Chapter 2 Physics of the ear

2.1 The structure of the ear

Learning objectives:

- What are sound waves?
- How does the ear work?
- Why does excessive noise damage your hearing?

Sound waves

Sound waves are longitudinal waves that pass through any solid, liquid or gas. Consider how they are produced in air using a loudspeaker connected to a signal generator, as shown in Figure 1.

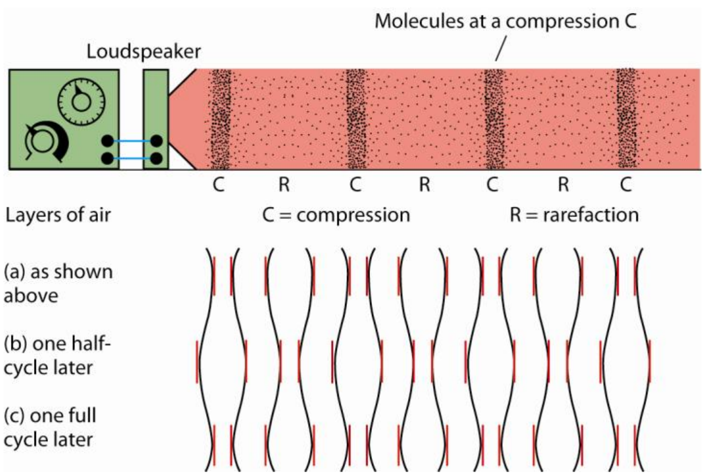

Figure 1 *Creating sound waves:*

The alternating current supplied by the signal generator makes the loudspeaker diaphragm vibrate. Each time the diaphragm moves forward, it compresses the surrounding air slightly, pushing the surrounding air molecules into molecules further away which push into other molecules further away again so the compression travels through the air away from the loudspeaker.

When the diaphragm moves backwards, it expands the air slightly so creating a low-density region, referred to as a rarefaction, which nearby air molecules move into so vacating space which molecules further way move into.

In this way, the vibrations of the diaphragm create sound waves consisting of alternate compressions and rarefactions that travel through the air away from the loudspeaker. Any vibrating object has this effect on a solid, liquid or gas it is in contact with.

Notes and noise

A note of sound consists of sound waves that vary smoothly and rhythmically which makes them easy to listen to. In contrast, noise generally consists of sound waves that change abruptly and randomly. In effect, noise is unwanted sound.

Inside the ear

The normal human ear can hear sound waves that can range in amplitude by a factor of about 10^{12} and in frequency from about 20 Hz to 18 000 Hz. It is largely maintenance free and it filters out unwanted body noises such as from the blood system and the digestive system.

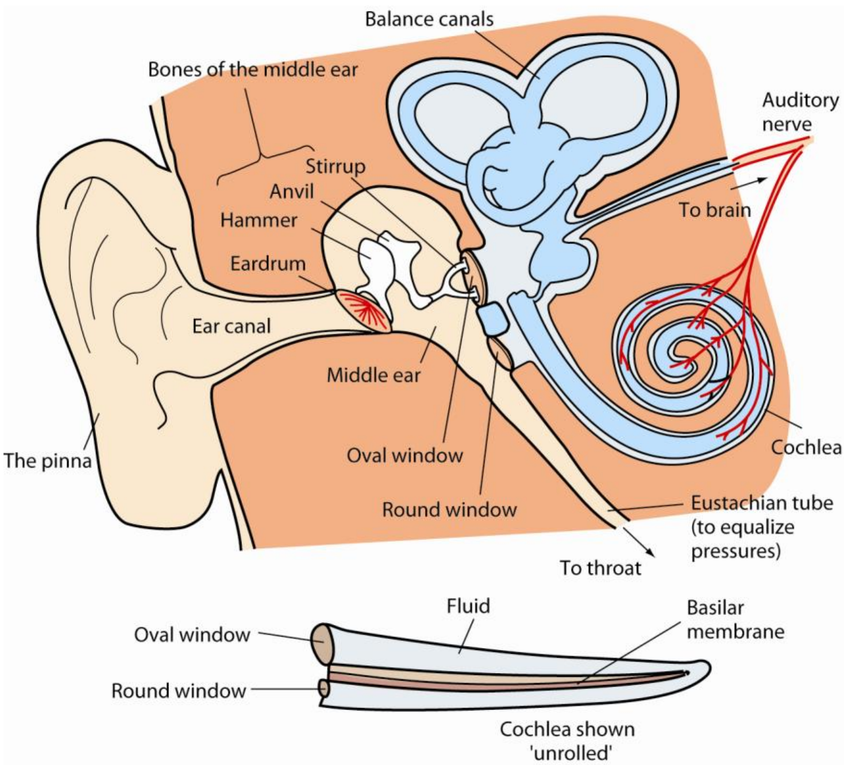

Figure 2 *The human ear*

Figure 2 shows a cross-section of the human ear.

The outer ear

The outer ear consists of the pinna and the ear canal. The pinna reflects sound waves into the ear canal. The pressure waves travel along the ear canal to the tympanic membrane (the eardrum) which vibrates as a result. Sounds of frequency about 3000 Hz corresponding to wavelengths of about 0.03 m resonate in the ear canal which is why the ear is most sensitive at about this frequency.

The middle ear

The middle ear is a cavity containing the three bones of the middle ear. These are called the hammer, the anvil and the stirrup due to their shape. They transmit the vibrations of the tympanic membrane to the oval window of the inner ear. Pressure differences between the middle ear and outside are equalised by air flow through the Eustachian tube. This connects the middle ear to the pharynx (back of the throat).

The bones of the middle ear:

- act as a lever system to amplify the force of the vibrations by about 50%, giving a ×1.5 increase in force
- filter out noise generated in the body

- protect the ear from excessive vibrations by switching to a less-efficient mode of vibration at high sound levels.

In a quiet environment, the muscles that hold the bones of the middle ear together contract to pull the bones tightly against each other, giving maximum effectiveness as transmitters of sound energy. If the ear is subjected to excessive noise, the muscles become slack and allow the bones to vibrate differently so they are less efficient as transmitters of sound energy. Temporary deafness can occur on leaving a noisy environment until the muscles become taut again. Hearing damage occurs if the exposure to excessive noise is prolonged.

The inner ear

The inner ear is a fluid-filled enclosed cavity which receives the sound vibrations from the middle ear at its **oval window**. The vibrations are transmitted through the fluid of the **cochlea** as pressure waves, making the **basilar membrane** vibrate, and then onto the **round window** where they leave the inner ear. Tiny sensitive 'hair cells' on the basilar membrane send nerve impulses to the brain as a result of being stimulated by the vibrations of the membrane. Different frequencies cause the hair cells along the basilar membrane to vibrate at different positions, each pattern of vibration causing a pattern of nerve impulses which the brain learns to interpret.

The oval window has an area of about 3 mm^2 which is about 15 times less than the area of the ear drum. The pressure on the oval window is over 20 times greater than the pressure on the ear drum because:

- the force on the oval window is about 1.5 times the force on the eardrum
- the area of the oval window is about 15 times smaller than the area of the ear drum.

Therefore

$$\frac{\text{pressure on oval window}}{\text{pressure on ear drum}} = \frac{\text{force on oval window}}{\text{area of oval window}} \div \frac{\text{force on eardrum}}{\text{area of eardrum}}$$

$$= \frac{\text{force on oval window}}{\text{force on ear drum}} \times \frac{\text{area of ear drum}}{\text{area of oval window}}$$

$$= 1.5 \times 15 \approx 20$$

Summary questions

1 Outline the process by which vibrations of the ear drum, due to sound waves, reach the inner ear.

2 **a** Explain how the ear automatically responds to excessive loudness.

b Explain why temporary deafness can occur after leaving a very noisy environment.

3 An ear detects sound waves of constant frequency which causes the pressure on the eardrum to vary with an amplitude of 2.0×10^{-5} Pa. The eardrum has an area of 50 mm^2. The bones of the middle ear amplify the force from the eardrum by 50%. Calculate:

a the maximum force on the eardrum

b the maximum pressure on the oval window, assuming its area is 3.0 mm^2.

4 **a** State the function of the following parts of the inner ear.

i The oval window

ii The basilar membrane

iii The round window

b Discuss the effect on hearing if the area of the oval window was much greater than about 3 mm^2.

2.2 Sound measurements

Learning objectives:

- What do we mean by intensity?
- What is the decibel scale?
- Why do we use the decibel scale?

The decibel scale

The **intensity** of a sound wave (and of any type of wave) is defined as the energy per second per unit area incident normally on a surface. The unit of intensity is $J\,s^{-1}\,m^{-2}$ or $W\,m^{-2}$.

If an eardrum that has an area of $3.0\,mm^2$ ($3.0 \times 10^{-6}\,m^2$) receives sound energy at normal incidence at a rate of $3.0 \times 10^{-12}\,J\,s^{-1}$, the intensity of the sound waves at the eardrum is $1.0 \times 10^{-6}\,J\,s^{-1}\,m^{-2}$ ($3.0 \times 10^{-12}\,J\,s^{-1} \div 3.0 \times 10^{-6}\,m^2 = 1.0\,\mu W\,m^{-2}$). In case you think that this value of intensity would be too small to hear, it is in fact about the same as the sound intensity you experience when people are talking to you.

The least intensity the human ear can hear at a frequency of 1000 Hz is $1.0 \times 10^{-12}\,W\,m^{-2}$ (1 picowatt m^{-2}). This is referred to as the **threshold intensity** of hearing, I_0. At the other extreme, sound intensities over about $1\,W\,m^{-2}$ are painful to the ear and can cause permanent deafness.

The **intensity level in decibels (dB)** of a sound of intensity I is defined as $10 \log\left(\frac{I}{I_0}\right)$ where I_0 is the threshold intensity of the human ear, as defined above.

$$\textbf{Intensity level in decibels} = 10 \log\left(\frac{I}{I_0}\right)$$

Figure 1 shows the intensity level in decibels of a range of different sounds. Intensity level in decibels is a more convenient measure than intensity because it covers the very large range of intensities which the ear responds to. In addition it matches the response of the human ear in terms of changes of loudness. Notice it has an upper limit of about 140 dB above which the listener would experience pain and the eardrum may rupture.

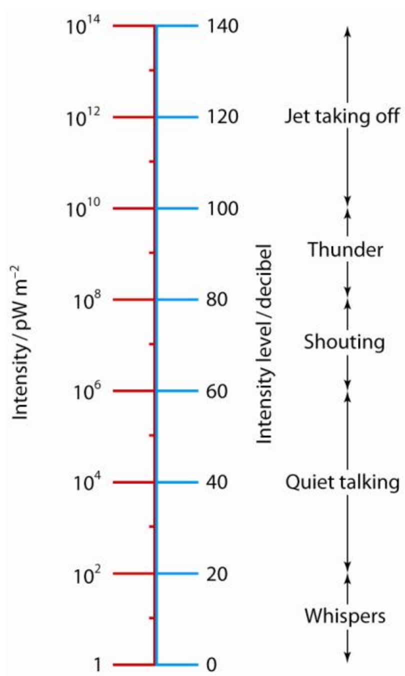

Figure 1 *The decibel scale*

Worked example

$I_0 = 1.0 \times 10^{-12}\,\mathrm{W\,m^{-2}}$

Calculate the intensity level in decibels of a sound of intensity $2.0 \times 10^{-6}\,\mathrm{W\,m^{-2}}$.

Solution

Intensity level in dB = $10\log\left(\frac{I}{I_0}\right) = 10 \times \log(2.0 \times 10^{-6} \div 1.0 \times 10^{-12}) = 10 \times 6.3 = 63\,\mathrm{dB}$

The response of the ear to changes of sound intensity is directly proportional to the percentage change of intensity.

Suppose a hearing test is conducted using sound of constant frequency from a loudspeaker connected to a signal generator, as shown in Figure 2. If the sound intensity is increased in steps by a certain percentage each step, the person who is the subject of the test will detect equal responses (i.e. equal increases of loudness).

The frequency control on the signal generator should be set at a constant value and the loudness control adjusted so the sound intensity can just be heard by the subject. A sound-level meter at a fixed position near the subject's ear could be used to measure the intensity level of the sound in decibels.

Increasing the 'volume' control of the signal generator would increase the sound intensity at the subject and the reading of the sound-level meter. Equal increases in the decibel reading of the meter would be due to equal percentage increases in the sound intensity. For example, successive increases of 10 decibels would be due to successive '×10' increases in the sound intensity. Such increases would give equal increases of loudness as judged by the subject.

If the initial intensity is I_0 (the threshold of hearing) and the intensity is increased by ×10 in each step (increased by 1000% in each step), equal increases of loudness will be heard when the intensity is increased from I_0 to $10I_0$, then from $10I_0$ to $100I_0$ then from $100I_0$ to $1000I_0$ etc.

After n steps, the intensity $I = 10^n I_0$ and the subject would have experienced n successive equal increases of loudness. Using base 10 logarithms gives $n = \log\left(\frac{I}{I_0}\right)$

This tells us how many '×10' increases of loudness would be needed to increase the intensity of a sound from I_0 to I. The response of the ear is therefore **logarithmic**. The decibel scale is also logarithmic, so it is a useful scale to use as a measure of the response of the human ear to changes of sound intensity.

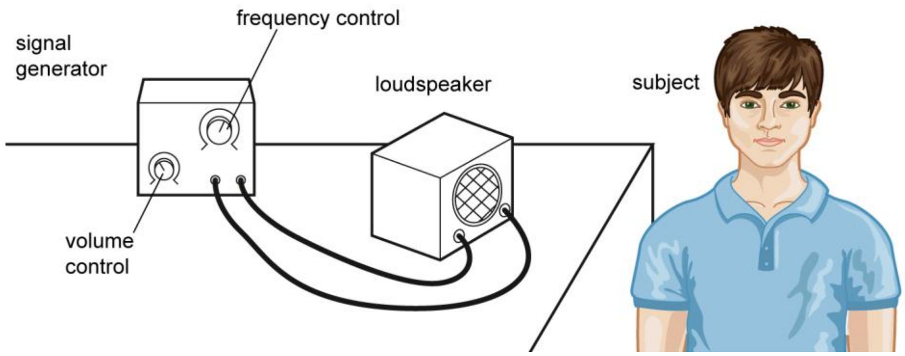

Figure 2 *Hearing tests*

Using the decibel formula

Calculating the intensity I of a sound

To calculate the intensity I of a sound, given the intensity level in decibels, it is necessary to rearrange the formula: Intensity level (dB) = $10 \log\left(\frac{I}{I_0}\right)$ to make $\left(\frac{I}{I_0}\right)$

1 $\log\left(\frac{I}{I_0}\right) = \frac{\text{dB}}{10}$

2 $\frac{I}{I_0} = \text{inv} \log\left(\frac{\text{dB}}{10}\right)$

Note: inv log $n = 10^n$

Worked example

$I_0 = 1.0 \times 10^{-12}\ \text{W m}^{-2}$

Calculate the intensity of a sound that has an intensity level of 94 dB.

Solution

Substituting 94 dB into the intensity level equation gives $94 = 10 \log\left(\frac{I}{I_0}\right)$

$\log\left(\frac{I}{I_0}\right) = 9.4$

$\frac{I}{I_0} \times \text{inv} \log 9.4 \times 2.5 \times 10^9$ (2 s.f.)

$I \times 2.5 \times 10^9 \times I_0 = 2.5 \times 10^9 \times 1.0 \times 10^{-12} = 2.5 \times 10^{-3}\ \text{W m}^{-2}$

(Note: inv log $9.4 = 10^{9.4} = 10^{0.4} \times 10^9 = 2.5 \times 10^9$)

Calculating the intensity level of two sounds

To calculate the intensity level of two sounds, given the intensity level of each sound in decibels, it is necessary to:

1 calculate the intensity of each sound as explained above
2 add the two intensities to give the total intensity
3 use the intensity level formula again to calculate the total intensity level.

Worked example

A lathe in a workshop exposes its operator to sound at an intensity level of 80 dB when it is in operation. The operator standing at the lathe also experiences sound at an intensity level of 78 dB from a drill when that is in operation with the lathe switched off. Calculate the intensity level experienced by the lathe operator at the lathe when both machines are switched on.

Solution

Intensity level due to the lathe = 80 dB

$\therefore$ intensity due to the lathe, I_1, is given by $80 = 10\log\left(\frac{I_1}{I_0}\right)$

Hence $\left(\frac{I_1}{I_0}\right)$ = inverse $\log\left(\frac{80}{10}\right) = 10^8$ so $I_1 = 1.0 \times 10^8\, I_0$

Intensity level due to the drill = 78 dB

$\therefore$ intensity due to drill, I_2, is given by $78 = 10\log\left(\frac{I_2}{I_0}\right)$

Hence $\left(\frac{I_2}{I_0}\right)$ = inverse $\log\left(\frac{78}{10}\right) = 10^{7.8}$ so $I_2 = 6.3 \times 10^7\, I_0$ (2 s.f.)

Intensity due to both machines $I = I_1 + I_2 = 1.0 \times 10^8\, I_0 + 6.3 \times 10^7\, I_0 = 1.63 \times 10^8\, I_0$

$\therefore$ intensity level due to both machines $= 10\log\left(\frac{I}{I_0}\right) = 10\log(1.63 \times 10^8) = 82$ dB

Summary questions

$I_0 = 1.0 \times 10^{-12}\,\mathrm{W\,m^{-2}}$

1 An eardrum that has an area of $3.0\,\mathrm{mm^2}$ ($3.0 \times 10^{-6}\,\mathrm{m^2}$) receives sound energy at normal incidence at a rate of $6.6 \times 10^{-8}\,\mathrm{J\,s^{-1}}$.

Calculate:

a the intensity of the sound waves at the eardrum

b the intensity level of sound of this intensity.

2 A certain aircraft taking off creates sound at an intensity level of 123 dB near a building when it passes over the building. Calculate the intensity of the sound waves from the aircraft near the building.

3 A signal generator is connected to a loudspeaker which is near a decibel meter. When the sound intensity from the loudspeaker is increased at constant frequency, the meter reading increases from 60 dB to 65 dB.

a What would be the increase of the reading of the meter if the intensity of the sound were to be increased again by the same amount?

b Calculate the intensity of a 65 dB sound.

4 A toll-booth operator experiences a sound intensity level of 102 dB when a lorry is next to the booth.

Calculate:

a the intensity of a 102 dB sound

b the intensity level in decibels due to two such lorries either side of the toll booth.

2.3 Frequency response

Learning objectives:

- How does the normal ear respond to different frequencies?
- What is the dBA scale?
- What can cause hearing to deteriorate?

Frequency response of the normal ear

The normal human ear can detect sounds of frequencies from about 20 Hz to 18 000 Hz. Figure 1 shows equal loudness curves for the human ear. The lowest curve shows how the least detectable intensity level varies with frequency. This and the other curves show that the ear is less and less responsive at frequencies approaching the lower and upper limits of about 20 Hz and 18 000 Hz respectively.

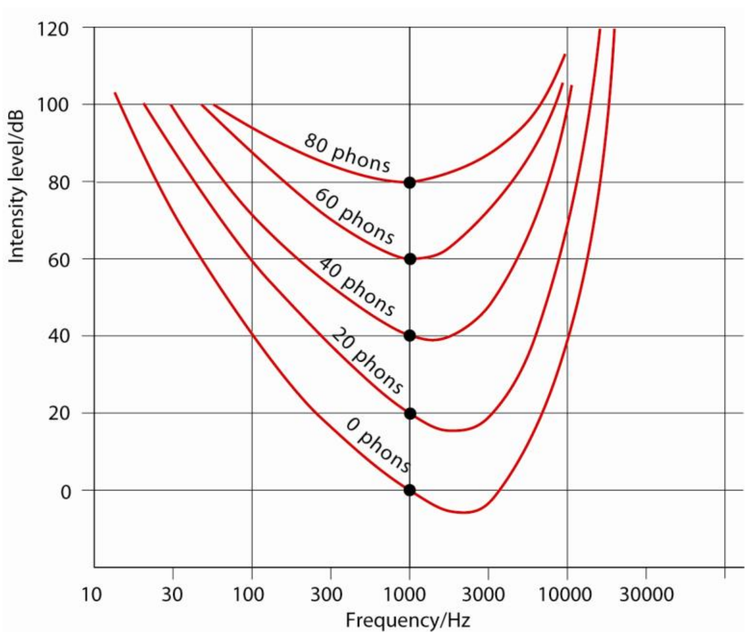

Figure 1 *Equal loudness curves for a normal human ear*

- The lowest curve shows the variation of the threshold of hearing with frequency. Notice that the zero level for the decibel scale is at 1000 Hz. This is because I_0 in the intensity level formula $10 \log\left(\frac{I}{I_0}\right)$ is defined as the least detectable intensity at 1000 Hz.
- All the curves are equal loudness curves. For example, the middle curve (labelled '40 phon') shows that a 100 dB sound at 10 000 Hz has the same loudness as a 40 dB sound at 1000 Hz.

Note

The phon is not required in this specification and is included here to develop a clear grasp of the meaning of loudness. The loudness of a sound in phons is defined as the intensity level in decibels of a sound at 1000 Hz that has the same loudness as the sound. Thus a 100 dB sound at 10 000 Hz has a loudness of 40 phons.

Obtaining equal loudness curves

1 The frequency of the signal generator is first set to 1000 Hz then the volume control adjusted until the sound-level meter indicates a certain intensity level in decibels which is then noted as the loudness.

2 The frequency is then set to a different value (e.g. 2000 Hz) and the volume control readjusted to make the loudness as judged by the subject the same as at 1000 Hz. The intensity level of the sound is then noted from the sound-level meter.

3 The procedure is then repeated for other frequencies to cover the whole frequency range from about 100 Hz to the upper frequency limit of the subject.

To obtain further loudness curves, the procedure outlined above is repeated for different initial intensity levels at 1000 Hz.

The dBA scale

Sound-level meters are usually calibrated on an adjusted decibel scale, the dBA scale, which matches the ear's response at different frequencies. This is particularly important where people are subjected to sounds dominated by low or high sound frequencies. This is because the normal ear is less sensitive at these frequencies than it is in the middle part of its frequency range. For example, using Figure 1:

- a 100 dB sound at 10 kHz would give a reading of 60 dBA on the dBA scale corresponding to the normal ear's response. The reading of 60 dBA means the intensity level of the sound is 60 dB above the threshold of hearing at 10 kHz which is 40 dB.
- a 60 dB sound at 100 Hz would give a reading of 20 dBA on the dBA scale corresponding to the normal ear's response. The reading of 20 dBA means the intensity level of the sound is 20 dB above the threshold of hearing at 100 Hz which is 40 dB.

Defects of hearing

Deterioration of hearing can occur due to age and due to exposure to excessive noise. Figure 2 shows the effect of age on the threshold of hearing.

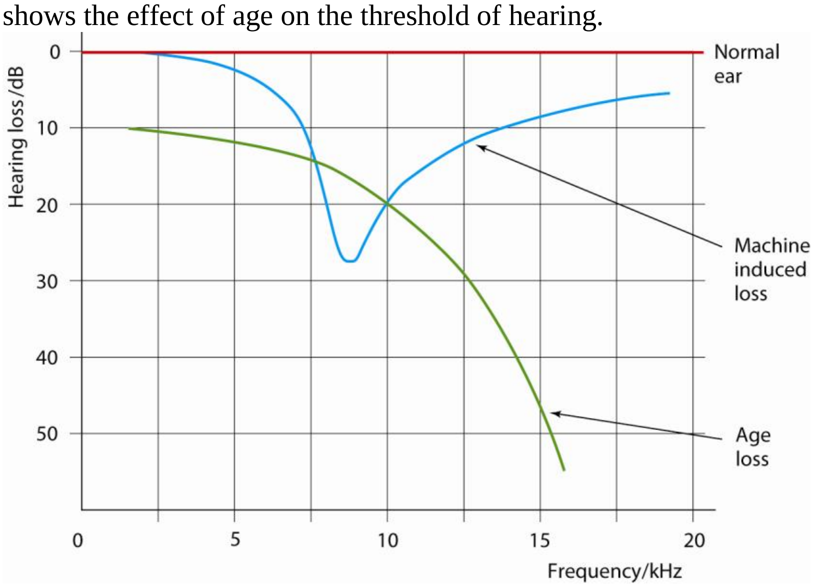

Figure 2 *The effect of hearing defects*

- Age-related deterioration occurs at all frequencies and is greater the higher the frequency.
- Excessive and prolonged exposure to noise in a narrow frequency range (e.g. machine noise) can cause deterioration in that frequency range only.

Hearing loss can be tested by obtaining equal loudness curves and comparing the results with the corresponding curves for normal hearing. The hearing loss at any given frequency may be expressed as the difference between the threshold intensity level for normal hearing and for the person being tested. For example, a person with a threshold intensity level of 65 dB at 10 kHz in comparison with 40 dB for a person with normal hearing has a hearing loss of 25 dB at that frequency.

The results for different frequencies can be presented on a grid of hearing loss against frequency. This is shown in Figure 3. Some results for a person with machine-related hearing loss are shown. Further measurements would need to be made to find the frequency at which the hearing loss is a maximum and the extent of the hearing loss over 10 kHz.

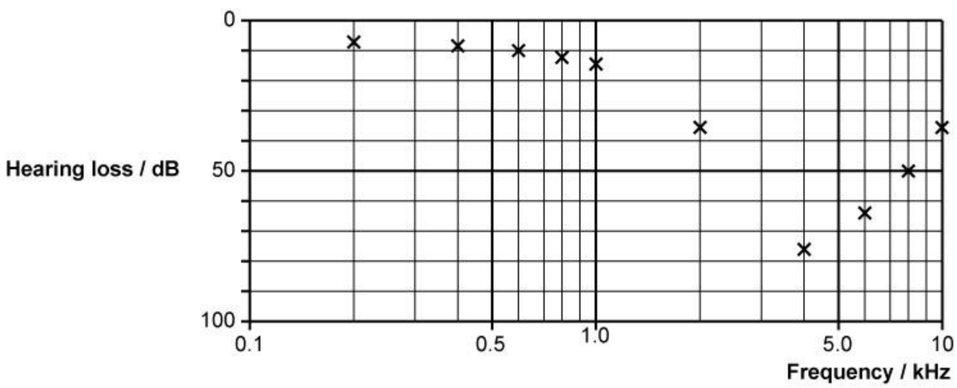

Figure 3 *Hearing loss results*

Summary questions

1 Describe the frequency response of a person with normal hearing from:

a 1000 Hz to 5000 Hz

b 10 000 Hz upwards.

2 A sound-level meter has a dB scale and a second meter has a dBA scale.

a What is meant by a dBA scale?

b If the meters are used to read the sound level of a sound of constant intensity level 60 dB, use Figure 1 to determine the dBA reading and the difference between the readings of the two meters if the frequency of the sound is:

i 100 Hz

ii 1000 Hz

iii 10 000 Hz

3 Describe how you would carry out a test to measuring the hearing loss of a person at a particular frequency. State the equipment you would use and the measurements you would make to determine the hearing loss in decibels.

4 **a** State two types of hearing loss, stating the cause of the loss in each case.

b Describe one similarity and one difference between the two types of hearing loss stated in **a**.