4

HEARING

4.1 THE NATURE OF SOUND

Sound is a longitudinal wave motion propagated by means of oscillations of the particles of the medium through which it is travelling. The human ear is sensitive to those sound waves with frequencies between about 20 Hz and 20 kHz. Frequencies above and below the range of human audibility are known as **ultrasonic** and **infrasonic**, respectively.

The speed c of sound in a fluid (i.e. a gas or a liquid) of density ρ and bulk modulus of elasticity K is given by

$$c = \sqrt{\frac{K}{\rho}} \quad \text{(for a fluid)} \qquad [4.1]$$

In a solid of density ρ and Young's modulus, E

$$c = \sqrt{\frac{E}{\rho}} \quad \text{(for a solid)} \qquad [4.2]$$

Notes (i) The speed of sound in a gas does not depend on the pressure of the gas. This follows from equation [4.1] (because both K and ρ are directly proportional to pressure) and is also confirmed by experiment.

(ii) It can be shown that for moderate pressures $c \propto T^{1/2}$, where T is the kelvin temperature of the gas.

(iii) The speed, c, frequency, f, and wavelength, λ, are related by

$$c = f\lambda$$

4.2 INTENSITY AND INTENSITY LEVEL: THE DECIBEL

The **intensity** of a sound wave is defined as the rate of flow of energy per unit area of a surface perpendicular to the direction of travel of the wave.

Note The intensity is proportional to the square of the amplitude of the wave, i.e.

$$\text{Intensity} \propto (\text{Amplitude})^2$$

The minimum intensity of sound that the human ear can detect is known as the **threshold of hearing** and is normally taken to be $1.0 \times 10^{-12}\,\mathrm{W\,m^{-2}}$ ($1.0\,\mathrm{pW\,m^{-2}}$). The maximum that can be experienced without the risk of permanent damage is about $100\,\mathrm{W\,m^{-2}}$. This is an enormous range, but it is not perceived as such by the ear – equal changes in intensity do not produce equal changes in **loudness**. Experiments indicate that **the ear has a logarithmic response to intensity**. Though it may not be obvious, this is equivalent to saying that increase in loudness is proportional to the fractional increase in intensity, i.e.

$$\text{Increase in loudness} \propto \frac{\text{Increase in intensity}}{\text{Initial intensity}} \qquad [4.3]$$

It can be shown that the loudness L of a sound of intensity I is given by

$$L = k\log_{10}\left(\frac{I}{I_0}\right)$$

where I_0 is the threshold intensity ($1.0 \times 10^{-12}\,\mathrm{W\,m^{-2}}$). It follows that the loudness increases by an amount k whenever the intensity increases by a factor of 10.

Note Equation [4.3] is an example of the **Weber–Fechner law** which states that sensations such as loudness and brightness increase in proportion to the fractional increase in the stimuli producing them.

Since the ear has a logarithmic response to intensity, it is useful to define a quantity that reflects this. Thus the **intensity level** or **relative intensity** of a sound of intensity I is defined by

$$\text{Intensity level in decibels} = 10\log_{10}\left(\frac{I}{I_0}\right) \qquad [4.4]$$

where I_0 is the **reference intensity**, normally taken to be $1.0 \times 10^{-12}\,\mathrm{W\,m^{-2}}$.

Whenever the intensity increases by a factor of 10, the intensity level increases by 10 decibels (10 dB) regardless of the initial intensity – see Table 4.1.

Table 4.1 Representative sound levels

Sound	*Intensity level*/dB	*Intensity*/$\mathrm{W\,m^{-2}}$
Threshold of hearing	0	10^{-12}
Rustling leaves	10	10^{-11}
Whispering	20	10^{-10}
Normal conversation	60	10^{-6}
Busy street	70	10^{-5}
Pneumatic drill	90	10^{-3}
Jet overhead	100	10^{-2}
Threshold of feeling	120	$10^{0} = 1$
Threshold of pain	140	$10^{2} = 100$

It is a simple matter to show this. It follows from equation [4.4] that if the intensity increases from I_1 to I_2, then

$$\begin{aligned}\text{Increase in intensity level} &= \left[10\log_{10}\left(\frac{I_2}{I_0}\right) - 10\log_{10}\left(\frac{I_1}{I_0}\right)\right]\text{ dB}\\ &= 10\left[\log_{10}\left(\frac{I_2}{I_0}\right) - \log_{10}\left(\frac{I_1}{I_0}\right)\right]\text{ dB}\\ &= 10\log_{10}\left(\frac{I_2}{I_1}\right)\text{ dB}\\ &= 10\text{ dB} \quad \text{when}\ \frac{I_2}{I_1} = 10\end{aligned}$$

Notes

(i) A decibel (dB) is one tenth of a **bel (B)**, a unit named in honour of Alexander Graham Bell. The bel is too large for most purposes – the ear can detect changes of as little as about 1 decibel, hence its use.

(ii) An increase in intensity level of 1 dB corresponds to an increase in intensity of approximately 26% ($10\log_{10} 1.26 \approx 1$).

(iii) Intensity levels cannot be added and subtracted directly, they must first be converted to intensities.

QUESTIONS 4A

Assume, where necessary, that the reference intensity (I_0) is $1.0 \times 10^{-12}\ \text{W m}^{-2}$.

1. What are the intensity levels of sounds whose intensities are:
(a) $1.0 \times 10^{-4}\ \text{W m}^{-2}$,
(b) $3.0 \times 10^{-10}\ \text{W m}^{-2}$, **(c)** $7.0\ \text{pW m}^{-2}$?

2. What are the intensities of sounds whose intensity levels are:
(a) 110 dB, **(b)** 68 dB? (Note, if $x = \log_{10} y$, then $y = 10^x$ – use the 10^x key on your calculator.)

3. A source of sound increases in intensity from $10^{-9}\ \text{W m}^{-2}$ to $10^{-7}\ \text{W m}^{-2}$. By how much does the intensity level increase?

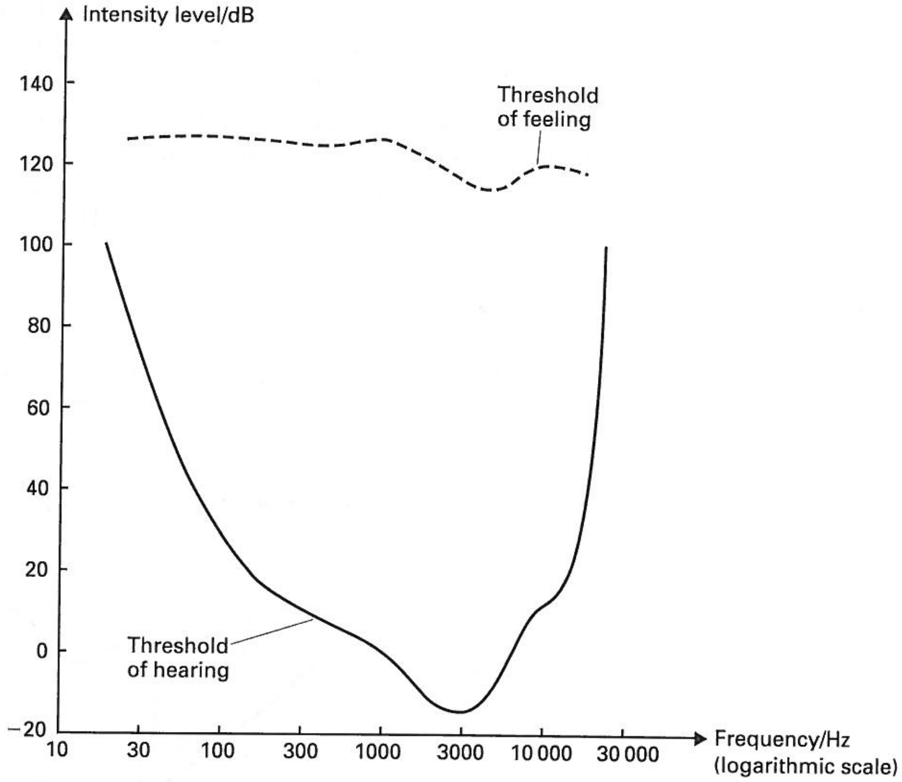
4. The intensity level of the noise on a busy street is 70 dB. An aeroplane passes overhead and contributes a further 80 dB. What is the new intensity level?

5. The intensity level at a distance of 4.0 m from a point source of sound is 40 dB. What is the power output of the source?

4.3 FREQUENCY RESPONSE

The **range of frequencies** which the human ear can detect varies considerably from one individual to another. The lower limit is typically around 20 Hz. The upper limit decreases with age but is about 20 kHz for an average young adult. The threshold of hearing depends very much on the frequency at which it is measured (see Fig. 4.1) and has its minimum value at about 3 kHz. Note that the **threshold of feeling**, the level at which the sensation changes from that of hearing to one of discomfort, is close to 120 dB at all frequencies.

Fig. 4.1
Frequency range of a normal ear



Note The decibel is defined in such a way that the intensity level of the threshold of hearing is 0 dB at 1 kHz. The threshold levels around 3 kHz, where the ear is more sensitive, are therefore negative.

Frequency discrimination is the ear's ability to distinguish different frequencies and is most acute at low frequencies. Between 60 Hz and 1 kHz frequencies as close as 3 Hz can be distinguished. This ability decreases with increasing frequency and is practically non-existent above 10 kHz.

4.4 LOUDNESS

Loudness is a subjective quantity – it depends on the intensity of the sound and on the hearing of the listener. A sound which is regarded as being loud by one person appears less loud to a person whose hearing is poorer. Furthermore, because the ear has different sensitivities to different frequencies, two notes which are of equal intensity, but which differ in pitch, may not sound equally loud, even to a single observer. (We cannot hear ultrasonic sounds, no matter how intense they are.)

The reader must not think that intensity level is a measure of loudness. Although it takes account of the logarithmic response of the ear to intensity, it takes no account of individual observers nor of the frequency response of the ear. It is also worth noting that **the decibel is a unit of intensity level; it is not a unit of loudness.**

The phon is a unit of loudness; it takes account of the fact that loudness is frequency dependent. To measure the loudness of a sound in phons, the source of the sound is placed next to a standard source with a frequency of 1000 Hz. The intensity of the standard source is then adjusted until the two sources are judged, by a normal observer, to be equally loud. If the standard source then has an intensity level of n decibels, the loudness of the sound being measured is n phons.

Measurements obtained in this way can be used to produce **curves of equal loudness** (Fig. 4.2). The curves illustrate the fact that loudness becomes less frequency dependent as the level of loudness increases. Note too that loudness and intensity level are numerically equal at 1 kHz.

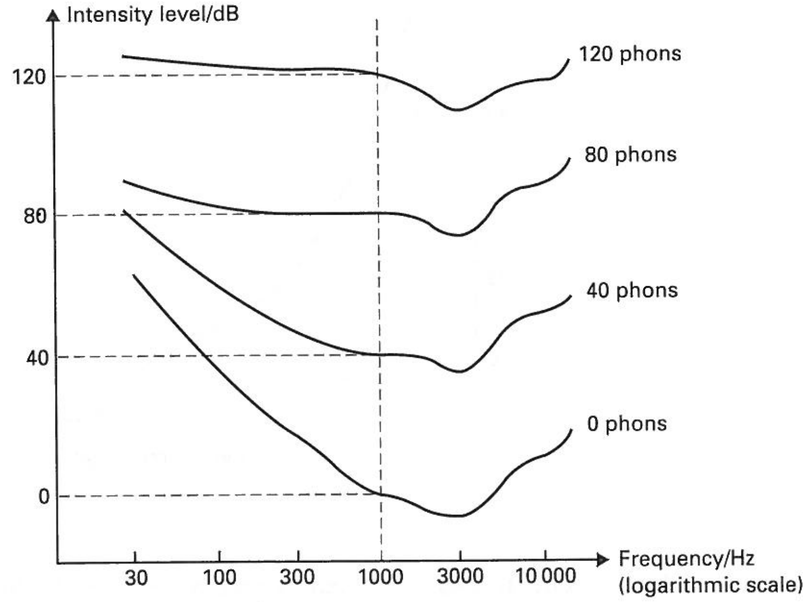


Fig. 4.2
Curves of equal loudness for a normal ear

Another way of taking account of the frequency dependence of loudness is to use a sound level meter calibrated on a scale known as the **dBA scale**. The meter is essentially a microphone coupled to electronic circuitry that suppresses certain frequencies in such a way that the response of the microphone mimics that of a normal ear.

Sounds which have the same loudness (either in phons or dBA), but which have different frequencies, will not necessarily sound equally loud to someone with defective hearing – the two scales are based on the frequency response of a normal ear.

4.5 SENSITIVITY

The sensitivity of the ear is a measure of its ability to detect small changes in intensity. It is strongly frequency dependent and is defined by

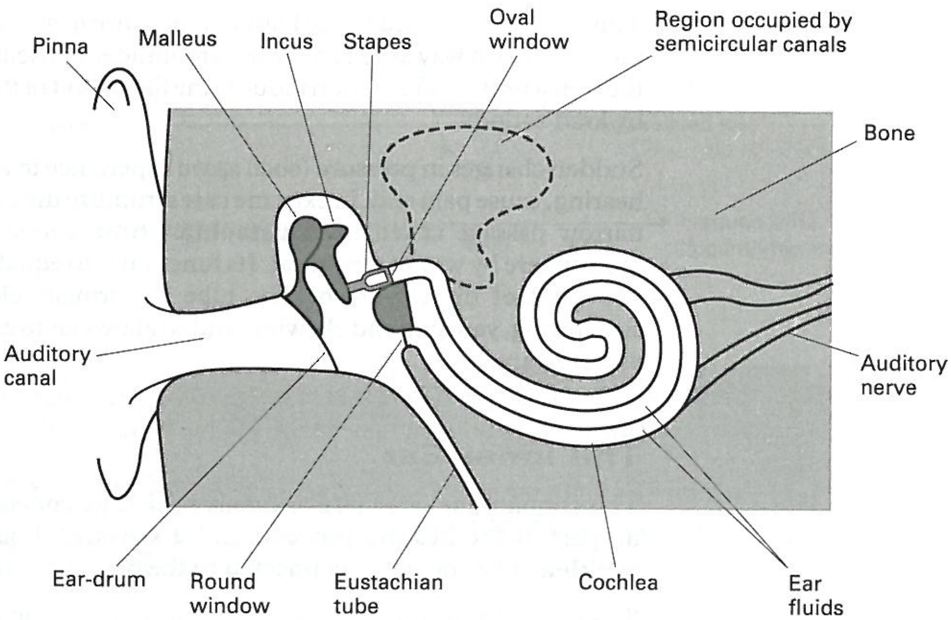
$$\text{Sensitivity} = \log_{10}\left(\frac{I}{\Delta I}\right)$$

where $\Delta I/I$ is the smallest fractional change in intensity the ear can detect at the frequency concerned. **Sensitivity has its maximum value at a frequency of about 2 kHz.**

4.6 THE STRUCTURE AND FUNCTION OF THE EAR

The ear is divided into three main parts, the outer, middle and inner ears, by three thin membranes – the **tympanic membrane** (or **ear-drum**) between outer and middle, and the **oval window** and the **round window** between middle and inner (Fig. 4.3).

Fig. 4.3
Structure of the ear



The inner ear contains transducers that convert the mechanical vibrations transmitted to it, via the outer and middle ears, into electrical impulses which then pass to the brain for interpretation.

The Outer Ear

The visible part of the ear (the **pinna**) funnels sound through the **auditory canal** to the ear-drum. The canal is about 2.5 cm long and about 7 mm in diameter. It is closed at one end by the ear-drum, a thin (~0.1 mm) membrane with an area of about 65 mm^2, which vibrates with small ($\sim 10^{-11}$ m) amplitude when sound waves enter the ear. The auditory canal acts like a tiny organ pipe with a resonant frequency of about 3 kHz – the frequency at which the ear has its maximum response (see Fig. 4.1).

The Middle Ear (Tympanic Cavity)

This is a small (~0.6 cm^3) air-filled chamber containing a chain of three small bones – the **malleus, incus** and **stapes** (or **hammer, anvil** and **stirrup**). They are known collectively as the **ossicles** and they provide a mechanical linkage that transmits the oscillations of the ear-drum to the oval window. (Note. The inertia of the ossicles is such that they cannot vibrate at frequencies in excess of about 20 kHz – hence the ear's upper frequency limit of 20 kHz.) The 'handle' of the hammer is attached to the ear-drum. Its other end is connected, by a synovial joint, to the anvil, and this in turn is connected, by another synovial joint, to the stirrup. Finally, the 'footplate' of the stirrup is attached to the oval window.

The ossicles act as a series of levers with a combined mechanical advantage of 1.3. Furthermore, the area of the ear-drum is 20 times that of the oval window, and therefore the pressure (force / area) at the oval window is $20 \times 1.3 = 26$ times that at the ear-drum. This offsets, to a large extent, the mismatch in the acoustic impedances of the outer and inner ears (see section 8.3).

Tiny muscles attached to the hammer and stirrup allow them, when necessary, to move in such a way as to reduce the amplitudes of oscillation of the ear-drum and the oval window. This action reduces the likelihood of the inner ear being damaged by loud sounds.

Sudden changes in pressure (such as we experience in aeroplanes and lifts) impair hearing, cause pain and, in extreme cases, rupture the ear-drum. To prevent this, a narrow passage called the **Eustachian tube** connects the middle ear to the atmosphere by way of the throat. Its function is to equalize the air pressures on the two sides of the ear-drum. The tube is normally closed but it opens during swallowing, yawning and chewing, and so allows air to enter or leave the middle ear as necessary.

The Inner Ear

This contains the semicircular canals (which are concerned with balance and play no part in the hearing process) and a sensitive, liquid-filled organ called the **cochlea**. The cochlea is connected to the brain by way of the **auditory nerve**.

When the oval window vibrates, a pressure wave propagates through the fluids in the cochlea, stimulating nerve cells and creating the sensation of hearing. Different parts of the cochlea are responsive to different frequencies, and therefore the neurons activated by any particular frequency are specific to that frequency. This allows the brain to distinguish one frequency from another. (The high-frequency receptors are close to the oval window; the low-frequency receptors are deep inside the cochlea.)

4.7 AUDIOMETRY

Hearing threshold levels are determined with a device known as an **audiometer**. This supplies pure-frequency notes, generated electronically, to headphones worn by the patient. The controls allow the operator to alter both the frequency and the intensity level. In a standard audiometric examination, the patient is tested at 8 frequencies from 250 Hz to 8 kHz. The audiometer is calibrated in such a way that a person with normal hearing would register 0 dB at each of the frequencies tested. The volume is gradually increased and the intensity level (in dB) at which the patient can just hear the sound is determined at each frequency in turn. The amount by which this exceeds 0 dB is the hearing loss at that frequency. The results are plotted against frequency to produce an **audiogram**.

Fig. 4.4 compares the audiogram of a person aged 65, whose hearing loss is due solely to ageing, with that of a (younger) person who has been subjected to excessive levels of noise over many years. The curves are typical of the two conditions.

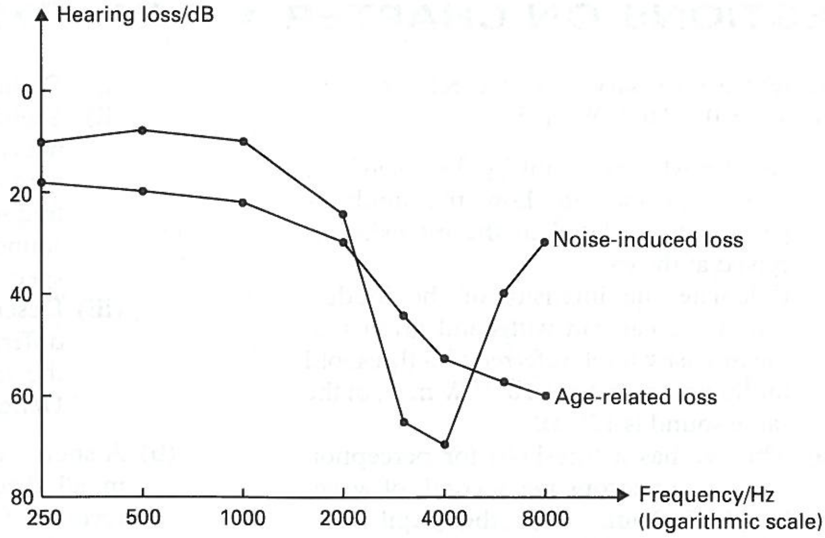


Fig. 4.4
Audiogram showing age-related loss and noise-induced loss

Age-related hearing loss is characterized by a loss in sensitivity across the whole spectrum but which is most marked at the higher frequencies.

Noise-induced hearing loss is characterized by a marked dip in sensitivity around 4 kHz, regardless of the frequencies of the sounds to which the sufferer has been exposed.

CONSOLIDATION

The frequency range of a normal young adult is from 20 Hz to 20 kHz. The upper limit decreases with age. The maximum response (minimum threshold of hearing) is around 3 kHz.

The reference intensity (the minimum intensity the ear can detect) is normally taken to be $1.0 \times 10^{-12}\,\mathrm{W\,m^{-2}}$.

The ear has a logarithmic response to sound intensity, i.e. increase in loudness is proportional to fractional increase in intensity.

Intensity level takes account of the logarithmic response of the ear. It is measured in **decibels (dB)**. The decibel is used, rather than the bel, because one decibel is (approximately) the smallest change the ear can detect,

Loudness is a subjective quantity. It can be measured in **phons** and on the **dBA scale**. Both scales take account of the ear's logarithmic response to intensity and of its unequal response to different frequencies.

Sensitivity is the ability to detect small changes in intensity; it has its maximum value at about 2 kHz.

QUESTIONS ON CHAPTER 4

Assume, where necessary, that the reference intensity (I_0) = $1.0 \times 10^{-12}\,W\,m^{-2}$.

1. **(a)** Explain what is meant by the *intensity of sound* and indicate how the loudness perceived is related to the intensity received at the ear.
Calculate the intensity of the loudest sound the ear can withstand given that the intensity level, referred to a threshold for human hearing of $10^{-12}\,W\,m^{-2}$, of the same sound is 120 dB.

(b) The eye has a threshold for perception when 100 photons per second, of wavelength 510 nm, enter the pupil. The effective area of the external entrance of the auditory canal (auditory meatus) is $65\,mm^2$.
If the threshold sensitivity of either organ is defined as the least power required to produce a perceptible signal, calculate the ratio of the threshold sensitivity of the eye to that of the ear.
Comment on the significance you think this result has for man.
Planck's constant = $6.6 \times 10^{-34}\,J\,s$
Speed of light = $3.0 \times 10^{8}\,m\,s^{-1}$
[N, '81]

2. **(a)** Explain what is meant by the decibel scale for comparing two quantities, and give a definition of a reference level for such a scale for sound intensities.

(b) A listener wears headphones connected to the output of a stereo amplifier whose output is initially 2.0 mW. The listener slowly increases the output power and subjectively does not discern an increase in sound intensity until the power has risen to 2.5 mW. Successively discernible increases then occur at 3.2 mW and 4.0 mW.
Use these results
(i) to show why the decibel scale is a useful one,
(ii) to calculate the ratio of the amplitudes of the pressure waves of two sounds whose difference in intensity is just discernible. [N, '79]

3. **(a)** The loudness of a sound as heard by an individual depends on the frequency and intensity of the sound.
(i) Define *frequency* and *intensity*.
(ii) Sketch a graph to show how loudness of a sound, as heard by a person with normal hearing, depends on frequency when the intensity of the sound is constant. Point out any special features of the graph.
(iii) Describe the response of the ear to different intensities of sound with the frequency remaining constant. Hence define *intensity level*.

(b) A source emits sound energy uniformly in all directions. A sound-level meter records 92 dB when situated 2.5 m from the source. Given that I_0, the threshold intensity of hearing, is $1.0 \times 10^{-12}\,W\,m^{-2}$, calculate the total sound power emitted by the source.
[C, '92]

4. **(a)** With the aid of a labelled diagram of the middle ear, explain how sound energy is transmitted across the tympanic cavity. Give a reason why the pressure changes due to sound are increased as a result of this transmission and state an approximate value for the increase.

(b) A meter, which measures relative intensity level of sound referred to $1\,pW\,m^{-2}$, records a value of 97 dB when a pneumatic drill is switched on some distance away. Calculate the intensity of sound at the meter.
A second drill, identical to the first, is placed close to it. State the intensity of sound at the meter when both drills are working and hence calculate the *increase* in the meter reading.
Explain why it is convenient to use the decibel scale for such measurements.
[N, '85]

5. **(a)** Give a **short** outline of the **physical** processes which give rise to the sensation of hearing when a sound wave is directed towards the human ear.

(b) The auditory canal along which the sound waves pass can be thought of as being like a pipe closed at one end. In a normal adult the length of this canal is about 0.025 m.

Estimate the fundamental resonant frequency of the canal if the speed of sound in air is $340\,\mathrm{m\,s^{-1}}$. Neglect end effects.

(c) **(i)** Sketch a graph showing how the threshold of hearing of the normal adult human ear varies with frequency when listening to a source of sound of constant intensity over the whole of the audible range.

(ii) Label the axes with appropriate numerical values and units.

(iii) The sound intensity at the threshold of hearing for a frequency of about 3 kHz is $10^{-12}\,\mathrm{W\,m^{-2}}$. What do you think sets this lower limit?

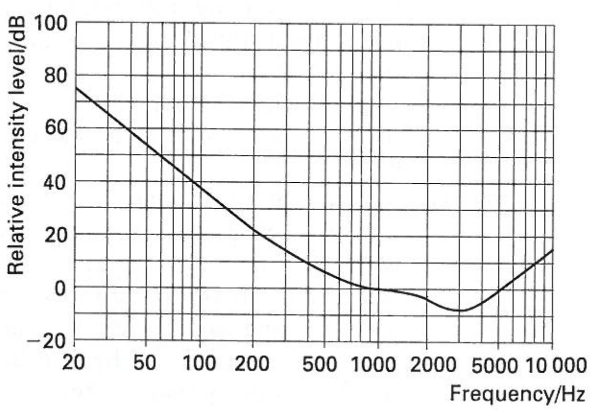
(d) A foghorn situated at the top of a tall mast may be considered to be a point source of sound. When the horn is in operation the sound intensity measured 0.8 m from the horn is $2.0 \times 10^{-3}\,\mathrm{W\,m^{-2}}$. An observer sailing towards the horn can just hear it at a distance of 900 m.

(i) What is the sound intensity at the ear of the observer when the sound is first heard?

(ii) Suggest why the intensity in **(i)** is much larger than the intensity at the threshold of hearing. [N, '93]

6. **(a)** Define *intensity of sound* and give a formula for relative intensity level measured in decibel (dB) units. Explain why it is convenient to compare intensity levels of sound in decibel units.
The value of the *standard reference intensity* is $10^{-12}\,\mathrm{W\,m^{-2}}$. Explain what this value represents.

(b) The graph shows the threshold of hearing, for a young person with good hearing, as a function of frequency.



(i) Estimate the frequency at which the subject's ear is most sensitive.

(ii) Estimate the least intensity of sound the subject can detect at 100 Hz.

(iii) The external auditory canal of the subject behaves like a tube of effective length 2.8 cm closed at one end by the eardrum. Show, with the aid of a calculation, that this is consistent with your answer to **(i)** above.

The speed of sound in air $= 340\,\mathrm{m\,s^{-1}}$.

[N, '83]

7. **(a)** A certain source of sound of variable frequency produces sound of the same intensity at all frequencies.

(i) Sketch a graph, labelled Graph 1, showing the relationship between the response to sound from the source of a sound level meter scaled in dB (vertical axis) and the frequency (horizontal axis) as the latter is varied from 10 Hz to 20 kHz. Indicate numerical values on the frequency axis.

(ii) On the same set of axes sketch a graph, labelled Graph 2, to show the relationship for a meter scaled in dBA as the frequency is varied over the same range.

(iii) Why do most sound level meters use the dBA scale?

(b) A lightning flash is seen some distance away and 4 s later the accompanying thunderclap is heard at a site where a sound level meter produces a maximum reading of 100 dB. Assuming the thunder behaves as if it came from a point source from which the sound intensity falls off with distance according to an inverse square law, calculate

(i) the distance between the lightning stroke and the observation site,

(ii) the peak sound intensity at the meter,

(iii) the peak acoustic power, in watts, produced by the thunderclap.

Neglect absorption of sound during transmission through the air. (Speed of sound in air $= 331\,\mathrm{m\,s^{-1}}$.)