Building Physics

5. Acoustics

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Acoustics

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In this chapter, the basic principles in relation to sound come up for discussion: what is sound, how do people experience sound, how does sound absorption work. We also discuss how the sound situation in spaces can be evaluated and how to deal with this in the design.

10.1 Basic terms

Sound is energy that is produced by a source in the form of vibrations (variations in pressure), which moves through a medium (such as air) as sound waves and is received by a detector (such as the ear):

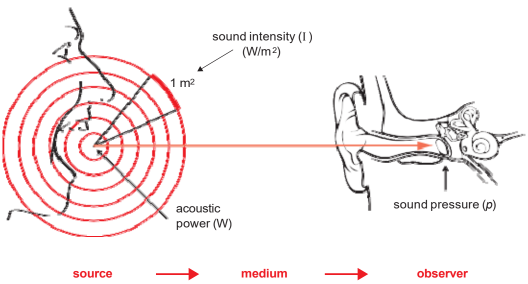


Figure 10.1 Sound production and perception

The energy produced or generated by the source is called acoustic power. This is expressed in watt (W). The energy at a random place inside the medium is called the sound intensity and is expressed in W/m^2. The energy perceived by an observer is called the sound pressure, which is expressed in pascal (Pa).

Sound source

If a source is made to vibrate (the vocal chords for instance) then the adjacent medium (air for instance) will also start to vibrate. Acoustic power is primarily used to describe the noise production from machines and appliances. Acoustic power is also used in calculating sound propagation through air duct systems.

Sound waves

The sound source will make the adjoining medium (for instance air) vibrate. These vibrations are called sound waves. If you move the end of a piece of rope up and down then a wave will propagate through the rope as shown in figure 10.2. The direction of movement in the rope is perpendicular to the propagation direction of the wave. This is known as a transverse wave motion. The wave propagates, the particles of the rope remain in place and move around a point of equilibrium.

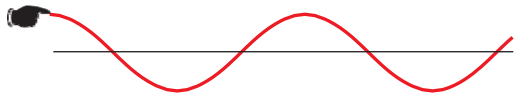


Figure 10.2 Propagation of a transverse wave

It is somewhat different for a sound wave. Here the direction of movement of the particles is the same as the direction of propagation. This is known as a longitudinal wave motion.
This can be illustrated using a number of spherical balls that are suspended on wires in a frame (see figure 10.3). If you allow the left hand ball to fall onto the row of stationary balls, then a longitudinal wave propagates through the row of balls and the right hand ball is flung out.

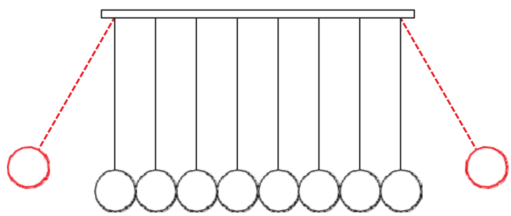


Figure 10.3 Propagation of a longitudinal wave

In a sound wave in air there are rarefactions and compressions (negative and positive sound pressures): the air particles vibrate around an equilibrium position (see figure 10.4). The air particles remain in their locations, the wave propagates. Longitudinal sound waves arise also when driving a pile in the ground. When this pile receives a blow, a shockwave is produced which travels to the end of the pile.

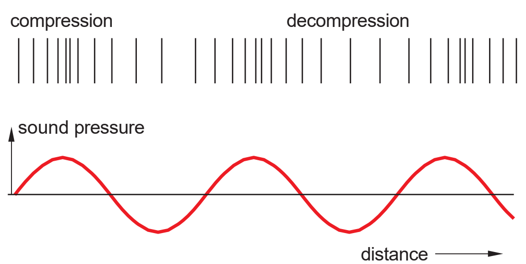


Figure 10.4 Propagation of a sound wave through the air

A number of characteristic values can be derived in relation to wave motions, specifically, the frequency (f), the wavelength (λ) and the propagation speed (c).

Frequency, wavelength and propagation speed

The sound wave (λ) in a longitudinal wave is the distance between two compressions (or two rarefactions).
In general, the wave length is the distance between two points which are in an identical state (they are in phase). The number of vibrations per second is the frequency (f), which is expressed in Hertz (Hz).

Different tones have different frequencies. This way low tones have a low frequency (therefore a small number of vibrations per second or a ‘long wavelength’) and high tones have a high frequency (therefore a large number of vibrations per second or a short wavelength).
A pure tone consists of a sound whose sound pressure changes in time in the shape of a sine wave (see figure 10.5). Pure tones are rare. The tone produced by a musical instrument is also built up of a base tone and various harmonics (see figure 10.6). The composite sound then displays an image similar to that shown in figure 10.7-1.
Most sounds occurring in the environment are build up of many different tones causing the progression of the sound pressure to become very jagged with time (see figure 10.7-2).

The propagation speed (c) of longitudinal waves is the same for all frequencies and depends on the medium and the temperature of the medium. However, the temperature differences in structures are relatively small in practice so that a single propagation speed can be used for calculations. The propagation speed in air is approximately 340 m/s (20 °C).

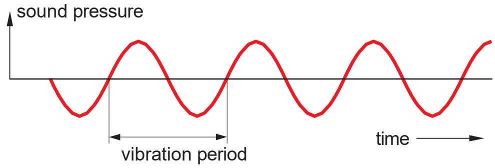


Figure 10.5 The progress of a sound wave as a function of time for a pure tone

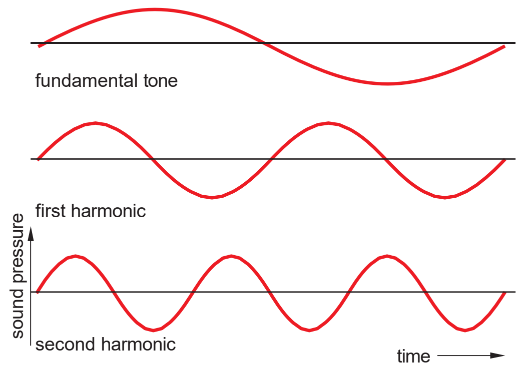


Figure 10.6 Base tone and harmonics

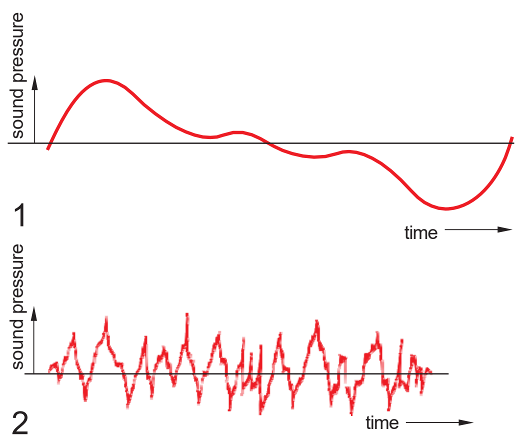


Figure 10.7 Composite sounds

The following propagation speeds apply for other media:

- $c_{\text{aluminium}}$ = 5100 m/s
- c_{steel} = 4900 m/s
- c_{concrete} = 4000 m/s
- c_{masonry} = 2000 m/s
- c_{water} = 1450 m/s

The following relationship exists between the propagation speed, the frequency and the wavelength:

$$c = f \cdot \lambda \text{ [m/s]}$$

The meaning of the symbols is:
c the propagation speed of the sound in m/s
f the frequency in Hz
λ the wavelength in m

The wavelength of a specific frequency (in air) can therefore be calculated as follows:

$$\lambda = \frac{c}{f} = \frac{340}{f} \text{ [m]}$$

This is shown for a number of frequencies in the table in figure 10.8.

Sound spectrum

When we want to know how the sound energy is distributed across the frequency range we generally use an internationally standardised system of octave bands. An octave band gets its name from the fact that the upper threshold frequency is twice as high as the lower threshold frequency. The upper threshold frequency forms the octave of the lower threshold frequency. Octave bands are designated by their mid frequency.

f [Hz]	λ [m]
63	5.40
125	2.72
250	1.36
500	0.68
1000	0.34
2000	0.17
4000	0.09
8000	0.04

Figure 10.8 Frequencies and wavelengths

In addition to octave bands, one-third octave bands are also frequently used (particularly in Germany). These are 1/3 octave bands. Figure 10.9 shows the frequency range with the octave bands of a keyboard and the register of a number of musical instruments and singing voices.

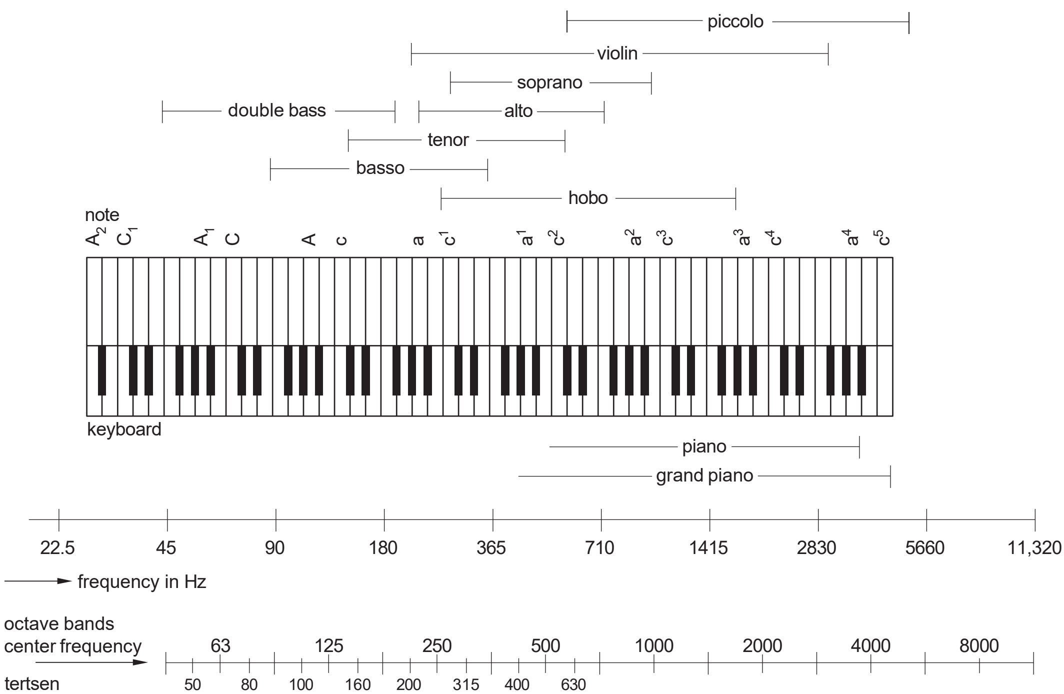


Figure 10.9 Arrangement of the frequency range into octave bands and thirds

Sound propagation

The energy produced by the sound source, will spread through the medium and arrive at the observer. Here we can make a distinction between sound propagation in the free field (unhindered sound expansion is possible) and sound expansion in a closed room (no unhindered sound propagation is possible). In the free field sound waves can, therefore, expand 'unhindered'. In that case we mean progressing waves. In a closed room the sound waves will not be able to expand unhindered because of the limited space: they will quickly reflect from the wall. In this case the sound waves can propagate through the room in a random fashion. We then talk about a diffuse sound field. In other words:

- The conditions for a progressing wave are roughly met by a sound that comes from a specific direction, as is often the case outdoors (industrial noise etc.).
- There is a diffuse sound field when the sound waves run in all directions, such as is roughly the case inside a room.

This distinction is very important. We will use this for deriving relationships in the course of this and subsequent chapters.

Sound intensity in the free field

Sound propagation in the free field depends on the characteristics of the source. Here a distinction can be made between:

- a point source (a loudspeaker for example),
- line source (for example a busy motorway with a continuous flow of cars).

In sound propagation from a point source the energy will expand spherically (equal energy in all directions). In sound expansion from a line source the energy will expand cylindrically. When the sound intensity (the energy per square metre) at a specific point has to be determined this is relatively simple. It is equal to the energy produced by the source divided by the area over which the energy has been spread. The amount of energy that is determined using this method is known as the sound intensity (I).

The following applies for a point source:

$$I = \frac{W}{\left(\frac{4\pi r^2}{Q}\right)} \ [\mathrm{W/m^2}]$$

The following applies for a line source:

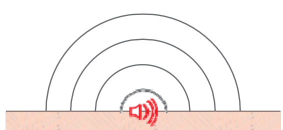
$$I = \frac{W}{\left(\frac{2\pi r}{Q}\right)} \ [\mathrm{W/m^2}]$$

The meaning of the symbols is:

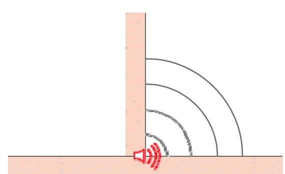
I the intensity in watts per m^2
W the acoustic power of the source in W
r the radius of the sphere or cylinder in m
Q the direction factor

Q is the direction factor of the source. If the source is transmitting an equal amount of energy in all directions, the direction factor is $Q = 1$, a source that is free in space for example (see figure 10.10). If the same source is placed on a hard surface then the same amount of energy will spread over a hemisphere ($2\pi r^2$). This leads to a direction

1
free field
Equal amount of sound propagation in all directions, in a sphere (4nr^2), Q = 1



2
free field
Reflection via a hard surface. Energy distributed in a hemisphere (2nr^2), Q = 2



3
free field
Reflection via the bottom and a wall. Energy distributed in a quarter of a sphere (nr^2), Q = 4

Figure 10.10 Direction factor Q

factor $Q = 2$. The intensity is therefore twice as great. If, however, the source is placed on a soft (absorbent) surface, then the direction factor Q is equal to 1. Approximately half the quantity of energy will immediately be absorbed by the soft surface.

Sound intensity in a closed room

In a closed room the sound waves will hit the surrounding structure. Part of the sound wave is reflected by the structure, but part of it is also absorbed by the structure (particularly if the structure comprises acoustically 'soft' material).
We can use the difference between an empty house and a furnished house as an example. In an empty house with a lot of concrete everything sounds much louder than when the same house has been furnished (with carpeting, curtains and furniture for example). The difference in sound intensity is caused by the absorption of the sound waves by the acoustically 'soft' materials.
The amount of sound absorption is expressed in m^2 sabin (square metres open window). Section 10.3 discusses this subject in detail.
For sound propagation in a closed room, a diffuse field, it holds that the relationship between the acoustic power and the sound intensity depends on the quantity of absorbing material in the room:

$$I = \frac{W}{A} \; [\mathrm{W/m^2}]$$

The meaning of the symbols is:
I the intensity in $\mathrm{W/m^2}$
W the acoustic power of the source in W
A the total sound absorption in a room in m^2 open window (see section 10.3)

Sound pressure

As a result of vibrations, pressure variations (under pressure and over pressure) are created in relation to the barometric air pressure (B = 100,000 Pa of 10^5 Pa). The human ear can detect these vibrations and from the sound pressure (p) it can determine the strength-impression of the sound from the rapid changes in pressure at a specific method of averaging. This (quadratic) average is known as the effective sound pressure. When effective sound pressure is mentioned in this chapter it is indicated by p_{eff}.

$$p_{\mathrm{eff}} = \sqrt{\overline{p^2}} \; [\mathrm{Pa}]$$

The sound pressure is very small in relation to barometric pressure. A radio playing loudly for example creates an effective sound pressure of $p_{\mathrm{eff}} = 0.2$ Pa. This is 500,000 times smaller than barometric pressure.

Relationship between sound pressure and sound intensity

Just as there is a relationship between acoustic power and the sound intensity there is also a relationship between sound pressure and sound intensity. For a progressing wave this is:

$$I = \frac{p_{\mathrm{eff}}^2}{\rho \cdot c} \; [\mathrm{W/m^2}] \text{ (free field)}$$

And for a diffuse field it is:

$$I = \frac{p_{\mathrm{eff}}^2}{4 \cdot \rho \cdot c} \; [\mathrm{W/m^2}] \text{ (closed room)}$$

The meaning of the symbols is:
p_{eff} the effective sound pressure in Pa
ρ the density of the air in $\mathrm{kg/m^3}$
c the propagation speed of the sound in m/s

Under average conditions the expression $\rho \cdot c$ has a numerical value of approximately 400 $\mathrm{kg/(m^2{\cdot}s)}$.

Limits of hearing

When a sound is too soft, the ear can no longer detect it. There is therefore a limit of hearing. This is at a sound pressure of p = approx. $2 \cdot 10^{-5}$ (0.00002) Pa. This is $5 \cdot 10^9$ times smaller than barometric pressure.
There is also an upper limit of hearing where the sound pressure is so great that the ear is damaged. This 'pain threshold' is at p = approx. 200 Pa. This is still 500 times smaller than barometric pressure. Even below the pain threshold there is, however, a risk of

type of sound	sound pressure (p_{eff}) [Pa]	$\frac{p_{eff}}{p_0}$	$\frac{p^2_{eff}}{p^2_0}$	L_p [dB]
limit of hearing	$2 \cdot 10^{-5}$	1	1	0
rustling leaves	$2 \cdot 10^{-4}$	10	10^2	20
whispering at 1 m distance	$2 \cdot 10^{-3}$	100	10^4	40
conversation at 1 m distance	$2 \cdot 10^{-2}$	1000	10^6	60
loud radio	$2 \cdot 10^{-1}$	10,000	10^8	80
nearby car horn	2	100,000	10^{10}	100
jet engine	20	1,000,000	10^{12}	120
pain threshold*	200	10,000,000	10^{14}	140

* The sound pressure level at which a 'feeling of pain' occurs, differs widely from individual to individual however.

Figure 10.11 Examples of sound pressures and sound levels

damage to hearing depending on the length of time that someone is exposed to the sound pressure. Consider the noise from pneumatic picks, compressors and suchlike.

Sound pressure level

The human ear therefore has a 'measurement range' for sound pressure from $2 \cdot 10^{-5}$ to 200 Pa. These extremes differ a factor of 10^7. Because it is difficult to work with figures that are so widely spread, sound pressure cannot be directly used as a dimension of the sound intensity. A logarithmic relationship has therefore been introduced: the sound pressure level (L_p). For this, p_{eff} is compared to a fixed comparison pressure (p_0), that matches the lower limit of hearing:

$$p_0 = 2 \cdot 10^{-5} \text{ Pa} = 0.00002 \text{ Pa}$$

Because the square of the effective sound pressure is a measure of the intensity of the sound, the following expression is used to determine the sound pressure level (L_p):

$$\frac{p^2_{eff}}{p^2_0}$$

The sound pressure level is the logarithm of this relationship multiplied by 10:

$$L_p = 10 \log \left(\frac{p^2_{eff}}{p^2_0} \right) \text{ [dB]}$$

The factor 10 has been introduced to obtain an agreeable scale distribution. Now the scale runs from 0 to 140 dB (decibels) (see the example sound pressure levels in the table in figure 10.11). Without the factor 10, the scale would run from 0 to 14 (bel).

A logarithmic scale is used for sound pressure for reasons of usability. This also means that the intensity of the acoustic power can be expressed logarithmically.

Power: $L_W = 10 \log\left(\frac{W}{W_0}\right)$ [dB]

Intensity: $L_I = 10 \log\left(\frac{I}{I_0}\right)$ [dB]

Sound pressure: $L_p = 10 \log \left(\frac{p^2_{eff}}{p^2_0} \right)$ [dB]

The meaning of the symbols is:

L_W the acoustic power level in dB
W the acoustic power in W
W_0 the reference power (10^{-12} W)
L_I the sound intensity level in dB
I the sound intensity in W/m²
I_0 the reference intensity (10^{-12} W/m²)
L_p the sound pressure level in dB
p_{eff} the effective sound pressure in Pa
p_0 the reference sound pressure ($2 \cdot 10^{-5}$ Pa)

As already mentioned, the value of the reference level for sound pressure has not been chosen at random but it is based on the limit of hearing. The reference level for the sound intensity and the sound power can then also be derived as follows:

$$I_0 = W_0 = \frac{p_0^2}{\rho \cdot c} = 10^{-12}\ [\mathrm{W/m^2}]$$

Because the acoustic power, the sound intensity and the sound pressure are logarithmic functions, the calculation rules in respect of the logarithm apply. These rules are shown below for the sake of completeness:

$$g^x = y \Leftrightarrow x = {}^g\log y$$

$$\log(ab) = \log a + \log b$$

$$\log\left(\frac{a}{b}\right) = \log a - \log b$$

$$\log(a^b) = b \cdot \log a$$

$$10 \log 2 = 3$$

$$10 \log 3 = 4.7$$

$$10 \log 4 = 6$$

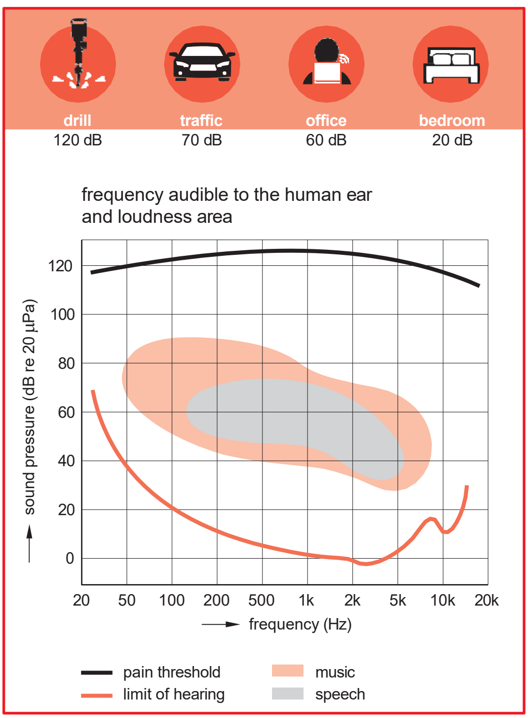


Figure 10.12 Range of human hearing

Adding sound pressure levels

Because of their logarithmic scale, sound levels cannot be added just like that (see the calculation rules for this). You must first add the values for $\frac{p_{eff}^2}{p_0^2}$ together and then find the logarithm again. This is how when you add two sound pressure levels of 60 dB together, the total is only 63 dB:

$$\frac{p_{eff}^2}{p_0^2} = 10^6 \Rightarrow \frac{p_{eff}^2}{p_0^2} + \frac{p_{eff}^2}{p_0^2} = 2 \cdot 10^6 \Rightarrow$$

$$10 \log(2 \cdot 10^6) = 10 \log 10^6 + 10 \log 2 = 63\ \mathrm{dB}$$

The following applies in the same way:
40 dB + 40 dB = 43 dB.

When two unequal sound pressure levels are added together, then the final result is a minimum of 0 to a maximum of 3 dB more than the highest value of the two (60 dB + 60 dB = 63 dB, 60 dB + 50 dB = 60.4 dB).

The following can be used as a rule of thumb:

- When added together two equal (independent) sound pressure levels give an increase of 3 dB (10 log 2).
- When two (independent) sound pressure levels differ by more than 10 dB you can ignore the smallest value and the total sound pressure level is equal to the highest value.

Adding together two sound pressure levels can be done using the graph in figure 10.13. On the horizontal axis you take the difference between the two sound pressure levels ($L_{p1} - L_{p2}$) and on the vertical axis you find the highest level (L_{p1}) for the value to be added (C). See the table in figure 10.14 also.

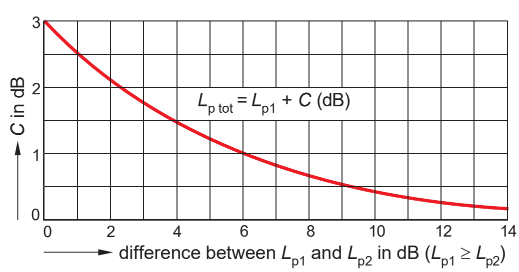


Figure 10.13 Adding sound pressure levels

$L_{p1} - L_{p2}$	C	L_{p1}	L_{p2}	$L_{p1} + C$	$= L_{p;tot}$
0	3.0	60	60	60 + 3.0	= 63.0
0.5	2.8	60	59.5	60 + 2.8	= 62.8
1	2.5	60	59	60 + 2.5	= 62.5
2	2.1	60	58	60 + 2.1	= 62.1
3	1.8	60	57	60 + 1.8	= 61.8
4	1.5	60	56	60 + 1.5	= 61.5
5	1.2	60	55	60 + 1.2	= 61.2
7	0.8	60	53	60 + 0.8	= 60.8
10	0.4	60	50	60 + 0.4	= 60.4
20	0.04	60	40	60 + 0.04	= 60.0
30	0.004	60	30	60 + 0.004	= 60.0

Figure 10.14 Example of adding sound pressure levels

When a number of sound pressure levels have to be added, this can be done two by two. See the example in figure 10.15.

Adding sound pressure levels can be expressed in the following formula:

$$L_{p;tot} = 10 \log \left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}} + 10^{\frac{L_{p3}}{10}} + \ldots \right) \text{ [dB]}$$

The meaning of the symbols is:

$L_{p;tot}$ the resulting sound pressure level
L_{p1} the sound pressure level of sound 1
L_{p2} the sound pressure level of sound 2
... etc.

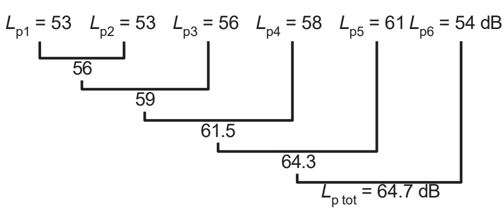


Figure 10.15 Example of adding sound pressure levels

The example in figure 10.15 can therefore be calculated as follows:

$$L_{p;tot} = 10 \log \left(10^{\frac{53}{10}} + 10^{\frac{53}{10}} + 10^{\frac{56}{10}} + 10^{\frac{58}{10}} + 10^{\frac{61}{10}} + 10^{\frac{54}{10}} \right) = 64.7 \text{ [dB]}$$

Relationship between acoustic power, sound intensity and sound pressure

As we have seen, earlier mutual relationships can be shown between acoustic power, sound intensity and sound pressure. These relationships can also be converted into logarithms. In doing so we must always make a distinction in the conditions under which the sound can propagate: the free field or the diffuse sound field.

Free field

For the sake of simplicity we assume a point source. The relationship can easily be worked out for other sources. The formulas discussed earlier apply for the sound intensity of decaying waves (i.e.: at a long distance from the source).

$$I = \frac{W}{\left(\frac{4\pi r^2}{Q}\right)} \text{ [W/m}^2\text{]}$$

$$I = \frac{p_{eff}^2}{\rho \cdot c} \text{ [W/m}^2\text{]}$$

$$I_0 = \frac{p_0^2}{\rho \cdot c} = 10^{-12} \text{ [W/m}^2\text{]}$$

$$L_I = 10 \log \left(\frac{I}{I_0} \right) \text{ [W/m}^2\text{]}$$

The relationship between the sound intensity level and the acoustic power level now follows with:

$$L_I = 10\log\left(\frac{\frac{W}{4\pi r^2}Q}{10^{-12}}\right) \Rightarrow L_I = L_W + 10\log\left(\frac{Q}{4\pi r^2}\right)$$

And the relationship between the sound intensity level and the sound pressure level is then:

$$L_I = 10\log\frac{\left(\frac{p_{eff}^2}{\rho \cdot c}\right)}{\left(\frac{p_0^2}{\rho \cdot c}\right)} = 10\log\left(\frac{p_{eff}^2}{p_0^2}\right) \Rightarrow L_I = L_p$$

Using the relationships derived above we can now determine the relationship between the sound pressure level and the acoustic power level as follows:

$$L_p = L_W + 10\log\left(\frac{Q}{4\pi r^2}\right)\ [\text{dB}]$$

Or:

$$L_p = L_W - 10\log\left(\frac{4\pi r^2}{Q}\right)\ [\text{dB}]$$

If the distance from the source doubles ($2r$) then we can derive from the formulas above that the sound pressure level decreases by 10 log 4 = 6 dB.

Diffuse sound field

In a diffuse sound field equally strongly decaying waves arrive from every direction. This assumption applies particularly to closed rooms that are not too big. This assumption will not however apply to large rooms or rooms with a strongly segmented floor plan. We will derive the relationships between the sound intensity, the sound pressure level and the acoustic power level in the same way as for the free field. The formulas discussed earlier apply for sound intensity in a diffuse field:

$$I = \frac{W}{A}\ [\text{W/m}^2]$$

$$I = \frac{p_{eff}^2}{4 \cdot \rho \cdot c}\ [\text{W/m}^2]$$

$$I_0 = \frac{p_0^2}{\rho \cdot c} = 10^{-12}\ [\text{W/m}^2]$$

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

The relationship between the sound intensity level and the acoustic power level is determined as follows:

$$L_I = 10\log\frac{\left(\frac{W}{A}\right)}{10^{-12}} \Rightarrow L_I = L_W - 10\log A\ [\text{dB}]$$

And the relationship between the sound intensity level and the sound pressure level follows from:

$$L_I = 10\log\frac{\left(\frac{p_{eff}^2}{4 \cdot \rho \cdot c}\right)}{\left(\frac{p_0^2}{\rho \cdot c}\right)}$$

$$= 10\log\left(\frac{p_{eff}^2}{p_0^2}\right) - 10\log 4 \Rightarrow$$

$$L_I = L_p - 10\log 4\ [\text{dB}]$$

Using the relationships derived above we now determine the relationship between the sound pressure level and the acoustic power level as follows:

$$L_p = L_I + 10\log 4$$

$$L_i = L_w - 10\log A \Rightarrow$$

$$L_p = L_W + (10\log 4 - 10\log A)$$

or

$$L_p = L_W + 10\log\left(\frac{4}{A}\right)\ [\text{dB}]$$

Note: this is a greatly simplified derivation, which, however, provides sufficient insight for practical purposes. For the complete derivation, the last term is 10 log $\frac{4 \cdot (1 - a_{gem})}{A}$ · a_{gem} is the average absorption coefficient of all surrounding walls. Only in rooms with extremely absorbent finishings will this make an important difference.

10.2 Evaluating sound

The sensitivity of the ear

The human ear is not equally sensitive to all tones. In this way a tone of 1000 Hz and 30 dB will be evaluated as being equally as loud as a lower tone of 63 Hz and 56 dB. Isophones have been determined using tests. These are lines of equal loudness (see figure 10.16).

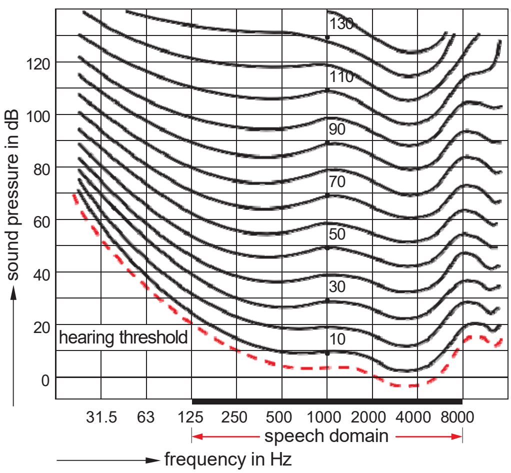


Figure 10.16 Isophones (lines of equal loudness)

Measuring a sound spectrum

An electronic measuring instrument can be used to determine the sound pressure level. This type of measuring instrument consists of a microphone that converts the sound pressure (vibrations) into an electronic signal. This signal is amplified and the effective value is determined using a network of electronics and compared to the comparison value. The result (in dB) is made visible using a pointer on a scale or using a display (figures).

When we want to determine the spectrum of a sound (the distribution of the sound energy across the frequency range) then an electronic filter is included in the sound level meter. This type of filter allows only part of the frequency range to pass through.
Normally a so-called octave filter is used, which works with the standardised octave bands mentioned in section 10.1. When the filter has been set to an octave band of 500 Hz for example, then only frequencies between 355 Hz and 710 Hz are allowed to pass through and be measured. In this way the sound pressure level can be determined in every octave band. From the octave band levels we can eventually determine the final sound pressure level (across the entire frequency range) by adding them logarithmically (see section 10.1).
For a more accurate analysis a different filter can be used to split every octave band into three for example. Even smaller frequency bands are also possible.

Figure 10.17 Sound meter

Weighted sound level

When you want to evaluate a sound spectrum, you have to consider the sensitivity of the human ear to each octave band. A sound level *A* has been introduced to be able to make a single measurement suffice.
A measuring instrument with a filter that mimics the sensitivity of the human ear is used for this. The entire frequency range can then be determined in a single (weighted) measurement. For a sound level L_A measured in this fashion, the used unit is often dB(A).
In international standards however, L_A is expressed in dB.
The attenuation or amplification that the A-filter produces is shown for each frequency in the table in figure 10.18.

frequency [Hz]	A-weighting [dB]
63	-26.1
125	-16.1
250	-8.6
500	-3.2
1000	0.0
2000	1.2
4000	1.0
8000	-1.0

Figure 10.18 Attenuation or amplification in accordance with the A-weighting

The total sound level of an octave spectrum in dB is found by adding together (algebraically) the corrections shown against the octave values in figure 10.18 and then totalling the octave values logarithmically (see section 10.1). Figure 10.19 shows a couple of examples of spectra.

Line I is the spectrum (the sound production) for traffic noise. Line II is the spectrum (the sound production) of a jet plane landing. Line III is the spectrum (the sound production) of a jet plane taking off.

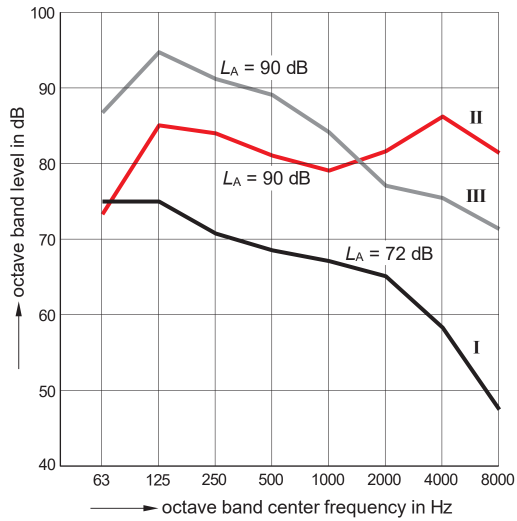


Figure 10.19 Example of a number of sound spectra

When you compare spectrum II and III to each other, you might at first sight conclude that a jet plane taking off causes more noise than a jet plane landing.
However, as you can see from the example below, this is an incorrect conclusion. When taking the auditory sensitivity of the human ear into account, reducing the low frequencies in the measurements, the total sound level of both jet planes is equal, namely 90 dB. See also figure 10.20.

centre frequency [Hz]	L_p [dB] source II	source III	A measurement [dB]	L_p [dB] source II	source III
63	73	87	-26.2	46.8	60.8
125	85	95	-16.1	68.9	78.9
250	84	91	-8.6	75.4	82.4
500	81	89	-3.2	77.8	85.8
1000	79	84	0	79.0	84.0
2000	82	78	1.2	83.2	79.2
4000	86	75	1.0	87.0	76.0
8000	81	72	-1.0	80.0	71.0
resulting sound pressure L_A [dB]				90.0	90.0

Figure 10.20 Calculation example

The sound level L_A in dB does not provide information about the shape of the spectrum. When it comes to taking measures such as improving the sound insulation of a facade, the shape of the spectrum is, however, important. In this way the sound insulation of all structures (including glass therefore) is the smallest for low frequencies (see section 11.1). The sound of spectrum III will therefore cause more problems than the sound of spectrum II, despite the fact that both represent a sound level of L_A = 90 dB. Luckily the shape of the spectrum is known for many types of sounds so that it usually suffices to determine L_A in dB when taking measurements.

Evaluating a sound with a widely varying strength

A simple measurement cannot suffice when evaluating a sound where the sound pressure level varies widely with time, such as next to a motorway. Here it is necessary to record the course of the sound pressure levels over a longer period, so that some kind of average can be determined.
The so-called equivalent sound pressure level (L_{eq}) is used most frequently. This is the level of a sound of constant strength which, taken over a specific time, represents an acoustic energy equivalent to the sound that varies widely in strength over the same period. The equivalent sound pressure level can be calculated as follows:

$$L_{eq} = 10 \log\left(\frac{1}{T} \cdot \int \frac{p_t^2}{p_0^2} \cdot dt\right) \text{ [dB]}$$

The meaning of the symbols is:

L_{eq} the equivalent sound pressure level in dB
T the exposure time in s
p_t the effective sound pressure in Pa during the exposure time
p_0 the reference sound pressure in Pa

Example

The sound pressure level is measured for 1 hour in a factory building. The meter is read 100 times during this hour.

number of readings	sound pressure level [dB]
30	75
20	80
20	85
20	90
10	95

The equivalent sound pressure level can now be calculated as follows:

$$L_{eq} = 10 \log\left(\frac{30}{100} \cdot 10^{7.5} + \frac{20}{100} \cdot 10^{8.0} + \frac{20}{100} \cdot 10^{8.5} + \frac{20}{100} \cdot 10^{9.5} + \frac{10}{100} \cdot 10^{9.5}\right)$$

$$= 88 \text{ dB}$$

It is also possible to determine the sound pressure level that is exceeded during a specific percentage of the time. In this way L_{10} represents the sound pressure level that is being exceeded during 10% of the time. L_5 and L_{10} form a measure for the ‘recognisable sound peaks’, L_{90} and L_{95} form a standard for the ‘background noise’.

Permissible sound levels

The permissible sound levels in relation to indoor noise depends on the nature of the activities that take place inside the room. In this way the requirements for indoor noise in a bedroom will be more stringent than in a living room, etc. There is also a difference if a sound is at a continuous strength (traffic, factories) or if it displays significant peaks (aircraft, trains).
This is why regulations set requirements to facade sound proofing, distinguishing between traffic noise, industrial noise and air traffic noise.

10.3 Sound absorption

When sound strikes a structure, part of it is reflected, part is allowed to pass through and part remains inside the structure (see figure 10.21). The amount of sound that is allowed through is generally small in proportion. In a normal half brick wall this is only approximately 1/10,000th part of the sound energy striking the wall and even with a simple hardboard door this is still only approximately a 1/100th part.

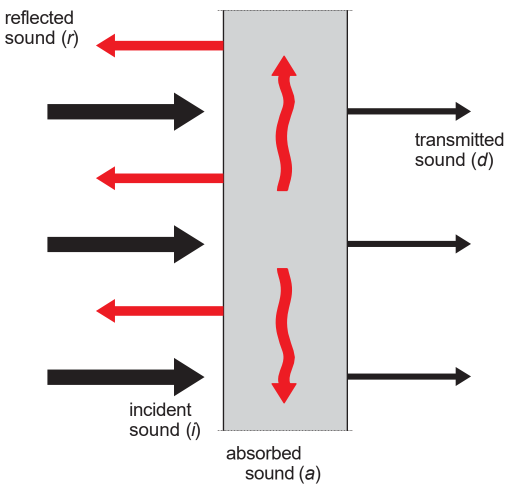


Figure 10.21 Sound energy striking and allowed to pass through, absorbed and reflected

The sound that is permitted to pass through is ignored in absorption problems so that the following applies for the coefficient of absorption and reflection:

$$a + r = 1 \quad \text{or} \quad a = 1 - r$$

The meaning of the symbols is:

a the absorption coefficient (the absorbed sound)

r the reflection coefficient (the reflected sound)

So, what is not reflected is absorbed, and vice versa.

The harder the structure, the more sound is reflected. Porous surfaces can absorb more sound. Structures that absorb efficiently can achieve an absorption coefficient of a = 0.7–0.9 across the frequency range from 500-2000 Hz (see the book of tables).

Reflection of sound waves from a wall

On reflection of a wave movement from a wall, a standing sound wave will occur of which the antinodes (maximum amplitude) and the nodes (no amplitude) occur at fixed distances from the wall. This can be demonstrated by Melde's experiment (see figure 10.22).

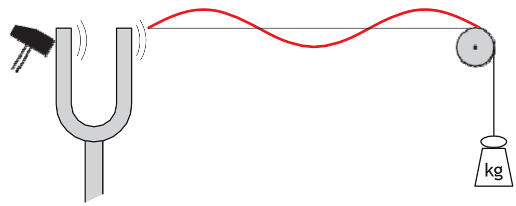


Figure 10.22 Melde's Experiment

One end of a wire is connected to a tuning fork and the other end is attached to a weight (fixed end). The tuning fork is made to vibrate. The outgoing wave is reflected from the far end (interference). It can now be seen that at mutually identical distances there are points that remain fully at rest (nodes) and that different parts of the wire vibrate with unequal amplitudes. The points with the greatest amplitude fall in the middle between two nodes. The points are known as antinodes. The speed of the parts is at its maximum at a distance of $\frac{1}{4}\lambda$ from the weight (which is comparable with a wall). The antinodes are at a large distance from the wall particularly for the low and middle frequencies (with a relatively high λ value) (see the table in figure 10.23). This has consequences for the effectiveness of the sound insulation applied to the wall.

f [Hz]	λ [m]	$\frac{1}{4}\lambda$ [m]
63	5.40	1.35
125	2.72	0.68
250	1.36	0.34
500	0.68	0.17
1000	0.34	0.09
2000	0.17	0.04
4000	0.09	0.02
8000	0.04	0.01

Figure 10.23 Frequencies, wavelength and $\frac{1}{4}$ wavelength (distance to first antinode).

Sound absorption capacities

Absorption of sound is, in fact, nothing more than the conversion of vibrations into heat. In principle, sound absorption can be achieved in two ways:

- by friction with air movement in porous materials.
- by means of resonance.

Friction

When a sound wave penetrates a porous material there is friction between the coming and going air particles in the pores of the material. This friction causes the sound energy (movement) to be converted into heat. The sound is absorbed by the material.
In order to ensure that the sound can penetrate the material it must be as porous as possible. Too much noise must not be reflected at the passage from air to material. This is indicated using the airflow resistance of the material. Absorbing material must have a low airflow resistance so that the passage from the air to the material is such that not too much sound is reflected. On the other hand, the airflow resistance must not be too low, otherwise there will not be sufficient friction and absorption will be inadequate.
The thickness of the material is also important. As shown the particle speed is at its maximum at $\frac{1}{4}\lambda$ from the wall. This is where the majority of the energy is. Absorption material that is fitted to a wall must therefore have a thickness of one quarter wavelength ($\frac{1}{4}\lambda$) of the sound to be absorbed in order to absorb effectively (see figure 10.24). This will not be a problem for the high frequency area. In the low frequency area, a stack of absorption material offering enough absorption will be too thick.

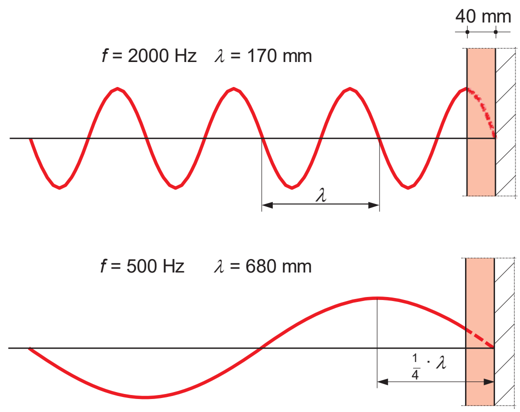


Figure 10.24 Influence of wavelength and layer thickness (porous material) on sound absorption.

This is, however, not necessary. By applying the material at a certain distance from the wall you can ensure that it is exactly at the place where the particle speed is greatest (see figure 10.25).

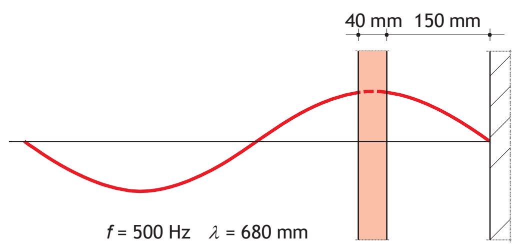


Figure 10.25 Apparent increases in the layer thickness produces better sound absorption.

The effect described above is used productively in suspended ceilings for example. It is also the reason why wall cladding is often fitted on framing. See the book of tables for the absorbing properties of the various structures. The frequency range at which absorbing materials are most effective is between 500 and 2000 Hz.

Absorbing materials are often very soft and delicate (mineral wool and suchlike) and must be protected against mechanical damage.

This can be done with a perforated sheet of metal, hardboard, plaster, etc.

In order that the absorbent qualities are not affected, the percentage of perforations must, however, be greater than approximately 20% and the intermediate distance between the openings must not be greater than 20 mm, otherwise the perforated surface acts as a wall. It is also possible to use wooden laths between which a space is kept open. The laths must, however, be kept as small as possible. In addition, the material could be covered with a porous fabric or membrane, or with a very thin plastic foil.

It is clear that painting the surface of absorbent materials could make them so closed that the airflow resistance is increased and that sound waves are no longer able to penetrate the material. This must be duly taken into account when considering the choice of material. Rough-fibred materials can sometimes be painted using a roller which should not block the pores and only colours the outer surface. You must, therefore, select materials that do not, or do not easily become dirty, or which can easily be cleaned.

Resonance

All objects have a frequency at which they spontaneously start to vibrate (their natural frequency). When an object is struck by a vibration that is equal to this natural frequency, the object will spontaneously start to vibrate.
Example: if two identical tuning forks are set up some distance from each other and one tuning fork is struck, then the vibrations are taken up by the second tuning fork (check this by stopping the arms of the first tuning fork, the second continues to emit sound). This phenomenon is known as resonance. To prevent resonance in a structure then, for example, soldiers have to break step to march across an unstable bridge. If they didn't, it would be possible for the construction is 'triggered' at its frequency of oscillations and will start to vibrate spontaneously, causing an instable construction to collapse.

The way in which the previously mentioned perforated panels work is based on the resonance principle. The air in the holes forms a kind of mass that can vibrate on the air layer that lies behind it, acting as a kind of spring. This type of mass-spring system has a natural frequency (or resonance frequency).

The mass-spring resonance of these structures lies in the frequency range from approximately 300-1500 Hz (see figure 10.26). In that case, however, the percentage of perforations must not be too high (5 to 10%). The absorption (by the porous material) of higher frequencies is, perhaps, lost by this degree of perforation, but in return there is a gain in absorption in the lower and middle frequencies.

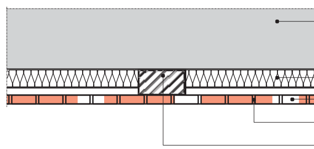


Figure 10.26 Perforated panels: good absorption in a frequency range from approx. 300-1500 Hz

Sheet material such as plywood, chipboard, metal etc., can also have a sound absorbing effect when they are fitted at a certain distance from the wall. The sheet forms a mass-spring system with the underlying air layer (see figure 10.27). The natural frequencies of these structures fall in the range from approximately 50-500 Hz. In addition, all kinds of bending waves occur in the sheet with specific natural frequencies.

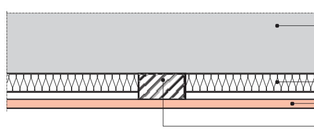


Figure 10.27 Un-perforated panels: absorption in a frequency range from approx. 50-500 Hz

When the sheet is struck by sound waves at its natural frequency, then it easily starts to vibrate. This vibration is converted into heat in the sheet's fixing points. The absorption takes place in a limited frequency range, but it does have a high absorption coefficient. Filling the cavity with an absorbent material (mineral wool) reduces the absorption coefficient to a = 0.25 to 0.50, but the range across which absorption takes place is much wider. Absorption by this type of sheets is always at lower frequencies (50-500 Hz).

Combination

The now antiquated bored or sawn-in softboard tiles or combination tiles of hardboard and softboard or other fibre materials form a kind of absorption material that combines the properties of the two aforementioned types. The fibre material (board) is, in fact, not porous enough to be used as it is as an insulation material. The resonance in the holes or grooves gives rise to good absorption in the middle frequencies range. In addition, the sheet acts as an un-perforated panel, which means that the lower tones are absorbed a little more. This type of sheet can safely be painted (with a roller) because the outside surface does not contribute to sound absorption behaviour. The absorption occurs in the holes or grooves in the underlying material.

Absorption characteristics

The absorption characteristics of the various materials can be summarised as follows:

Porous material:

- Absorbs well in the 500-2000 Hz frequency range.
- Preferably place the absorbing material at $\frac{1}{4}$ wavelength from the wall.
- Preferably use material with a low flow resistance.
- Protect using a perforated sheet with a degree of perforation >20% and intermediate opening distances < 20 mm.
- Do not paint due to blockage of the pores.

Perforated panel:

- Absorbs well in the 300-1500 Hz frequency range.
- The desired degree of perforation is 5-10%.
- When using absorption material in the cavity, the absorption coefficient is lower but the range across which absorption takes place is wider.
- Can be painted.

Un-perforated panel:

- Absorbs well in the 50-500 Hz frequency range.
- When using absorption material in the cavity, the absorption coefficient is lower, but the range across which absorption takes place is wider.
- Can be painted.

Figure 10.28 shows how the absorption behaviour of the previously described materials looks. In addition, it can be clearly seen that a good absorption across the entire frequency range can only be achieved by a combination of different materials. Remember again that the absorption coefficient of a material is different for every frequency.

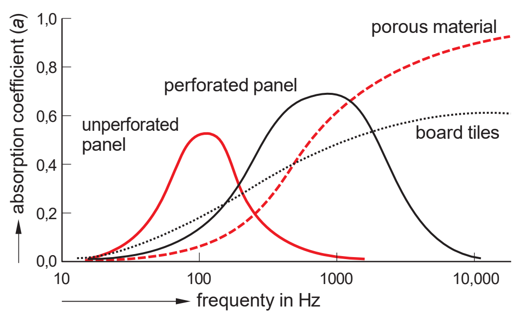


Figure 10.28 Absorption characteristics

Amount of sound absorption in a room

In a room that has just been delivered (and is therefore empty), voices sound much louder and the noise level is higher than in a furnished dwelling. If you want to lower the noise level in a 'hard' room with a large amount of stony walls and ceiling and/or a large amount of glass, then you need to fit the previously discussed sound absorbing coverings to the ceiling and walls. Textiles such as heavy curtains and deep-pile carpets and upholstered furniture can contribute to this.

The amount of sound absorption in the room influences the reverberation time. This reverberation time is discussed in section 10.4.

The unit used for sound absorption is the 'square meter open window' (m^2 sabin). This is based on the fact that, seen from the point of view of a room, all sound energy falling on an open window disappears to the outside. This comes down to the same as all sound energy that falls upon it being absorbed. The total sound absorption in a room (A) is found by multiplying the surface area of all surrounding walls (S) by the absorption coefficient (a) associated with the material:

$$A = a_1 \cdot S_1 + a_2 \cdot S_2 + a_3 \cdot S_3 + \dots \ [\mathrm{m}^2 \text{ sabin}]$$

The meaning of the symbols is:

A the total amount of absorption in m^2 sabin

$a_1, a_2, a_3, \dots$ the absorption coefficient of the materials

$S_1, S_2, S_3, \dots$ the surface areas of the structures in m^2

People and objects (furniture etc.) in the room also contribute to the absorption of sound. The furnishings must therefore be taken into account when determining the total absorption. If a dense cupboard is placed in front of an absorbing wall, the part of the wall that is shielded by the cupboard will not contribute to the total sound absorption. Concert halls always have well-upholstered chairs. If the chairs are not occupied, they will contribute to the total sound absorption. If the chairs are occupied, the absorbing surface area is shielded by the people sitting on the chairs. These people in turn will absorb sound through their clothing.

Functional absorbers

Functional absorbers, also known as baffles, can be used for reducing the sound pressure level in larger rooms and halls. In their most simple form – for industrial use – these consist, for example, of thick sheets of mineral wool with a width of approximately 0.5 m coated in thin plastic foil which are suspended in vertical strips below the ceiling (see figure 10.29). It is preferable that the baffles are included as a separate element in the calculation of the total absorption. An absorption coefficient of approximately a = 1.6 can be achieved if the absorption by the baffles is assigned to the ceiling – calculated on a square metre ceiling surface area. This would make the reflection factor negative and that is physically incorrect.

Figure 10.29 Functional absorbers (baffles)

The advantage of baffles below the ceiling is that the ceiling or roof does not become thermally insulated. This means that there will be no increased risk of condensation. This is as opposed to sealed acoustic ceilings: these cannot just be applied below the roof structure without considering the damp engineering consequences.

10.4 Acoustics of the room

Reverberation time

The reverberation time (T) is one of the most significant acoustic properties of a room. In rooms for which high standards are set in connection with speech or music, there are also matters such as the diffusivity of the room and the correct use of reflections from walls or specially applied panels.

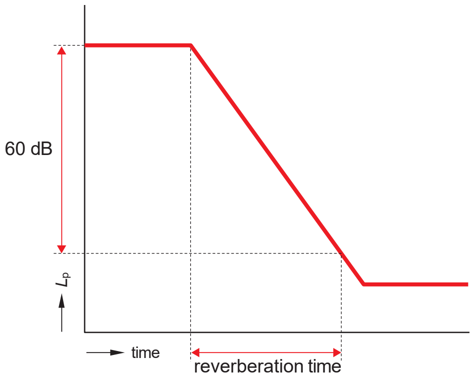


Figure 10.30 Reverberation time

The reverberation time is defined as the time that expires before the sound level has decayed by 60 dB after the sound source has been switched off (see figure 10.30).

The reverberation time depends on the absorption in the room. The more sound absorption that is present the shorter the reverberation time. The reverberation time can be calculated using Sabine's formula:

$$T = \frac{1}{6} \cdot \frac{V}{A} \text{ [s]}$$

where $A = a_1 \cdot S_1 + a_2 \cdot S_2 + ...$

The meaning of the symbols is:
T the reverberation time in s
V the volume of the room in m^3
A the sound absorption present in m^2 sabin

Figure 10.32 shows an example of the calculation of the reverberation time. The

Example calculation of reverberation time

As an example we calculate the absorption and from that the reverberation time for a room with a linoleum floor covering. The walls comprise plastered masonry and glass and the ceiling is 25 mm woodwool cement sheet on a 30 mm cavity. See figure 10.31 and the table in figure 10.32. The absorption coefficients of the materials used can be found in the book of tables.

The volume of the room is:

$$V = 4.0 \cdot 7.0 \cdot 2.7 = 75.6 \text{ m}^3$$

Because the absorption coefficient (a) of the materials depends on the frequency, the reverberation time (T) of the room is also a function of the frequency.

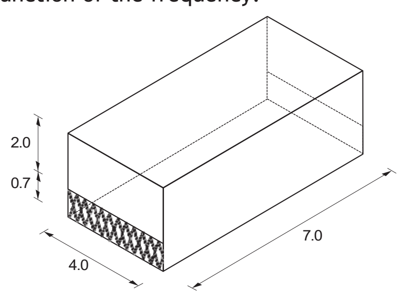


Figure 10.31 Room dimensions

		frequency [Hz]											
		125		*250*		*500*		*1000*		*2000*		*4000*	
surface	S [m²]	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$	a	$a \cdot S$
ceiling	28.0	0.25	7.0	0.29	8.1	0.79	22.1	0.76	21.3	0.74	20.7	0.93	26.0
floor	28.0	0.02	0.6	0.02	0.6	0.03	0.8	0.03	0.8	0.04	1.1	0.04	1.1
plasterwork	43.4	0.01	0.4	0.01	0.4	0.02	0.9	0.02	0.9	0.02	0.9	0.04	1.7
glass	16.0	0.10	1.6	0.04	0.6	0.03	0.5	0.02	0.3	0.02	0.3	0.02	0.3
A [m² sabin]			9.6		9.7		24.3		23.3		23.0		29.1
$T = \frac{1}{6} \cdot \frac{V}{A} = \frac{1}{6} \cdot \frac{75.6}{A}$			1.3		1.3		0.5		0.5		0.5		0.4

Figure 10.32 Calculation of reverberation time

activities that take place in a room determine which reverberation time is best for that room. The table in figure 10.33 shows examples for guide values.
The size of the room (hall) also plays a role in determining the required reverberation time for the room, as does the diffusivity of the room. In principle, the reverberation time should be the same across the entire frequency range. In general, a longer reverberation time is allowed for the lower frequencies and a somewhat shorter time for the higher frequencies (see the table in figure 10.34).

room	*T* [s]
well-furnished room	approx. 0.5
office room	0.5-0.7
open-plan office	0.7-0.9
school classroom	0.6-0.8
music room	0.8-1.2
theatre	0.9-1.3
chamber music room	1.2-1.5
opera	1.2-1.6
concert hall	1.7-2.3
church (organ music)	1.5-2.5

Figure 10.33 Guide values for the reverberation time in various rooms

	frequency range [Hz]					
	125	*250*	*500*	*1000*	*2000*	*4000*
deviation relat. to 500 Hz	1.4	1.15	1.0	0.9	0.9	0.9

Figure 10.34 Permitted deviations from 500 Hz

Measuring the reverberation time

When measuring the reverberation time a high sound pressure level is created in a room using a noise source (a starting pistol was used in the past). The decay of the sound pressure level is directly determined using an integrated soundmeter (see figure 10.17).
However, a level recorder can also be used for this. A paper runs inside this at a set speed. The pen moves vertically on the paper with the sound pressure level. Figure 10.35 shows the sound pressure level during a specific time for three frequencies.
As can be seem from this figure it is generally not possible to measure the full 60 dB decay.

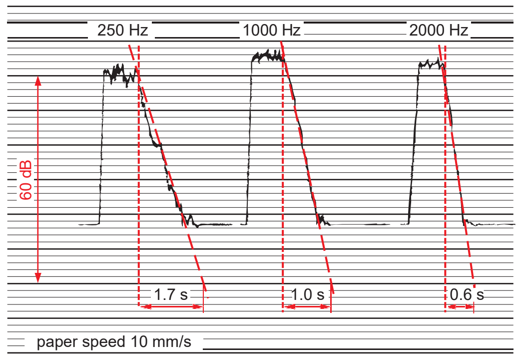


Figure 10.35 Example of determining reverberation time

You would then have to start more than 60 dB above the background noise level. Because the decay curve is straight at the start, the reverberation time can be determined by extrapolation. The reverberation time associated with the three curves is given in the figure.

Sound pressure level in a room

Both direct and reflected sound will be detected in a room. As discussed earlier, for the direct sound the formula is:

$$L_p = L_W + 10 \log \frac{Q}{4\pi r^2} \text{ [dB]}$$

And for the diffuse sound:

$$L_p = L_W + 10 \log \frac{4}{A} \text{ [dB]}$$

The resulting sound pressure level is derived from:

$$L_p = L_W + 10 \log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right) \text{ [dB]}$$

The meaning of the symbols is:
L_p the sound pressure level in dB
L_W the acoustic power level in dB
i the distance to the source in m
Q the direction factor
i the total sound absorption in the room in m^2 sabin

Close to the source the direct sound field will dominate and at a large distance from the source the diffuse sound field will dominate. At a certain distance in the room the direct sound will be equal to the indirect sound. This distance is know as the reverberation radius and is calculated as follows:

$$\frac{Q}{4\pi r^2} = \frac{4}{A} \Rightarrow r^2 = \frac{Q \cdot A}{16\pi}$$

$$r_{\text{reverberation}} = \sqrt{\frac{Q \cdot A}{16\pi}} \text{ [m]}$$

If the distance to the source is much smaller than $r_{\text{reverberation}}$, then the direct sound field dominates and the formula for the direct sound field as derived in section 10.1 can be used for calculations:

$$L_p = L_W - 10 \log\left(\frac{4\pi r^2}{Q}\right) \text{ [dB]}$$

If the distance to the source is much greater than $r_{\text{reverberation}}$ then the indirect, diffuse sound field dominates. The formula for the diffuse sound field as derived in section 10.1 applies for this too.

$$L_p = L_W + 10 \log\left(\frac{4}{A}\right) \text{ [dB]}$$

In the area around the radius of reverberation we have to take account of both the direct and the diffuse sound field.

The radius of reverberation is of great significance if measures for improving the acoustics are required. If the direct field is dominant there is little sense in taking measures for total absorption – measures must be taken in relation to the source. If the diffuse sound field dominates then it is exactly those measures for total absorption that are required.

Diffusivity of a room, reflections

We understand diffusivity to mean the degree to which the sound is distributed regularly (equal strength) across the room. The sound reaches the listener from all directions instead of a few angles.

This is almost never a problem in smaller rooms. Diffusivity can cause problems in bigger rooms however. In these types of rooms a great deal of attention has to be paid to the path of the sound and the possible occurrence of useful and unwanted reflections.

It is in larger rooms in particular where the diffusivity is not self-evident that a distinction will have to be made between the sound that reaches the listener directly (direct sound) and sound that arrives at the listener via reflections (indirect sound). Sound arriving at the listener via reflections will have to follow a longer path (and therefore be en-route longer) than sound that arrives at the listener directly.

For speech, if the path time difference is not more than 50 ms (17 m) the indirect sound (the reflection) is heard as a useful contribution to the direct sound. A longer path time difference of approximately 80 ms (27 m) applies for music.

Specially installed panels (sound reflectors, see figure 10.36) can be used in a room where the sound from a specific location (podium, stage, etc.) has to reach the entire room. Such useful reflections promote the effective transmission of sound in the hall. In order to avoid indirect sound arriving with the listener with too long a delay in relation to the direct sound and being heard as an echo, parts of the ceiling concerned and the rear wall are clad with sound absorbing material.

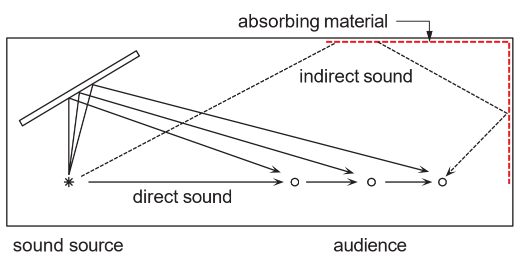


Figure 10.36 Supporting the direct sound with useful reflections and preventing echoes by applying absorbing material.

It is often different in smaller rooms (conferences rooms, classrooms etc.). All those present have to be able to hear each other. In this case it makes sense not to fit sound absorption to the ceiling, but to the walls and the floor. The ceiling is then built as a hard structure and serves as a reflector (see figure 10.37).

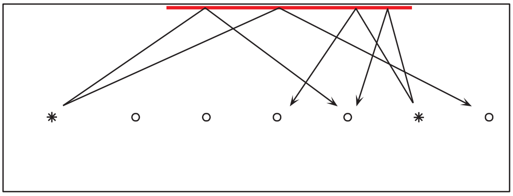


Figure 10.37 Reflective ceiling (conference room)

The shape of rooms also plays an essential role in speech intelligibility. In this way rectangular rooms contribute less to useful reflection. They can also lead to problems in relation to unwanted echoes. If two parallel walls are good reflectors and are more than 7 m from each other then flutter echoes can occur (consider a sports hall for example). The sound can be reflected back and forth between these walls a number of times.
There are two possible solutions in this case. One solution is to clad one (or both) of the walls in absorbing material. The other is to build the walls so that they are not parallel to each other and give them a relief. That is why one or more of the walls or the ceiling is often fitted with sloping surfaces or other irregularities, such as in figure 10.38.

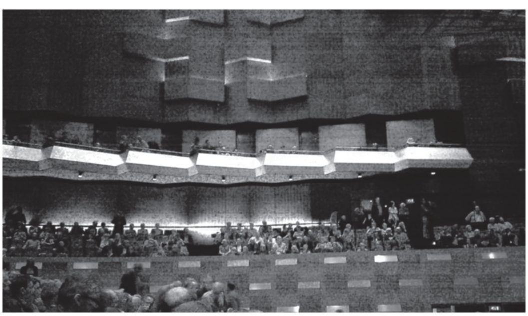


Figure 10.38 Surfaces in relief and large objects (balconies) for diffusion of the sound.

If these irregularities are to have an effect on the diffusion of the sound then the dimensions must be of the same order of magnitude as the wavelength of the sound (see section 10.1).
Good speech intelligibility is achieved in rooms where the walls are so formed as to deliver a good contribution to the useful reflections.
In addition to avoiding two parallel reflective walls in connection with flutter echoes, round hall shapes should also be avoided. Reflections of sound on a round (arched) wall will lead to a focussing of the sound at a single point.

Lowering the sound pressure level using extra absorption

When a great deal of noise is being produced in a room (workshop, reproduction department, etc.) you can try to lower the sound pressure level (diffuse sound) by fitting extra absorption. This will reduce the term $10 \log\left(\frac{4}{A}\right)$ (see above) and make it stronger negative. The sound pressure level (L_p) will therefore decrease.
Doubling the amount of absorption doubles the amount of sound absorbed (see figure 10.39). This means a reduction of the sound pressure level by 3 dB. If we want to lower the sound pressure level by 6 dB we have to quadruple the amount of sound absorption.
A reasonable reduction in level will only be achieved in very ‘bare’, reverberating rooms. In rooms where more absorption already exists (suspended ceilings and suchlike) there is usually no space left for two or four times as much absorbing material.

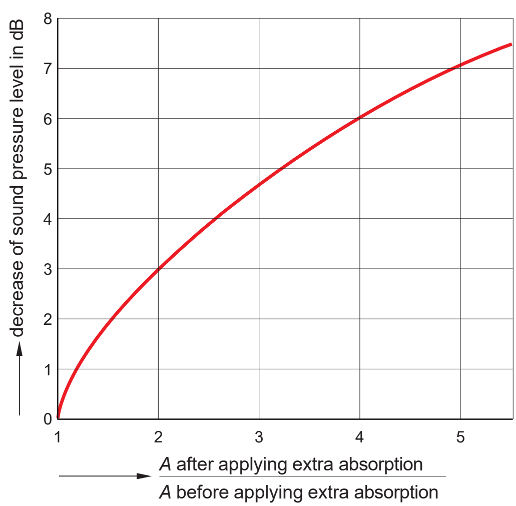


Figure 10.39 Reduction in the sound pressure level by the application of additional sound absorption in a room

11

Sound insulation and sound proofing

A.C. van der Linden; A. Zeegers

This chapter discusses sound insulation and sound proofing between rooms and between the inside and outside of rooms (facade sound proofing). We explain how sound insulation can be calculated and how this can be measured in practice and in the laboratory.

11.1 Sound insulation between rooms

In sound insulation we differentiate between airborne sound insulation and impact sound insulation. The former relates to insulation against sound waves generated in the air (speech for example). The latter relates to the degree to which vibrations caused by walking or slamming of doors propagate in structures and are retransmitted into the air, for example (see figure 11.1).

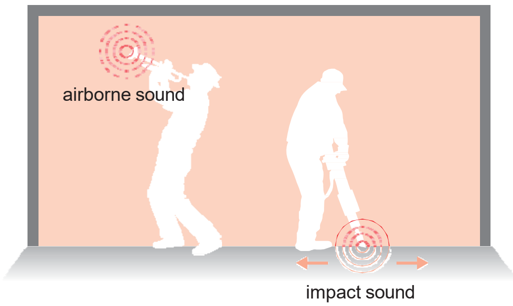


Figure 11.1 Airborne sound causes a structure to vibrate which causes it to emit sound on the other side.
A structure can also be caused to vibrate mechanically and thereby begin to emit sound (impact sound)

Airborne sound insulation

When we consider the airborne sound insulation between two rooms there are three significant transmission routes (all three of which are determinative for the sound insulation that is finally realised):

1 direct sound emission from the partition wall
2 the partition wall causes the adjacent structures to vibrate
3 transmission via the sidewalls.

The latter two routes are known as flanking sound. All of this is illustrated in figure 11.2. First we will consider direct transmission.

In the previous chapter we discussed sound absorption being important for sound management in the room concerned. Sound insulation is of great importance where nuisance arises from sound outside (traffic noise, for example) or from a neighbouring

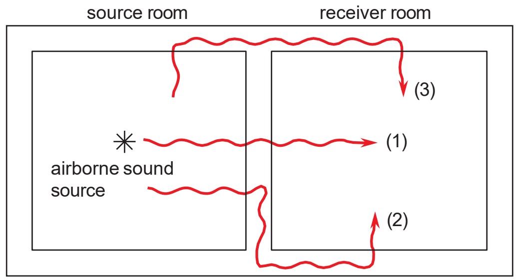


Figure 11.2 Direct and flanking sound transmission

dwelling (radio, TV and suchlike) or a room in the same building (sound produced in a reproduction room causing nuisance to the occupants of an office room for example). The sound insulation of an element is determined by the part of the sound that passes through. The part of the sound allowed to pass through is that part which is not reflected or absorbed (see figure 10.21 also). The following applies:

$$r + a + d = 1$$

The meaning of the symbols is:
r the reflected part of the sound energy
a the absorbed part
d the part allowed to pass through

Sound insulation is defined as the relationship between the sound striking the structure and the sound allowed to pass through. This relationship is expressed in dB. This means that the logarithm of the relationship has to be evaluated:

$$R = 10 \log\left(\frac{1}{d}\right) \text{ [dB]}$$

The meaning of the symbols is:
R the airborne sound insulation in dB
d the part of the sound striking the structure that is allowed to pass through

The part that is allowed to pass through a normal hardboard door amounts to approximately $d = 0.01$ (see figure 11.3-1). This means that the sound insulation (R) is equal to:

$$R = 10 \log\left(\frac{1}{0.01}\right) = 20 \text{ [dB]}$$

Likewise, in a half brick wall d = 0.0001 (see figure 11.3-2), thus:

$$R = 10 \log \left(\frac{1}{0.0001}\right) = 40 \text{ [dB]}$$

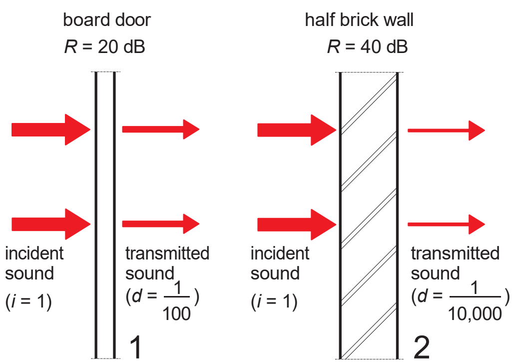


Figure 11.3 Airborne sound insulation

The insulation mechanism can broadly be described as follows. The impacting sound energy causes the wall to vibrate. On the other side of the wall the air is caused to vibrate. The sound pressure, which consists of rapid changes in pressure, forms a force to the wall. This force can be calculated with the following formula:

$$F = m \cdot a \text{ (force = mass} \cdot \text{acceleration)}$$

The force on the wall (in the transmitting room) imparts a specific acceleration to the wall (mass). A heavy wall receives a smaller acceleration and it is therefore harder to cause it to vibrate. This smaller vibration in the wall causes a smaller sound pressure in the receiving room (the other side of the wall). Something similar applies to the number of vibrations per second (the frequency) of the impacting sound. A high frequency (many small vibrations per second) will be less easily taken up by the (generally more rigid) wall and cause a smaller sound pressure in the receiving room.

In summary:
larger mass → better sound insulation
higher frequency → better sound insulation

Mass law

It is possible to theoretically derive what the sound insulation should be for homogeneous structures (a single layer of concrete, stone, wood, etc.). This depends on the mass of the structure and the frequency of the sound. The values found in practice are different to those predicted by the theoretical mass law due to all kinds of peripheral effects. Such a 'practical mass law' has come about experimentally where the sound insulation can be calculated:

$$R = 17.5 \log m + 17.5 \log \left(\frac{f}{500}\right) + 3 \text{ [dB]}$$

The meaning of the symbols is:
R the sound insulation of the structure in dB
m the mass of the structure in kg/m^2
f the frequency in Hz

This practical mass law is shown in the graph in figure 11.4. The graph shown is for sound insulation at a frequency of 500 Hz. Sound insulation at other frequencies can be found by adding approximately 5 dB to the R_{500} value found for each doubling of the frequency. Approximately 5 dB per octave has to be substracted for lower frequencies.

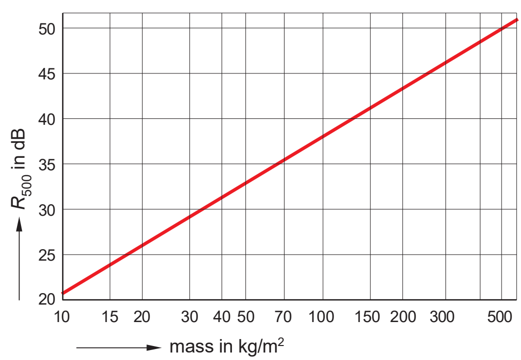


Figure 11.4 Practical mass law for sound insulation at 500 Hz

The heavier the structure the better the sound insulation. But in masses below 100 kg/m^2 in particular the value according to the graph in figure 11.4 is only a very general guide value. Special effects such as coincidence often occur which significantly affect the sound insulation.

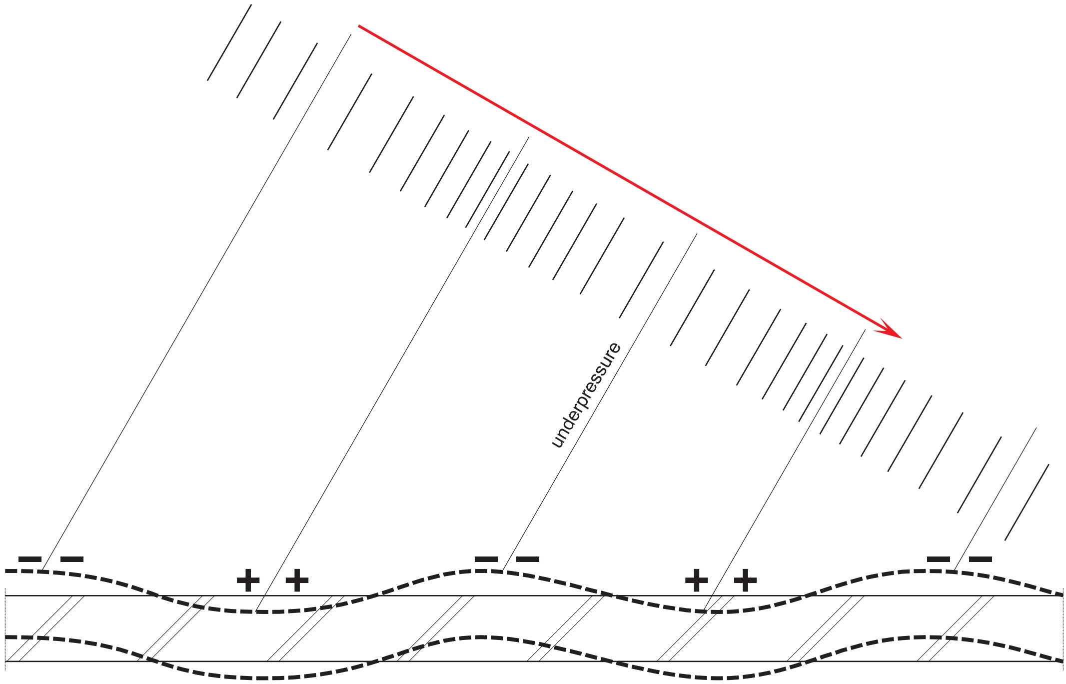


Figure 11.5 Generation of a forced bending wave in a sheet-like structure by an impacting sound

Coincidence

When a sound wave strikes a wall at an angle, a bending wave is generated in that wall by the under and over pressures (rarefactions and compressions) of the sound wave in the air (see figure 11.5). When the frequency of this wave motion matches the natural frequency of the wall (the frequency at which the wall vibrates very easily) then the sound energy is allowed to pass through very easily. This is known as coincidence (falling together).
Coincidence causes a deviation from the mass law as can be seen from the general insulation graph in figure 11.6.

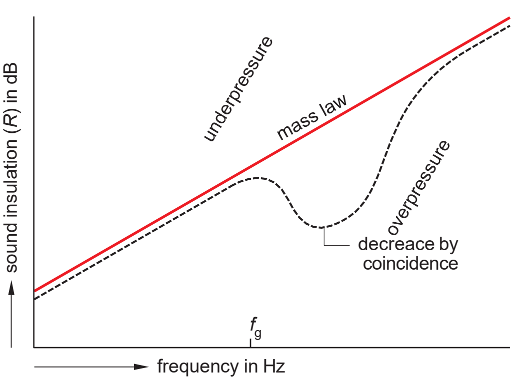


Figure 11.6 Effect of coincidence on sound insulation

This so-called coincidence frequency depends on the rigidity of the wall and therefore the thickness and type of material.
The threshold frequency for coincidence (f_g) is found using the following formula:

$$f_{g;coincidence} = \frac{f_g \cdot d}{d} \text{ [Hz]}$$

The meaning of the symbols is:

$f_g \cdot d$ a material-dependent constant in Hz·mm

d the thickness of the structure in mm

The table in figure 11.7 shows the constant $f_g \cdot d$ for various materials, with the coincidence frequency for two commonly used thicknesses of the material as an example. Here the material-dependent constant is expressed in Hz·mm. In order to determine the coincidence frequency the constant has to be divided by the thickness in millimetres.
When choosing a partitioning structure, it is important to know what the frequency range is of the sound which is to be insulated by the partitioning structure.
For an effective sound insulation, the coincidence frequency of the partitioning

material	$f_g \cdot d$	example d [mm]	f_g [Hz]	example d [mm]	f_g [Hz]
aluminium	12,500	2	6250	5	2500
steel	12,800	1	12,800	3	4267
glass	12,800	4	3200	8	1600
concrete	17,300	120	144	200	87
aerocrete	38,000	80	475	200	190
lime-sand brick	21,400	105	204	210	102
porous brick	26,100	50	520	90	289
lightweight concrete	32,000	80	400	200	160
plaster	35,500	50	710	70	507
plasterboard	35,500	9	3944	15	2367
wood	25,000	12	2083	22	1136
chipboard	25,000	8	3125	18	1389
lead	51,200	0.5	102,400	2	25,600

Figure 11.7 Threshold frequency for coincidence in various materials

structure must be outside the frequency area of the sound which the structure should block.

In general, the coincidence frequency of a partitioning structure should not be in the frequency range of 300 to 3000 Hz (this range includes the human voice).
From figure 11.7, it can be derived that for heavy walls the influence of the coincidence is less noticeable. The coincidence frequency of a concrete wall for example is around the 100-150 Hz. Furthermore the table in figure 11.7 clearly shows that, for instance, 50-90 mm porous brick and 50-70 mm plaster have a very unfavourable insulating behaviour because the range in which the coincidence frequency falls (300-700 Hz) is exactly the range in which the human voice falls.
Increasing the thickness of the material (for example, the glass in a partition wall from 4 mm, f_g = 3200 Hz to 8 mm, f_g = 1600 Hz) does not always have to produce better sound insulation by moving the threshold frequency.

The practical mass law does not take account of coincidence and can therefore only be used as a general guideline value. The plateau method has been developed to predict the behaviour of simple walls in a better way. This method does take the effects of coincidence into account. The method is somewhat more laborious but approximates reality more closely than the practical mass law.

Plateau method

If we want to predict the sound insulation more accurately we have to take the effect of coincidence into account. To this end, we introduce the plateau method. This method can be used to predict the airborne sound insulation of single structures.
In this method the sound insulation is split into three (see figure 11.8):

- I the range before the area of influence around the coincidence frequency
- II the range around the coincidence frequency
- III the range after the area of influence around the coincidence frequency

Effectively, you need to determine only the start and end frequencies (f_1 and f_g) of the coincidence area (the plateau) and the level of insulation when determining the sound insulation. The rest will follow automatically.

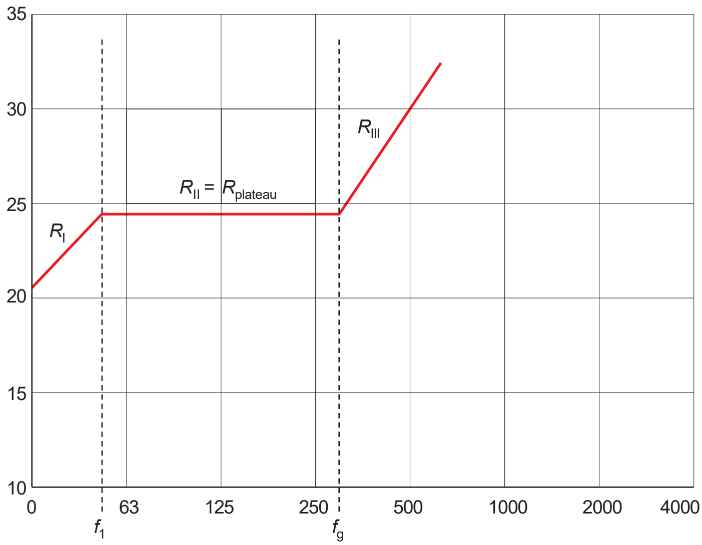


Figure 11.8 Plateau method

The range around the coincidence frequency (II) is known as the plateau. This range is marked by the frequencies f_1 and the previously discussed frequency f_g where:

$$f_1 = 1.57 \cdot f_g \cdot \eta^{\frac{1}{2}} \text{ [Hz]}$$

The meaning of the symbols is:

f_1 the lower threshold frequency of the plateau (the start point of the plateau) in Hz

f_g the upper threshold frequency of the plateau (the end point of the plateau) in Hz

η the loss factor (see figure 11.9)

$$f_g = \frac{f_g \cdot d}{d} \text{ [Hz]}$$

The meaning of the symbols is:

$f_g \cdot d$ the material-dependent constant in Hz·mm (see figure 11.7)

d the thickness of the structure in mm

The sound insulation between two frequencies is determined by the following formula:

$$R_{plateau} = 20 \log(m \cdot f_g) + 10 \log\eta - 44 \text{ [dB]}$$

The meaning of the symbols is:

m the mass in kg/m²

f_g the threshold frequency in Hz

η the loss factor

material	η values
steel	$1 \cdot 10^{-4}$ to $2 \cdot 10^{-4}$
glass	$4 \cdot 10^{-3}$
concrete	$7 \cdot 10^{-3}$
aerocrete	10^{-2}
lime-sand brick	10^{-2}
porous brick	10^{-2}
plasterboard	$3 \cdot 10^{-2}$
wood	10^{-2}
lead	$2 \cdot 10^{-2}$

Figure 11.9 η values of various materials

For area I, there is a decrease of 6 dB per octave starting at frequency f_1. For area III, an increase applies of 7.5 dB per octave.

The heavier the structure the less the influence of the coincidence-effect will be. In the calculation used we should therefore obtain a negative performance. If the mass is greater than 70 kg/m² then we can increase the plateau. The permitted increase is:

$$\Delta R = 20 \log\left(\frac{m}{70}\right) \text{ [dB]}$$

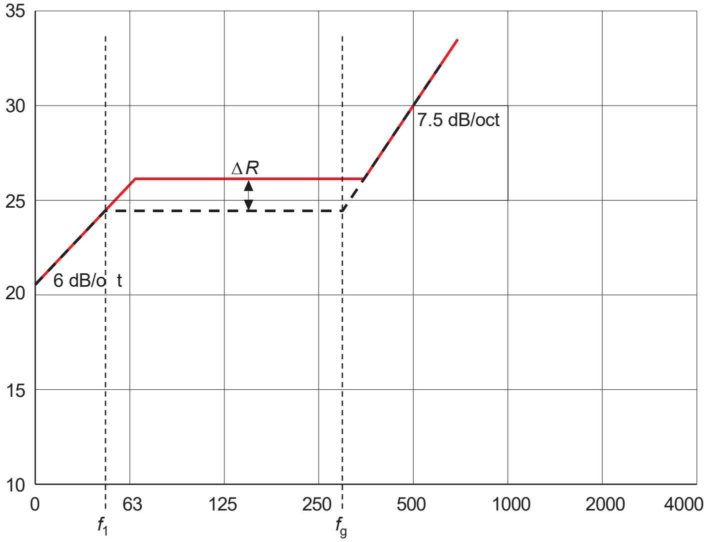


Figure 11.10 Plateau method for masses greater than 70 kg/m^2

The meaning of the symbols is:

ΔR the increase in sound insulation (plateau increase) in dB

m the mass in kg/m^2

The following working method should be used to sketch the new situation (see figure 11.10):

1 Draw the original situation (i.e. without plateau increase, see the dotted line).

2 Draw the new plateau in the graph (a horizontal line).

3 Extend the line for the frequency range f_1 until it reaches the new plateau.

4 Extend the line for the plateau until it touches the line for the frequency range after f_g.

The frequencies f_1 and f_g will therefore move.

Example (see also figure 11.11)

The following is given for cellular concrete (aerocrete):

ρ = 650 kg/m^3

d = 0.14 m

$\eta = 10^{-2}$

$f_g \cdot d$ = 38,000 Hz·mm

Calculation:

$$m = \rho \cdot d = 650 \cdot 0.14 = 91 \text{ kg/m}^2,$$

so take a plateau increase into account!

$$f_g = \frac{f_g \cdot d}{d} = \frac{38{,}000}{140} = 271 \text{ Hz}$$

$$f_1 = 1.57 \cdot f_g \cdot \eta^{\frac{1}{2}} = 1.57 \cdot 271 \cdot (10^{-2})^{\frac{1}{2}}$$

$$= 43 \text{ Hz}$$

Therefore:

$$R_{plateau} = 20 \log(91 \cdot 271) + 10 \log 10^{-2} - 44$$

$$= 24 \text{ dB}$$

The plateau increase is:

$$\Delta R = 20 \log\left(\frac{m}{70}\right) \Rightarrow$$

$$\Delta R = 20 \log\left(\frac{91}{70}\right) = 2.3 \text{ dB}$$

Therefore, the new plateau lies at 24 + 2.3 = 26.3 dB

After the threshold frequency the sound insulation will increase by 7.5 dB per octave (doubling of the frequency). For frequency f_1 the sound insulation will decrease by 6 dB per octave.

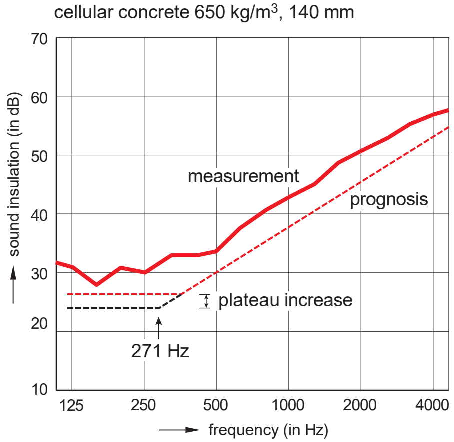


Figure 11.11 Comparison between calculation with plateau method and measured sound insulation

Structure built up from a number of layers

Constructing a wall (or other structure) in two parts with air in between (cavity structure) can achieve a large degree of sound insulation for a relatively low mass because of the lack of direct transmission of vibration from one leaf to the other.
In the best case (total disconnection of the cavity leaves, cavity width 100 mm or more, sufficient absorption in the cavity etc.) the insulation values of both cavity leaves can be added together. This does not apply, however, for cavity walls of normal dimensions. There are also a number of other special effects.

Mass-spring resonance

The two cavity leaves (masses) can vibrate on the intervening air layer (spring). As mentioned earlier all mass-spring systems have a natural (resonance) frequency at which the system can very easily be caused to vibrate. This significantly reduces the insulation value, at one frequency theoretically to zero.
When sound strikes the wall perpendicular this resonance frequency (f_0) can be found using the following formula:

$$f_0 = 60 \sqrt{\frac{m_1 \cdot m_2}{m_1 + m_2} \cdot \frac{b}{1}} \text{ [Hz]}$$

The meaning of the symbols is:

f_0 the resonance frequency of perpendicular impacting sound in Hz
m_1 the mass of the first cavity leaf in kg/m²
m_2 the mass of the second cavity leaf in kg/m²
b the width of the cavity in m

The sound insulation associated with the resonance frequency can be calculated as follows:

$$R_0 = 20 \log \left(\frac{m_1}{2 \cdot m_2} + \frac{m_2}{2 \cdot m_1} \right) \text{ [dB]}$$

If the walls are of the same mass theoretically the sound insulation will reduce to $R = 0$ dB.

The resonance frequency for a number of structures is shown in the table in figure 11.12. For the sake of ease we assume two equally thick cavity leaves here.
Because of this resonance-effect, the insulation effect of a double-glazed window is sometimes worse than a single glazed window when the intention is to stop traffic noise. The traffic noise is exactly at its maximum in frequencies from 100-200 Hz. The fact that this window is still seen as an improvement mostly comes from the improved sealing along the joints and gaps.
Good insulation requires a mass-spring resonance of $f_0 < 80$ Hz.

Cavity resonances

Cavity resonances are caused by standing waves in the cavity. The frequency depends on the width of the cavity (see the formulas in figure 11.13). In this way the lowest cavity resonance frequency is found for a cavity with a width of 12 mm (cavity width = half wavelength):

$$\tfrac{1}{2}\lambda = 0.012 \text{ m} \Leftrightarrow \lambda = 2 \cdot 0.012 = 0.024 \text{ m}$$

$$f = \frac{c}{\lambda} = \frac{340}{0.024} = 14{,}000 \text{ Hz}$$

For a cavity with a width of 120 mm this is $f_{sp} = 1400$ Hz.

	$m_1 = m_2$ [kg/m^2]	b [m]	f_0 [Hz]
plasterboard (12 mm)	14	0.080	80
glass (6 mm)	15	0.012	200
glass (6 mm)	15	0.100	69
porous brick (70 mm)	85	0.030	53

Figure 11.12 Resonance frequencies

The formula above can be rewritten so that there is a relationship between the frequency, the resonance and the width of the cavity. The first cavity resonance is:

$$\tfrac{1}{2}\lambda = b \Leftrightarrow \lambda = 2 \cdot b \Rightarrow f_{sp} = \frac{340}{2 \cdot b} = \frac{170}{b}$$

The second cavity resonance is:

$$\lambda = b \Leftrightarrow f_{sp} = \frac{340}{b} = \frac{2 \cdot 170}{b}$$

The third cavity resonance is:

$$1\tfrac{1}{2}\lambda = b \Leftrightarrow \lambda = \tfrac{2}{3} \cdot b \Rightarrow f_{sp} = \frac{340}{\left(\frac{2}{3} \cdot b\right)} = \frac{3 \cdot 170}{b}$$

The fourth cavity resonance is:

$$2\lambda = b \Leftrightarrow \lambda = \tfrac{1}{2}\, b \Rightarrow f_{sp} = \frac{340}{\left(\frac{1}{2} \cdot b\right)} = \frac{4 \cdot 170}{b}$$

And so on.

Sound insulation is quite minimal at a resonance frequency. For cavity resonances a similar threshold can be drawn as for coincidence. Cavity resonances should not, in fact, occur below 3000 Hz.
In order to still use the useful effect of wide cavities the resonations have to be suppressed by introducing absorbing material into the cavity. In closed structures this can be in the form of sheets of mineral wool, in glass structures it can be in the form of edge absorption (in the clear space of the cavity). This will also suppress the mass-spring resonance.

The diagram in figure 11.14 gives a general view of the sound insulation of a cavity structure. Below the mass-spring resonance frequency a double wall has approximately the same insulation value as a single wall with the same mass as the composite wall. Insulation is quite minimal at a resonance frequency. Far above this the sound insulation is roughly the same as the sum of the insulation values of both individual cavity leaves. In the intervening area the air layer acts somewhat like a link between both cavity leaves, but there is still a considerable gain in relation to a single structure.

Composite walls

A wall structure is often built up from parts with different sound insulation, for example, a door (R = 20 dB) in a half brick wall (R = 40 dB). What is the average insulation of the wall with the door?

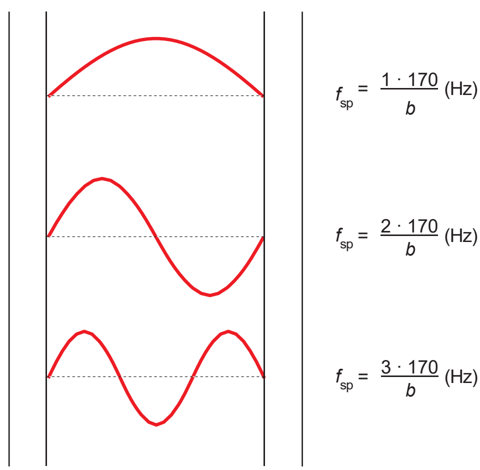


Figure 11.13 Cavity resonances (standing waves in the cavity)

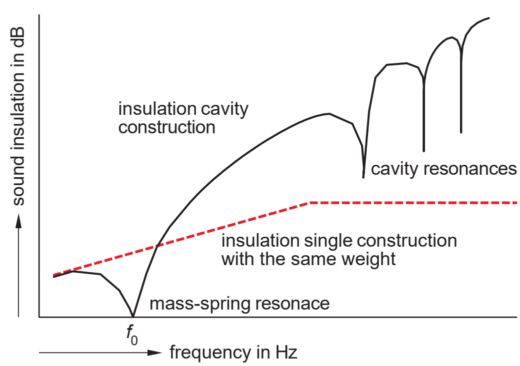


Figure 11.14 General insulation curve of a cavity structure

The insulation difference of 20 dB between the wall and the door means that for every m² a hundred times more sound energy passes through the door than through the rest of the wall (10 log 100 = 20). But in addition to the insulation values of the composite parts the relationship of the area is also significant.

The average insulation can be calculated using the following equation:

$$R_{res} = -10 \log\left(\frac{S_1}{S_{tot}} \cdot 10^{\frac{-R_1}{10}} + \frac{S_2}{S_{tot}} \cdot 10^{\frac{-R_2}{10}} + \dots\right) \quad \text{[dB]}$$

The meaning of the symbols is:

- R_{res} the resultant sound insulation of the structure in dB
- S_1, S_2 the area of element 1 and element 2 respectively in m²
- S_{tot} the total area of the structure in m²
- R_1, R_2 the sound insulation of element 1 and element 2 respectively in dB

In addition to the calculation a quick estimate of the reduction in insulation as a result of a part with less insulation can also be made using figure 11.15.

The meaning of the symbols in the graph is:

- ΔR the value to be substracted from R_1
- R_1 the insulation of the best insulating part in dB
- R_2 the insulation of the worst insulating part in dB
- S_2 the area of the worst insulating part in m²
- S_{total} the total area of the wall in m²

The following applies for the example in figure 11.16:

- total area of wall + door = 17.8 m²
- area of door = 1.6 m²
- area of wall = 16.2 m²

$$R_{res} = -10 \log\left(\frac{1.6}{17.8} \cdot 10^{\frac{-20}{10}} + \frac{16.2}{17.8} \cdot 10^{\frac{-40}{10}}\right)$$

$$= 30 \text{ dB}$$

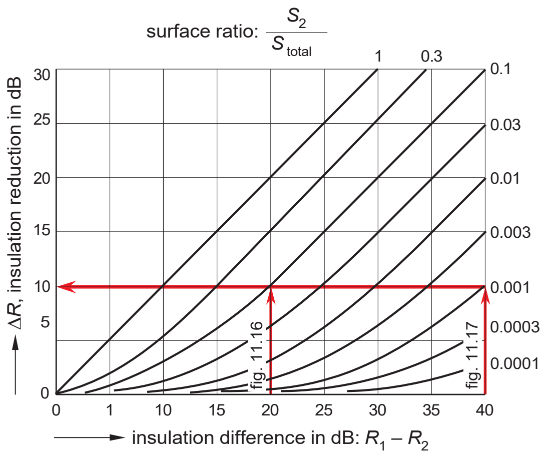


Figure 11.15 Insulation reduction in a wall as a result of a part having less insulation

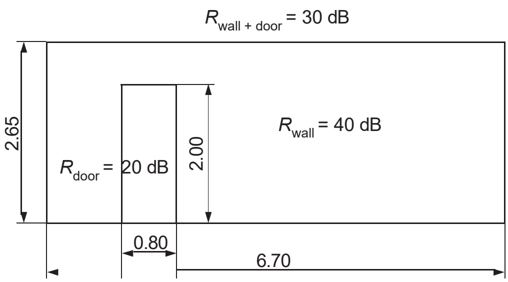


Figure 11.16 Wall built from parts having different sound insulation

The same value can also be derived from figure 11.15:

- the insulation difference between the wall and the door is 20 dB
- the area relationship between the door and the wall is $\frac{1.6}{16.2} = 0.1$.

These two values can be used to derive that the insulation reduction because of the door will amount to approximately 10 dB.

In principle this calculation must be performed for each octave band. Both constituent parts can have a very different insulation spectrum.

An example of a wall where a gap of approximately 2.5 mm (R_{gap} = 0 dB, see figure 11.17) has been left in the join with the ceiling can be examined in the same way. In this case:

- total area of wall + door = 17.755 m^2
- area of gap = 0.017 m^2
- area of wall = 17.738 m^2

$$R_{res} = -10 \log\left(\frac{0.017}{17.755} \cdot 10^{\frac{-0}{10}} + \frac{17.738}{17.755} \cdot 10^{\frac{-40}{10}}\right) = 30 \text{ dB}$$

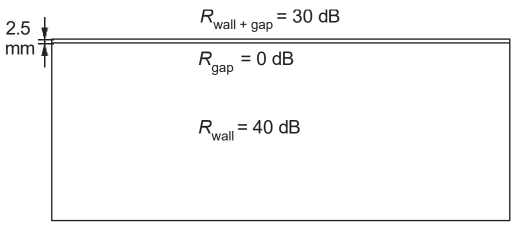


Figure 11.17 Sound insulation of wall with a gap at the joint

The same value can also be derived from figure 11.15.

These two values can be used to derive that the insulation reduction because of the gap will amount to approximately 10 dB.
The influence of a gap will be much greater in a wall with an even higher insulation value. See figure 11.18 for a practical example.

There are also other effects that occur with gaps and cracks that are not discussed here.

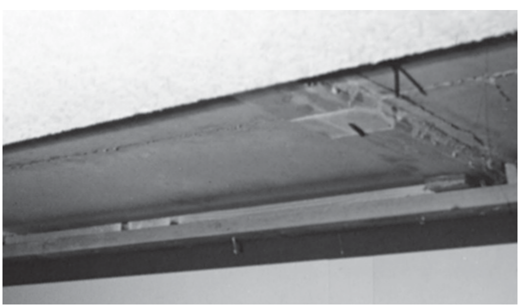


Figure 11.18 The sound insulation expected in this situation is not achieved due to the poor sealing of a wooden rail against the concrete ceiling. After sealing with mastic the sound insulation is a good 6 dB better.

Flanking sound transmission

Earlier we discussed direct sound transmission. Sound propagation also occurs via the flanking structure however (see figure 11.2). This can occur in two ways:

- Sound waves that cause the partition wall to vibrate propagate through the structure so that the sidewalls, floor and ceiling of the receiving room also start to vibrate and start to transmit sound (2 in figure 11.2).
- Vibrations (sound waves) that are generated in a sidewall of the transmitting room propagate through the structure and are transmitted in the receiving room (3 in figure 11.2).

This phenomenon is known as flanking sound transmission. The anticipated sound reduction by a partition wall can be significantly affected by this type of effect.
Particularly the light partition walls of gypsum blocks, aerocrete, light concrete stone, light brick etc. used in house building can very significantly reduce the sound reduction of a massive wall which, itself, has sufficient sound insulation (see figure 11.19). The light walls have to be disconnected from the massive wall to prevent this. This can be done by including an elastic layer (cellular rubber, cork and suchlike) in the joint. In doing so care must be taken that sound leaks do not occur between the rooms that are separated by the light walls. In addition, the effect on very massive walls shown in figure 11.19 is less strong because of the larger transmission damping.

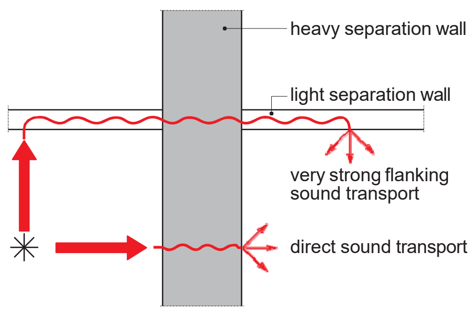


Figure 11.19 Flanking sound transmission in joints with light walls

Another example of flanking sound transmission is a light facade (a wooden lower front, for example) that runs in front of a concrete floor as shown in the cross section in figure 11.20.
In the transmitting room (bottom) the lower front is caused to vibrate. Via the struts the vibration propagates to the room situated above where it is transmitted in the form of sound. Disconnecting the lower front will lead to improved insulation. With inaccurate sealing this type of structure also easily leads to sound leaks.

As a rule of thumb the sound insulation of the wall will be reduced by approximately 5 dB as a result of flanking sound transmission. There is the possibility of calculating the flanking but that is a step too far within the current scope.

Impact sound insulation

The matter of insulation against airborne sound has been discussed above. That is to say: the insulation for sound vibrations that are generated by one or more sound sources (loudspeaker, voice, etc.) and are present in the air. The vibrations that this generates in the structure are propagated by the structure and can be retransmitted as airborne sound by the floors and walls elsewhere in the building. It is, however, also possible to generate sound by directly impacting the building structure (walking, vibrations from operating machinery, slamming a door, sliding a chair etc.). Water pipes fitted in or on the wall can also generate such vibrations in the building structure.
The same applies here too; more massive structures are less easily caused to vibrate than less massive structures. A concrete floor of a reasonable thickness ($m \geq 400$ kg/m^2) usually provides sufficient insulation against the sound of footsteps. With more stringent requirements or in light structures, thick carpets, floating covering floors or suspended ceilings have to be used. Machinery must be fixed using the appropriate vibration dampers and fixing means with rubber sleeves and suchlike must be selected for pipes.

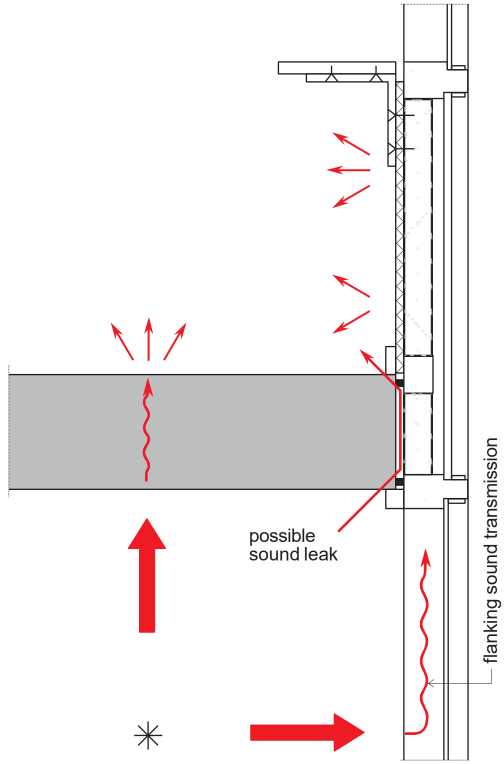


Figure 11.20 Flanking sound transmission and sound leaks in continuous facade lower fronts

11.2 Measuring airborne sound insulation in a laboratory

Section 11.1 showed how the sound insulation of a structure can be roughly calculated. As a guide this can suffice for a first indication, but in the end we want to know what the ‘actual’ sound insulation will be. To do this we need more precise values. The sound insulation of materials and structures can be measured more accurately in laboratories.
In the laboratory, special testing rooms are used to determine the sound insulation of a structure (see figure 11.21). Two rooms are built next to each other in such a way (separate foundations etc.) that no flanking sound transmission is possible. Therefore only the sound insulation of the element is measured.

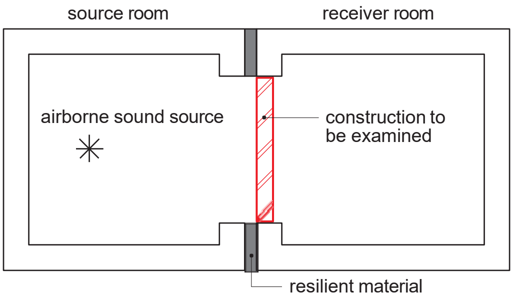


Figure 11.21 Acoustic testing rooms

In one room (the transmitting room) a sound source (loudspeakers) is used to generate airborne sound. The sound pressure level is then measured in both rooms. The measured level in the receiving room (the amount of sound allowed to pass through) is, however, dependent on the area of the partitioning structure and the presence of absorbing material in the receiving room. In order to determine the absorption present, the reverberation time in the receiving room is measured. With the help of formula $A_o = 1/6\ (V/T)$, the absorption value in the receiving room can be determined.

The formula below can now be used to calculate the sound insulation of the structure:

$$R = L_z - L_o + 10 \log\left(\frac{S_z}{A_o}\right) \text{ [dB]}$$

The meaning of the symbols is:

L_z the sound pressure level in the transmitting room in dB
L_o the sound pressure level in the receiving room in dB
S_z the area of the partitioning structure at the transmitting side in m²
A_o the absorption in the receiving room in m² sabin

Laboratories usually measure sound insulation in 1/3 octave bands. For use in practice these measurements are 'translated' to octave bands by the following formula:

$$R_{octave} = -10 \log \frac{1}{3}\sum_{1}^{3} 10^{\frac{-R_{\frac{1}{3}oct,i}}{10}} \text{ [dB]}$$

Example

Using the formulas from section 10.1, the example below will explain how the formula above relating to sound insulation was derived.

The formula for calculating sound insulation (section 11.1) is:

$$R = 10 \log\left(\frac{1}{d}\right) \text{ [dB]}$$

The meaning of the symbols is:
R the sound insulation of the structure in dB
d the part of the sound striking the structure that is allowed to pass through

This formula can also be written as:

$$R = 10 \log\left(\frac{W_{in}}{W_{af}}\right) \text{ [dB]}$$

The meaning of the symbols is:
R the sound insulation of the structure in dB
W_{in} the impacting acoustic power in W
W_{af} the acoustic power delivered in W

A diffuse sound field will dominate in the transmitting room. Section 10.1 gives the relationships in connection with the diffuse sound field. This is what we are using now. The acoustic power striking the wall is:

$$W_{in} = I_z \cdot S_z = \left(\frac{p^2_{eff;z}}{4 \cdot \rho \cdot c}\right) \cdot S_z \text{ [W]}$$

The meaning of the symbols is:
W_{in} the impacting acoustic power in W
I_z the intensity in the transmitting room in W/m²
S_z the area of the wall in the transmitting room in m²
$p_{eff;z}$ the effective sound pressure in the transmitting room in Pa

Part of this acoustic power radiates from the receiving room and there results in a certain sound intensity. Transmitted sound power and sound intensity in the receiving room relate to each other as follows:

$$W_{af} = I_o \cdot A_o = \left(\frac{p^2_{eff;o}}{4 \cdot \rho \cdot c}\right) \cdot A_o \text{ [W]}$$

The meaning of the symbols is:

W_{af} the acoustic power delivered in W

A_o the absorption in the receiving room in m² sabin

I_o the intensity in the receiving room in W/m²

$p_{eff;o}$ the effective sound pressure in the receiving room in Pa

The sound insulation is that part of the impacting sound that is finally allowed to pass through the structure:

$$\frac{1}{d} = \frac{W_{in}}{W_{af}} = \frac{I_z \cdot S_z}{I_o \cdot A_o} = \frac{\left(\frac{p^2_{eff;z}}{4 \cdot \rho \cdot c}\right) \cdot S_z}{\left(\frac{p^2_{eff;o}}{4 \cdot \rho \cdot c}\right) \cdot A_o}$$

Because the term 4 · ρ · c appears in both the numerator and the denominator they cancel each other out. This leads to:

$$\frac{1}{d} = \frac{p^2_{eff;z} \cdot S_z}{p^2_{eff;o} \cdot A_o}$$

The sound insulation is now:

$$R = 10 \log\left(\frac{1}{d}\right) = 10 \log\left(\frac{p^2_{eff;z} \cdot S_z}{p^2_{eff;o} \cdot A_o}\right)$$

$$= 10 \log\left(p^2_{eff;z} \cdot S_z\right) - 10 \log\left(p^2_{eff;o} \cdot A_o\right)$$

$$= 10 \log\left(p^2_{eff;z}\right) + 10 \log\left(S_z\right)$$

$$- 10 \log\left(p^2_{eff;o}\right) - 10 \log\left(A_o\right) \text{ [dB]}$$

If we divide all the expressions by the square of the reference sound pressure ($p_0{}^2$) the formula then becomes:

$$R = 10 \log\left(\frac{p^2_{eff;z}}{p^2_0}\right) + 10 \log\left(\frac{S_z}{p^2_0}\right)$$

$$- 10 \log\left(\frac{p^2_{eff;o}}{p^2_0}\right) - 10 \log\left(\frac{A_o}{p^2_0}\right)$$

$$= L_z - L_o + 10 \log\left(\frac{S_z}{A_o}\right) \text{ [dB]}$$

In principle the indices for the absorption and the area of the partitioning structure are omitted causing the formula to become:

$$R = L_z - L_o + 10 \log\left(\frac{S}{A}\right) \text{ [dB]}$$

The meaning of the symbols is:

R the sound insulation of the structure in dB

L_z the sound pressure level in the transmitting room in dB

L_o the sound pressure level in the receiving room in dB

S the area of the wall in the transmitting room in m²

A the absorption in the receiving room in m² sabin

The sound insulation is a property of the structure to be investigated, the same value must always be found regardless of the rooms between which it forms the partition.

The correction term $10 \log\left(\frac{S}{A}\right)$ makes the sound insulation independent of the room.

Correction term 10 log (*S/A*)

$\frac{S_z}{A_o} = \frac{1}{4}$ ⇒ correction term = −6 dB

$\frac{S_z}{A_o} = \frac{1}{2}$ ⇒ correction term = −3 dB

$\frac{S_z}{A_o} = 1$ ⇒ correction term = 0 dB

$\frac{S_z}{A_o} = 2$ ⇒ correction term = 3 dB

$\frac{S_z}{A_o} = 4$ ⇒ correction term = 6 dB

Example

When the wall becomes twice as big, twice as much sound energy is allowed to pass through to the receiving room, which causes a sound pressure level 3 dB (10 log 2) higher to be measured there. When there is twice as much sound absorption in the receiving room a sound level 3 dB lower will be measured. In the first case, without the correction expression a sound insulation would be measured that is 3 dB too low, and in the second case it would be 3 dB too high.

11.3 Sound insulation in practice

In practice, not the sound insulation of an element is important, but rather the difference in level of sound pressure between rooms, or between inside and outside. In other words: how much do I notice of the sound from another room (either airborne noise or impact sound), or from outside. The sound insulation of an element is important, but other aspects also play an important role, such as flanking sound propagation, sound leaks, dimensions of the room, etc. Besides these aspects, the properties of the sound source are also important. Measurements are taken with a sound generator and amplifier.
In practice, the sound which is to be reduced will deviate from the sound used to determine the sound insulation. Two conversion values are determined for airborne noise, with which the effect of the reference spectrum of the source sound and the A-weighting can be set off (see figure 11.22).

Such a standard spectrum has also been formulated for impact sound (see figure 11.23).

Determining the airborne sound level difference between two rooms happens in separate steps:

1 Determining normalised sound level difference. Per octave band (mid frequencies 125, 250, 500, 1000 and 2000 Hz) the normalised sound level difference is determined. This is done through measurements.

2 Correction for the standard spectrum. The normalised sound level difference is 'weighted' in relation to the appropriate standard spectrum and the results per octave band are added up. The results for the weighted unit are rounded to the nearest integer. If the unrounded number ends in .5, it should be rounded up.

3 Room correction. From the building practice, there is a need for flexible and variable lay-out. This means that, basically, the building is delivered as a shell and the user can choose the lay-out. Because an undivided room must also meet requirements, the weighted values must be corrected for the room factor.

The same approach applies to impact sound, provided that in this case no room corrections take place.

standard reference spectrum airborne noise	octave band mid frequencies (in Hz)				
	125 *i* = 1	250 *i* = 2	500 *i* = 3	1000 *i* = 4	2000 *i* = 5
K_i values neighbour noise spectrum (speech, music, TV, playing children)	-21	-14	-8	-5	-4
K_i values road traffic noise	-14	-10	-6	-5	-7

Figure 11.22 Airborne noise

standard impact sound weighing spectrum	octave band mid frequency (in Hz)				
	125 *i* = 1	250 *i* = 2	500 *i* = 3	1000 *i* = 4	2000 *i* = 5
H_i	-15	-15	-15	-15	-15

Figure 11.23 Impact sound

Normalised airborne sound level difference D_{nT}: calculation method

In section 11.1, we examined the transmission paths significant for the airborne noise insulation of a partitioning wall. We will repeat them here:

1 direct sound emission from the partition wall;
2 the partition wall causes the adjacent structures to vibrate;
3 transmission via the sidewalls.

If you want to determine exactly what the impact of flanking is, you have to include the surface area, the mass, the type of joints between the different structures in your calculation. However, this is beyond the scope of this book.
For the preliminary calculations it suffices to work with a guideline. In practice, the sound insulation as a consequence of flanking is set to approximately 5 dB below the laboratory values. In this section we are going to work out what the normalised airborne sound level difference (D_{nT}) is based on the sound-insulation value (R value). We can do this based on previously introduced formulas:

$$R = L_z - L_o + 10 \log \frac{S_z}{(A_0)} \Rightarrow$$
$$L_z - L_o = R - 10 \log \frac{S_z}{(A_0)} \Rightarrow$$
$$L_z - L_o = R + 10 \log \frac{A_0}{(S_z)}$$

$$D_{nT} = L_z - L_o + 10 \log \frac{T}{(T_0)} \Rightarrow$$
$$D_{nT} = R + 10 \log \frac{A_0}{(S_z)} + 10 \log \frac{T}{(T_0)}$$
$$= R + 10 \log \frac{A_0 \,.\, T}{(S_z \,.\, T_0)}$$

$$T = \frac{V}{6 \,.\, A_0} \Rightarrow A_0 = \frac{V}{6 \,.\, T}$$

$$D_{nT} = R + 10 \log \left(\frac{V \,.\, \cancel{T}}{6 \,.\, S_z \,.\, \cancel{T} \,.\, T_0}\right)$$
$$= R + 10 \log \left(\frac{V}{6 \,.\, S_z \,.\, T_0}\right)$$

The reference reverberation time is 0.5 s. This changes the formula into:

$$D_{nT} = R + 10 \log \frac{V}{(3 \cdot S_z)} \quad \text{[dB]}$$

Airborne sound level difference between rooms: measurement method

Airborne sound comes from a source that causes the air to vibrate. These vibrations will cause the adjacent structure to vibrate. The structure will then cause the air in the adjacent room to vibrate (source → air → structure → air).

When taking measurements, you effectively want to find out what the difference is between the sound levels in de sound source room and the sound receiving room (what can I hear from my neighbours). For measuring the normalised sound pressure difference, a sound source is placed in a room and the difference in sound pressure level per octave band between the sound source room and the sound receiving room is measured. Because often measurements are taken in an unfurnished room, the reverberation time is longer than in a furnished room, resulting in a higher sound level. In order to get an impression what the sound insulation will be in practice, the measured reverberation time will have to be corrected to the reference reverberation time (T_0); the reverberation time you can expect in practice in a furnished space. For classrooms (primary and secondary, higher or university education) the reverberation time amounts to 0.8 s. For other rooms, such as homes and offices, the reverberation time amounts to 0.5 s. The formula for this is:

$$D_{nT,i} = L_z - L_o + 10 \log \left(\frac{T_i}{T_0}\right) \text{[dB]}$$

The meaning of the symbols is:

$D_{nT,i}$ the normalised airborne sound level difference in dB in octave band *i*
L_z the sound pressure level in the transmitting room in dB
L_o the sound pressure level in the receiving room in dB

T_i the average reverberation time in the receiving room in s
T_0 the reference reverberation time in s

If the reverberation time in the room is equal to the reference reverberation time (0.5 s) then the correction factor is 0. The table in figure 11.24 shows the magnitude of the correction term for a number of reverberation times.

T [s]	correction term [dB]	*T* [s]	correction term [dB]
0.20	- 4.0	0.8	2.1
0.25	- 3.0	0.9	2.6
0.30	- 2.1	1.0	3.0
0.35	- 1.5	1.2	3.8
0.40	- 1.0	1.4	4.5
0.45	- 0.5	1.6	5.1
0.50	0.0	1.8	5.6
0.60	0.8	2.0	6.0
0.70	1.5	2.5	7.0

Figure 11.24 Magnitude of the correction term 10 log T/T_0 (T_0 = 0.5 s) for determining normalised airborne sound level difference (D_{nT})

Weighted airborne sound level difference

In order to compare structures with each other, it would be preferable to express the sound level difference of a structure in one number. For this purpose, the $D_{nT,A}$ value is introduced. In order to calculate this value, the following formula is used:

$$D_{nT,A} = -10 \log \sum_{i=1}^{5} 10^{\frac{K_i - D_{nT,i}}{10}} \text{ [dB]}$$

The meaning of the symsbols is:

$D_{nT,A}$ weighted airborne sound level difference (dB)
$D_{nT,i}$ normalised airborne sound level difference per octave band (dB)
K_i reference spectrum of the source sound and the A-weighting (dB), see figure 11.22

See the example in figure 11.25.

Example

Determining the A-weighted normalised airborne sound pressure level difference
In this example, the calculation of an airborne noise measurement between two rooms is given.

	octave band mid frequencies (in Hz)				
	125 *i* = 1	250 *i* = 2	500 *i* = 3	1000 *i* = 4	2000 *i* = 5
standard reference spectrum neighbour noise K_i [dB]	-21	-14	-8	-5	-4
normalised air pressure level difference $D_{nT,i}$ [dB]	38.3	44.5	50.2	53.8	57.4
K_i - $D_{nT,i}$	-59.3	-58.5	-58.2	-58.8	-61.4

$$D_{nT,A} = -10 \log \sum_{i=1}^{5} 10^{\frac{K_i - D_{nT,i}}{10}} = -10 \log\left(10^{\frac{-59,3}{10}} + 10^{\frac{-58,5}{10}} + 10^{\frac{-58,2}{10}} + 10^{\frac{-58,8}{10}} + 10^{\frac{-61,4}{10}}\right)$$

= 52.1 dB, rounded down to 52 dB

Figure 11.25

Typical airborne sound level difference

The $D_{nT,A}$ value is derived from the D_{nT} value and is a unit dependent on room type and use. This space-dependent unit has to be transferred into room-independent unit. To this end the typical airborne sound level difference ($D_{nT,A,k}$) is introduced. The formula for deriving the $D_{nT,A,k}$ value for offices spaces is as follows:

$$D_{nT,A,k} = D_{nT,A} - 10 \log \frac{0.16 \cdot V}{(T_0 \cdot S_r)} \text{ [dB]}$$

The meaning of the symbols is:

- $D_{nT,A,k}$ typical airborne sound level difference in dB
- $D_{nT,A}$ weighted airborne sound level difference per octave band in dB
- V volume of the receiving room in m^3
- T_0 the reference reverberation time in s
- S_r surface area of the communal partition structure between transmission and receiving structure in m^2

If there is no communal part of the partitioning structure between transmission and receiving room, or if the surface area between transmission and receiving room (S_r) is smaller than $(0.16 \cdot V)/(2.5 \cdot T_0)$, then, for the calculation of the typical airborne sound level difference, the surface area between transmission and receiving room (S_r) must be set equal to $(0.16 \cdot V)/(2.5 \cdot T_0)$ with a minimum of 7 m^2.

Impact sound transmission between rooms

For measuring the impact sound insulation, a standard impact sound generator is used (tapping machine). This device has a number of steel or brass hammers weighing 500 grams in total, which make a free fall from a height of 40 mm for a total of ten times a second and strike the floor (see figure 11.26). This way, vibrations are generated in the floor which propagate through the building structure and are then transmitted into other rooms in the shape of airborne sound.

In the receiving room the impact sound level is measured (L_i) in the five octave bands mentioned above. This receiving room may be situated under the impacted floor, but it could also be a room adjacent to the one where the tapping machine is set up.

The measured impact sound level (L_i) is again normalised for the reverberation time of T_0 = 0.5 s (except for classrooms). This results in the following formula:

$$L_{nT,i} = L_i - 10 \log \left(\frac{T_i}{T_0}\right) \text{ [dB]}$$

The meaning of the symbols is:

- $L_{nT,i}$ the normalised impact sound level in dB
- L_i the sound pressure level in dB measured in the receiving room
- T_i average reverberation time in the receiving room determined in octave band i in s
- T_0 the reference reverberation time (= 0.5 s, except for class rooms)

The formula shows that the higher $L_{nT,i}$, the worse the sound insulation!

Weighted contact sound insulation level

When we compare the impact sound level of a variety of structures, we again want to compare them to each other in one number. For this purpose, the $L_{nT,A}$ value is introduced. The weighted impact sound level $L_{nT,A}$ is found by adding up the H_i weighted normalised impact sound level values ($L_{nT,i}$) as measured with the tapping machine. The formula for this is:

$$L_{nT,A} = -10 \log \sum_{i=1}^{7} 10^{\frac{L_{I,i}+H_i}{10}} \text{ [dB]}$$

The weighted impact sound insulation level relates to the protection of a room against impact sounds which can arise from a floor, stairs or another surface meant for walking on. All this does not apply only to rooms on top of each other, but also to rooms next to each other.

Contrary to the weighted airborne sound level difference, no correction is applied for the room in determining the weighted impact sound level. The weighted impact sound level appears to a large extent to be independent of

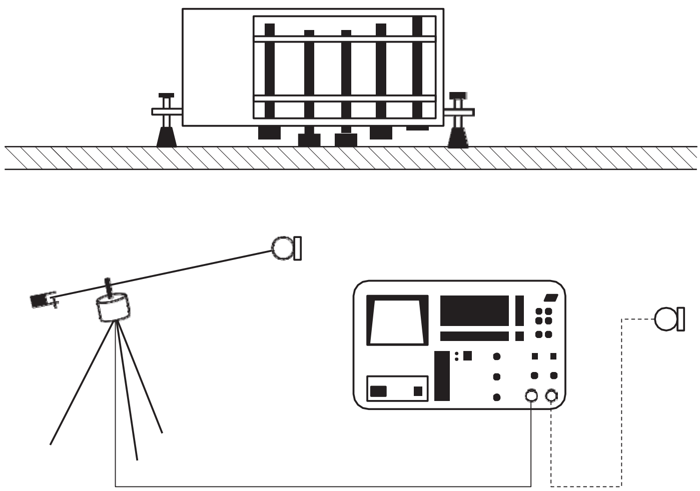


Figure 11.26 Impact sound insulation measurement

the lay-out variants. From the viewpoint of the variable layout, the $L_{nT,A}$ value appears to be a suitable unit already so it does not need to be adjusted.

Legislation on sound insulation

Legislation sets requirements on homes in terms of the typical airborne sound level difference ($D_{nT,A,k}$) and the weighted impact sound level ($L_{nT,A}$).

These are the minimum requirements. Especially when there is a big difference in the daily lives of the various residents, nuisance may still occur even when the requirements are met. Consider for example nuisance because of radio, television, playing musical instruments, practising loud hobbies and walking on hard shoes (e.g.) on a hard floor finish (tiles, stone, parquet) without taking special precautions.

Example

Determining the A-weighted normalised impact sound pressure level

In this example, an impact sound measurement between two rooms is performed.

	octave band mid frequencies (in Hz)				
	125	250	500	1000	2000
	i = 1	i = 2	i = 3	i = 4	i = 5
normalised impact sound pressure level $L_{nT,i}$	60.3	61.7	63.1	63.5	59.2
weighing values standard impact sound spectrum H_i (see figure 11.23)	-15	-15	-15	-15	-15
$L_{nT,i} + H_i$	45.3	46.7	48.1	48.5	44.2

$$L_{nT,A} = -10 \log \sum_{i=1}^{5} 10^{\frac{L_{nT,i}+H_i}{10}} = -10 \log\left(10^{\frac{-45.3}{10}} + 10^{\frac{-46.7}{10}} + 10^{\frac{-48.1}{10}} + 10^{\frac{-48.5}{10}} + 10^{\frac{-44.2}{10}}\right)$$

$= 53.8$ dB, rounded up to 54 dB

Figure 11.27

In general, there is no legislation regarding sound insulation between rooms inside one and the same office building, because they strongly depend on the type of work that is carried out. The Central Government Real Estate Agency does however make room-dependent $D_{nT,A}$ en $L_{nT,A}$ demands on office spaces. The level of demands is based on the level of privacy to be realised (see figure 11.28).

As supplement to the desired insulation value, the table of figure 11.29 provides recommendations for the maximum equivalent background noise level as a result of outside noise ($L_{A,eq}$) and as a result of technical installations ($L_{i,A}$). This latter numerical value also needs to be used as guideline for the devices present in the rooms for the same categories of rooms as in figure 11.28.

11.4 Installation noise

Installations in buildings produce noise; think for example of air handling units, lifts, etc. To what extent users of the building are affected by this noise depends on many factors and cannot be easily determined in advance. Measuring the installation noise is often the only option.

The way the typical A-weighted installation sound level ($L_{I,A,k}$) is determined does not differ greatly from the way the typical A-weighted airborne sound level difference is measured. Here too there are three steps for determining the typical A-weighted installation sound level:

1 For each octave, determine the installation sound pressure level in the receiving room ($L_{I,i}$). The octave bands with mid frequencies of 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz must be used for the installation sound pressure level.

2 Determine the A-weighted installation sound level ($L_{I,A}$) with the following formula:

$$L_{I,A} = 10 \log \sum_{i=1}^{7} 10^{\frac{L_{I,i}+W_i}{L_{I,i}}} \text{ [dB]}$$

In the case of installation noise, there is no spectrum. For this reason, only the A-weighting (W) is used as derivation value (figure 10.18).

3 Determine the typical A-weighted installation sound level ($L_{I,A,k}$) for a room with the formula:

$$L_{I,A,k} = L_{I,A} + 5 \log \frac{V}{(V_o)} \text{ [dB]}$$

The meaning of the symbols is:

$L_{I,A,k}$ typical A-weighted installation sound level in dB
$L_{I,A}$ A-weighted installation sound level
V volume of the receiving room
V_o 25 m^3 reference volume of the receiving room

11.5 Sound insulation and sound proofing of facades

A-weighted sound proofing (G_A): measurement method

Sound proofing of the facade is effectively the difference between the indoor and outdoor level, normalised for the reverberation time.

$$G_A = L_{bu} - L_{bi} + 10 \log \left(\frac{T}{T_0}\right) \text{ [dB]}$$

The meaning of the symbols is:

G_A sound proofing of the facade in dB
L_{bu} the outdoor sound pressure level in dB
L_{bi} the sound pressure level in the receiving room in dB
T the reverberation time in the room in s
T_0 the reference reverberation time in s

For measurements of sound proofing of the outside partitioning structure, you have to determine the indoor and outdoor level difference and the reverberation time per octave band (mid frequencies 125, 250, 500, 1000, 2000 Hz). The room has to be corrected for the reverberation time to the reference reverberation time T_0 (= 0.5 s, except for classrooms). Sound proofing of the facade is measured by using a sound source aimed at the facade with an angle of 45°. The incoming

Performance level Acoustic guidelines matrix					
	Enclosed spaces			Open spaces	
	Category 1	Category 2	Category 3	Category 4	Category 5
Air born sound pressure level difference minimum requirement $D_{nT,A}$ in dB					
to rooms	45	52	39	NA	NA
to traffic areas	33	33	27	NA	NA
to rooms via wall with door		33	33	NA	NA
to bathrooms	48	48	48	48	48
to other rooms	45	42	33	33	33
Maximum impact sound pressure level $L_{nT,A}$ in dB including floor finish					
to rooms	57	57	57	57	57
to traffic areas	67	67	67	67	67
to rental or user partition	48	48	48	48	48
Example situations for enclosed spaces					
category 1	high level of speech privacy e.g. meeting centre				
category 2	increased level of speech privacy in office location e.g. consulting rooms				
category 3	private work space/concentration area (1-4 people)				
Example situations for open spaces					
category 4	open, grouped work space (4-6 people)				
category 5	open meeting area, call centre				

Figure 11.28 Performance requirements for airborne and impact sound insulation (source: *Handboek Bouwfysische kwaliteit gebouwen*)

Type of background noise	Enclosed spaces			Open spaces	
	Category 1	Category 2	Category 3	Category 4	Category 5
sound pressure level as a result of outdoor sound (industrial railway, road and air traffic sound) ($L_{A,eq}$ in dB)	< 35	< 40	< 40	< 40	< 45
installation sound pressure level ($L_{I,A}$ in dB)	< 35	< 35	< 35	< 40	< 40

Figure 11.29 Recommended values for background noise level in dB in offices (source: *Handboek Bouwfysische kwaliteit gebouwen*)

sound level is derived from sound level measurements taken 2 metres in front of the facade.

The formula for this is:

$$D_{2m,nT} = L_{bu} - L_{bi} + 10 \log \left(\frac{T}{T_0}\right) \quad [\text{dB}]$$

The meaning of the symbols is:

$D_{2m,nT}$ sound proofing of the facade in dB
L_{bu} the outdoor sound pressure level in dB
L_{bi} the sound pressure level in the receiving room in dB
T the reverberation time in the room in s
T_0 the reference reverberation time in s

Because reflections against the facade occur, the measured sound level will be higher than the actual incoming sound level. This has to be corrected for with derivation term C_r. For a level facade C_r = 3 dB. Basically, you measure the sound twice, assuming that virtually everything is reflected. For facades with balconies and suchlike, you will find values between 1 and 3 dB. Instructions regarding measurements and calculation provide the values depending on the facade structure.
As a result of the position of the building in relation to the source, it is possible that the sound level on the facade is not the same for all areas of the facade. This could for example be a building parallel to a traffic route. The facades at right angles to the road effectively see half of the length of the total road. This means that the sound level at that spot is 3 dB less. This is accounted for with the derivation value C_L. Here too, instructions provide values for all possible situations.
The partial facade sound proofing (G_i) can now be determined per octave band with the following formula:

$$G_i = 10 \log 10^{\frac{-D_{2m,nT,i} - C_r + C_L}{10}} \quad [\text{dB}]$$

The meaning of the symbols is:

G_i partial sound proofing of an external partitioning structure for octave band *i* (sound level derivation term) in dB
$D_{2m,nT,i}$ normalised facade sound level difference between a room and outdoor space for octave band in dB
C_r derivation term for the influence of reflections and geometrical factors in dB (3 dB for flat facades)
C_L derivation term for variations in sound levels due to screening and reflection (sound level derivation term) in dB

A standard spectrum is also defined for traffic noise which takes into account the typical sound production of the source and the auditory sensitivity of the observer. In order to determine the A-weighted facade sound proofing (G_A) per octave band, the partial sound proofing is subtracted from the standard airborne noise reference spectrum and the aggregate logarithmic sum of the results is determined.

$$G_A = -10 \log \Sigma\, 10^{\frac{K_i - G_i}{10}} \quad [\text{dB}]$$

The meaning of the symbols is:

G_A A-weighted sound proofing of an external partitioning structure in dB
G_i partial sound proofing of an external partitioning structure for octave band in dB
K_i reference spectrum of the source sound and the A-weighting in dB (see figure 11.22)

As a result of the wish for variable lay-out, the G_A must finally be defined as a value which is lay-out independent. The following formula applies:

$$G_{A,k} = G_A - 10 \log \left(\frac{0.16 \cdot V}{T_0 \cdot S_{r,u}}\right) \quad [\text{dB}]$$

The meaning of the symbols is:

$G_{A,k}$ A-weighted typical sound proofing of an external partitioning structure in dB
G_A A-weighted sound proofing of an external partitioning structure in dB
V volume of the room in m^3
T_0 the reference reverberation time in s
$S_{r,u}$ surface area of the external partitioning structure between outside area and the receiving room in m^2

Typical sound proofing of external partitioning structures

A facade generally consists of multiple elements, such as a cavity wall, windows, ventilation provisions, etc. The acoustic quality of the total facade depends among other things on the quality of the individual elements, the surface area of the element in relation to the total facade and the way in which the elements are attached. In order to estimate the typical facade sound proofing in practice and to determine whether the regulations are met, calculations need to be performed. In general, a computer program will do the work, but for simple situations (when, for example, there is only a single facade surface) the calculation can also be performed manually.

The typical sound proofing of the external partitioning structure can be determined in three steps:

- Determine for each octave band with mid frequencies of 125, 250, 500, 1000, 2000, and 4000 Hz the sound insulation of the composite facade (R_i). This does not say anything about the sound proofing of the structure, but only about the quality of the facade (comparable to the sound insulation R of a partitioning structure between rooms).
- Determine the A-weighted facade sound proofing (G_A) for the reference spectrum.
- Determine the typical sound proofing of the external partitioning structure ($G_{A,k}$).

Sound insulation of composite facade

First we have to calculate or determine the sound insulation value of the external partitioning structure per octave band.

Each part of a certain material has its own specific sound insulating characteristics. An enormous number of materials have been measured in laboratories and we can look up the sound insulation of many materials, per octave band, in books of tables. The values that are determined in laboratories depend on the situation in which they will eventually be placed.

If the facade comprises more than one element we first determine the total sound insulation of the facade using the following formula (see section 11.1 also):

$$R_{A;i} = -10 \log \left(\sum_{j=1}^{n} \frac{1}{S_{tot}} \left(S_j \cdot 10^{\frac{-R_{j;A;i}}{10}} + 10 \cdot 10^{\frac{-D_{n;e;i}}{10}} \right) + K \right)$$

The meaning of the symbols is:

$R_{A;i}$	the sound insulation value of the facade in dB
Σ	the sum of n facade elements
S_j	the area of facade element j in m^2
S_{tot}	the total facade area, seen from inside the sound-sensitive room in m^2
$R_{j;A;i}$	the A-weighted sound insulation value of the facade element j in dB
$D_{n;e;i}$	the A-weighted normalised sound level difference of a ventilation provision, normalised to 10 m^2 sabin, in dB
K	the gap term

Ventilation provisions such as ventilation grids and cantilever windows are often little more than an opening in the facade. The sound insulation of such provisions is therefore not as high and that will dramatically limit the sound insulation of the facade. Ventilation provisions that provide better sound insulation will have to be used in order to still be able to ventilate naturally under higher sound loads. Sound attenuators have been developed for this purpose. Put simply, a sound attenuator is a box containing sound absorbing material. The air, and therefore the sound also, is conducted across the sound-absorbing material. This dampens a large proportion of the sound before the ventilation air enters the room (see figure 11.30).
Because the air is conducted across the absorbing material, which increases the air flow resistance, the net flow through opening cannot be determined as simply as for cantilever windows. The amount of air that can be introduced into the room through the sound attenuator is determined in laboratories in accordance with standard norms and expressed in a (fictional) net flow through opening for the ventilation provision. As can

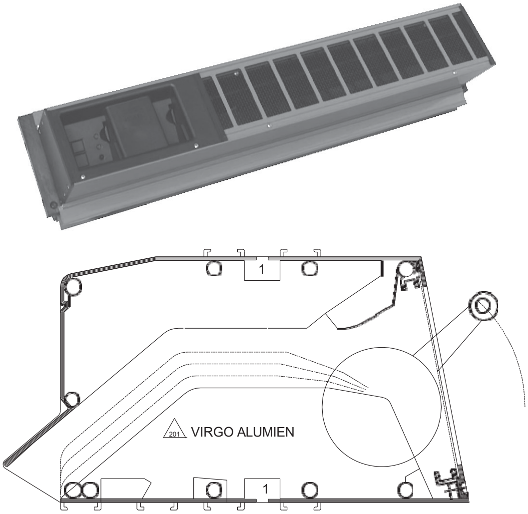


Figure 11.30 Alusta Vigro type sound attenuator

Source: www.alusta.nl

be seen from the formula for sound insulation, no area for the sound attenuator is taken into consideration in the calculation.

All sound transmission via the sound attenuator is assigned the fictional flow through opening in measurements in the laboratory. This means that the closed part of the box does not have to be included as a separate component in the calculation of the facade sound proofing. The entire gross box area must be included in determining the total facade area *S*.

The ventilation capacity of a ventilation provision is expressed in dm^3/s. This is the ventilation capacity per m^1 of sound attenuator. In order to meet ventilation requirements we have to determine the total linear metres of sound attenuator needed. The longer the box the lower the sound insulation. The contribution from the sound attenuator is determined as follows:

$$D_{n;e} = D_{n;e;lab} - 10\log\left(\frac{Q_{vent}}{C}\right) \text{ [dB]}$$

The meaning of the symbols is:

$D_{n;e}$ the A-weighted normalised sound level difference normalised to 10 m^2 sabin, in dB

$D_{n;e;lab}$ the A-weighted normalised sound level difference normalised to 10 m^2 sabin, as measured in the laboratory, in dB

Q_{vent} the required ventilation capacity in dm^3/s

C the pass-through measured in the laboratory in dm^3/s per m^1

The presence of joints and gaps influences the sound insulation of the facade. In calculations it is assumed that the total length of the gaps is related to the area of the facade and does not have to be measured separately. The value of the gap term depends on the manner in which the gap and joint sealing has been handled. The total sound insulation required must be taken into consideration in the choice of joint and gap sealant. If the sound proofing of the facade can be realised using a gap term of 10^{-4}, then there is no sense in using a much better gap sealant as this will only have a marginal effect. The table in figure 11.31 shows various gap terms.

Sound proofing of a partitioning structure

The sound insulation R_i relates to the structure but tells us nothing about the final sound proofing of the facade. The room that lies behind, the structure of the facade and the effect of values measured in the laboratory versus reality, are not included in the calculation. Therefore, the sound insulation of the facade has to be converted into the sound proofing of the partitioning structure (G_i) using the following formula:

$$G_i = R_i + 10\log\left(\frac{V}{6 \cdot T_0 \cdot S}\right) - 3 + C_g \text{ [dB]}$$

The meaning of the symbols is:

G_i the partial sound proofing of the partitioning structure for octave band *i* in dB

R_i the sound insulation of the composite facade based on the laboratory insulation of the constituent parts, in dB

V the volume of the room in m^3

T_0 the reference reverberation time in s

S the area of the external partitioning structure in m^2

-3 a constant term that can be used to calculate the difference between the sound striking in practice (point source/ line source) and in the laboratory

C_g the facade structure correction term in dB

situation	gap term K	R_A
existing dwellings		in dB
facades		
• without provisions	$3 \cdot 10^{-3}$	25
• single gap sealing	$1 \cdot 10^{-3}$	30
• double gap sealing and improved joint sealing	$3 \cdot 10^{-4}$	35
• special double gap sealing*	$3 \cdot 10^{-5}$	45
roofs		
• with gaps in roof boarding	$1 \cdot 10^{-3}$	30
• with gap-tight roof boarding	$1 \cdot 10^{-4}$	40
new build dwellings		
facades		
• single gap sealing and good joint sealing	$3 \cdot 10^{-4}$	35
• double gap sealing and good joint sealing	$1 \cdot 10^{-4}$	40
• special double gap sealing*	$1 \cdot 10^{-5}$	50
roofs		
• with single scale roof elements < 30 kg/m^2	$3 \cdot 10^{-5}$	45
• other roof structures	$3 \cdot 10^{-6}$	55

* – remaining good joint sealing
– two or three-point clamp fixing
– draught mouldings welded in the corners
– sound attenuator connection, carefully sealed

Figure 11.31 Gap term values

The facade sound proofing is a room-dependent variable. By adding the term $10 \log\left(\frac{V}{6 \cdot T_0 \cdot S}\right)$ the influence of the room that lies behind is included in the total facade sound proofing. Because room-independent variables – in connection with variable layout – are used in legislation, this term will be subtracted later when calculating the typical sound proofing. The sound insulation values (R_i values) are based on laboratory measurements (diffuse sound field). In practice, there is a direct sound field outside. This means that the insulation values differ from the laboratory values. Research has proven that this causes a reduction in the sound insulation of 3 dB. The construction of the facade also has an influence on the sound level just in front of the facade. Some facade structures can shield the striking sound to a certain degree. This means a reduction of the sound levels immediately in front of the facade. This could be a balcony/loggia with a closed parapet (glass) and possibly an additional sound absorbing ceiling. If you plan things carefully, this could reduce the sound pressure level by values of up to 3 dB. The term used for correcting the facade structure is shown by C_g. Calculation instructions provide values for C_g for all possible situations. Subsequently, the normalised A-weighted sound proofing (G_A) and the typical facade sound proofing ($G_{A;k}$) are determined with the formulas as given above.

Performing calculations with one-number values

Manufacturers often mention the R_A value along with the sound-insulation values. The R_A value is a single-number value for the sound insulation of the element for which the spectrum of road traffic has already been set off. If we are dealing with railway or aircraft traffic noise we can assume the same value but have to make a correction of 3 dB for railway traffic and of 2 dB for air traffic.

Example

Imagine that a facade has to have a sound proofing of 30 dB. For railway traffic the facade only needs a sound proofing of 27 dB, calculated with the standard spectrum for road traffic and 28 dB for air traffic.

Performing calculations with one-number values does not differ much from the calculation method discussed earlier. The advantage of this method is that it is faster, since we don't have to make calculations for all octave bands separately. Below, it is briefly explained which steps ultimately lead to the normalised A-weighted sound proofing. First, the R_A value of the total facade is calculated by finding the aggregate of all elements:

$$R_A = -10 \log \left[\sum_{j=1}^{n} \frac{S_j}{S} 10^{-\frac{R_{A,j}}{10}} + \frac{10}{S} 10^{-\frac{D_{ne,A}}{10}} + K \right]$$

The meaning of the symbols is:

$R_{A,j}$ the weighted (laboratory) sound insulation of facade element j in dB

S_j the surface area of facade element j in m^2

$D_{ne,A}$ laboratory value of a weighted sound level difference normalised at 10 m^2 of a sound-insulated ventilation provision in dB

K the gap term [-]

Because adjustment of the road traffic reference spectrum has already been applied to the sound insulation, the normalised A-weighted sound proofing can now be immediately determined with the formula:

$$G_A = R_A + 10 \log \frac{V}{(6 \cdot T_0 \cdot S)} - 3 + C_g \text{ [dB]}$$

The meaning of the symbols is:

R_A the (laboratory) sound insulation of the facade surface in dB for the relevant standard reference spectrum; without any further specification this concerns outside noise

V volume of the room in m^3

S the surface area of the facade in m^2

C_g the facade structure correction term in dB

The conversion of G_A into $G_{A,k}$ takes place as described above.

Situations may arise where it is useful or necessary to start from the actual spectrum. If elements are used in the facade elements that provide good sound insulation in exactly the high frequencies for example, or if the spectrum differs from the standard spectrum. Calculation based on the R_A value can then return sound insulation values that are incorrect.

Requirements for typical sound proofing of facades in legislation

The typical sound proofing that must be achieved depends on the sound load on the facade from industry, road or railway traffic, and the use of the room. Threshold values are given for the sound level that has to be achieved in an accommodation area (that which, as an occupant, you eventually hear from outside).
The typical sound proofing of an external partitioning structure forming the partition between an accommodation area and outside is the difference between the sound pressure level outside (determined in accordance with the Noise Abatement Act) and the inside level prescribed by the Building Decree, with a minimum of 20 dB.
The threshold value of the interior level for a dwelling function, with the exception of a dwelling function of a caravan, is 35 dB.
A threshold value of 40 dB applies for offices.
For accommodation rooms a typical sound proofing applies that is 2 dB lower than the typical facade sound proofing of an accommodation area in which the accommodation room lies.

We speak of Kosten units (Ke) in relation to air traffic noise. The Ke is the average sound load from aircraft considered over a full year. The number of flights, the type of aircraft and a night correction have been incorporated into

Example

We give an example of the calculation method using the R_A value and the R_i value. Given:

- A flat facade of a new build dwelling (3.6 · 3.0 m) comprising a cavity wall and 35% double glazing (glass thickness 4 mm, cavity width 6 mm).
- The facade structure correction is 0.
- The gap sealing is double.
- The joint sealing is good.
- The volume of the room lying behind is 52 m^3.

octave band [Hz]	125	250	500	1000	2000	R_A [dB]
stony cavity wall + mineral wool	33	37	41	46	52	41.6
double glazing (4-6-4)	22	23	24	32	34	26.9
road traffic noise spectrum	-14	-10	-6	-5	-7	

Further details:

The gap term is $K = 10^{-4}$ (see figure 11.31).

The area of the facade is 3.6 · 3 = 10.8 m^2.

The area of the glass, including the frame is 3.6 · 3 · 0.35 = 3.78 m^2.

The area of the cavity wall is 3.6 · 3 · 0.65 = 7.02 m^2.

Calculation using the average of the R_A value gives:

$$R_A = 10 \log \left(\sum_{j=1}^{n} \frac{1}{S_{tot}} \left(S_j \cdot 10^{-\frac{R_{j;A}}{10}} + 10 \cdot 10^{-\frac{D_{n;j;A}}{10}} \right) + K_{tr} \right)$$

$$= -10 \log \left(\frac{3.78}{10.8} \cdot 10^{-2.69} + \frac{7.02}{10.8} \cdot 10^{-4.16} + 10^{-4} \right) = 30.7 \text{ dB}$$

As there are no ventilation provisions, the term $10 \cdot 10^{-\frac{D_{n;j;A}}{10}}$ is omitted.

$$G_A = R_A + 10 \log\left(\frac{V}{6 \cdot T_0 \cdot S}\right) - 3 + C_g$$

$$= 30.7 + 10 \log\left(\frac{52}{6 \cdot 0.5 \cdot 10.8}\right) - 3 + 0 = 29.8 \text{ dB}$$

It is a flat facade, therefore the facade correction equals 0. In addition, it is a dwelling, so we have to take a reverberation time of 0.5 s into account.

$$G_{A;k} = G_A - 10 \log\left(\frac{V}{6 \cdot T_0 \cdot S}\right)$$

$$= 29.8 - 10 \log\left(\frac{52}{6 \cdot 0.5 \cdot 10.8}\right) = 27.7 \text{ dB}$$

We perform the same calculation once again, but this time based on the spectrum.

The formulas required are:

$$R_i = -10 \log \left(\sum_{j=1}^{n} \frac{1}{S_{tot}} \left(S_j \cdot 10^{-\frac{R_{i;j}}{10}} + 10 \cdot 10^{-\frac{D_{n;i;j}}{10}} \right) + K_{tr} \right) \text{ [dB]}$$

$$G_i = R_i + 10 \log \frac{V}{(6 \cdot T_0 \cdot S)} - 3 + C_g \text{ [dB]}$$

$$G_A = -10 \log \Sigma 10^{-\frac{G_i - K_{tr}}{10}} \text{ [dB]}$$

$$G_{A;k} = G_A - 10 \log \frac{V}{(6 \cdot T_0 \cdot S)} \text{ [dB]}$$

From the table and formulas it follows that:

G_A = 29.8 dB

$G_{A;k}$ = 27.7 dB

Both calculations arrive at the same value (naturally).

Other details are:

octave band [Hz]	125	250	500	1000	2000
stony cavity wall + mineral wool	33	37	41	46	52
double glazing (4-6-4)	22	23	24	32	34
gap term	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
R_i	25.8	27	28.1	34.7	36.1
G_i	24.9	26.1	27.2	33.8	35.2
road traffic noise spectrum K_{tr}	-14	-10	-6	-5	-7
G_i - K_{tr}	38.9	36.1	33.2	38.8	42.2

this unit. Lines of equal Cost unit can be drawn around airports based on these calculations. Based on this a check can be made of the sound proofing that has to be met.

Converting sound insulation units from other units

In the context of the standardisation of European regulations, the methods of determining airborne noise and impact sound have changed drastically over the last years. Suppliers have adapted their products as much as possible to the new regulations, but in older literature the original terms are still mentioned. In order to be able to use them, a number of different unambiguous relationships between the old and new units are provided below:

$D_{nT,A} \approx I_{lu}$ + 51 dB

$D_{nT,A,k} \approx I_{luk}$ + 52 dB

$L_{nT,A} \approx$ 59 - I_{co} dB

$R_w \approx I_{lu}$ + 54 dB [practice value]

$R'_w \approx I_{lu}$ + 59 dB [laboratory value]

$D_{g,Atr} \approx G_A$ + 3 dB

$L_{I,A} \approx L_A$ for furnished rooms

$\approx L_A$ - 5 for unfurnished rooms and other rooms

$L_{n,A} \approx L_{n,w} + C_I \approx$ 59 - $I_{co,lab}$

$R_A \approx R_w + C \approx I_{lu;lab}$ + 51 dB

$R_{A;tr} \approx R_w + C_{tr} \approx R_A$ (road traffic)

$R_A \approx R_w + C \approx R_{Ar}$ (railway traffic)

12

Applied sound insulation

A.C. van der Linden; A. Zeegers

During the design process the architect or advisor will need design tools on the basis of which estimates can be made of the sound insulation to be achieved for the structure, without having to perform 'complicated' calculations. This chapter describes a number of rules of thumb that can be used to make a quick estimate. A number of things must always be checked or measured later in the design process.

12.1 Desired sound insulation

Before a designer starts designing and selecting the right materials, he or she must first determine which requirements have been set for the room, the facade and the interior walls. Regulations pose demands to the sound insulation between rooms in homes. It is very well possible that you want to realise a sound insulation between rooms which do not have specific regulatory requirements, e.g. between office rooms. In order to set proper requirements, it is important to determine the goal to be realised with the requirements, which could be:

- prevent the noise produced in the room from becoming a nuisance to other rooms;
- prevent outside noise (from adjoining rooms or from outside) from becoming a nuisance in the room itself;
- prevent information shared inside the room from being overheard in other rooms;
- ensure that everybody in the room can hear each other properly.

Speech privacy refers to the extent to which a conversation taking place inside a room is intelligible or audible in an adjoining room or in the vicinity. For office spaces, speech privacy is very important. For setting sound insulation requirements based on speech privacy, it must be clear:

- to what extent sound may be heard in other rooms
- what the voice volume is that is generally used (normal, raised or loud)
- to what extent the conversation is allowed to be overheard (clearly intelligible, intelligible with difficulty, audible but not intelligible, inaudible)
- what the background noise level is inside the room, e.g. due to sound installations, equipment inside or outside the room
- what the dimensions of the room are
- what the absorption capacity of the room is

In order to make a fair estimation of what the sound insulation should be, a simple determination method has been formulated.

The determination method takes into account the speech level, the extent of the nuisance, the background noise level and the desired level of privacy. The formula is:

$$D = S + P + 11 - 10 \log \left(\frac{A}{4}\right) - N - X \text{ [dB]}$$

The meaning of the symbols is:

D the sound level reduction present (or desired) between rooms ($L_z - L_o$) in dB

A the amount of absorption in the room where the conversation takes place in m² sabin

N the background level in the room to be protected in dB

X the extent of the nuisance, specified as:

- satisfied (no nuisance) = 0
- nuisance = 6
- serious nuisance = 12

S the speech level at 1 m distance from the speaker, specified as:

- normal = 60 dB
- raised = 66 dB
- loud = 72 dB

P an addition for the desired level of privacy, specified as:

- normal privacy = 9 dB
- confidential = 15 dB

Example

The sound insulation for a room (surface area 12 m², reverberation time 0.5 s) is determined Points of departure are:

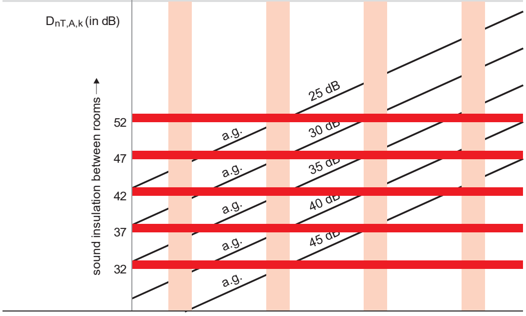
- increased privacy: $P = 15$ dB;
- no nuisance: $X = 0$;
- background level: $N = 30$ dB;
- normal speech level: $S = 60$ dB;
- sound absorption; A = 16 m² sabin.

$$D = 60 + 15 + 11 - 10 \log \left(\frac{16}{4}\right) - 35 - 0 \approx 45 \text{ dB}$$

Note: this is a rule of thumb which can be used at the start of the design process. On further specification, advanced determination methods must be used.

Speech privacy between rooms

voice volume	audibility of conversations			
loud	clearly intelligible	clearly intelligible	intelligible with difficulty	audible, not intelligible
raised	clearly intelligible	intelligible with difficulty	audible, not intelligible	inaudible
normal	intelligible with difficulty	audible, not intelligible	inaudible	inaudible
speech privacy	marginal	reasonable	good	very good



Based on room size 20 m² with reverberation time 0.5 seconds
a.g. = background noise in the receiving room

Figure 12.1 Relationship between audibility of conversations, sound insulation between rooms and background noise level (source: *Handboek Bouwfysische kwaliteit gebouwen*)

Various diagrams can be found in the literature, based on which speech privacy can be determined (see figure 12.1). From this figure, it can be determined that for a room of 20 m² with a reverberation time of 0.5 s for the points of departure mentioned in the example (where increased privacy refers to inaudibility), an A-weighted normalised typical airborne sound level difference of approx. 47 dB is required. Figure 12.1 clearly shows that the A-weighted normalised typical airborne sound level difference between two rooms can be lower if the background noise level in the receiving room increases.
The background noise ‘drowns out’ the sound of the adjoining room as it were. In smaller rooms, a background noise level of 35-40 dB is acceptable. A level higher than 40 dB will be experienced as a nuisance. For a background noise lever lower than 35 dB, the A-weighted normalised typical airborne sound level difference becomes so high that standard solutions will not suffice.

This is different in open-plan offices. Users produce a sound level of 40-45 dB. A background noise level of 40 dB will then be acceptable. A lower background noise level is not desirable, because conversations between people can then easily be overheard by others. The rule of thumb is that a conversation is not intelligible if the sound level of the conversation is 10 dB lower than the background noise level.

12.2 Construction of the walls

In construction of the walls we discuss, for a number of structures, how they perform in practice and the errors that must be avoided during construction.
Practice shows that as a consequence of connections, cracks, crevices and flanking noise, the sound insulation will at least be 5 dB lower than the values as measured in a laboratory. Bear this in mind when selecting walls.

Rules of thumb for single walls

Rules of thumb can be given for various types of walls which can be used during the design process to make a quick estimate in relation to the sound insulation of a wall. A number of frequently used rules of thumb are given below. However, do not forget that in practice the insulation can be lower than calculated as a result of flanking transmission and the construction of joints.
Section 11.1 discusses the practical mass law:

$$R = 17.5 \log m + 17.5 \log \left(\frac{f}{500}\right) + 3 \text{ [dB]}$$

The meaning of the symbols is:
R the sound insulation per octave band in dB
m the mass of the structure in kg
f the frequency in Hz

The abovementioned formula does not take the coincidence frequency into account. In order to make a correct estimate this is determined using the following formula:

$$f_{g;\text{coincidence}} = \frac{f_g \cdot d}{d} \text{ [Hz]}$$

The meaning of the symbols is:

f_g the coincidence frequency in Hz
$f_g \cdot d$ a material dependent constant in Hz·mm (see figure 11.7)
d the thickness of the structure in mm

The coincidence frequency must not fall in the speech range and therefore not be lower than 3000 Hz.

For a more accurate estimate of the sound insulation of a single structure it is better to use the plateau method (see section 11.1).

The following applies for converting the R value to the D_{nT} value:

$$D_{nT,A} = R_A + 10 \log \frac{V}{(6 \cdot T \cdot S)} \quad [dB]$$

$$D_{nT,A,k} = D_{nT,A} - 10 \log \frac{0.16 \cdot V}{(T_0 \cdot S_r)} \quad [dB]$$

$D_{nT,A}$ value of stony walls with m = 60-160 kg/m²

The following applies for gypsum blocks and cellular concrete:

$$D_{nT,A} = 25.4 \log m - 69 + 10 \log \left(\frac{V}{3 \cdot S}\right) - 51$$

The following applies for stone and lightweight concrete:

$$D_{nT,A} = 12.7 \log m - 41 + 10 \log \left(\frac{V}{3 \cdot S}\right) - 51$$

The meaning of the symbols is:

m the mass of the (single) wall in kg
V the volume of the room in m³
S the area of the partitioning structure in m²

Stony walls with $D_{nT,A} \geq 41$ dB

A number of internal wall types are listed below, which, with good construction and attention to detail, can provide airborne sound insulation of $D_{nT,A} \geq 41$ dB.

- Half stone masonry (brick), plastered on one or two sides, possibly in neatwork, but then very carefully laid (shoved joints) and pointed. Cracked or damaged bricks must not be used.
- Porous brick masonry, 90 mm thick, plastered on one or two sides. Because this structure is on the limit of the insulation requirement, small shortcomings in the joints can lead to insufficient insulation. Neatwork is not possible.
- Porous brick masonry, twice 70 or 90 mm with a mortar joint between. This mortar joint should guarantee the air tightness of the wall so that the outsides can be constructed in neatwork.
- Light concrete stone. Because of the high porosity of these stones it is not possible to realise neatwork in a half stone wall. These walls, which must have a mass m > 150 kg/m², should be plastered on one or two sides. They can also be made airtight by treating them on one or two sides with a thick latex paint (see figure 12.2). Double walls with a mortar joint in the middle must also be used for neatwork in concrete stone.
- Building blocks (concrete, sand-lime brick, etc.) with a minimum mass of m = 150 kg/m² plastered on one or two sides or treated with latex paint. Neatwork is not possible as, due to the large dimensions of the blocks, it is not possible to guarantee that all joints are sealed sufficiently with mortar during laying.

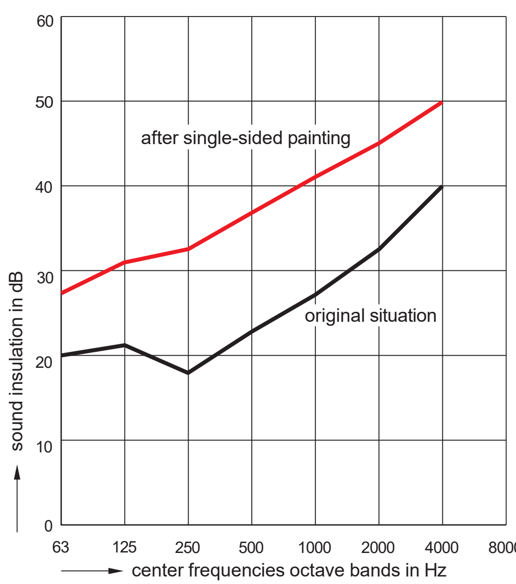


Figure 12.2 Example of improvement of the airborne sound insulation of a porous concrete stone wall using a single sided paint treatment

Double walls with a mortar joint in between must actually function as a single mass. Therefore, mortar must be used in such a way that a very strong bond is achieved. Both cavity leaves must be erected simultaneously. The use of anchors (or better yet: continuous reinforcement strips) is a necessity. When both halves of the wall disassembly by shrink a cavity structure is created with a very narrow cavity, which could have a very unfavourable (mass-spring) resonance frequency.
Walls that are plastered or carefully jointed must also receive this treatment above a suspended ceiling, as otherwise there is a risk of circulating noise (see section 12.4).

Stony walls with $D_{nT,A} \geq 51$ dB

A structure meeting $D_{nT,A} \geq 51$ dB can be, amongst other things, a monolith wall of concrete or stone, with a minimum mass of $m = 400$ kg/m^2. Neatwork is not possible (see figure 12.3-1).

Rules of thumb for double structures with cavity

The sound insulation of this type of wall is difficult to predict because of various aspects such as mass-spring resonance and cavity resonations. With cavity structures it is important to know the frequency at which resonation occurs. This resonance frequency can be calculated using the following formula (see section 11.1 also):

$$f_0 = 60 \sqrt{\frac{m_1 + m_2}{m_1 \cdot m_2} \cdot \frac{1}{b}} \text{ [Hz]}$$

The meaning of the symbols is:

f_o the resonance frequency in Hz
m_1, m_2 the mass of cavity leaf 1 and cavity leaf 2 respectively in kg/m^2
b the cavity width in m

If the resonance frequency is higher than 80 Hz, then it is necessary to suppress this by, for instance, inserting mineral wool in the cavity.

Stony cavity walls with $D_{nT,A} \geq 51$ dB

Stony cavity walls that meet this requirement can be:

- A cavity wall of porous stone, light concrete stone, etc. with leaves of unequal thickness, plastered (rendered) on the inside or outside to achieve good airtightness, and where the cavity is filled with mineral wool.
- A cavity structure of brick masonry or massive concrete stone, where at least one cavity leaf is rendered on the inside to realise good airtightness. Sometimes the mistake is made of building-in wall sockets opposite each other on either side of the wall (for electricity, radio and television or telephone for example) which causes a sound leak (see figure 12.3-2). In addition, in existing situations sealing the openings in the boxes (cable feed-in) and other joints with sealant is useful.

The previously mentioned flanking sound transmission can seriously reduce the sound insulation at joints between light partition walls and the massive wall.

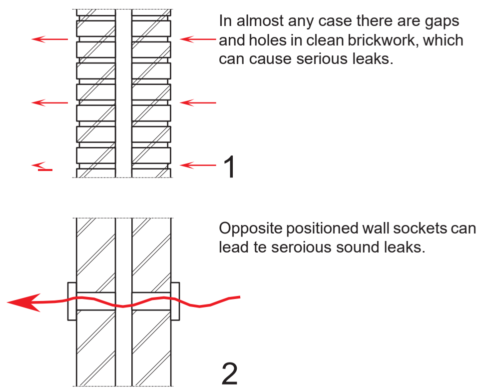


Figure 12.3 Sound leaks in cavity walls

Stony cavity walls with $D_{nT,A} \geq 55$ dB

The unanchored cavity wall provides good opportunities for achieving very good results ($D_{nT,A} \geq 55$ dB). The cavity leaves should both have good airtightness and the cavity must continue through to the foundation in order to avoid flanking sound transmission. In any event, the floors must not continue through. In order to avoid mortar bridges and suchlike, the cavity widths in masonry cavity walls must, preferably, be at least 50 mm.

Naturally care must be taken at the joints (such as with the facade) to avoid circulation noise and flanking sound transmission. The details can be implemented analogous with the principle given in figure 12.17-2. In joints with the roof too we must be aware of flanking sound transmission and sound leaks. Roof girders must not continue through and the ceiling must be constructed well sealed (see figure 12.4).

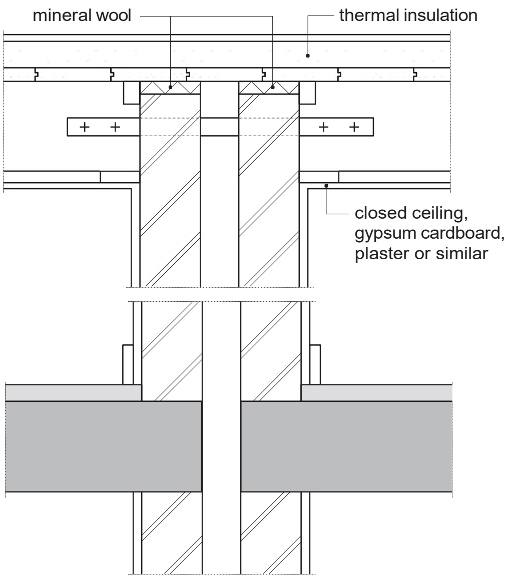


Figure 12.4 Unanchored cavity wall

Light walls

Light walls only provide reasonable insulation when they have been constructed with a cavity. These walls derive their sound insulation not from mass but from the properties of cavity structures (see section 11.1). This relates to plasterboard walls with wooden or metal framing.
In order to achieve a good result, the cavity leaves must not have any (rigid) joints between them to prevent the direct transmission of vibrations from the one cavity leaf to the other.

Construction

The plasterboard wall is constructed as follows (see figures 12.5 and 12.6 also):

- one or more plasterboards
- a cavity structure, whether or not filled with absorbent material, and framing (separated or otherwise) made from wood or metal
- one or more plasterboards.

The quality of the wall is derived from its flexible character. If the flexible character is affected,

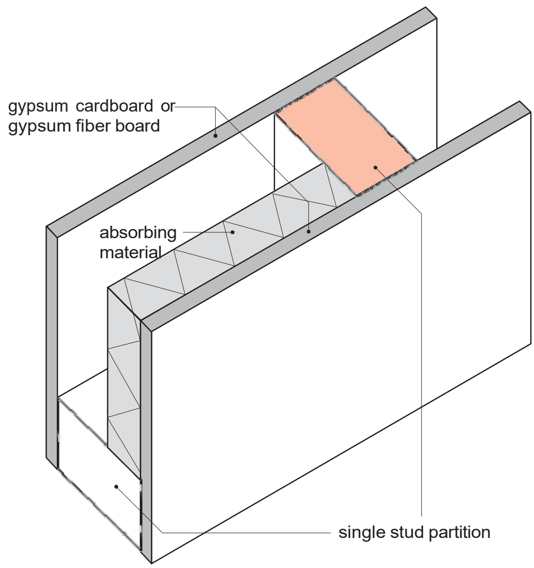


Figure 12.5 Construction of single framing

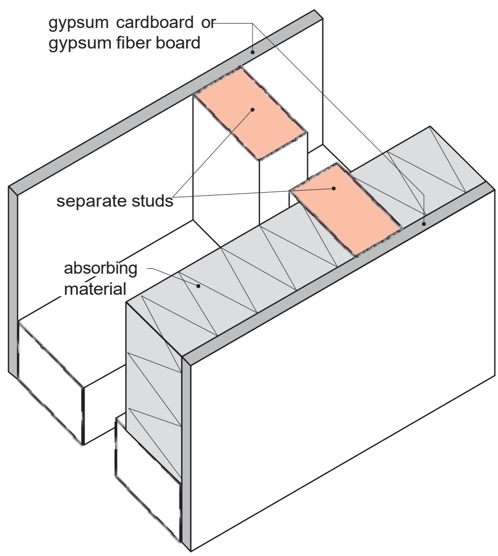


Figure 12.6 Construction of separated framing

the acoustic quality of the wall diminishes significantly. This must be continuously taken into account when selecting or designing a wall.

Mass

Very good sound insulation can be achieved using plasterboard walls while the mass of the wall remains limited. In principle, increasing the mass often leads to better sound insulation (mass law). The sound insulation of plasterboard walls is, however, based on the fact that they are flexible and not so much on their mass (which is too low for this). If the mass of the plasterboards were to be increased the flexible character would be affected and there would be less sound insulation.

If more boards are fitted one on top of the other without there being rigid connections between them (so the flexible character is retained) then better sound insulation can be achieved.

Framing

The more framing that is used the more the rigid the structure becomes. And if the structure becomes more rigid, the sound insulation become worse.
If the boards are fixed rigidly to the framing, the flexibility of the structure is affected and the sound insulation is reduced. When separated framing and flexible fixing of the boards to the framing are used this would, in principle, create the ideal situation. Transmission can then only occur through the air cavity.

Cavity

The resonance frequency depends on the width of the cavity and the mass of the structure (see section 11.1). Wider cavities are preferred over narrow cavities. As a result of the sound absorbent cavity filling (such as mineral wool) the sound in the cavity will be dampened and the mass-spring resonance will be reduced, increasing the sound insulation.

Joints

The aspects mentioned up to now are determinative for the quality of the plasterboard wall in general. Apart from the wall itself we must, however, also consider the joints between the wall and the surrounding structure. The good sound insulation properties of a wall can be totally destroyed as a result of incorrect or careless connections. There are three ways in which Sound leaks can occur at joints (see figure 12.7):

- between side connections, the covering floor and the subfloor and the edge profile (a)
- between the plasterboards and the edge profile (b)
- via the edge profile itself (c).

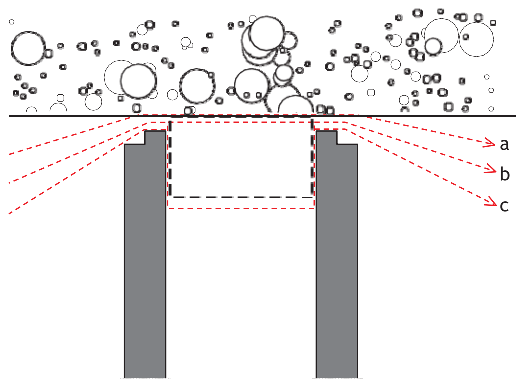


Figure 12.7 Possible sound leaks at connections between an insulating wall and the surrounding structure

In addition to the wall itself and the method of connection to the surrounding structure there are also countless aspects that have to be taken into account:

- preventing connections of disconnected framing
- breaking the plasterboard at expansion joints
- the detailing of feed-throughs
- the building-in of technical services such as wall sockets
- the fixing of the various facilities to a wall

Airborne sound insulation

Empirical formulas have been arrived in relation to the airborne sound insulation of plasterboard walls based on laboratory research. The standard deviation is approximately 2-2.5 dB. The $D_{nT,A,lab}$ should be approximately 5 dB

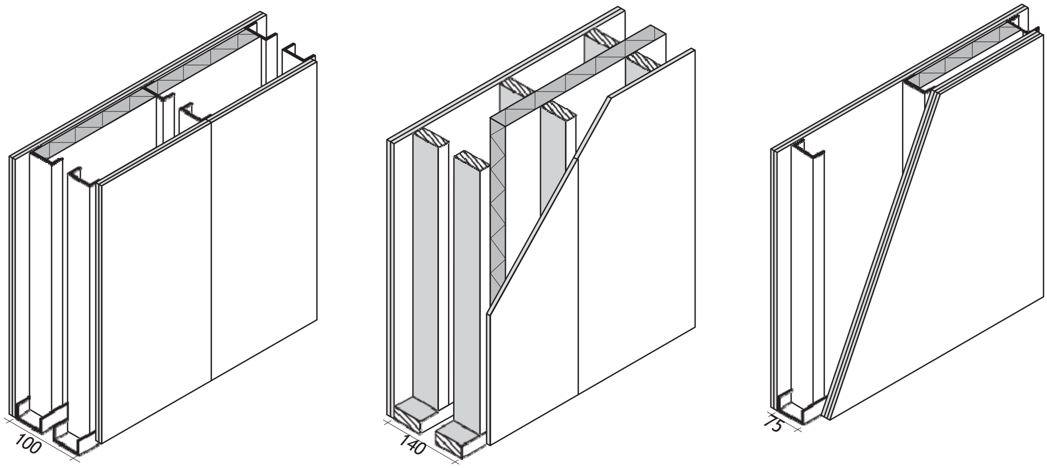


Figure 12.8 Solutions for plasterboard walls $D_{nT,A,k} = 52$

better than the practical value. This must be properly taken into account.

The following applies for cavity walls on single, wooden framing:

$$D_{nT,A,lab} = v + b + 1{,}5 \log m'' + 60 \cdot s - 39 - 51 \text{ [dB]}$$

The meaning of the symbols is:

v the cavity filling:
- 0 = unfilled cavity
- +3 = cavity filled with mineral wool

b the fixing of the plasterboards to the framing:
- 0 = normal (rigid) fixing
- +6 = flexible fixing

s the cavity width in m:
- between 0.03 and 0.08 m

m″ the total mass of the cavity leaves in kg/m²:
- between 18 and 50 kg/m²

The following applies for cavity walls on single, metal framing:

$$D_{nT,A,lab} = v + 30 \log m'' + 150 \cdot s - 61 - 51 \text{ [dB]}$$

The meaning of the symbols is:

v the cavity filling:
- 0 = unfilled cavity
- +5 = cavity filled with mineral wool (1.5 kg/m²)

s the cavity width in m:
- between 0.04 and 0.075 m
- for a cavity between 0.075 and 0.1 m a maximum of s = 0.075 m

m″ the total mass of the cavity leaves in kg/m²:
- between 10 and 70 kg/m²
- maximum of 15 kg/m² per board

The following applies for cavity walls with separated framing:

$$D_{nT,A,lab} = v + 20 \log m'' + 30 \cdot s - 32 - 51 \text{ [dB]}$$

The meaning of the symbols is:

v the cavity filling:
- 0 = unfilled cavity and/or $m'' > 30$ kg/m²
- +3 = cavity filled with mineral wool (3 kg/m²) provided $m'' < 30$ kg/m²

s the cavity width in m:
- between 0.07 and 0.2 m

m″ the total mass of the cavity leaves in kg/m²:
- between 10 and 70 kg/m²
- maximum of 15 kg/m² per board

Cavity walls built in-situ

When cavity walls are built in-situ it is easiest to work with separated framing (see figure 12.9). It is important that the flexible character of the wall is affected as little as possible so that there is no negative effect on the acoustic quality.

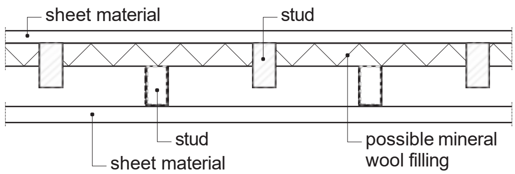


Figure 12.9 Light wall with separated framing

Plasterboard sheets of various thicknesses can be used for cladding. The cavity can be filled with mineral wool to suppress resonations. Polystyrene foam or other 'closed cell' materials are not suitable as they are not porous and therefore do not have any sound absorbing capacity.
With this type of structure sound insulation indices of $D_{nT,A} \geq 36$ dB can be achieved in any event. Even better values are possible with careful construction and larger sheet thicknesses (or more layers not connected to each other or not rigidly connected to each other). In doing so the joints between the insulation boards must also be well sealed.

Industrially produced walls

It is going to far to discuss every type of system wall here. The principle is the same as discussed above. When choosing a wall you must not begin only with the value for average insulation between 100 and 3200 Hz that is (often) specified by the manufacturer. It is best to request test reports with the insulation at various frequencies so that the A-weighted sound level difference can be calculated from them. In addition, it must be understood that the measurement data generally represents laboratory values. Because of flanking sound transmission and incorrectly constructed connections values approximately 5 dB lower are easily found in practice.
It is generally the case that the walls themselves provide sufficient options for good sound reduction from room to room. The final result succeeds or fails with the design and construction of the connection details.

Noise reduction walls

It is possible to place an extra wall in front of a stony wall. Herewith you can provide better sound insulation for existing walls or limit the transmission of impact sound.
The extra walls can consist of boards on framing (see figure 12.10). The usual materials can be used for this (plasterboard, plastered wood wool cement, etc.). Wood or metal profiles are often used for the framework.
Noise reduction walls can also be glued against the back wall. Acoustic elements (sheeting and insulation) are attached against the underlying wall with glue dots. Naturally the best results are achieved if the framing is kept free from the wall, of if elastic material is used to fix it to the wall instead of rigid material.
Filling the cavity with mineral wool avoids the occurrence of troublesome resonations.

Figure 12.10 Noise reduction wall consisting of metal profiles with springy underlay and finished with plasterboard attached free from the wall

existing wall construction	weight	noise reduction wall construction	improvement airborne noise insulation
cavity wall	400	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+1
	400	• metal framework • 40 mm mineral wool • 2 × 12.5 mm plasterboard	+2
sand-lime brick 265 mm	500	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+3
	500	• metal framework • 40 mm mineral wool • 2 × 12.5 mm plasterboard	+3
half-brick masonry	200	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+5
	200	• metal framework • 40 mm mineral wool • 2 × 12.5 mm plasterboard	+6
concrete 180 mm	400	• 50 mm mineral wool (glued) • 10 mm plasterboard	+6
gypsum blocks 70 mm	65	• 30 mm mineral wool (glued) • 10 mm plasterboard	+8
	65	• metal framework • 40 mm mineral wool • 12.5 mm plasterboard	+10
	60	• metal framework • 40 mm mineral wool • 2 × 12.5 mm plasterboard	+14

Figure 12.11 Improvement of the airborne noise insulation by applying a detached noise reduction wall in relation to the airborne noise insulation of the existing wall (source: SBR info sheet 388)

Values as high as $D_{nT,A}$ = 54 dB can be achieved by placing a flexible wall in front of a monolith wall (masonry, concrete) with a mass of $m \geq 200$ kg/m^2.
See figure 12.11 for the improvements of the airborne noise insulation attainable in many situations.

12.3 Floor construction

The acoustic quality of floors is an important point for attention, particularly if residential buildings are involved. Impact sound in particular (walking across the floor) can be an enormous source of nuisance and often leads to rows with the neighbours. In addition to the quality of the floor, the floor finish also plays a significant role. Floor covering will have a dampening effect. Hard floor finishes on the other hand (such a parquet, natural stone, etc.) do not provide a positive contribution.

Impact sound insulation of floors

It can be argued that a massive floor starts to vibrate less easily and therefore provides better impact sound insulation (lower $L_{nT,A}$) than a light floor. Floors with a mass of $m \geq 400$ kg/m^2 (approx. 160 mm of concrete) are needed with requirements of $L_{nT,A} \leq 59$ dB. A number of figures are shown in the table in figure 12.12 as a guide.

	$L_{nT,A}$ [dB]
wooden floor frame with wooden floor and ceiling	approx. 71
bare concrete floor, m = 300 kg/m^2	approx. 63
bare concrete floor, m = 410 kg/m^2	approx. 59
bare concrete floor, m = 490 kg/m^2	approx. 57
bare concrete floor, m = 525 kg/m^2	approx. 55

Figure 12.12 Impact sound insulation of a number of floor types

Roughly the total weight per m^2 (including ribs) can be used for beam-and-slab or caisson slab floors. A covering floor can also provide some improvement. An improvement of 5-8 dB is possible with screed covering floors with cork or wooden fibre as added material. The improvement from floor covering is limited and only thick and special types provide a noticeable improvement. Thin floor coverings (linoleum, PVC, needle punch carpet, etc.) only provide a slight improvement (0-5 dB) for walking sounds. For sound as a result of moving chairs and suchlike, needle punch carpet, for example, can provide a significant improvement. Floor coverings such as cork linoleum, carpet or plastic on a thick backing (foam rubber, waffle backing etc.) can provide an improvement to approximately 15 dB. Thick, deep pile carpets with underlay can provide even greater improvement as can a floating covering floor (approx. 25 dB).

Airborne sound insulation of floors

Heavy floors

In general, few problems occur with the floors that are normally used (concrete). A concrete floor with a mass of $m \geq 400$ kg/m^2 usually achieves an $D_{nT,A} \geq 51$ dB.
When a higher $D_{nT,A}$ is required, a suspended ceiling can be used which, when well constructed (see later), has the same effect as a flexible extra wall. However, this effect can only be expected if there is no flanking sound transmission.

Light, stony floors

Lights floors (m = 200 to 300 kg/m^2) can comprise thin concrete slabs, light concrete, hollow concrete elements and brick, etc. Suspended ceilings must be used with these where high requirements are set ($D_{nT,A} \geq 51$ dB). This is not necessary for use within a single dwelling ($D_{nT,A} \geq 36$ dB). Flanking sound transmission does not exist, or does not exist to a serious degree, if the connecting walls have approximately the same mass (m in kg/m^2) as the floor, or if they have a greater mass, or if the walls are kept free from the floors.

Wooden floor structures

A number of examples of wooden floors are given in figure 12.13 as a guide.

Although adding mass to a floor structure is, in principle, correct from an acoustic perspective, it is often not possible in connection with the permitted load on the beams. In existing situations, it would appear that installing a relatively heavy, free-hanging suspended ceiling is the most attractive solution. If the joints in the floor are well sealed (hardboard sheets, edges sealed etc.) and if sufficient absorbent material is fitted in the cavity, then it may be possible to achieve values a few decibels higher than those mentioned here. Suspended ceilings are dealt with in greater detail later.
A wooden floor is also not attractive from the impact sound insulation perspective. Both aspects of sound insulation mean that a wooden floor cannot meet the requirements for a dwelling partitioning floor ($D_{nT,A} \geq 51$ dB).

A free-hanging suspended ceiling is, in fact, a requirement even for rooms within a dwelling.

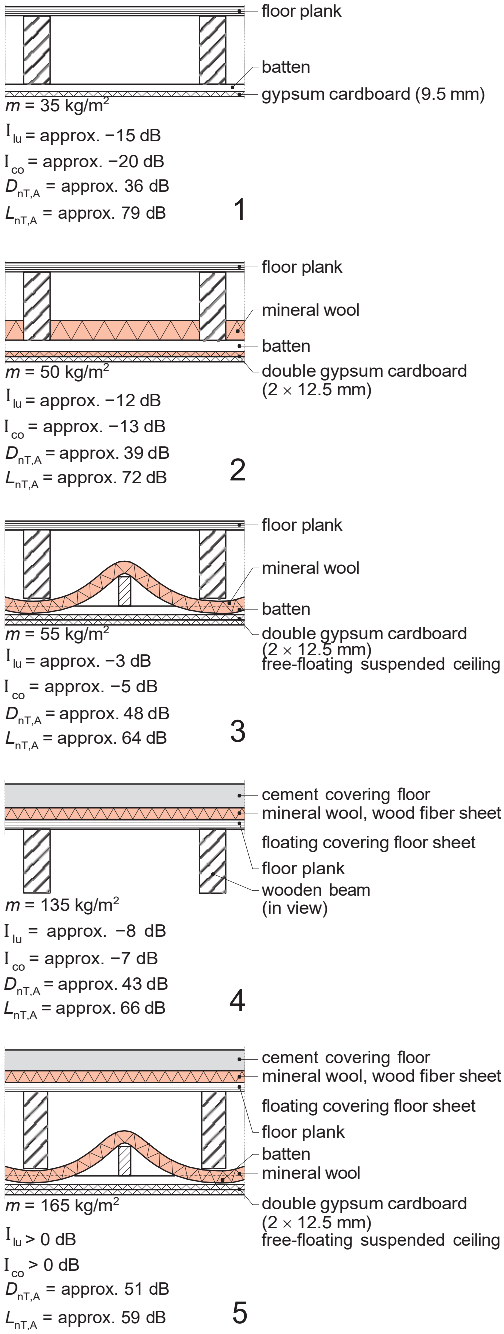


Figure 12.13 Guide to sound insulating properties of wooden floors. Naturally the sealing of the joints and gaps and any flanking sound transmission have a significant effect on the final result. As a reference the (older) I_{lu} and I_{co} values are also given.

Much lower values than those indicated here can be found in practice due to the gaps between the parts of the floor and in the connections between the floor and the walls. Another solution for improving the sound insulation of a wooden floor is the use of a stony, floating covering floor (cast floor). Floating covering floors are discussed later on.

Suspended ceilings

With the aforementioned suspended ceilings we can expect the following improvements for the various construction types (the figures apply in the absence of flanking sound transmission and other leaks):

- Porous boards (wood wool cement, mineral wool, etc.) can provide an improvement of 3-5 dB.
- System ceilings with somewhat thicker panels that fit closely into the suspension structure provide an improvement of 3-8 dB.
- Closed ceilings, suspended, not fitted to the floor or with an elastic fitting to the floor and with a sufficiently high mass ($m \geq 5$ to 10 kg/m^2) provide an improvement of 10 to 15 dB with a reasonable cavity height (≥ 0.2 m).

With a narrow cavity (plasterboard on a cavity of 30 to 50 mm) resonations can occur that actually decrease the sound insulation at some frequencies (see section 11.1).

Floating covering floors

A floating covering floor is kept fully free (using elastic materials) of all surrounding structures (see figure 12.14). Three different systems can be distinguished:

- wet systems with cement or calcium sulphate bonded (anhydrite) covering floors (most used)
- dry (light) systems made from wood or (fibre-reinforced) plasterboard with insulation on the underside
- the constructional floating floor comprising a profiled metal sheet with a covering floor of fine concrete.

The light (dry) systems generally provide less insulation ($L_{nT,A}$ = 52-54 dB) than the heavy

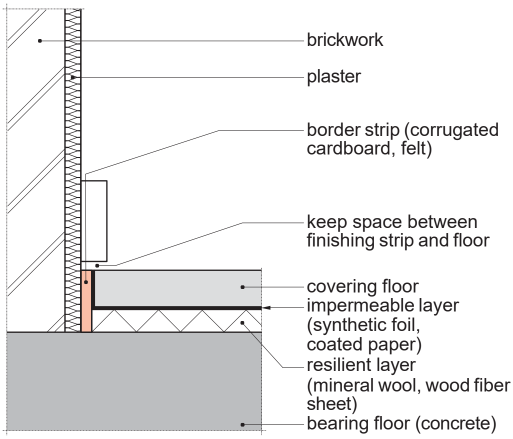


Figure 12.14 Floating covering floor

(wet) systems ($L_{nT,A}$ = 45-49 dB). The rigidity of the elastic layer is a very significant factor. The lighter the supporting floor, the softer the elastic layer has to be. In addition, the insulation must again be so rigid that it can accept the loads without overly large deformations occurring.

Sheets of the following are suitable as materials: mineral wool in a special, fairly dense pressing, elasticised polystyrene foam, specially intended for acoustic floating floors, foam, specially intended for floating covering floors, soft flake foam, cork, etc. Other organic materials can also be used.
The thickness of the insulation material must be 15 to 25 mm in a compressed state. Smaller thicknesses only have a marginal effect or no effect.

The waterproof layer is of great importance in preventing cement water penetrating the elastic layer. This could lead to the formation of sound bridges. Their influence is shown in the table in figure 12.15.

	improvement [dB]
floating covering floor	approx. 25
with one sound bridge	approx. 15
with ten sound bridges	5-10

Figure 12.15 The effect of sound bridges in floating covering floors

The conditions for a good floating covering floor are:

- The base must be smooth. If this is not the case the substructure must still be evened out.
- The floating covering floor, including floor finish, should be kept fully free of the rising structure (walls and facades). Sound bridges at the connection to a wall may influence the improvement in the frequency range from approximately 1000 Hz. For this reason a thinner (more rigid) elastic layer can suffice (corrugated cardboard, polystyrene foam sheet 2 to 3 mm thick, etc.). There will be a small decrease in the insulation over time because of aging of the elastic layer. In practice, however, this does not appear to amount to more than 3 to 4 dB, if, at least, good material is used and the elastic layer is not trodden ‘mushy’ during construction.
- The plinths must be kept free from the floating covering floor, including finishing.

12.4 Circulation noise

In addition to the flanking sound transmission that was described in section 11.1 there is also the so-called circulation noise. Here we must consider:

- sound via other rooms
- sound via connecting details
- sound via a suspended ceiling
- sound via coves, unit housings and suchlike
- sound via air ducts.

The latter two types of circulation travel via installations. These are dealt with in the following section.

Sound via other rooms

The sketch in figure 12.16 shows how sound can still reach the adjacent room via roundabout routes.

A good partitioning wall between two office rooms is of little use if there is any serious degree of circulation noise. Two doors that are close to each other in the corridor wall can undo good sound insulation if they are not provided with reasonable gap sealing (thresholds are often not used). The same applies for ventilation provisions that are close to each other or windows that can be opened in the facade (particularly in the direction of rotation drawn). Because of this, it is often possible to hold a conversation from one room to another without raising the voice.

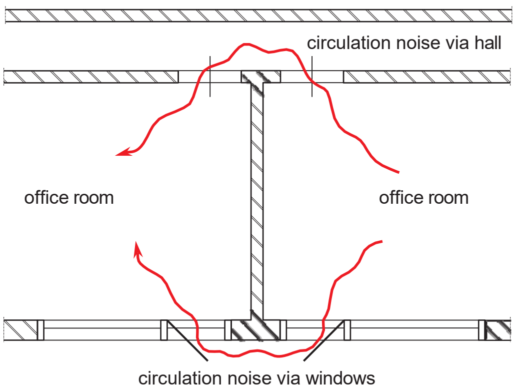


Figure 12.16 Circulation noise via windows and doors

Sound via connection details

Connection details often lead to all kinds of sound leaks. A common shortcoming is found in the connection between a common wall and a facade, such as shown in figure 12.17. Adding mineral wool and sound air sealing of the connection between the frame and the wall can significantly improve the sound insulation (see figure 12.17-2).

Another example is the connection of a light partitioning wall to a concrete beam, as in figure 12.18. A good connection between wall and ceiling is created using a strip of multi-ply. The sound that penetrates the very porous wood wool cement sheet will however, find an easy route to the other room via the remaining gap.

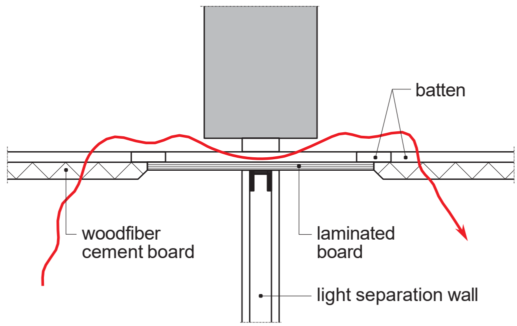


Figure 12.18 Circulation noise at the connection between a light partitioning wall and a ceiling and concrete beam

Sound via a suspended ceiling

Figure 12.19-1 shows how sound can enter the other room via the space above a suspended ceiling Sometimes it is desirable to connect movable partitioning walls to a suspended ceiling, in connection with flexibility within the building. In the first instance direct gaps (route A) must be avoided when doing this.

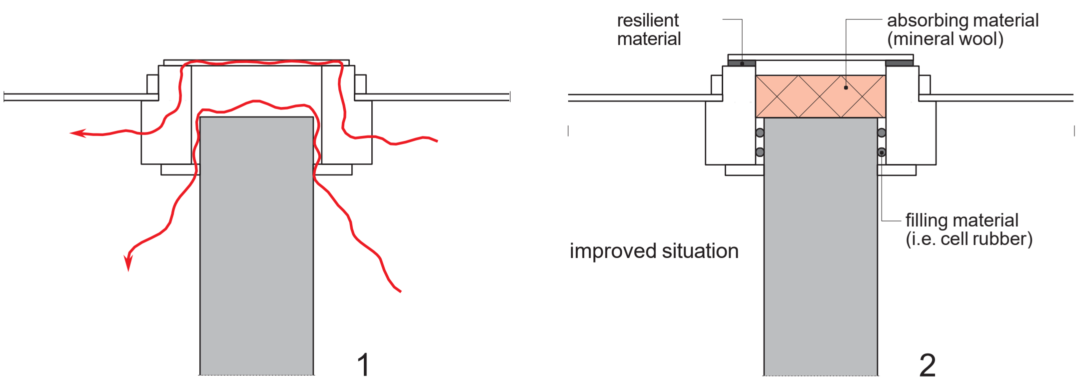


Figure 12.17 Sound leaks and flanking sound transmission at the joint of facade ends to the common wall

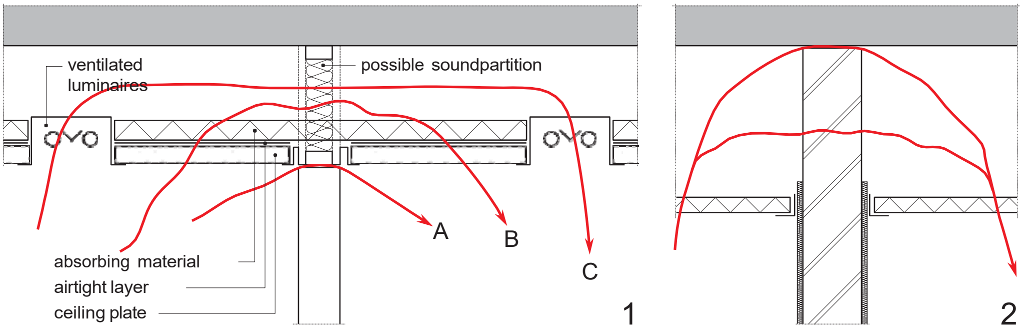


Figure 12.19 Circulation noise above a suspended ceiling

Keeping circulation noise via route B within limits is not so simple. Only very massive ceiling panels that have good connections to the supporting profiles will be able to achieve reasonable sound insulation. In doing so the cavity must not be higher than approximately 0.3 m. In addition, a large amount of absorbent material has to be fitted in the cavity. Furthermore, an airtight layer, which can be combined with a ceiling panel or with the absorbent material, is required. It is still, however, difficult to meet a requirement of $D_{nT,A} \geq 37$ dB as has been set for office rooms.
Sound via route C can be avoided by fitting light fittings with sound damping shades or by connecting them directly (via acoustic damping hoses) to an air duct.
The best method is still to continue the wall through to the bottom of the structural floor or by placing a sound baffle or a 'silencer' between the ceiling and the bottom of the structural ceiling These additions are certainly necessary if requirements of $D_{nT,A} \geq 41$ dB are set.

Problems can also occur with stony partitioning walls, as can be seen from figure 12.19-2. When the plaster layer above the ceiling is not continued through there is a significant risk of a porous wall. Often the backing up against the structural floor is not properly airtight. Significant sound leaks can then occur in a ceiling that is not soundproof (mineral fibre tiles or suchlike).

12.5 Construction of installations

Sound via coves, unit housings and suchlike
A familiar sound leak is the leak from one room to another via continuous coves, cable ducts, unit housings and suchlike (see figure 12.20). This type of though-channel must be sealed in every partitioning wall with a baffle. In the case of a cable channel it is sometimes possible to fill a piece with mineral wool along a length of approximately 0.5 m.

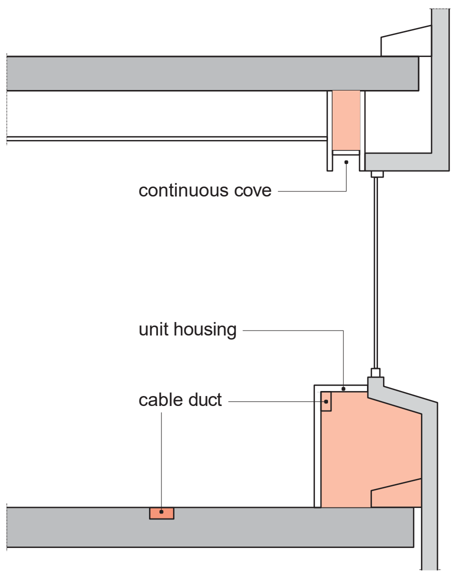


Figure 12.20 Circulation sound via through-coves, unit housings and suchlike

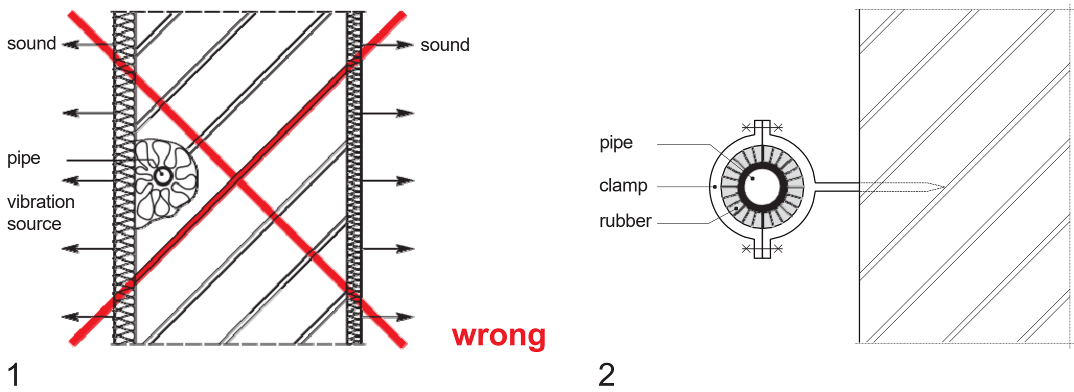


Figure 12.21 Transmission of sound by a pipe fitted into a wall (1) and a pipe fitted to a wall using a proper acoustic fitting (2)

Sound via air ducts

When a room is connected to an air duct sound transmission to the adjacent room can occur via this duct. Often the grids have to be connected to the duct using acoustically dampened hoses or sound absorbers have to be included in the system.

Pipes and sanitary fittings

Water carrying pipes and sanitary fittings must be connected to the walls and floor in such a way that the noise nuisance from vibrations transmitted directly to the structure is avoided. 'Cutting' pipes into the walls of sound sensitive rooms is therefore not a good solution (see figure 12.21-1). It is best to use acoustically dampened fixing materials for fixing pipes, as in figure 12.21-2. Nothing should be fitted to the walls of sound sensitive rooms (such as a toilet next to an office room). In addition, it is important to pay attention to the sound production when selecting fittings. There are many 'low-noise' fittings.

Feeding-through pipes

Pipe feed-throughs through floors and walls often cause sound leaks (airborne sound) and the transmission of impact sound. The pipe must not be in contact with the floor and leaks must not occur (see figure 12.22-1).

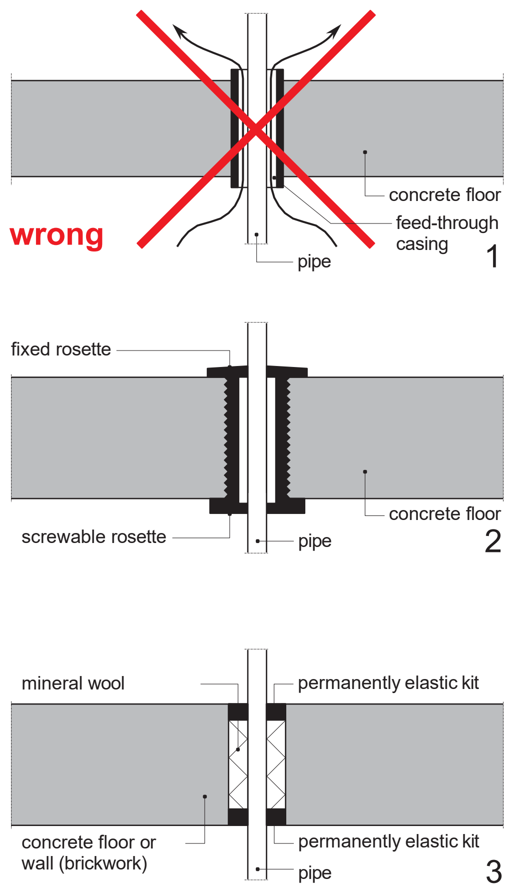


Figure 12.22 One bad and two good pipe feed-throughs

Naturally loose rosettes hardly form a seal at all. The opening between the pipe and the pipe sleeve can be sealed by including cast in situ feed-through casings to which a covering rosette can be screwed (see figure 12.22-2). It is also possible to ensure a permanent seal using sealant and mineral wool (see figure 12.22-3).
Additionally, a seal by injecting plastic foam is a good option (see figure 12.23). Other solutions are also possible, all kinds of special feed-through casings can be obtained from the trade.

Figure 12.23 Pipe feed-throughs can often cause sound leaks. In this case the feed-throughs have been sealed using (injectable) plastic foam.

Machines

Most machines are fitted with appropriate vibration dampers in the factory to prevent impact sound. Details about the sound production must be requested in order to determine the airborne sound insulation requirements that have to be set for the surrounding walls of the rooms in which these machines are set up.

The examples quoted above are certainly not exhaustive. We have only tried to show that good sound insulation requires continuous attention to detail both in the design and in the implementation.