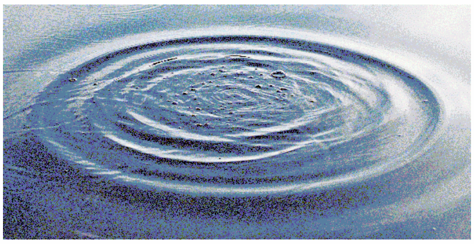
Basic Concepts of Sound



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Abstract

This lecture introduces sound and sound measurements by describing sound pressure, sound level and units for sound level measurements.

Before undertaking sound measurements, it is important to be familiar with the terminology of acoustics, the basic rules of sound propagation, and the features of sound measuring equipment. This lecture describes sound pressure, sound level, and units for sound level measurements.

LECTURE NOTE

English BA 7666-11

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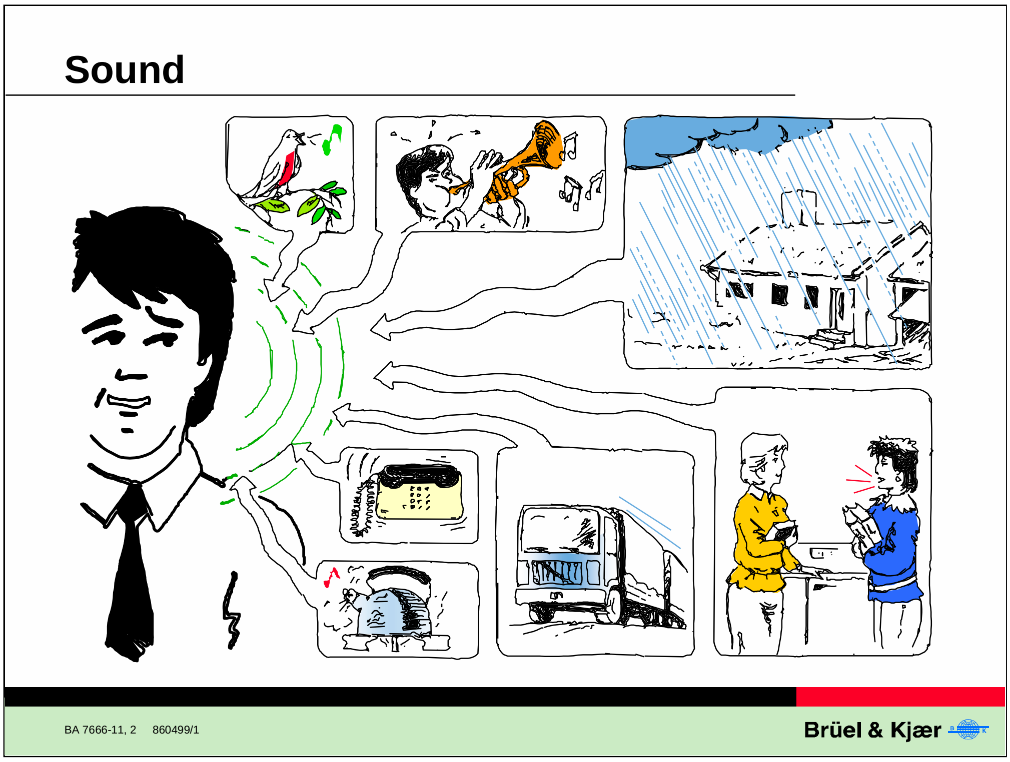
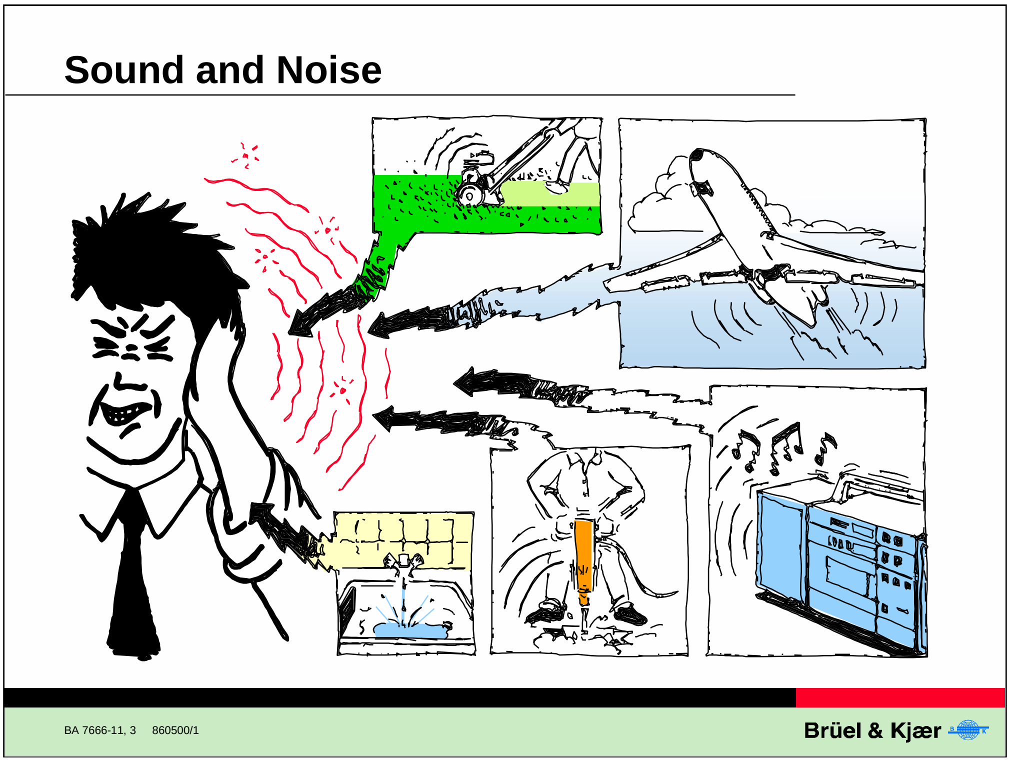
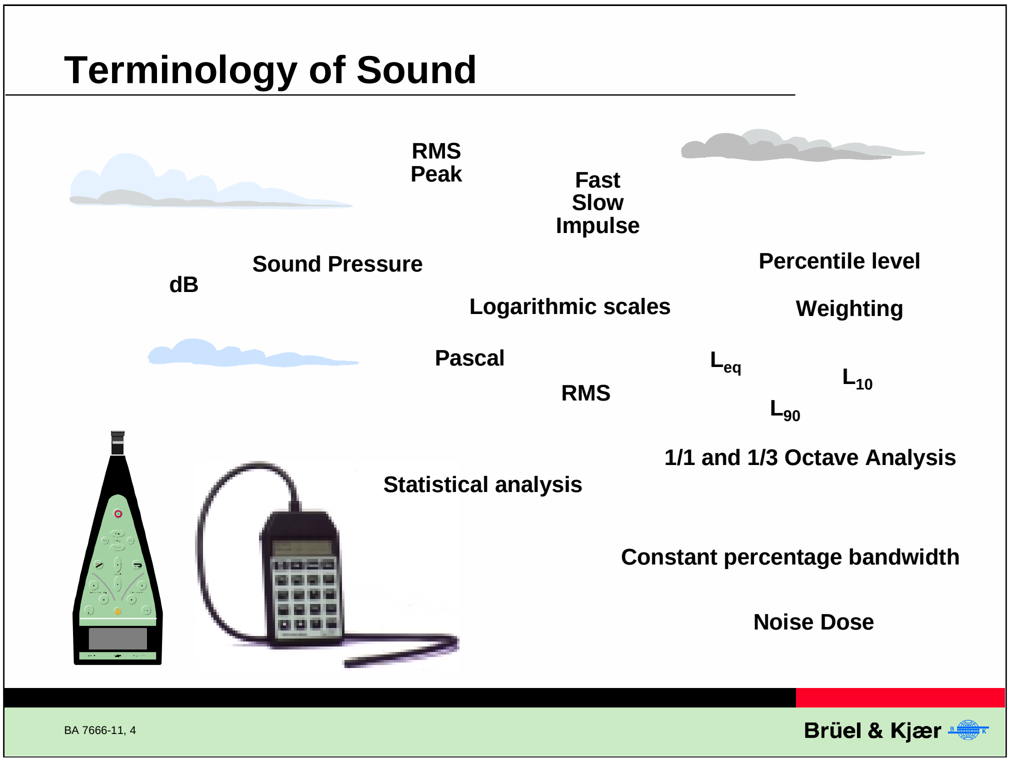


Sound is such a common part of everyday life that we rarely appreciate all of its functions. It provides enjoyable experiences such as listening to music or to the singing of birds. It enables spoken communication and it can alert or warn us - for example, with the ringing of a telephone, or a wailing siren. Sound also permits us to make quality evaluations and diagnoses - the chattering valves of a car, a squeaking wheel, or a heart murmur.



Yet, too often in our modern society, sound annoys us. Many sounds are unpleasant or unwanted - these are called noise. However, the level of annoyance depends not only on the quality of the sound, but also our attitude towards it. For example the type of music enjoyed by some people could be regarded as noise by others, especially if it is loud. But sound doesn't need to be loud to annoy. A creaking floor, a scratch on a record, or the intermittent sound of a dripping tap can be just as annoying as loud thunder. The judgement of loudness will also depend on the time of the day. For example, a higher level of noise will be tolerated during the day than at night.

Sound can also damage and destroy. A sonic boom can shatter windows and shake plaster off walls. But the most unfortunate case is when sound damages the delicate mechanism designed to receive it - the human ear.

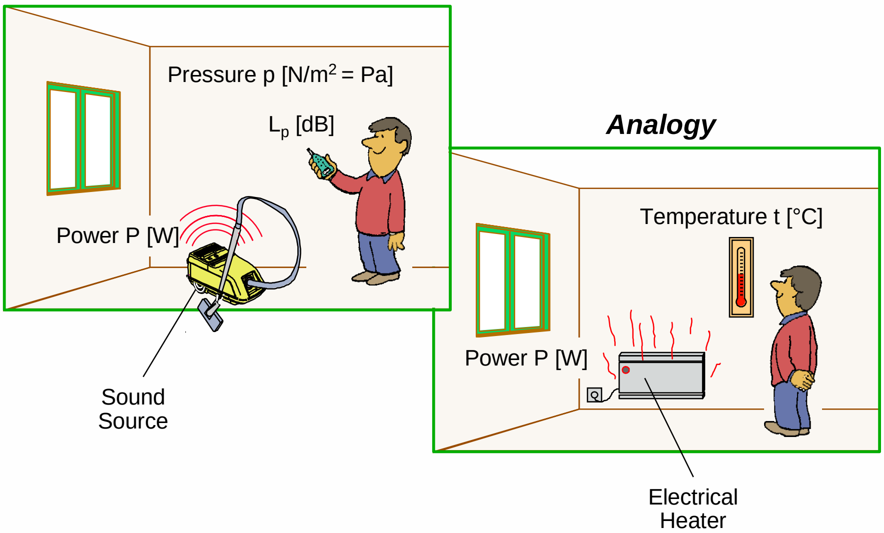


Sound is defined as any pressure variation that the ear can detect ranging from the weakest sounds to sound levels which can damage hearing.

The study of sound is called ACOUSTICS and covers all fields of sound production, sound propagation and sound reception, whether created and received by human beings or by machines and measuring instruments.

Noise is an unavoidable part of everyday life and technological development has resulted in an increase in noise level from machines, factories, traffic etc. It is therefore important that steps towards a reduction in noise are taken, so that noise is not something we have to accept. In connection with this fight against noise, we must be able to assess the noise properly i.e. to perform reliable sound measurement. However, before noise measurements are undertaken, it is important to be familiar with the terminology and the basic principles of sound measurement.

Pressure vs. Power



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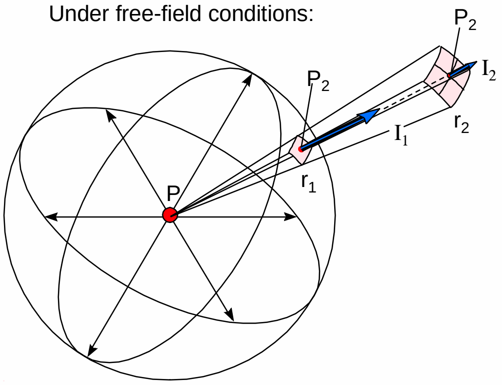
Before describing the physical properties of sound, let's make an analogy between sound, and a maybe better known physical quantity - heat.

An electrical heater produces a certain amount of energy per unit time [Joule/sec] i.e. it has a certain power rating in W [Watt = Joule/sec]. This is a basic measure of how much heat it can produce and is independent of the surroundings. The energy flows away from the heater raising the temperature in other parts of the room and this temperature can then be measured with a simple thermometer in ºC or ºF. However, the temperature at a particular point will not only depend on the power rating of the heater and the distance from the heater, but also on the amount of heat absorbed by the walls, and the amount of heat transferred through the walls and windows to the surroundings etc.

A sound source will produce a certain amount of sound energy per unit time [Joule/sec], i.e. it has a certain sound power rating in W [Watt = Joule/sec]. This is a basic measure of how much acoustical energy it can produce, and is independent of its surroundings. The sound energy flows away from the source giving rise to a certain sound pressure in the room. When the sound pressure is measured this will not only depend on the power rating of the source and the distance between the source and the measurement point, but also on the amount of sound energy absorbed by the walls and the amount of sound energy transferred through the walls and windows etc.

Basic Parameters of Sound

Under free-field conditions:



The Sound Intensity vector, $\vec{I}$, describes the amount and direction of flow of acoustic energy at a given position

$$I = \frac{P}{4\pi r^2} = \frac{p^2}{\rho c}$$

Power:	P [W]
Intensity:	I [J/s/m^2] = W/m^2
Pressure:	p [Pa = N/m^2]

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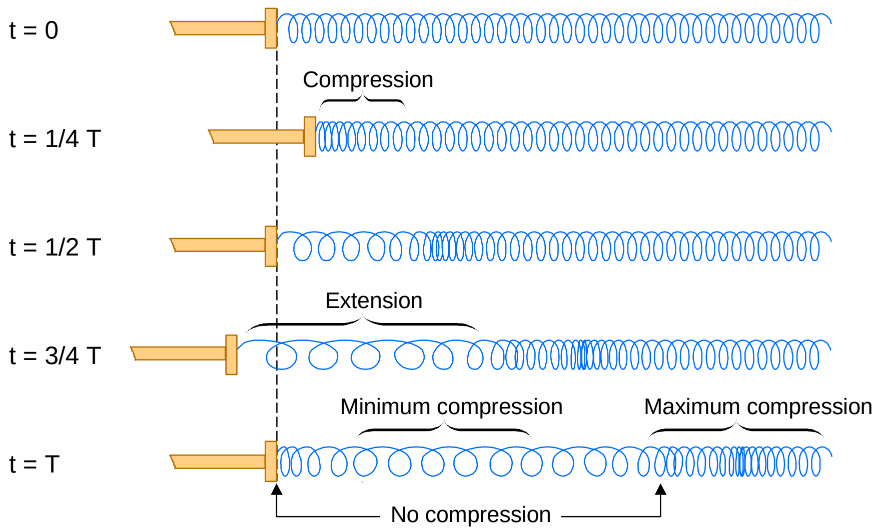
When sound is produced by a sound source with a sound power, P, a transfer of energy from the source to the adjacent air molecules takes place. This energy is transferred to outlying molecules. Thus the energy spreads away from the source rather like ripples on a pond. The rate at which this energy flows in a particular direction through a particular area is called the sound intensity, I. The energy passing a particular point in the area around the source will give rise to a sound pressure, p, at that point.

ρ is the density of air, c is the speed of sound.

Note that sound intensity is a vector quantity - it has magnitude as well as direction.

Sound intensity and sound pressure can be measured directly by suitable instrumentation. Sound power can be calculated from measured values of sound pressure or sound intensity levels and a knowledge of the area over which the measurements were made. The main use of sound power is for the noise rating of machines etc. and sound intensity is mainly used for location and rating of noise sources. When it comes to evaluation of the harmfulness and annoyance of noise sources, sound pressure is the important parameter.

Propagation of Sound



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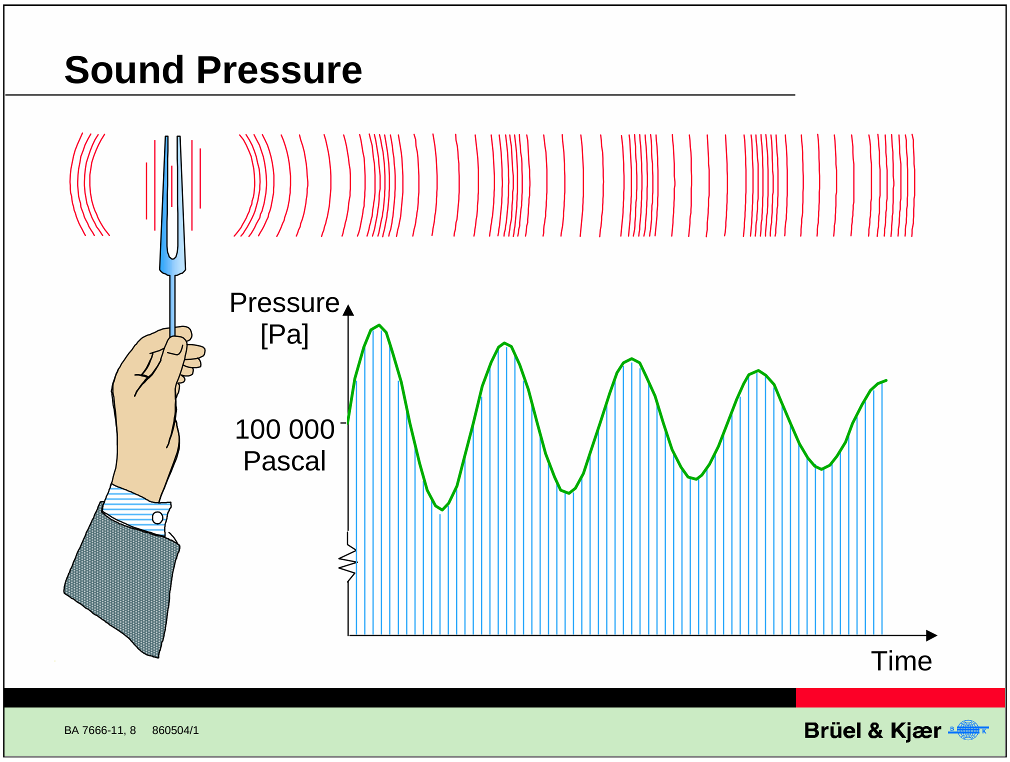
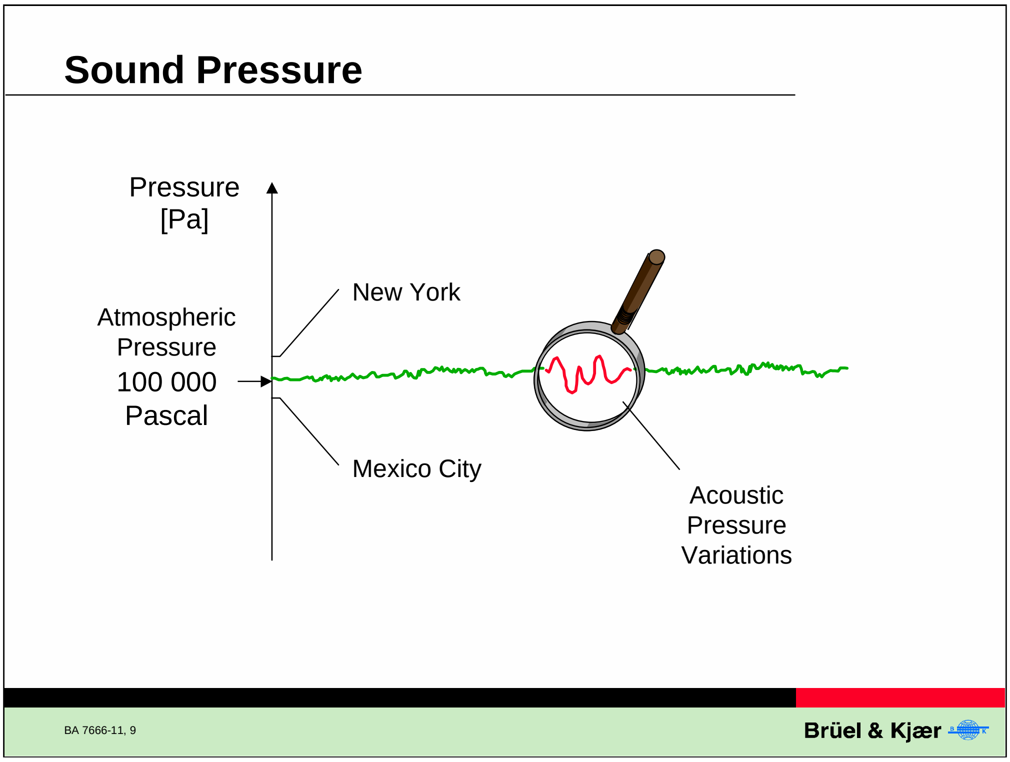
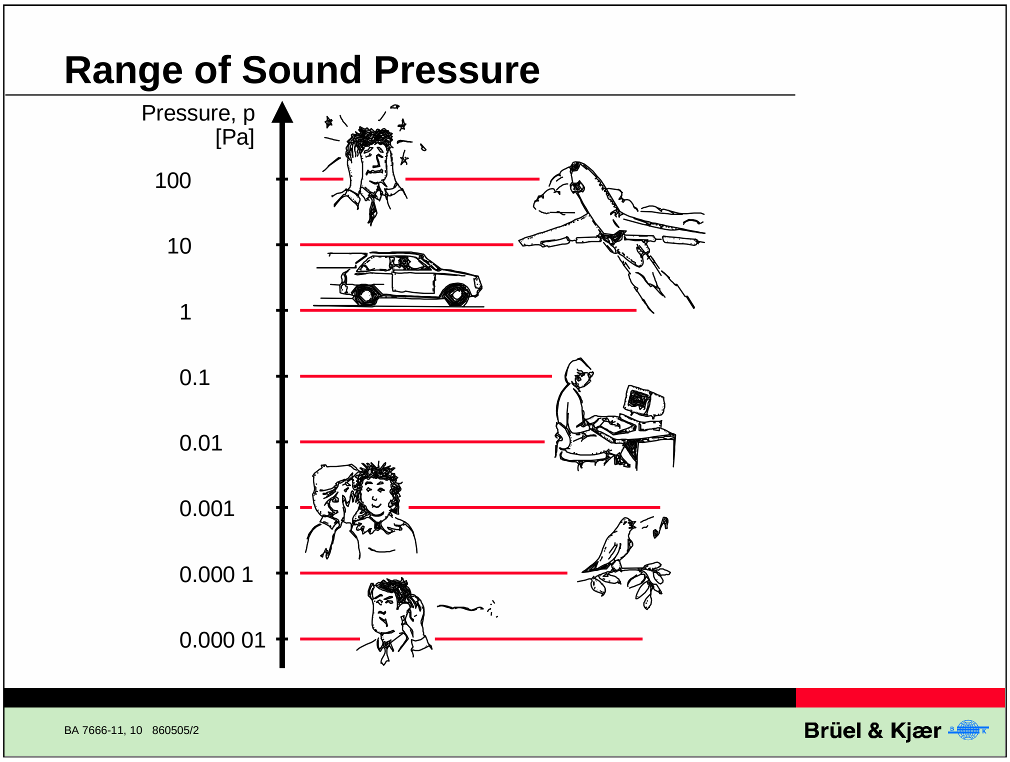
When a spring is compressed, the ‘compression’ travels along the spring. The same happens when air molecules are compressed and extended; the ‘compression’ and ‘extension’ or changes of pressure travel or radiate in air.



When a sound source such as a tuning fork vibrates it sets up pressure variations in the surrounding air. The emission of the pressure variations can be compared to the ripples in a pond coused by a stone thrown in the water. The ripples spread out from the point where the stone entered. However the water itself does not move away from the center. The water stays where it is, moving up and down to produce the circular ripples on the surface. Sound is like this. The stone is the source, the pond is the air, and the ripples are the resulting sound wave.



The acoustic pressure vibrations are superimposed on the surrounding static air pressure which has a value of 10^5 Pascal.



Compared with the static air pressure, the audible sound pressure variations are very small ranging from about 20 µPa (10^{-6} Pa) to 100 Pa. 20 µPa is the quietest sound that can be heard by an average person and it is therefore called the threshold of hearing. A sound pressure of approximately 100 Pa is so loud that it causes pain, and it is therefore called the threshold of pain. The ratio between these two extremes is more than a million to 1. The direct application of linear scales, in Pa, to the measurement of sound pressure would therefore lead to the use of enormous and unwieldy numbers. Additionally, the ear responds not linearly but logarithmically to stimulus. For these reasons, it has been found more practical to express acoustic parameters as a logarithmic ratio of the measured value to a reference value - a logarithmic ratio called a decibel or just dB.

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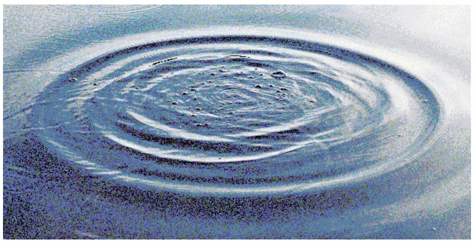

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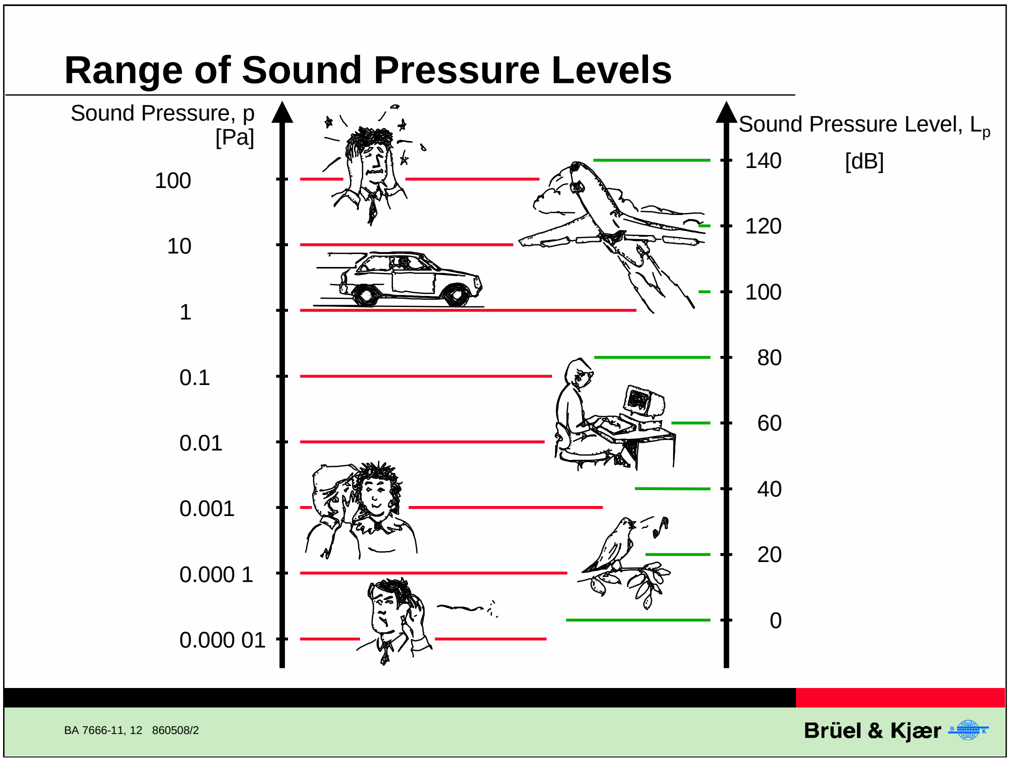

The advantage of using dB's is clearly seen when a dB scale is drawn on the illustration shown earlier. The linear scale with its large and unwieldy numbers is converted into a much more manageable scale from 0 dB at the threshold of hearing (20 µPa) to 130 dB at the threshold of pain.

dB – decibel

$$L_p = 20 \log \frac{p}{p_0} \text{ dB re } 20\ \mu\text{Pa}$$

$$(p_0 = 20\ \mu\text{Pa} = 20 \times 10^{-6}\ \text{Pa})$$

Ex. 1: p = 1 Pa

$$L_p = 20 \log \frac{1}{20 \times 10^{-6}}$$

$$= 20 \log 50\,000$$

$$= 94 \text{ dB}$$

Ex. 2: p = 31.7 Pa

$$L_p = 20 \log \frac{317}{20 \times 10^{-6}}$$

$$= 20 \log 1.58 \times 10^{-6}$$

$$= 124 \text{ dB}$$

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The sound pressure level, L_p, in dB's is defined as 20 log p/p_0 , where p is the measured value in Pa, and p_0 is a standardised reference level of 20 µPa - the threshold of hearing. Note here that the word level is added to sound pressure to indicate that the quantity has a certain level above the reference level, and the symbol for sound pressure level is L_p. The illustration shows two examples of how to use the formula for calculation of dB levels. Besides being examples of calculation, these two levels are interesting because they are the levels used for sound level meter calibration

Perception of dBs

Change in Sound Level (dB)	Change in Perceived Loudness
3	Just perceptible
5	Noticeable difference
10	Twice (or 1/2) as loud
15	Large change
20	Four times (or 1/4) as loud

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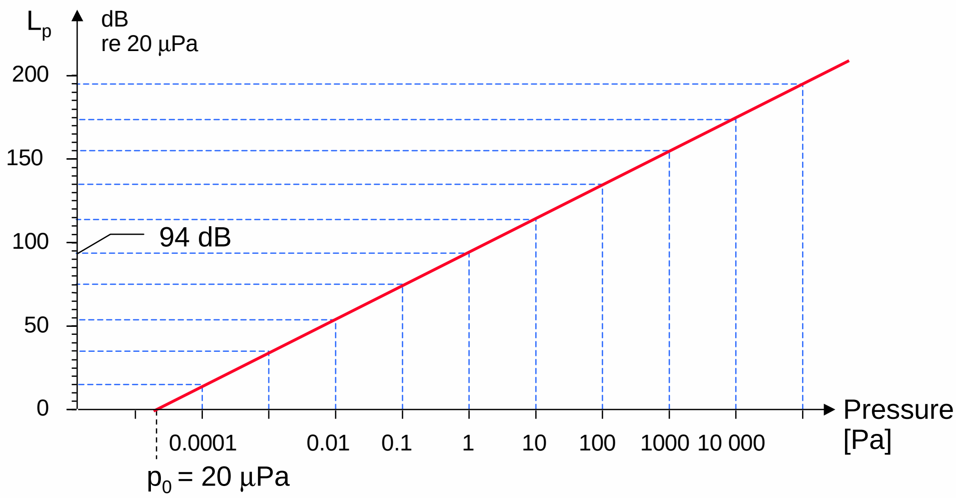
An increase of 3 dB in pressure (corresponding to 1.4 times) is just perceptible. A change of 10 dB or 3.16 times is perceived as twice as loud.

There is no linear relationship between the loudness level in dB and the perception by man.

Conversion to dB using Charts



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Instead of using the formula for conversion between pressure values and dB levels (or vice versa) it is possible to use a simple graph for conversion. The graph here is based on dB values re 20 µPa and the dashed lines give an example of how 1 Pa converts to 94 dB.

Conversion to dB using Tables

dB to Pressure Ratio

Pressure Ratio	– db +	Pressure Ratio	Pressure Ratio	– db +	Pressure Ratio
1.00	0.0	1.000	0.501	6	1.995
0.989	0.1	1.012	0.447	7	2.239
0.977	0.2	1.023	0.398	7	2.512
0.966	0.3	1.035	0.355	9	2.818
0.955	0.4	1.047	0.316	10	3.162
0.944	0.5	1.059	0.251	12	3.981
0.933	0.6	1.072	0.200	14	5.012
0.923	0.7	1.084	1.158	16	6.310
0.912	0.8	1.096	0.126	18	7.943
0.902	0.9	1.109	0.100	20	10.000
0.891	1.0	1.122	0.0316	30	31.62
0.841	1.5	1.189	0.0100	40	100
0.794	2.0	1.259	0.0032	50	316.2
0.708	3.0	1.413	10^{-3}	60	10^{3}
0.631	4.0	1.585	10^{-4}	80	10^{4}
0.562	5.0	1.778	10^{-5}	100	10^{5}

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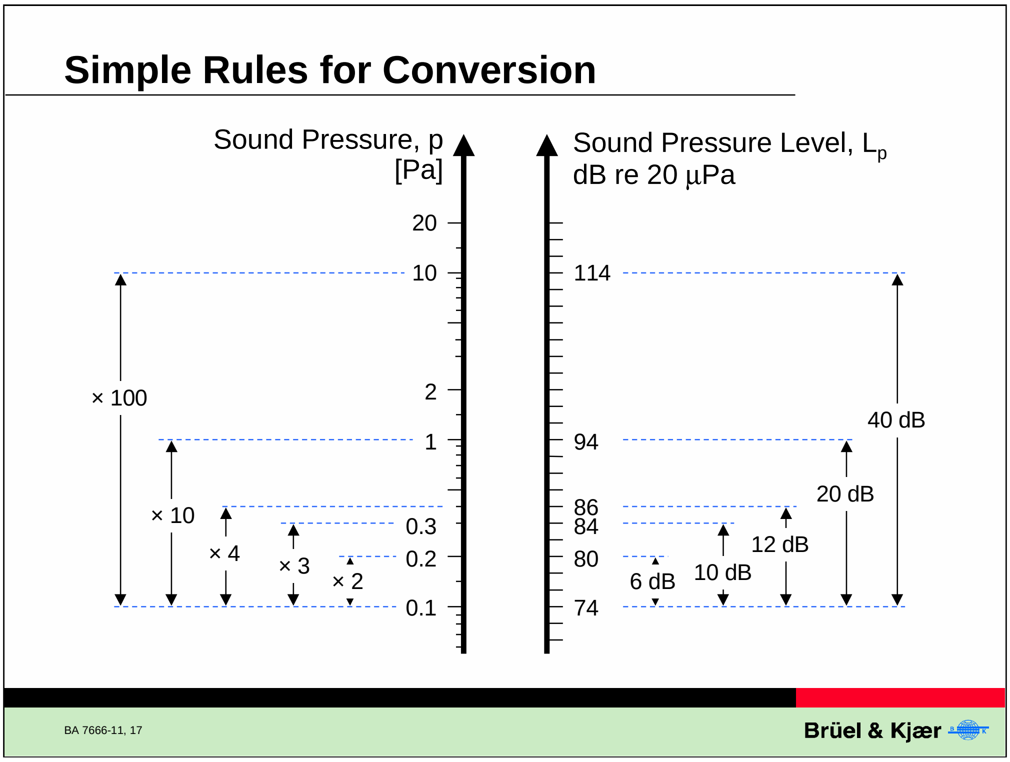
The conversion can also be made with the aid of a table as the one shown. Note that it operates with positive as well as negative dB values. For pressure ratios < 1 , values are negative and for pressure ratios > 1 , values are positive. When comparing two measured sound pressure levels, where the reference is the quietest, the source measured will have a positive dB value and vice versa.



When dealing with sound measurements, it is often useful to know some "rule of thumb" values for conversion between linear values and dB's. The most useful of these approximate values are shown in the illustration.

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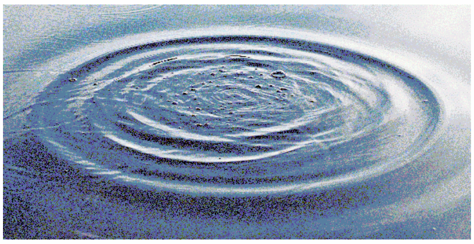

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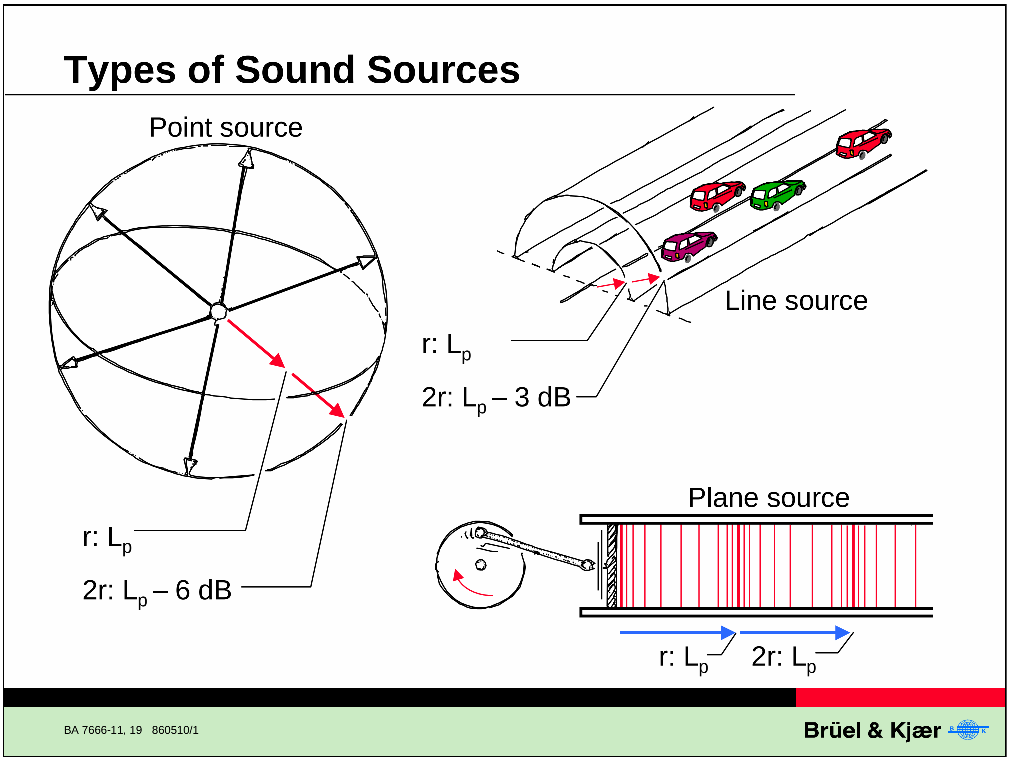
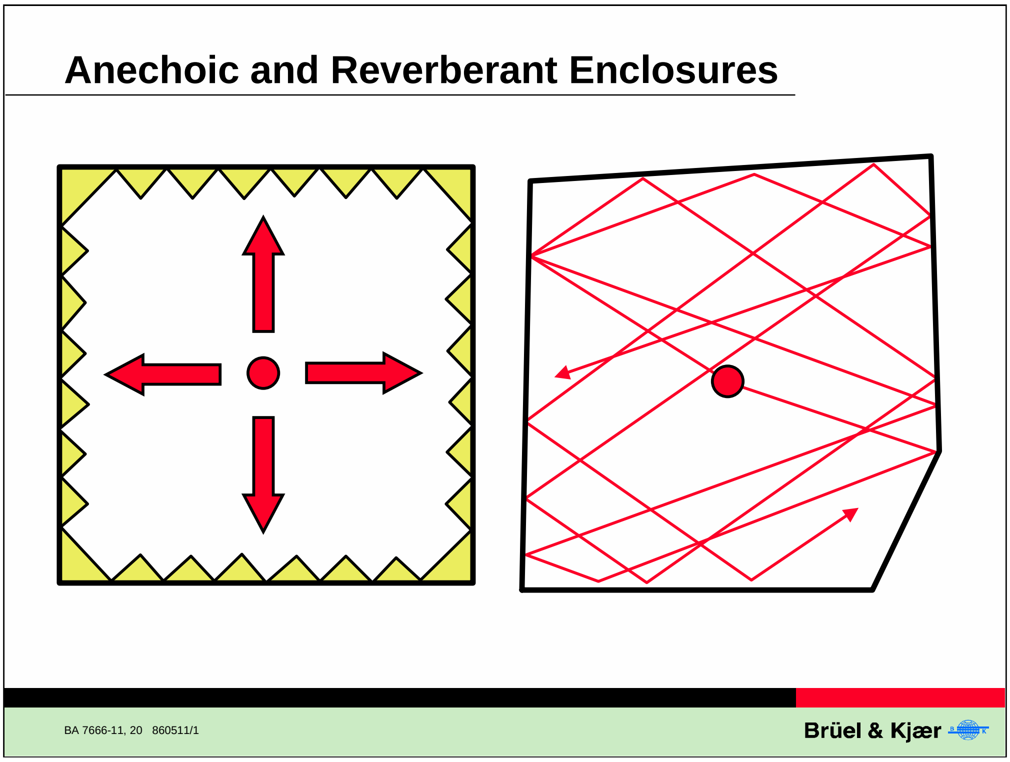


The source we looked at earlier is called a point source and for such a source it was mentioned that the sound pressure drops to half it's value when the distance to the source is doubled. This correspond to a drop in sound pressure of 6 dB.

Another type of source is the line source, which could be a pipe carrying a turbulent fluid, or a road with a high traffic flow. The sound pressure from a line source only drops by approximately 3 dB for a doubling of distance from the source, because the sound spreads out from the source as a wavefront in a direction perpendicular to the line source.

The most rarely found type of sound source when dealing with normal noise measurements is the plane source. A plane source will in principle consist of a piston from which energy is radiated into a tube setting up a plane wave in the tube. Assuming no loss of energy through the walls of the tube, the intensity, i.e. the acoustic energy flowing through the tube, is independent of the distance from the source. Since the intensity is the same everywhere in the tube, the sound pressure level will not drop with an increase in distance from the piston.

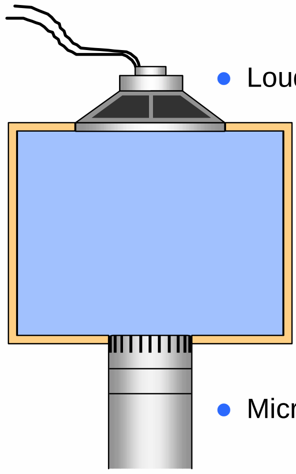


The sound energy will not always be allowed to radiate freely from the source. When sound radiated in a room reaches the surfaces, i.e. walls, ceiling and floor, some energy will be reflected and some will be absorbed by, and transmitted through the surfaces.

In a room with hard reflecting surfaces, all the energy will be reflected and a so-called diffuse field with sound energy uniformly distributed throughout the room is set up. Such a room is called a reverberation room.

In a room with highly absorbent surfaces all the energy will be absorbed by the surfaces and the noise energy in the room will spread away from the source as if the source was in a free field. Such a room is called an anechoic room.

Pressure Field



- Loudspeaker
- Enclosure
- Microphone

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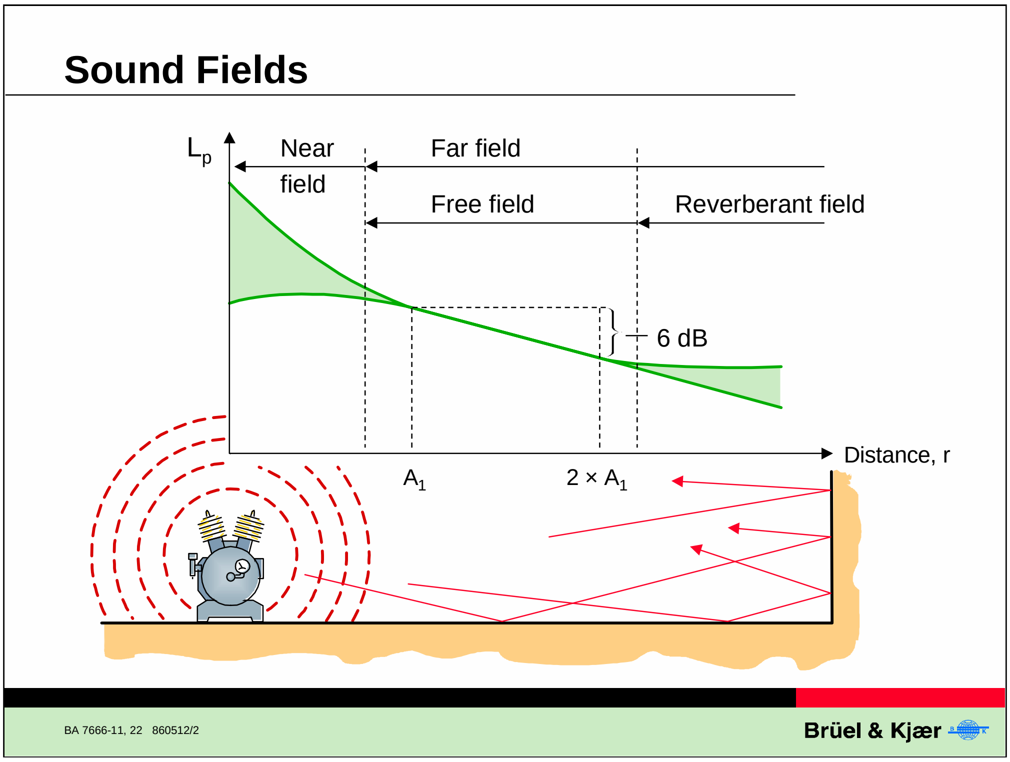
In a pressure field where the wavelength is long compared to the dimensions of the enclosure, the pressure is uniform in the enclosure. This is used in calibrators where an exact sound pressure is applied to an enclosure.



In practice, the majority of sound measurements are made in rooms that are neither anechoic nor reverberant - but somewhere in between. This makes it difficult to find the correct measuring positions where the noise emission from a given source must be measured.

It is normal practice to divide the area around a noise source e.g. a machine into four different fields:

Near field. Far field. Free field. Reverberant field.

The near field is the area very close to the machine where the sound pressure level may vary significantly with a small change in position. The area extends to a distance less than the wavelength of the lowest frequency emitted from the machine, or at less than twice the greatest dimension of the machine, whichever distance is the greater. Sound pressure measurements in this region should be avoided.

The far field is divided into the free field and the reverberant field.

In the free field the sound behaves as if in open air without reflecting surfaces to interfere with its propagation. This means, that in this region the sound level drops 6 dB for a doubling in distance from the source.

In the reverberant field, reflections from walls and other objects may be just as strong as the direct sound from the machine.

Directivity Index

Source Location	Directivity Factor	Directivity Index, dB	
Free field	1	0	$L = L_p$
On a flat plane	2	3	$L = L_p + 3$ dB
At a junction of two planes	4	6	$L = L_p + 6$ dB
At a junction of three planes	8	9	$L = L_p + 9$ dB

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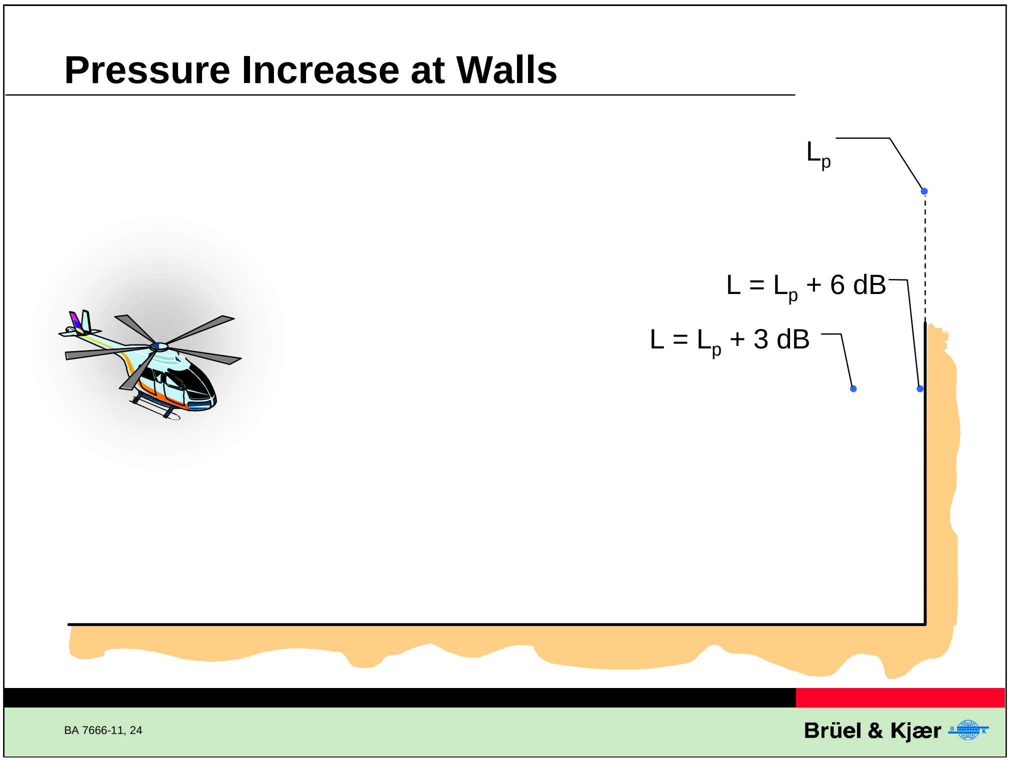
If a sound source is close to a plane the radiation will be over a hemisphere as the sound source is reflected from the plane. With two reflecting planes the emission will be similar to a1/2 hemisphere and with three reflecting planes to a 1/4 hemisphere. The sound pressure depends on the number of reflections and their magnitude.

The sound has a directivity factor Q and a corresponding Directivity Index (dB).



The sound pressure L_p close to a reflecting surface will be 'mirrored' and should be considered as two pressure levels with same magnitude and phase. Thus the sound pressure close to the surface L will be doubled:

$$L = L_p + 6\text{dB}$$

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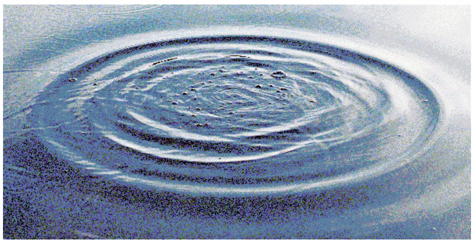

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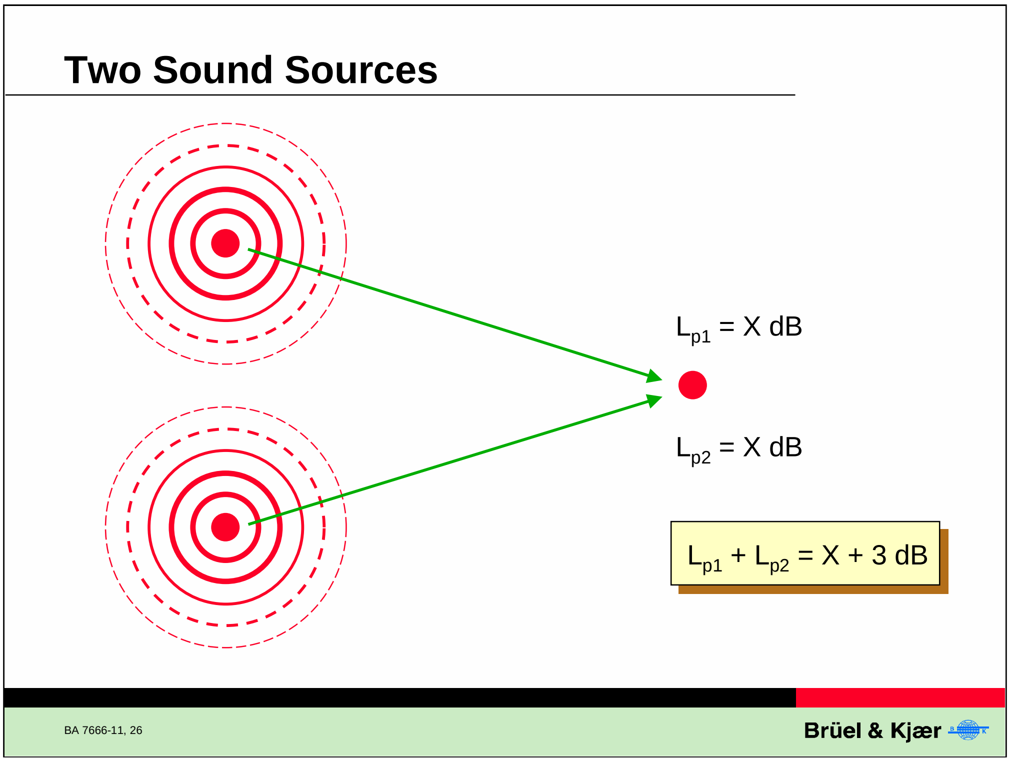
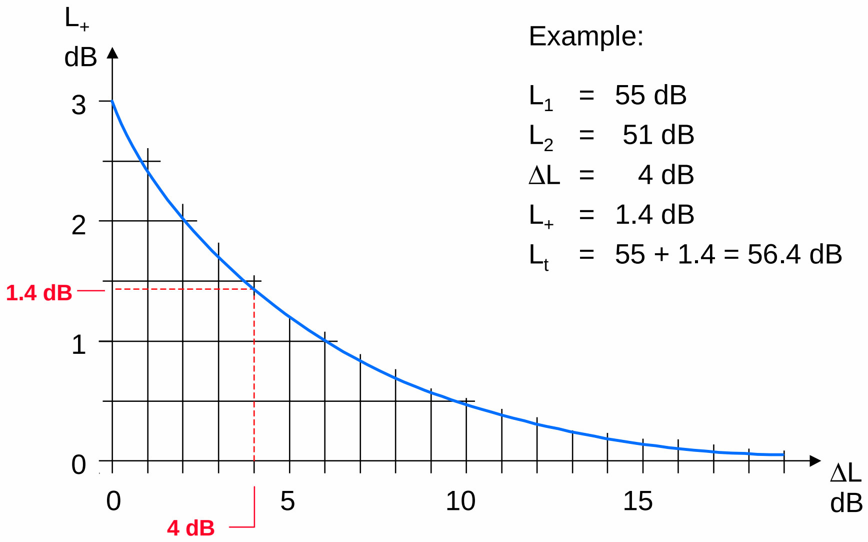


When two sound sources radiate sound energy, they both contribute to the sound pressure level at distances away from the sources.

If they radiate the same amount of energy, and a point equidistant from both sources is considered, then the sound intensity at that point will be twice as high as when only one source is radiating. Since intensity is proportional to pressure squared a doubling in intensity results in an increase in sound pressure of $\sqrt{2}$ corresponding to 3 dB.

Note that the result when adding the contribution from two (or more) sound sources is not the numerical sum of the individual dB values. The reason is that sounds from more than one source combine on an energy basis. In the example here, if x is 50 dB the total sound pressure level when both sources are operating will be 53 dB.

Addition of dB Levels



Example:

L_1 = 55 dB
L_2 = 51 dB
ΔL = 4 dB
L_+ = 1.4 dB
L_t = 55 + 1.4 = 56.4 dB

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If the contribution from the two sources differ, the total sound pressure level can be found by converting the individual dB values to linear values, adding these and converting back to dB. But a somewhat easier method is to use this simple curve for addition of dB levels.

To use the curve proceed as follows:

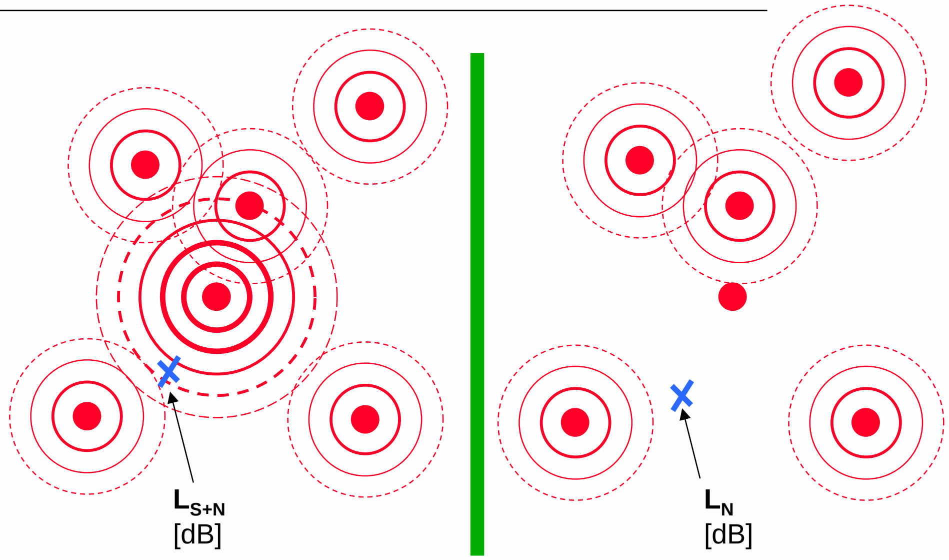
1. Calculate the difference, Δ L, between the two sound pressure levels.
2. Use the curve to find L_+.
3. Add L_+ to the highest level to get L_t, the total level.

In the example shown here $\Delta L = 4$ dB whereby L_+ is found to be 1.4 dB and $L_t = 56.4$ dB.

Note that a difference of $\Delta L = 0$ corresponds to the situation shown in the previous illustration where 3 dB was added to the level caused by one source alone.

If the difference between the two sound pressure levels is more than 10 dB the contribution from the quietest source can be discarded.

Subtraction of Noise Levels



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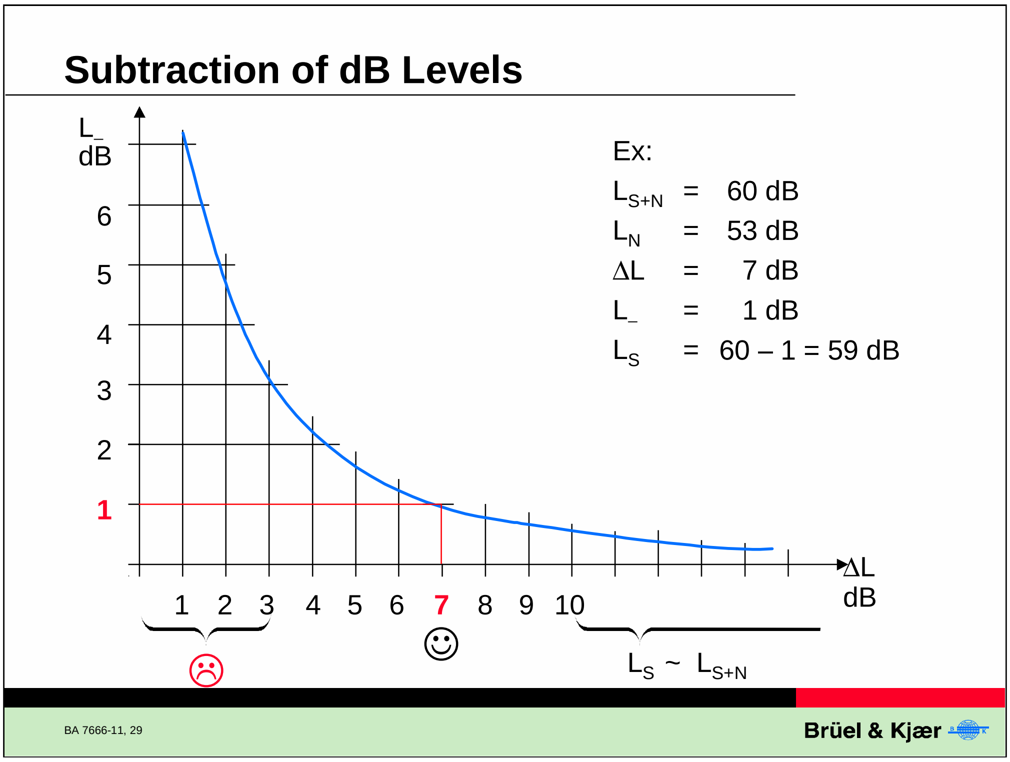
In some cases it is necessary to subtract noise levels. This could, for example, be the case where noise measurements on a particular machine are carried out in the presence of background noise. It is then important to know if the measured noise is due to the background noise, the noise from the machine, or the combined influence. The procedure when performing the test is as follows:

1. Measure the combined effect of machine noise and background noise, L_{S+N}.

2. Switch off the machine and measure the background noise, L_N. In most cases it is possible to switch off the machine under test, whereas the background noise normally cannot be switched off.

3. Finally calculate the difference, $\Delta L = L_{S+N} - L_N$ and use the following simple curve to find the correct noise level caused by the machine.



If Δ L is less than 3 dB, the background noise is too high for an accurate measurement and the correct noise level cannot be found until the background noise has been reduced. If on the other hand the difference is more than 10 dB, the background noise can be ignored. If the difference is between 3 dB and 10 dB, the correct noise level can be found by entering the value of ΔL on the horizontal axes and read the correction value, L_- off the vertical axes. The correct noise level caused by the machine is now found by subtracting L_- from L_{S+N}.

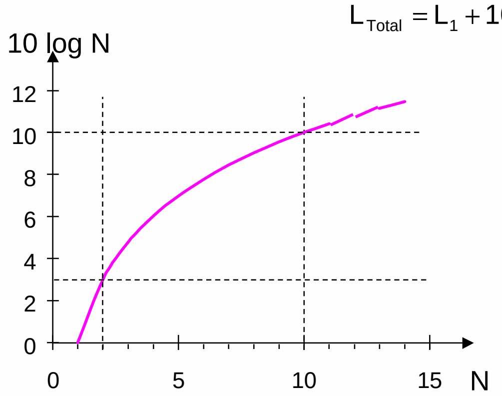
The illustration shows a practical example.

Addition of many dB values

Addition of sound levels : $L_1 + L_2 ..... + L_N = ?$

For $L_1 = L_2 = L_3..... = L_N$

$L_{Total} = L_1 + 10 \log N$



Examples:

N = 2: $L_{Total} = L_1 + 3$ dB

N = 10: $L_{Total} = L_1 + 10$ dB

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Addition of many dB values is done using the following equation:

$$L_{Total} = 10 \log (10^{0.1\,L1} + 10^{0.1\,L2} + 10^{0.1L3} .... + 10^{0.1Ln})$$

For equal levels the curve for adding values can be used.

Conclusion

- Sound pressure level in dB is related to 2 * 10 $^{-5}$ Pascal.
- The range of human hearing is 130 dB.
- To add or subtract dB-values use charts or formulas

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Sound Pressure Level = $10\log (P/P_0)^2$

The range of human hearing is from 0 dB (2 × 10 $^{-5}$ Pa = Threshold of hearing) to 130 dB (Threshold of pain)

Literature for Further Reading

- Acoustic Noise Measurements
  Brüel & Kjær (BT 0010-12)
- Noise Control - Principles and Practice
  Brüel & Kjær (188-81)