IBPM Acoustics

Reader for the Course 7S3X0

Building Acoustics Group

THE BUILT ENVIRONMENT AND SOUND 1

Two aspects can be distinguished concerning sound in buildings:
1. noise annoyance;
2. the acoustical quality of a room.

Buildings should be built such that noise annoyance is prevented: levels from traffic noise should be low, conversations of neighbours should not be heard, toilet sounds should be avoided in the living room and the central heating system should not lead to sleep disturbance. Conversely, noise produced in buildings should not disturb the outdoor surroundings (for example a disco).

The acoustic quality of an indoor space is dependent on the geometry (the shape and the dimensions of the space) and the finishing of the partitions. Smaller spaces such as can be found in dwellings usually cause little acoustical problems, though a fully tiled bathroom can soon sound unpleasant "hollow". However, larger spaces deserve more care regarding the acoustic quality, in particular when it concerns areas that need to be suitable for speach and/or music.

In order to take into account the above aspects in the design of buildings, knowledge of sound as a physical phenomenon is needed. This chapter discusses the sound intensity and frequency and how to compute them.

1.1 What is sound?

Walking on gravel, flushing the toilet, playing the piano, closing a door, all of this creates sound. What produces sound is in motion. This movement causes waves in the air: the air is vibrating. These waves can be characterized by wave speed (pitch/frequency) and vibration level (intensity). The first term is usually expressed by the number of vibrations per second (with corresponding unit hertz, symbol: Hz), the second can be expressed in different ways. The commonly used unity is decibel (symbol: dB). The definition of decibel is discussed later.

The shoes and the gravel, the water and the toilet bowl, the hammer and the string, the door and the door frame, these are all mechanical systems that produce sound and are also called sound sources. They excite air particles and cause them to vibrate. These air particles on their turn put other air particles into motion et cetera. A well-known example is one where a sound source is placed under a cloche from which the air is sucked out: the more air is sucked out, the weaker the sound becomes until it turns silent in vacuum. A medium is needed for propagation of sound waves. The medium is not limited to air. Sound can propagate in gases, liquids and solids.

As the phenomenon of light has been defined by reference to the human eye, sound has been defined based of the human ear. Waves caused by mechanical vibration, with a frequency within the range of human hearing, i.e. between 20 Hz and 20,000 Hz, is called sound. Inaudible low-frequency vibrations are called infrasound and inaudible vibrations at high frequency are called ultrasound. Thus like invisible light, there is inaudible sound. According to this definition, however, inaudible sound (as well as invisible light) does not exist.

1.2 Propagation of sound in air

Air particles excited by a sound source vibrate. That is to say that they oscillate around a state of equilibrium. The direction in which they move is the same as or opposite to the direction in which sound propagates, which is known as a longitudinal wave (This is in contrast to a transverse wave in which the direction of movement of the particles is perpendicular to the direction of propagation). The speed at which the vibration is passed in the air is approximately 344 m/s for a temperature of 293 K. The propagation velocity sound is expressed as c, which is different from the velocity of the air particles, v.
The propagation speed depends on the medium. In water, the velocity of sound is almost 5 times higher as in air.

1.3 Sound pressure

The strength of sound is described by the pressure amplitude changes as caused by a sound source. Sound waves are positive and negative pressure oscillations around an average pressure, which is the static atmospheric pressure of about 10^5 Pa (pascal = N/m^2). These time-varying pressure fluctuations are called the sound pressure (symbol $p(t)$, unit Pa). The p stands for pressure and (t) for the time.

The experienced 'strength' of the sound (loudness) is not determined by the maximum sound pressure neither by the time averaged sound pressure (which is 0). It is dependend on the effective sound pressure (p_{eff}):

$$p_{\text{eff}} = \sqrt{\overline{p^2(t)}} \tag{1.1}$$

Where:

p_{eff}	=	effective sound pressure	[Pa]
p	=	pressure difference in comparison to atmospheric pressure	[Pa]
(t)	=	corresponds to the fact that we use the averaged pressure for a certain period of time	

Expressed in words, the effective sound pressure is the root mean square of the sound pressure over a period of time (and always has a positive value). This is called the RMS value (Root Mean Square).

The effective sound pressure can range from $2x10^{-5}$ Pa (hearing threshold) to 200 Pa (pain threshold). This holds for a frequency of 1000 Hz (see also chapter 2).

1.4 Sound pressure level

The effective sound pressure is not commonly used to express the strength of sound. The reason is that the ratio between the effective sound pressures for the threshold of pain to the hearing threshold is 10^7. A more manageable quantity is obtained by using the sound pressure level (L_p):

$$L_{\mathrm{p}} = 10 \log_{10} \left(\frac{p_{\mathrm{eff}}^2}{p_0^2} \right) \tag{1.2}$$

Where:

L_p	=	sound pressure level	[dB]
p_0	=	reference sound pressure ($2x10^{-5}$ Pa)	[Pa]

The sound pressure level is thus the logarithm (with as a base value 10) of the ratio between the square of the effective sound pressure and the square of a reference pressure. For the latter we take, in general, the value of $2x10^{-5}$ Pa (p_0), the threshold of hearing.

1.5 The decibel

L_p is actually a dimensionless number, but it is generally accepted to use the unit decibels (dB), as a tribute to Alexander Graham Bell, the inventor of the telephone. The term 'deci' refers to the decimal factor of 10 with which the outcome of the logarithm is multiplied.
The decibel unit has a clear range from 0 dB (threshold of hearing) to 140 dB (pain threshold), see figure 1.1.

This clarity comes with a price, calculating with decibels needs some time to get used to.
One decibel is approximately the smallest difference between two sound pressure levels just perceptible for the human ear (under ideal conditions). Differences of 2 to 3 dB are clearer to observe. For differences of 5 dB, we speak of a 'class' difference in strength. Therefore, in practice, it makes little sense to write L_p in much decimals. We restrict ourselves to one decimal.

1.6 Sound power

With the sound power, the strength of sound is described as a measure of the energy flow that represents the sound. Sound power is an energy flow: it can be expressed as an amount of energy per unit of time. The sound transmitted by a source, such as a speaker, may thus be expressed in terms of watt (W = J/s). We call this the sound power of a noise source. The symbol of sound power is (also) W. It has a clear analogy with for example the power output of a lamp and the capacity of a radiator. Both of these are also sources that emit energy and although the type of the respective energy flow is different, in all cases the power of the source can be expressed in watt (W).
The range in the occurring sound power values can become very large. This is why we typically use another variable: the sound power level.

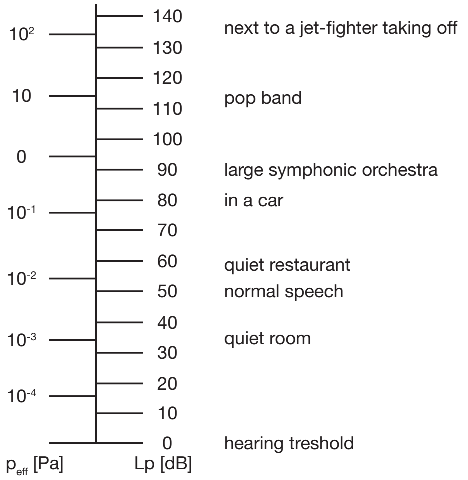


Figure 1.1: Several examples of sound pressure levels in daily practice.

Figure 1.2: Sound pressure level meter

1.7 Sound power level

Similar to the sound pressure level, the sound power level can be defined as follows:

$$L_W = 10 \log_{10} \left(\frac{W}{W_0} \right) \tag{1.3}$$

Where:

L_W	=	sound power level	[dB]
W	=	sound power of the source	[W]
W_0	=	reference sound power (10^{-12} W)	[W]

Again, this is actually a dimensionless quantity that we express in dB. Numerical example 1.1 clarifies this.

1.8 Sound intensity

As we express illuminance in lumen/m² and the heat flux density in W/m² we express the sound intensity in W/m². The sound intensity is the amount of sound power on a (imaginary) surface of 1 m². This plane has a certain place, but also a certain direction. The sound intensity is dependent on location and direction.

If the intensity of the sound reaching our ears is 10^{-12} W/m² is we can just hear it (hearing threshold). The pain threshold is reached at an intensity of approximately 100 W/m².

Here again there is a very large range and for that reason we use a replacement variable: the sound intensity level.

1.9 Sound intensity level

The sound intensity level can be defined as:

$$L_I = 10 \log_{10} \left(\frac{I}{I_0} \right) \tag{1.4}$$

Numerical example 1.1

Given

A loudspeaker source with a power of 0.3 W (comparable with the power of a backlight of a bicycle).

Asked

The sound power level of the source.

Calculation

$$L_W = 10 \log_{10} \left(\frac{W}{W_0} \right) = 10 \log_{10} \left(\frac{0.3}{10^{-12}} \right) = 114.8 \text{ dB}$$

Explanation

According to theory, a loudspeaker box with a power of 200 W should correspond to a power level of more than 140 dB. In practice this might result in sound pressure levels equal to that of a fighter jet taking off at close distance. However, due to the low efficiency of the loudspeaker boxes (a few percents of the stated power) this will turn out lower in practice. The largest part of the electrical energy provided to the speaker is converted into heat. With this, it is clear that not only the power of a loudspeaker should be stated, but also the efficiency to be able to make an estimation of the produced sound eventually.

Where:

L_I	=	sound intensity level	[dB]
I	=	sound intensity	[W/m^2]
I_0	=	reference sound intensity (10^{-12} W)	[W/m^2]

Also the sound intensity level is dimensionless, but will be expressed in dB.

1.10 Calculating with decibels

In this section we pay attention to performing calculations with decibels. We will do this by using numerical examples with relevance to the sound pressure (levels).

Assume we have two sound sources, than:

$$p_{\mathrm{eff}1+2}^2 = p_{\mathrm{eff}1}^2 + p_{\mathrm{eff}2}^2 \tag{1.5}$$

Calculating the total sound pressure level is more complicated. With the aid of equation 1.2 we can rewrite equation 1.5 in the form of a logarithmic sum.

$$L_{\mathrm{p}1+2} = 10\log_{10}\left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{p2}}{10}}\right) \tag{1.6}$$

The summation rules 1.5 and 1.6 can be extended when calculating with more sources. Equation 1.6 will be clarified in numerical example 1.2.

From the general summation rule of Equation 1.6, several practical guidelines can be determined:

Guideline 1

Two sound sources emitting the same sound pressure level results in a total sound pressure level 3 dB higher than the sound pressure level of one of the sources individually:

Numerical example 1.2

Given

Machine A produces a sound pressure level of 83 dB.
Machine B produces a sound pressure level of 84 dB.
Machine C produces a sound pressure level of 85 dB.

Asked

Calculate the total sound pressure level as emitted by machine A, B and C together.

Calculation

$$L_{\mathrm{p,tot}} = 10\log_{10}\left(10^{\frac{L_{\mathrm{p},1}}{10}} + 10^{\frac{L_{\mathrm{p},2}}{10}} + 10^{\frac{L_{\mathrm{p},3}}{10}}\right) = 10\log_{10}\left(10^{\frac{83}{10}} + 10^{\frac{84}{10}} + 10^{\frac{85}{10}}\right) = 88.8\ \mathrm{dB}$$

$$L_{\mathrm{p1+2}} = L_{\mathrm{p1}}\,(\mathrm{or}\ L_{\mathrm{p2}}) + 3 \tag{1.7}$$

The sounds must be independent of each other, meaning $L_{p1} = L_{p2}$ but $p_1(t)$ is not equal to $p_2(t)$, so an equal effective sound pressure level, but uneven pressure distribution in time. We can also conclude that summation of two different sound pressure levels can never yield in a sound pressure level more than 3 dB higher than the highest.

Guideline 2

Three equally strong sounds together have a sound pressure level (about) 5 dB higher than the individual levels, for ten equally strong noises that is 10 dB, and for 100 that is 20 dB. More generally:

$$L_{\mathrm{p1+2+\ldots n}} = L_{\mathrm{p1}} + 10\log_{10}(\mathrm{n}) \tag{1.8}$$

Numerical example 1.3 shows a summation by 8 equally strong sound sources.

Guideline 3

When two sound pressure levels mutually differ 10 dB or more, the overall sound pressure level is (almost) equal to the highest sound pressure level. Summing up the sound pressure levels is than not needed.

1.4 Pure tones

As we have seen, the intensity with which the air particles move in sound waves determines the intensity of the sound. We can express the intensity in the particle velocity (v), but also in the sound pressure (p). We prefer the latter.

The manner in which the sound pressure varies over time, determines the character of the sound. The sound pressure can develop frequently in time, but also completely irregular (chaotic).

Numerical example 1.3

Given

Eight identical computers in a computer room each produce a sound pressure level of 35 dB, measured in the middle of the room.

Asked

The total sound pressure level caused by the computers, collectively.

Calculation 1

$$L_{\mathrm{p,tot}} = 10\log_{10}\left(8 \cdot 10^{\frac{35}{10}}\right) = 35 + 10\log_{10}(n) = 35 + 9 = 44.0\ \mathrm{dB}$$

Calculation 2

Computer	1		2		3		4		5		6		7		8
L_p [dB]	35		35		35		35		35		35		35		35
		38				38				38				38	
				41								41			
								44							

Numerical example 1.4

Given

Machine A produces a sound pressure level of 80 dB.
Machine B produces a sound pressure level of 80 dB.
Machine C produces a sound pressure level of 85 dB.
Machine D produces a sound pressure level of 76 dB.

Asked

Calculate the total sound pressure level as emitted by machine A, B, C and D together.

Calculation

$$A + B = 80 \text{ dB} + 80 \text{ dB} \approx 83 \text{ dB}$$

$$A + B + C = 10\log_{10}\left(10^{\frac{83}{10}} + 10^{\frac{85}{10}}\right) = 87.1 \text{ dB}$$

$$A + B + C + D = 87.1 \text{ dB} + 76 \text{ dB} \approx 87.1 \text{ dB}$$

The sound pressure level of machine D is more than 10 dB below than the level of machines A + B + C. The sound pressure level of machine D may therefore be neglected.
The actual sound pressure level (without using rules of thumb used) can be calculated as follows.

$$L_{\text{p,tot}} = 10\log_{10}\left(10^{\frac{83}{10}} + 10^{\frac{83}{10}} + 10^{\frac{85}{10}} + 10^{\frac{76}{10}}\right) = 87.5 \text{ dB}$$

Explanation

The difference between the global (fast) calculation and the exact calculation is 0.4 dB.

The latter is the case with by far the most sound. Only in exceptional cases we hear noise whose sound pressure runs regularly. We speak of a harmonic oscillation: a pure tone. A tuning fork and a flute produce such a pure tone.
Despite the fact that they are so rare, here we are still interested in that pure tones because they can easily be described mathematically: their service can prove the theoretical underpinnings of sound. We can describe the sound pressure of a pure tone with the following equation:

$$p(t) = \hat{p}\sin\left(\frac{2\pi t}{T}\right) \tag{1.9}$$

Where:

p(t)	=	time-dependent sound pressure	[Pa]
$\hat{p}$	=	maximum ocurring sound pressure	[Pa]
t	=	time	[s]
T	=	repetition period	[s]

T is called the repetition period of the harmonic oscillation. It is expressed in seconds, since after *T* seconds *p(t)* has the same value again. The reciprocal value *1/T* equals the number of vibrations per second. This is called the frequency *f* expressed in Hertz (Hz) or (s^{-1}):

$$f = \frac{1}{T} \tag{1.10}$$

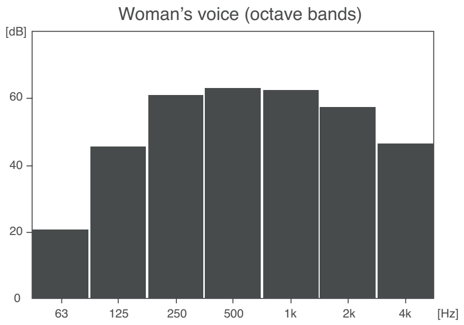
At a point in time, equal to the period *T*, sound has travelled a distance of *cT*. This distance is called the wavelength λ (m). For a transverse wave it can be stated that, in places located at a distance λ from each other, in the direction of propagation, the air particles are in the same phase (vibration state). The wavelength λ is therefore equal to:

$$\lambda = cT \tag{1.11}$$

Using equation 1.10, this can be written as:

$$\lambda = \frac{c}{f} \tag{1.12}$$

As mentioned, most sounds we observe have a chaotic character: for each frequency a more or less noise is produced. With measurement we can investigate how the sound energy is divided across the audible frequency range (20 - 20,000 Hz). We do this by dividing this frequency range into frequency bands. By measuring the sound pressure level in each frequency band we can form an insight on the spectral composition of the sound recording. We shall see later that this information is necessary to be able to form conclusions on the degree of noise nuisance and which measures can be taken for noise abatement.



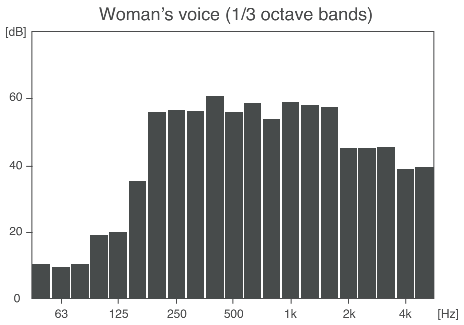


Figure 1.7: Octave and 1/3-octave band analysis of a woman's voice.

1.5 Frequency analysis

In acoustics, the audible frequency range is divided onto two parts.

- The octave bands. This is a division of the audible frequency range in 11 frequency bands;
- The 1/3 octave bands. This is a division into 33 frequency bands.

We speak of a sound frequency analysis when we measure the sound pressure level in each frequency band. We can then speak of an octave band analysis and a third octave band analysis. The graphical representation of such an analysis is called an octave band spectrum and a third octave band spectrum. Figure 1.7 gives an example of the results of an octave and third octave band analysis of a woman's voice.
With a one-third octave band analysis, we unravel the sound slightly finer than for an octave band analysis. In building acoustics an octave band analysis usually gives a sufficiently accurate insight of the spectrum. The bands are identified by their normalized centre frequencies, f_c.
The sum of the sound pressure levels of all bands together, we call the overall sound pressure level, often referred to as "linear" or "overall" (also see numerical example 1.5).

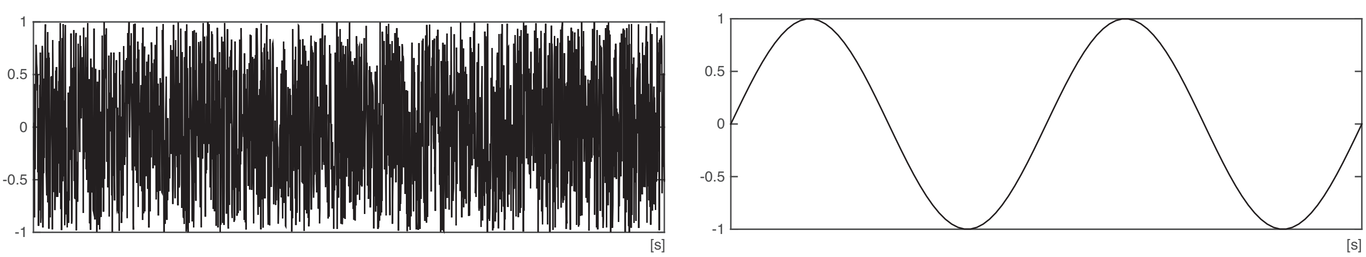


Figure 1.6: Graphical representation p(t) of a noisy signal (left) and a pure tone (sine, right).

The idealized reality

The world is a lot more predictable as we idealize him. Pure tones, diffuse sound fields, plane waves, spherical sources, line sources, et cetera, in reality they come rarely in these pure forms. Yet, they are often the starting point for calculations because they are so easy to calculate. This does not form a problem as long as we approach reality only with sufficient precision. This will require sufficient information so that we do not model it in an impermissible manner to an ideal situation.

Numerical example 1.5

Given

A sound source with the following measured 1/3 octave bands:

	1/3 octave band, f_c [Hz]					
	100	125	160	200	250	315
Sound pressure level, L_p [dB]	87	91	85	80	75	62

Asked

1. The sound pressure level in the octave bands of 125 and 250 Hz;
2. The overall sound pressure level.

Calculation

1. The 125 Hz octave band consists of the 100 Hz, 125 Hz and 160 Hz 1/3 octave bands. Energetic summation of the sound pressure levels of these third octave bands results in the sound pressure level of the octave band.

   $$L_{\mathrm{p,125Hz,oct}} = 10\log_{10}\left(10^{\frac{87}{10}} + 10^{\frac{91}{10}} + 10^{\frac{85}{10}}\right) = 93.2\ \mathrm{dB}$$

   The 250 Hz octave band consists of the 200 Hz, 250 Hz and 315 Hz 1/3 octave bands.

   $$L_{\mathrm{p,250Hz,oct}} = 10\log_{10}\left(10^{\frac{80}{10}} + 10^{\frac{75}{10}} + 10^{\frac{62}{10}}\right) = 81.2\ \mathrm{dB}$$

2. The linear or overall sound pressure level is the total sound pressure level. In other words, the energetic summation of all unweighted octaveband levels or all unweighted 1/3 octaveband levels.

   $$L_{\mathrm{p,linear}} = 10\log_{10}\left(10^{9.32} + 10^{8.12}\right) = 93.5\ \mathrm{dB}$$

   or

   $$L_{\mathrm{p,linear}} = 10\log_{10}\left(10^{\frac{87}{10}} + 10^{\frac{91}{10}} + 10^{\frac{85}{10}} + 10^{\frac{80}{10}} + 10^{\frac{75}{10}} + 10^{\frac{62}{10}}\right) = 93.4\ \mathrm{dB}$$

Table 1.3: Normalized frequency bands and their centre frequencies in Hz

Octave band f_c	Octave band limits f_1 - f_2	1/3 octave band f_c	1/3 Octave band limits f_1 - f_2
		50	44.7 - 56.2
63	44-88	63	56.2 - 70.7
		80	70.7 - 89.1
		100	89.1 - 112
125	88-177	125	112 - 141
		160	141 - 178
		200	178 - 224
250	177-355	250	224 - 282
		315	282 - 355
		400	355 - 447
500	355-710	500	447 - 562
		630	562 - 708
		800	708 - 891
1000	710-1420	1000	891 - 1122
		1250	1122 - 1413
		1600	1413 - 1778
2000	1420-2840	2000	1778 - 2239
		2500	2239 - 2818
		3150	2818 - 3548
4000	2840-5680	4000	3548 - 4467
		5000	4467 - 5623
		6300	5623 - 7079
8000	5680-11360	8000	7079 - 8913
		10000	8913 - 11220

Questions

1. What is sound?
2. What is the difference between a longitudinal and transverse wave?
3. What is the speed with which sound propagates through air?
4. What is the difference between sound pressure and sound pressure level?
5. What was the reason to introduce the term sound pressure level?
6. Explain what theoretically, under terrestrial conditions, the lowest and highest possible sound pressure levels are.
7. What are the lowest and highest hearable sound pressure levels, for the averaged human being?
8. What is meant with the sound power of a source?
9. What is meant with sound intensity?
10. What is the total sound pressure level from two independent sound sources, each emitting a sound pressure level of 50 dB?
11. What is the total sound pressure level from two independent sound sources, when one source emits a sound pressure level of 80 dB and the other 95 dB?
12. What is the difference between a pure tone and noise?

MANKIND AND SOUND

2

As we have seen, light and sound are two very different phenomena. To perceive them, our bodies also have two very different organs. Yet there are physical similarities: both phenomena are wave phenomena. That is, they can be characterized by its frequency (number of vibrations per second, Hz) and wavelength (λ, in m). If one is known, the other is also known ($\lambda = c \ / \ f$). If the wavelength or frequency of light changes, the colour changes, and as the wavelength or frequency of a sound wave changes, the pitch changes.
Light is a part of a very broad spectrum of electromagnetic waves and sound is part of a very broad spectrum of mechanical waves in air (we limit ourselves to sound in air). For light the EM-waves have a length between 340 nm and 780 nm. Sound waves have a length between 17 m and 17 mm or, rather, a frequency between 20 and 20,000 Hz. For sound, we use the frequency rather than the wavelength.
For both light and sound, the strength of a predetermined value must be exceeded in order to be able to be registered by our senses. Just as the eye is not equally sensitive to wavelengths of the whole range from 340 nm to 780 nm, the ear is not equally sensitive to all frequencies of the entire range of 20 to 20,000 Hz.

2.1 The human ear

Our hearing sense can be regarded as a barometer coupled with a harp. The barometer comes into force when it is hit by sound waves which after all cause pressure differences. The harp ensures that we can make a distinction in the frequency of the sound waves or, in other words, in the pitch. The short strings of the harp are vibrated by sound with high frequency and long strings of noise by a low frequency.
More in detail, the human hearing sense consists of three parts:
1. The outer ear;
2. The middle ear;
3. The inner ear.

1. The outer ear and ear canal forms the external ear. The auricle helps to determine the direction of the sound. The ear canal acts as a frequency-selective pipe: it enhances frequencies between 2000 and 4000 Hz. The sound in which a mother would communicate with her baby is said to lie in this range: a beautiful,

romantic assumption. The eardrum is located between the external ear and the middle ear (the barometer).

2. Behind the eardrum are the ossicles: hammer, anvil and stapes. They strengthening the vibrations of the eardrum on transport it to the so-called oval window. This is located between the middle ear and the inner ear.
3. The inner ear contains the fluid-filled cochlea, where the vibrations are converted into signals in the auditory nerve, using cilia (harp).

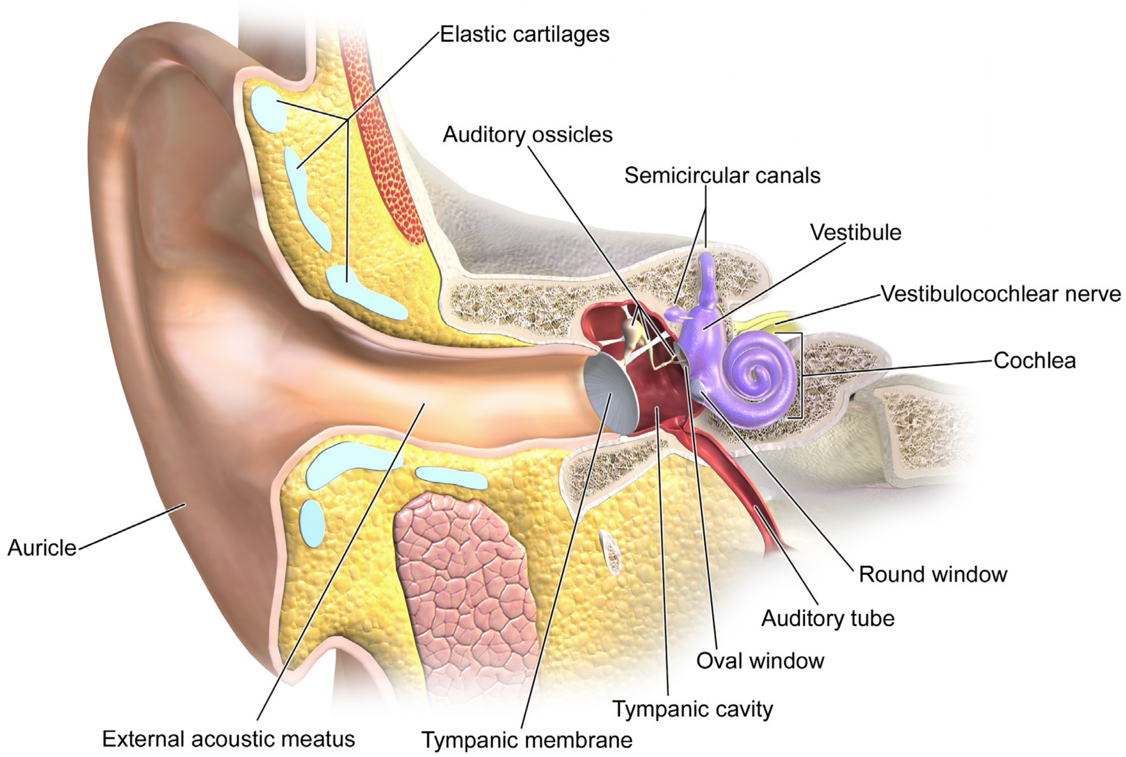


Figure 2.1: The human ear. (Blausen.com staff. "Blausen gallery 2014". Wikiversity Journal of Medicine.)

2.2 Isophones

Mankind is able to unravel complex sounds into separate frequencies. Not all frequencies are perceived equally strong by the human ear, even though if their sound pressure is equal. For example, when we experience the same sound pressure level, a tone of 100 Hz is less loud than a tone of 1000 Hz. To let the tone of 100 Hz sound as loud as that of 1000 Hz, the sound pressure level of the tone of 100 Hz should be increased. This increase, expressed in dB, indicates the difference in hearing sensitivity between 100 and 1000 Hz.

This characteristic of the hearing can be captured in so-called isophones (iso means same, phone means audio). Figure 2.2 shows a number isophones. We see that compared to 1000 Hz, the human ear is less sensitive as the frequency is lower, the maximum sensitivity lays around 3000 Hz, and the sensitivity decreases at higher frevquencies.

An isophone is a line of which the loudness level (expressed in phones) is constant. That is to say, at any point of the line, any combination of frequency and corresponding sound pressure level sounds equally loud.

2.3 dB(A)

Although the sensitivity of hearing is frequency dependent, it provides an overall assessment of the loudness of a sound (which is composed of all sorts of frequencies).

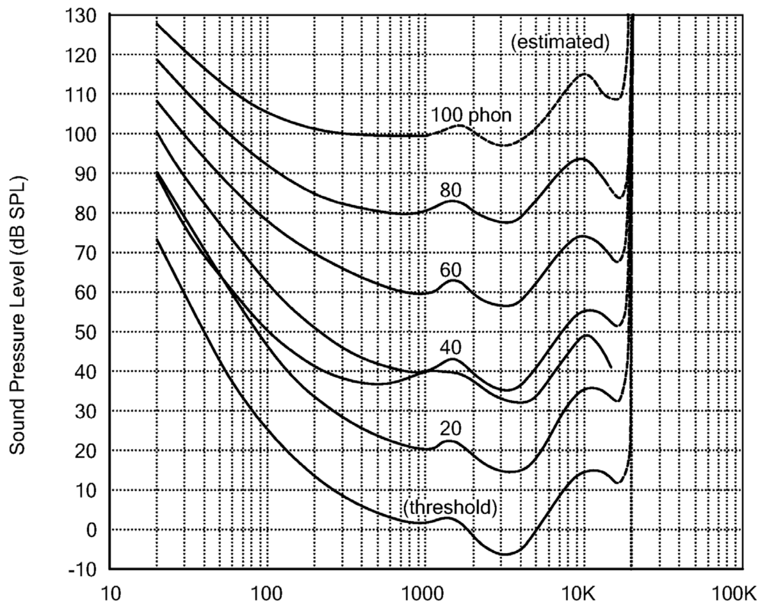


Figure 2.2: Isophones, curves of equal loudness.

The sound pressure level should be correctd for the hearing sensitivity, per frequency. This corrected sound pressure levels are then summed. The result is a "weighted" sound pressure level: weighted to the sensitivity of the human ear. Distinct from the "physical" sound pressure level that we express in dB, we express the weighted sound pressure level in dB(A):

$$L_{\mathrm{A}} = 10\log_{10}\left(\sum_{\mathrm{i}} 10^{\frac{L_{\mathrm{p,i}}+A_{\mathrm{i}}}{10}}\right) \tag{2.1}$$

Table 2.1: The normalized A-corrections

f_c [Hz]	A_i [dB]
63	-26.2
125	-16.1
250	-8.6
500	-3.2
1000	0
2000	1
4000	1.1
8000	-1

The corrections A_i which are applied per frequency band, known as the A-corrections are listed in table 2.1. From this table it can be concluded that the ear is least sensitive to the lowest octave bands and the most sensitive to the 4 kHz octave band. Numerical example 2.1 shows a calculation of the sound pressure level in dB(A).

2.4 Fluctuating sounds

The strength and frequency of many sounds are constantly changing over time. This change is also called fluctuation. We experience a noise as fairly constant when the sound pressure level does not vary more than 5 or 6 dB(A) over time. If there is such a variation in a measurement, we can read the average value as a measure for the strength of the sound.

Many sounds, such as road and rail traffic, music, et cetera, fluctuate much stronger over time. Not only the sound level but also the frequencies, or, in other words, the spectral composition varies over time. How can we measure the loudness for these cases? We cannot be satisfied with an estimation of the average value. For a more objective measure we need a statistical approach. On the basis of the statistical distribution of sound pressure levels over a period of time, we can determine which levels are exceeded for a certain percentage of the time. For example, we define L_1, L_5, L_{10}, L_{50} and L_{95} as the sound pressure levels that respectively exceed 1, 5, 10, 50 and 95 % of the time. L_{10} means that the sound pressure level is exceeded for 10 % of the time. L_1 or L_5 is used for example for plumbing noise and L_{95} for background noise.

2.5 The equivalent sound level in dB(A)

In the Netherlands, it is common to look at the energy content of a fluctuating sound and use this as a measure of discomfort. This results in the fact that the sound pressure level measured over a longer period of time (minutes, hours, day) is 'energetically averaged'. The result is called the equivalent sound pressure level, with symbol L_{eq}. Also, in the determination of L_{eq}, we can apply the A-weighting so that we obtain the equivalent sound pressure level in dB(A). The symbol used for this is L_{Aeq}: the A-weighted equivalent sound pressure level. This is a commonly used measure to establish criteria for acceptable sound levels from fluctuating sounds. Numerical example 2.2 discusses a calculation on the equivalent sound level.

Numerical example 2.1

Given

A sound source with the following measured octave bands:

	Octave band, f_c [Hz]					
	125	250	500	1000	2000	4000
Sound pressure level, L_p [dB]	87	91	85	80	75	62

Asked

The sound level in dB(A) caused by the source.

Calculation

	Octave band, f_c [Hz]					
	125	250	500	1000	2000	4000
Sound pressure level, L_p [dB]	87	91	85	80	75	62
A-correction [dB]	-16.1	-8.6	-3.2	0	1	1.1
L_p A-weighted [dB]	70.9	82.4	81.8	80	76	63.1

$$L_A = 10\log_{10}\left(10^{\frac{L_{p1}+A_1}{10}} + 10^{\frac{L_{p2}+A_2}{10}} + 10^{\frac{L_{p3}+A_3}{10}} + ...\right)$$

$$L_A = 10\log_{10}\left(10^{\frac{70.9}{10}} + 10^{\frac{82.4}{10}} + 10^{\frac{81.8}{10}} + 10^{\frac{80.0}{10}} + 10^{\frac{76.0}{10}} + 10^{\frac{63.1}{10}}\right) = 86.8 \text{ dB(A)}$$

Explanation:

The A-weighted sound pressure levels of 125 Hz and 4000 Hz are more than 10 dB below the other values. This means that we could neglect these values in this calculation. Energetic summation of the rest of the values results in a noise level from 86.7 dB(A). This means a difference of 0.1 dB(A) with the exact calculation.

Numerical example 2.2

Given

A machine in operation, produces a stationary noise level of 60 dB(A) and every half an hour it produces a level of 80 dB(A) for a period of 10 minutes.

Asked

The equivalent sound level, L_{Aeq}.

Calculation

$$L_{\mathrm{Aeq}} = 10\log_{10}\left(\frac{1}{T}\sum_{\mathrm{i}=1}^{n} t_{\mathrm{i}} \cdot 10^{\frac{L_{p,i}}{10}}\right)$$

$$L_{\mathrm{Aeq}} = 10\log_{10}\left(\frac{1}{30}\left(20 \cdot 10^{\frac{60}{10}} + 10 \cdot 10^{\frac{80}{10}}\right)\right) = 75.3\ \mathrm{dB(A)}$$

2.6 Sound criteria

People are sensitive to background noise. To what extent depends partly on the activity they perform. If we are engaged in a complex design problem we soon experience loud music as disturbing. If the design is ready and we are working on the finishing, then music is a welcome distraction. For each activity, we can see how big the nuisance of a given dose of disturbing noise is: the dose-effect-relationship. Based on this research, we can establish criteria for permissible noise interference. We should remember that not every man is equally sensitive to disturbing noise. Research indicates that 20 to 30 % of the people is very sensitive, 40 and 50 % somewhat sensitive and about 30 % is sound insensitive.
Criteria should obviously be chosen such that the majority of people are not hindered. They are usually expressed in L_{Aeq}, the equivalent sound level in dB(A). This value must not be exceeded.

Questions

1. Between which frequency-boundaries does, for mankind, the hearable frequency range lay?
2. What is the relation between the frequency (f, [Hz]) and the wave length (λ, [m])?
3. What is a octave band and a 1/3 octave band?
4. To which octave band, mankind is most sensitive to?
5. What is the difference between sound pressure level and sound level?
6. What is meant with the equivalent sound (pressure) level?

SOUND INSULATION 3

3.1 Introduction

Sound insulation can be described in both words and formulas. In words: sound insulation is the reduction of disturbing sound in a space, originating from another space; or the decrease of sound transmission from one space to another space. This concerns for example the reduction of traffic noise to a bedroom (transmission from outside to inside), noise from the neighbours to the living room (transmission from inside to inside), or the reduction of sound originating from a disco bar (transmission from inside to outside and possibly to inside again). When expressing sound insulation using formulas, two different types of sound excitation can be distinguished: airborne sound and structure-borne sound (figures 3.1 and 3.2).

Airborne sound (longitudinal waves) originates from a source that directly excites air (e.g. vocal cords, a flute, a radio). Airborne sound transmission from one space to another implies that a source excites the air, which excites the building construction and then excites the air in the other space (figure 3.1).

Structure borne sound originates from a source (e.g. hammer drill, footsteps, slamming doors, sanitary) that directly excites a construction (wall or floor), after which the construction again excites the air. The construction acts as a sound radiating board of source vibrations and in such a way increases the radiation efficiency of the source. In case of structure borne sound transmission between two spaces, excitation of one building element excites other building elements attached to it. The total building construction is then radiating its vibration energy into the adjacent space (as well as the own space) as airborne sound (figure 3.3).

Some sources produce both airborne and structure borne sound (figure 3.4). The complexity of sound transmission reduction lies in the prevention of the conversional of different wave types: longitudinal vibrations (sound waves in air) are converted in transverse construction vibrations (bending waves) and vice versa.

The transmission of sound from one space to another is not only dependent on the properties of the partition, but also the connection

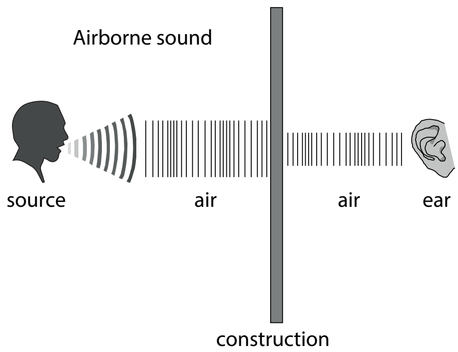


Figure 3.1: Airborne sound transmission.

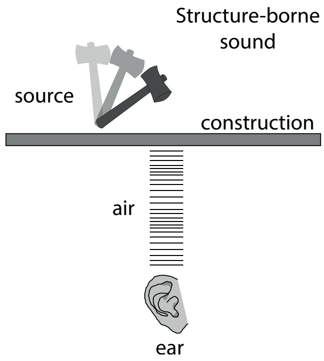


Figure 3.2: Structure-borne sound transmission.

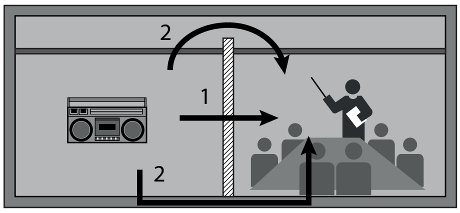


Figure 3.3: Sound transmission paths: direct transmission (1), flanking transmission (2).

Figure 3.4: Combination of structure-borne and airborne sound transmission.

of this construction with other construction elements: the so-called flanking transmission (figure 3.3). In addition, the open connections between the various construction elements from unintentional openings (e.g. cracks, sound leaks) and technical measures (e.g. ventilation ducts) play a role. Depending on the type of sound (airborne or structure borne) and the situation (inside-inside, outside-inside, inside-outside) the contribution of every particular transmission path to the total sound transmission will be different. For example, flanking transmission will generally play a bigger role in inside-inside situations, than in other situations. In outside-inside situations, where façade elements are important, direct transmission and sound leaks play a bigger role. For this reason, a distinction is made of sound insulation between:

- An element: wall, floor, roof, window, door, ventilation opening;
- A composite construction: the composition of elements in one plane (2-dimensional): façade plane with window, parapet and ventilation opening;
- Two spaces: a 3-dimensional composition of planes (whether or not being composite constructions).

3.2 What is the sound insulation

3.2.1 Definition

The sound reduction index of a construction element is a property of the element: the element alone determines how much sound is transmitted. When a sound wave with intensity I_i (W/m^2) hits an element and the intensity of the transmitted sound wave is I_τ (transmission), the sound reduction index R of the element is defined by:

$$R = 10\log_{10}\left(\frac{I_\mathrm{i}}{I_\tau}\right) = 10\log_{10}\left(\frac{1}{\tau}\right) \tag{3.1}$$

Where:

R = the sound reduction index of the construction [dB]
τ = the transmission coefficient [-]

For constructions made from one construction element with surface area S, it is possible to write (3.1) as (using $W_i = S.I_i$ and $W_\tau = S.I_\tau$):

$$R = 10\log_{10}\left(\frac{W_\mathrm{i}}{W_\tau}\right) \tag{3.2}$$

Where:

W_i = power of the incident sound on the construction element [W]
W_τ = power of the transmitted sound through the construction element [W]

The sound reduction index that is defined in this way is not dependent on the surface area of the element. A sound reduction of 20, 30, 40 or 50 dB means that 1/100 (1 %), 1/1000 (0.1 %), 1/10000 (0.01 %) or 1/100000 (0.001 %) of the incident intensity is transmitted.

Because acoustical intensities cannot be measured in a simple way, (3.2) is usually changed into formulas, in which simple measurable sound pressure levels occur. These formulas, however, are dependent on the situation.

3.2.2 The sound reduction index of composite constructions

A plane separating two spaces is usually composed of multiple building elements, for example:

- A partition with a door and/or window;
- A façade, consisting of a parapet, glazing and possibly a ventilation opening.

The sound reduction index R_{plane} of such a plane is defined as:

$$R_{\text{plane}} = 10 \log_{10}\left(\frac{W_{\text{i}}}{W_{\tau}}\right) \tag{3.3}$$

The transmitted sound power Wτ is the sum of the sound power transmitted by the separate elements:

$$W_{\tau} = \sum W_{\tau,n} \tag{3.4}$$

This can be rewritten by:

$$W_{\tau} = \sum S_n I_{\tau,n} \tag{3.5}$$

If we then write (3.3) as:

$$R_{\text{plane}} = -10 \log_{10}\left(\frac{W_{\tau}}{W_{\text{i}}}\right) \tag{3.6}$$

with:

$$W_{\text{i}} = S_{\text{plane}} I_{\text{i}} \tag{3.7}$$

then R_{plane} can be calculated from the sound reduction and surface area of the composite elements:

$$R_{\text{plane}} = -10 \log_{10}\left(\frac{1}{S_{\text{plane}}} \sum_{\text{n}} S_n 10^{\frac{-R_n}{10}}\right) \tag{3.8}$$

This expression is applicable for planes that consist of many parts. Often, the formula is limited to two terms indicating how much the sound reduction index R_1 of a well-isolating plane decreases when a fraction is replaced by another plane with a lower sound reduction index R_2. This is easily shown in a graphical way and provides insight in the consequences of the layout of a plane consisting of elements with high and low sound reduction.

3.3 Measurement methods for sound reduction index

3.3.1 Laboratory measurements

In the preceding part, it was discussed that the sound transmission between two spaces is determined by the total of direct and flanking sound transmission, as well as the transmission via sound leaks and other paths. Direct transmission plays the most important role in most cases. To measure the sound reduction index R of a construction element, the experimental environment should be such that the sound transmission can only take place through that construction element. Furthermore, the sound field in the rooms at both sides of the element should be as diffuse as possible. Such a measurement is performed in laboratory conditions and takes place in a so-called sound transmission room according to ISO 140 conditions. A sound source produces sound in one of the rooms. In the arising diffuse sound field, the intensity I_1 is homogeneous, and thus equals the intensity incident to the investigated construction element. According to (3.2) the transmitted sound intensity I_τ is equal to:

$$I_\tau = I_\mathrm{i} 10^{\frac{-R_n}{10}} \tag{3.9a}$$

The sound power transmitted by the construction element to the receiving room is equal to:

$$W_\tau = S I_\tau \tag{3.9b}$$

This sound source causes an intensity I_2 in the diffuse sound field:

$$I_2 = \frac{W_\tau}{A_2} \tag{3.10}$$

in which A_2 is the total sound absorption in the receiving room. If we further consider that in both the source and receiving room a diffuse sound field is present, for which the following is valid:

$$I_1 = \frac{p_1^2}{4\rho c} \quad \text{and} \quad I_2 = \frac{p_2^2}{4\rho c} \tag{3.11}$$

Then the sound transmission index R can be expressed in measureable quantities p_1, p_2 and A_2. Using the definition of the sound pressure level this results in:

$$R = L_1 - L_2 + 10 \log_{10} \left(\frac{S}{A_2} \right) \tag{3.12}$$

To determine R, a noise-like sound is produced by a noise generator-amplifier-loudspeaker combination in the source room. The noise signal covers a sufficiently wide frequency area (100 .. 10000 Hz). The sound pressure level L_1 in the source room and the sound pressure level L_2 in the receiving room are measured per frequency band (octave or 1/3-octave band). The sound absorption A_2 in the receiving room is determined per frequency band from the reverberation time T_2 in the receiving room and Sabine's formula:

$$T = \frac{1}{6} \frac{V}{A} \tag{3.13}$$

The sound reduction index R, measured according to (3.6) is independent of the size of the partition surface area S and the absorption A_2 in the receiving room. Increasing S with a factor 2, according to (3.5) results in doubling of W_τ and thus of I_2 (according to (3.10)), so that eventually L_2 increases with 3 dB. This 3 dB difference compensated by the 3 dB increase of the third term in (3.12). A similar reasoning is valid for the influence of A_2. The sound absorption A_1 in the source room does not have influence on R: when A_1 changes, L_1 and L_2 change in equal sense. Note that the sound reduction index R is a quality measure of a construction element. In practice, the resulting sound pressure level in the receiving room, not only depends on R, but also on S and A_2. For example, if we assume that all the sound reaches the receiving room through the direct partition, the received sound pressure level L_2 can be determined with (3.12):

$$L_2 = L_1 - R + 10 \log_{10} \left(\frac{S}{A_2} \right) \tag{3.14}$$

3.3.2 Field measurements

In practice the amount of a sound produced in a room (source room), that reaches another room (receiving room) is of interest. The sound reduction between two rooms should then be considered. Initially this can be indicated by the difference in sound pressure level (per frequency band) between the two spaces:

$$L_\mathrm{p} = L_1 - L_2 \tag{3.15}$$

For some spaces, for example outside, the sound field is not diffuse. This implies that the sound pressure levels are different on each location. As a consequence, the definition of the sound reduction between two spaces according to (3.12) is not correct. For sound transmission between an indoor space and another indoor space it is allowed to assume a diffuse sound field as approximation, just like in laboratory measurements.

To measure sound transmission in the field between two indoor spaces, sound is also produced in the source room and source and receiving sound pressure levels are measured per frequency band, averaged over the space. Then the difference L_1 - L_2 is not dependent on the location. The sound pressure level in the receiving room now only has to be corrected for the absorption in the receiving room. This is done by adding the correction term 10log(T_2/T_0) to L_1 - L_2. The result is the so-called normalised sound pressure level difference between two spaces:

$$D_\mathrm{nT} = L_1 - L_2 + 10\log_{10}\left(\frac{T_2}{T_0}\right) \tag{3.16}$$

This way, the receiving sound pressure level is normalised to a standard furnishing of the receiving room with the corresponding reverberation time T_0. The D_{nT} is used to indicate the quality of the sound reduction between two spaces, belonging to different houses or the same house. The normalised (reference) reverberation time T_0 is hereby set to 0.5 s:

$$D_\mathrm{nT} = L_1 - L_2 + 10\log_{10}\left(\frac{T_2}{0.5}\right) \tag{3.17}$$

Before 1976, the sound reduction between dwellings was measured in practice according to NEN 1070 (1962):

$$R' = L_1 - L_2 + 10\log_{10}\left(\frac{S}{A_2}\right) \tag{3.18}$$

This is similar to (3.12), but with a different symbol: R' for field measurements and R for laboratory measurements. With help of (3.13) the relation between R' and D_{nT} for two diffuse sound fields can be written as:

$$D_\mathrm{nT} = R' + 10\log_{10}\left(\frac{V_2}{3S}\right) \tag{3.19}$$

This shows that, when $V_2/3S$ increases, D_{nT} increases in relation to R'. This means that the depth of the receiving space and the size of the partition also play a role. Furthermore relation (3.19) can be used to calculate what difference in normalised sound pressure level D_{nT} can be achieved at maximum by placing a partition in practice. However, we should note that sound transmission via other paths usually leads to lower D_{nT} values.

3.4 Single leaf homogeneous constructions

3.4.1 Theoretical mass law

In section 3.1 it has been mentioned that the direct sound transmission usually is the most important part among all possible transmission paths between two spaces. This is of course dependent on the physical properties of the partition. It is therefore obvious to investigate the mathematical relation between the sound reduction index R and those physical properties. This has been done by several researchers, in which they assumed a specific physical model (behaviour) of the partition.
For a single leaf partition the frictionless piston model is usually used (figure 3.5), in which it is assumed that the partition moves as a whole without any friction. Then, the movement of the partition is only dependent on the strength and frequency of the incident sound wave and the mass (inertia) of the partition.
For perpendicular incident sound waves to the partition, the following applies:

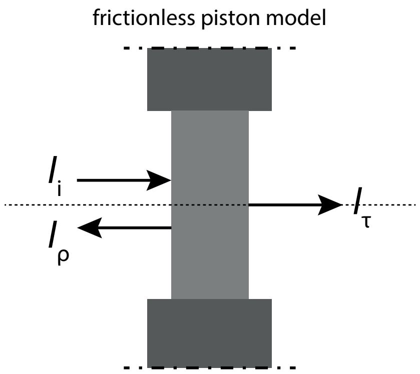


Figure 3.5: The frictionless piston model as a base for the theoretical mass law.

$$R = 20\log_{10}\left(\frac{\omega m}{2\rho c}\right) \tag{3.20}$$

In practice, certainly in case of transmission between two enclosed spaces, sound hits the partition from all directions, and $0 < \theta < 90°$. Based on the derivation of angled incidence, it is possible by means of integration over θ from 0 to 80° (if $\theta = 90°$, then $R = 0$!) to determine the sound reduction of a single leaf partition in case of random wave incidence:

$$R = 20\log_{10}\left(\frac{\omega m}{2\rho c}\right) - 5 \tag{3.21}$$

The formulas (3.20) and (3.21) are called the theoretical mass laws for perpendicular incident sound waves and sound waves with random incidence respectively. Note that $\omega = 2\pi f$ is a property of the incident sound, m (kg/m^2) of the partition and ρc of air.

The theoretical mass law implies that:
- The sound reduction index R increases by 6 dB by doubling the mass per surface area;
- The sound reduction index R increases by 6 dB by doubling the frequency (per octave).

3.4.2 Practical mass law

For the theoretical mass law, several assumptions have been made that are not in agreement with practice:
- Wall has infinite dimensions;
- Wall moves as a whole;
- Wall does not possess any stiffness.

As a result, the mass laws provides optimistic results for real situations. Therefore, various 'relations' have been derived that show a simpler relation between the mean sound reduction R_m of the sound reduction at 500 Hz R_{500} and the mass m per unit surface area (kg/m^2). These are called practical mass laws. An example of this is:

$$R_{500} = 17.5\log_{10}(m) + 3 \tag{3.22}$$

For higher octave bands 5 dB should be added, for lower octave bands 5 dB should be subtracted. Table 3.1 gives an overview of sound reduction indices R_{500} of walls with different masses per surface area, which are calculated with the two different mass laws.

Table 3.1: R_{500} in dB calculated from the theoretical and practical mass law

m [kg/m^2]	Theoretical mass law	Practical mass law
10	26.7	20.5
20	32.7	25.8
50	40.7	32.7
100	46.7	38.0
200	52.7	43.3
400	58.7	48.5

While the theoretical mass law yields a 6 dB higher sound reduction per doubling of the mass, this is about 5 dB for the practical mass law. The discussed mass laws are, if used with common sense, very usable when comparing partitions. The limitation of the formulas lies in neglecting the bending stiffness of the wall.

3.4.3 Bending waves

The bending stiffness is an important property of building constructions; due to this property we are able to build after all. The bending stiffness also has a large influence on the sound reduction, as transverse bending waves can occur in a wall or a floor under influence of both airborne and structure-borne sound sources. Because the possible occurrence of (transverse) bending waves, the sound reduction of a single leaf homogenous construction changes in relation to the mass laws due to two phenomena, namely standing and traveling waves.

3.4.4 Standing waves

Plate or bending resonances can occur. These are called standing waves, which are comparable with the standing waves of a tensioned violin string. The wavelengths of standing waves, and thus the resonance frequencies, have a direct relation with the dimensions. For construction elements this concerns a series of resonance frequencies, which can be seen as fundamental tones and (non-harmonic) overtones, and are dependent on the length and the width of the element, as well as the bending stiffness and the way the element is connected to the surrounding construction: simply supported or fixed. For these eigenfrequencies, the sound reduction will be lower than what the mass laws indicate. This effect is strongest for the lowest eigenfrequency f_0. For most stone-like materials with dimension of 3 to 4 m, the lowest eigenfrequency lies beneath approximately 70 Hz. In this frequency area the sound reduction in relation to noise annoyance is less important. Moreover, these lowest frequencies are difficult to excite. The higher eigenfrequencies are generally weakened very fast by the internal damping of the material itself. This effect is highest in case of thin panels with low damping (steel, aluminium, glass), which are easily excited. Elements with small dimensions, like walls from air handling units, can possess a lowest eigenfrequency above 100 Hz. Since the sound reduction below f_0 is determined by bending stiffness and not by mass, an increase of the stiffness under these specific circumstances (small, undamped, lightweight panels at low frequencies) can be an effective measure to increase the sound reduction at these low frequencies. Furthermore, the vibration level of these panels can be decreased by the addition of vibration damping pastes or foils (mats), by which the internal damping is increased.

3.4.5 Propagating bending waves

A second, more important result of the bending stiffness is the occurrence of propagating bending waves. While these bending waves are reflected at the edges of the construction element (summation of waves travelling back and forth), for understanding of the occuring phenomena a plate of infinite size is assumed below, such that the propagation wave definition can be maintained.

Traveling waves can be excited in two ways:

1. By a point excitation (with a hammer or a small structure-borne sound source) or a line excitation (for example a junction line with another construction element). As a result of this excitation a bending wave will start to propagate from the excitation point or line. A stone that falls into a pond is an analogy to this phenomena. The propagation velocity of these bending waves is proportional to the square root of the frequency: high frequencies travel faster than lower ones:

$$c_{\mathrm{B}} = \sqrt[4]{\frac{Ed^3}{12m}}\sqrt{2\pi f} \tag{3.23}$$

Where:

E	=	Young's modulus	[N/m2]
d	=	plate thickness	[m]
m	=	mass	[kg/m3]
f	=	frequency	[Hz]

Analogous to this, the following applies:

$$c_{\mathrm{B}} = \lambda_{\mathrm{B}} f \tag{3.24}$$

For plate thicknesses $d > \lambda_B/4$, the occuring wave type deviates from a bending wave. The phenomenon that higher frequencies have a higher propagation velocity than lower frequencies is called dispersion; this also occurs for other wave phenomena, as for light (colour separation in prisms).

2. By excitation of airborne sound: if for example a plane traveling airborne sound wave hits a wall (or floor) under an angle (angle φ with normal), then a pattern of under- and overpressure travels along the wall. As a result of these under- and overpressures the wall is pushed into a specific shape from its equilibrium (figure 3.6). This shape travels together with the pattern of under- and overpressures along the wall. We call this a forced bending wave: the airborne sound determines the vibration form. The propagation velocity c' of this forced bending wave is dependent on c and φ:

$$c' = \frac{c}{\sin(\phi)} \tag{3.25}$$

3.4.6 Coincidence

For a certain angle of incidence φ of a sound wave on a construction, c' will remain constant over frequency, but c_B will increase over frequency. For specific frequencies c' is equal to c_B: the projected sound wave on the construction coincides with the bending wave, because both waves propagate with the same velocity (coincidence = fall together). This results in large plate vibrations and a high radiated sound power. At this frequency, the so-called coincidence frequency, the sound reduction is theoretically zero (in practice it will always be larger than zero). For every angle of incidence, a different coincidence frequency can be found., and is lowest for φ = 90°. We call this frequency the critical frequency f_c; no coincidence occurs below f_c, for all frequencies above f_c there is. If a sound wave with a random incident angle hits a wall, coincidence will occur for all frequencies above f_c. However, this effect will be the strongest for frequencies near f_c. The critical frequency can be calculated from:

$$c_\mathrm{B} = c' \quad \text{for} \quad \phi = 90^\circ \tag{3.26}$$

such that:

$$\sqrt[4]{\frac{Ed^3}{12m}}\sqrt{2\pi f} = \frac{c}{\sin(\phi)} \tag{3.27}$$

which ultimately results in:

$$f_\mathrm{c}d = \frac{c^2}{2\pi}\sqrt{\frac{12\rho}{E}} \tag{3.28}$$

With use of:

$$c_\mathrm{L} = \sqrt{E}\rho \tag{3.29}$$

this can be written as:

$$f_\mathrm{c}d = \frac{c^2\sqrt{12}}{2\pi c_\mathrm{L}} \tag{3.30}$$

and by inserting the constants:

$$f_\mathrm{c}d = \frac{64000}{c_\mathrm{L}} \tag{3.31}$$

The product of the critical frequency and the plate thickness is thus a constant that is determined from material properties, and is independent of length and width of the element. Including the bending stiffness in the sound reduction definition of a single leaf homogeneous construction completes the theory. The extent to which the sound reduction decreases due to coincidence, depends on a number of circumstances. For the following conditions:

- Directed sound;
- Infinite plate dimensions;
- Low internal damping.

the sound reduction will be larger. The practical consequences of this can be summarised as follows:

- In a directed sound field (outside-inside situation) the sound insulation will be low and in a narrow frequency region around:

$$f_\mathrm{c} = \frac{64000}{c_\mathrm{L}d\sin^2(\phi)} \tag{3.32}$$

- At the transition inside-inside (2 diffuse sound fields) the sound insulation is not as low but a wider frequency range around f_c is affected;
- At bending wavelengths that are much smaller than the plate dimensions, or at high critical frequencies (thin plates), the sound

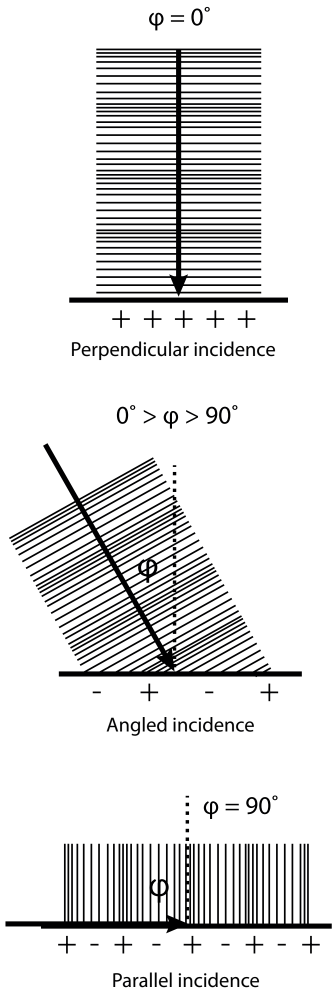


Figure 3.6: Sound pressure distribution over a plane due to a forced bending wave by excitation of airborne sound.

insulation will again be low and in a narrow frequency region around f_c;
- Undamped (thin) plates as metal and glass strongly show the coincidence effect.

Note: The coincidence effect is better noticeable at measurements in 1/3-octave bands (or even smaller bands) than in full octave bands.

3.4.7 3-step model

The shape of the sound reduction curve can be made schematic (figures 3.7 and 3.8). This schematic curve can be used to predict the sound reduction of single leaf constructions:

- Line segment a (step 1): $f < f_1$:

$$R_{\text{omni}} = 20\log_{10}(m) + 20\log_{10}\left(\frac{f}{250}\right) \tag{3.33}$$

- Line segment b (step 2): $f_1 < f < f_c$:

$$R_{\text{plateau}} = 20\log_{10}(mf_c) + 10\log_{10}(\eta) - 44 \tag{3.34}$$

- Line segment c (step 3): $f > f_c$:

$$R = R_{\text{plateau}} + 25\log_{10}\left(\frac{f}{f_c}\right) \tag{3.35}$$

with:

$$f_1 = 2\sqrt{\eta}f_c \tag{3.36}$$

For $m > 70$ kg/m² the plateau sound reduction (figure 3.8) needs to be increased with:

$$R = 20\log_{10}\left(\frac{m}{70}\right) \tag{3.37}$$

Table 3.2 provides the necessary material information for these calculations. With the formulas discussed above, an indication of the sound reduction of a single leaf construction can be obtained. Comparing these calculations with laboratory measurements can result in deviations due to different values for internal damping. Differences in $R_{plateau}$ of 3 to 5 dB are not unusual.

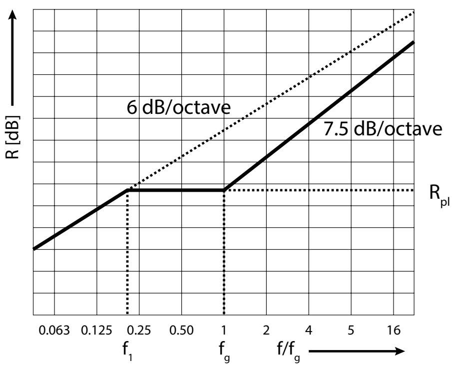
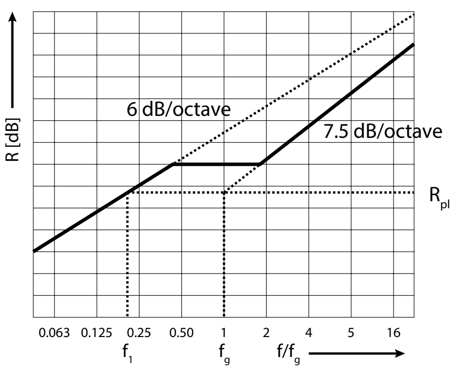


Figure 3.7: Schematic airborne sound reduction curve (3-step model) for a single leaf homogeneous construction.



Usual classification are:
- Heavy stiff walls: $f_c < 100$ Hz;
- Light stiff walls: $100 < f_c < 1000$ Hz;
- Light non-stiff walls: $f_c > 1000$ Hz.

3.5 Double leaf constructions

A high sound reduction of a single leaf construction can only be achieved with a high mass per surface area. For values of $R_m = 50$ dB, stone-like constructions of approximately 400 kg/m² are needed. These walls are stiff by definition ($f_c = 100$ Hz). Higher values generally are hard to achieve with single leaf constructions. However, in some situations a sound reduction of 55 to 60 dB is required. Generally speaking, one can achieve a significant higher sound reduction with the same mass (kg/m²), by dividing the mass over two walls placed behind each other,

Table 3.2: material properties for calculating airborne sound reduction of single leaf construction

material	ρ [kg/m²]	c_1 [m/s]	f_c*d [Hz*m]	m*f_c [kg*Hz/m²]	η [-]	$R_{plateau}$ [dB]
Aluminium	2700	5100	12.5	3.40E+04	1.00E-02	28
Steel	7800	5050	12.8	9.80E+04	1.00E-02	38
Glass	2500	5000	12.8	3.20E+04	1.00E-02	27
Concrete	2400	3700	17.3	4.10E+04	7.00E-03	29
Cellular concrete	650	1700	38	2.50E+04	1.00E-02	26
Sand-lime bricks	1900	3000	21.4	4.10E+04	1.00E-02	30
Poriso	1200	2500	26	3.10E+04	1.00E-02	28
Lightweight concrete	900	2000	32	2.90E+04	1.00E-02	27
Gypsum	1200	1800	35.5	4.20E+04	5.00E-03	28
Gypsum board	1200	1800	35.5	4.20E+04	3.00E-02	35
Wood, chipboard	700	2500	25	2.00E+04	1.00E-02	24
Lead	1130	1250	51.2	5.70E+05	2.00E-02	56

in other words by creating a double leaf construction. The thus created leafs are then separated by a layer of air. Such a cavity construction resembles the one of the resonating panel. Here as well, the air layer functions as a spring, to which two masses are attached. In an analogous way, a mass-spring resonance frequency can be assigned to this mass-spring-mass system. For perpendicular incident sound waves on the construction this leads to:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{\rho}{d}\left(\frac{1}{m_1}+\frac{1}{m_2}\right)} \qquad (3.38)$$

Where:

c	=	speed of sound in air	[m/s]
m_1, m_2	=	mass per unit surface area for both leafs	[kg/m²]
ρ	=	density of air	[kg/m³]
d	=	cavity width	[m]

At frequency f_0 the system is excited easily (resonance), and as a consequence the sound reduction of the construction is then very low. Several variants of (3.38) are obtained for:

- Angled incident sound wave (under angle θ with normal to surface):

$$f_0 = \frac{c}{2\pi\cos(\theta)}\sqrt{\frac{\rho}{d}\left(\frac{1}{m_1}+\frac{1}{m_2}\right)} \qquad (3.39)$$

- Symmetrical cavity construction: $m_1 = m_2 = ½\, m_{tot}$:

$$f_0 = \frac{120}{\sqrt{m_{\text{tot}} d}} \qquad (3.40)$$

- A lightweight wall lining in front of a heavy (stone-like) wall: $m_1 << m_2$:

$$f_0 = \frac{60}{\sqrt{m_1 d}} \qquad (3.41)$$

Similar to the theoretical mass law for single leaf constructions, a mass law can be derived for double leaf constructions as well. This law does have the same shortcomings as the theoretical mass law for single leaf constructions: the bending stiffness is not taken into account. Taking into account the bending stiffness of both leafs is mathematically complex, and only a description of the behaviour of a double leaf construction is therefore given here, as well as an indication on the influence of the bending stiffness on that behaviour. Comparing the sound reduction curve of double leaf constructions without a connection to that of single leaf constructions (figures 3.9 and 3.10), the following can be noted:

- For frequencies below f_0 the sound reduction of the double leaf construction is equal to that of the equally heavy single leaf construction;
- For frequencies around f_0, the sound reduction of the double leaf construction is lower than the single leaf construction reduction due to mass-spring resonance;
- For frequencies above f_0, the sound reduction of the double leaf construction increases more rapid for increasing frequencies than that of the single leaf construction, first 18 dB per octave, later 12 dB per octave; this is where the double leaf construction is more profitable in relation to the single leaf one;
- The sound reduction of a double leaf construction can be decreased by so-called cavity-resonances, standing sound waves in the cavity; for the perpendicular direction to both leafs the resonance frequencies f_n are calculated as follows:

$$f_{\rm n} = \frac{nc}{\sqrt{2d}} \qquad n = 1, 2, \dots \tag{3.42}$$

The addition of a porous absorbing material in the cavity can significantly decrease the influence of cavity resonances, especially for lightweight double leaf constructions.

Also for double leaf constructions, the sound reduction is lowered due to the occurrence of the coincidence-effect, as a result of the bending stiffness. This effect is most noticeable when both leafs possess the same critical frequency. If this is not the case, then the sound reduction 'dip' at the critical frequency f_{c1} is reduced by the higher sound reduction of the second leaf. This is the reason why good acoustically insulating glazing has two panes with different thicknesses.

Unfortunately, the sound reduction of double leaf constructions is often reduced in practice due to the presence of (wanted and unwanted) mechanical connections between the leafs. Furthermore, the influence of sound transmission via additional paths (flanking transmission) on the sound reduction between two spaces will be larger, as the direct transmission becomes lower, as in case of a well-built (connectionless) double leaf construction. Figure 3.11 shows an open section of a double leaf construction (wall lining with board material on both sides).

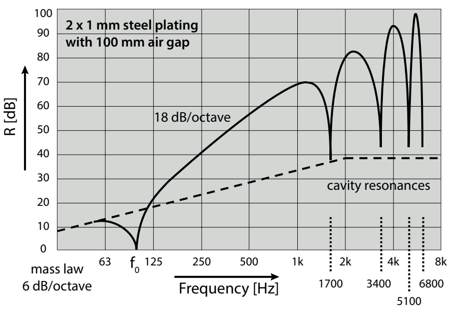


Figure 3.9: Schematised airborne sound reduction curves for a construction with an air gap.

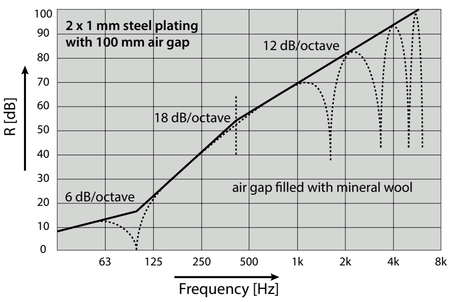


Figure 3.10: Schematised airborne sound reduction curves for a construction with a cavity filled with mineral wool.

3.6 Flanking sound transmission

As already is discussed briefly in section 3.1, sound transmission between two spaces takes place via several transmission paths. From those paths, only the direct transmission is discussed until now. A flanking transmission path can be divided into three parts:

1. A boundary surface of the source room, the direct partition or an adjacent surface, is excited by airborne or structure borne sound;
2. The vibrations partially propagate over the junction to a boundary surface of the receiving room, are partially reflected or propagated to other surfaces;
3. The vibration energy that is now present in the boundary surfaces

of the receiving room are now radiated as airborne sound in the receiving room.

The energy transmittance according to 1, 2 and 3 can thus occur:
- From a flanking surface to a flanking surface;
- From a flanking surface to the partition surface;
- From the partition surface to a flanking surface.

In total there are 12 possible flanking transmission paths in case of 2 rectangular rooms. The total energy transmittance over these 12 paths, the flanking sound transmission, determines the decrease in the direct sound reduction. The influence of the flanking sound transmission on the sound reduction becomes larger as:
- The sound reduction of the direct partition is higher;
- The surface area of the flanking surfaces is larger: a large surface area can radiate more power.

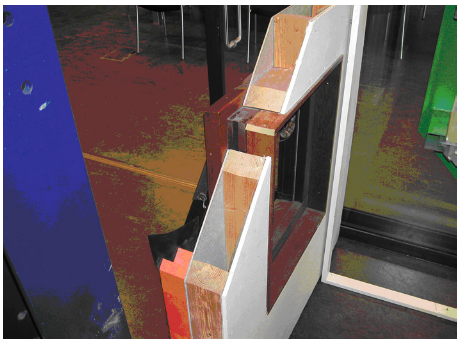


Figure 3.11: Example of a section of a double leaf construction.

In practice, the influence of the flanking sound transmission is limited to a decrease of the direct sound reduction of approximately 2 - 4 dB. Normally a decrease of 2 dB is seen as a 'common' flanking transmission. A higher flanking transmission is mainly caused by lightweight stiff constructions (30 kg/m^2 < m < 100 kg/m^2 with 200 Hz < f_c < 1000 Hz) that are fixed to the partition. For double leaf constructions, for example cavity walls, flanking sound transmission can effectively be suppressed by proper dimensioning. We should note the character of flanking sound transmission when improving sound reduction of constructions in practice. Expected improvements of 10 to 15 dB by placing, for example, wall linings, etc., are generally not achieved because the flanking transmission is determining the sound reduction. In extreme cases one must even build box-in-box constructions to reduce both the direct and the flanking sound transmission.

4.3 Practical sound reduction

The acoustic quality of a building cannot be seen separate of the environment and its associated sounds. The use and experience of a garden, terrace, solarium and balcony for example also depend on the environmental sound pressure level. A too high sound exposure on one or more façades restricts the freedom of arranging a floor plan. Sound-sensitive spaces will have to be placed on the low-noise side of the building. In case of sound exposure of more than 55 dB(A), additional sound reducing measures for the façade and roof are needed. In case of a sound exposure of more than 65 dB(A), achieving the prescribed sound reduction becomes technically more challenging and thus more costly. In a very quiet environment the sound originating from adjacent buildings is noticeable more easily. Where complying with the legislation would normally suffice, now a higher sound reduction is needed. Sound reduction needs attention during the design process. For architects and designers the following guidelines are of importance.

4.3.1 Protection against sound from the outside environment

- Locate sound-sensitive spaces on the quiet side;
- Maintain a small glass surface area;
- Do not use rotating parts (windows or doors) on sound-exposed façades;
- Use a mechanical ventilation system or a damper (figure 4.5)

4.3.2 Sound reduction between spaces

- A partition that separates dwellings determines the airborne and structure borne sound reduction;
- A (bed)room under an inclined roof deserves additional measures and is sensitive to construction failures;
- Do not use masonry for a partition that separates dwellings;
- Do not place wall sockets opposite to each other in a partition that separates dwellings;
- Prevent flanking sound transmission via air ducts;
- Prevent flanking sound transmission via reflecting surfaces like open windows in mirrored rooms or dwellings;
- Seal duct holes of HVAC-systems through separating walls and floors;
- Pay attention to the placement of sound-sensitive and sound-intensive spaces;
- Do not use fire places with a shared chimney outlet;
- When applying wooden or stone floors, place a special layer in between the structural floor and the applied floor and keep the floor mechanically free from surrounding walls;
- Provide vibration-free installation for a shared staircase;
- Use sound-absorbing ceilings in shared spaces.

4.3.3 Protection against sound of HVAC systems

- Use low-noise systems;
- Support or suspend systems with a spring-construction;
- Fine-tune systems properly;
- Place systems in a separate space;
- Place sanitary free of partitions that separate dwellings;
- Do not fix ducts against separating constructions.