Measuring Sound

Contents:

- The Microphone
- The Sound Level Meter
- L_{eq}
- Statistics and Noise Dose

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Abstract

This gives an overview of how sound is measured and an explanation of some of the primary parameters used to describe sound.

LECTURE NOTE

English BA 7667-11

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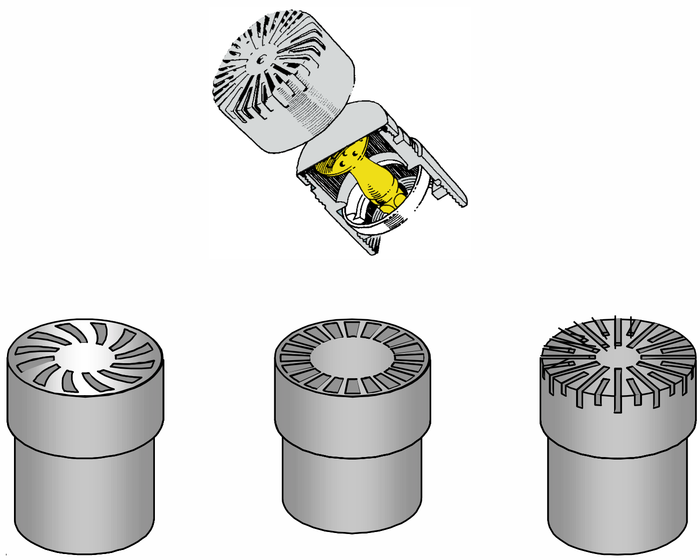
Measuring Microphones

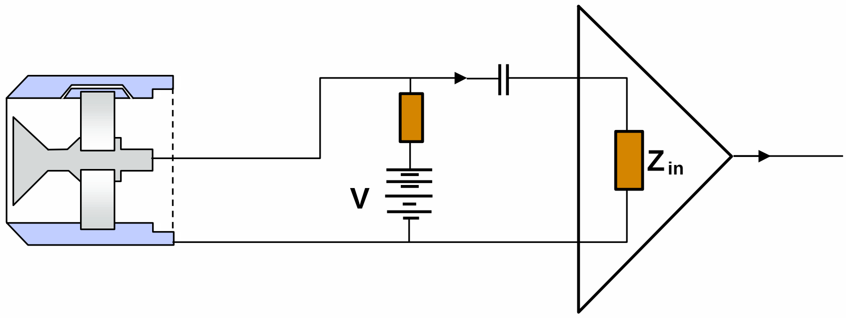


Introduction

The condenser microphone is to-day accepted as the standard acoustical transducer for all sound and noise measurement because of its very high degree of accuracy; an accuracy which is higher than what is possible with any other acoustical transducer. Not only is the condenser microphone an accurate laboratory tool used by standards laboratories, it is also used for a broad range of field measurements under many different and often severe environmental conditions.

The Polarised Condenser Microphone

Principle of Operation



$$\left.\begin{aligned} Q &= CV \\ C &= \varepsilon\frac{A}{d} \end{aligned}\right\} \Rightarrow V = \frac{Q}{C} = \frac{Q}{\varepsilon A}d \Rightarrow \Delta V = \frac{Q}{\varepsilon A}\Delta d$$

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Principle of Operation for the Polarised Condenser Microphone

The microphone consists of a thin metallic diaphragm in close proximity to a rigid backplate. This forms an air dielectric capacitor whose capacitance is variable since the diaphragm moves when excited by external forces such as a sound wave. The variable capacitance is changed into an electric signal in the following way:

Combining the formulae Q=CV and C=εA/d gives V=Q/C = (Q/εA)d

where Q = Charge on backplate, C = Microphone Capacitance, V = Polarisation Voltage, A = Area of Microphone, d = Distance between diaphragm and backplate.

A change in distance between diaphragm and backplate, d, is converted into a change in voltage: ΔV=Q/C = (Q/εA)Δd

The microphone will work according to the theory provided that Q is held constant. This required constant charge can be provided by connecting a DC voltage through a very high impedance charging resistor. This in combination with the capacitance of the microphone gives a long time constant compared to the period of the sound waves. Hence, practically no current will flow through the charging resistor – the criterion for conservation of charge. By connection of the condenser microphone to an amplifier via a coupling capacitor the DC voltage is removed, leaving the AC voltage which is an electrical replica of the sound pressure variations.

In order for the diaphragm to move, a pressure difference must exist between the front and back of the diaphragm. If the air behind the diaphragm were in direct communication with the outside, the instantaneous pressure on both sides of the diaphragm would be the same and no diaphragm motion would occur. The pressure inside the microphone must therefore be kept constant which is achieved by sealing the cavity except for a small vent to equalize the static pressure.

How much does the diaphragm move ?

$$\frac{\Delta V}{V} = \frac{\Delta d}{d}$$

For typical measurement microphone:

- diameter 12.5 mm
- thickness of diaphragm 5 µm
- distance between diaphragm and backplate 20 µm
- polarisation voltage 200 V
- sensitivity 50 mV/Pa

For 94 dB = 1 Pa the diaphragm moves

$$\Delta d = \frac{\Delta V \times d}{V} = \frac{50\ \text{mV} \times 20\ \mu\text{m}}{200\ \text{V}} = 5\ \text{nm}$$

Diameter of diaphragm	Pressure (level re 20µPa	Diaphragm's movement
12.5mm	1Pa (94dB)	5nm (5×10^{-9} m)
12.5mm	0.02Pa (60dB)	1 Å (10^{-10} m)
12500km (thickness of diaphragm 5km)	0.02Pa (60dB) 0.0002Pa (20dB)	0.1m (10^{-1} m) 0.001m (10^{-3} m)

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How much does the diaphragm move?

Take an example based on microphone 4190 and use the relationship ΔV/V = Δd/d you will be surprised at the results.

Requirements for microphone diaphragms are that:

1. The ratio of the elasticity of the diaphragm to the density should be a maximum. Ideally it should be massless! The greater its mass the more the device operates as an accelerometer and less as a microphone.

2. Corrosion resistant.

3. Temperature coefficient should be the same as the housing.

4. The mechanical characteristics should be stable with time.

There are many possible candidates each with advantages and disadvantages. Examples of materials which have been used are steel, steel alloys, nickel, palladium, titanium, monel, and beryllium.

Brüel & Kjær traditional microphones use mostly nickel, or nickel coated with a thin layer of quartz or with a layer of hyperlon. Brüel & Kjær Falcon™ range use a stainless steel alloy. By looking at a microphone diaphragm, one can see whether it is:

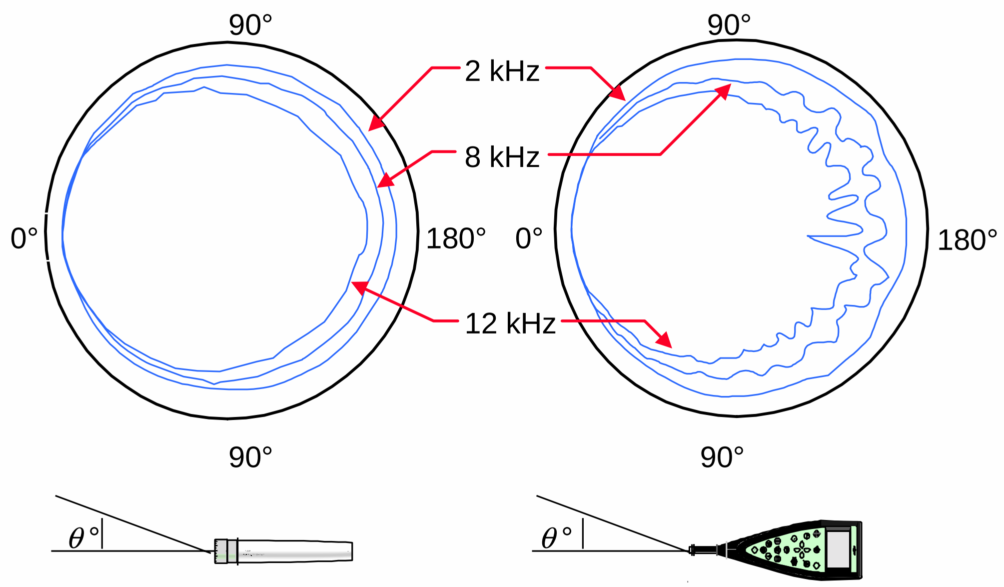
1. Pure nickel (in which case it will give a clear specular [mirror-like] reflection).

2. Nickel with a coating of quartz (diffraction causes rainbow colours to be seen on the diaphragm).

3. Nickel with a coating of hyperlon (the diaphragm appears yellowish and looks greasy).

4. Stainless steel alloy (the diaphragm appears greyish relative to a nickel diaphragm).

Directional Characteristics



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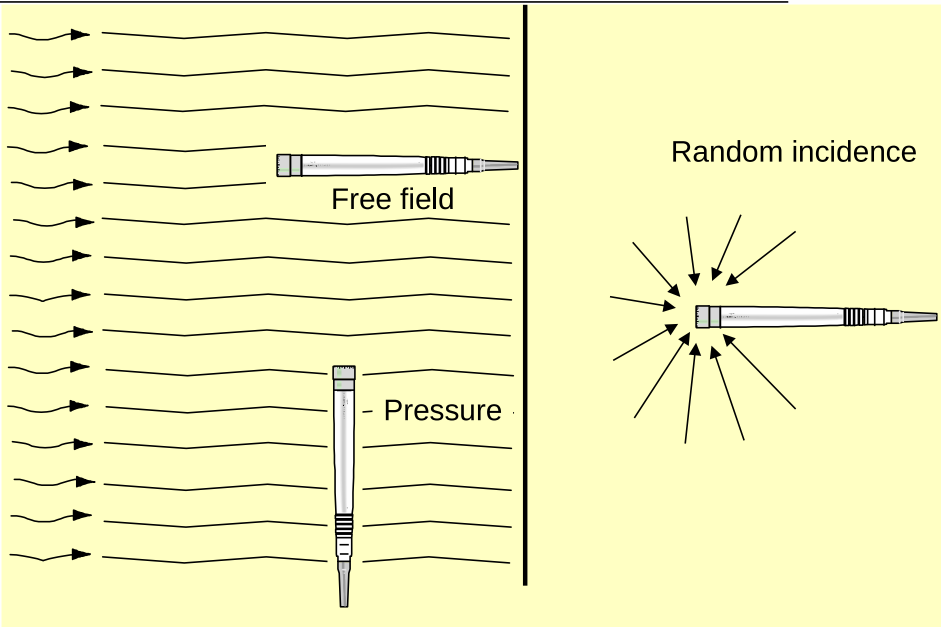
Directional Characteristics

The microphone will not respond equally well to sound coming from different directions with different angles of incidence. At low frequency the microphone is nearly perfectly omnidirectional, whereas for high frequencies the sensitivity to sound coming from behind the microphone is considerably reduced.

Comparing the characteristics of the microphone alone and when mounted on a sound level meter, it is clearly seen that the sound level meter case affects the directional characteristics. This also gives an indication of how the presence of the operator will affect measurement, a topic which is discussed later in the lecture “Noise Measurement and Documentation”.

Types of Microphones



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Types of Microphones

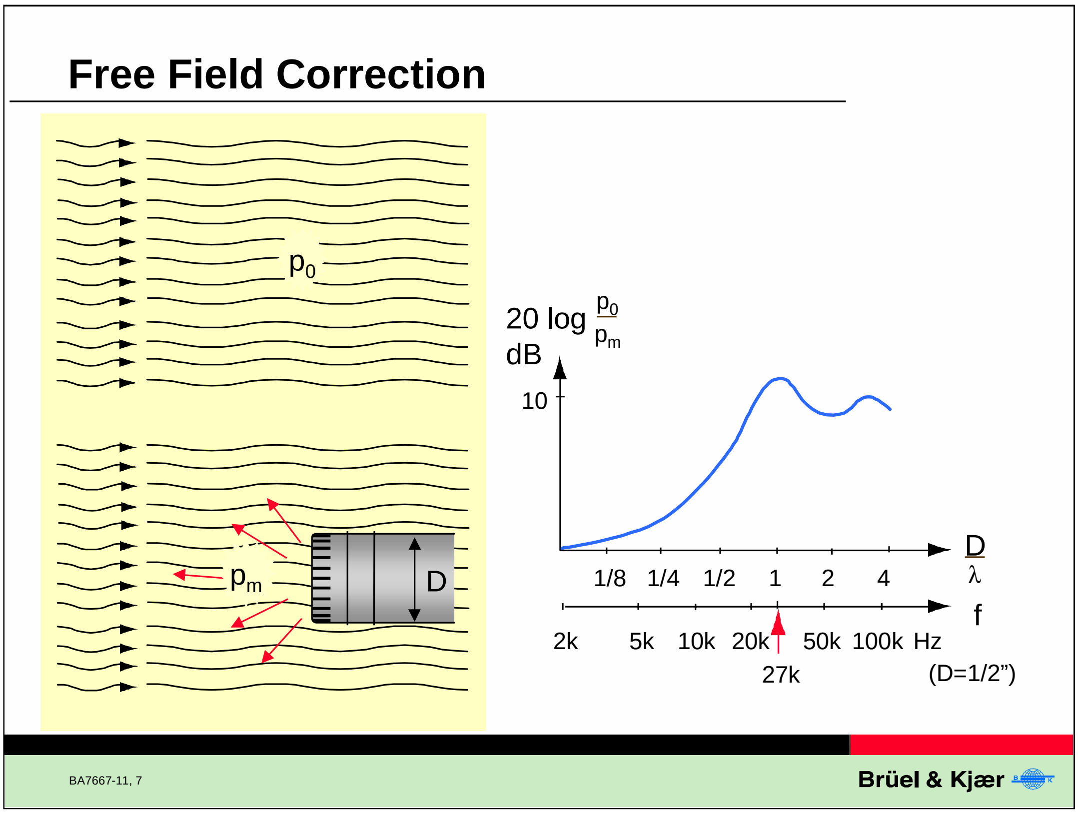
Microphones are divided into 3 types according to their response in the sound field: free field, pressure, and random incidence.

Free field microphones have uniform frequency response for the sound pressure that existed before the microphone was introduced into the sound field. It is of importance to note that any microphone will disturb the sound field, but the free field microphone is designed to compensate for its own disturbing presence as discussed later.

The pressure microphone is designed to have a uniform frequency response to the actual sound level present. When the pressure microphone is used for measurement in a free sound field, it should be oriented at a 90° angle to the direction of the sound propagation, so that the sound grazes the front of the microphone.

The random incidence microphone is designed to respond uniformly to signals arriving simultaneously from all angles. When used in a free field it should be oriented at an angle of 70° – 80° to the direction of propagation.

In the following, we will have a closer look at the reason for the difference between the microphones and when each type should be used.

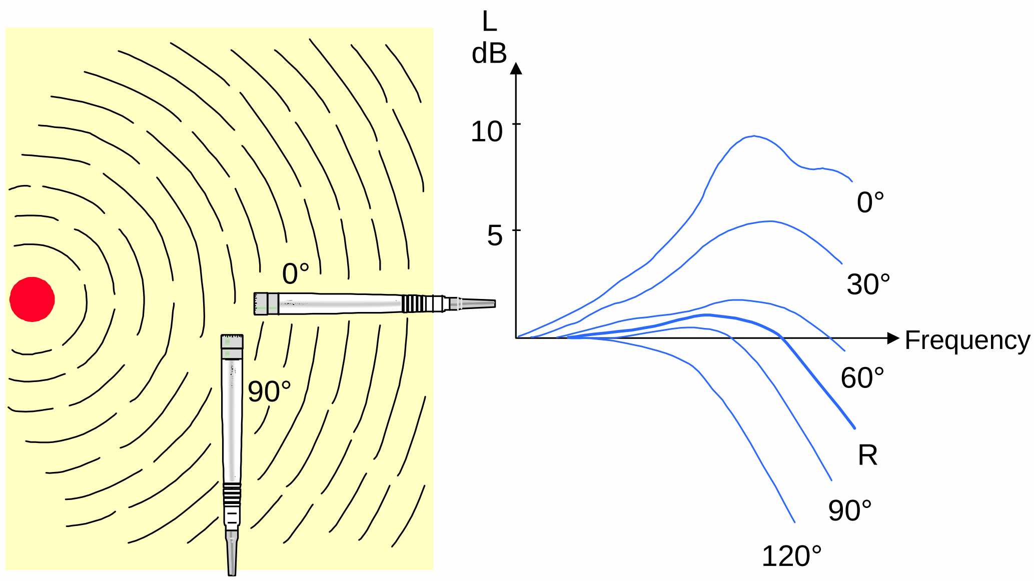


Free Field Correction

When a microphone is placed in a sound field, it modifies the field. The illustration shows a free field where sound comes from only one direction. The sound pressure in this field without the microphone is called p_0.

When the microphone is placed in the field a pressure rise will take place in front of the microphone caused by local reflections and the microphone will measure too high a sound pressure pm. This rise in “sensitivity” is frequency dependent, with a maximum at the frequency where the wavelength is equal to the diameter of the microphone, D/λ. If the corresponding frequency axis for a 1/2" microphone is plotted along the D/λ axis it is seen that the increase starts at 2 kHz with a maximum of approximately 10 dB at 27 kHz.

Free Field Correction



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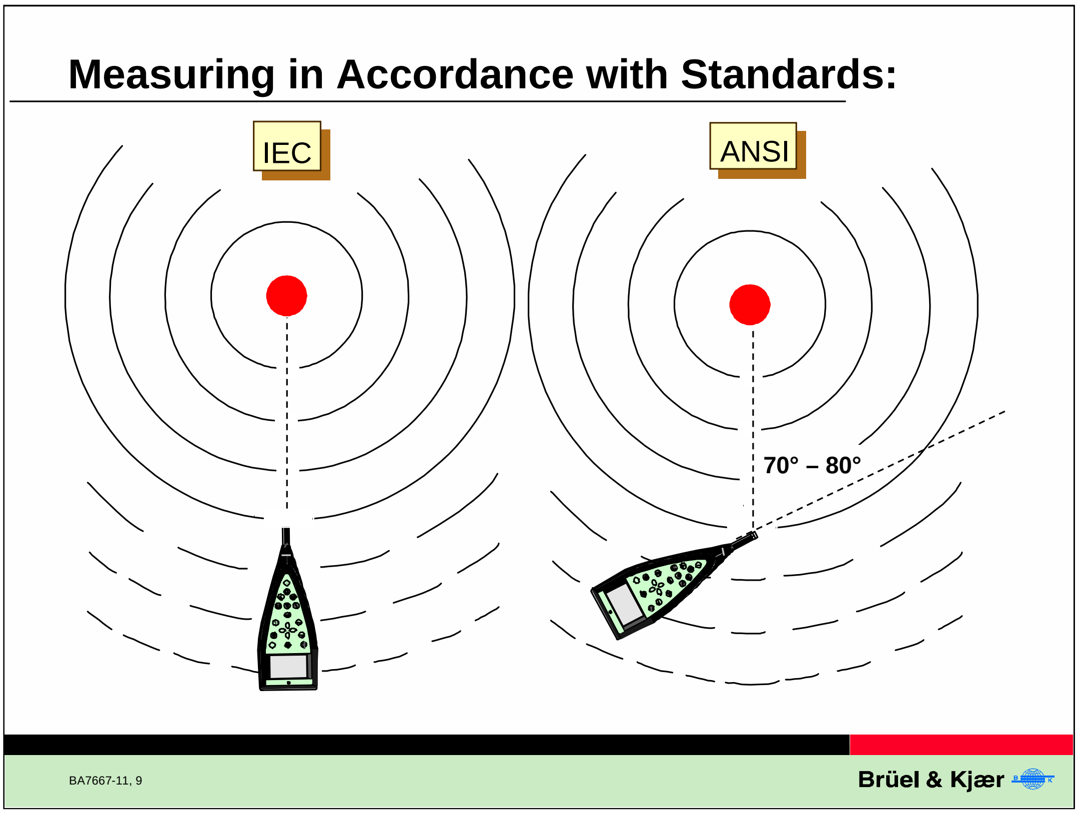
The biggest increase in “sensitivity” is obtained when the sound wave comes from a direction perpendicular to the diaphragm (defined as 0° incidence). At all other angles the increase will be less pronounced as shown here. The curve labeled R, which stands for random incidence, is a calculated average response to sound arriving with equal probability from all directions.

The free field correction curves shown are typical, as they not only depend on the diameter of the microphone but also to some extent on the design of the microphone’s protection grid, and to a very small degree the acoustical impedance of the diaphragm.

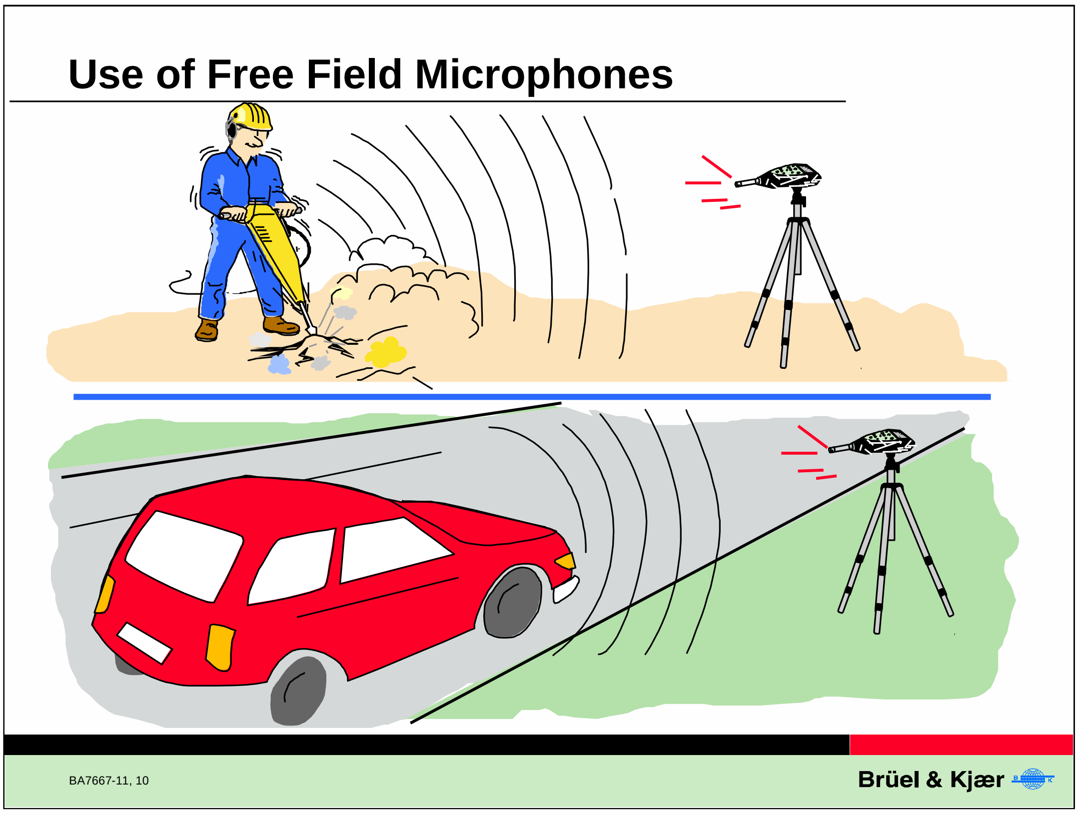
In a sound field where the sound comes mainly from one direction, the free field correction must be applied to all microphones independent of their type. This is shown in the following.



Measuring in Accordance with Standards: IEC or ANSI

The two most important standards governing the design of sound level meters are the IEC Publication 651 and the American National Standard ANSI S 1.4. For practical purposes the two standards are completely alike – except for the direction of incidence of the sound field. The IEC specifies use of free field microphones and ANSI use of random incidence microphones. This means that when sound level measurements are made in accordance with IEC a free field microphone should be used, and the sound level meter pointed towards the source (0° incidence). When measurements are made in accordance with ANSI a random incidence microphone should be used, and the sound level meter held at an angle of 70° – 80° to the direction of incidence.

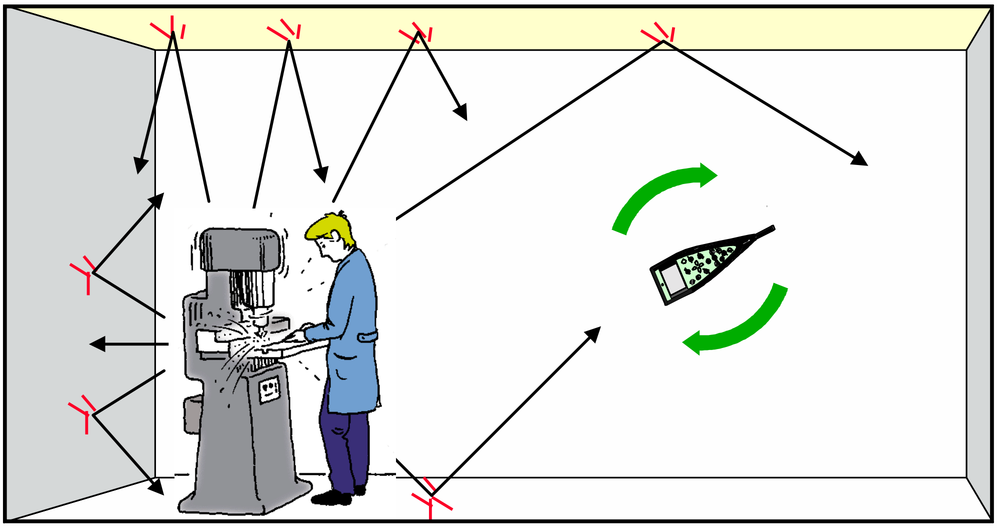
It would be desirable if forthcoming standards specify both the free field and the random incidence microphone as standard, and indicate when each should be used. For many sound level meters used today, the response of the microphone can be changed either by the use of small corrector fitted on the microphone or electronically in the sound level meter.



Use of Free Field Microphones

The free field microphone is used in all applications where the sound mainly comes from one direction. Therefore the microphone must be pointed directly at the sound source during a measurement. Typical applications of the free field microphone are in outdoor measurements and for measurements indoors where there are very few or no reflections, so that the sound is mainly from one direction only. An example of the latter is measurements in an anechoic chamber where a free field microphone should always be used.

Use of Random Incidence Microphones



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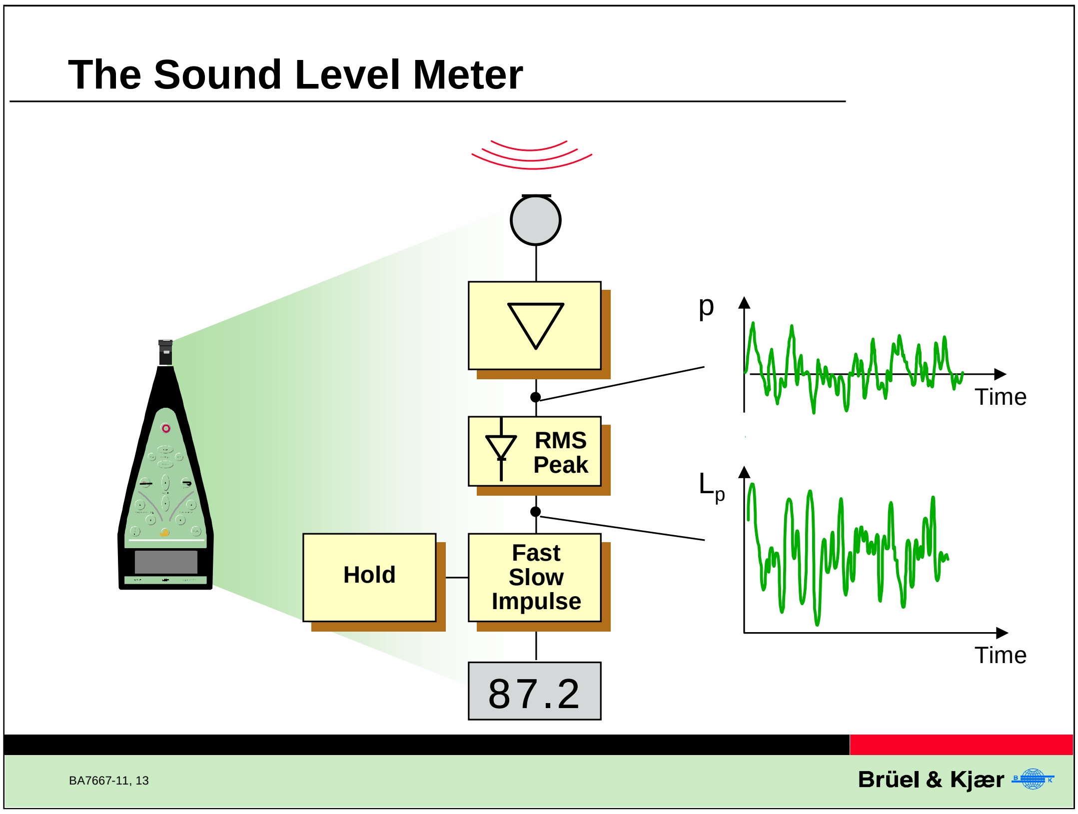
Use of Random Incidence Microphones

The random incidence microphone is designed to respond uniformly to signals arriving simultaneously from all angles. It should therefore not only be used for measurement in reverberation chambers, but in all situations where the sound field is a diffuse sound field e.g. in many indoor situations where the sound is being reflected by walls, ceilings, and objects in the room. Also in situations where several sources are contributing to the sound pressure at the measurement position, a random incidence microphone should be used.

Measuring Sound

Contents:

- The Microphone
- The Sound Level Meter
- L_{eq}
- Statistics and Noise Dose



The sound level meter is an integral measurement unit which can provide you with a readout of the noise levels in a standardised form.

It consists of a:

• microphone

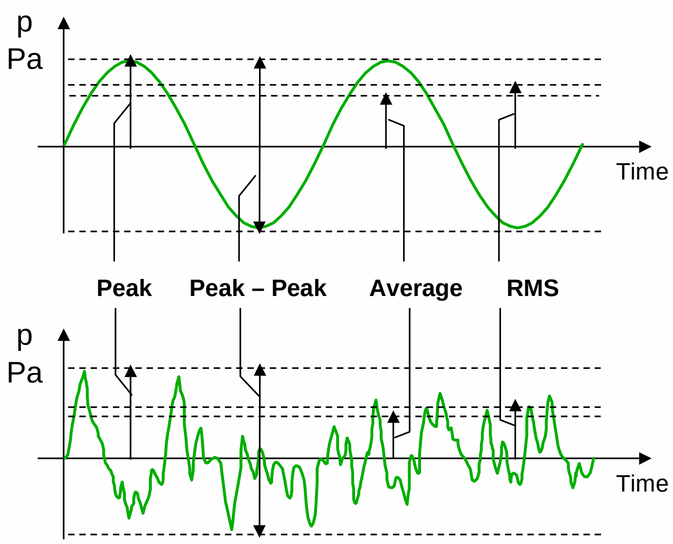
• preamplifier

• detectors to give the RMS and Peak levels of the signal (shown here as the square root of the square of the signal)

• standardised time weightings (see later) with hold functions

• display

Sound Level Parameters



RMS = $\sqrt{\frac{1}{T}\int_0^T x^2(t)dt}$

Average = $\frac{1}{T}\int_0^T |x|dt$

Crest factor = $\frac{\text{Peak}}{\text{RMS}}$

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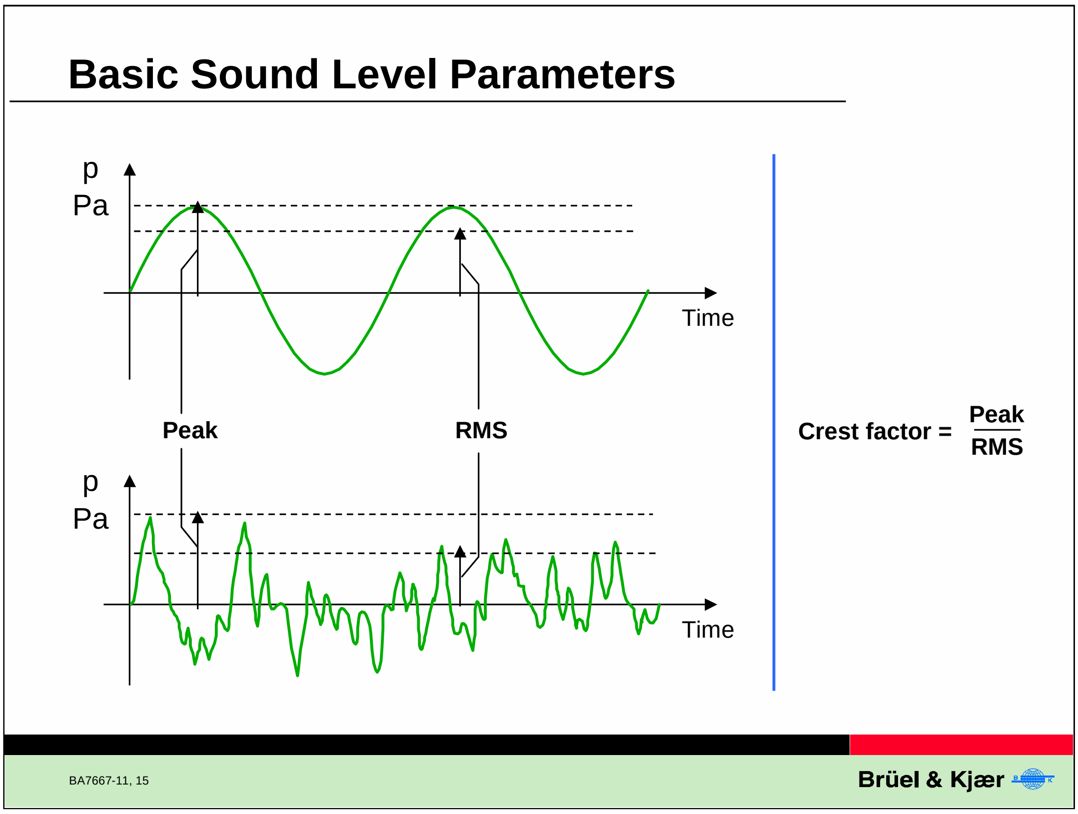
Here you can see several ways of describing a signal.

The most frequently used are the Peak and the RMS (root mean squared).

The average is not used as does not give meaningful information about the signal.

The Peak is the maximum value (positive or negative) of the signal.

The crest factor indicates how sinusoidal the signal is - a signal with a few high peaks will have a large crest factor.

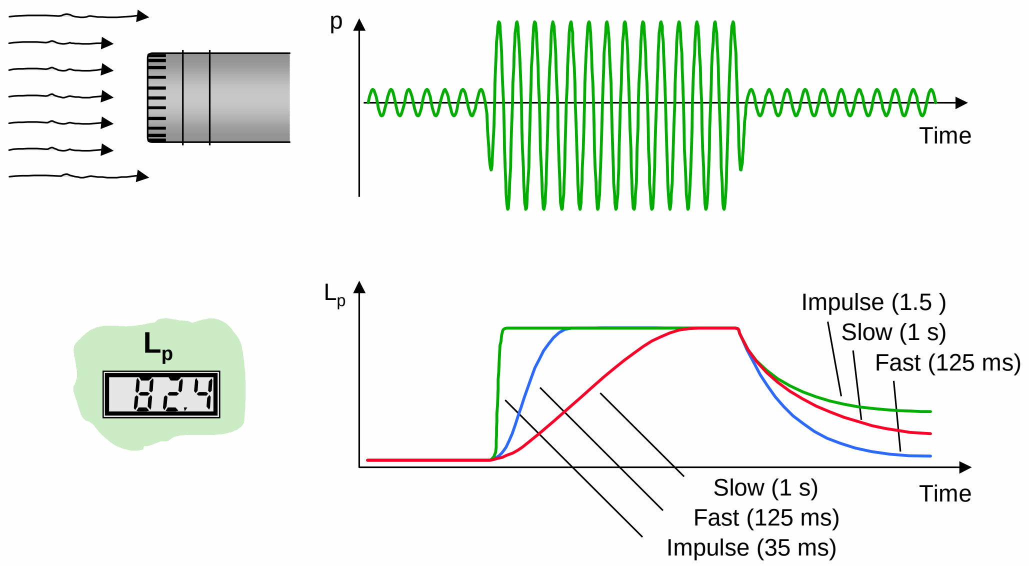


Here you can see the usual ways of describing a signal - the Peak and the RMS (root mean squared).

The Peak is the maximum value (positive or negative) of the signal.

The crest factor indicates how sinusoidal the signal is - a signal with a few high peaks will have a large crest factor.

Time Weighting



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Tone burst response of time weightings standardized by the International Electrotechnical Commission (IEC).

All time weightings give same levels with a long enough signal.

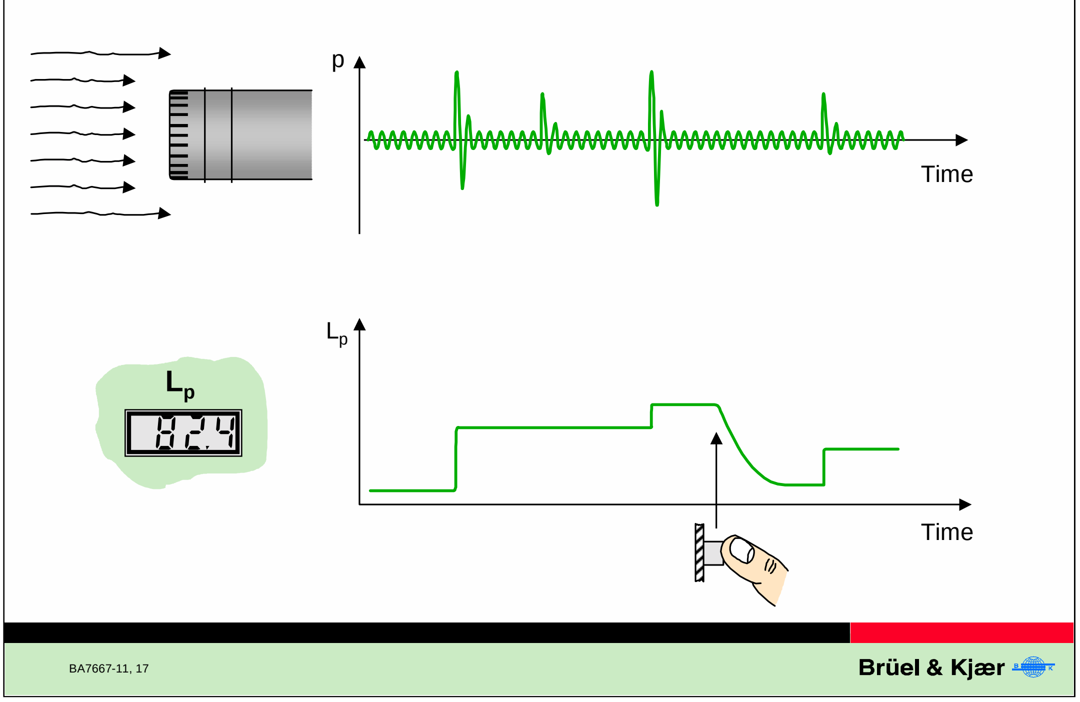
Time weightings operate on the RMS signal.

F, S have equal rise & decay times.

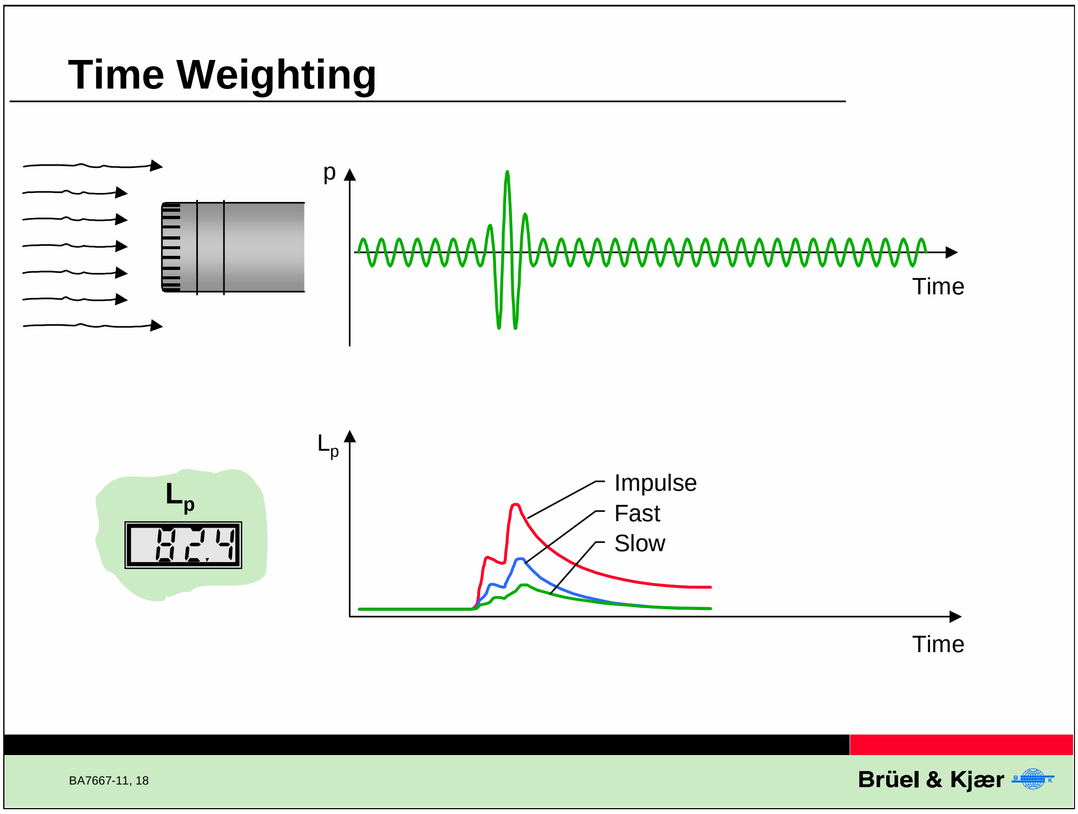
I has fast rise and slow decay (from earlier moving coil meters to enable reading of impulse levels).

F, S mostly used today.

Peak Hold



Similarly, the Peak is also defined with very fast rise and decay times (in µs). Normally, in modern sound level meters, a hold function is available so that you can see the maximum peak level of a signal. This normally includes a reset function.

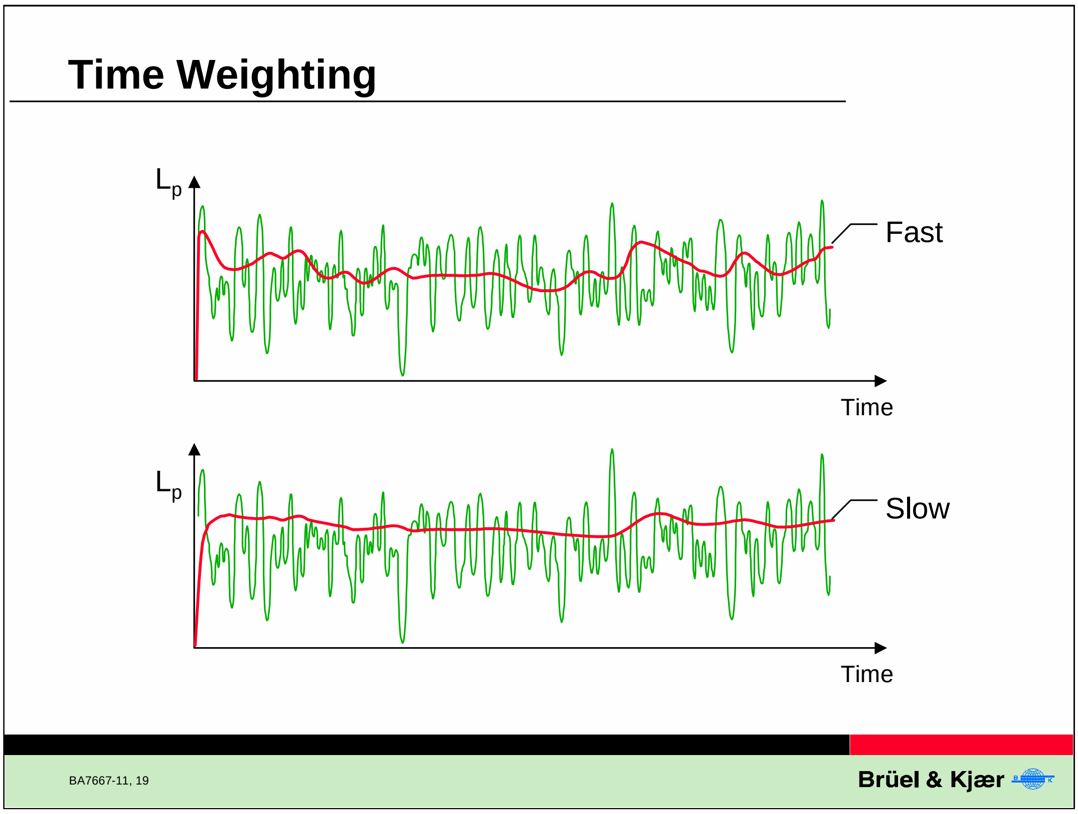


Impulse response of time weightings:

A short (impulsive) signal will give different levels with different time weightings.

Impulse will be highest and will be held longest.

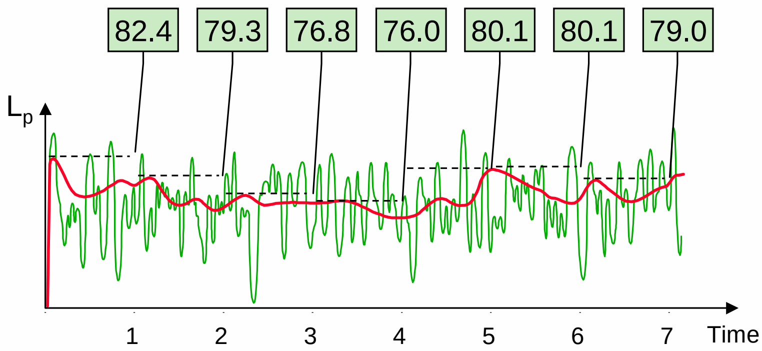
Fast will give a bigger level than Slow which has a slower response.



Here you can see the effects of Fast and Slow time weightings on the resulting level (red line) of a real input signal (green line).

The Fast weighted level follows the input signal more closely than the Slow weighted signal.

The Digital Display



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Shown here is Sound Pressure Level (max within 1 s).

Another similar parameter is Instantaneous (last sample in second)

Usually, Sound Pressure Level (SPL) is preferred. In Japan, Instantaneous is preferred.

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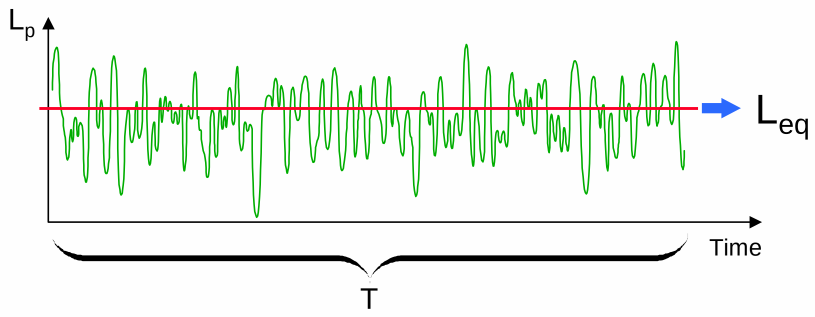
L_{eq} is a parameter which is used to describe fluctuating noise.

Equivalent Level, L_{eq}

$$L_{eq} = 10 \log_{10} \frac{1}{T} \int_0^T \left(\frac{p(t)}{p_0} \right)^2 dt$$



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The equivalent Sound Level L_{eq} is an electronically calculated mean RMS level which integrates all the energy in a signal measured over a certain time period, T. L_{eq} can be considered as the continuous noise which would have the same total acoustic energy as the real fluctuating noise measured over the same period of time. The mathematical definition of L_{eq} is as shown in the illustration where:

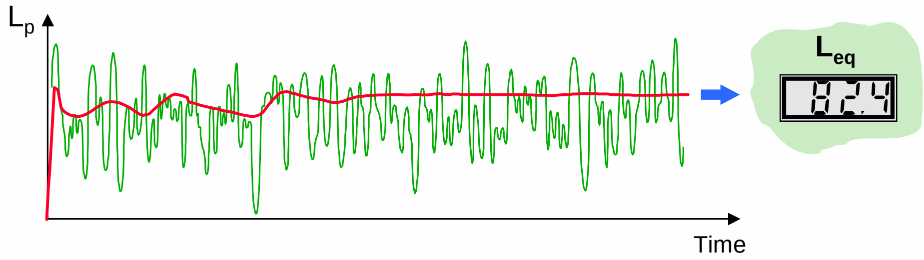
T is the total measurement time

p(t) is the instantaneous sound pressure

p_0 is the reference sound pressure (20 µPa)

Most often, the instantaneous sound pressure is A-weighted and the unit of L_{eq} therefore becomes dB(A).

Measuring L_{eq}



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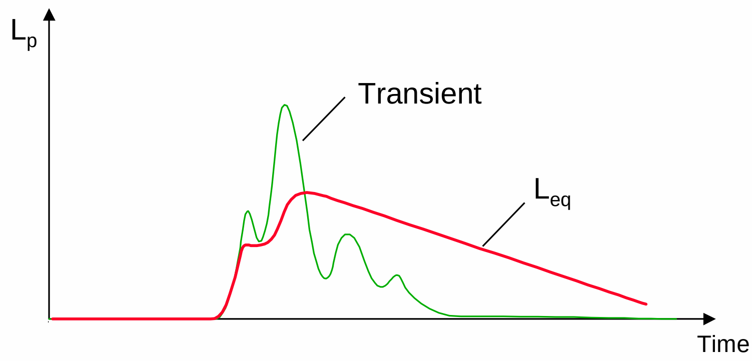
At the start of a measurement, the L_{eq} (red line) is 0, it then quickly rises and follows the signal (green line). As it is averaged over the entire measurement time, the variation of the L_{eq} becomes less and less.

You can see that the variations of the L_{eq} are larger at the start of the measurement period than later on.

You can use the fact that the L_{eq} stabilises to determine when your measurement is complete. A stable level indicates a representative measurement.

L_{eq} for Transient Noise



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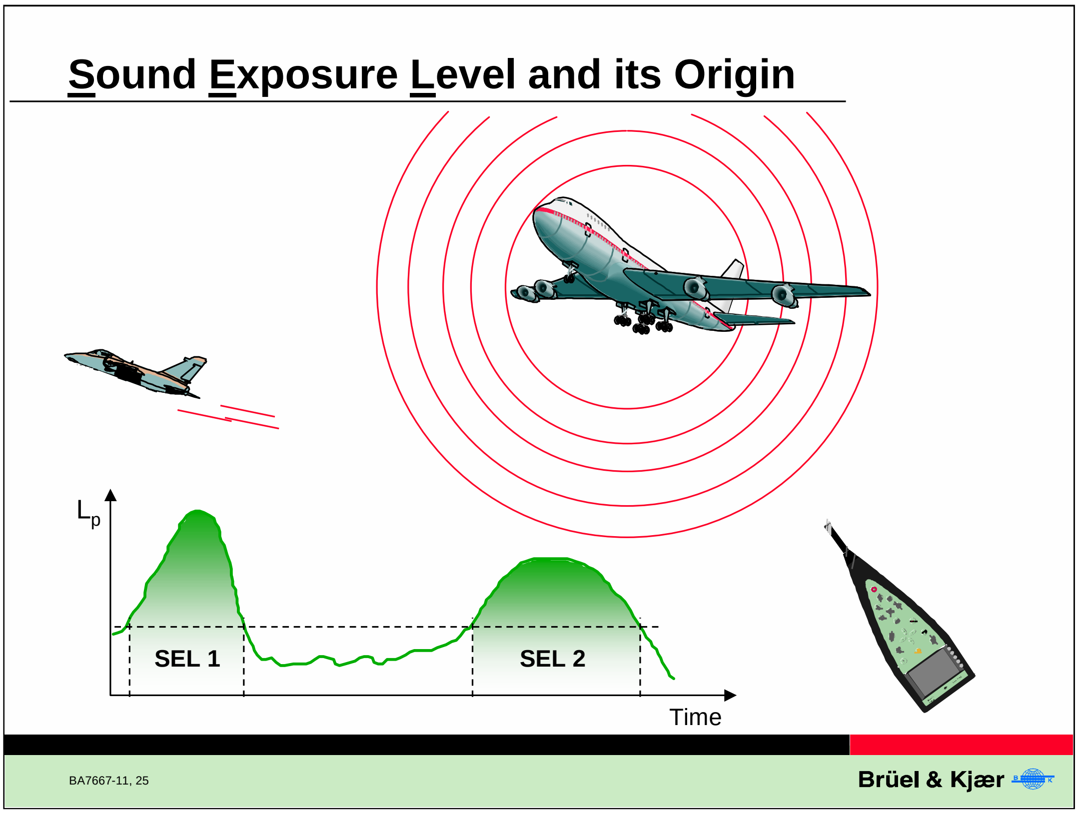
This is how the L_{eq} will develop in the event of a transient (short duration) noise. As in the previous slide the average energy, and thereby the L_{eq}, will increase at the onset of the transient. When the transient has passed, the average energy will decrease and thus the L_{eq} will also decrease with time.



Origin of SEL

The origin of SEL lies in describing aircraft fly-over noise where each fly-over is regarded as a single event for which the SEL gives just one single value. A series of SEL values from corresponding aircraft fly-overs can later be compared or combined, to give an overall SEL value. L_{eq} cannot be used for comparison, as you may have two different levels over two different times.

With the advent of integrating sound level meters which can display the SEL value directly, SEL has found widespread use in other fields for comparison of single events e.g. for comparison and combination of the noise from different workshop operations.

Sound Exposure Level, SEL

$$SEL = L_{eq} + 10 \log\left(\frac{t}{1s}\right)$$

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Sound Exposure Level SEL

The quantity SEL (Sound Exposure Level) is defined as that constant sound level in dB(A) which would dissipate the same amount of sound energy in one second as the original noise event.

Many integrating sound level meters can calculate and display the SEL directly. The calculation is based on the L_{eq} value to which is added a term 10 log (t/1s) normalising the measured L_{eq} value to a time period of one second. In other words all SEL values represent the sound energy of a time period of one second and they can therefore be compared directly. The advantage of SEL compared with L_{eq} is that the measured event can have any duration and the measured levels can still be compared directly.

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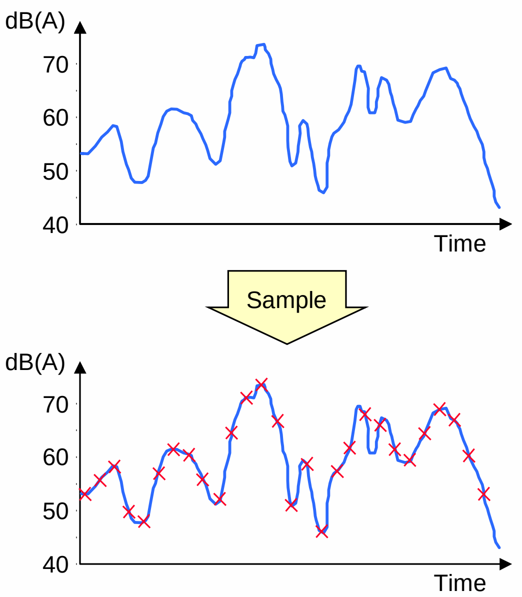
Statistics are another set of parameters which is used to describe fluctuating noise such as road traffic.

Noise dose is used to determine the level of noise exposure of an employee at work.

Level Sampling



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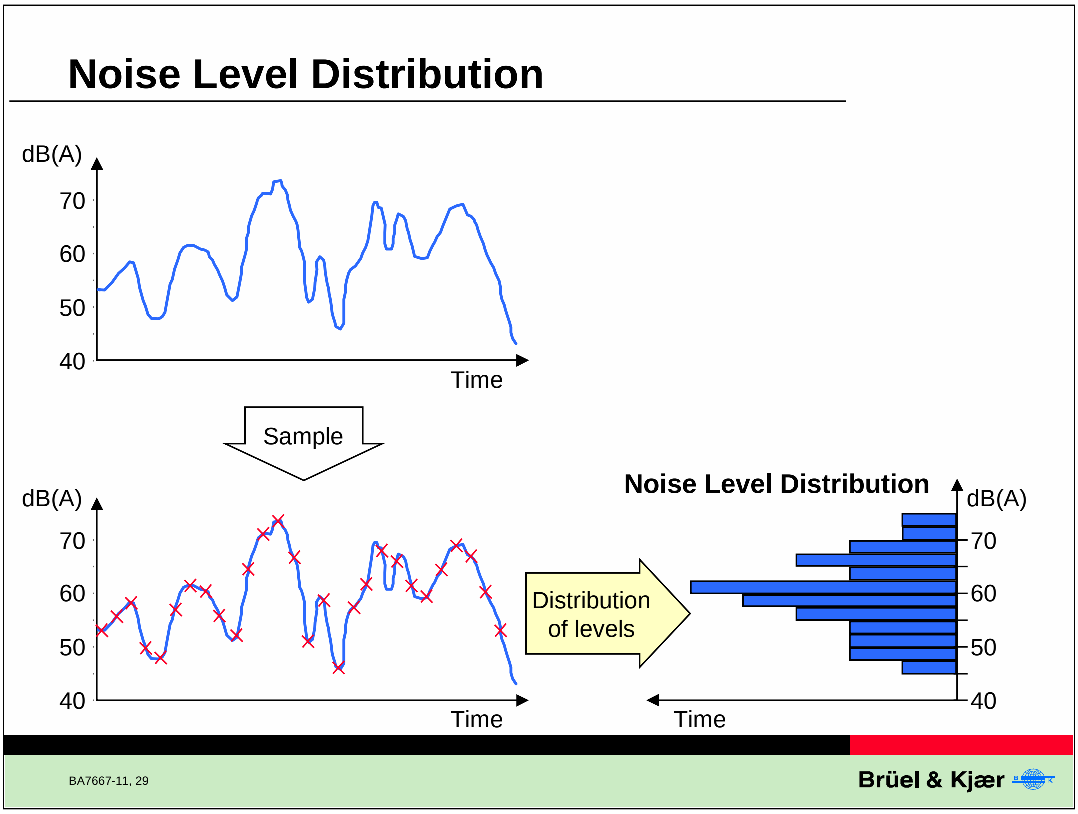
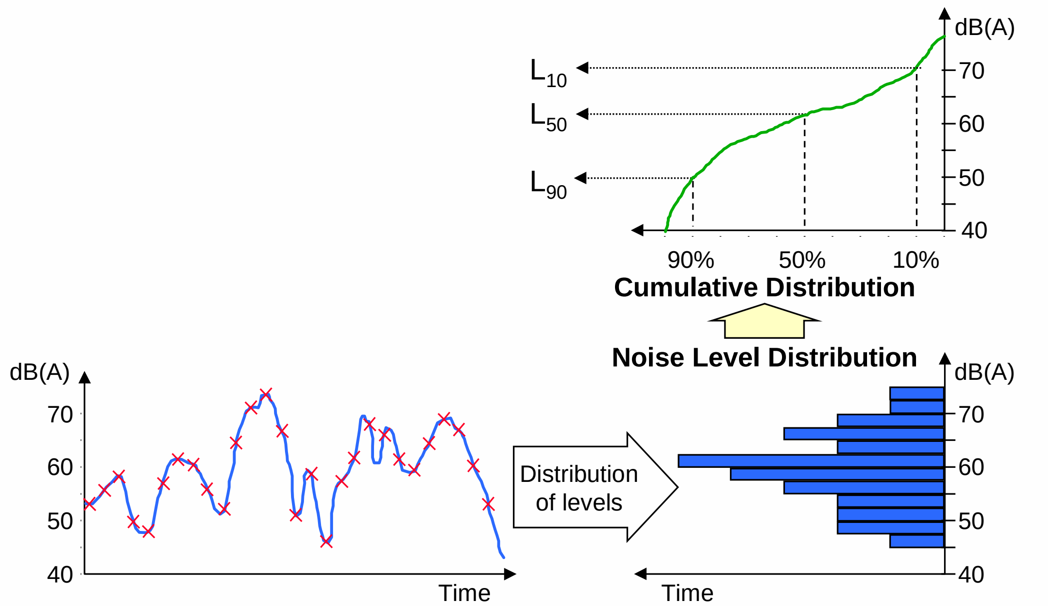
With modern digital instruments, the noise signal is sampled at regular intervals (for example, 100 times/s). I can use this to statistically describe the signal.



Once I have sampled the signal, I divide my measurement range up into small sections called classes (e.g of 0.2 dB) and, every time a sample falls within a class, a counter is incremented. The resulting curve as a % of the total number of samples (counters) is the Level Distribution of the noise.

In this example you can see that the class width is about 2.5 dB and that the signal is mostly between 60.0 - 62.5 dB. The signal is never above 75 dB and never below 45 dB.

Cumulative Distribution



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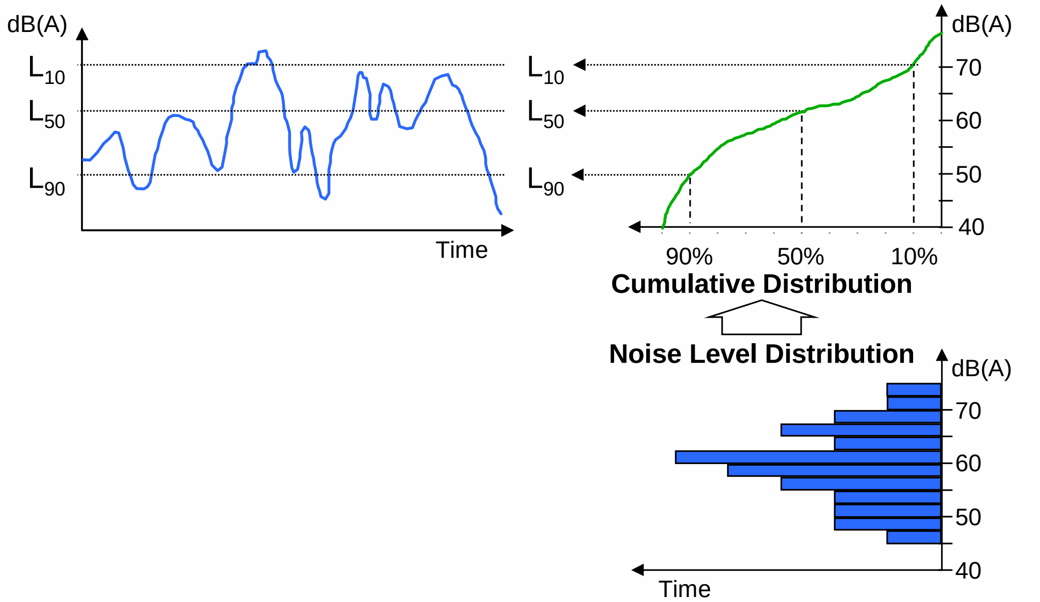
I can now use this Level Distribution to create a Cumulative Distribution by taking the contents of each class from the top of the measurement range and working downwards, adding the results as I go.

This results in a series of percentile levels (L_N values) at which you can say that the noise was above for N% of the time. In this example you can see that the signal was above 70 dB for 10% of the time, above 60 dB for 50% of the time and above 50 dB for 90% of the time.

Percentile Levels



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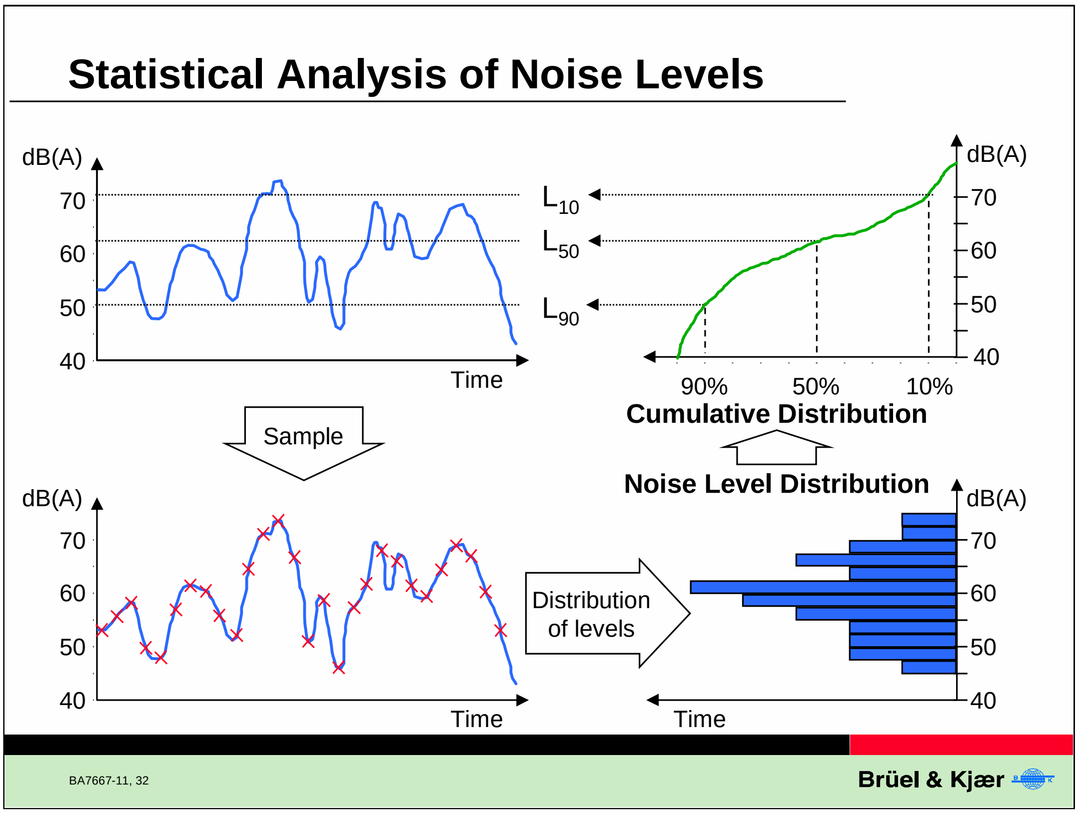
I can now put this information back on my signal to give me a percentile levels (L_N values) - a statistical description of the time history of the noise. Percentile levels are often used for describing traffic noise, background noise and extremes of noise (L_1 approximates the maximum RMS level, L_{99} approximates the minimum RMS level).

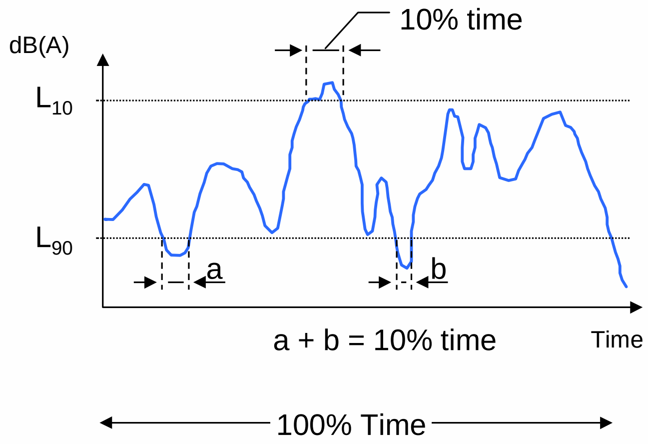
Frequently used levels are, for example, L_{10}, L_{90} and L_{95}.



To statistically analyse a signal:

- sample the signal
- divide the samples into classes according to level
- add the distribution levels to get the cumulative distribution
- calculate the percentile levels from this curve

Percentile Levels, L_N



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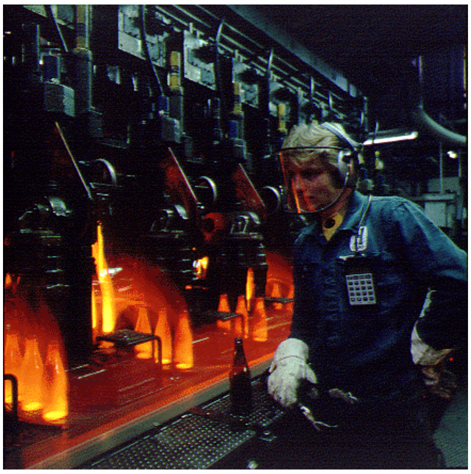
Note that the signal exceeds the L_{10} level for 10% of the measurement time.
Note that the signal is under the L_{90} level for 10% of the measurement time.
In other words, the percentile levels are complementary.

Noise Dose Measurement in Practice



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When we are exposed to noise over a period of time, we risk damaging our hearing if the levels are high. As a result, in order to protect our hearing, many countries have introduced noise exposure limits at work which must not be exceeded.

For steady noise, good correlation has been demonstrated between hearing damage risk and A-weighted sound level measurements, and this unit is now universally employed when rating noise for this purpose. But not only the level is of importance: the duration of exposure also has to be considered.

This Noise Dose is a way of showing how much noise exposure a person has received in relation to this limit. It is often measured by wearing a noise dose meter during the course of a working day.

Definition of Noise Dose

= 100 % Noise Dose

The actual dB level depends on National Legislations. In some countries the level is 80 dB

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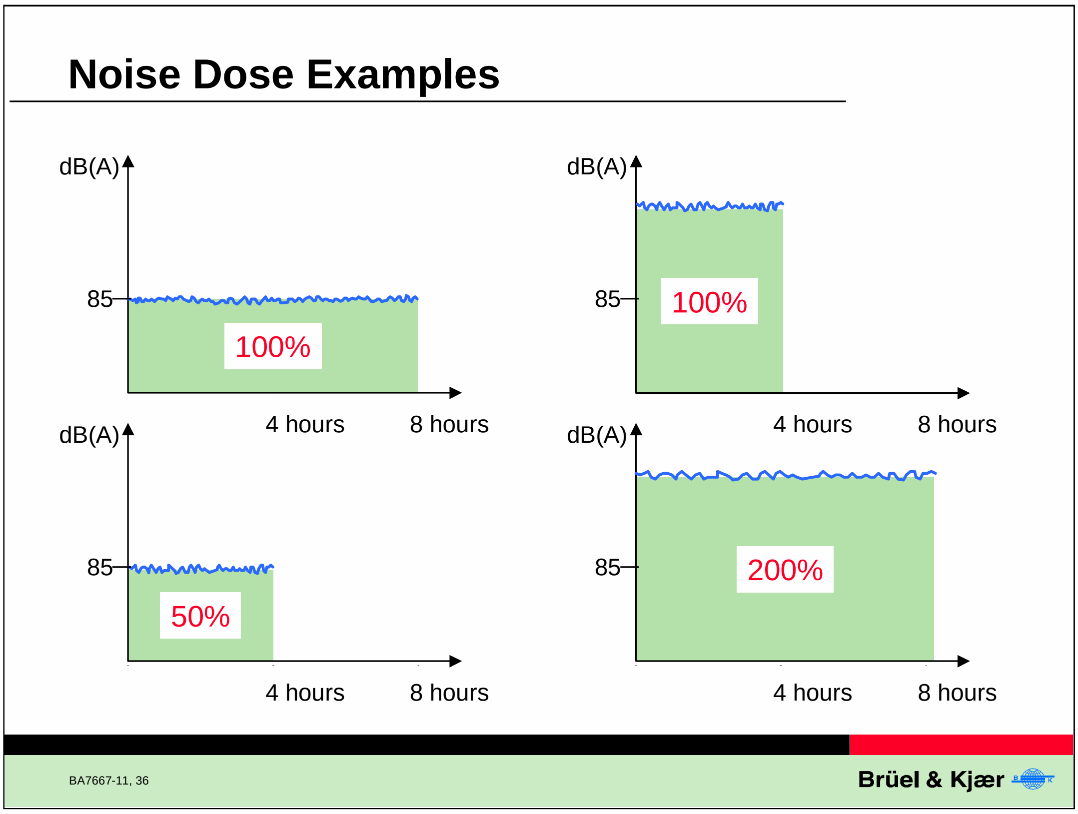
Noise dose is defined as the A-weighted equivalent noise level (the A-weighted L_{eq}), to which a person may be subjected for a normal working day of 8 hours, or a normal working week of 40 hours before he runs a significant risk of permanent hearing loss.

The allowable dose varies slightly between countries but is usually 85 or 90 dB(A) and is referred to as the criterion (or 100%) noise dose.

The advantage of expressing the noise dose in this manner is that 100% will always represent the criterion dose whatever the measurement duration and however it is accumulated.



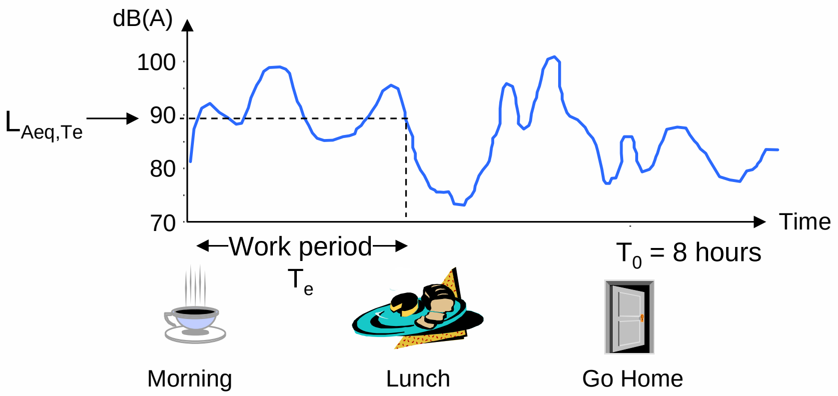
A man exposed to 85 dB for 8 hours has a 100% dose according to the legislation described on the previous slide (this level and time may differ according to national legislation). He has been exposed to all the noise he is allowed to be.

A man exposed to 85 dB for 4 hours has a 50% dose (exposure) in this period. He has received half of his allowable exposure. He can still be exposed to noise without exceeding his limit.

A man exposed to a higher level than 85 dB for 4 hours can still receive a 100% dose (exposure) in this period. He can still be exposed to noise without exceeding his limit. This level depends on the national legislation used (see later).

A man exposed to this same level (the one which gave a 100% dose after 4 hours) for 8 hours will have been exposed for twice as long as above and will therefore have received a 200% dose (exposure). This man is over-exposed.

Daily Personal Noise Exposure, $L_{EP,d}$



$$L_{EP,d} = L_{Aeq,Te} + 10\log_{10}\frac{T_e}{T_0}$$

Example:

$L_{Aeq,Te}$ = 89.2 dB and T_e = 4 hours

$$L_{EP,d} = 89.2 + 10\log_{10}\frac{4}{8} = 89.2 - 3 = \underline{\underline{86.2\text{ dB}}}$$

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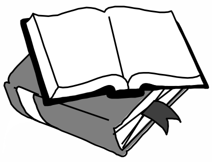
The Daily Personal Noise Exposure, $L_{EP,d}$, is another way of determining whether a worker has been exposed to too much noise.

To calculate the $L_{EP,d}$, measure the L_{Aeq} over the work period and normalise this level to the reference period of 8 hours.

The Daily Personal Noise Exposure, $L_{EP,d}$, is useful when determining whether a worker has been over-exposed during a period other than 8 hours.

Standards



- ISO 9612

  Guidelines for the measurement and assessment of exposure to noise in a working environment

  International

- ISO 1999

  Determination of occupational noise exposure and estimation of noise-induced hearing impairment

  International

- IEEC Directive EEC/86/188

  The protection of workers from the risk related to the exposure to noise at work

  The European Union

- OSHA

  Occupational Safety and Health Act

  USA and others

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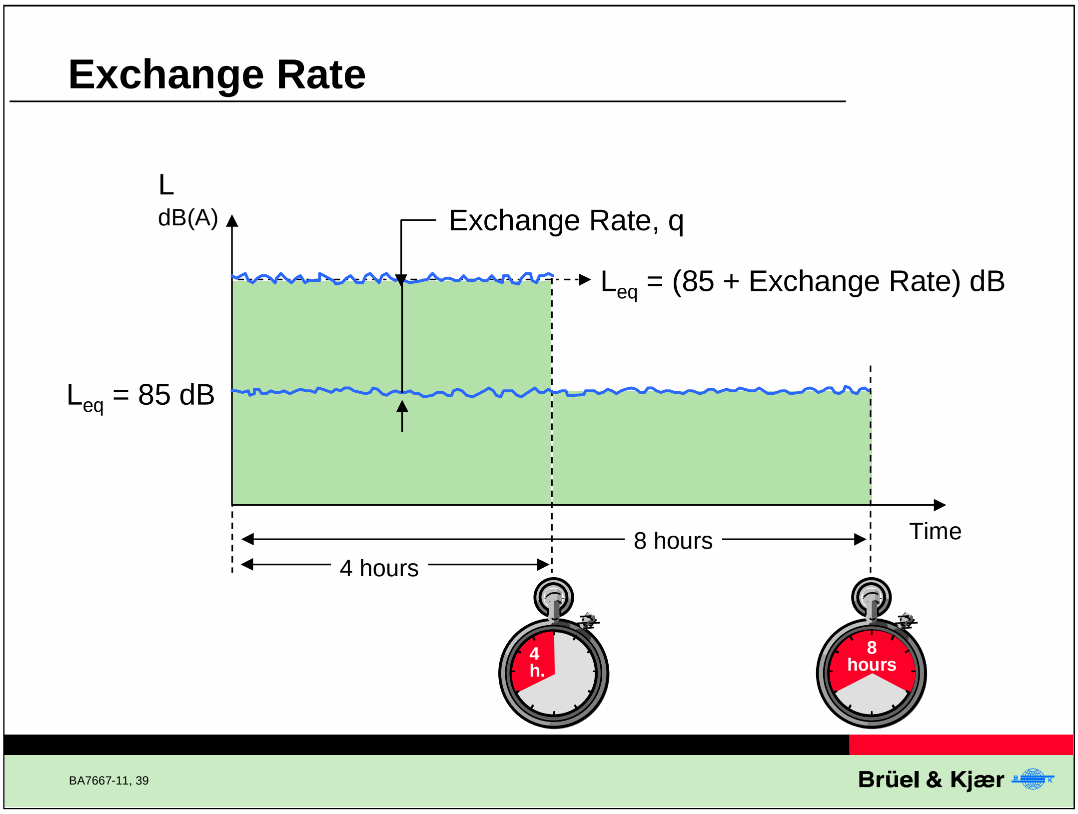
The major international and regional standards are as shown here. ISO 1999 and ISO 9612 are complementary.

The major difference between the OSHA standard and the others concerns something called Exchange Rate.



Exchange Rate

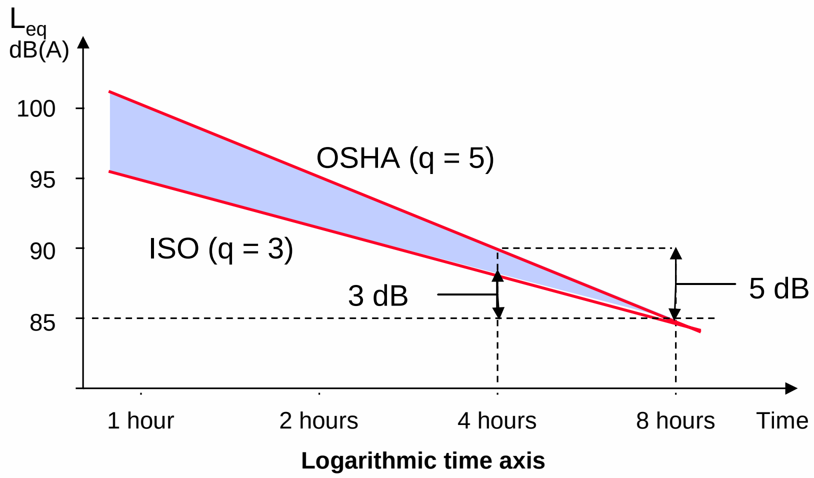
The allowable exposure is a question of level and duration. A high level is acceptable as long as it is compensated for by periods of low level and it is in this trade-off between noise level and exposure time that the main divergence of opinion exists between the different standards. Both ISO and OSHA specify a certain halving rate i.e. they specify a rise *q* in noise level for each halving in exposure time as follows:

- ISO 1999: $q = 3$ dB
- OSHA: $q = 5$ dB

This means that if the criterion level is 90 dB(A) in both cases, ISO will allow an exposure of 93 dB(A) and OSHA an exposure of 95 dB(A) for 4 hours during a full day if the rest of the day is spent in an area where the noise exposure is below 80 dB(A). If the exposure is reduced to 2 hours, ISO will allow 96 dB(A) and OSHA 100 dB(A) etc.

Another US military standard (DOD) uses $q = 4$ dB

ISO vs. OSHA



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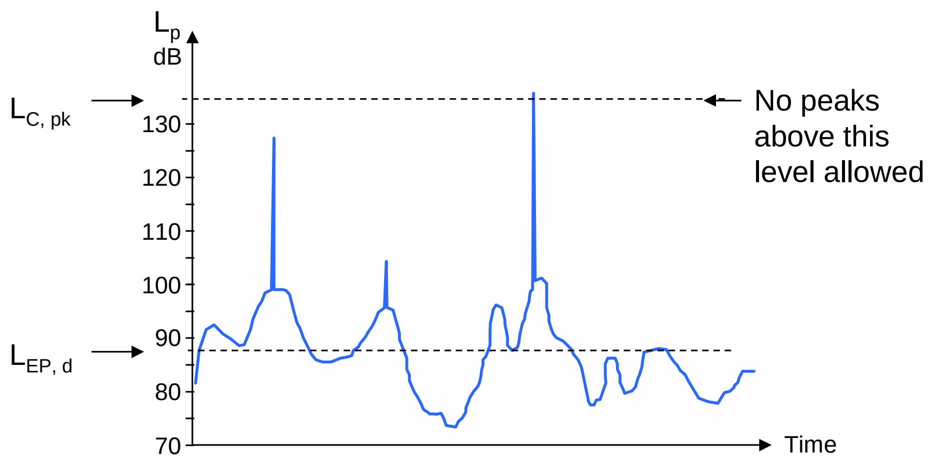
ISO vs. OSHA

This is how the two standards compare with each other in general. The OSHA standard accepts a higher level for a reduction in exposure time than the ISO does. The reverse is true for exposure times greater than 8 hours or levels under the criterion value.

Note here that noise dose as specified by ISO, q = 3, is based on an equal energy principle which means that a person exposed to a noise level of 90 dB for 8 hours receives the same amount of noise energy as during a period of 4 hours with a noise level of 93 dB.

Besides the difference in allowable noise exposure between different standards, there are other differences which make a study of the relevant documents imperative before assessing the risk. The overriding limit varies in value as well as in the manner in which it is measured, as also does the peak impulse allowed, and some countries, e.g. the USA, also stipulate a maximum daily “dose” of impulses.

Noise Dose and Peak



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In addition to noise exposure, loud noises can also permanently damage hearing. While the Noise Dose and the Daily Personal Noise Exposure, $L_{EP,d}$, are measures of the noise exposure, the Peak level is a measure of the damage caused by loud noises.

This is why most countries include some form of maximum allowable value which must not be exceeded. In most countries this is a C-weighted Peak level and the limits are set to 135 or 140 dB. The C-weighting is used instead of the A-weighting as it is more representative of the human ear's sensitivity to noise at such high levels.

Conclusion

- The sensitivity of a microphone depends on the direction of the noise - that is why there are free-field and random-incidence microphones
- Sound level meters are integrated measurement equipment with standardized time weightings and measurement parameters
- The L_{eq} is the energetic average of the noise over a period of time and is one of the most important noise measurement parameters
- The Noise Dose and Daily Personal Noise Exposure ($L_{EP,d}$) are ways of showing how much noise exposure a person has received in relation to legal limits

Literature for Further Reading

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

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These publications are available from your local Brüel & Kjær representative.