9 SOUND

9.1.1 Introduction

Sound is the term given to pressure fluctuations in the air that we can perceive through our sense of hearing. Acoustics is the name given to the science of sound. Figure 9.1 lists the general topics that we are going to cover in the next two weeks.

Measurement of sound

External noise climate

Planning of Building areas

Noise transmission

Room acoustics

Figure 9.1 Topics in Acoustics

Sound waves are produced when a surface is cyclically moved forwards and backwards to alternatively produce a compression and a rarefaction of air next to the surface. These pressure disturbances are then propagated outwards from the disturbing surface as is shown in Figure 9.2 which depicts a piston cyclically moving to and fro within a cylinder. Such pressure waves from a single source are Plane Waves.

In Figure 9.2 the compression of air within the cylinder is shown as a thickening of the vertical lines and the rarefaction as a thinning of the lines. Below the cylinder is shown the variation in the acoustic pressure in the air. The ambient air pressure will be at zero acoustic pressure. Compressed air will have a positive acoustic pressure and rarefied air will have a negative acoustic pressure.

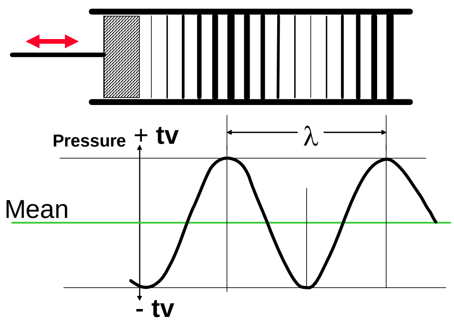


Figure 9.2 Nature of Sound

The amplitude of the sound is the difference between the maximum and the zero acoustic pressure and in this case it will be a function of the distance the piston travels on each stroke. The higher the amplitude of a pressure wave the louder will be the perceived sound.

The frequency with which the piston is moved to and fro will determine the frequency of the sound. Different frequencies will be perceived as being of different tones.

As with the other wave phenomena that we have considered, there is a clear relationship between the frequency, wavelength and speed,

$$\textit{speed of sound} = \textit{wavelength} \times \textit{frequency} \quad \text{ms}^{-1}$$

Where:

c = speed of sound in air, 343 ms^{-1}

λ = wavelength of sound in m.

f = frequency of sound in Hz.

$$c = \lambda \,.\, f \quad \text{ms}^{-1}.$$

We can hear sounds between the frequencies of 20 Hz and 20 000 Hz and a comparison between these audible frequencies and the associated wavelengths of sound are shown in Figure 9.3. The wavelengths of sound at important frequencies are comparable to the scale of some of the physical features in a room and therefore in room

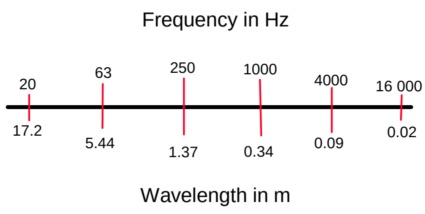


Figure 9.3 λ vs. f

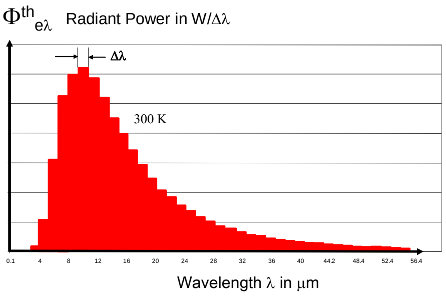


Figure 9.4 - Spectro-radiometric curve

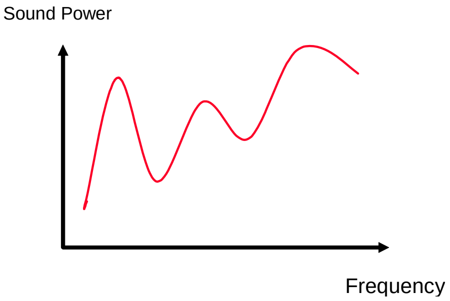


Figure 9.5 - Sound power vs

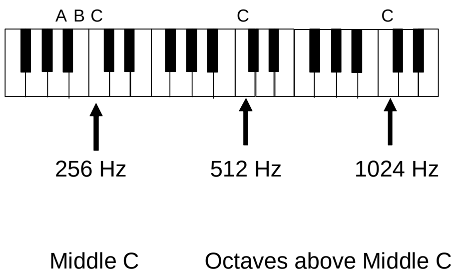


Figure 9.6 - Middle C on Piano keyboard

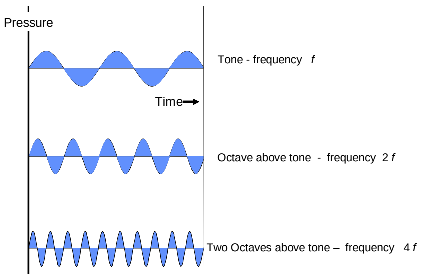


Figure 9.6A Notes that are Octaves

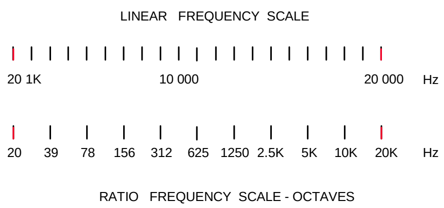


Figure 9.7 - Ratio vs linear Frequency

acoustics it may be necessary to consider diffraction effects i.e. the bending of sound around corners. But this will be left till later.

When describing the power distribution of a radiation source (see pages 12-14), the power of the radiation over a whole range of bandwidths was plotted on a spectroradiometric curve. The total power emitted was found by summing the power emitted over each of the bandwidths for all the wavelengths in the spectrum. As is shown in Figure 9.4, the wavelengths were plotted on a linear scale of wavelength.

A similar curve may be drawn for the acoustic power that is emitted from a sound source, and an example is shown in Figure 9.5. A difference that you will notice, is that the sound power is plotted against the frequency of the sound rather than the wavelength. This is partly for historical reasons and also because frequency is the invariant property when sound travels through different materials.

We perceive different frequencies of sound as having different tones. Additionally, we hear relationships between the tones produced by particular intervals of frequency. Perhaps the most well known of these is the interval of the Octave – one of the intervals used to create musical scales.

Consider the piano keyboard shown in Figure 9.6. A note known as middle C has a frequency of 256 Hz. As the higher notes above middle C are played, one reaches another note that is recognisably similar to middle C. It is found that the frequency of sound emitted by this note is 512 Hz, exactly twice the frequency of middle C. Playing notes even higher, then another note sounding similar to middle C is found, and this has a frequency of 1024 Hz, i.e. exactly four times that of middle C. This is shown graphically in Figure 9.6A. A note that is in this manner similar in sound to another note, is said to differ by the interval of an Octave, i.e. a tone that is one Octave higher will have a frequency exactly twice that of the lower sound.

Clearly the octave is of real significance in the perception of music. But also with ordinary sounds, it is found that the subjective impressions that result from changes in frequency are better conveyed by an octave scale than a linear scale. Additionally, the octave scale provides a more convenient scale against which to plot acoustic power. A scale of frequency using octaves is in effect a ratio scale and Figure 9.7 shows a comparison of a linear and ratio scale over the auditory frequency range.

The acoustic power spectrum of a sound is therefore generally plotted against a scale of octaves as is shown in Figure 9.7A.

The power of sound radiated must be measured over some bandwidth, or range of frequencies. This is easy enough where power is measured over a linear scale, but here the frequency scale is a ratio scale. The question that needs to be answered is; between what frequencies is the sound power measured.

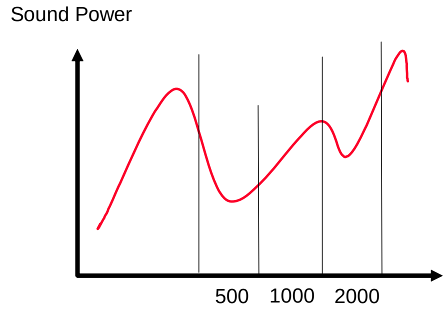


Figure 9.7A - Power vs Octaves

First, let each of the frequencies that describe each octave be the mid-frequency of the octave. Thus in Figure 9.7A, the frequencies given as 500 Hz, 1000 Hz and 2000 Hz are the mid-frequencies of the octave band.

Because the frequency scale is a ratio scale, then the middle of the frequency range should have the same ratio relationship between its lower boundary and its upper boundary. Thus, the frequencies that define the boundaries should follow the following rules:

a) an upper boundary of frequency f_U has the same ratio above the middle frequency f_M,

b) as the mid frequency f_M is above the lower boundary f_L.

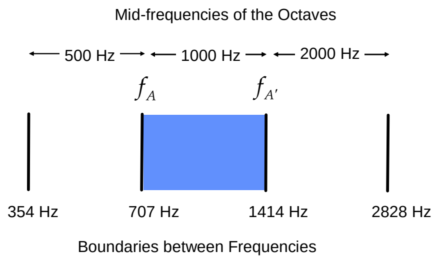


Figure 9.8 - Upper and lower boundaries of an Octave

In algebraic form, this is stated as:

$$f_U = f_M \times x$$
$$f_M = f_L \times x$$

Because it is an Octave scale, the upper frequency is twice the lower frequency and so,

$$f_U = 2 f_L$$

Substituting into this relationship the rules for f_U and f_L that were stated previously, then,

$$f_M \times x = 2 \times \frac{f_M}{x}$$
$$x^2 = 2$$
$$x = \sqrt{2}$$

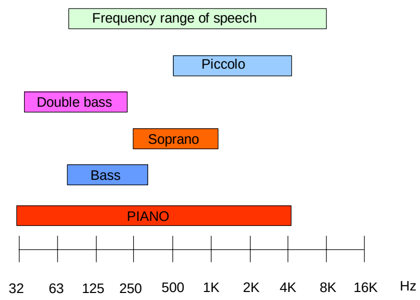


Figure 9.9 – Frequencies of

This value of x has been used to calculate the upper and lower boundaries for the three octaves, centred on 500 Hz, 1000 Hz and 2000 Hz. These are shown in Figure 9.8. In all the work to follow, the upper and lower boundaries will not be referred to, and the different octaves will be described only by their mid-frequencies.

Figure 9.9 shows the range of frequencies produced by a number of musical instruments and the approximate frequency range of produced by the human voice.

In Figure 9.10 there is listed the total sound power emitted by a number of different sound sources. From this figure it can be seen that a really vast range of sound powers are produced by different sources, indeed as large a ratio as 10^{15}. In order that this range can be accommodated, use is made of a logarithmic scale of measurement. An additional attraction of the logarithmic scale is that the logarithm

Sound Source	Power in Watts
Saturn Rocket	50×10^{6}
Jet airliner	50×10^{3}
Orchestra	10
Chipping hammer	1
Shouted Speech	0.001
Conversation	20×10^{-6}
Whisper	1×10^{-9}

Figure 9.10 – Sound Powers

of the stimulus of sound is again better related to the subjective effect than a simple linear scale.

9.2 Logarithms

Logarithms are used less frequently than they used to be because calculators have taken over one of their principal uses. Before calculators were common, logarithms were used to simplify and speed up the process of multiplying large numbers.

Consider the sum;

$$2 \times 2 \times 2 = 8\ ,$$

this can be re-written,

$$2^3 = 8\ .$$

Where the number 3 represents the '*power*' to which the base number 2 has been raised i.e. the number of times the base number has been multiplied by itself.

The logarithm of the number 8 is the power to which the base has to be raised in order to give the number 8, and so;

$$\log_{Base\ of\ 2}(8) = 3\ .$$

The benefit of using logarithms can be appreciated by considering the following example;

Take the number 4, $4 = 2 \times 2 = 2^2$,
& the number 8, $8 = 2 \times 2 \times 2 = 2^3$

If the numbers are written as powers of the number 2, the result of their multiplication is the total number of times the number 2 is multiplied by itself. This total is just the addition of the number of times each part is multiplied by 2.

$$4 \times 8 = (2 \times 2) \times (2 \times 2 \times 2) = 2^{(2+3)} = 2^5 = 32$$

Using logs,

$$\begin{array}{r} \log_2(4) = 2 \\ +\log_2(8) = 3 \\ \hline \log(4 \times 8) = 5 \\ \hline\hline \end{array}$$

Taking the anti-logarithm of 5,

$$anti\log_2(5) = (base\ of\ 2)^{Logarithm} = 2^5 = 2 \times 2 \times 2 \times 2 \times 2 = 32$$

Thus, by using logarithms, the process of multiplication can be replaced by that of addition – a much simpler process and one less prone to error.

In acoustics the base of the logarithms used is usually to the base of 10. Sound Power Level

Sound Power, Watts	Sound Power Level, dB
100 000 000	200
1 000 000	180
10 000	160
100	140
1	120
0.01	100
0.000 1	80
0.000 001	60
0.000 000 01	40

Figure 9.11 – Sound Power Levels

In acoustics there is a special term used to describe a particular measure of sound. This term is 'Level' and it is always used to describe a quantity that relates some absolute measure to some reference level.

For instance, in the case of Sound Power, where the reference level of power is,

$$W_0 = 10^{-12} \text{ Watt,}$$

then the Sound Power Level is defined as,

$$SWL = 10\log_{10}\left(\frac{Power\ of\ Sound\ Source}{Reference\ Power}\right) \text{ decibels}$$

$$SWL = 10\log_{10}\left(\frac{W_1}{W_0}\right) \text{ dB}$$

The two aspects of Levels that are significant are that they utilize logarithms and that they are a relative measure. A feature of relative measures is that they commonly use the unit of the Bel. The Bel is a rather large unit and therefore the smaller unit of the decibel is used, i.e. one tenth of a Bel. Note that 10 decibels is the same as 1 Bel.

Figure 9.11 shows the Sound Powers for a range of sound sources and corresponding Sound Power Levels in dB.

9.3 Sound Intensity

Sound intensity is the concentration of power per unit area through which the sound moves. Figure 9.12 shows a sound source that radiates sound equally in all directions. The sound from such a source will be simple Plane Waves. As the sound radiates outwards the sound power will be spread over an ever increasing surface area of sphere that is centred on the sound source. The intensity of the sound at any distance R from the sound source will be defined as the sound power per unit area of the sphere at distance R,

$$Sound\ Intensity = I = \frac{Power}{Area} \text{ in W/m}^2.$$

And for a sound source of sound power W_S Watt, then at a distance R the area of the sphere over which the sound will be spread is:

$$A_{SPHERE} = 4\pi R^2,$$

And so the sound intensity will be given by:

$$I_R = \frac{W_S}{4\pi R^2} \text{ W/m}^2.$$

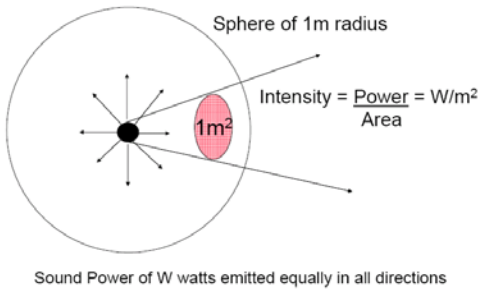


Figure 9.12 – Sound Intensity

9.3.1 Sound Intensity Level

The reference intensity that is used to give the Sound Intensity Level is the intensity of sound that can be just heard i.e. the threshold of hearing, and it has an accepted value of,

$$I_0 = 10^{-12} \quad \text{W/m}^2.$$

the Sound Intensity Level is then defined as,

$$SIL_1 = 10\log_{10}\left(\frac{\text{Intensity of sound source}}{\text{Reference intensity}}\right)$$

$$SIL_1 = 10\log_{10}\left(\frac{I_1}{I_0}\right) \quad \text{dB}$$

Sound intensities are difficult quantities to measure and generally it is much easier to use a microphone to measure the acoustic pressure produced by a sound.

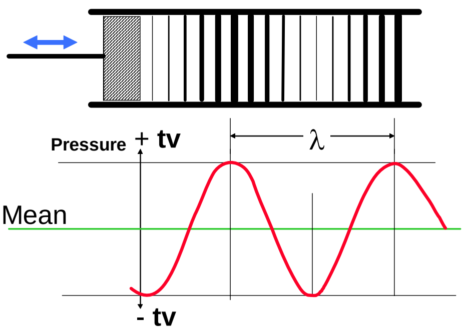


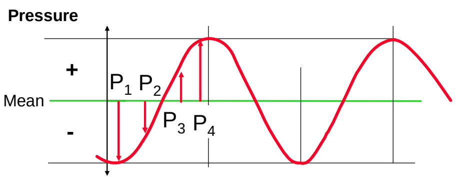
Figure 9.13 – Nature of Sound

9.4 Sound Pressure

The reciprocating piston in Figure 13 creates the cyclic rarefaction and compression of air that propagates the pressure wave in the air that stimulates our ears. This pressure wave is partly above the average air pressure and partly below the average air pressure as shown in Figure 9.13.

The mean air pressure of the wave is the average ambient air pressure because the over and under pressure of the pressure wave cancel each other out. Therefore the pressure wave is instead characterised by a quantity known as the Root Mean Square of the pressure, P_{RMS} that is shown diagrammatically in Figure 9.14,

$$P_{RMS} = \frac{\sqrt{\left(P_1^2 + P_2^2 + P_3^2 + P_4^2\right)}}{4},$$



$$P_{RMS} = \frac{\sqrt{P_1^{\,2} + P_2^{\,2} + P_3^{\,2} + P_4^{\,2}}}{4}$$

Figure 9.14 – Root Mean Square

More correctly it should be written,

$$P_{RMS}^2 = \frac{1}{T}\int_0^T P^2 dt$$

Where T is the time of one period or cycle.

No proof is going to be given, but the power radiated by a wave phenomenon is proportional to the square of the force that is driving it:

$$Power = \frac{(Driving\ Force)^2}{Resistance}.$$

Sound is the transport of power through the process of an alternating pressure wave and thus the relationship between power transported and the driving force is:

$$Sound\ Intensity = \frac{(Pressure)^2}{Resistance}$$

$$Sound\ Intensity = \frac{P_{RMS}^2}{\rho c} \quad \text{W/m}^2,$$

where: ρ = density of air 1.21 kg/m^3,
c = speed of sound in air 343 m/s,
and ρc is the acoustic impedance of the air in rayls.

9.4.1 Sound Pressure Levels

The Sound Pressure Level is defined as;

$$SPL = 10\log_{10}\left(\frac{P_1^2}{P_0^2}\right) \quad \text{dB},$$

which from earlier work on logarithms is equivalent to,

$$SPL = 20\log_{10}\left(\frac{P_1}{P_0}\right) \quad \text{dB}$$

The reference pressure P_0 is chosen to be 2×10^{-5} Pa (N/m^2). This pressure is chosen as the reference level because it is the Threshold of Hearing at a frequency of 1000 Hz i.e. it is the pressure at which on average a sound of frequency 1000 Hz just can be heard.

The reference intensity used to establish a sound intensity level is chosen so that at threshold the sound pressure level and the sound intensity level are equivalent, thus:

$$SPL_1 = SIL_1.$$

This equivalence is only true for plane sound waves, i.e. those that emanate from a point source of sound. However, it is not true for reverberant sound fields which will be covered in greater detail in later years.

Figure 9.16 gives the acoustic sound pressures and Sound Pressure Levels of a number of typical sources of sound.

Figure 9.17 lists the reference values used when determining the Levels of Sound Power, Sound Intensity and Sound Pressure.

Sound	Pressure Pa	Pressure Level
Jet taking off	63	130 dB
Pneumatic drill	2	100 dB
Inside a car	0.4	85 dB
General office	0.02	60 dB
Living room	0.002	40 dB
Countryside	0.0001	15 dB
Threshold	0.00002	0 dB

Figure 9.16 – Sound Pressure

Sound Intensity at threshold $I_0 = 10^{-12}$ W/m^2
Reference Pressure $P_0 = 2 . 10^{-5}$ N/m^2
Reference Sound power $W_0 = 10^{-12}$ Watts

Figure 9.17 – Sound reference

9.5 Adding Sounds together

The sound intensity of two sounds comprising plane sound waves is found by adding together the sound intensities of the two individual sounds,

$$I_{TOTAL} = I_1 + I_2 \quad \text{W/m}^2.$$

Indeed, for as many individual sounds as one would wish to consider, the final total sound intensity is simply the sum of all the constituent sound intensities,

$$I_{TOTAL} = I_1 + I_2 + I_3 + I_4 \cdots I_N \quad \text{W/m}^2.$$

However, we generally describe a sound in terms of Levels, e.g. Sound Power Levels – SWL, Sound Intensity Levels – SIL or Sound Pressure Levels – SPL.

Therefore when we want to add together the effects of a number of sounds then we need to first convert our Levels back to Sound Intensities, then to combine the intensities and reconvert back into the appropriate Level.

Given a sound intensity level of SIL_1 dB, then from the definition of SIL's,

$$SIL_1 = 10\log_{10}\left(\frac{I_1}{I_0}\right) dB$$

Dividing both sides by 10,

$$\frac{SIL_1}{10} = \log_{10}\left(\frac{I_1}{I_0}\right) B$$

Taking anti-logs on both sides,

$$antilog_{10}\left(\frac{SIL_1}{10}\right) = antilog_{10}\left(\log_{10}\left(\frac{I_1}{I_0}\right)\right)$$

$$10^{\left(\frac{SIL_1}{10}\right)} = \frac{I_1}{I_0}$$

So in order to add two sounds together,

$$\frac{I_T}{I_0} = \frac{I_1}{I_0} + \frac{I_2}{I_0}$$

Using the relationship just derived,

$$\frac{I_T}{I_0} = 10^{\left(\frac{SIL_1}{10}\right)} + 10^{\left(\frac{SIL_2}{10}\right)}$$

And so,

$$SIL_T = 10\log_{10}\left(\frac{I_T}{I_0}\right) dB$$

Giving,

$$SIL_T = 10\log_{10}\left(10^{\left(\frac{SIL_1}{10}\right)} + 10^{\left(\frac{SIL_2}{10}\right)}\right) dB$$

This equation is performed quite easily if you have a hand calculator with logs and anti-logs. Where you need to add together a large number of sounds then evaluating this formula is the most sensible method of calculation.

However, if you wish to add just two or three sound levels together, then there is a graphical method using the chart shown in Figure 9.19 that is quite quick.

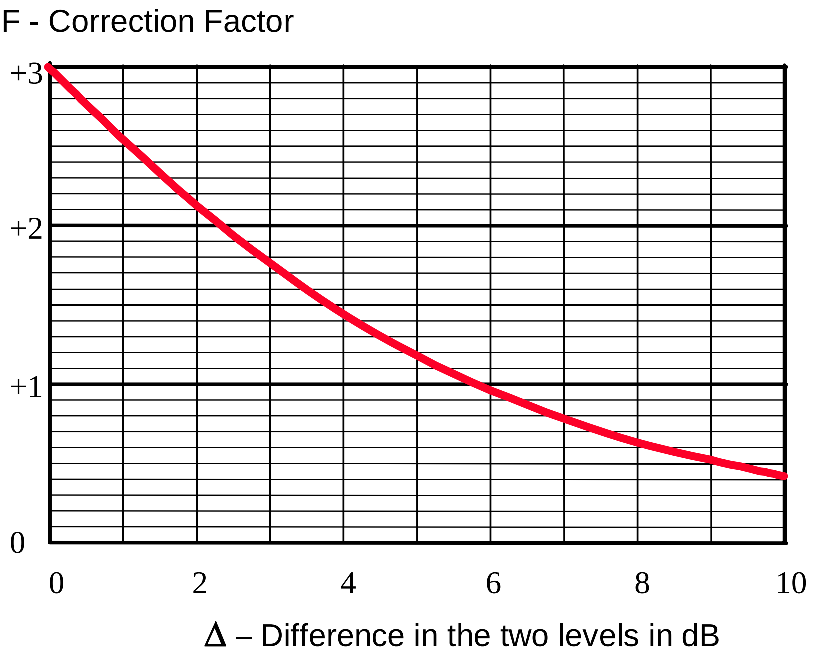


Figure 9.19 – Correction chart for adding levels together

Given two intensity sound levels to add together, SIL_{HIGHER} and SIL_{LOWER}, then the total sound intensity level, SIL_T will be given by,

$$SIL_T = SIL_{HIGHER} + correction\ factor\ F$$

Where the correction factor F is read from the Chart of Figure 19 and the difference between the two sound levels is,

$$\Delta = SIL_{Higher} - SIL_{Lower}$$

9.5.1 Example with two sounds.

Find combined effect of the two sound levels 63 dB and 68dB.

Initially find the difference between the two sound levels,

$$\Delta = 68 - 63 = 5dB\,,$$

Then read from the chart in Figure 9.19 that for a difference of Levels of $\Delta = 5dB$, the correction factor F is 1.2 dB, and so the sound level of the combined sounds is,

$$SIL_{TOTAL} = 68 + 1.2 = 69.2\ dB$$

Using the formula method,

$$\begin{aligned} SIL_T &= 10\log_{10}\left(10^{\left(\frac{SIL_1}{10}\right)} + 10^{\left(\frac{SIL_2}{10}\right)}\right) dB \\ &= 10\log_{10}\left(10^{6.8} + 10^{6.3}\right) \\ &= 10\log_{10}(8304835.8) \\ &= 10 \times 6.919 \\ &= 69.2\,dB \end{aligned}$$

9.5.2 An Example of combining a sound spectrum

Add together the following six Sound Intensity Levels that were measured over each octave,

Mid-frequency	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Sound Level	60 dB	63 dB	64 dB	55 dB	72 dB	65 dB

Using the graphical method first, and putting the sum into a table:

<table>
<tr><th>f</th><th>dB</th><th>Δ</th><th>F</th><th>Sub-Total</th><th>Δ</th><th>F</th><th>Sub-Total</th><th>Δ</th><th>F</th><th>Total</th></tr>
<tr><td>125</td><td>60</td><td rowspan="2">3</td><td rowspan="2">1.8</td><td rowspan="2">64.8</td><td rowspan="4">0.3</td><td rowspan="4">2.9</td><td rowspan="4">67.7</td><td></td><td></td><td></td></tr>
<tr><td>250</td><td>63</td><td rowspan="5">5.1</td><td rowspan="5">1.2</td><td rowspan="5">74</td></tr>
<tr><td>500</td><td>64</td><td rowspan="2">9</td><td rowspan="2">0.5</td><td rowspan="2">64.5</td></tr>
<tr><td>1000</td><td>55</td></tr>
<tr><td>2000</td><td>72</td><td rowspan="2">7</td><td rowspan="2">0.8</td><td rowspan="2">72.8</td><td colspan="3" rowspan="2">72.8</td></tr>
<tr><td>4000</td><td>65</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Consider adding the first two SIL's in column 2, the difference in sound levels Δ is 3dB and from Figure 19 the correction factor F is 1.8 dB. This is added to the higher SIL 63 dB and gives a SIL of 64.8 dB.

This process is continued with pairs of SIL's that are summed together until a final value is obtained, in this case a value of 74 dB.

Checking by calculation using a calculator,

$$
\begin{aligned}
SIL_T &= 10\,\boldsymbol{log}_{10}(10^{6.0} + 10^{6.3} + 10^{6.4} + 10^{5.5} + 10^{7.2} + 10^{6.5}) \\
&= 10\,\boldsymbol{log}_{10}(1000000 + 1995262.32 + 2511886.43 + \\
&\qquad + 316227.8 + 15848931.9 + 3162277.7) \\
&= 10\,\boldsymbol{log}_{10}(24834586.11) \\
&= 73.95dB \\
&= 74\,dB
\end{aligned}
$$

The two answers are very close together and therefore it really is a matter of convenience as to which method is used. I personally find the graphical method quicker when adding together a small number of sounds, but less convenient and accurate than the calculation method when adding together the octave levels from a whole sound spectrum.

9.6 Stimulus of Hearing

Figure 9.21 shows the range of hearing at different frequencies and typical Sound Pressure Levels that are experienced when listening to voices and to an orchestra.

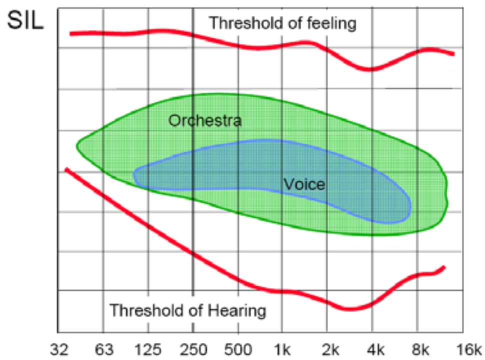


Figure 9.21 – Range of hearing

Of particular interest is the lower curve that gives the 'Threshold of hearing' i.e. the SPL's at various frequencies that can just be heard by the average human ear. Use the threshold at a frequency of 1000 Hz as a standard for comparison.

At frequencies below 1000 Hz, a higher SIL is required for a sound to be heard. Or put another way, the ear is less sensitive to the lower frequencies, and increasingly less sensitive as the frequency drops.

At frequencies between 1000 Hz and 5000Hz the ear can detect sounds at SPL's that are less than that required at 1000 Hz, i.e. the ear is more sensitive to the frequencies between 1000 Hz and 5000 Hz.

At frequencies beyond 5000 Hz, the ear becomes less sensitive than at 1000 Hz.

If we wish to choose a measure of sound level that gives a good indication of the subjective effect, then it is important to take into account this change in the sensitivity of the ear to different frequencies of sound. Applying a correction factor to the raw values of Sound Intensity Levels will give a measure of sound that relates better to what we hear. When the whole spectrum of sound is then added together we will have a single number that gives a fair indication of the loudness of the sound.

This correction factor is called a weighting and for normal average conditions the ‘A’ weighting is applied to the raw SILs. In all the work done this year only the ‘A’ weighting will be used.

The weighting corrections that should be used in normal circumstances are:

Frequency in Hz	63	125	250	500	1000	2000	4000	8000
dB(A) correction	-26	-16	-9	-3	0	+1	+1	-1