14 Room acoustics

Learning objectives

Study of this chapter will enable the reader to:

1. know the potential sources of sound and vibration within buildings;
2. know what is meant by noise;
3. understand how sound travels through a building;
4. understand what is meant by sound pressure wave, sound power level and sound pressure level;
5. know how to calculate sound pressure levels for normal building services design examples;
6. use sound levels at the range of frequencies commonly used in building services engineering;
7. understand how sound and vibration are transmitted through buildings;
8. be able to identify the need for sound attenuation vibration isolation;
9. understand and use the decibel unit of measurement of sound energy;
10. know the meaning and use of direct and reverberant sound fields;
11. calculate the sound pressure level in a plant room, a space adjacent to the plant room, in the target occupied room and in the external environment outside the plant room;
12. use logarithms to base 10 in acoustic calculations;
13. understand the principle of sound absorption;
14. calculate the sound absorption constant for a room at different frequencies;
15. know the sound absorption coefficients for some common building materials and constructions;
16. understand and use reverberation time and attenuation;
17. calculate sound pressure levels at different frequencies within a plant room;
18. know what a reverberant room and an anechoic chamber are;
19. use directivity index sound absorption coefficients, mean absorption coefficient and room absorption constant;

20. understand the behaviour of equipment at resonant conditions and how to minimize or avoid its occurrence;
21. calculate and use the sound pressure level in a plant room;
22. calculate the sound pressure level experienced at an external location from a plant room;
23. calculate the sound pressure level generated in a room or space that is adjacent to a plant room;
24. calculate the sound pressure levels at different frequencies that are produced in the target occupied room;
25. understand, calculate and use noise rating data;
26. know how the acoustic design engineer relates the noise output from plant systems to the human response;
27. be able to calculate noise rating curves;
28. know the noise rating criteria used for building services design;
29. plot noise rating curves, plant and system sound pressure levels and find a suitable design solution;
30. know the formulae used in practical acoustic design work;
31. be able to carry out sound pressure level and noise rating design calculations, try different solutions to attenuate plant noise and be able to produce a practical design to meet a design brief.

Key terms and concepts

absorption 324; absorption coefficient 326; acoustic 324; acoustic barrier 326; acoustic energy 323; acoustic power 323; air-duct lining 324; air ducts 324; air pressure 323; anechoic chamber 327; atmospheric pressure 323; attenuation 332; audible frequencies 324; Bel 324; building 334; compressible medium 323; compressors 330; decibel 324; directivity 325; direct sound field 325; ear response 323; elastic medium 323; electric impulses 323; engines 330; fan blades 331; fan noise spectrum 331; fans 331; flexible connections 324; fluid 324; free field 325; frequency 324; hemispherical sound field 325; Hertz (Hz) 324; human ear 323; intermediate room 334; logarithm 325; mean absorption coefficient 326; mechanical service equipment 330; molecular vibration 324; multiple reflection 326; natural vibration 326; noise 324; noise rating 336; outdoor environment 333; pipes 324; plant room 325; plant vibrations 330; porous material 326; pressure wave 323; pump blades 331; pumps 331; resonance 332; reverberant sound field 326; reverberation 326; reverberation time 326; room absorption constant 326; rotation 330; rubber mountings 324; solid materials 324; sound 323; sound power 323; sound power level 324; sound pressure 323; sound pressure level 324; springs 324; structure 324; target room 335; total sound field 325; turbulent flow 324; vibration 324; Watts (W) 323; wave 323.

Introduction

This chapter uses the worksheet file DBPLANT.WKS to find the noise rating that will be produced within an occupied room by direct transmission through the building from the noise-producing plant. The plant noise source creates sound pressure levels within the plant room. The plant room noise can pass through an intermediate space, such as a corridor, and then into the target occupied space. Sound can be transmitted from the plant room to a recipient outdoors for an environmental impact noise rating.

Sufficient reference data is provided on the worksheet for examples within this chapter and for some real applications. Reference data from any source can easily be added. This chapter allows for most practical examples of mechanical plant to be assessed quickly and without having to deal with the equations themselves. Data is provided for frequencies from 125 to 4000 Hz as this range is likely to cover the important noise levels for comfort. The range of frequencies can be added to should the need arise. The reader may wish to study the principles of acoustics in the appropriate text books and the references made as it is not the intention of this chapter to teach the subject in its entirety. However, it is the purpose of this chapter to provide an easily understandable method of analysing practical noise applications. Consequently, the reader should not find it difficult to enter correct data and acquire suitable results for educational reasons and in practical design office cases. The worksheet DBDUCT.WKS is used to calculate the noise rating in the target room that is produced by noise being transmitted from the air-conditioning fan through the ductwork system. Further examples of spreadsheet applications and explanation of spreadsheet use are provided in *Building Services Engineering Spreadsheets* (Chadderton, 1997b).

Acoustic principles

The building services design engineer is primarily concerned with controlling the sound produced by items of plant such as boilers, supply air and exhaust air fans, refrigeration compressors, water pumps, diesel or gas engine-driven electrical generating sets and air compressors. An excess of sound that is produced by the plant, above that which is acceptable to the recipient, is termed noise. All the mechanical service equipment and distribution systems to be installed within an occupied building are capable of generating noise.

Sound travels through an elastic, compressible medium, such as air, in the form of waves of sound energy. These waves of energy are in the form of variations in the pressure of the air above and below the atmospheric air pressure. The human ear receives these air pressure fluctuations and converts the vibration generated at the eardrum into electric impulses to the brain. What we understand to be recognizable language, music and noise is the result of human brain activity. Animals and the mythical person from another planet do, or may, process what we determine as normal sounds and come to a different conclusion from those of us who are conditioned to life on earth. These variations in the pressure of the atmospheric air are very small when measured in the Pascal or millibar values that engineers use. A scale of measurement that relates to the subjective response of the human ear is used. Although absolute units of measurement are taken and normal calculation procedures are adopted, it is important to remember that the smallest unit of sound is that which can be detected by the human ear. The waves of air pressure which pass through the atmosphere are measured in relative pressure units. The acoustic energy of the source which caused the air pressure waves has an acoustic power, or rate of producing energy, in the same way that all thermodynamic devices have a power output. There are two ways of assessing the output and transmission of acoustic energy:

1. source sound power: Watts;
2. sound wave atmospheric pressure variation: Pascals.

Sound waves are generated at different frequencies measured in cycles per second, Hertz (Hz). The plant which produces the noise has components that rotate, move and vibrate at a range of different speeds, or frequencies of rotation. The flowing fluid is vibrated by the passage of fan or pump blades and it transfers the plant vibration through to downstream parts of the connected services systems. The fluid is either water, oil, air, gas, refrigerant or steam, and can either simply transmit the plant vibrations and noise or add to them by means of its own pulsations due to its turbulent flow. Turbulence means that a fluid flow contains recirculatory parcels of fluid in the form of eddy currents. These parcels of swirling eddy currents move in all directions, that is, along with the general direction of the main flow, but also in the reverse direction and transversely across the main flow. Viewing wave action on a beach or a fast river flow from a bridge or at a bend reveals the nature of turbulent flow. The turbulent eddy currents occur at a range of frequencies, parcels of recirculating fluid per second, depending upon the overall diameter of the eddy current. The physical movement of the swirling fluid can vibrate the containing water pipe or air duct, causing vibration and noise. Obstructions in the air or waterway occasioned by sharp edges, dampers, grilles, temperature sensors and changes in duct cross-section, can cause the turbulent fluid to shear into additional swirling eddy currents and produce more vibration and noise. Turbulent fluid can vibrate air ducts, pipes and terminal heat exchange units. The structure of the building transmits noise by the vibration of its solid material particles and continuous steel frame and reinforcing bars within concrete framework. Acoustic energy is transferred between pressure waves in the air and vibration through solid materials in either direction. The vibration of fans, compressors, engines and pumps is controlled by mounting them on coiled steel springs, rubber feet and rubber matt. Fluid pipes and air ducts are separated from fans, air-handling units and pumps with flexible connections. These minimize, or stop, plant vibration being transferred to the reticulation system. Fluid-borne noise is reduced by selective absorption with a porous lining to the air duct. Sound waves are absorbed into the thickness of the lining material through a perforated surface material which protects the absorber from fluid damage and erosion. Sound energy is dissipated within the absorber by multiple reflections among the fibrous material.

Sound power and pressure levels

Sound power and pressure levels are measured over a range of frequencies that are representative of the response of the human ear to sounds, Fig. 14.1. The unit of measurement of sound is the Bel (B). The smallest increment of sound that the human ear can detect is one-tenth of a Bel, one decibel (dB). This means that the smallest change in sound level that is perceptible by the human ear is 1 dB, so any decimal places that are produced from calculations using sound power or pressure level are not relevant. A calculated sound level of 84.86 can only be 84 dB as the 0.86 decimal portion is not detectable by the ear. The 'A' scale of measurement gives a weighting to each frequency in the range 20 Hz to 20 kHz in the same ratio as can be heard. For example, the human ear is more sensitive to sounds at 1000 Hz than at higher frequencies.

The acoustic output power of a machine is termed its sound power level, *SWL* dB. Think of *SWL* as the sound watts level of the acoustic output power of the machine. The value of acoustic power in watts from building services plant is very small, much less than 1 watt of power. The word level is used because it is not the actual value of the number of watts that is normally used; it is the sound level produced in acoustic units of measurement, dB, that are taken for practical use. The manufacturer of the plant provides the sound power levels produced by a particular machine from test results and predictions for known ranges of similar equipment. The sound power level of a machine at the range of frequencies from 125 to 8000 Hz is required by the building services design engineer in order to assess the acoustic affects upon the occupied spaces of the building. The overall sound power level for a range of frequencies is also quoted by the manufacturer of a machine.

14.1 Sound pressure level meter (reproduced by courtesy of Casella CEL Ltd).

Sound pressure level

A sound field is created by the sound power output from a machine within a plant room. It is made up of a direct sound field, that is, directly radiated sound, and a reverberant sound field, that is, general sound that reflects uniformly from the hard surfaces around the room. The direct sound field reduces with the inverse square of the distance from the sound source and is not normally of importance as it only applies to very short distances from the sound source. The reverberant sound field results from the average value of the sound pressure waves passing around the room. These waves try to escape from the plant room and find their way into the occupied spaces where the air-conditioning engineer is attempting to create a quiet and comfortable environment. The sound pressure level, *SPL* dB, of the total sound field, direct plus reverberant, that is generated within a room from a sound source of sound power level *SWL* dB, is found from

$$SPL = SWL + 10 \times \log\left(\frac{Q}{4 \times \pi \times r^2} + \frac{4}{R}\right) \text{ dB}$$

(CIBSE [1985] and Sound Research Laboratories Limited), where,

SPL = sound pressure level produced in room	dB
SWL = sound power level of acoustic source	dB
log = logarithm to base 10	dimensionless
Q = geometric directivity factor	dimensionless
r = distance from sound source to the receiver	m
R = room sound absorption constant	m^2

Logarithms to base 10, $\log_{10}$, are used throughout the calculation of acoustic values. A sound source that radiates sound waves uniformly in all directions through unobstructed space will create an expanding spherical sound field and have a dimensionless geometric directionality factor *Q* of 1. A sound source that is on a plane surface radiates all its sound energy into a hemispherical sound field moving away from the surface. This has a directionality factor *Q* of 2, that is, twice the sound energy passes through a hemisphere. Similarly, if the sound source occurs at the junction of two adjacent surfaces that are at right angles to each other, such as the junction of a wall and ceiling, Q is 4. When there are three adjacent surfaces at the sound source, such as two walls and a ceiling, Q is 8. Distance r is that from the sound source to the receiving person, surface or measurement location, such as an air outlet duct from the plant room or outdoor air grille.

Absorption of sound

The room sound absorption constant, R m^2, is found from the total surface area of the enclosing room, S m^2, and the mean sound absorption coefficient of the room surfaces, α, at each of the relevant frequencies:

$$R = \frac{S \times \overline{\alpha}}{1 - \overline{\alpha}}$$

where

$\overline{\alpha}$ = mean absorption coefficient of room surfaces

S = total room surface area m^2

Mean absorption coefficient, α, is found from the area and absorption coefficient for each surface of the enclosing space. All the absorbing surfaces within the space, such as seats and people in a theatre, are included in the overall sound absorbing ability of the room:

$$\overline{\alpha} = \frac{A_1 \times \alpha_1 + A_2 \times \alpha_2 + A_3 \times \alpha_3}{A_1 + A_2 + A_3}$$

where

A_1 = surface area of surface number 1 m^2

α_1 = absorption coefficient of surface number 1

Materials absorb different amounts of sound energy at each frequency due to the frequency of natural vibration of their fibres and the method of their construction. Stiff, dense materials, such as brickwork walls, absorb sound by molecular vibration. Highly porous materials, such as glass wool, have large air passageways that allow the sound waves to penetrate the whole of the material thickness quickly. The strands of glass wool are vibrated by the sound waves and the sound energy is dissipated as heat. Dense materials are very efficient at absorbing acoustic energy. The reduction in sound level between the surfaces of a sound barrier is proportional to the mass of the barrier. The absorption coefficients of some common surface materials are given in Table 14.1. This data is repeated on the worksheet from line 201.

Reverberation time

Reverberation time is the time in seconds taken for a sound to decrease in value by 60 dB. This effectively means the time taken for the sound source to decay to an imperceptible level, as a sound pressure of 30 dB is very quiet to the human ear. An echo is produced by sound waves bouncing, or reverberating, from one or more hard surfaces and this may last for several seconds. A room that has a long reverberation time sounds noisy, lively and it allows echoes. A room having a short reverberation time, less than 1 s, sounds dull and there is no echo. The ultimate in short

Table 14.1 Absorption coefficients of common materials.

Material	*Absorption coefficient at*					
	125 Hz	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*
25 mm plaster, 18 mm plasterboard, 75 mm cavity	0.3	0.3	0.6	0.8	0.75	0.75
18 mm board floor on timber joists	0.15	0.2	0.1	0.1	0.1	0.1
Brickwork	0.05	0.04	0.04	0.03	0.03	0.02
Concrete	0.02	0.02	0.02	0.04	0.05	0.05
12 mm fibreboard, 25 mm cavity	0.35	0.35	0.2	0.2	0.25	0.3
Plastered wall	0.01	0.01	0.02	0.03	0.04	0.05
Pile carpet on thick underfelt	0.07	0.25	0.5	0.5	0.6	0.65
Fabric curtain hung in folds	0.05	0.15	0.35	0.55	0.65	0.65
15 mm acoustic ceiling tile, suspended 50 mm mineral fibre wool or glass fibre matt	0.5	0.6	0.65	0.75	0.8	0.75
50 mm polyester acoustic blanket, metallized film	0.25	0.55	0.75	1.05	0.8	0.7
50 mm glass fibre blanket, perforated surface finish	0.15	0.4	0.75	0.85	0.8	0.85

reverberation time is found in the anechoic chamber that is used for the acoustic testing of equipment. The walls and ceiling of the chamber are lined with thick acoustic absorbent wedges. The floor is a suspended wire mesh, and beneath the floor more absorbent wedges complete the coverage of all the room surfaces. The sound source radiates outward and upon reaching the surfaces is instantly absorbed, allowing no reverberation or echo. This is as close to a free field test method as can be achieved because there is no reverberant field caused by reflected sound waves.

An interesting example of a large semi-anechoic chamber is the car testing facility at Gaydon, England. The four walls and the ceiling are covered with acoustic wedges, while the floor is a plain concrete surface. This simulates an open road, hemispherical acoustic field under laboratory repeatable conditions (CIBSE, 1995).

Reverberation time of a room is found from

$$\text{reverberation time } T = \frac{0.161 \times V}{S \times \overline{\alpha}}$$

(CIBSE [1986] and Sound Research Laboratories Limited).

EXAMPLE 14.1

A plant room for an air-conditioning fan is 4 m × 3 m in plan and 2.5 m high. It has four brickwork walls, a concrete floor and a pitched sheet steel deck roof having 50 mm thickness of glass fibre and an aluminium foil finish to the underside. Ignore the effects of the metal plant, air ductwork and the door into the plant room. Calculate the room constant and the reverberation time for the plant room.

Table 14.2 Solution to Example 14.1.

Surface	*Absorption data at frequency*					
	125 Hz	*250 Hz*	*500 Hz*	*1 kHz*	*2 kHz*	*4 kHz*
Floor α	0.02	0.02	0.02	0.04	0.05	0.05
Ceiling α	0.15	0.4	0.75	0.85	0.8	0.85
Walls α	0.05	0.04	0.04	0.03	0.03	0.02
Floor ($S \times \alpha$)	0.24	0.24	0.24	0.48	0.6	0.6
Ceiling ($S \times \alpha$)	1.8	4.8	9.0	10.2	9.6	10.2
Walls ($S \times \alpha$)	1.75	1.4	1.4	1.05	1.05	0.7
$\bar{\alpha}$	0.064	0.109	0.18	0.199	0.191	0.195
Room constant R m^2	4.03	7.21	12.95	14.66	13.93	14.29
Reverberation T s	1.28	0.75	0.45	0.41	0.43	0.42

The surface absorption coefficients are selected from Table 14.1. It can be seen that there will be a different room constant and reverberation time for each frequency. The solution is presented in Table 14.2.

$$\text{Room volume } V = 4 \times 3 \times 2.5 \text{ m}^2$$
$$= 30 \text{ m}^3$$
$$\text{floor area} = 12 \text{ m}^2$$
$$\text{ceiling area} = 35 \text{ m}^2$$
$$\text{wall area} = 35 \text{ m}^2$$
$$\text{Room surface area } A = (2 \times 4 \times 3) + (4 + 4 + 3 + 3) \times 2.5 \text{ m}^2$$
$$= 59 \text{ m}^2$$

For 125 Hz, the mean absorption coefficient is,

$$\overline{\alpha} = \frac{12 \times 0.02 + 12 \times 0.15 + 35 \times 0.05}{12 + 12 + 35}$$
$$= 0.064$$
$$\text{room constant } R = \frac{S \times \overline{\alpha}}{1 - \overline{\alpha}} \text{ m}^2$$
$$= \frac{59 \times 0.064}{1 - 0.064} \text{ m}^2$$
$$= 4.03 \text{ m}^2$$
$$\text{reverberation time } T = \frac{0.161 \times V}{S \times \overline{\alpha}}$$
$$= \frac{0.161 \times 30}{59 \times 0.064} \text{ s}$$
$$= 1.28 \text{ s}$$

EXAMPLE 14.2

An air-conditioning centrifugal fan has an overall acoustic output power level *SWL* of 87 dB on the 'A' scale. The fan is to be installed centrally within the air-handling plant room described in Example 14.1. Calculate the sound pressure level that will be produced in the plant room at 1000 Hz when the fan is operating, close to the fan and also generally within the room.

Room absorption constant from Example 14.1 at 1000 Hz

$R = 14.66\ \text{m}^2$

The fan is on the centre of a concrete floor in the plant room. Sound pressure waves leaving the fan will radiate into a hemispherical field above floor level. The sound waves are concentrated into half of a completely free field. The directivity, Q, of the sound field is 2. A person within the plant room can stand in the range of 100 mm–2 m away from the fan. A typical distance between the fan and the recipient is 1 m. The room sound pressure level is calculated for 100 mm and 1 m distances from the sound source. When

$$r = 100\ \text{mm}$$

$$SPL = SWL + 10 \times \log_{10}\left(\frac{Q}{4 \times \pi \times r^2} + \frac{4}{R}\right)\ \text{db}$$

$$= 87 + 10 \times \log_{10}\left(\frac{2}{4 \times \pi \times 0.1^2} + \frac{4}{14.66}\right)\ \text{db}$$

$$= 87 + 10 \times \log_{10}(16.188)\ \text{dB}$$

$$= 87 + 10 \times 1.2092\ \text{dB}$$

$$= 99\ \text{dB}$$

The smallest change in sound level that is perceptible by the human ear is 1 dB, so the decimal places are not relevant. The plant room sound pressure level at 100 mm radius from the fan is 99 dB. At 1 m from the fan, the recipient experiences a sound pressure level of

$$r = 1\ \text{m}$$

$$SPL = 87 + 10 \times \log_{10}\left(\frac{2}{4 \times \pi \times 1^2} + \frac{4}{14.66}\right)\ \text{dB}$$

$$= 87 + 10 \times \log_{10}(0.432)\ \text{dB}$$

$$= 87 + 10 \times -0.3645\ \text{dB}$$

$$= 83\ \text{dB}$$

The direct sound field diminishes with distance from the source. The reverberant sound field establishes the general room sound pressure level when the recipient is sufficiently far away from the source.

Table 14.3 Fan sound spectrum in Example 14.3.

Item	*Data at frequency*					
	125 Hz	*250 Hz*	*500 Hz*	*1 kHz*	*2 kHz*	*4 kHz*
Room constant R m^2	4.03	7.21	12.95	14.66	13.93	14.29
Reverberation T s	1.28	0.75	0.45	0.41	0.43	0.42
Fan *SWL* dB	78	82	86	87	70	60
Room *SPL* dB	78	79	81	82	65	55

EXAMPLE 14.3

The spectrum of sound power levels produced by the centrifugal fan being installed in the 4 m × 3 m × 2.5 m high plant room in Example 14.1 is 78 dB at 125 Hz, 82 dB at 250 Hz, 86 dB at 500 Hz, 87 dB at 1 kHz, 70 dB at 2 kHz, and 60 dB at 4 kHz. Use the surface absorption data from Example 14.1 and calculate the room sound pressure level at a radius of 1.5 m from the fan for each frequency from 125 Hz to 4 kHz.

At 125 Hz,

SWL is 78 dB.

$$r = 1.5 \text{ m}$$

$$Q = 2$$

$$R = 4.03 \text{ m}^2$$

$$SPL = SWL + 10 \times \log_{10}\left(\frac{Q}{4 \times \pi \times r^2} + \frac{4}{R}\right) \text{ dB}$$

$$= 78 + 10 \times \log_{10}\left(\frac{2}{4 \times \pi \times 1.5^2} + \frac{4}{4.03}\right) \text{ dB}$$

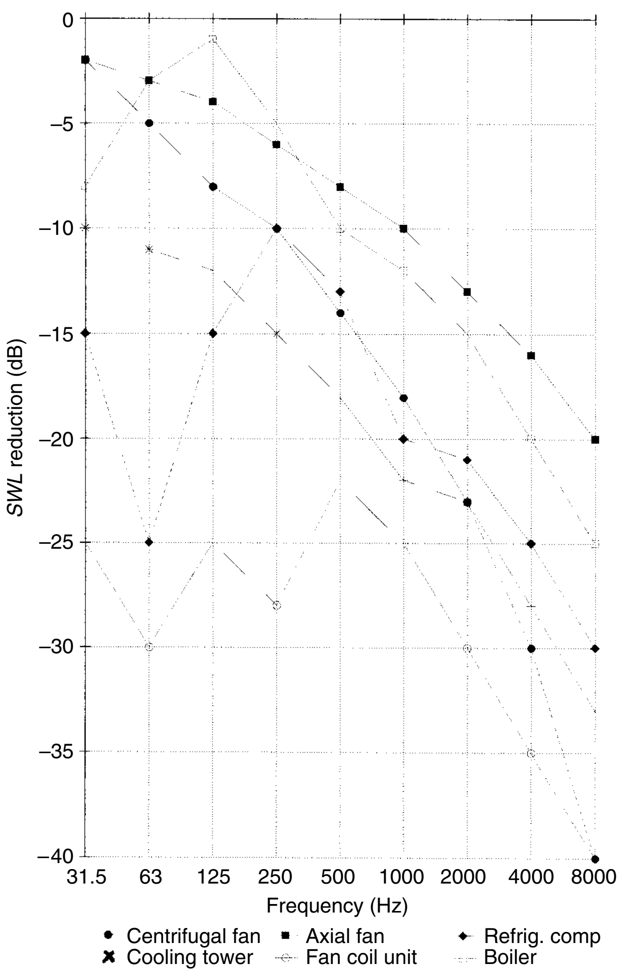
$$= 78 \text{ dB}$$

The results are shown in Table 14.3.

Plant sound power level

The design engineer requires to know the sound power level of the, potentially, noise-producing items of plant. These plant items will be the supply air fan, extract air fan, exhaust fans from toilets, kitchens and some store rooms, fan coil units in ceiling spaces above occupied rooms, packaged air-handling units incorporating fans, direct refrigerant expansion outdoor condensing units, direct refrigerant expansion packaged air-conditioning roof-mounted units, gas- and oil-fired boilers, packaged air conditioners and heat pumps within rooms, external cooling towers and dry-air-cooled heat exchangers, refrigeration compressors and water chilling refrigeration plant. In addition to these major items of plant, supply air grilles, extract air grilles, room terminal air-handling units, dampers, air volume control boxes and fan-powered variable air volume control boxes can also generate noise. The manufacturer of these items will provide the results of acoustic test data for the building services design engineer. Current acoustic data, rather than catalogue information, is acquired and the manufacturer then becomes responsible for the numbers used. The designer needs the sound power level at each frequency that is to be analysed. These are normally 125–4000 Hz. Often the critical frequency for design will be 1000 Hz and this corresponds to a sensitive band in the human ear response.

For the worked examples and questions within this book, sound power levels are provided, either in the form of a discrete value for each frequency, or a single value for all frequencies for the plant item. Figure 14.2 gives an indication of the variations in sound power level from a single value for centrifugal fans, axial fans, refrigeration compressors, cooling towers, fan coil units and boilers. The reader will find the spectral sound power level by subtracting the variances from the single value quoted in the example or question. This data is not to be used in real design work as it is provided for illustration purposes only. The numbers that were used to produce Fig. 14.2 are listed in Table 14.4. Figure 14.2 is also provided as a chart on the worksheet file.



14.2 Plant *SWL* dB, spectral variation.

Table 14.4 Illustrative sound power level variances from Figure 14.1.

Plant item	*Sound power level dB variance at frequency*								
	31.5 Hz	*63 Hz*	*125 Hz*	*250 Hz*	*500 Hz*	*1 kHz*	*2 kHz*	*4 kHz*	*8 kHz*
Centrifugal fan	−2	−5	−8	−10	−14	−18	−23	−30	−40
Axial fan	−2	−3	−4	−6	−8	−10	−13	−16	−20
Refrigeration compressor	−15	−25	−15	−10	−13	−20	−21	−25	−30
Cooling tower	−10	−11	−12	−15	−18	−22	−23	−28	−33
Fan coil unit	−25	−30	−25	−28	−22	−25	−30	−35	−40
Boiler	−8	−3	−1	−5	−10	−12	−15	−20	−25

Transmission of sound

The sound pressure within a space will cause the flow of acoustic energy to an area that has a lower acoustic pressure. Sound energy converts into structural vibration and passes through solid barriers. A reduced level of sound pressure is established in the adjacent space due to the attenuation of the separating partition, wall, floor or ceiling. Air passageways through the separating partition act as sound channels that have little, or no, sound-reducing property, or attenuation. The reader can validate this effect by partially opening a window when the outdoor sound level is substantial. Compare the open and closed window performance when a train, lorry or high traffic volumes are present. A well-air-sealed single-glazed window imposes a sound reduction of 30 dB on external noise but a poorly sealed or open window has little attenuation.

Sound reduction by a surface is from the reflection of sound waves striking the surface and by the absorption of sound energy into a porous material. Absorbed acoustic energy is dissipated as heat within the solid components of the absorber. Dense materials are often efficient sound attenuators. The exception is metal. Sound travels easily through metals for great distances due to their molecular vibration. When the imposed sound frequency coincides with a natural frequency of vibration of the metal, resonance occurs and an increased sound level may be generated. This happens in particular when the shape of the metal creates an air space for the sound waves to resonate within, such as in a bell, an empty tank or a pipe. The structural steel within a building, service pipework, air ducts and railways lines can all transfer noise and vibration over long distances.

The sound pressure level generated within a room by mechanical plant, or sound systems for entertainment, will be passed through sound barrier materials and constructions such as walls and the ceiling, to adjacent spaces, occupied rooms and to the external environment around the building. The sound pressure levels received at each frequency depend upon the barrier attenuation, distance between the sound source and the recipient and the acoustic properties of the receiving space. The low-frequency sound waves, below 1000 Hz, are more difficult to attenuate than those above 1000 Hz. This is because the commonly used building and sound absorbing materials and vibration-isolating rubber all have a low natural frequency of vibration. They will resonate at a frequency often as low as 100 Hz. A material loses its attenuation property at the resonant frequency. Worse still, of course, is that when a rotary machine passes through or runs at its natural frequency of vibration, during start-up procedures, additional noise can be generated and the amplitude of its vibration may escalate to the point of physical destruction. It is vital that variable-speed controllers run the rotary machine speed through its resonant frequency band as quickly as possible to minimize noise and vibration. Attenuation materials such as brick, concrete, timber and acoustic fabric are good at absorbing sounds at the higher frequencies.

The human ear is most sensitive to sounds around 1000 Hz, making this the critical frequency for the acoustic design engineer.

Sound pressure level in a plant room

The sound source space is normally the mechanical services plant room. The reverberant sound pressure level in a plant room can be taken as

$$SPL_1 = SWL + 10 \times \log(T_1) - 10 \times \log(V_1) + 14 \text{ dB}$$

(Sound Research Laboratories Limited; see also, Smith *et al*. (1985)), where

SPL_1 =	sound pressure level in plant room	dB
SWL =	sound power level of source mechanical plant	dB
T_1 =	reverberation time of plant room	s
V_1 =	volume of plant room	m^3

The reverberant sound pressure level is independent of the measurement location within the room. When a sound pressure level is required at a known location, the earlier equation is used with the radius from the source, r m,

$$SPL = SWL + 10 \times \log_{10}\left(\frac{Q}{4 \times \pi \times r^2} + \frac{4}{R}\right) \text{ dB}$$

EXAMPLE 14.4

A refrigeration compressor has an overall sound power level of 86 dB on the 'A' scale. The plant room has a reverberation time of 2 s and a volume of 70 m^3. Calculate the plant room reverberant sound pressure level.

$$SWL = 86 \text{ dBA}$$
$$T_1 = 2 \text{ s}$$
$$V_1 = 70 \text{ m}^3$$
$$SPL_1 = SWL + 10 \times \log(T_1) - 10 \times \log(V_1) + 14 \text{ dB}$$
$$= 86 + 10 \times \log(2) - 10 \times \log(70) + 14 \text{ dB}$$
$$= 83 + 3 - 18 + 14 \text{ dBA ignoring decimal places}$$
$$= 85 \text{ dBA}$$

Outdoor sound pressure level

The sound pressure level in the outdoor environment immediately external to the plant room can be taken as:

$$SPL_2 = SPL_1 - B + 10 \times \log(S_2) - 20 \times \log(d) + DI - 17 \text{ dB}$$

(Sound Research Laboratories Limited), where

SPL_2 =	outdoor air sound pressure level	dB
SPL_1 =	sound pressure level in source room	dB
B =	sound reduction index of exterior wall or roof	dB
S_2 =	surface area of external wall or roof	m^2
d =	distance between plant room surface and recipient	m
DI =	directivity index	dB

EXAMPLE 14.5

A refrigeration compressor generates an overall sound pressure level of 85 dBA within a plant room. The plant room has an external wall of 12 m^2 that has an acoustic attenuation of 30 dB. Sound radiates from the plant room wall into a hemispherical field that has a directivity index of 2 dB. Bedroom windows of an hotel are at a distance of 4 m from the plant room wall. Calculate the external sound pressure level at the hotel windows.

$$SPL_1 = 85 \text{ dBA}$$

$$B = 30 \text{ dBA}$$

$$S_2 = 12 \text{ m}^2$$

$$d = 4 \text{ m}$$

$$DI = 2 \text{ dB}$$

$$SPL_2 = SPL_1 - B + 10 \times \log(S_2) - 20 \times \log(d) + DI - 17 \text{ db}$$

$$= 85 - 30 + 10 \times \log(12) - 20 \times \log(4) + 2 - 17 \text{ dB}$$

$$= 85 - 30 + 10 - 12 + 2 - 17 \text{ dB}$$

$$= 38 \text{ dBA}$$

Sound pressure level in an intermediate space

The sound which is generated within a plant room may be transferred into an intermediate space within a building before being received in the target occupied room. Such intermediate spaces are corridors, store rooms, service ducts or roof voids. While it may not be important what the sound pressure level is within the intermediate space, the acoustic performance of this space affects the overall transfer of sound to the target occupied area. When the intermediate space is very large and has thermally insulated surfaces, for example, in a roof space, a considerable attenuation is possible. The sound pressure level in such an intermediate room or space can be taken as

$$SPL_3 = SPL_1 - SRI + 10 \times \log(S_4) + 10 \times \log(T_2) - 10 \ \log(0.16 \times V_2) \text{ dB}$$

(Sound Research Laboratories Limited), where

SPL_3 =	sound pressure level in intermediate space	dB
SPL_1 =	sound pressure level in plant room	dB

SRI = sound reduction index of common surface dB
S_4 = area of surface common to both rooms m^2
T_2 = reverberation time of intermediate space s
V_2 = volume of intermediate space m^3

EXAMPLE 14.6

A showroom has floor dimensions of 25 m × 10 m and a height of 3.6 m to a suspended tile ceiling. The average height of the ceiling void is 1.8 m. An air-conditioning system has distribution ductwork in the roof void above the suspended acoustic ceiling tiles. The air-handling plant room is adjacent to the roof void and there is a common plant room wall of 5 m × 2.5 m high in the roof void. The sound pressure level in the plant room is expected to be 50 dB. The reverberation time of the roof void is 0.8 s. The plant room wall adjoining the roof void has a sound reduction index of 10 dB. Calculate the sound pressure level that is produced within the roof void as the result of the air-handling plant room noise.

$$SPL_3 = 50 \text{ dB}$$

$$SRI = 10 \text{ dB}$$

$$S_4 = 12.5 \text{ m}^2$$

$$T_2 = 0.8 \text{ s}$$

$$V_2 = 25 \times 10 \times 1.8 \text{ m}^3$$

$$= 450 \text{ m}^3$$

$$SPL_3 = SPL_1 - SRI + 10 \times \log(T_2) - 10 \times \log(0.16 \times V_2) \text{ dB}$$

$$= 50 - 10 + 10 \times \log(12.5) + 10 \times \log(0.8) - 10 \times \log(0.16 \times 450) \text{ dB}$$

$$= 50 - 10 + 10 + 0 - 11 \text{ dB}$$

$$= 39 \text{ dB}$$

Sound pressure level in the target room

The sound pressure level in the target occupied room or space can be taken as:

$$SPL_4 = SPL_3 - SRI + 10 \times \log(S_5) + 10 \times \log(T_3) - 10 \times \log(0.16 \times V_3) \text{ dB}$$

(Sound Research Laboratories Limited), where

SPL_4 = sound pressure level in target room dB
SPL_3 = sound pressure in adjacent room dB
SRI = sound reduction index of common surface dB
S_5 = area of surface common to both rooms m^2
T_3 = reverberation time of target room s
V_3 = volume of target room m^3

The target room may be adjacent to, or close to, the plant room, or it may not be influenced by the plant room other than by the transfer of noise through the interconnected air-ductwork system. Analysis of the ductwork route for noise transfer is calculated separately and is not covered in this book.

EXAMPLE 14.7

The showroom in Example 14.6 has floor dimensions of 25 m × 10 m and a height of 3.6 m to a suspended tile ceiling. The reverberation time of the showroom is 0.5 s. The air-conditioning plant room generates a sound pressure level of 39 dB in the roof space. The acoustic tile ceiling has a sound reduction index of 12 dB. Calculate the sound pressure level that is produced within the showroom by the air-conditioning plant.

$$SPL_3 = 39 \text{ dB}$$

$$SRI = 12 \text{ dB}$$

$$S_5 = 250 \text{ m}^2$$

$$T_3 = 0.5 \text{ s}$$

$$V_3 = 25 \times 10 \times 3.6 \text{ m}^2$$

$$= 900 \text{ m}^3$$

$$SPL_4 = SPL_3 - SRI + 10\log(S_5) + 10 \times \log(T_3) - 10 \times \log(0.16 \times V_3) \text{ dB}$$

$$= 50 - 12 + 10 \times \log(250) + 10 \times \log(0.5) - 10 \times \log(0.16 \times 900) \text{ dB}$$

$$= 50 - 12 + 23 - 3 - 21 \text{ dB}$$

$$= 37 \text{ dB}$$

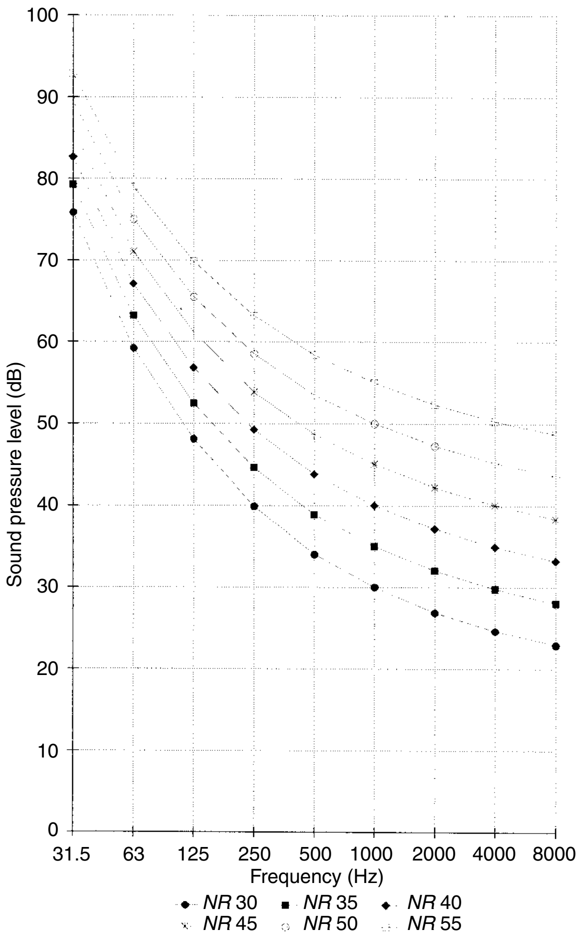
Noise rating

The human ear has a different response to each frequency within the audible range of 20–20 000 Hz. It has been found that a low-frequency noise can be tolerated at a greater sound pressure level than a high-frequency noise. Noise rating (*NR*) curves are used to specify the loudness of sounds. Each curve is a representation of the response of the human ear in the range of audible frequencies.

The design engineer makes a comparison between the sound pressure level produced in the room at each frequency and the noise rating curve data at the same frequency. When all the noise levels within the room fall on or below a noise rating curve, that noise rating is attributed to the room. Noise rating curves for *NR* 25 to *NR* 50 are shown on Fig. 14.3. The values are plotted from,

$$SPL = NR_f \times B_f + A_f \text{ dB}$$

SPL = sound pressure level at frequency f and noise rating NR		dB
NR_f = noise rating at frequency f Hz		dimensionless
B_f and A_f = physical constants		dB
f = frequency		Hz



14.3 Noise rating curves.

Table 14.5 Physical constants for noise rating calculation.

Frequency f (Hz)	A_f *(dB)*	B_f *(dB)*
31.5	55.4	0.681
63	35.5	0.79
125	22.0	0.87
250	12.0	0.93
500	4.8	0.974
1000	0	1.0
2000	−3.5	1.015
4000	−6.1	1.025
8000	−8.0	1.03

The values of the physical constants to calculate noise rating are shown in Table 14.5 (Australian Standard AS 1469–1983).

The normal applications of noise rating are shown in Table 14.6.

Table 14.6 Noise rating applications.

Application	*Noise rating*	*Comment*
Acoustic laboratory	*NR* 15	Critical acoustics
Radio studio	*NR* 15	Critical acoustics
Concert hall	*NR* 15	Critical acoustics
TV studio	*NR* 20	Excellent listening
Large conference room	*NR* 25	Very good listening
Hospital, home, hotel	*NR* 30	Sleeping, relaxing
Library, private office	*NR* 35	Good listening
Office, restaurant, retail	*NR* 40	Fair listening
Cafeteria, corridor, workshop	*NR* 45	Moderate listening
Commercial garage, factory	*NR* 50	Minimum speech interference
Manufacturing	*NR* 55	Speech interference
Heavy engineering to industrial	*NR* 60 to *NR* 80	Sound levels judged on merits, leading to risk of hearing damage

EXAMPLE 14.8

An air-conditioning fan produces the sound spectrum shown in Table 14.7 within an occupied room. Calculate the sound pressure levels for noise ratings *NR* 35, *NR* 40, *NR* 45, *NR* 50 and *NR* 55, and plot the noise rating curves for the frequency range from 31.5 to 8000 Hz. Plot the room sound pressure levels on the same graph and find which noise rating is not exceeded.

Table 14.7 Noise spectrum in Example 14.8.

Frequency *f* (Hz)	31.5	63	125	250	500	1k	2k	4k	8k
Room *SPL* (dB)	39	44	48	52	55	49	36	33	28

A manually calculated example for one noise rating curve is shown. The reader should use the spreadsheet graph or chart facilities to plot the whole figure. Calculate the *SPL* values for *NR* 55.

$$NR_{fd} = 55$$

$$SPL = NR_f \times B_f + A_f \text{ dB}$$

Calculate the *SPL* at each frequency for the values of B_f and A_f from Table 14.5. For 31.5 Hz,

$$SPL = 55 \times 0.681 + 55.4 \text{ dB}$$

$$= 92 \text{ dB}$$

For 63 Hz,

$$SPL = 55 \times 0.79 + 35.5 \text{ dB}$$

$$= 78 \text{ dB}$$

For 125 Hz,

$$SPL = 55 \times 0.87 + 22 \text{ dB}$$
$$= 69 \text{ dB}$$

For 250 Hz,

$$SPL = 55 \times 0.93 + 12 \text{ dB}$$
$$= 63 \text{ dB}$$

For 500 Hz,

$$SPL = 55 \times 0.974 + 4.8 \text{ dB}$$
$$= 58 \text{ dB}$$

For 1000 Hz,

$$SPL = 55 \times 1.0 + 0 \text{ dB}$$
$$= 55 \text{ dB}$$

For 2000 Hz,

$$SPL = 55 \times 1.015 - 3.5 \text{ dB}$$
$$= 52 \text{ dB}$$

For 4000 Hz,

$$SPL = 55 \times 1.025 - 3.5 \text{ dB}$$
$$= 50 \text{ dB}$$

For 8000 Hz,

$$SPL = 55 \times 1.03 - 8.0 \text{ dB}$$
$$= 48 \text{ dB}$$

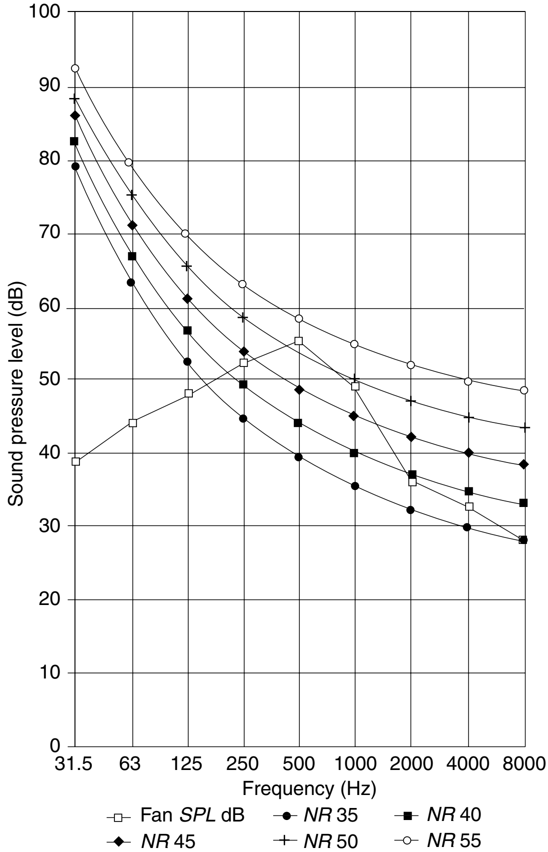
These sound pressure levels are compared to the room data in Table 14.8.

The closest approach to the *SPL* limit for *NR* 55 occurs at 500 Hz. Check that *NR* 50 is exceeded. For 500 Hz,

$$SPL = 50 \times 0.974 + 4.8 \text{ dB}$$
$$= 53 \text{ dB}$$

Table 14.8 Noise spectrum in Example 14.8.

Frequency *f* (Hz)	31.5	63	125	250	500	1k	2k	4k	8k
NR 55 *SPL* (dB)	92	78	69	63	58	55	52	50	48
Room *SPL* (dB)	39	44	48	52	55	49	36	33	28



14.4 Noise ratings, solution to Example 14.8.

It should now be possible to check manually any sound pressure level against noise rating. Once the frequency that produces the greatest sound pressure level from the sound source is identified, other *SPL* values can be obtained for the peak frequency to check which *NR* is not exceeded.

The room does not exceed the *NR* 55 curve data but it does exceed *NR* 50. Plot the chart with the spreadsheet functions for *NR* 35 to *NR* 55 and with the room noise *SPL*. The spreadsheet will produce curves for six sets of data, so five *NR* curves and the one room curve can be displayed on one chart. The results are shown in Fig. 14.4.

Questions

Questions 1 to 31 do not need to be evaluated on the worksheet. The worksheet is to be used for Questions 32 onwards. The solution to Question 32 is shown on the original file DBPLANT.WKS. Solutions to descriptive questions are to be found within the chapter, except where specific answers are provided.

1. List the sources of noise that could be found within an air-conditioned building.
2. What is meant by noise?

3. State which items of mechanical services plant, equipment and systems within an occupied building are not likely to create noise.
4. Explain how sound travels from one location to another.
5. Explain what is meant by the term sound pressure wave.
6. Why is sound important?
7. Explain how we 'hear' sounds.
8. State what is meant by sound power and sound pressure level. State the units of measurement for sound power, sound pressure, sound power level and sound pressure level.
9. Explain why any decimal fraction of a decibel is not used in engineering design.
10. List the ways in which mechanical and electrical services plant, equipment and systems generate sound.
11. Explain, with the aid of sketches and examples, how sound is transferred, or can be, through a normally serviced multi-storey occupied building.
12. Discuss the statement: 'Turbulent flows in building services systems create a noise nuisance.'
13. State how the building structure transfers sound.
14. Explain, with the aid of sketches, ways in which the noise and vibration produced by the mechanical and electrical services of a building can be reduced before they become a nuisance for the building's users.
15. Explain how sound energy is dissipated into the environment.
16. State the range of frequencies that are detectable by the human ear and the frequencies that are used in acoustic design calculations. State the reasons for these two ranges being different, if they are.
17. Define the terms 'sound power level' and 'sound pressure level'.
18. Explain what is meant by direct and reverberant sound fields.
19. A plant room for a refrigeration compressor is 6 m $\times$ 4 m in plan and 3 m high. It has four brickwork walls, a concrete floor and a concrete roof. Select the surface absorption coefficients for the frequency range 125–4000 Hz from Table 14.1. Calculate the room absorption constant and the reverberation time for the plant room at each frequency. Do the calculations manually and then enter the same data onto the worksheet to validate the results.
20. An air-conditioning centrifugal fan has an overall sound power level *SWL* of 75 dBA. The fan is to be installed centrally within a plant room that has a room absorption constant R of 12 m^2. Calculate the sound pressure level that will be produced close to the fan, in the plant room at 1000 Hz when the fan is operating, and also generally within the room.
21. A 900 mm diameter axial fan is to be installed on the concrete floor of an 8 m $\times$ 4 m $\times$ 3 m high plant room. The fan sound power level at 1000 Hz is 89 dB. The room absorption constant R at 1000 Hz is 8 m^2 and the reverberation time is 0.4 s. Calculate the room sound pressure level at a radius of 300 mm from the fan, and the reverberant room sound pressure level.
22. A reciprocating water chilling refrigeration compressor has an overall sound power level of 92 dBA. It is to be located within a concrete-and-brick plant room that has a reverberation time of 1.8 s and a volume of 250 m^3. Calculate the plant room reverberant sound pressure level.
23. An air-handling plant has an overall sound power level of 81 dB. The plant room has an external wall of 10 m^2 that has an acoustic attenuation of 35 dB and ventilation openings having a free area of 3 m^2. The windows of residential and office buildings are at a distance of 12 m from the plant room wall. Calculate the external sound pressure level at the windows and recommend what, if any, attenuation is needed at the plant room.

24. A forced-draught gas-fired boiler has an overall sound pressure level of 96 dB. The boiler plant room has an external wall of 60 m^2 that has an acoustic attenuation of 25 dB and two louvre doors to admit air for combustion. Calculate the external sound pressure level at a distance of 20 m from the plant room wall. State your recommendations for the attenuation of the boiler and the plant room.
25. A single-storey office building has floor dimensions of 40 m × 30 m and a height of 3 m to a suspended acoustic tile ceiling. The average height of the ceiling void is 1.5 m. A plant room is adjacent to the roof void. There is a common plant room wall of 10 m × 1.5 m high in the roof void. The sound pressure level in the plant room is expected to be 61 dB. The reverberation time of the roof void is 0.6 s. The plant room wall adjoining the roof void has a sound reduction index of 13 dB. Calculate the sound pressure level that is produced within the roof void as the result of the plant room noise. Comment on the resulting sound pressure level.
26. A hospital waiting area has floor dimensions of 8 m × 12 m and a height of 3 m to a plasterboard ceiling. A packaged air-conditioning unit is housed in an adjacent room. There is a common wall of 15 m^2 and sound reduction index of 35 dB to the two rooms. The sound pressure level in the plant room is expected to be 72 dB. The reverberation time of the waiting room is 1.3 s. Calculate the sound pressure level that will be produced in the waiting room.
27. A meeting room has floor dimensions of 8 m × 6 m and a height of 2.7 m to a suspended tile ceiling. The reverberation time of the room is 0.7 s. A fan coil heating and cooling unit creates a sound pressure level of 43 dB in the ceiling space. The acoustic tile ceiling has a sound reduction index of 8 dB. Calculate the sound pressure level in the meeting room.
28. An hotel bedroom is 6 m long, 5 m wide and 2.8 m high and it has a reverberation time of 0.4 s. The air-conditioning plant room generates a sound pressure level of 56 dB in the service space above the ceiling of the bedroom. The plasterboard ceiling has a sound reduction index of 16 dB. Calculate the sound pressure level in the bedroom.
29. Explain how noise rating curves relate to the response of the human ear and are used in the design of mechanical services plant and systems.
30. The centrifugal fan in an air-handling plant produces the noise spectrum shown in Table 14.9 within an office. Calculate the sound pressure levels for noise ratings *NR* 35, *NR* 40, *NR* 45, *NR* 50 and *NR* 55 and plot the noise rating curves for the frequency range 31.5 Hz–8 kHz. Plot the room sound pressure levels on the same graph and find which noise rating is not exceeded.
31. A model XT45 water chiller is to be located within a plant room on the roof of an hotel in a city centre. The plant room is 12 m long, 10 m wide and 3 m high. The room directivity index is 2. The plant operator will normally be 1 m from the noise source. The floor is concrete, the roof is lined internally with a 50 mm polyester acoustic blanket with a metallized film surface. The plant room walls are 115 mm brickwork. There are no windows. The water chiller manufacturer provided the sound power levels as 100 dB overall, 74 dB at 63 Hz, 89 dB at 125 Hz, 95dB at 250 Hz, 97 dB at 500 Hz, 99 Hz at 1 kHz, 97 dB at 2 kHz and 90 dB at 4 kHz.

    (a) Check that the correct data is entered onto the working copy of the original worksheet file DBPLANT.WKS and find the noise rating that is not exceeded within the plant room.

Table 14.9 Noise spectrum in Question 30.

Frequency *f* (Hz)	31.5	63	125	250	500	1k	2k	4k	8k
Room *SPL* (dB)	30	35	32	40	42	31	28	20	10

(b) The plant room has three external walls. The nearest openable window in nearby buildings is at a distance of 15 m from a plant room wall. There is no acoustic barrier between a plant room wall and the recipient's window. The directivity index for the outward projection of sound is taken as 3 dB. Find the noise rating at the recipient's window and state what the result means.

(c) A corridor adjoins the plant room. The target sound space, an office, is on the opposite side of the corridor. The corridor is 10 m long, 1 m wide and 3 m high. It has a room directivity index of 2, a carpeted concrete floor, plastered brick walls and a plasterboard ceiling. The common wall between the plant room and the corridor is 10 m long, it is constructed with 115 mm plastered brickwork and it does not have a door. There are no windows. There is no other sound barrier. Find the noise rating which would be found at a distance of 0.5 m from the plant room wall while within the corridor.

(d) The target office is 10 m long, 10 m wide and 3 m high. The room directivity index is 2. The nearest sedentary occupant of the office will be 1 m from the corridor wall. The floor has pile carpet, the walls are plastered brick and there is a suspended ceiling of 15 mm acoustic tile and 50 mm glass fibre matt. The office has four 2 m $\times$ 2 m single-glazed windows on two external walls. The office wall that adjoins the corridor is 115 mm plastered brickwork and it has one 2 m^2 door into the corridor. Find the noise rating, *NR*, and sound pressure levels, *SPL* dB, that are experienced in the target office. State what effect the office and plant room doors will have on the noise rating in the target room. Recommend appropriate action to be taken with these doors.

32. A centrifugal fan is located within the basement plant room of an office building. The plant room is 8 m long, 6 m wide and 3 m high. The room directivity index is 2 and the plant operator will normally be 1 m from the noise source. The floor and ceiling are concrete, there are four 230 mm brick walls and one acoustically treated door. There are no windows in the plant room. The sound power levels of the fan are 86 dB overall, 64 dB at 63 Hz, 66 dB at 125 Hz, 72 dB at 250 Hz, 80 dB at 500 Hz, 86 Hz at 1 kHz, 82 dB at 2 kHz and 77 dB at 4 kHz.

(a) Find the noise rating that is not exceeded within the plant room.

(b) A corridor and staircase connect the plant room to the Reception area of the building. The corridor is 6 m long, 1 m wide and 3 m high. It has a room directivity index of 2. The corridor has a concrete floor, plastered brick walls and a plasterboard ceiling. The common wall between the plant room and corridor is 2 m long. The sound reduction index of the plant room door is 20 dB at each frequency from 125 Hz to 4 kHz. There is no other sound barrier. Find the noise rating that would be found at a distance of 1 m from the plant room in the corridor.

(c) The Reception area is 12 m long, 8 m wide and 3 m high. The room directivity index is 2. There are 10 m^2 of single-glazed windows in the Reception. There is a door at the top of the staircase down to the plant room. The stairs door is 1 m wide, 2 m high and it has a sound reduction index of 20 dB at each frequency from 125 Hz to 4 kHz. The nearest occupant will be 1 m from the stairs door. The floor has thermoplastic tiles on concrete, the walls are plastered brick and there is a plasterboard ceiling. Find the noise rating which is not exceeded in the Reception.

33. Oil-fired hot-water boilers are located in a plant room in the basement of an exhibition and trade centre building in a city centre. The plant room is 10 m long, 10 m wide and 5 m high.

The room directivity index is 2. The floor, walls and ceiling are concrete. There are no windows. The reference sound power level of the boiler plant is 88 dBA.

(a) Find the anticipated spectral variation in the sound power level for the frequency range from 63 Hz to 4 kHz from Table 14.4 and Fig. 14.1, enter the data onto the worksheet and find the noise rating that is not exceeded within the boiler plant room.
(b) The plant room has three 100 mm concrete external walls. The nearest recipient can be 1 m from the external surface of a boiler plant room wall. There is no acoustic barrier between a plant room wall and a recipient. The directivity index for the outward projection of sound is taken as 3 dB. Find the noise rating at the nearest recipient's position and state what the result means.
(c) A hot-water pipe and electrical cable service duct connects the boiler plant room to other parts of the building. The concrete-lined service duct is 30 m long, 2 m wide and 1 m high. Both ends of the service duct have a 100 mm concrete wall. Calculate the noise rating within the service duct at its opposite end from the boiler plant room.
(d) A conference room 115 mm brick wall adjoins the service duct at the furthest end from the boiler plant room. The conference room is 12 m long, 10 m wide and 4 m high. The room directivity index is 2. The nearest sedentary occupant will be 0.5 m from the service duct wall. The floor has pile carpet, the walls are plastered brick and there is a suspended ceiling of 15 mm acoustic tile and 50 mm glass fibre matt. There are no windows. Find the noise rating that is produced in the conference room by the boiler plant.

34. A four-pipe chilled- and hot-water fan coil unit is located within the false ceiling space above an office in an air-conditioned building. Conditioned outdoor air is passed to the fan coil unit through a duct system. The office is 5m long, 4 m wide and 3 m high. The room directivity index is 2. The office has a concrete floor with thermoplastic tiles and 115 mm plastered brick walls. The 700 mm deep suspended ceiling has 12 mm fibreboard acoustic tiles, recessed fluorescent luminaires, ducted supply and return air with a supply air diffuser, a return air grille and a concrete ribbed slab for the floor above. The office has a double-glazed window of 2 m x 2 m. The reference sound power level of the fan coil unit is 85 dBA. Enter the ceiling space as the plant room and bypass the intermediate space data as directed.

(a) Find the anticipated spectral variation in the sound power level of the fan coil unit for the frequency range from 63 Hz to 4 kHz from Table 14.4 and Fig. 14.2. Enter the data onto the worksheet and find the noise rating that is not exceeded within the ceiling space above the office.
(b) Find the noise rating that is not expected to be exceeded within the office at head height. Assume that the sound reduction of the acoustic tile ceiling is maintained across the whole ceiling area.
(c) Sketch a cross-section of the fan coil unit installation and identify all the possible noise paths into the office.
(d) List the ways in which the potential noise paths into the office can be, or may need to be, attenuated.

35. Presbycusis is:

1. Hearing loss due to long-term exposure to noise above 90 dBA.
2. Hearing loss due to ear disease.
3. Normal deterioration in hearing due to ageing.

4. A church presbytery committee.
5. Temporary shift in hearing ability from exposure to high industrial noise levels above 95 dBC.

36. Hearing range is:

    1. 20 Hz to 20 kHz.
    2. 2 Hz to 20 MHz.
    3. 200 Hz to 200 MHz.
    4. Infinitely wide.
    5. 2 kHz to 20 MHz.

37. What is noise?

    1. Sound.
    2. Acoustic power.
    3. Unwanted sound.
    4. Age-related sound.
    5. Traffic, aeroplanes, pneumatic drills, fans, refrigeration compressors.

38. How do we judge sound?

    1. With absolute measurement.
    2. Comparing a sound with absolute zero sound level.
    3. Relatively.
    4. Subjectively.
    5. Qualitative judgement.

39. What is sound?

    1. Electromagnetic radiation.
    2. Molecular vibration of solid materials.
    3. Radio frequency waves.
    4. Anything that causes an ear response.
    5. Pressure waves.

40. Sound travels through air because it is:

    1. Incompressible.
    2. Supporting molecular vibration.
    3. Compressible.
    4. Inelastic.
    5. Plastic.

41. Reference point for sound level measurement is:

    1. Absolute zero sound.
    2. Lowest audible level by a domestic animal.
    3. Smallest sound detectable by human ear.
    4. Zero atmospheric pressure as found in space.
    5. Inaudible level created in a test laboratory.

42. Sound waves repeat at a frequency due to:

    1. Absorption by porous surfaces.
    2. Wind forces.

3. Multiple sources of sound.
4. Passage of blades in a rotary machine such as a compressor, pump or turbine.
5. Variations in air pressure.

43. An eight-cylinder formula one car engine peaks at 20 000 RPM. One of the sound frequencies it produces is:

    1. 8 Hz.
    2. 20 kHz.
    3. 400 Hz.
    4. 2000 Hz.
    5. 2667 Hz.

44. A gas turbine rotates at 60 000 RPM and has 50 blades on its largest diameter. One of the sound frequencies it produces is around:

    1. 50 kHz.
    2. 50 Hz.
    3. 5000 Hz.
    4. 60 kHz.
    5. 20 kHz.

45. How can the structure of a building transmit noise?

    1. Concrete-framed structures cannot as noise is dampened.
    2. Steel and concrete structures absorb all acoustic energy.
    3. Structures always absorb acoustic energy and dissipate it as heat.
    4. Molecular vibration.
    5. Physical movement.

46. How is noise transmission from plant reduced?

    1. Cannot be reduced, only contained within plant room.
    2. Select quieter plant.
    3. Seal plant room doors.
    4. Locate plant room away from occupied rooms.
    5. Flexible rubber and spring mountings.

47. Which is the smallest increment of sound pressure level detectable by the human ear?

    1. 1 W/m^2.
    2. 1 Bel.
    3. 60 Bel.
    4. 100 N/m^2.
    5. 1 decibel.

48. Explain the meaning of *SWL*:

    1. Selective wind loading.
    2. Sound wind level.
    3. Sound watts level, meaning power.
    4. Sound pressure level, meaning energy.
    5. Sound watts loudness, meaning loudness power.

49. How much acoustic power is experienced within buildings?

    1. 10% of electric motor power becomes acoustic energy.
    2. Around 10 W/m^2 floor area.
    3. Above 1 kW.
    4. Always below 500 W.
    5. Less than 1 W.

50. The frequency range used for assessment of sound power level, SWL, from machines is:

    1. 0–200 MHz.
    2. 1 kHz to 2 MHz.
    3. 125 Hz to 8 kHz.
    4. 63–20 000 Hz.
    5. 125 kHz to 8 MHz.

51. By what mechanism do ears respond to sound power level, *SWL*?

    1. Ears have no mechanism.
    2. Sound power radiates to vibrate the eardrum.
    3. Acoustic vibration energy vibrates the body, which transfers through the body muscle and bone structure, to vibrate eardrums.
    4. Acoustic power raises air pressure on eardrums.
    5. Acoustic output power pulsates and vibrates air, raising air pressure waves; eardrum vibrates from air pressure waves.

51. What is a reverberant sound field?

    1. Sound transmitted over a large distance.
    2. Sound passing through a structure.
    3. What remains within an enclosure after source energy is absorbed by the building structure.
    4. Reflected sound.
    5. Sound pressure level measured in an anechoic laboratory chamber.

53. Direct sound field:

    1. Increases in intensity further from the source.
    2. Remains at a constant noise at any distance from the source while hearer remains in the source plant room.
    3. Decreases linearly with distance from source.
    4. Falls with the inverse square of the distance from the sound source.
    5. Doubles the value of the reverberant sound field.

54. Which of these is not correct about absorbing sound energy?

    1. Dense materials absorb acoustic energy efficiently.
    2. Highly porous materials are good sound absorbers.
    3. The denser the material mass, the greater the sound absorption.
    4. A 75 mm air cavity behind a sheet of plasterboard is a good sound absorber.
    5. A plastered brick wall has a low sound absorption coefficient.

55. Which is not correct about reverberation time:

    1. When short, below a second, room seems lively.
    2. Long reverberation time causes room to sound noisy and echoes.
    3. A lecture theatre needs a short reverberation time.
    4. A large volume car-manufacturing building has a long reverberation time.
    5. When short, below a second, room seems dull.

56. Which is not correct about an anechoic chamber?

    1. Used to measure sound power level from acoustic sources such as fans and compressors.
    2. Must have no reverberant sound field.
    3. Lined with fully absorbent foam wedges.
    4. Sounds perfectly dull.
    5. Used to measure reverberant field sound pressure level from acoustic sources such as fans and compressors.

57. What does natural frequency of vibration mean?

    1. Damped vibration.
    2. Strike a guitar string and it vibrates at up to four times its natural frequency depending on volume of sound box.
    3. Bounce a coil spring and it vibrates at its natural frequency of vibration.
    4. A frequency mechanically forced upon an item, such as by a motor.
    5. A material never vibrates at this frequency.

58. Which does *NR* stand for?

    1. Noise resonance.
    2. Normal rating.
    3. No resonance.
    4. Noise ratification.
    5. Noise rating.

59. How are noises related to human ear response?

    1. Humans respond to sound power level within a range of audible frequencies.
    2. Humans respond to loudness produced over a range of audible frequencies.
    3. Sound pressure levels are added to create an overall relationship to ear response.
    4. Sound power levels are added to create an overall relationship to ear response.
    5. Loudest sound at any frequency is taken as ear response.