{4\rho c \,\mathrm{Re}\{Z_s\}}{|Z_s + \rho c|^2}$$

Hint: express $|Z_s + \rho c|^2$ as $[\mathrm{Re}\{Z_s\} + \rho c]^2 + [\mathrm{Im}\{Z_s\}]^2$

(b) What value of Z_s gives the highest absorption coefficient?

1.52 (a) Show that the sound power reflection coefficient for sound impinging normally on the interface between two fluids of characteristic impedance $\rho_1 c_1$ and $\rho_2 c_2$ respectively is

$$|R_p|^2 = \left[\frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}\right]^2$$

(b) Repeat the calculation of (a) for a plane wave incident at an angle of θ measured from the normal to the interface.

1.53 A pressure release boundary (such as the surface of the ocean for an acoustic wave in the ocean) is characterised by zero acoustic pressure.

(a) Show that for a plane wave propagating in a semi-infinite medium and reflected normally from a pressure release boundary (with its normal along the y-axis), the total acoustic pressure anywhere in the sound field is

$$p_T = 2\mathrm{j} A_i \sin ky \, \mathrm{e}^{\mathrm{j}\omega t}$$

where A_i is the amplitude of the incident wave and y is the normal distance from the boundary.

(b) Explain why (referring to characteristic impedance) the amplitude of a wave reflected from the surface back into the ocean may be considered approximately similar in amplitude to the ocean propagating incident wave.

(c) Show that the particle velocity amplitude on a pressure release surface is twice that of the incident wave.

1.54 (a) A sound wave in air with a frequency of 500Hz and a pressure level of 60dB re 20μPa is normally incident on a boundary between air and a second medium having a characteristic impedance of ρc = 830 MKS rayls. Calculate the r.m.s. pressure amplitudes of the incident and reflected waves.

(b) For what angle of incidence will the sound be totally reflected for the conditions specified in part (a)?

1.55 Consider a plane wave propagating through the atmosphere into the ocean. Assume that the characteristic impedance of the atmosphere is ρc and that of the ocean is $\rho_w c_w$. At the interface between the sea surface and the atmosphere, the acoustic pressure and normal component of the particle displacement must be the same in the air as it is in the water. On striking the water, some of the sound wave energy will be reflected and some will be transmitted into the water.

(a) If the sound wave strikes the water at an angle θ to the normal to the surface and the wave transmitted into the water is at an angle ψ to the normal to the surface, derive an expression for the ratio of the pressure amplitude of the reflected wave divided by the amplitude of the incident wave (pressure reflection coefficient). **Hint**: The trace wavelength in air must equal that in the water so according to Snells law:

$$\frac{\sin\theta}{c} = \frac{\sin\psi}{c_w}$$

where c and c_w = speed of sound in air and water respectively.

(b) Derive an expression for the ratio of the intensity of the transmitted wave to the intensity of the incident wave (transmission coefficient).

(c) Given an angle of incidence θ = 10° for the sound wave, calculate the numerical values of the pressure reflection and transmission coefficients.

(d) What is the incidence angle above which all the acoustic energy will be reflected?

(e) Discuss the significance of the answer to (d) in terms of the amount of sound power entering the water from a helicopter as it climbs from the surface of the water.

(f) Derive an expression for the velocity reflection coefficient.

1.56 A bubble in the ocean acts as a small resonator having a characteristic resonance frequency determined by its size and local hydrostatic pressure.

(a) Derive a simple relationship for the bubble acoustic pressure in terms of the bubble radius r and the surface acceleration, a. [**Hint:** Use the spherical wave specific acoustic impedance and assume $kr \ll 1$ at the bubble surface].

(b) Assuming adiabatic compression (PV^{γ} = Const.), relate the surface acceleration to the variation in bubble volume. [**Hint:** the hydrostatic pressure in this problem is used like atmospheric pressure in an atmospheric acoustics problem].

(c) Show that the resonance frequency of the bubble is

$$f = \frac{c}{2\pi}\frac{\sqrt{3}}{r}$$

where c is the speed of sound in air.

(d) Comment on the effectiveness of a bubble screen as a sound absorber.

2

Problems relating to the Human Ear

2.1 (a) Given that 1 atmosphere equals 101.3×10^3 Pa, and that the minimum audible sound is equivalent to 20×10^{-6} Pa, what would the variation in height of a water column equivalent to 1 atmosphere have to be to simulate this pressure at the bottom of the column?

(b) Given that the maximum level at the threshold of pain is 120dB above the threshold of hearing, what would be the corresponding variation in column height?

(c) If the minimum audible sound corresponds to zero sound pressure level at about 4kHz, how much greater in pressure amplitude is the minimum audible sound at 31.5Hz?

(d) What is the gain, in decibels, provided by the mechanical linkage of the middle ear?

2.2 The pinna of the human ear is of the order of 70mm in major dimension, while that of the mouse is of the order of 7mm.

(a) Assuming that the physical dimensions of the ear of the mouse are scaled relative to that of humans in the same proportion, what does that suggest about the frequency range of hearing of the mouse?

(b) As the basic transduction mechanism, the hair cell, is probably the same in both mouse and human, what is implied about the sound pressure sensitivity of the mouse? (Hint: treat the ear as a simple microphone - see Ch. 3.)

(c) Contrary to the conclusion of (b), the mouse's ear is probably as sensitive in its frequency range as that of a human. What is implied about the mouse's transduction mechanism?

(d) In other words, would you expect significant morphological differences in the physical dimensions of the mouse's ear relative to that of a human ear?

(e) If your answer to (d) is yes, where would you expect to find significant differences in relative dimensions?

2.3 The minimum audible field (MAF) is determined as a frontally presented sound which is just audible. However, due to diffraction effects associated with the pinna, the ear is more sensitive to lateral presentation of a 1.0kHz tone by 5dB and a 6kHz tone by 10dB than when frontally presented.

(a) What does this suggest about the threshold of hearing, as determined using earmuffs? The latter threshold is known as the minimum audible pressure (MAP).

(b) The transformation of sound pressure from the free field (in the absence of the auditor) to the human eardrum is highly variable, being dependent upon frequency and direction of presentation. Variations as large as +21dB and -16dB have been observed. In a diffuse field, in which sound travels in all directions with equal probability, how would you expect the threshold for the minimum diffuse field (MDF) to compare with the MAF and MAP?

2.4 What are the first symptoms of the onset of noise induced hearing loss? What physical damage is responsible for the first symptoms and later on, the more advanced symptoms? Why is a conventional hearing aid not much help?

2.5 If you suffer from a temporary auditory threshold shift after attending a rock concert, does this mean that you have permanent hearing damage?

2.6 Describe how your ear and brain determine pitch and loudness with reference to the low, mid and high frequency ranges.

2.7 As suggested in the text, the ear performs a continuous frequency analysis on any signal that it receives, converting spectral amplitude information into digital pulses which it transmits by way of the auditory nerve to the brain for interpretation as sound. In the process, phase relationships between the various frequency components appears to have been discarded.

(a) Two signals presented separately through a single speaker may look quite different when measured with a microphone and displayed on an oscilloscope, but sound exactly the same to a listener. Explain the phenomenon.

(b) Two signals from a single source but transmitted to a listener over two paths of different lengths may be distinguished as separate sounds if one is sufficiently delayed with respect to the other. However, if the delay is sufficiently short, a single sound will be heard. The cross over time from one type of perception to the other is about 0.05 seconds. Explain how this is related to the lowest frequency that we hear as a tone rather than as a sequence of auditory events.

(c) In the design of an auditorium, sound reinforcement is achieved by reflection; however, echoes are highly undesirable and are to be avoided. Explain how the dimensions of an auditorium are thus defined.

2.8 (a) In view of the way in which the ear hears would you recommend a high frequency or a low frequency warning device for use in an environment characterised by intense noise in the 500Hz octave band? Explain.

(b) Speech sounds radiate forward more effectively than they do to the rear of the head. For normal speech of a male speaker the octave band levels shown in the table at 2m may be typical.

For speech recognition the bands <u>above</u> 250Hz and <u>below</u>

8000Hz are most important.

Convert the octave band levels shown in the table to sones and phons.

Octave Band Centre Frequency (Hz)	63	125	250	500	1k	2k	4k	8k
Forward	40	44	49	54	56	55	45	33
Side	39	43	47	51	53	49	39	27
Rear	38	42	44	48	49	44	27	15

(c) In a quiet environment, would a young, normal person without hearing loss be able to understand the speaker of 2.8(b) at 2 metres whatever the speaker's orientation relative to the listener?

(d) If the speaker of 2.8(b) moves to 10m what will the situation be?

(e) If masking noise just allows speech recognition when the speaker looks toward the listener at 2m, but does not allow speech recognition when the speaker's back is presented to the listener, will the situation be improved if the speaker speaks twice as loudly?

2.9 How loud (dB sound pressure level) would a single frequency noise at 630Hz need to be so that it could be heard at the same time as a single frequency noise at 60dB sound pressure level at 800Hz.

3

Problems relating to instrumentation and measurement

3.1 (a) Define the microphone pressure, free-field and random incidence responses and explain the relationship between them.

(b) Give examples to illustrate measurements for which each microphone type is most suited. Briefly state the reason in each case.

3.2 A condenser microphone has a nominal sensitivity of -26dB re 1V/Pa and when mounted on a sound level meter the system has a lower limit for signal detection set by internal circuitry noise of -110dB re 1V.

(a) If the sound level meter reads 13dB re 20μPa in the presence of a 1000Hz pure tone, what is the true sound pressure level of the tone?

(b) How much more or less sensitive is the human ear than this microphone for detection of a 2kHz tone in free field?

3.3 A free field microphone has the following calibration data:
Pressure sensitivity at 250Hz: -25dB re 1V per pascal.

The free field response at 0° incidence and 10kHz is +4.5dB relative to 250Hz.

Free field and random incidence corrections at 10kHz are:-

Angle of incidence	0°	80°	180°	Random
Correction (dB)	+5	+1	-0.2	1.5

Find:

(a) the pressure sensitivity at 250Hz expressed in volts per pascal;

(b) the pressure sensitivity at 10kHz expressed in dB re 1V per pascal;

(c) the overall sensitivity when measuring a 0° incident sound field

(d) the overall sensitivity in highly reverberant enclosures at 10kHz;

(e) the free field sensitivity at 180° incidence at 250Hz and 10kHz.

3.4 Explain how the concepts of *MAF, MAP* and *MDF* are similar and dissimilar to the corresponding calibration of a microphone.

3.5 Why is a microphone with flat response to random incidence sound often used to measure industrial noise rather than a microphone with a flat response to normally incident sound? How would the random incidence microphone best be orientated to minimise measurement error?

3.6 What would be the effect of connecting a condenser microphone to a low impedance amplifier input?

3.7 Explain why the A-weighting network is used in evaluating noise levels and comment on its validity for evaluation of industrial noise exposure. Discuss the advantages and limitations of A-weighted sound levels for characterising noisy equipment and workplaces.

3.8 (a) Given the following octave band noise measurements in dB, calculate the overall level in dB(A) and in linear (dB).

Octave band Centre Frequency	63	125	250	500	1k	2k	4k
SPL (dB)	95	93	90	87	80	80	82

(b) What is the main source of error that is likely to occur using this method to calculate dB(A) rather than using a filter in the measuring circuit. How would you get an approximate idea of the maximum error involved?

3.9 Measured sound pressure levels in dB re 20μPa for the octave bands between and including 63Hz and 8kHz are 76, 71, 68, 70, 73, 76, 79, 80. Calculate the overall A-weighted sound pressure level. Estimate the maximum possible difference between your calculation and what would be measured on a sound level meter using an overall A-weighting network. Would this spectrum sound hissy, neutral or rumbly?

3.10 The sound pressure levels measured at a particular location in a noisy factory with and without one particular machine operating are given in the table below in octave bands. Calculate the noise level (in dB(A)) due to the machine alone.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k	4k
Machine on	98	94	90	90	86.5	84.2	76.1
Machine off	97	90	85	88	83	80.1	74

3.11 (a) Calculate the A-weighted noise level, given the following unweighted band levels. Levels in frequency bands not specified may be ignored.

Octave band centre frequency	125	250	500
Sound pressure level (dB)	94	91	87

(b) Why is this not an ideal way to determine the A-weighted noise level?

3.12 What are the unweighted octave band levels (for a signal with a flat spectrum level) in the range 63Hz to 8kHz which give an overall A-weighted level of 105dB(A)? Spectrum level is the level in a frequency band 1Hz wide.

3.13 Explain what equal loudness contours are and how they are used as a basis for the A-weighted decibel scale. Explain why the A-weighted scale may not provide an accurate measure of the apparent loudness of industrial noise.

3.14 Write brief notes on the following:

(a) The effect of the proximity of the observer and instrument case on sound level meter (SLM) measurements.

(b) The `slow/fast response' control of the SLM.

(c) The `frontal/diffuse' control of the SLM.

3.15 A tonal noise at 250Hz varied over a period of 8 hours with its rms pressure as a function of time given by,
$p = (t^2 + 8t + 4) \times 10^{-2}$ Pascals (t is in hours). Calculate the A-weighted value of L_{eq}.

3.16 Why is L_{Aeq} the quantity generally used to describe the level of a time varying noise? Calculate the L_{Aeq} of a noise which is 80dB(A) for 15 minutes, 70dB(A) for 2 hours, 90dB(A) for 2 hours, 99dB(A) for 5 minutes and 75dB(A) for 4 hours.

3.17 If noise measurements are being taken in support of a legal case, why would you use a sound level meter on site, rather than a tape recording which you could analyse at your leisure?

3.18 Describe the sources of error that could affect noise level measurements made with a sound level meter. Describe how you could minimise the effects of wind noise on an outdoor sound measurement taken with a Sound Level Meter.

3.19 (a) Outline the operating principle of the two-microphone Sound

Intensity Meter.

(b) Explain the limitations of the two-microphone system:

(i) at low frequencies

(ii) at high frequencies

(iii) in very reactive sound fields and

(iv) in sound power measurements with external noise sources.

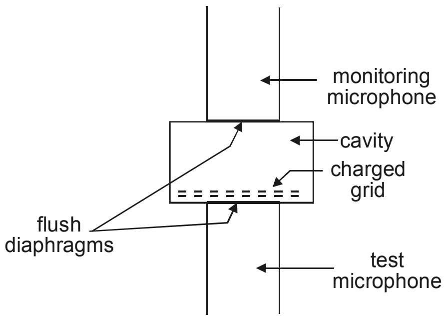
3.20 (a) Outline the theory behind sound intensity measurement.

(b) List likely sources of measurement error.

(c) List some applications.

(d) Give a summary of the equipment available and describe two different techniques to determine acoustic particle velocity.

(e) Give a list of steps involved in taking an intensity measurement to determine the sound power output of a compressor.



3.21 The acoustic coupler shown in the figure at right can be used to determine the internal impedance of a condenser type test microphone. An alternating charge applied to the charged grid mounted very close to the test microphone causes the test microphone diaphragm to move back and forth as if it were subjected to an alternating sound pressure field. The motion of the test microphone diaphragm in turn causes a sound pressure fluctuation in the cavity which is measured by the monitoring microphone. Comparing the output of the monitoring microphone with the expected output resulting from a given alternating charge on the grid, allows the test microphone pressure calibration to be completed, and the mechanical input impedance of the test microphone to be determined.

For the coupler shown in the figure, the microphone diameters are 12mm, the cylindrical cavity diameter is 20mm and the cavity length is 10mm.

(a) What is the r.m.s. force induced by the electrostatic grid on the test microphone if its output is equivalent to a sound pressure level of 95dB, at 500Hz?

(b) What is the r.m.s. velocity of the diaphragm? Hint: Use equation 9.17 in your text.

(c) The sound pressure in the cavity as read by the monitoring microphone is 65dB. What is the volume displacement?

(d) What is the mechanical input impedance of the test microphone where the latter quantity is defined as the ratio of the excitation force divided by the diaphragm velocity?

(e) If the monitoring microphone is of identical design to the test microphone, is its volume change during the measurement important?

(f) What limits the upper frequency that may be tested with the proposed arrangement?

4

Problems relating to criteria

4.1 What is the allowable time of exposure to a noise level of L_{Aeq} = 99dB(A) using

(a) European criteria

(b) USA criteria

4.2 Given the measured 1/3 octave band sound pressure levels in the table below, calculate the following, assuming that noise levels at other frequencies are insignificant:

1/3 octave band centre frequency (Hz)	250	500	1000
L_p (dB)	95	97	99

(a) the A-weighted sound pressure level.

(b) the allowed daily exposure time for a person exposed to the noise in Australia and in the USA.

4.3 As well as being exposed to noise originating from her own machine, the operator of circular saw is exposed to the fan noise from the wood dust removal duct attached to her saw. With the saw shut down, the fan noise is 91dB(A). With the fan shut down, the saw noise is 88dB(A) during idling and averages 93dB(A) during cutting. Assuming that the saw cuts wood for 20% of the time, what is the required fan noise reduction to ensure that the operator's noise exposure satisfies

(a) European criteria, (90dB(A) for 8 hours)

(b) USA criteria.

4.4 A foreman in an Australian factory operates for 2 hours each day a machine that produces 95dB(A) sound pressure level at the operator position. For the rest of the 8-hour day the foreman is in an office where the sound pressure level is 70dB(A).

(a) Calculate the foreman's equivalent continuous sound level averaged over 8 hours.

(d) Calculate the foreman's A-weighted sound exposure level (8-hour).

(e) What is the maximum number of hours per day that the foreman could use the machine and still maintain a noise dose of 1.0 or less.

(f) If the level at the operator location of the machine is 91dB(A) with the machine switched off, what is the sound pressure level due to the machine only.

4.5 If crossing the hearing loss criterion of figure 4.3 in the text puts the rock band player who stands in front of the loudspeakers in the class with old folk's who can't hear the punch line, how old will he be when he joins the old folk's if he begins his exposure at age 20? Assume that he is exposed for 1900 hours each year to a level of 110dB(A).

4.6 (a) If a disco band plays at an average level of 105dB(A) for 4.5 hours each evening and recorded music plays at 95dB(A) for 1.5 hours while the band takes breaks, what is the average $L_{Aeq,8\text{h}}$ exposure level suffered by the employees? Assume any other exposure is to levels less than 80dB(A).
Use both European and USA exposure criteria rules.

(b) Assuming the same ratio of live to recorded music time, how long are employees permitted to work if their eight hour equivalent level is not to exceed 90dB(A)? Use both European and USA exposure criteria rules.

4.7 (a) Calculate the HDI for a person exposed to the following sound pressure levels for an average of 1900 hours per year.
85dB(A) for 5 years, 90dB(A) for 3 years, 95dB(A) for 6 years, 100dB(A) for 1 year and 80dB(A) for 10 years.

(b) What is the person's percentage risk of developing a median loss corresponding to the person's calculated HDI?

4.8 Calculate the daily noise dose for an employee who works 8 hours per day and spends 30% of the time in an environment of 85dB(A), 20% at 88dB(A) 25% at 91dB(A) and 25% at 96dB(A). Use:

(a) USA criteria; and

(b) European criteria.

By how much would the work day of the employee need to be reduced to meet each of the regulations, assuming the percentage of time in each environment remained unchanged?

4.9 A punch press operator is subjected to impact noise each time the punch impacts the work piece. The press is capable of 80 impacts per minute and operates for approximately 60% of the eight hour day. If the peak sound pressure level measured at the operator position is 125dB and the B duration of the impact is 100 milli-seconds, will the operator be overexposed according to

(a) the United States criteria,

(b) the European criteria.

If the operator is overexposed, then by how much in each case does the working day need to decrease, or alternatively by how much would the peak sound pressure level need to be reduced, assuming the B duration remained the same? Use both methods for your calculation of noise dose; that is, ratio of number of impulses to allowable number and difference between actual peak noise level and allowable peak noise level.

Assume that the ambient noise level during the 40% of the day that the press is not operating is 85dB(A), and assume that the allowable level is 90dB(A) for 8 hours.

4.10 (a) What is the noise dose (using both USA and European criteria) of an employee exposed during an 8 hour work day only to impact noise consisting of a total of 40,000 impacts with a peak sound pressure level of 135dB? (Each impact takes 60 milli-seconds to fall 20dB below the peak level; the average ambient noise level between impacts is 87dB(A)).
(b) By how much would the number of impacts have to be reduced to result in a DND (daily noise dose) of 1 using USA criteria and European criteria?

4.11 What voice level is expected (give a range) and required if a talker is to make himself understood to someone 3 metres away in a noise environment of 75dB(A)?

4.12 If two people wish to communicate over a distance of 2m in an environment where the background noise level is 70dB(A), will they need to shout to be heard? Will they need to talk more loudly than they expect based on their interpretation of the noise environment? What if their separation distance were 0.5m? Would they talk too loudly or too softly?

4.13 Noise Criteria curves are designed for evaluating noise spectra which have been frequency averaged over an octave band. How would you evaluate the NC or RC value of a noise spectrum presented as 1/3 octave band levels.

4.14 Explain why overall dB(A) numbers for noise level specification and control are inadequate. What is a preferable method for these tasks? What are single, overall dB(A) numbers good for and why?

4.15 Noise was measured at a location in a factory and resulted in the octave band spectrum levels in the table below.

Frequency (Hz)	63	125	250	500	1k	2k	4k	8k

L_p (dB re 20µPa)	100	101	97	91	90	88	86	81

(a) Calculate the A-weighted overall sound pressure level.

(b) How many hours would a UK employee be permitted to work at this location?

(c) What is the NR level of the noise?

(d) What is the loudness level in Phons and Sones?

(e) When one noisy machine is turned off, the A-weighted sound level at the measurement location dropped by 1.5dB(A). What was the contribution (in dB(A)) of this machine to the noise level at the measurement location?

4.16 The octave band noise spectrum in the table below represents ambient noise levels due to an air conditioning system in a small church.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k	4k	8k
L_p (dB re 20µPa)	48	48	43	38	30	20	16	12

(a) Is the system sufficiently quiet? Hint: Calculate the NC and NCB values of the spectrum.

(b) Will it sound rumbly, hissy or well balanced (neutral)?

(c) What would be the optimum spectrum levels for producing a bland masking noise of a suitable level to mask the air conditioning system noise?

4.17 The sound levels measured in octave bands in an office space are listed in the table below.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k	4k	8k
L_p	55	49	43	37	33	33	32	30

(a) Determine the NCB number of the noise.

(b) Does the noise sound rumbly or hissy? Explain how you arrived at your answer.

4.18 The estimated noise levels at the boundary of a proposed new factory are given below for each octave band shown.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k	4k	8k
L_p (dB re 20μPa)	60	55	55	50	55	55	50	45

(a) Calculate the A-weighted sound level and NR rating

(b) Would the noise sound rumbly, hissy or neutral?

(c) If the surrounding neighbourhood is described as "residences bordering an industrial area" and the noise is characterised by just detectable tones what public reaction may be expected throughout the day, evening and night? (Use A-weighted criteria.)

(d) The noise reductions (in dB) between the inside and outside of a typical house with closed windows may be assumed to be as listed in the table below:

Octave band centre frequency (Hz)	63	125	250	500	1k	2k	4k	8k
Expected noise reduction (dB)	5	5	8	10	14	16	20	21

What public reaction may be expected in cold weather when people generally have their windows closed? What would be the effect of warm weather, on public reaction to the noise, when people may be expected to open their windows? The increase in interior noise levels (in dB) due to open windows may be taken as 5dB for all octave bands between 63Hz and 8kHz. (Use NR criteria).

(e) Should the factory be built? If so should its hours of operation be restricted? What would be your conclusion if the noise only occurred 25% of the time?

4.19 An old bus terminal located in a light commercial area bordering a residential area is considered for use as a long distance truck terminal which will operate 24 hours per day, every day. Noise levels on the boundary of the terminal are expected to be as high as 65dB(A). Estimate the expected community response to the proposed use of the site.

5

Problems relating to sound sources and outdoor sound propagation

5.1 A simple point source of sound radiates spherical waves into free space at 400Hz with a power of 10mWatts. Calculate at a distance of 0.5m (where applicable) from the source:

(a) the sound intensity

(b) the acoustic pressure amplitude

(c) the acoustic particle velocity amplitude, after showing that it is related to the acoustic pressure by:

$$\frac{|p|}{\rho c} \left| 1 - \frac{j}{kr} \right|$$

You may start with the potential function solution of the wave equation for harmonic spherical waves.

(d) the sound pressure level

(e) the sound power level

(f) the source strength (rms volume flux at the source surface).

5.2 (a) A simple source in free field radiating at a frequency of 100Hz produces a sound pressure level of 110dB re 20μPa at 1m. What is the sound pressure level at 10m?

(b) Evaluate the amplitude and phase (relative to the acoustic pressure) of the acoustic particle velocity at each of the two locations.

5.3 A spherical source of diameter 20mm is driven with an r.m.s. surface velocity of 0.5m/s. Calculate the acoustic power and sound power level radiated into the surrounding air for excitation at 100Hz and 800Hz.

5.4 A pulsating sphere of radius 0.01m has a radial surface displacement which varies harmonically at 50Hz with a surface velocity magnitude of 0.1m/s.

(a) Calculate the magnitude of the pressure fluctuations generated at a distance of 10m from the centre of the sphere.

(b) Calculate the phase difference between the radial acoustic particle velocity and acoustic pressure at 0.5m and 10m from the centre of the sphere and comment on the difference in the two results.

5.5 A simple source of radius, a, radiates single frequency sound of frequency ω into a free field in which the speed of sound is c. Show that the radiation impedance per unit area at the surface of the source due to fluid loading is given by:

$$Z_R = \rho c \left(\frac{\omega^2 a^2 + \mathrm{j}\omega a c}{c^2 + \omega^2 a^2} \right)$$

5.6 By matching the radial particle velocity adjacent to a spherical pulsating source with the velocity of the surface of the source ($U e^{\mathrm{j}\omega t}$), show that for a source of radius a, and for sound having a wavelength which is large compared with a, the radiated sound power is given by:

$$W = 2\pi \rho c k^2 a^4 |U|^2$$

where $k = \omega / c$.

5.7 The wave equation in terms of the acoustic potential function φ in spherical coordinates is as follows.

$$\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)\right.$$

$$\left.+\frac{1}{r^2\sin^2\theta}\frac{\partial^2}{\partial\psi^2}\right]\varphi - \frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} = 0$$

(a) Show that the potential function given by equation 5.25 in the text is an approximate solution which becomes exact at great distance from the origin

(b) Verify that equations 5.32 and 5.33 in the text are solutions of the spherical wave equation. [**Hint:** Use equations 1.6 and 1.7 in the text to first find an expression for the acoustic potential function.]

5.8 Show that equation 1.35 is a solution of the spherical wave equation given in the previous problem.

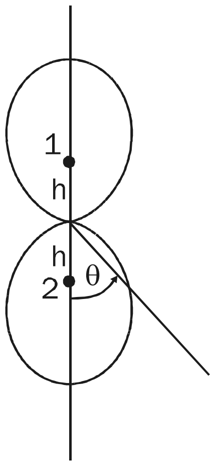
5.9 A monopole source which forms one half of a dipole radiates 0.5watts of acoustic power at 250Hz. What acoustic power and sound power level is produced by the dipole if the separation between the two sources making it up is 0.08m?

5.10 The sound field at a radial distance r from a harmonic point monopole source of complex strength q can be written as:

$$p(r) = \frac{j\omega\rho q\,e^{-jkr}}{4\pi r}$$

Two such sources are separated by a distance $2h$. One (of strength q_2) is adjusted in order to produce zero sound pressure in the far field of the two sources at angular location θ_0. Making clear any assumptions, show that the sound field produced by the source combination can be written as:

$$p(r,\theta) = p_1(r,\theta)\left[1 - e^{-2jkh(\cos\theta_0 - \cos\theta)}\right]$$



where $p_1(r,\theta)$ is the sound field radiated by the source of complex strength q_1. Draw a sketch of the far field pressure amplitude distribution produced when $kh << 1$ and $\theta_0 = 90°$. (The angle θ is that made between the axis of the two sources and the line joining the field point to the centre of the source axis as shown in the figure).

5.11 Calculate the following for a dipole source made up of two simple sources which, on their own, radiate 10mW each, and which are separated by 5mm. Frequency = 500Hz.

(a) The intensity at 0.5m from the source and in a direction, $\theta = 45°$ (θ is measured from the dipole axis and is defined in Fig. 5.2 of the text).

(b) The sound pressure level at the same point.

(c) If the dipole source were a vibrating sphere what would be the r.m.s. force required in Newtons to drive the sphere?

5.12 Three speakers are mounted in line and flush with a rigid concrete floor out in the open away from any other reflecting surfaces. All three speakers are very small compared with the wavelength of sound they radiate. The distance between the centres of adjacent speakers is 0.1m. Calculate the expected sound pressure level at a height of 1m above the floor and a horizontal distance of 20m from the centre speaker at an azimuthal angle of 30° from the line connecting the three speakers for the following cases (ignore air absorption and meteorological effects).

(a) A 125Hz pure tone from the same source is fed to all three speakers such that centre speaker is 180° out of phase with 2 outer ones (which are in phase). The centre speaker (in isolation) radiates 1 watt and the two outer speakers (in isolation) each radiate 0.5 watts of sound.

(b) All three speakers are fed 125Hz one third octave band random noise and each (in isolation) radiate 0.5 watts of sound power.

5.13 You wish to reduce a 250Hz tonal noise emerging from an access hole where wood is fed into a planer machine by introducing a speaker arranged such that it produces the same noise level (but 180 degrees out of phase).

(a) Assuming that the centre of the speaker is 0.2m above the centre of the access hole and in the same plane, calculate the maximum noise reduction which can be achieved at 5m from the hole along the normal axis to the centre of the hole.

(b) What would be the improvement if 2 speakers were used and arranged with the access hole to form a longitudinal quadrupole noise source?

5.14 Discuss the physical significance of the difference between equations 5.62 and 5.70 in the text and thus with the aid of equation 5.65, deduce an expression for the sound pressure squared radiated by a finite coherent line source.

5.15 The sound power radiated from a 20m length of pipe, located 2m above ground level, in the 500Hz octave band is estimated to be 130dB and to consist only of random noise components due to turbulent fluid flow.

Calculate the sound pressure level at 80m from the centre of the pipe in a horizontal direction. Assume a ground reflection loss of 3dB. What would the difference be if the same power were radiated from a 200m length of pipe?

5.16 A pipe of length 50m is radiating uncorrelated noise to a community at a distance of 200m in a direction normal to the centre of the pipe. The sound field generated by the pipe has a directivity of two in the direction of the community.

If the sound power radiated by the pipe in the 2kHz octave band is 2 watts, calculate the sound pressure level (in dB re 20μPa) in the community for the 2kHz octave band. Include the effects of air absorption but ignore other atmospheric effects. Assume that the sound intensity loss due to ground reflection is 2dB, and that the pipe is 2m above the ground. Atmospheric temperature is 15°C and relative humidity is 25%. Assume no obstacles exist between the pipe and the community and assume incoherent combination of the direct and ground reflected waves.

5.17 Assume that a line of traffic on a freeway can be modelled on average as a line source with an average separation distance of 6 meters between sources and an average source pressure level of 88dB(A) at one meter. What will be the sound pressure level at 50 meters from the road? (Assume that ground and atmospheric effects are negligible).

5.18 A line of traffic is radiating sound into the community. The nearest residence is 250 m away. The average sound power of each vehicle is 2 Watts in the 500 Hz octave band. and the average vehicle spacing is 7 metres. Assuming that only noise in the 500 Hz octave band is of interest, calculate the sound pressure level at the nearest residence if the ground surface between the road and the residence is concrete. Assume a community location 1.5 m above the ground and a vehicle acoustic centre 0.5 m above the ground. State any other assumptions that you make.

5.19 A speaker has a radiation pattern given by the following equation where the angle θ measured from the axis of the speaker varies from -π/2 to π/2 radians (no radiation from speaker back):

$$I = (\overline{p}_o^2 / 3\rho c r^2)\,(2 + \cos\theta)$$

In the equation I is the intensity, $\overline{p}_o^2$ is the mean square acoustic pressure on axis at 1 metre, r is the distance in metres from the effective centre of the source and ρc is the characteristic impedance of air equal to 412kg m^{-2}s^{-1} for this problem. Assume that the speaker only radiates into half space.

(a) What is the sound power radiated by the speaker when placed well away from any reflecting surfaces?

(b) What is the sound power radiated by the speaker if it is a constant volume source, and it is mounted flush in a hard extended surface (wall) with its axis normal to the surface and outward?

(c) If the speaker is mounted as in (b) above but it is assumed to be a constant pressure source, what is the sound power radiated?

5.20 (a) Describe in general terms how the expression for the acoustic pressure at a distance r from a monopole source in free space can be used to calculate the pressure field due to a piston harmonically moving in and out of an infinite baffle.

(b) The far-field complex pressure due to such a piston of radius a and volume velocity U is given by:

$$p(r,\theta) = \frac{j\omega\rho_o U}{2\pi r}\, e^{-jkr} \left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right]$$

Sketch the variation of $2J_1(x)/x$ with the parameter x.

Hence sketch the polar directivity patterns of a piston of radius 0.1m being driven at a frequency of

(i) 500Hz,

(ii) 2.5kHz and

(iii) 10kHz.

5.21 (a) A rigid circular piston of area S radiates sound of frequency ω from a co-planar baffle into a uniform fluid where the speed of sound is c. Show that for small ω, the radiation resistance (or mechanical resistance) due to fluid loading on the piston is:

$$R_R = \rho c S^2 \omega^2 / (2\pi c^2)$$

(b) What is the piston radiation efficiency for small ω?

(c) Show graphically how the radiation efficiency varies with frequency.

5.22 A piston is mounted so as to radiate on one side of an infinite baffle into air. The radius of the piston is a, and it is driven at a frequency such that the wavelength of the radiated sound is πa.

(a) If the radius $a = 0.1$m and the maximum displacement amplitude of the piston is 0.0002m, how much acoustic power is radiated.

(b) What is the axial intensity at a distance of 2m?

(c) What is the radiation mass loading acting on the piston?

(d) What is the SPL on axis at 2m?

5.23 A square opening of 200mm on a side is required for access into an enclosure containing a source of low frequency noise. Suppose that speakers could be mounted on either side of the opening with centres 205mm from the centre of the opening, and that they could be driven in antiphase and at half the amplitude of the sound issuing from the opening. The two speakers and the opening, as sound sources, would form a longitudinal quadrupole in the wall of the enclosure.

(a) Referring to the discussion of Chapter 5 determine the lengths L and h. Draw a picture and identify dimensions.

(b) Assume that with the speakers turned off, the sound power issuing from the opening is W and all wavelengths of interest are long compared to the dimensions of the opening. By how much in decibels will the sound power be reduced when the speakers are turned on in the octave bands 63Hz to 500Hz?

(c) When the speakers are turned on what will be the expected changes in sound pressure level at $\theta = 0$, $\pi/4$ and $\pi/2$ radians in the octave bands 63Hz and 125Hz? Describe the sound field?

5.24 The sound power radiated by a small source in free space is 120dB. When the source is placed on a concrete floor, the sound pressure level at a particular location 10 metres away is measured as 110dB. What is the directivity index (dB) of the source in the direction of the measurement point due to:

(a) the location of the source on the floor.

(b) the non uniform radiation characteristics of the source.

5.25 An enclosure surrounding some noisy machinery has a square opening 0.5m × 0.5m in the centre of one of the sides which has dimensions 4m × 4m. The average sound intensity over the opening is 0.01W/m^2 in each of the 125Hz and 2kHz octave bands. What would be the sound pressure level in each of these octave bands on-axis and 25m from the opening? Assume a hard ground surface.

5.26 A square opening (3m × 3m) in the side of a building is leaking noise into the surrounding community. The internal room surfaces are sufficiently hard that the sound field incident at the opening may be considered diffuse. The centre of the opening is 3m above ground level. The closest community location is at a distance of 150m from the opening in a direction normal to the plane of the opening. The sound power radiated through the opening in the 2000Hz octave band is 2watts. The ground between the opening and the community is grass covered. The following questions refer only to the 2000Hz octave band.

(a) Calculate the sound power level L_w radiated through the opening.

(b) Calculate the excess attenuation A_g due to ground reflection for sound travelling from the opening to the nearest community location (1.5m above ground) (use Fig. 5.18 in your text).

(c) Calculate the loss due to atmospheric absorption (in dB). Assume RH = 25%, and a temperature of 20°C.

(d) Ignoring all other losses not mentioned above, calculate the sound pressure level at the community location of (b) above.

(e) If a second opening of the same size (and radiating the same power), with its centre horizontally 5m from the centre of the existing opening, were introduced, what would be the total sound pressure level at the community location of (b) above?

5.27 The propeller of a surface ship radiates underwater noise which is picked up by a submarine at a horizontal range of 10km. The submarine is 90m below the surface of the ocean and the propeller depth is 5m. Calculate the lowest frequency at which destructive interference (cancellation) occurs between the direct and surface reflected waves arriving at the submarine. Assume that there is no loss or phase shift on reflection from the surface of the ocean.

5.28 You specified an operator noise level for a machine of 85dB(A). However you forgot to specify where it would be located and the manufacturer claimed it met specification when mounted on a hard floor in a semi-anechoic room. In fact the manufacturer measured 84dB(A). In your factory the machine is located such that its effective acoustic centre is 2m from a wall and the operator is located 4m from the wall. If the noise is predominantly in the 500Hz to 2000Hz band, would you expect to measure 84dB(A) at the operators position? If so why? If not, why not and what would you expect?

5.29 (a) Explain the difference between specific acoustic impedance and characteristic impedance.

(b) The normal specific acoustic impedance of a surface is given by $Z_s = \rho c(2.0 - 3j)$. Determine the angle of incidence for maximum absorption and the maximum value of the absorption coefficient.

5.30 A window of area 1 m^2 in the side of a building has its centre 2 m above the ground and is radiating sound into the community. The nearest residence is 750 m away. The average sound intensity over the outside of the window is 0.1W/m^2 in the 500 Hz octave band.

Assuming that only noise in the 500 Hz octave band is of interest, calculate the sound pressure level at the nearest residence if the ground surface between the window and the residence is concrete. Assume a community location 1.5 m above the ground. State any other assumptions that you make.

5.31 A single frequency sound wave propagates in the x direction with a decaying pressure amplitude proportional to $e^{-\alpha x}$. Find the decibel decay rate (dB per unit distance) in terms of α. Describe the factors influencing α in the audio frequency range.

5.32 An aircraft in level flight, 600m above ground level, travelling at

400km/hr, approaches an observer on the ground. The atmosphere is still, and the sound speed falls off by 1m/s per 10m height. At what range does the aircraft emerge from the ground shadow?

6

Problems relating to sound power, its use and measurement

6.1 Consider the case of a constant pressure source of sound. This is the analog of the well known constant voltage source of electrical circuit theory.

(a) What will be the effect upon the radiated sound power of placing a constant pressure source adjacent to a large flat wall; at the junction of two walls; at the corner of three walls?

(b) Alternatively, if a source placed in a reverberant room at several locations chosen at random, produces a sound pressure level, averaged over all room positions, of L_p, what would you expect for the average reverberant field sound level for the source placed in the corner of the room, assuming (i) constant power (ii) constant volume-velocity and (iii) constant acoustic-pressure source types?

(c) Aerodynamic noise arises from the impingement of turbulent flow on some solid surface. Because of the turbulence, the force exerted by the fluid on the surface is unsteady, giving rise to a fluctuating pressure without motion of the surface. What type of source model would you use for this source and why?

6.2 (a) Describe the difference between sound power level and sound pressure level.

(b) Show how the equations $L_w = L_p + 10\log_{10}S$ and $W = \langle p^2 \rangle S/\rho c$ are equivalent.

(c) If the average sound pressure level at 2 metres from a machine on a hard floor is 85dB(A) what is the sound power level? State any assumptions.

(d) Which is the desirable quantity (sound pressure level or sound power level) to use when specifying equipment noise levels. Give reasons.

6.3 (a) Explain what is meant by the far field, geometric near field and hydrodynamic near field.

(b) For a source of largest dimension 1m, at what frequency will the hydrodynamic near field become negligible at a distance of 1m?

(c) At what distance from the source will the far field become dominant at the frequency of (b) above?

6.4 You have been commissioned to design a test facility to measure sound power levels radiated by an engine in octave bands from 63Hz to 8kHz. The engine dimensions are approximately 1.5m × 0.4m × 0.6m high. If you wish to take measurements using a "test" room, how large would the room need to be if it were

(a) an anechoic room, or

(b) a reverberant room?

6.5 A machine radiates sound approximately uniformly in all directions. When sitting on a hard concrete floor in the absence of other reflecting surfaces, it produces a sound pressure level of 70dB at 2m. Calculate its radiated power and its sound power level.

6.6 A hemisphere of 0.1m radius is mounted in a baffle large enough to be considered infinite and radiates spherical waves into water at a frequency of 250Hz. The measured sound pressure level at a distance of 2m from the centre of the hemisphere is 66dB re 20μPa.

(a) What is the r.m.s. acoustic pressure at this point?

(b) Is this location in the far field of the source?

(c) What is the acoustic intensity at this point?

(d) What is the total acoustic power radiated by the hemisphere?

(e) What is the peak displacement amplitude of the surface of the hemisphere?

6.7 Space average sound pressure levels measured in the reverberation room designed in question 6.4 above are respectively for the 63Hz to 8kHz octave bands 85, 105, 100, 90, 95, 98, 90, 88. If the corresponding room reverberation times (in seconds) are 8.1, 7.5, 5.5, 4.5, 3.5, 2.5, 2.0, 1.5, what are the corresponding octave band and overall sound power levels?

6.8 Calculate the average sound pressure level at 1m from a machine surface in the 500Hz octave band, given the following measurements at a number of individual locations.

Location number	1	2	3	4	5
Sound pressure level (dB) (500Hz octave band)	85	83	80	87	86

If the machine were 1m wide by 2m long by 1m high and rested on the floor, calculate the radiated sound power in dB re 10^{-12}W, assuming that the average of the 5 measurements is representative of the true average sound pressure 1m away from the machine surface.

6.9 A machine is located on the floor amongst other machines in a noisy factory of dimensions 20m × 20m × 5m with no acoustical treatment. You wish to measure the sound power level of the machine to compare with specifications. Measured sound pressure levels at a number of regularly spaced points over a cubic surface of area 40m^2 spaced 1m from the machine surface in the 500Hz octave band are:

85, 88, 86, 90, 84, 85, 87, 88, 89, 90, 90, 88, 87, 88, 89, 85.

Calculate the machine sound power level in the 500Hz octave band if the influence of nearby reflective surfaces is ignored and noise measurements corresponding to the above numbers with the machine turned off are:

80, 82, 80, 81, 80, 79, 81, 79, 80, 81, 83, 83, 82, 80, 80, 79

6.10 Measurements for the machine in problem 6.9 were taken on a second surface further from the machine and of area 120m^2. The average was found to be 2dB less than the average for the first test surface after the background noise effects due to other machinery had been subtracted. Calculate the machine sound power level using the two surface method.

6.11 A machine located in a building occupies an approximate rectangular volume 8m × 4m × 3m high. The space average sound pressure level at 1m from this rectangular surface is 86dB and at 3m from the surface it is 84dB in the 500Hz octave band. Calculate the room constant and the sound power level of the machine in the 500Hz octave band.

6.12 To determine the sound power level radiated by a machine in the 500Hz octave band in a building, two imaginary measurement surfaces surrounding the machine have been chosen, at distances of 0.5m and 2.5m from the machine surface respectively which was modelled as a rectangular box of dimensions 5m × 5m × 2m. The average noise level on both test surfaces with the machine turned off is 80dB in the 500Hz octave band. With the machine turned on the average sound pressure level on the smaller test surface is 90dB while that on the larger surface is determined from averaging the following measured values: 87, 87.5, 86, 85, 86.5, 88, 86.8, 87.2, 86, 85.8 and 85.3dB.

(a) What is the average noise level on each test surface due only to the machine?

(b) As the sound power is to be determined, what is the reverberant field correction in dB.

(c) What is the correction (in dB) for non-normal sound propagation?

(d) What is the sound power level of the machine in the 500Hz octave band?

6.13 The reverberant field level in an equipment room with all existing machinery running is 82dB(A). Three additional machines are to be installed and precautions are to be taken to ensure that the resulting new reverberant field level does not exceed 85dB(A). Proceed as follows:

(a) Calibrate a reference noise source outside the plant in an empty asphalt car park. The average sound pressure level at 3m is determined to be 75dB(A). What is the A-weighted sound power level of the reference sound source?

(b) With the reference source turned on and on the concrete floor in the equipment room, and with the room machinery turned off, the reverberant field level is 87dB(A). What is the sound power level of the existing machinery?

(c) What is the maximum sound power the three new machines together may produce?

(d) If the sound from each of the three new machines may be expected to be about equal, what is the upper bound on the A-weighted source power level of each which will allow the objective given above to be met?

6.14 Discuss the advantages and disadvantages of using sound intensity measurements rather than sound pressure measurements to determine

(a) the sound power radiated by noisy equipment

(b) the transmission loss of building partitions

(c) the localisation and identification of noise sources.

6.15 (a) Define the term, "radiation efficiency" in both physical and mathematical terms.

(b) Explain how published values may be used in practice to estimate the sound power radiated by machinery and to identify possible paths of sound transmission between rooms.

(c) Under what conditions is the radiation efficiency of a vibrating surface close to one?

6.16 A machine is made up of several flat panels and the sound power which is radiated by one particular panel of thickness 3mm and dimensions 1m × 1m is to be determined. The panel has a root mean square velocity averaged over the surface of 5mm/sec in the 500Hz octave band and 2mm/sec in each of the 250Hz and 1000Hz octave bands. Vibration levels in the other octave bands are negligible.

(a) Calculate the radiated sound power in each of the octave bands.

(b) Calculate the sound pressure level at 10 metres from the panel, on an axis normal to the panel which passes through the centre of the panel. Assume that the machine is on a concrete floor which extends a distance of 20m around it.

(c) Calculate the sound pressure level in dB(A) at the 10 metre location.

(d) What would be the approximate average r.m.s. panel accelerations in each of the octave bands?

7

Problems relating to sound in enclosed spaces

7.1 Define what is meant by "direct field" and "reverberant field"

7.2 Calculate the modal overlap in the 250Hz octave band for a room if there are four resonant modes, in the 250Hz band, with bandwidths (3dB below the peak) of 20Hz, 25Hz, 30Hz and 32Hz respectively.

7.3 A simple point monopole source is located in a rectangular room at (0**i**, 0**j**, (L_z/2)**k**) where **i**, **j**, and **k** are unit vectors in the x, y and z directions respectively and L_z is the room dimension in the z direction.

(a) For the four modes defined by mode numbers $n_x = n_y = 0$ and $n_z = 0$, 1, 2, and 3, state whether the mode will or will not be excited by the source.

(b) Undertake the same procedure for a point dipole source placed at the same point as the monopole and with its axis parallel to the z-axis.

(c) Confirm that the pressure distribution of equation 7.19 in the text satisfies the enclosure rigid wall boundary condition and use your analysis to derive an expression for the modal natural frequencies.

(d) For an enclosure of dimensions 10m × 5m × 2m high, calculate the natural frequency of the 1,1,1 mode and sketch its shape.

7.4 The sound pressure distribution for sound propagating in an infinite rigid walled duct (of cross-sectional dimensions L_y and L_z) in the positive axial direction (x-axis) is given by:

$$p = \sum_{m,n}^{\infty} A_{mn} \cos\frac{m\pi z}{L_z} \cos\frac{n\pi y}{L_y} \mathrm{e}^{j(\omega t - \kappa_{mn}x)}$$

where the wavenumber, κ_{mn} is defined as:

$$\kappa_{mn} = \sqrt{k^2 - [(m\pi/L_z)^2 + (n\pi/L_y)^2]}$$

(a) Explain the meaning of "cut-on frequency"

(b) For a duct of dimensions $L_y = L_z/3$, derive an expression as a function of L_z for the acoustic pressure drop in dB per unit length of duct for the m = 3, n = 2 mode for an excitation frequency equal to one third of the cut-on frequency.

(c) Derive an expression for the phase speed of the 3,2 mode and sketch its variation as a function of frequency, giving a qualitative explanation of the dependence, with particular reference to frequencies near the mode cut-on frequency.

7.5 A loudspeaker is mounted in the centre of a wall in a rectangular room of dimensions 4.6m × 6.2m × 3.5m such that it faces along the longest room dimension. A microphone is mounted in a corner of the room to measure the resulting pressure response. Assume that c = 343m/s.

(a) What is the lowest frequency at which the room will resonate?

(b) The energy density, ψ, of sound in the room is given by:

$$\psi = \frac{\langle p^2 \rangle}{\rho c^2}$$

where $<p^2>$ is the mean square sound pressure in the room. Compute the energy, E, stored in the acoustic field in the room at the lowest resonance frequency, where $E = \int_V \psi \, \mathrm{d}V$ and the measured sound pressure level in the corner of the room is 80dB re 20μPa.

(c) When the speaker is shut off, the sound field decays; however, a single mode is involved, not the many mode diffuse field discussed in the text. Thus the equations derived in the text will be inappropriate for this case. Derive an expression for the Sabine absorption coefficient, $\bar{\alpha}$, of the walls in terms of the reverberation time, T_{60}. Follow the procedure on p238 and 239 of the text and use the following expression for the energy decay in the room:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{ESc\bar{\alpha}}{V}$$

where S is the area of wall on which the speaker is mounted and V is the room volume.

(d) Calculate the acoustic power produced by the speaker at the lowest resonance frequency of the room given that the reverberation time, T_{60} = 5 seconds. Assume that the rate of power consumption is the same in steady state as during sound decay.

7.6 In the text, sound in a rectangular room is considered and the response is shown to be modal. A rectangular room was chosen for study for mathematical convenience: rooms of any shape will respond modally but generally the modes will be more complicated than for rectangular rooms. A relatively simple example of modes in a non-rectangular room is furnished by a cylindrical room in which the resonance frequencies are given as follows:

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

where c = 343m/sec, a is the radius and L is the height of the room.

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 table. The quantity n_z is the number of nodal planes normal to the axis of the cylinder.

m\n	0	1	2	3	4
0	0.0000	1.2197	2.2331	3.2383	4.2411
1	0.5861	1.6970	2.7140	3.7261	4.7312
2	0.9722	2.1346	3.1734	4.1923	5.2036
3	1.3373	2.5513	3.6115	4.6428	5.6624
4	1.6926	2.9547	4.0368	5.0815	6.1103
5	2.0421	3.3486	4.4523	5.5108	6.5494
6	2.3877	3.7353	4.8600	5.9325	6.9811
7	2.7034	4.1165	5.2615	6.3477	7.4065

(a) If L = 2.7m and a = 5.5m, what is the lowest order resonance frequency?

(b) Describe with the aid of a diagram the lowest order mode pressure distribution.

(c) Recall that in a standing wave the acoustic pressure and particle velocity are always in quadrature (ie 90° out of phase). How is the air in the room behaving in the lowest order mode?

(d) Construct a list of modes shown in the table (for $n_z = 0$) in order of ascending frequency, identifying each mode by its mode number.

(e) What is the resonance frequency of the $n_z = 1$, $n = m = 0$ mode?

(f) Determine axial, tangential and oblique modes, as for a rectangular room. At frequencies below the first oblique mode, how many axial and how many tangential modes are resonant?

7.7 In your text (p 285 - 287) an expression is derived for the effective intensity in a 3-D enclosed sound field. Occasionally rooms or spaces are found which are better modelled as 1- or 2-dimensional.

(a) Give an example of a 2-dimensional space and derive an expression for the effective intensity in a particular direction as a function of the measured sound pressure.

(b) Give an example of a 1-dimensional space and derive an expression for the effective intensity in a particular direction as a function of the measured sound pressure.

(c) Derive an expression for the mean square sound pressure for a decaying sound field as a function of time in a 2-D space. You will need the results of part (a) for this. [Hint: see the analysis on p285-286 in the text for a 3-D space.]

(d) Derive an expression for the mean square sound pressure for a decaying sound field as a function of time in a 1-D space. You will need the results of part (b) for this. [Hint: see the analysis on p285-286 in the text for a 3-D space.]

(e) The mean free path in your text is defined as the mean distance travelled by a sound wave in a room between reflections and for a 3-D space it is shown to be $4V/S$. Determine similar expressions for the 2-D and 1-D spaces and define in a diagram all quantities used.

7.8 (a) Calculate the electrical to acoustic power conversion efficiency for a speaker in the 500Hz octave band if when driven with 10 watts of electrical power it produces 95dB re 20μPa space averaged sound pressure level in a reverberant room 7m long, 5m wide and 3m high, which has a reverberation time in the 500Hz octave band of 2.5 seconds.

(b) The possibility of an acoustic interpretation for combustion instability observed in a power station furnace is investigated in this problem. The fire box is a large spacious enclosure with rigid walls and approximate dimensions as follows: 10m length, 12m width, 20m height. The gas within is hot and the speed of sound is estimated to be 864m/sec. When combustion instability occurs, the furnace shakes violently at a frequency estimated to be about 36Hz. Furthermore, the acoustic pressure on the wall is estimated to be of the order of 155dB re 20μPa during the onset of instability.

(i) What acoustic mode is likely to be excited by the instability and what kind of mode is it?

(ii) Where will the acoustic pressure be largest?

(iii) What is the amplitude of the cyclic force on the walls of the furnace?

(iv) The quality factor Q for the resonant mode is estimated to be 30 and the density of the hot gas in the furnace is estimated to be 1.16kg/m^3.

Estimate the power W which must be injected to drive the mode in steady state. Use the following equations:

$$Q = \frac{f_n T_{60}}{2.2}$$

where $\bar{\alpha}$ is the fraction of energy absorbed by each wall, and L is the distance between opposite walls and f_n is the resonance frequency of the acoustic mode.

For a 1-D diffuse sound field, the mean square sound pressure, $\langle p^2 \rangle$, at any time, t, after the sound source is turned off is given by:

$$\langle p^2 \rangle = \langle p_0^2 \rangle e^{-c\bar{\alpha}t/L}$$

where $\langle p_0^2 \rangle$ is the steady state mean square sound pressure before the sound is turned off and L is the length of the 1-D room.

[**HINT**: the sound pressure at the wall is made up of an incident and reflected wave, the amplitudes of which have been added together arithmetically. The power input is equal to the power absorbed at the walls - incident wave only].

(v) If the flame in the furnace is modulated by acoustic feed back, what is the energy conversion efficiency required to produce the observed instability if 800kW of power is introduced into the furnace by the combustion process?

7.9 A cubical enclosure has sides of length 5m and an effective absorption coefficient of 0.05 for the floor and ceiling and 0.25 for the walls.

What are the reverberation times of the enclosure for the following wave types (ignore air absorption)?

(a) axial waves between floor and ceiling

(b) tangential waves reflected from all four walls

(c) 3-D (diffuse) (all waves combined)

[**Hint:** The expressions for the mean square pressure as a function of time in a decaying sound field are:

$$\langle p^2 \rangle = \langle p_o^2 \rangle \, e^{-P\bar{\alpha}ct/\pi S} \quad \text{for a 2-D field}$$
$$\langle p^2 \rangle = \langle p_o^2 \rangle \, \mathrm{e}^{-c\bar{\alpha}t/L} \quad \text{for a 1-D field}$$

where P is the perimeter of the 2-D field and L is the length of the 1-D field.]

7.10 Explain why a sound intensity meter may give difficulties when used in a reverberant room to determine source sound power, especially if measurements are made at some distance from the source.

7.11 The net sound intensity at any location in an ideal reverberant field is zero. Clearly this cannot be the case adjacent a wall. Consider a rectangular reverberant room in which the reverberant field sound pressure level is 95 dB.

(a) Calculate the energy density of the field

(b) Calculate the sound power incident on one of the walls of area 30 square metres.

7.12 A room $10 \times 10 \times 4\text{m}^3$ has an average Sabine absorption coefficient $\bar{\alpha}$

= 0.1.

(a) Calculate the room reverberation time (seconds).

(b) The steady state reverberant field pressure level is 60dB. What is the acoustic power output level (dB re 10^{-12}W) of the noise source producing this pressure level?

(c) At what rate (in W/m^2) is the sound energy incident on the walls of the room?

(d) At what distance from the noise source is the reverberant field pressure level equal to the direct field pressure level? (Assume that the noise source is on the floor in the centre of the room).

7.13 An electric motor produces a steady state reverberant sound level of 74dB re 20μPa in a room 3.05 × 6.10 × 15.24m^3. The measured reverberation time of the room is 2 seconds.

(a) What is the acoustic power output of the motor in dB re 10^{-12} W?

(b) How much additional Sabine absorption (in m^2) must be added to the room to lower the reverberant field by 10dB?

(c) What will be the new reverberation time of the room?

7.14 A burner is fixed to the centre of one end of a furnace and radiates sound uniformly in all directions. The furnace is 6.0 m long and 4.0 m diameter. The average absorption coefficient of the walls is 0.050 for the 125 Hz octave band. If the sound power radiated by the burner is 3.10 watts:

(a) Calculate the radiated sound power level (dB re 10^{-12}W)

(b) Calculate the sound pressure level at 3.00 m from the burner for the 125 Hz octave band if the furnace temperature is 1200 degrees C, the pressure of the gas in the furnace is atmospheric, the molecular weight of the gas in the furnace is 0.035 kg/mole and the ratio of specific heats is 1.40.

7.15 The 1/3 octave band sound pressure levels in the table below were measured at one location in a factory plant room of dimensions 10m × 10m × 3m and average Sabine absorption coefficient of 0.09, with one item of uniformly radiating equipment in the centre of the hard floor. Determine how far from the acoustic centre of the equipment the measurements taken if the sound power of the equipment in the 250Hz band is 100dB.

1/3 octave band centre frequency (Hz)	250	500	1000
L_p (dB)	95	97	99

7.16 It is proposed to add sound absorbing material to the walls and ceiling of the room to reduce the interior noise levels produced by a machine mounted on the floor in the centre of the room. Assume that there are no other significant sound sources. If the room size is 10m × 10m × 5m and the Sabine sound absorption coefficient for all surfaces in the 250Hz octave band is 0.08 before addition of the absorbing material and will be 0.5 on the surfaces covered after addition of the sound absorbing materials, what is the expected noise reduction (in dB) 3m from the machine in the 250Hz octave band. Assume that the floor is concrete and that the machine radiates noise omni-directionally (same in all directions).

7.17 A room of dimensions 8m × 6m × 3m high has an average surface absorption coefficient of 0.05, apart from the ceiling which is covered with acoustic tiles having an absorption coefficient of 0.15 (random incidence values, for the octave band centred at 125Hz).

(a) Estimate the average reverberant sound pressure level due to a broadband source in the room which radiates 25mW of acoustic power in the 125Hz octave band.

(b) At what distance from the source do you expect the direct and reverberant sound pressure levels to be equal, for the room described above?

(Assume the source is non-directional.)

7.18 A machine in a factory of dimensions 50 m × 50 m × 5 m emits a sound power level of 130 dB in the 500 Hz octave band. The machine is located in the centre of the factory mid-way between the floor and ceiling.

(a) Calculate the direct and reverberant sound pressure levels 5 m from the acoustic centre of the machine. Assume the machine radiates uniformly in all directions, the room has a specular reflecting floor and ceiling and no other machines or reflecting surfaces are in the room. Assume that the pressure reflection coefficient amplitude is 0.7 for both the floor and ceiling.

(b) If the factory dimensions were 10 m × 10 m × 5 m, and the pressure reflection coefficient amplitude for all surfaces was 0.7, what would be the total sound pressure level 5 m from the acoustic centre of the machine.

(c) For the case in part (b), at what distance from the machine would the direct and reverberant fields be equal.

(d) What would be the reverberation time in the room of part (b)?

(e) If the factory walls had a Transmission Loss of 25 dB in the 500 Hz octave band, what would be the sound level at a distance of 50 m from the outside of the wall across an asphalt car park?

7.19 A machine to be mounted on the concrete floor of a factory has a sound power level of 95dB in the 1000Hz octave band. The factory has an average Sabine absorption coefficient of 0.08 in the same frequency band and sound radiation from the machine may be considered omnidirectional. Calculate the sound pressure level at a distance of 1 metre from the machine if the surface area of the floor, walls and ceiling is 400m^2.

7.20 Consider a computing room where the average noise level is 75dB in the 1000Hz octave band. In practice, all octave bands from 63Hz to

8000Hz are usually of interest. However, for the purpose of this problem we will only consider the 1000Hz band.

Three new line printers are to be installed and after installation the total allowable noise level in the room should not exceed 80dB in the 1000Hz octave band with all printers operating simultaneously.

You are required to specify a maximum sound power level in the 1000Hz octave band for each machine which cannot be exceeded by the manufacturer. Assume that the acoustic characteristics of all three machines are identical. Proceed as follows:

(a) Place a reference sound source on a hard asphalt car park (empty of cars) outdoors. The sound pressure level measured at 3m is 80dB in the 1000Hz octave band. What is the sound power level?

(b) Place the reference source in the computer room. The average sound pressure level measured in the 1000Hz octave band is 85dB. What is the room constant, R?

(c) What is the average Sabine absorption coefficient? (Room is 14m long × 6m wide × 4m high).

(d) What is the maximum allowable sound power level in the 1000Hz octave band of <u>each</u> new line printer which the manufacturer cannot exceed?

(e) Acoustic tile having a Sabine absorption coefficient of 0.5 could be put on the ceiling if necessary. What would be allowable sound power level of each of the line printers in this case?

7.21 A machine to be operated in a factory produces 0.01 watts of acoustic power. The building's internal dimensions are 10 × 10 × 3 metres. All surfaces <u>except</u> the concrete floor can be lined with acoustic material.

(a) Specify the absorption coefficient for the lining material so that the sound pressure level in the reverberant field of the factory is about 83dB.

(b) Specify the radius of an area around the machine in which the sound pressure level will exceed 90dB.

7.22 The reverberant field sound pressure level in a factory containing several noisy machines is 88dB in the 500Hz octave band and the corresponding average sound pressure level measured at the nearest residence 300m away is 44dB.

(a) Assuming that the factory operates 24 hrs/day and you wish to add 5 new identical machines, what would be the maximum sound power level of each machine which could be tolerated to ensure that no complaints would be received from the nearby residences. Assume that the neighbourhood may be classified as suburban with some commerce or industry and that the noise contains no tones or impulses. For the purposes of this problem assume that the only significant noise occurs in the 500Hz octave band. The factory dimensions are 25m × 20m × 5m high and the measured reverberation time in the 500Hz octave band is 2.1 seconds.

State clearly any additional assumptions you make in obtaining your answer.

(b) What would be the allowable sound power level for each of the five machines if a suspended ceiling having a Sabine absorption coefficient of 0.5 at 500Hz were added to the factory? Again, state any assumptions you make.

7.23 An ultrasonic sound source, in a reverberant enclosure of dimensions 200 × 150 × 120mm, is required to produce 140dB re 20μPa at 43.1kHz. The effective Sabine absorption coefficient (including air absorption) of the enclosure walls is 0.1 and the speed of sound is 343m/s.

(a) What is the energy density in the enclosure at the required sound pressure level?

(b) What is the power absorbed by the air and enclosure walls?

(c) If the source is 20% efficient how much power is required to drive it?

7.24 A machine radiating an A-weighted sound power level of 84dB is installed in the centre of the floor of a room of dimensions 10m × 6m × 3m with an average boundary Sabine absorption coefficient of 0.15.

(a) Calculate the reverberant field sound pressure level.

(b) Will a technician standing at the machine control panel located 1.5m from the centre of the room be in the direct or reverberant field assuming that the acoustic centre of the machine is in the centre of the room and level with the technician's ears.

(c) If the average sound absorption coefficient can be increased to 0.5, what will be the effect on the sound level experienced by the technician?

(d) A second machine producing an A-weighted sound power level of 89dB re 10^{-12}W is added to the room and is well separated from the first. Calculate the distances from each machine for which the reverberant field level is equal to the direct field level for each machine running separately and again for the machines running together. Assume an average Sabine absorption coefficient of 0.15.

(e) Recalculate the distances of (d) with the average Sabine absorption coefficient increased to 0.5.

(f) State any assumptions you need to make for the preceding calculations to be valid.

7.25 You have been given the task of installing 4 new machines in an enclosure housing other machinery and personnel, making sure that the overall reverberant sound level does not exceed 85dB re 20μPa when all of the new machines are operating. The enclosure is a large room of dimensions 10m × 15m × 6m high and the existing reverberant field sound pressure level is 75dB. Reverberation decay measurements indicate that the average wall, floor and ceiling Sabine absorption coefficient is 0.1. Assume for the purposes of this problem that the machine noise and room absorption measurements are confined to a single octave band.

(a) What is the room reverberation time?

(b) What is the room constant?

(c) The sound power level of each new machine is 94dB re 10^{-12}W without noise control and 84dB re 10^{-12}W with noise control at an additional cost of $1,600 per machine. The cost of acoustic tile with an average absorption coefficient of 0.6 is $50 + $3 per square meter. What will be the reverberant field sound pressure level if all four machines without noise control are operating.

(d) What is the level if all four machines have been provided with noise control treatment?

(e) Based on the preceding cost information, what is the least expensive way of meeting the design goal.

7.26 The sound power level of a machine that radiates sound equally in all directions in a factory of dimensions 20m × 25m × 5m is 113 dB in the 500Hz octave band. The space average Sabine absorption coefficient for the 500Hz octave band is 0.1.

(a) Calculate the distance from the machine (located in the middle of a hard floor and away from any other reflecting surfaces) that the reverberant sound pressure level will equal the direct sound pressure level at 500Hz.

(b) What would this distance be if the machine were located at the junction of the floor and one wall?

(c) What would be the result in part (a) if the ceiling were covered with ceiling tiles having a Sabine absorption coefficient of 0.5?

(d) Comment on the effectiveness of the ceiling tiles on the noise exposure of the machine operator if the distance of the operator from the machine is 0.5m.

7.27 A noisy machine is installed in one corner of a room of dimensions 5m × 5.5m × 3m. The room is characterised by hard surfaces with Sabine absorption coefficients as shown in the table below. Also shown in the table are the space average sound pressure levels measured in several octave bands when the machine is running and Sabine absorption coefficients for acoustic tile.

Octave band centre frequency (Hz)	Untreated room		Acoustic tile Sabine absorption coefficient
	Sabine absorption coefficient	L_p (dB re 20μPa)	
63	0.01	75	0.08
250	0.02	85	0.15
1000	0.02	84	0.20
4000	0.03	70	0.25

(a) Calculate the overall sound power level of the machine assuming that noise is only generated in the octave bands shown in the table.

(b) If the modal overlap should be 3 or greater to have reasonable confidence in the sound power estimation, does the room satisfy the criterion and over what frequency range?

(c) Determine by how much $25m^2$ of acoustic tile would reduce the noise level in the centre of the room in each of the octave bands shown in the table.

(d) By how much would the overall space average sound pressure level be reduced? State any assumptions made.

7.28 Consider a reverberant room of dimensions 6.84 × 5.565 × 4.72m. The average surface Sabine absorption coefficient for the 1000Hz one third octave band is 0.022.

(a) Calculate the sound power radiated by a source into the room in the 1000Hz octave band if the space averaged reverberant sound pressure level was measured as 95dB.

(b) What would the sound pressure level be at 0.5m from the sound source, assuming it to be mounted on the floor in the centre of the room, and assuming it to radiate omnidirectionally?

7.29 Consider a reverberant room of dimensions 6.84 × 5.565 × 4.72m high. The average surface Sabine absorption coefficients for the third octave bands between 63Hz and 8kHz are respectively:

0.010, 0.010, 0.011, 0.011, 0.013, 0.015, 0.017, 0.017, 0.018, 0.018, 0.019, 0.020, 0.022, 0.025, 0.028, 0.031, 0.034, 0.037, 0.040, 0.044, 0.047, 0.050

(a) Calculate the room reverberation times in each one third octave band.

(b) What is the lowest third octave band which can be used for accurate sound power measurements where a statistical description of the sound field is required?

(c) What is the lowest suitable frequency band for octave band noise measurements?

(d) What is the lowest suitable frequency for pure tone noise measurements?

7.30 A reference sound source having a sound power level of 92.5dB(A) produces a reverberant field of 87dB(A) in an equipment room. Existing equipment in the room produces a reverberant field level of 81dB(A).

(a) Calculate the room constant.

(b) If 4 new machines, all producing the same sound power level, are to be introduced, what is the allowable maximum sound power level of each machine so that the noise level in the room does not exceed 85dB(A)?
State any assumptions that have to be made to answer this

question.

(c) What would be the allowed sound power level of each machine if the room constant were doubled by adding sound absorbing material to the walls. Again state any assumptions you make.

7.31 A machine is mounted on the floor of a room of dimensions 15m × 15m × 5m high and the Sabine absorption coefficient for all room surfaces except the floor is 0.1 and that of the concrete floor is 0.01 at 500Hz. If sound absorbing material is added to the walls and ceiling of the room, what will be the noise reduction in the 500Hz octave band, 4m away from the machine mounted on the floor if the sound absorbing material has an absorption coefficient of 0.7 at 500Hz when attached to a rigid surface?

7.32 A machine with a sound power level of 105dB (re 10^{-12}W) in the 1kHz octave band is to be installed in a room having a volume of 100m^3, an effective surface area of 130m^2, and a reverberation time of 1.5 seconds in the 1kHz octave band. A partition of area 15m^2 separates this room from an office having a volume of 80m^3, an effective surface area of 100m^2, and a reverberation time of 0.75 seconds in the 1kHz octave band. The office already contains a machine with a sound power level of 85dB in the 1kHz octave band. Calculate the minimum partition noise reduction necessary to ensure that the reverberant field sound pressure level in the office is not increased by more than 1dB when the machine is installed in the adjacent room.

7.33 A sound source in an enclosure of volume 30m^3 radiates 1watt of sound power with a wavelength much smaller than the enclosure dimensions, resulting in a space averaged diffuse field sound pressure level of 116dB re 20μPa.

(a) If the surface area of the enclosure is 50m^2, calculate the average absorption coefficient of the enclosure surfaces.

(b) If the source is suddenly switched off, how long does it take for the sound pressure level to decay by 10dB?

(c) If 10m^2 of sound absorbing material having a Sabine absorption coefficient of 0.8 is placed on the walls, what would be the reduction in reverberant field sound pressure level?

(d) If three more similar sources were added to the room, what would be the increase in sound pressure level over that measured in part (a)?

7.34 Describe the various materials and techniques which may be used for sound absorption, mentioning the absorption mechanisms, the absorption characteristics, the applications, the advantages and the disadvantages of each technique.

7.35 Design a panel absorber to have a maximum Sabine absorption coefficient of 0.8 at 125Hz.

7.36 Find the mean Sabine absorption coefficient for a room of dimensions $6.84 \times 5.565 \times 4.72$m high, if the floor and ceiling have a mean absorption coefficient of 0.02, the two smaller walls a coefficient of 0.05 and the large walls a coefficient of 0.06.

7.37 A town band has constructed a practice room which may be approximated as a cylinder of 7m radius and 2.5m height.

(a) What would be the recommended octave band reverberation times in the frequency range 125Hz to 4000Hz? Assume a 50% increase for the 125Hz band and a 10% increase for the 250Hz band over the value calculated using equation 7.121 in your text.

(b) How much Sabine absorption (m^2) would you recommend?

(c) Would commercially available acoustic tile be adequate at 125Hz? Assume that the tile will be fixed to the ceiling with a small air gap and use the following values of $\bar{\alpha}$ corresponding to the octave bands from 125Hz to 4000Hz. That is, 0.20, 0.60, 0.80, 0.85, 0.80, 0.75.

(d) Design a suitable panel absorber with maximum absorption at 125Hz to be used in conjunction with acoustic tiles to achieve the desired reverberation times over the frequency range 125Hz to 4000Hz.

7.38 Noise measurements are taken at 5m distance from a diesel generator standing on a concrete base surrounded by asphalt. The following octave band sound pressure levels are measured at ground level and show no significant dependence on direction from the generator.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k
L_p (dB re 20μPa)	90	85	78	73	70	65

(a) Estimate the sound power output of the generator in each of the 6 frequency bands.

(b) The same machine is installed in a plant room of dimensions 5m × 3m × 2m high. Which of the standard third octave bands contain the 3 lowest natural frequencies of the room? How many room resonances do you expect to occur in the 125Hz third octave band?

(c) The reverberation times in the 6 octave frequency bands considered above are given in the following table.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k
Reverberation time (s)	5.5	5	4	3	2	1.5

Estimate the sound pressure level (dB(A)) in the room when the generator is running. Discuss any assumptions inherent in your calculations.

(d) By how much would the reverberant field sound level increase if two more similar diesel generators were installed in the room?

(e) If ceiling tiles having sound absorption coefficients listed in the table below were added to the enclosure ceiling what would be the new reverberant field sound pressure level with just one diesel generator running? State any assumptions that you make.

Octave band centre frequency (Hz)	63	125	250	500	1k	2k
Sabine absorption coefficient	0.15	0.25	0.55	0.85	1.0	1.0

7.39 You wish to optimise the acoustics in a small auditorium of dimensions 20m × 15m × 4m, for occupants to understand a lecture. Measured reverberation times in the octave bands from 63Hz to 8kHz are respectively (for an occupied room):

3.0, 2.6, 2.3, 2.1, 2.0, 2.0, 2.0, 1.8 seconds.

What would be the area and thickness of sound absorbing material which should be added to the room walls and ceiling if the material has a maximum statistical absorption coefficient of 0.85? The octave bands corresponding to this maximum are 250Hz and above for a 100mm thick sample, 500Hz and above for a 50mm thick sample and 1000Hz and above for a 25mm thick sample. Assume existing wall and ceiling absorption coefficients are equal to the existing room average.

7.40 A single storey factory has a single window of area 1.5 m^2 located in an otherwise blank concrete block wall: the window overlooks a house at a distance of 60m across an asphalted loading yard. The space-average reverberant sound pressure level in the factory is 88dB in the 1000Hz octave band, and the diffuse field transmission loss of the window is 27dB. Estimate the sound pressure level at the wall of the house due to transmission through the window in this frequency band. Identify possible sources of uncertainty in your calculation.

7.41 Calculate the frequency of maximum absorption, the specific normal impedance and the statistical absorption coefficient at the frequency of maximum absorption for a porous material bonded to a rigid wall and covered with a perforated steel facing. The porous material is 100mm thick with a flow resistivity of 10^4 MKS rayls m^{-1}. The perforated facing is 3mm thick, of 7% open area with uniformly spaced holes of 2mm diameter. The porous material is fixed to a rigid wall and may be assumed to be locally reactive.

7.42 Sound absorbing material with a noise reduction coefficient of 0.8 has been specified for use in hanging sound absorbers in a noisy factory. You are offered rockwool material characterised by the sound absorption coefficients shown in the table below. Does the material satisfy an NRC of 0.8?

Octave band centre frequency (Hz)	125	250	500	1k	2k
Sabine absorption coefficient	0.4	0.6	0.8	1.0	1.0

7.43 A truck travelling in a rectangular section tunnel with smooth, surfaces emits 110 dB of acoustic power in the 500 Hz octave band. The absorption coefficient of the tunnel surfaces is 0.1. Calculate the total sound pressure level 60 m from the truck in the 500 Hz octave band if the tunnel cross-section is 6 m × 6 m. State any assumptions that you make.

8

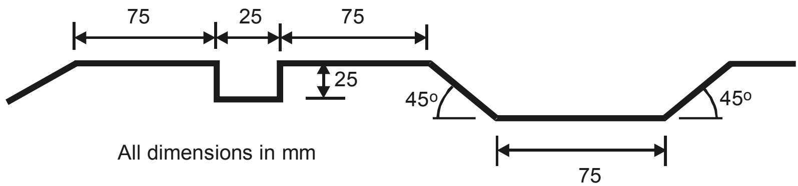
Problems relating to sound transmission loss, acoustic enclosures and barriers

8.1 (a) Define in physical terms the transmission loss of a partition and using mathematical analysis as an aid, explain the principles of its measurement.

(b) Explain why measurements often do not agree with theoretical calculations.

8.2 At what frequency does the mass law transmission loss for a 10mm thick steel panel immersed in water equal 4dB? Explain in physical terms why the transmission loss in air at this frequency is much greater.

8.3 Consider the steel panel with the cross-section shown in the following



figure, having E = 207 GPa and Poisson's ratio ν = 0.3.

(a) Calculate the bending stiffness in two directions: across the ribs and along the ribs. The panel thickness is 1.2mm.

(b) Calculate the bending wave speed in both directions for the panel at a frequency of 1000Hz.

(c) Calculate the range of critical frequencies for the panel.

(d) If the panel is one wall of an enclosure and has dimensions 2m × 2m, calculate its lowest resonance frequency.

(e) Calculate the transmission loss for the panel in octave bands from 63Hz to 8000Hz.

[**Hint**: Use a calculator program to calculate the TL at 1/3 octave centre frequencies, then average to get octave band data.]

$$TL_{oct} = -10\log_{10}\{(1/3)\,[10^{-TL_1/10} + 10^{-TL_2/10} + 10^{-TL_3/10}]\}$$

Alternatively plot a curve and read 1/3 octave values from the curve.

8.4 (a) Calculate the fundamental resonance frequency and the upper and lower critical frequencies for a corrugated steel panel of dimensions 3m × 3m and thickness 1.6mm. The corrugations may be described by $y = 20\sin\pi(x/40)$ where y is the corrugation height (or depth) and x is the distance in mm across the width of the panel.
(Hint: To find the panel bending stiffness across the corrugations, represent the sinusoidal shape by 3 straight panel sections per half cycle, and make the centre panel 10mm wide.)

(b) Calculate the transmission loss as a function of frequency for the panel in part (a). Express your answer graphically. Assume that the panel loss factor is 0.001.

(c) Calculate the transmission loss as a function of frequency for the panel in part (a) with a visco-elastic damping layer of equal mass bonded to it. Assume that the loss factor of the construction is 0.1.

(d) Calculate the transmission loss of a construction made from the panel in part (a) and a second panel attached to it with single 100mm × 100mm wooden studs to make a double wall. The second panel is flat and 13mm thick compressed hardboard composite (c_L = 2000m/s and η = 0.01), and may be considered line supported at 600mm intervals. The corrugated panels are nailed to the studs through rubber spacers at 600mm centres.

8.5 Explain why a double wall partition may perform more poorly at some frequencies than a single wall partition of the same total weight.

8.6 Calculate the transmission loss of a double wall in the frequency range 63Hz to 8kHz. There is a 100mm gap containing a 50mm thick rockwool blanket between the panels and the largest cavity dimension is 3m. The panels are line supported at 600mm intervals and have the properties listed in the table below. Plot your results on 1/3 octave graph paper indicating all important frequencies and transmission loss values.

	Density (kg/m^3)	Thickness (mm)	Young's modulus of elasticity (Pa)	Speed of sound (m/s)	Loss factor
Panel 1	1000	12	4×10^9	2100	0.02
Panel 2	7800	1.6	2.1×10^{11}	5400	0.01

8.7 The transmission loss of an enclosure wall which contains a 0.5m × 0.5m window and a 1m × 2m door is to be determined. The transmission loss of the well sealed door is 25dB and that of the window is 28dB. The side of the wall is 3m × 6m.

(a) What will be the required transmission loss of the enclosure wall if the overall transmission loss is to be 30dB?

(b) What is the greatest overall transmission loss that is theoretically possible?

(c) What would be the effect of a 25mm high crack underneath the door on the overall transmission loss of the construction in part

(a) at a frequency of 500Hz.

8.8 Design an enclosure with a steel outer skin and a plasterboard inner skin with single 100mm × 100mm studs and of overall dimensions 3m × 4m × 2.5m to enclose a hard surface machine of surface area 10m^2. A 0.5m × 0.5m inspection window in one wall and a 2.2m × 1m door in another wall are required. The required enclosure noise reductions in the octave frequency bands from 63Hz to 8kHz are 14, 18, 25, 35, 50, 40, 40, 40dB respectively.

8.9 In problem 8.8, what would be the effect on noise reduction if a 5mm air gap were allowed under the door? Give the quantitative effect for all octave bands considered in problem 8.8 and refer to the required enclosure wall *TL*.

8.10 Calculate the air flow required if the machine in the enclosure of problem 8.8 uses 10kW of electrical power and the allowed temperature rise in the enclosure is 3 °C above ambient. Assume that the machine is 95% efficient in converting electrical power to mechanical work. What would be the required insertion loss specifications of a silencer for the inlet and discharge cooling air?

8.11 You are required to design an enclosure for a noisy refrigeration unit attached to a supermarket and causing annoyance to nearby residents. Explain how you would proceed to quantify the problem and to estimate the required enclosure performance. Describe any other factors you should consider in the design of the enclosure.

8.12 A noisy compressor measures 2m × 0.5m × 0.5m, generates a sound power level of 105dB re 1pW in the 500Hz octave band and is located on a concrete pad. The Local Authority require that sound levels at the perimeter of the neighbouring residential premises (80m from the compressor) should not exceed 38dB in the 500Hz octave band. Design a suitable enclosure constructed with a single thickness, isotropic steel wall lined on the inside with 50mm thick mineral wool using the following steps.

(a) Calculate the required TL of the enclosure wall

(b) Select the necessary thickness of steel for the wall assuming thicknesses are available ranging from 1.0mm to 3.0mm in 0.5mm steps.

(c) List anything else you should consider in the design.

As distance to the residential perimeter is so small, you may ignore atmospheric sound absorption and meteorological influences. You may also assume that the ground is hard with a reflection coefficient of 1.0.

8.13 An enclosure is to be placed around a noisy machine with hard surfaces in a factory. If the enclosure is to be lined with 50mm thick rockwool, what would be the required transmission loss, in the 1000Hz octave band, of the enclosure walls (assume no ventilation is needed) to achieve a 15dB noise reduction in the factory (in the 1000Hz octave band).

8.14 (a) Explain why the performance of a machinery noise enclosure should not be expressed as a single dB(A) rating.

(b) Given the required noise reductions in the table below for an enclosure around an item of equipment, determine whether a standard single stud (0.6m centres) double gypsum board wall (100mm wide cavity, each panel 13mm thick) would be adequate. Assume that the machine and floor surfaces are hard, the enclosure is lined with sound absorbing material, sound absorbing material is placed in the enclosure wall cavity and that the panel loss factor is 0.02.

Octave Band Centre Frequency	63	125	250	500	1k	2k	4k	8k
Required Noise Reduction (dB)	10	15	20	25	30	35	40	20
Desired SPL Immediately Outside of Enclosure	80	83	78	73	70	60	60	60

(c) If the above gypsum board wall is inadequate, what would you suggest to improve the noise reduction at the required frequencies. Give 3 possible alternatives, but retain the double wall and use gypsum board panels. Do not do any calculations.

(d) If the equipment in the enclosure is driven by a 50kW electric motor which is 98% efficient, what would be the minimum required airflow through the enclosure to ensure a temperature in the enclosure less than 5°C higher than outside the enclosure?

(e) If the enclosure dimensions are 5m × 4m × 2.5m high, calculate the machine sound power in each octave band if the desired sound pressure levels immediately outside of the enclosure are as listed in the table of part (a). Use the required noise reductions in the same table for your calculations and assume the machine and enclosure are out-of-doors. For this and subsequent parts of this question assume $\rho c = 400$.

(f) Calculate the average sound pressure level 1m from the machine surface without the enclosure assuming that the machine is mounted on a concrete base out-of-doors away from any reflecting surfaces and can be approximated by a rectangular volume 2m × 1m × 1 m.

(g) Calculate the average sound pressure level 1m from the machine with the enclosure in place for each octave band. Use the internal acoustic conditions constant C to calculate the enclosure room constant R.

(h) Calculate the sound pressure level 200m from the enclosure in the 2000Hz octave band. Assume incoherent addition of the direct and ground reflected wave and assume a hard asphalt surface. Give a range to reflect the variability due to turbulence and wind and temperature gradients. Assume a temperature of 25°C and 50% relative humidity.

8.15 A machine mounted in an enclosure causes excessive noise levels at a location in a community 50m from the enclosure. The enclosure has well sealed doors and double glazed windows. However the wall construction and the wall transmission loss are unknown. The noise level inside the enclosure is 101dB re 20μPa in the 1kHz octave band and the noise level at the location 50 meters away in the same band is 70dB re 20μPa. The noise level measured on a surface spaced one meter from the enclosure averages 91dB in the 1kHz octave band. The enclosure dimensions are 3m × 3m × 3m.

(a) What is the sound power level radiated by the enclosure?

(b) If the enclosure is mounted on hard asphalt which extends 100 meters from it, what would you expect the sound level to be at a distance of 50m if the enclosure exhibits uniform directivity and there are no obstructions and no excess attenuation due to atmospheric absorption and meteorological influences?

(c) What then is the excess attenuation due to ground effects, atmospheric absorption and meteorological influences?

(d) A reference sound source placed inside the enclosure produces a measured sound pressure level difference of 30dB in the 1kHz octave band between inside and immediately outside of the enclosure. What could be the problem, as only 10dB is obtained when the machine is the noise source?

8.16 Explain why it is important to design acoustic enclosures with adequate internal absorption of acoustic energy.

8.17 (a) When installing an acoustic enclosure, it is important to either vibration isolate the machine from the floor or vibration isolate the enclosure from the floor. Explain why in one sentence.

(b) What is one possible acoustic performance disadvantage associated with vibration isolation of the enclosure from the floor? (One sentence).

(c) Give two examples of what else could also degrade the performance of an acoustic enclosure.

8.18 You are given the problem of designing a quiet foreman's office to be located in the middle of a factory containing a number of noisy machines which operate 12 hours/day. You use your text book to design a double wall enclosure which is duly constructed, unfortunately without your supervision. The noise levels in the enclosure are considerably higher than you predicted and you are told to "fix it".

List all of the reasons you can think of to explain the poor performance of the enclosure. Describe a test you could do to determine if structure borne noise transmission is a problem.

8.19 A barrier 3m high and 10m wide is inserted mid-way between a noisy pump and a residence located 40m away. With no barrier, noise levels at the residence in octave bands are as listed in the table below.

Octave Band Centre Frequency (Hz)	63	125	250	500	1k	2k	4k	8k
Noise Level at Residence (dB re 20μPa)	63	67	62	55	52	50	45	42

For the purposes of the following calculations assume the acoustic centre of the pump is 0.5m above the ground and the point of interest at the residence is 1.5m above the ground.

The ground surface is grass. Assume sound waves travelling from the pump to the residence along different propagation paths combine incoherently at the residence.

(a) Calculate the Noise Rating (NR) level and dB(A) level of the noise at the residence with no barrier in place.

(b) Is the noise at the residence with no barrier in place, acceptable if the area is zoned as residences bordering industrial areas and the noise occurs 24 hours/day? Assume the noise has no detectable tonal or impulsive components. Is the noise acceptable if it only occurs during the hours of 7.00 a.m. and 6.00 p.m.? Explain your answer.

(c) Would the noise at the residence with no barrier in place sound rumbly, hissy or neutral? Why?

(d) List the possible sound propagation paths from the noise source to the residence without the barrier in place and then with the barrier in place. Assume no obstacles other than the barrier exist.

(e) Estimate the attenuation of the ground reflected wave with no barrier in place for the 500Hz octave band.

(f) Calculate the overall attenuation in the 500Hz octave band due to the barrier for sound travelling from the pump to the residence.

8.20 Approximately how high would a barrier need to be between a compressor and the property line of the owner so that an NR curve of 50 is not exceeded at the property line? The distance from the compressor to the property line is 50m and the distance from the compressor to the barrier is 2m. The compressor noise source is 1.5m above the ground. Assume that the receiver location at the property line is 1.5m above the ground, that the barrier is mounted on asphalt and that losses due to ground absorption and atmospheric effects are negligible. The barrier is 10m wide and the 63Hz to 8000Hz octave band noise levels due to the compressor at the property line are respectively: 68, 77, 65, 67, 63, 58, 45, and 40dB prior to installation of the barrier.

8.21 If the excessive community noise emanating from your workplace existed only at residences adjacent to your property line, what would be the noise reduction obtained in the 500Hz octave band by building a 3m high brick wall around your facility, 10m from the residences? Assume that the distance from your facility to the wall is 50m, that the height of the noise sources is 2m, that the height of the complainant is 1.5m and that the noise reduction due to any ground reflection is

3dB. State any assumptions you make.

8.22 Calculate the noise reduction (in dB(A)) due to inserting a 4m high thin barrier, 15m in length midway between a noisy refrigeration unit and a residence located 50m from the unit across an asphalt covered lot. Assume that the acoustic centre of the refrigeration unit is 0.5m above the ground and the community location is 1.5m above ground level.

Without the barrier the noise levels due to the refrigeration unit in the octave bands between 63Hz and 8kHz were measured respectively as: 70, 75, 72, 60, 58, 56, 50, 52dB.
Use Fig. 5.18 in the text to calculate the ground reflection loss, assuming that no wind or temperature gradients exist and that sound from all paths combines incoherently at the receiver.

8.23 What would be the additional noise reduction (in dB(A)) if the barrier of problem 8.22 were a building, 4m deep?

8.24 Qualitatively describe the effect on noise reduction of moving the barrier of problem 8.22 to within 2m of the refrigeration unit?

8.25 To reduce noise levels in the assembly area of a factory, a barrier is to be installed between the manufacturing and assembly sections. The factory is a building 50m × 100m × 5m with an average Sabine absorption coefficient of 0.08 in all octave frequency bands. The barrier is 3m high and extends the full 50m width of the factory in the middle. The average barrier Sabine absorption coefficient is 0.15 in all octave bands. Assume that all sound sources are omnidirectional and are mounted on a hard floor. Calculate the noise reduction due to the barrier, in octave bands between 63Hz and 8kHz, for a listener standing in the centre of the building on the assembly side of the barrier, subjected to a noise source in the centre of the building on the other side of the barrier. Assume the acoustic centre of the noise source is 0.5m above the floor and the listener is 1.5m above the floor.

8.26 In a large open plan office, a person sitting 4m away from a line printer (mounted on a table 1m above the floor) finds the noise annoying. A proposal is to insert a 2.2m high screen midway between the printer and the complainant whose ears may be considered to be 1.2m above the floor. The ceiling is 3m above the floor and is covered with ceiling tiles having the Sabine absorption coefficients listed in the table below. The floor is covered in carpet with the absorption coefficients also listed in the following table.

Octave band centre frequencies (Hz)	500	1000	2000
Printer sound power output (dB re 10^{-12}W)	70	77	75
Ceiling Sabine absorption coefficient	0.75	0.95	0.99
Carpet Sabine absorption coefficient	0.57	0.69	0.71

Only noise in the 500Hz, 1000Hz and 2000Hz octave bands is of importance. Ignore any effects which contribute less than 0.2dB to the final result.

(a) Calculate the sound pressure level at the complainants location prior to installation of the barrier (see Ch. 7).

(b) Calculate the noise reduction in each of the octave bands due to the barrier. State any assumptions made.

(c) How could you position the screen to increase this noise reduction?

8.27 (a) Calculate the noise reduction in octave bands from 63Hz to 4kHz for a barrier placed in the centre of a factory midway between a noisy machine and personnel working at a bench for the following conditions:

Room height × width × length = 5m × 20m × 50m.
Source directivity index in the direction of the personnel is 5dB.

The distance between the source and the barrier is 5m and between the personnel and the barrier it is also 5m.
The source height is 1m.

Mean Sabine absorption coefficient of room surfaces is 0.08 in all frequency bands.

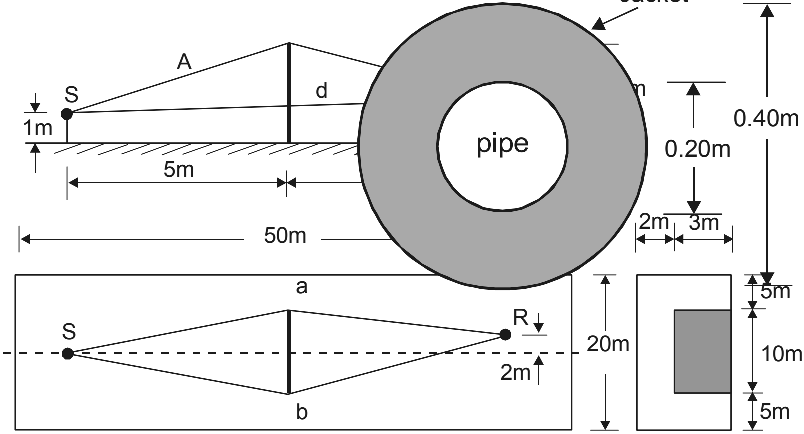
The machine lies on a centre line normal to the surface of the barrier while the personnel are 2m off the same centre line on the opposite side of the barrier (see figure). The barrier is 3m high and 10m wide. The barrier is covered with a 50mm thick layer of fibreglass with an approximate density of 60kg/m^3.

Assume the mean personnel height is 1.5m and that the transmission loss of the barrier is sufficient so that sound transmission through it may be ignored.

(b) Qualitatively describe the effect on the barrier Insertion Loss of moving the barrier to within 1m of the sound source.

(c) Qualitatively describe what would happen to the barrier Insertion Loss if the barrier length were extended to the entire room width?

8.28 Calculate the insertion



loss in octave bands between 63Hz and 8kHz due to wrapping a 200mm diameter steel pipe with a 100mm layer of 90kgm^{-3} glass fibre covered with an aluminum jacket weighing 6kgm^{-2}.

8.29 A 150mm diameter pipe with a wall thickness of 5mm is to be lagged to reduce sound radiation. The treatment is to consist of a 50mm layer of rockwool (density 80kg/m^3), covered with a 1mm thick lead-aluminium jacket weighing 6kg/m^2.

(a) Calculate the noise reduction in the one third octave frequency bands between 63Hz and 8kHz due to the lagging treatment. [**Hint:** In calculating the bending stiffness of the jacket, the combined bending stiffness of the lead and aluminium must be used.]

(b) How would you increase the low frequency noise reduction.

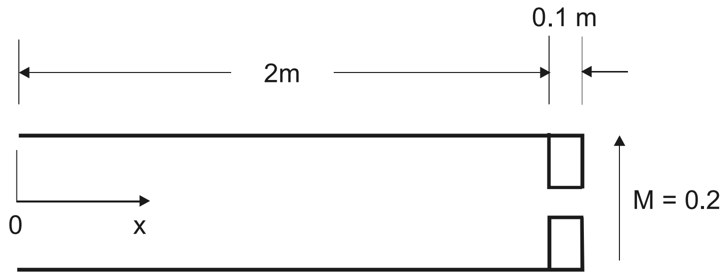
(c) Discuss the advantages and disadvantages of replacing the rockwool with porous acoustic foam.

9

Problems relating to muffling devices

9.1 Determine the effective end correction for a hole in a perforated panel of percentage open area P using equation 7.71 and the Helmholtz resonator analysis of Chapter 9. Explain why the Helmholtz resonator model is appropriate.

9.2



The tube shown in the figure above is terminated at the right end by an orifice plate. At 200 Hz, sound introduced into the left end of the tube produces a standing wave in the tube which has a minimum located 0.2 m from the inside edge of the orifice when the temperature in the tube is 20°C.

(a) Beginning with the harmonic solution to the wave equation for left and right travelling waves, calculate both the real and imaginary parts of the specific acoustic impedance looking into the inside end of the orifice at 200Hz if the standing wave ratio is 8 dB. In your analysis, let the left end of the tube be the origin of the coordinate system.

(b) If the cross flow is the dominant contributor to the acoustic resistance, estimate the Mach number of the flow if the orifice diameter is 0.1 m. [Hint: use the lumped analysis for an orifice from Ch 9 in the text].

(c) Based on your answer to (b) above, estimate the total end correction (both sides) for the orifice in this situation.

9.3 Describe how a quarter wave tuning stub works.

9.4 Quarter wave tubes are often used as side branch resonators to attenuate tonal noise propagating in ducts. The tubes are closed at one end. The open end "looks into" the duct through a side wall, and effectively presents zero reactive and small resistive impedance to the duct, at the tone frequency. The quarter wave tube can be made shorter by inserting baffles in it, each with a single central hole.

(a) If 3 equally spaced baffles are to be used to reduce the required tube length by 50%, write an equation which can be solved by computer to calculate the required hole diameter, assuming a tonal frequency of 100Hz. Assume that the baffle thicknesses are negligible and that the tube diameter is 200mm. Neglect resistive impedance.

(b) Why would this device with baffles not be quite as effective as a quarter wave tube in attenuating the tonal noise?

9.5 (a) Calculate the resistive impedance of each orifice of problem 9.4 if it is assumed that the orifice diameter is 44mm.

(b) Calculate the expected side branch insertion loss if the duct on which it is mounted is of square cross section 0.5m × 0.5m, and the side branch is mounted an odd number of quarter wavelengths from the open end of the duct and the sound source is a constant volume source.

9.6 (a) Explain why closed end side branch tubes usually provide greater peak insertion losses than open ended tubes.

(b) An infinitely long duct transmitting only plane waves has a side branch stub of the same diameter which is characterised by an impedance equal to $(j\rho c/A)(\omega - 10^4/\omega - j\omega 10^{-4})$, where A is the cross-sectional area of the side branch. Calculate the peak insertion loss of the side branch, assuming a constant volume velocity sound source.

9.7 The differential equation describing the motion of air in the neck of a Helmholtz resonator is:

$$M\frac{d^2\xi}{dt^2} + C\frac{d\xi}{dt} + K\xi = p_e S$$

where ξ is the displacement of air in the resonator neck (of cross sectional area S) and p_e is the external pressure providing the excitation. Explain the physical significance of the quantities M, C and K.

9.8 A Helmholtz resonator has a cylindrical cavity 200mm deep with a 100mm radius. The neck is 40mm long with a radius of 30mm.

(a) At what frequency will the device resonate?

(b) If the acoustic resistance of the device is 1000 acoustic ohms, what is the quality factor?

(c) Over what frequency band would the device be effective as an absorber?

(d) Suppose a plane wave of pressure level 80dB re 20μPa and frequency equal to the resonance frequency of the resonator is incident upon the resonator. Calculate the power dissipated by the resonator.

(e) What is the area of wavefront of a plane wave supplying power equal to that absorbed by the resonator?

(f) As an absorber, what is the Sabine absorption (m^2) of the device and how does it compare with the cross sectional area of the resonator volume. What does this result imply in terms of the number of resonators needed per square meter of wall area to make a wall look anechoic at the resonance frequency of the resonator.

(g) Based on your calculations would you expect such a device to be effective as part of the internal wall of an electrical transformer enclosure, given a likely ambient temperature variation from -5°C to 45°C. Suggest means of compensating for any loss of performance due to temperature variations about the design temperature.

9.9 (a) Show that the acoustic input impedance of a duct, which has a length l, a characteristic acoustic impedance Z_c and is terminated by an acoustic impedance of Z_L, is given by:

$$Z_i = Z_c \left[\frac{Z_L + jZ_c \tan(kl)}{Z_c + jZ_L \tan(kl)} \right]$$

(b) A duct has a square cross section of 0.2m × 0.2m, is of length 10.29m and is terminated by a material which has an entirely real pressure reflection coefficient of 0.5 at the frequency of operation, which is 100Hz.

Calculate:

(i) the characteristic acoustic impedance in the duct,
(ii) the acoustic impedance of the duct termination,
(iii) the acoustic input impedance of the duct.

9.10 (a) The complex acoustic pressure in an infinite rectangular hard-walled duct having sides of length L_x and L_y in the x and y directions can be written as:

$$p(x,y,z) = \sum_n A_n \cos\frac{n_x \pi x}{L_x} \cos\frac{n_y \pi y}{L_y} \, e^{-j\kappa_n z}$$

The wavenumber κ_n is given by:

$$\kappa_n^2 = (\omega/c)^2 - [(n_x\pi/L_x)^2 + (n_y\pi/L_y)^2]$$

Using this solution:

(i) derive an expression for the "cut-on frequency" of any given mode (corresponding to specific values of the integers n_1 and n_2). Hint: Cut-on is when $\kappa_n^2 = 0$.

(ii) derive an expression for the phase speed of a given mode and sketch its variation with frequency ω.

(b) Calculate the drop in sound pressure level over an axial distance $z = L_y/4$ that is associated with the contribution of the mode specified by $n_x = 2, n_y = 2$ when it is excited at a frequency of three-quarters of its cut-on frequency. Assume that $L_x = L_y/2$.

9.11 (a) Show that if a side branch of acoustic impedance Z_s is introduced into an anechoically terminated duct, then the power transmission coefficient across the side branch is given by:

$$\tau = \frac{R_s^2 + X_s^2}{(R_s + 1)^2 + X_s^2}$$

where $R_s + jX_s = AZ_s/\rho c$ and A is the duct cross sectional area.

(b) Show that the power reflection coefficient:

$$|R_p|^2 \text{ is } \frac{2R_s + 1}{(R_s + 1)^2 + X_s^2}$$

9.12 In a small reciprocating compressor installation, the blade passage frequency of 20Hz is causing excessive piping vibration on the inlet and a reduction of 10dB is needed. The intake pipe diameter is 0.15m and the length upstream of the expansion chamber is 0.3m.

(a) Design a suitable single expansion chamber to provide the required noise reduction.

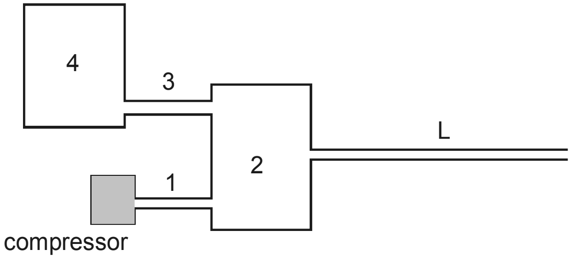
(b) How could the size of the attenuating device be reduced?

9.13 Design a pulsation attenuator to provide an insertion loss of 20dB minimum at the fundamental pulsation frequency of 10Hz for the discharge from a reciprocating compressor. The downstream pipework may be considered sufficiently long that the amplitudes of acoustic waves reflected from the end are negligible at the attenuator discharge. The pipe diameter is 0.1m. Allowable pressure loss is 0.5% of line pressure. Line pressure is 12 MPa. Gas flow rate is

250,000 m^3 per day at 15°C and 101.4kN m^{-2} pressure. The ratio of specific heats is 1.3. The temperature of the gas is 350°C and its molecular weight is 0.029kg/mole.

9.14 Design a low pass filter consisting of 2 in-line expansion chambers and three short tubes to reject a 40Hz tone generated by a fan. The tubes cannot be less than 0.05m in diameter (for pressure drop reasons) and the maximum allowed volume of each chamber is 0.03m^3.

9.15 Consider the muffler system shown in the figure below.

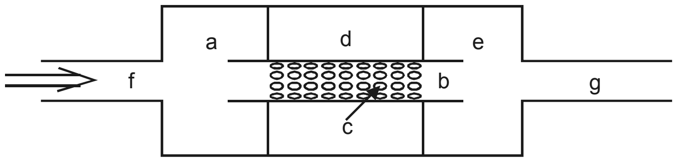


(a) Draw an equivalent acoustical circuit assuming that the termination pipe is of infinite length, and the sound source is a reciprocating compressor.

(b) Write an expression for the insertion loss of the muffler in terms of the impedances of each component numbered in the figure plus the termination impedance Z_L.

(c) If each of two expansion chambers have a volume of 0.2m^3 and each pipe 1 and 3 is 0.3m long by 0.02m diameter, calculate the insertion loss in dB at 10Hz. Assume that acoustic resistances in the system are negligible, and that the given pipe length includes the end correction. Also assume that the pipe *L* is sufficiently long that no reflected waves reach 2. Pipe *L* is also 0.02m in diameter.

9.16 (a) For the muffler shown in the following figure, *a* and *e* are two



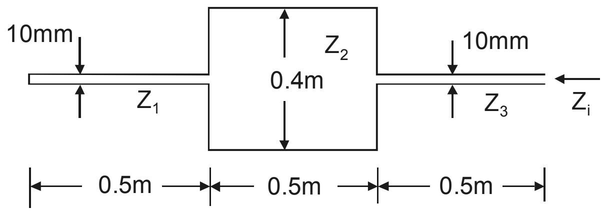
expansion chambers connected by way of tube b. The centre section of tube b is perforated with holes having an impedance Z_c. The holes open to a resonator volume d which is otherwise sealed.

Draw an equivalent circuit diagram for this muffler showing all impedances a through g. If necessary, the impedance Z_b may be divided in two.

(b) Write down the four system equations which need to be solved if the system is driven by a constant volume source.

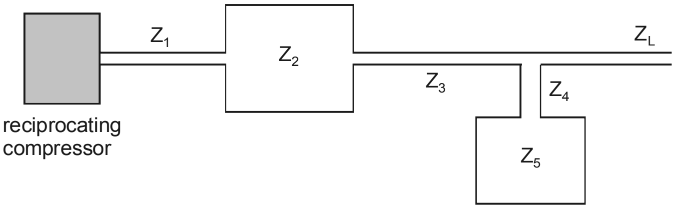
(c) Identify which impedances are capacitative and which are inductive. Which would be associated with a resistive component?

9.17 Consider the system shown in the following figure which is closed at the left end and open at the right end.



(a) Derive an expression for the acoustic impedance Z_i looking into the open end in terms of the impedances Z_1, Z_2 and Z_3 making up the system.

(b) Rewrite the expression derived in (a) in terms of the diameter d_i and length L_i (i = 1, 3) of each element. Assume that each element has a circular cross section.



(c) Calculate the fundamental resonance frequency of the system.

(d) Identify a location where the acoustic pressure would be a maximum at resonance and one where the acoustic particle velocity would be a maximum.

9.18 Consider the muffler system shown in the figure below

(a) Draw an equivalent electrical circuit showing impedances Z corresponding to each of the components labelled in the figure.

(b) Derive an expression for the insertion loss of the muffler (consisting of elements 1 to 5) in terms of the impedances Z_i (i = 1, 5) of each component.

(c) What is the upper frequency above which the result of (b) is no longer valid?

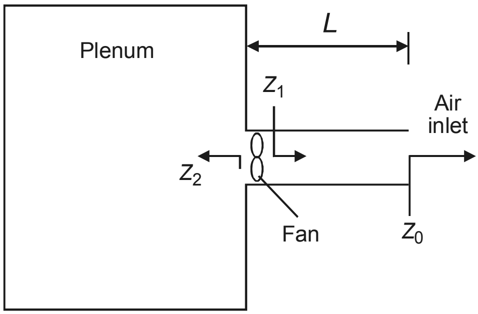
9.19 A loud-speaker is mounted so that the back of its diaphragm looks into a box of volume V. The box in turn is vented through an opening of negligible length and cross sectional area A.

(a) Set up an equivalent acoustical circuit and derive an expression for the load presented to the back of the speaker diaphragm. assume that the enclosure is a cylinder of diameter equal to its length.

(b) At very low frequencies air will move out of the vent as the speaker diaphragm moves into the box, but at higher frequencies the phase of the flow in the vent reverses so that it moves out as the diaphragm moves out. Demonstrate this effect and determine an expression for the cross-over frequency.

(c) If the area of the vent is 0.01m^2, what must the volume V be so that the outflow through the vent reinforces the outflow of the loud-speaker at and above 100Hz?

9.20 Using acoustical circuit analysis, derive an expression for the insertion loss at low frequencies of a 3 compartment plenum chamber installed in an air conditioning duct. The inlet and discharge duct diameters are 0.2m. The plenum chamber volumes are 1, 1.5 and 2m^3 respectively. The plenum chambers are connected by pipes 0.1m long and 0.2m diameter. The source is a fan located 10m upstream from the plenum chamber. The downstream ductwork is terminated in its characteristic impedance (such that no sound waves are reflected upstream from the termination). Define all impedances used in your expression and give numerical values to each quantity necessary to evaluate these impedances.



9.21 The figure shows a plenum chamber which is pressurised by an axial flow fan. The fan draws air in through a short inlet duct, of length L. The generation of low-frequency sound by the fan is modelled in terms of an oscillatory pressure difference Δp across the fan.

(a) Show that if Δp is confined to a single frequency, and Z_0, Z_1, Z_2 are the system complex acoustical impedances at the positions shown in the figure, the low frequency sound power radiated from the inlet duct is:

$$W_0 = \frac{1}{2} \, | \, \Delta p \, |^2 \, \frac{\mathrm{Re}\,\{Z_0\}}{|Z_1 + Z_0|^2}$$

What is the approximate value of $\mathrm{Re}\{Z_0\}$ at low frequencies?

(b) The system in the figure can be regarded as a Helmholtz resonator. Find expressions for Z_1 and Z_2, in the terms of the plenum volume V, the effective neck length L and neck cross sectional area A. Over what frequency range are your expressions valid?

(c) Explain what physical processes contribute to the resistive component of the impedance looking outwards from section (1), i.e. $R_1 = \mathrm{Re}\{Z_1\}$.

(d) Discuss the effect on the radiated sound power of varying the fan position along the inlet duct (instead of placing it at the plenum end, as in the figure).

9.22 Design an exhaust silencer for a small constant speed engine with an exhaust volume flow rate of 0.1 m^3 s^{-1}, temperature of exhaust gas 900°C, ratio of specific heats 1.3 and molecular weight of exhaust gas, 30 gm/mole. Insertion loss at engine speed of 3000 rpm (50Hz) is to be 25dB.

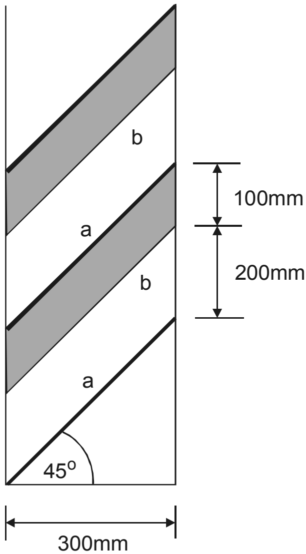
9.23 A lined circular duct is to have an open section 0.3m diameter. Find the duct length required to achieve a 15dB attenuation upstream at 500Hz, if the maximum allowable duct outside diameter is 0.6m and air is flowing in the duct at 17m sec^{-1} in the opposite direction to the sound propagation. (Include attenuation due to effective duct diameter increase.) What additional noise reduction could be expected due to the duct inlet if the direction of sound at the entrance were distributed equally in all directions?

9.24 A lined duct 450mm long and open cross section 75mm high and 300mm wide is required for venting an enclosure. Assume that one or all walls may be lined with a dissipative liner and that the depth of liner is restricted to a maximum $\ell/h = 4$ (see figure 9.15 in the text, centre curve on the left). Assume also that the air flow is negligible.

(a) Could you achieve a noise reduction of 30dB or more in each of the octave bands 1, 2 and 4kHz?

(b) What is the best attenuation you can expect at 500Hz?

9.25 An acoustic enclosure requires a ventilation system. To exhaust the air, a dissipative muffler in the form of a duct lined on all four sides is needed. An attenuation of 9 dB is needed at 125 Hz, 15 dB at 1000 Hz and 15 dB at 2000 Hz. Calculate the length of lined square section duct needed if the maximum allowed outer cross sectional area is 1 m^2 and the minimum allowed internal cross sectional area is 0.25 m^2.



9.26 A louvred inlet is shown in cross section in the following figure, where sides (a) are rigid and impermeable whilst sides (b) are permeable and arranged to contain a porous material of your choice

(a) Referring to figure 9.15 in the text, calculate the ratio ℓ/h.

(b) Using figures 9.15 to 9.18 in the text calculate the required flow resistance of the porous liner.

(c) Determine the expected sound attenuation in octave bands from 63Hz to 8000Hz, given that the louvre width is 400mm. Include inlet and exit losses.

9.27 (a) A broadband sound source is placed inside an open-ended pipe with rigid walls. An attenuator is inserted in the pipe to reduce the amount of low frequency energy escaping from the end. Explain the distinction between Insertion Loss (IL) and Transmission Loss (TL) in this situation.

(b) When placed in a duct terminated so that it appears infinite in length, the attenuator reflects a fraction $|R_p|^2$ and transmits a fraction τ of the acoustic energy incident upon it from either side. Show that under these conditions the attenuator IL and TL are equal and find their value in terms of τ and R_p.

(c) Explain the differences between dissipative, reactive and active attenuators and the preferred applications for each.

9.28 A small room of length 3.32m, width 2.82m and height 2.95m serves, by means of doors at opposite ends of the room, as a passage way connecting two larger rooms. Each door is 2.06m high and 0.79m wide.

(a) If the average absorption coefficient of the small room is 0.1, how much is the sound power in at one door reduced on leaving the second door if the doors are opposite each other in direct line of sight?

(b) If the average absorption could be increased to 0.5 what would be the effect?

(c) Would there be any worthwhile gain in transmission loss of sound power if direct line of sight between doors were prevented as by a screen?

(d) If the sound pressure level in the 500Hz octave band were 85dB re 20µPa in the first room what would be the level in the doorway of the second room? (For the case of $\overline{\alpha} = 0.1$, and no screen).

Assume for this calculation that the second room is essentially anechoic.

9.29 The sound power of noise in the 500Hz octave band, emerging from a 1m diameter a circular exhaust stack, 2m high is 135dB re 10^{-12}W. Calculate the sound pressure level at a distance of 100m in a horizontal direction from the top of the stack. Assume that the attenuation of the ground reflected wave is the same as the direct wave and that the two waves combine incoherently at the receiver.

10

Problems in vibration isolation

10.1 A building engineer's apartment is located on the top of a building next to the building plant room. Her husband complains of noise in the apartment. When the air conditioning plant is running, sound pressure levels in the plant room and apartment are shown in rows (a) and (b) of the table below. To determine the relative importance of structure-borne vs airborne sound, a loudspeaker sound source is place in the plant room (with the airconditioning equipment turned off) with the results shown in rows (c) and (d) in the table. Would better vibration isolation of the plant equipment be likely to reduce the excessive noise problem in the apartment?

Octave band centre frequency (Hz)	63	125	250	500
(a) Plant room sound pressure level (dB re 20μPa)	85	90	88	85
(b) Apartment sound pressure level (dB re 20μPa)	60	54	50	45
(c) Test source, plant room (dB re 20μPa)	75	75	74	73
(d) Test source, apartment (dB re 20μPa)	41	38	36	34

10.2 Explain why the commonly used single degree of freedom model for a resiliently mounted machine generally gives inaccurate estimations of vibration transmission for frequencies in the audio frequency range.

10.3 Equation 10.2 in the text has been derived assuming that the spring is massless and that the mass is infinitely stiff. For this problem, assume that the spring has a finite mass $m_s = S\sigma L$, where S is the effective cross-sectional area, σ is the effective density and L is the length.

(a) Using Rayleigh's method as follows, derive a more accurate form of equation 10.2 which includes the mass of the spring. Proceed by determining the maximum kinetic energy of the spring mass system and then equate this to the maximum potential energy stored in the spring. Assume single frequency excitation and for convenience write the velocity in terms of the amplitude of motion and the angular frequency.

(b) A second effect often neglected in the analysis is the possibility of wave motion in the spring which may result in very large amplitudes of motion called "surge". The surge frequency will depend upon the ratio, N, of the sprung mass, m, to the spring mass, m_s. For the case of $N = m/m_s = 0$, show that the frequency of surge is given by $f_s = 0.25\sqrt{k/m_s}$, where k is the spring constant and m_s is the spring mass. Proceed by writing an expression for the effective Young's modulus in terms of k, S, and L. Use the effective Young's modulus to write an expression for the longitudinal wave speed in the spring and finally assume that the spring is one quarter of a wavelength long at the frequency, f_s, of surge.

(c) The range of vibration isolation for a steel spring has been defined in the text in terms of a lower bound given by $f_0\sqrt{2}$. Determine an upper bound in terms of the surge frequency. In this case, N is not zero and the bound will be some fraction of the surge frequency dependent on the system damping. Assume that this bound is $0.9f_s$.

10.4 Consider a non-rigid frame mounted on isolators. For the purposes of this analysis, suppose that the frame may be represented as a mass on a spring in series with a single spring equivalent to that of the isolators. On this basis, derive the expression used to plot figure 10.6

in the text.

10.5 (a) Draw an equivalent electrical circuit for the mechanical system described by Equation 10.20 in the text, with and without an isolator.
Hint: Mobility is the analog of the reciprocal of electrical or acoustical impedance; force, acoustic velocity and electrical current are analogs; and mechanical velocity, electrical voltage and acoustic pressure are analogs.

(b) Use your two circuits to verify equation 10.20 in the text. Interpret the equation to be the reduction in force transmissibility as a result of including the isolating element.

10.6 Calculate the six resonance frequencies of the isolated mass (50kg) shown in Figure 10.4 if $2b = 0.7$m $2e = 1.0$m, $2h = 0.2$m, the vertical stiffness of each spring is 4kNm^{-1} and the horizontal stiffness of each is 1kNm^{-1}. Assume the mass is of uniform density with a centre of gravity 0.5m above the base of the mounts, and of shape shown in Figure 10.4. Assume the mass is 0.9m wide and 1.2 m deep.

10.7 Calculate the increase in force transmission from a machine through its isolators to a rigid foundation, if the rigid foundation is replaced by a flexible frame of mobility equal to one fifth of the isolator mobility and equal to twice the mobility of the isolated machine. Hint: Use Equation 10.20 from the text book.

10.8 Design an optimum vibration absorber with damping, for a machine of mass 1000kg mounted on a foundation of stiffness of 10 MNm^{-1} and a rotational speed of 3000 rpm, which is the frequency of troublesome vibration.

10.9 In what situations may damping a vibrating surface not significantly reduce its sound radiation?

10.10 The sensitivity of commercially available accelerometers in milli-volts per "g" is about equal numerically to the weight of the accelerometer in grams, although wide variations from this general rule do occur.

(a) If the minimum voltage which can be detected is about 100dB below 1 volt, what is the implied relation between accelerometer weight and the minimum acceleration which can just be detected?

(b) For a given thickness, *h*, of steel plate, what is the relation between minimum acceleration which can be measured and the upper frequency limit for valid measurements? [**Hint:** see equation 10.29 in text].

(c) The acceleration of a steel plate is to be measured. If the minimum acceleration to be expected is 0.01g, what is the upper frequency limit for valid measurements using a typical accelerometer?

10.11 A steel plate radiates a 1kHz tone. The plate is very large compared to a wavelength of sound and moves essentially like a piston.

(a) What is the acceleration of the plate if the sound pressure level close to the plate is 80dB re 20μPa?

(b) What is the displacement of the plate?

(c) What would be the best way to measure the response of the plate?

10.12 Explain under what circumstances the following treatments of a plane, isotropic vibrating surface will decrease its radiated sound level (or increase its Transmission Loss in cases where it is acting as a partition between a low noise environment from a high noise environment).
(a) adding damping
(b) adding stiffness
(c) adding mass

10.13 Vibration velocities measured in octave bands on a diesel engine are listed in the following table.

Octave band centre frequency (Hz)	63	125	250	500	1k

rms vibration velocity (mm/s)	5	10	5	2	0.5

(a) Calculate the overall rms velocity in mm/s
(b) Calculate the overall velocity in dB re the appropriate reference level
(c) Estimate the overall acceleration level in dB re the appropriate reference level
(d) Estimate the overall displacement level in dB re the appropriate reference level

10.14 (a) Describe how you would mount an accelerometer to measure the amplitude of a bending wave in a simply supported beam of rectangular cross-section.
(b) Explain qualitatively the effect that the presence of longitudinal waves in the beam would have on your estimate of the amplitude of the bending waves

10.15 A large machine weighing 1000kg is placed on a set of 4 isolating springs which stand on a rigid concrete foundation and which compress 2mm as they take the load of the machine. Calculate the following.
(a) Resonance frequency of the machine/isolator system for motion in the vertical direction
(b) Reduction (in dB) in the transmitted vertical force as a result of the isolators at the machine operating frequency of 3000rpm. Assume that the isolators have a critical damping ratio of 0.05.
(c) Assuming that the machine may be regarded as a rigid mass, what would be the approximate increase in transmitted force if the isolator were mounted on a floor with a mobility at 50Hz of $-2j \times 10^{-5}$ m/s/N instead of on the rigid concrete floor.

10.16 You are told that the damping of some "low-noise" steel is characterised by a logarithmic decrement of 0.5. Calculate the critical damping ratio and loss factor for the material and comment on how effective the material may be and where it may be used.

11

Problems in active noise control

11.1 Explain the various acoustical mechanisms associated with active noise control. For each of the applications listed below, state whether you think active noise cancellation would be a feasible solution and if so, state in qualitative terms where you would put the reference sensor, control source(s) and error sensor(s) and also outline the acoustical mechanism that would be involved.

(a) low frequency periodic sound propagating in an industrial air handling duct
(b) low frequency random noise emitted from the outlet of an air conditioning duct
(c) low frequency periodic noise emitted by a bank of 6 hydro-electric turbines in a large building
(d) low frequency random noise in a factory
(e) low frequency periodic noise in a factory
(f) propeller noise in an aircraft cabin
(g) propeller noise radiated into the community by a plane flying overhead
(h) aerodynamic noise transmitted into a large aircraft cabin
(i) electrical transformer noise radiated into the surrounding community.