Aalto University
School of Engineering

Comfortable and Healthy Indoor Climate

EEN-E4001

Lecture 6: Acoustics

Risto Kosonen

Learning outcomes

- Room acoustics
- Criterion for indoor noise
- Acoustics and mechanical ventilation

Discuss with your neighbour 3 minutes
Where Acoustical Comfort in relation to...

Acoustical Comfort in relation to…

Room acoustical quality

-> reverberation time <-> concrete core activation

-> undesirable echo's and reflections <-> room shapes

Sound insulation between rooms

-> air-borne sound insulation <-> circulation sound

-> structure-borne sound insulation <-> floor constructions

Background noise levels

-> technical installations <-> location of technical rooms

-> environmental noise <-> building site layout

Sound & Noise

- Sound Power Level (L_w):
  - A measure, in decibels, of the total acoustic power radiated by a given sound source. It is independent of any reference distance or other extraneous factors.
- Sound Pressure Level (SPL) (L_p):
  - A measure, in decibels, of the sound pressure at a particular point. It is dependent upon distance from the source and many other factors.
- Noise:
  - Noise is any sound which at the time of reception is unwanted or disturbing.
  - Structure-borne Noise arrives at a point of interest by propagation through a solid structure.
  - Air-borne Noise arrives at a point of interest by propagation through air.

Sound Power and Sound Power Level

- Sound Power
  - Sound power is the rate at which sound energy is emitted, reflected, transmitted or received, per unit time.
  - Sound power of a source is the total power emitted by that source in all directions.
  - The SI unit of sound power is the watt (W).
  - It is the power of the sound force on a surface of the medium of propagation of the sound wave.
  - For a sound source, sound power is neither room-dependent nor distance-dependent.
- Sound Power Level
  - Sound power level (SWL) is a logarithmic measure of the power of a sound relative to a reference value.
  - The SI unit of sound power level is the decibel (dB).

Examples of Sound Power Levels

Situation and sound source	Sound power (W)	Sound power level (dB ref 10^{-12} W)
Saturn V rocket	100,000,000	200
Turbojet engine	100,000	170
Turbofan aircraft at take-off	1,000	150
Turboprop aircraft at take-off	100	140
Machine gun	10	130
Heavy thunder	1	120
Rock concert	0.1	110
Car at highway speed	0.01	100
Large diesel vehicle	0.001	90
Alarm clock	0.0001	80
Noisy office	10^{-5}	70
Busy restaurant	10^{-6}	60
Quiet office, Average home	10^{-7}	50
Refrigerator, Low voice, Quiet home	10^{-8}	40
Quiet conversation, Broadcast studio	10^{-9}	30
Whisper, Wristwatch ticking	10^{-10}	20
Human breath	10^{-11}	10
Reference value	10^{-12}	0

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Source: Wikipedia

Sound Pressure Level (SPL)

- Human ear audible sound pressure levels range from 20 μPa (hearing threshold) till 20 Pa (pain threshold), resulting in the scale 1:10,000,000.
- Since using such a large scale is not practical, a logarithmic scale in decibels (dB) was introduced which is also in agreement with physiological and psychological hearing sensations.

- dB of sound pressure level (dB SPL) is defined as:

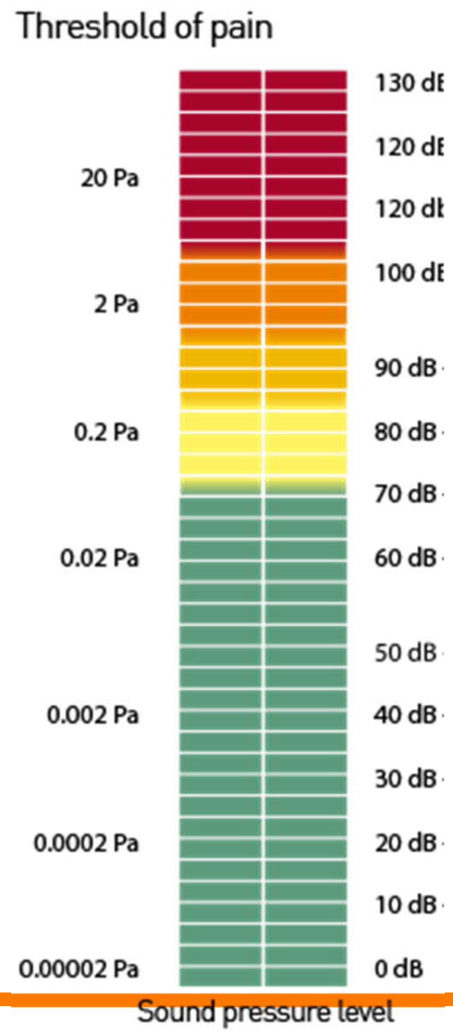
$$\mathbf{L_p = 20 \log_{10} (p1/p0)}$$

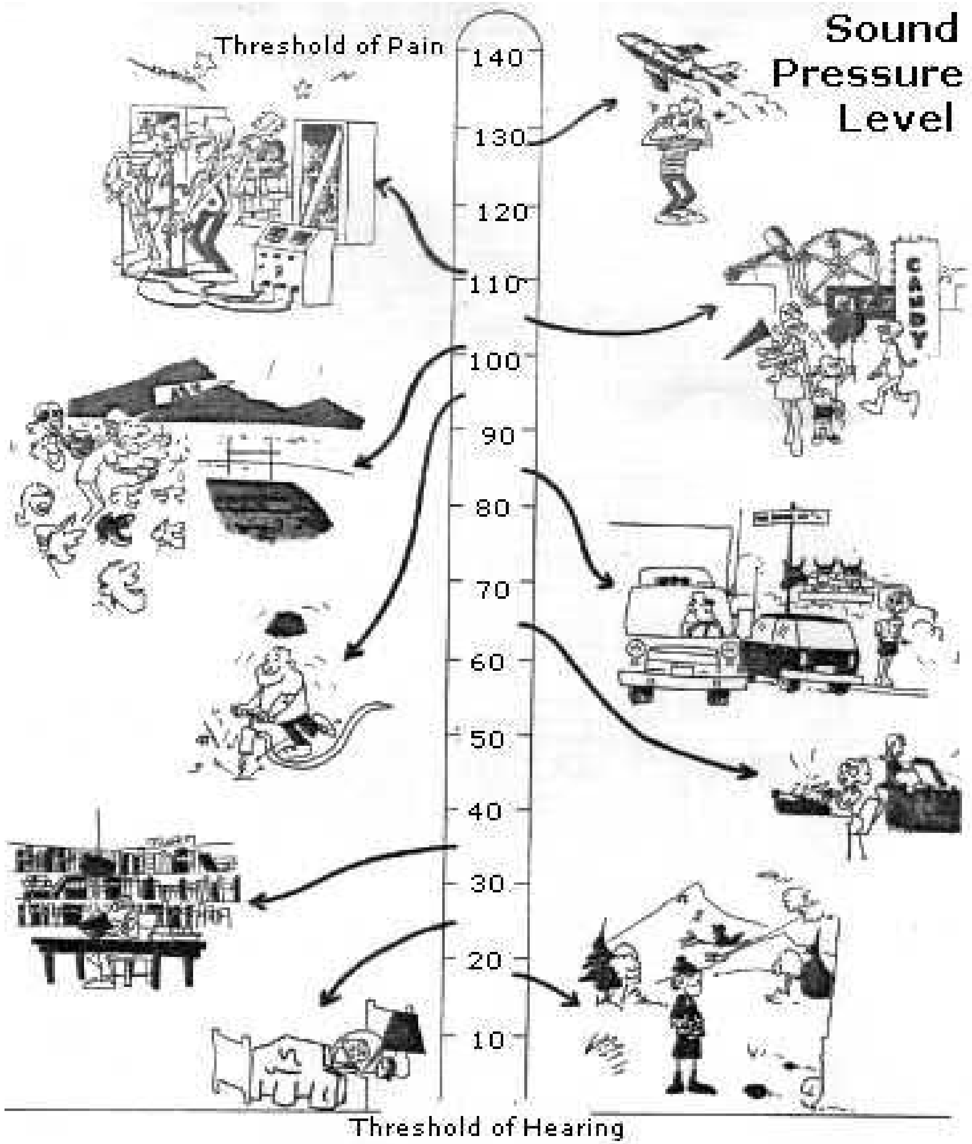
where

p1 is actually measured sound pressure level of a given sound,

p0 is a reference value of 20μPa, which corresponds to the lowest hearing threshold of the young, healthy ear.

- In the logarithmic scale the range of human ear's audible sounds is from 0 dB SPL (hearing threshold) to 120-140 dB SPL (pain threshold).





Sound Pressure Level

Noise = unwanted sound

Threshold of Hearing

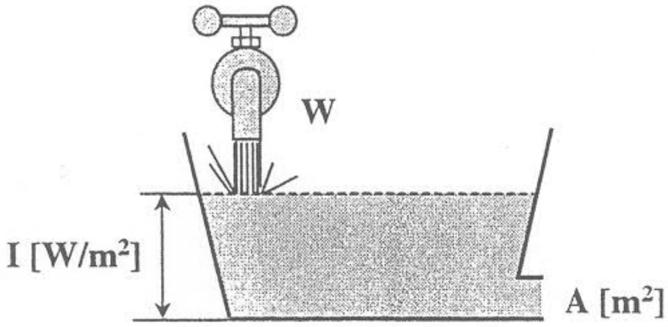
Threshold of Pain

Sound at 155 decibels can burn the skin.

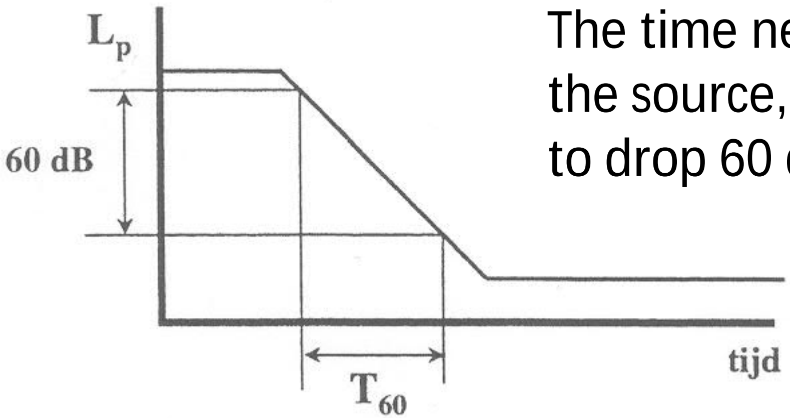
Sound at 180 decibels can kill.

Room acoustical quality

-> reverberation time



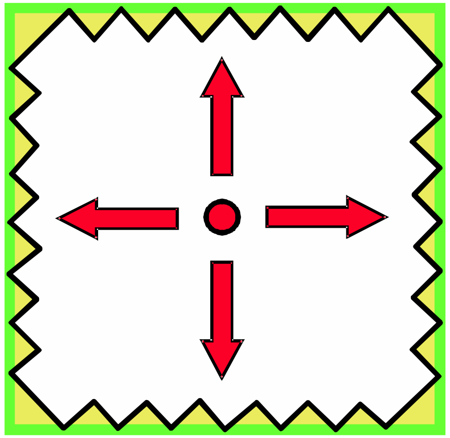
$$T_{60} = \frac{1}{6}\frac{V}{A}[\mathrm{s}]$$

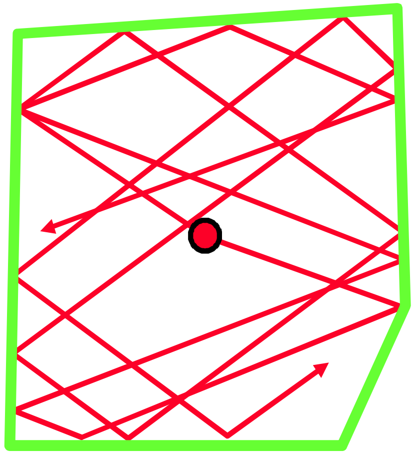


The time necessary, after switching off the source, for the sound pressure level to drop 60 dB.

Room acoustical quality

-> reverberation time





Sound absorbing space ⇩ Short reverberation time

⇔

Sound reflecting space ⇩ Long reverberation time

Room acoustical quality

-> reverberation time: target values

Type of room	Reverberation time
Furnished room	T = ca. 0,5 s
Office space	T = 0,5 – 0,7 s
Landscape office	T = 0,7 – 0,9 s
Classroom	T = 0,6 – 0,8 s
Music room	T = 0,8 – 1,2 s
Theatre	T = 0,9 – 1,3 s
Chamber music hall	T = 1,2 – 1,5 s
Opera	T = 1,2 – 1,6 s
Concerthall	T = 1,7 – 2,3 s
Church (organ music)	T = 1,5 – 2,5 s

Sound Absorption in Office

Silent Rooms in Open-plan Office

Room acoustical quality

-> reverberation time in seconds

$$T = 1/6 \times (V/A)$$

Room volume in m^3

Total absorption in the room in m^2

➡ The larger the room, the longer the reverberation time!

➡ The more absorbing materials present in the room, the shorter the reverberation time!

Room acoustical quality

-> total absorption in m^2

Surface area in m^2 of the material

$$A = \alpha_1 \times S_1 + \alpha_2 \times S_2 + \alpha_3 \times S_3 + \ldots$$

Absorption coefficient of the material $0 < \alpha < 1$

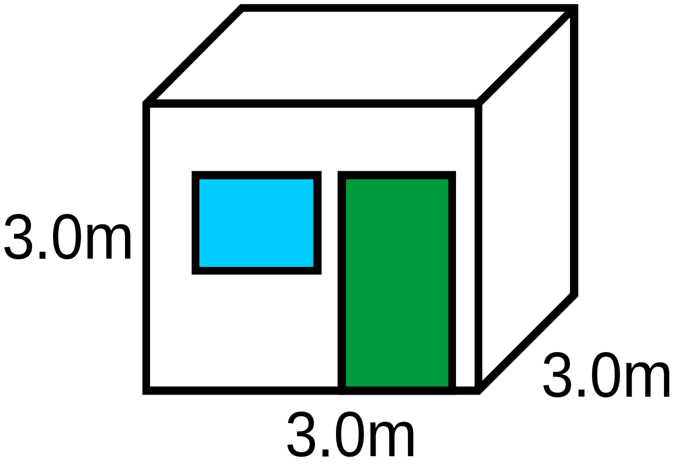
totally reflecting totally absorbing

An open window has an absorption coefficient α equal to 1 (all of the sound will disappear outside through the open window). If the surface area of the open window equals 1 m^2, then the total absorption of this window is equal to

$A = 1 \times 1 = 1\ m^2$

Room acoustical quality

-> calculation of reverberation time



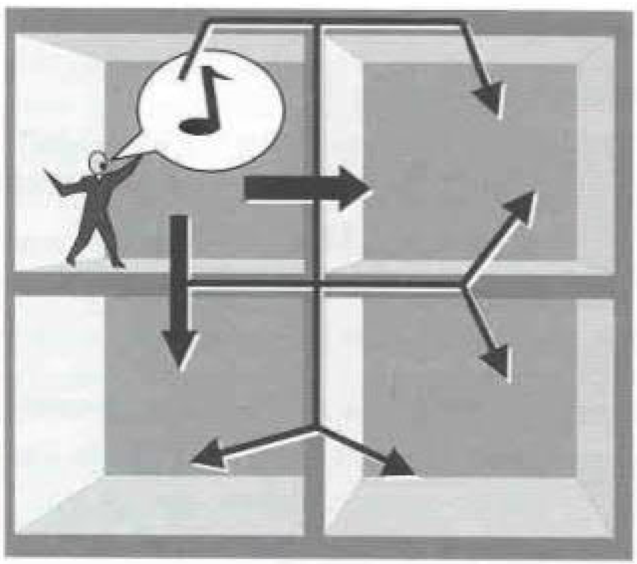
Surface	S [m²]	0 < α < 1	α x S [m²]
Ceiling	9	0,79	7,11
Floor	9	0,04	0,36
Window	1	0,03	0,03
Door	2	0,08	0,16
Walls	33	0,02	0,66
Total A [m²]			8,32

$$A = a_1 \times S_1 + a_2 \times S_2 + a_3 \times S_3 + \dots \ [m^2]$$

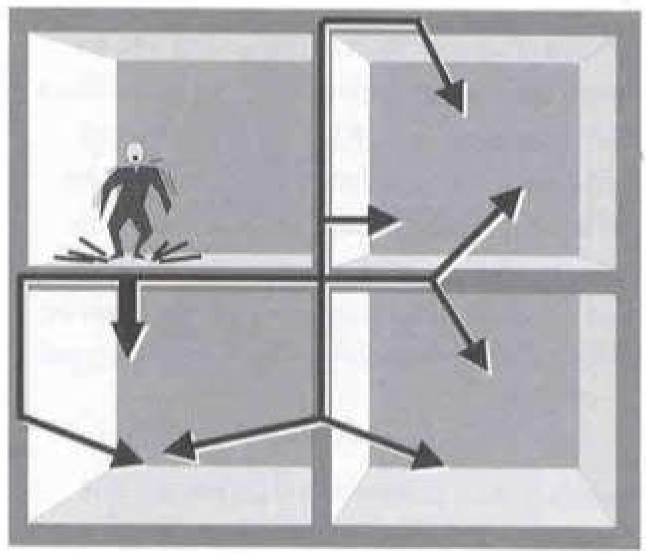
$$T = 1/6 \times (V/A) = 0{,}167 \times (27/8{,}32) = 0{,}54 \text{ s}$$

Sound insulation between rooms

air-borne
sound insulation



structure-borne
sound insulation



Speech Intelligibility

- Speech intelligibility is a subjective measure, traditionally measured by listening tests.
- Many objective descriptors have been used for determining the intelligibility of speech from another workstation.
  - AI = Articulation Index (later replaced by SII)
  - SII = Speech Intelligibility Index
  - RASTI = Room Acoustic Speech Transmission Index
  - STI = Speech Transmission Index (used in EU)

Speech Transmission Index (STI)

- STI is a physical parameter for speech intelligibility.
- STI=0.00 means that speech is unintelligible.
- STI=1.00 means that speech is perfectly intelligible.
- In open-plan offices, STI depends on speech effort, sound absorption, screens, the SPL of background sounds that mask speech, and the distance between a speaker and a listener.
- STI can be measured for each speaker-receiver combination on the measurement line, using a method described in IEC 60268-16.

Spatial Decay of SPL

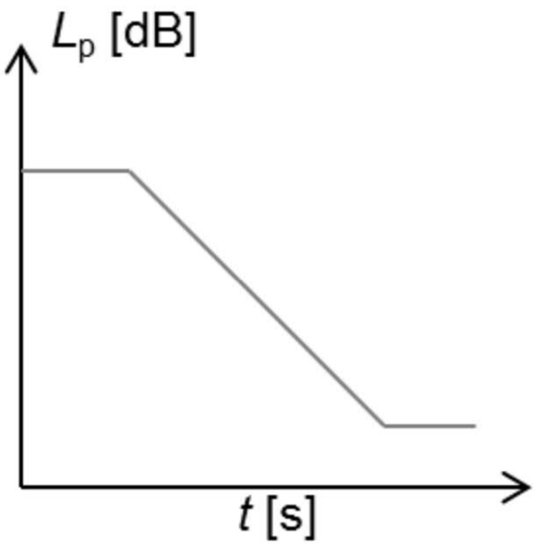
- The measurement of spatial sound distribution is one method for estimating the necessity to increase sound absorption in a space.
- The spatial decay of SPL is measured at several positions in the room, while the sound source produces a continuous test signal.
- The procedure for the measurement of spatial sound distribution in workrooms is described in ISO 14257.
- The default measurement path is a straight line parallel to the floor at a height of 1.20 m or 1.55 m. The line should be clear of any obstacles and away from any reflecting surfaces.
- Spatial sound distribution curves are measured in octave bands from 125 to 4000 Hz.

Privacy and Distraction Distance

- Privacy distance
  - Refers to the distance from a source at which speech is no longer intelligible due to attenuation and background noise.
  - Is the distance from sound source where **STI falls below 0.2**.
  - In some offices, however, this is longer than the total length of the office, which means privacy is not possible.
- Distraction distance
  - Refers to the distance where speech is only partly intelligible, but mostly contributes to the background noise.
  - The distraction to perform a work on a certain listener position can be avoided when **STI is below 0.5**.

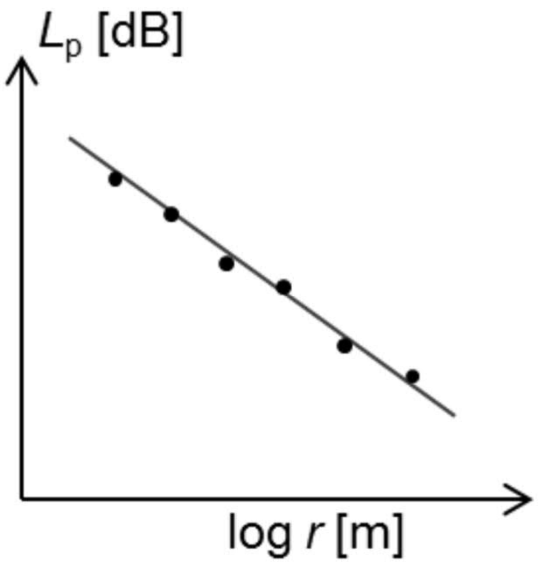
Difference between the measurements of temporal and spatial decay

Temporal decay



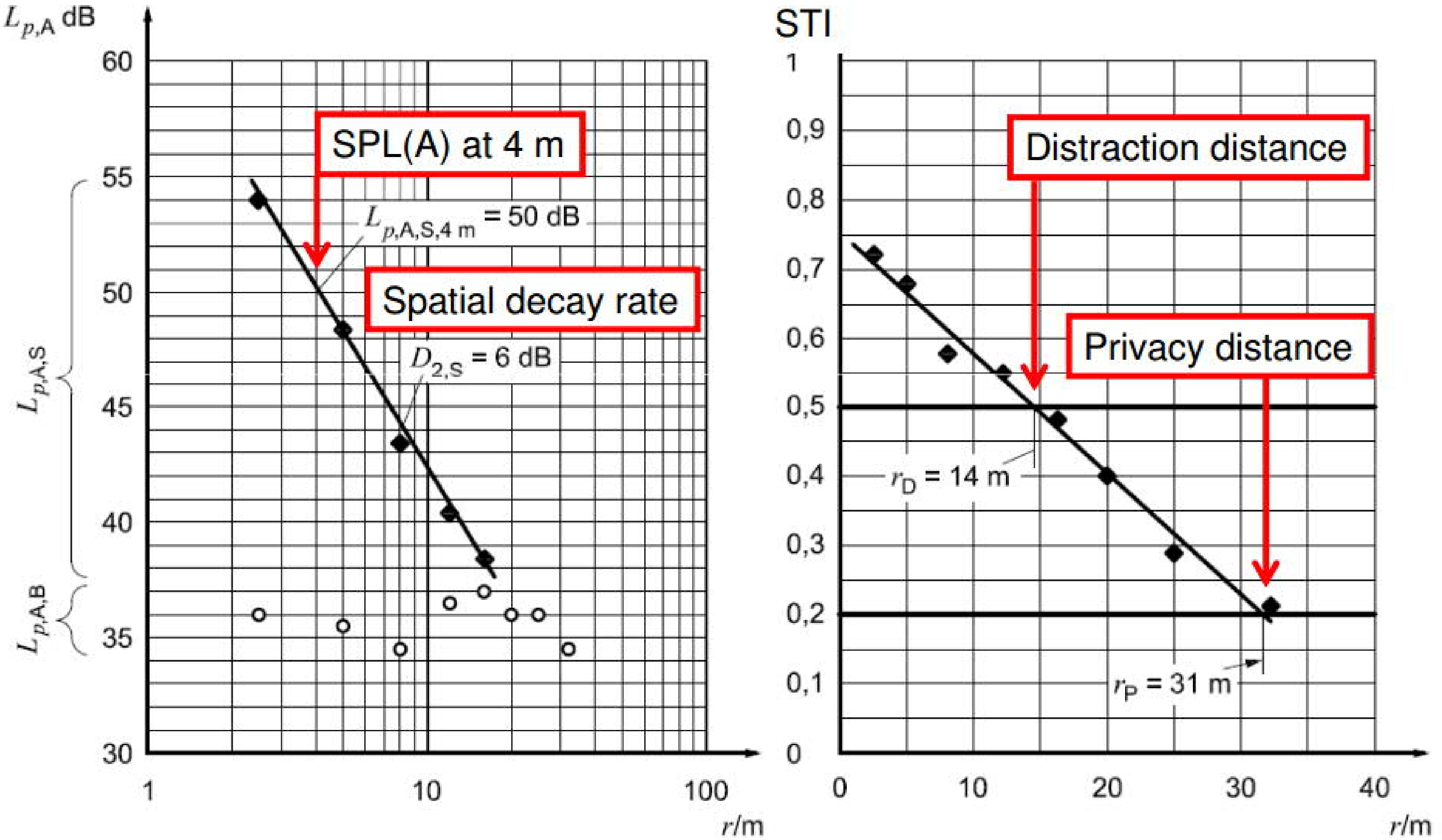
T, T_{20}, T_E

Spatial decay



DL_2, DL_f

Spatial Decay Curves

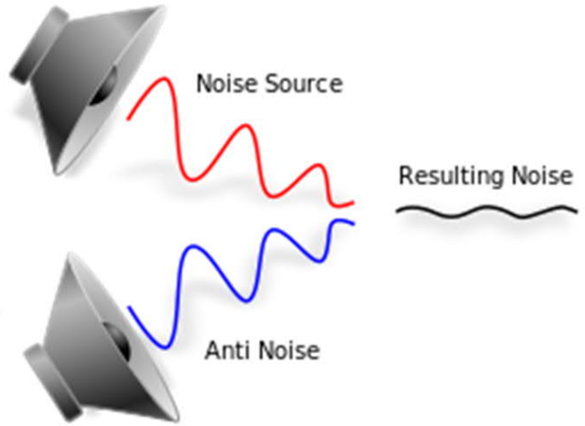


Target Values in Open-plan Office (ISO 3382-3)

Class	$DL_{2,S}$	$L_{p,A,S,4m}$	r_D
A	≥ 11 dB	≤ 46 dB	≤ 5 m
B	≥ 9 dB	≤ 49 dB	≤ 8 m
C	≥ 7 dB	≤ 52 dB	≤ 11 m
D	< 7 dB	> 52 dB	> 11 m

Active Noise Control

- Active noise control or active noise reduction is a method for reducing unwanted sound by the addition of a second sound specifically designed to cancel the first.
- A noise-cancellation speaker emits a sound wave with the same amplitude but with inverted phase to the original sound.
- The waves effectively cancel each other out - an effect which is called destructive interference.



Sound Masking

- Sound masking works on the principle that when background noise is added to an environment, speech is less intelligible.
- Speech Transmission Index STI is lowered by this change in the signal-to-noise ratio:
  - The “signal” would be, for example, the person speaking
  - The “noise” would be the sound masking.
- A high signal-to-noise ratio means that speech is very intelligible – an amphitheater would have a very high STI.
- Sound masking ensures that speaker’s words are unintelligible in order to obtain speech privacy.

Optimum masking sound level is 43 dB(A)

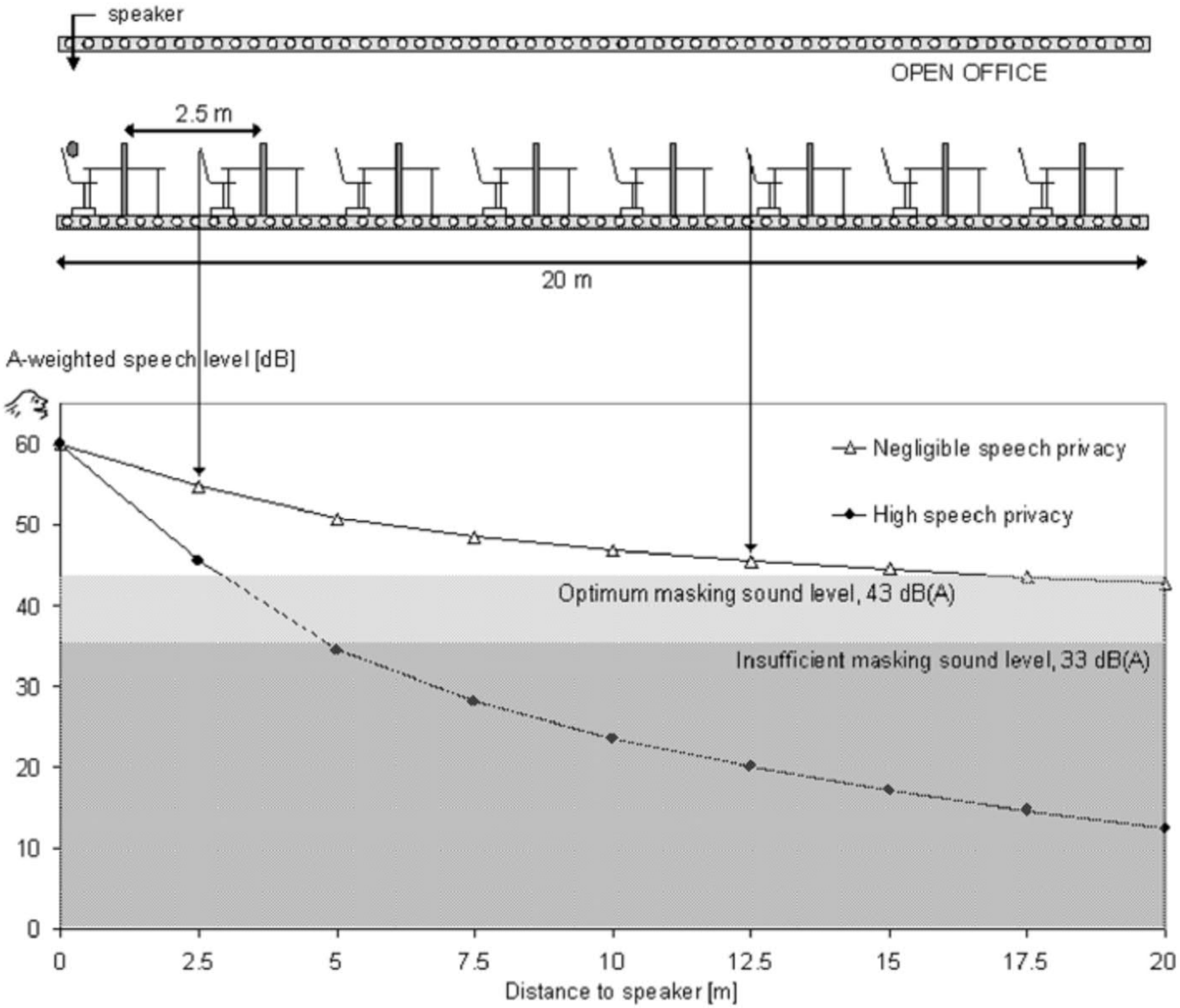


Figure 1. Illustration of spatial decay of A-weighted speech. Measurements are made at each workstation, and the results are plotted as a function of distance to the speaker. Speech privacy improves significantly when the speech level falls below the masking sound level of the office (grey).

Active Sound Masking in Use

- Any business or organization handling sensitive, personal, or financial information must take deliberate measures to safeguard the private information of its clients.
- Financial, personal, and medical privacy are now considered fundamental rights protected by law or governed by regulation – laws covering print, network security and verbal communication of private information.

Applications for Active Sound Masking

- Open Plan Offices
  - Open offices can benefit from sound masking because the added sound covers existing sounds in the area – making workers less distracted, more productive and improving speech privacy.
- Public Spaces e.g. reception areas, pharmacies, waiting rooms and financial institutions.
  - The system is provided in the area where conversations should not be heard – not necessarily in the area where the conversation is taking place.
- Private Offices
  - Walls are often lightweight and do not extend to the ceiling deck – only to the ceiling tile. In these cases, sound can easily travel through partitions or over the walls.

HVAC System Noise Management

- Fans:
  - Attenuator in the duct
  - Flexible connector
  - Complete enclosure
  - Fan speed reduction
  - Diverting duct openings away from receivers
  - Inertia block
  - Vibration isolator
- Ducts
  - Stiffen vibrating duct surface
  - Sound insulation material
  - Reduced air velocity
- Chillers:
  - Barrier
  - Partial enclosure
  - Complete enclosure
  - Silencer
  - Floating floor
  - Vibration isolator
- Cooling Towers
  - Barrier
  - Partial enclosure
  - Complete enclosure
  - Acoustic mat
  - Sound insulated ventilation cowl
  - Vibration isolator

Decibels and Sound levels

The **sound pressure level (SPL)** is defined as;

$$L_p = 10\lg\frac{p^2}{p_o^2}dB$$

or

$$L_p = 20\lg\frac{p}{p_0}dB$$

where the reference level p_0 is 2 x 10^{-5} Pa
and p is the measured r.m.s. sound pressure in Pascals

Sound intensity level is defined as:

$$L_I = 10\lg\frac{I}{I_o}dB$$

where I_0 is the reference sound intensity level = 1 x 10^{-12} Wm^{-2}
I is the sound intensity measured in Wm^{-2}

Sound power level (PWL) is defined as:

$$L_w = 10\lg\frac{W}{W_0}dB$$

where W_0 is the reference power level = 1 x 10^{-12} W
W is the measured sound power level in W

Decibel arithmetic

To calculate the effect of several sources:

$$L_{Wx} = 10 \lg \sum_i 10^{L_{Wi}/10}$$

L_{Wi} = power of individual source

Example

Three sources 89, 92 and 95 dB create

LW = 10 lg ($10^{89/10}$ + $10^{92/10}$ + $10^{95/10}$) = 97,4 dB

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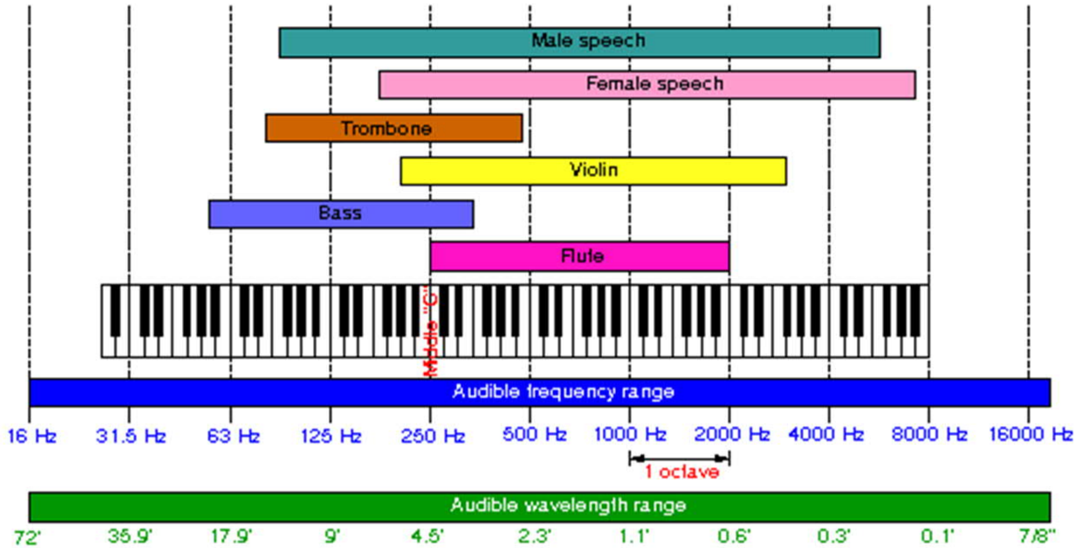
Different Criterion for Indoor Noise

Noise criteria is typically given to each space based on:

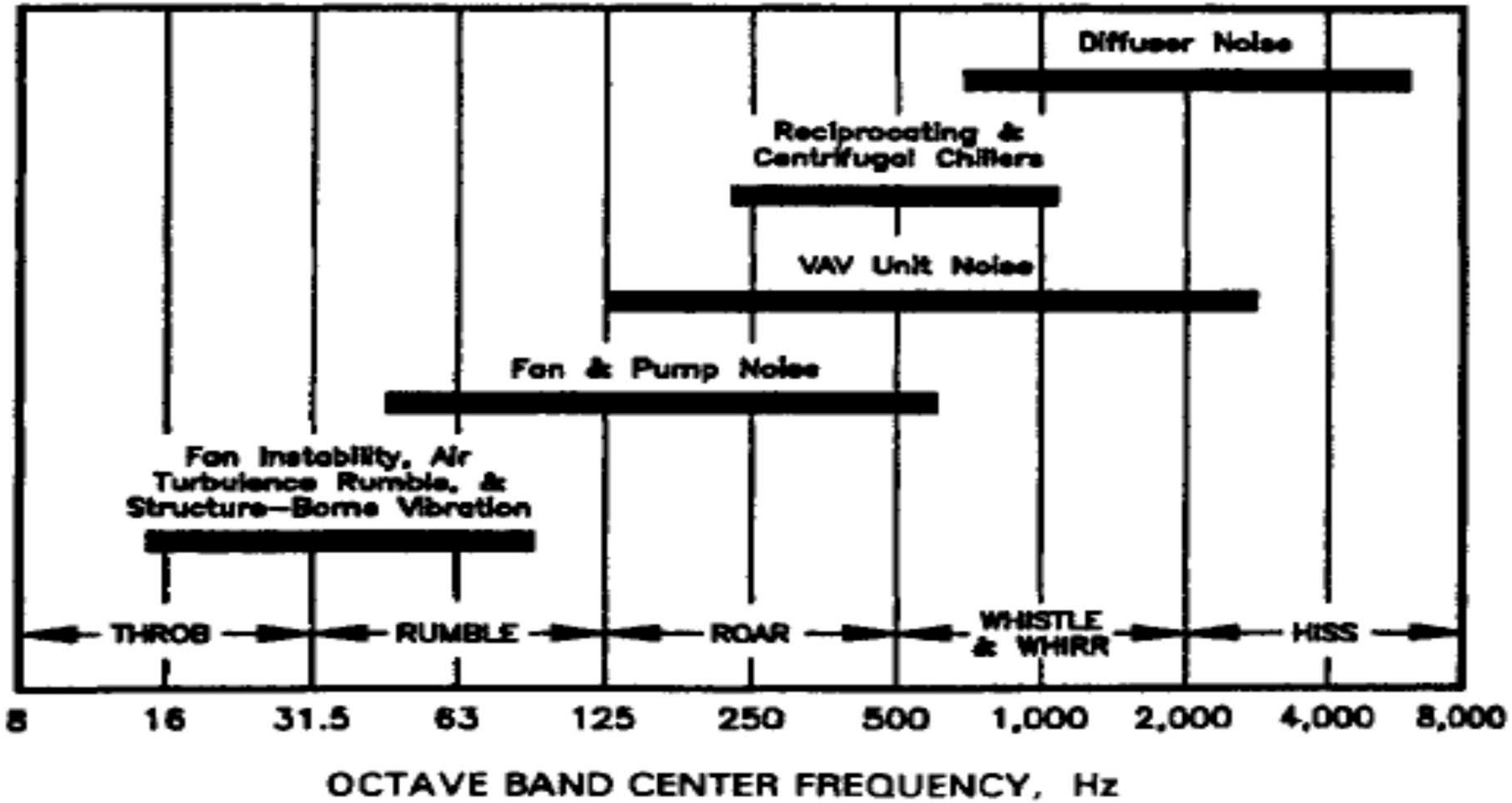
- Maximum A-weighted sound pressure level SPLA, which is typically given in national or international design standards like EN 15251.
- Equivalent Continuous Sound Level (Leq)
- NC criterion, which were established in U.S.
- NR criterion, which is commonly used in Europe.

Octave Bands

- Sound Pressure Level is measured in octave bands, and the centre frequencies of these bands are defined by ISO - 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 8 kHz, 16 kHz to divide the audio spectrum into 10 equal parts.
- The sound pressure level of sound that has been passed through an octave band pass filter is termed the octave band sound pressure level.



Typical frequence levels of HVAC products



A-weighted Sound Pressure Level (SPLA)

- The human ear is more sensitive to sound in the frequency range 1 kHz to 4 kHz than to sound at very low or high frequencies.
- Higher sound pressures are therefore acceptable at lower and higher frequencies than in the mid range.
- A-filtered sound pressure level is widely used as it corresponds to the inverse of the *40 dB* (at *1 kHz*) equal-loudness curve for the human ear.

	Octave band frequency (Hz)							
	62.5	125	250	500	1000	2000	4000	8000
Measured Sound Pressure Level (dB)	54	60	64	53	48	43	39	32
A filter (dB)	-26	-16	-9	-4	0	+1	+1	-1
A-weighted Sound Pressure Level (dB(A))	28	44	55	49	48	44	40	31

Total effect of different octave bands

Using similar principle than source multiplisation octave bands effect can be computed:

$$L_{Ax} = 10\lg\sum_i 10^{L_{pAi}/10}$$

L_{pAi} = The A-weighted noise level

Example

	Taajuus, Hz 63	125	250	500	1k	2k	4k	8k
noise	55	48	40	38	35	32	31	25
A- weight	-26	-16	-9	-3	0	+1	+1	-1
L_{pAi}	29	32	31	35	35	33	32	24

$\boxed{L_{pA}\ 41.4\ \text{db(A)}}$

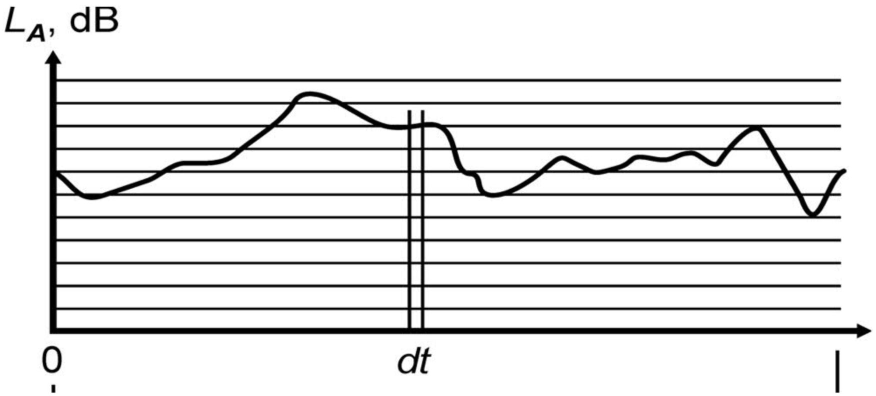
Examples of Design Sound Level, EN 15251

	Building Sound Level, LmaxF, nT,A [dB(A)]		
	I	II	III
Residencies	<32	<36	<40
Hotels rooms	<30	<34	<38
Hospital patient room	<30	<34	<38
Office	<32	<36	<40

- $L_{A,F,max}$ = A-weighted, Fast (125 ms), Maximum, Sound Pressure Level
- Values are for non-continuous sources.

Equivalent Continuous Sound Level (L_{eq})

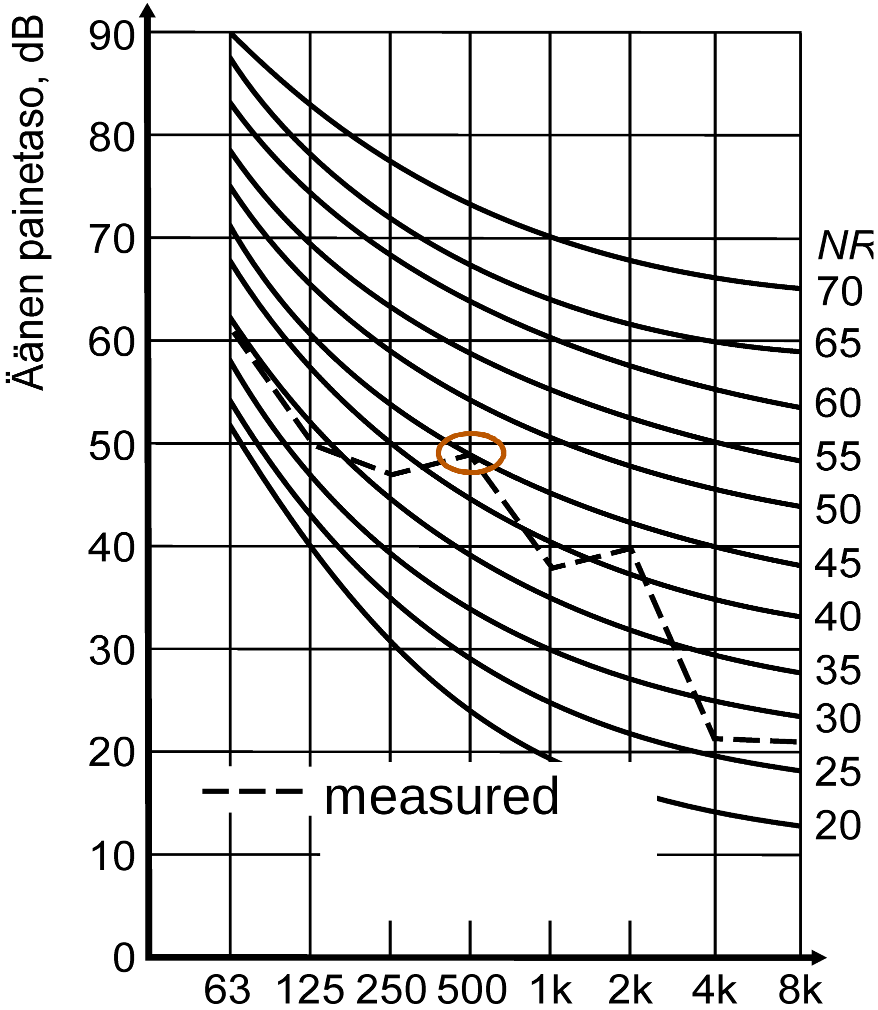
- L_{eq} is the average sound pressure level during a period of time and is often described as the “average” noise level during a noise measurement (e.g 8 h average) .
- The Equivalent Continuous Sound Level is the preferred single decibel value to describe Sound Levels that vary over time and would produce the same Sound Energy over the same period of time T.



$$L_{Aeq} = 10 \lg \left[\frac{1}{T} \int_0^T 10^{L_A(t)/10} dt \right]$$

NR Noise Criterion

- NR- value is the highest measured doted measured curve that reached plotted NR-frequancy lines.
- NR ~dB(A)- 6



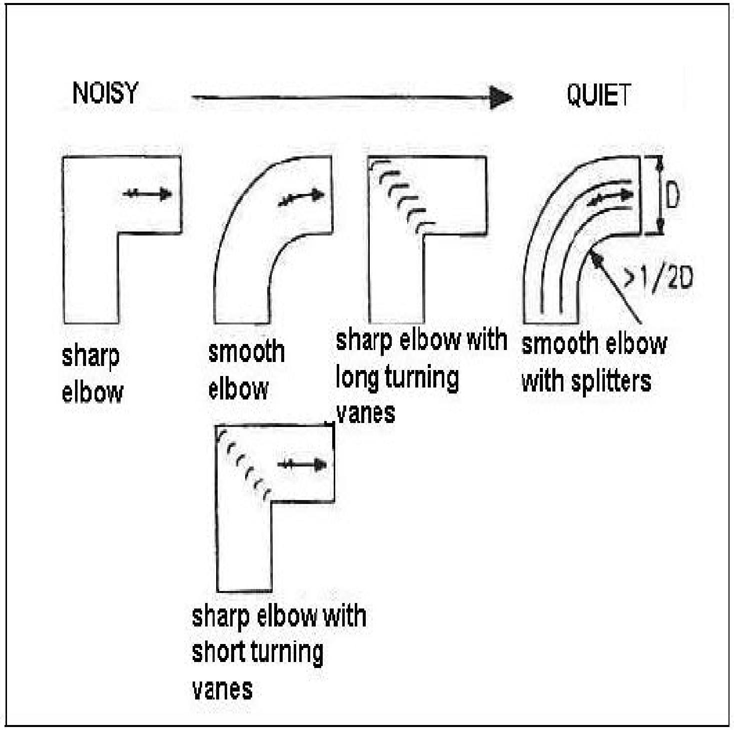
NR Levels Based on Application

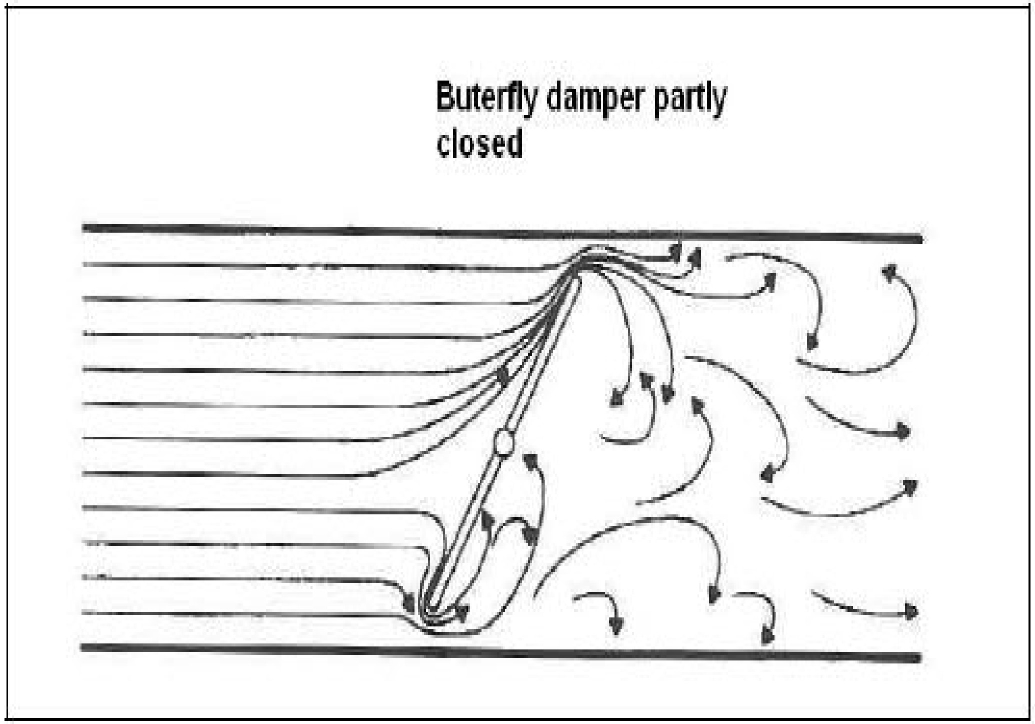
Noise rating curve	Application
NR 25	Concert halls, broadcasting and recording studios, churches
NR 30	Private dwellings, hospitals, theaters, cinemas, conference rooms
NR 35	Libraries, museums, court rooms, schools, hospitals operating theatres and wards, flats, hotels, executive offices
NR 40	Halls, corridors, cloakrooms, restaurants, night clubs, offices, shops
NR 45	Department stores, supermarkets, canteens, general offices
NR 50	Typing pools, offices with business machines
NR 60	Light engineering works
NR 70	Foundries, heavy engineering works

NC Noise Criterion (NC ~ dB(A) + 5)

Noise Criterion	Octave Band Center Frequency (Hz)							
	63	125	250	500	1000	2000	4000	8000
	Sound Pressure Levels (dB)							
NC-15	47	36	29	22	17	14	12	11
NC-20	51	40	33	26	22	19	17	16
NC-25	54	44	37	31	27	24	22	21
NC-30	57	48	41	35	31	29	28	27
NC-35	60	52	45	40	36	34	33	32
NC-40	64	56	50	45	41	39	38	37
NC-45	67	60	54	49	46	44	43	42
NC-50	71	64	58	54	51	49	48	47
NC-55	74	67	62	58	56	54	53	52
NC-60	77	71	67	63	61	59	58	57
NC-65	80	75	71	68	66	64	63	62
NC-70	83	79	75	72	71	70	69	68

Turbulence creates noise





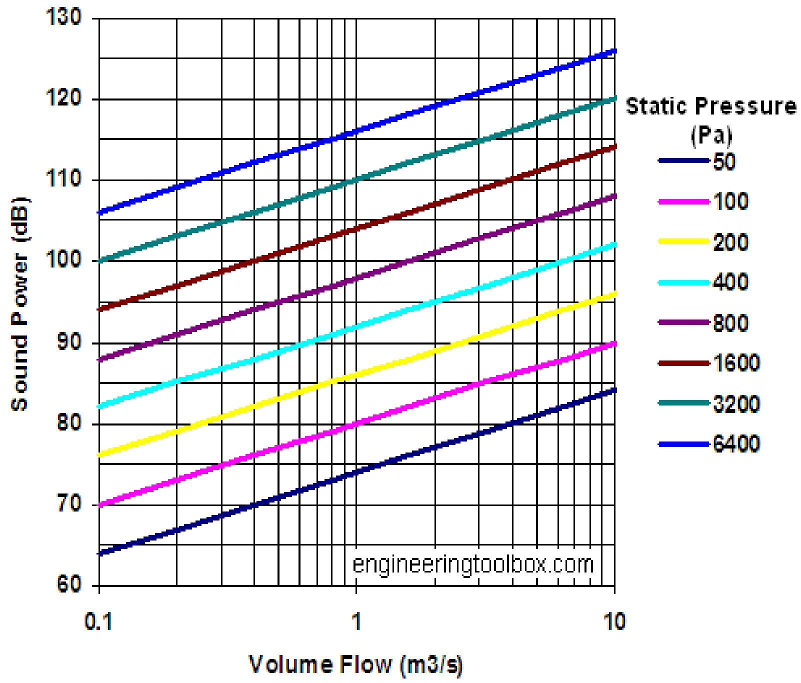
Small details are important.

Fan Noise

- The empiric expressions below can be used as an indication of Sound Power Levels from fans. Sound Power Level - SI-units
  - **Lw = 67 + 10 log(S) + 10 log(p)**
  - **Lw = 40 + 10 log(Q)+ 20 log(p)**
  - **Lw = 94 + 20 log(S) - 10 log(Q)**

  where

  - Lw = sound power level (dB)
  - S = rated motor power (kW)
  - p = fan static pressure (Pa)
  - Q = volume discharged (m3/s)



Note:

Exact Sound Power Levels should be obtained from manufacturers' data.

Fan Noise in Octave Bands

- Sound power level in the octaves can be calculated by adding the values below to the sound power level calculated in the expressions or diagram above

Fan Type	Octave band							
	63	125	250	500	1000	2000	4000	8000
Centrifugal fan, backward-curved blades	-4	-6	-9	-11	-13	-16	-19	-22
Centrifugal fan, forward-curved blades	-2	-6	-13	-18	-19	-22	-25	-30
Centrifugal fan, straight radial blades	-3	-5	-7	-7	-8	-11	-16	-18
Axial fan	-7	-9	-7	-7	-8	-11	-16	-1

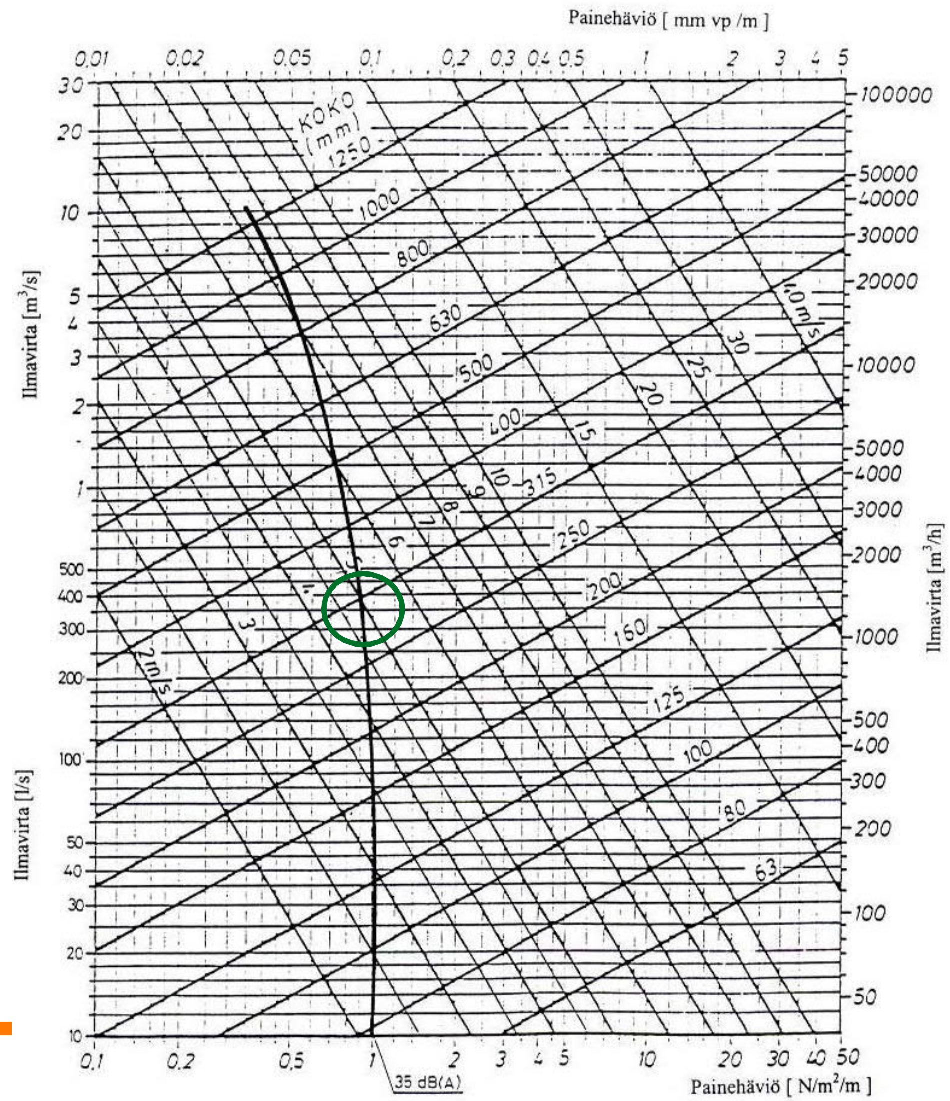
Noise generation of round duct.
Design target 35 dB

$$L_{wtot} = 10 + 50 \log v + 10 \log s$$

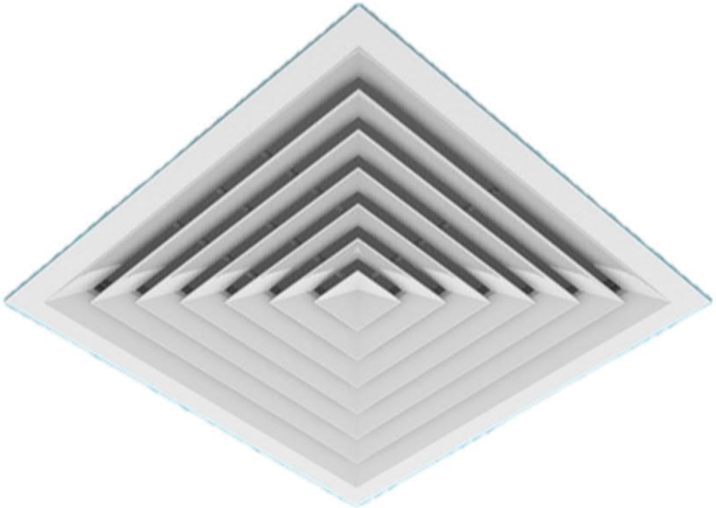
v = air velocity in the duct in m/s

s = cross-sectional area of the duct in m²

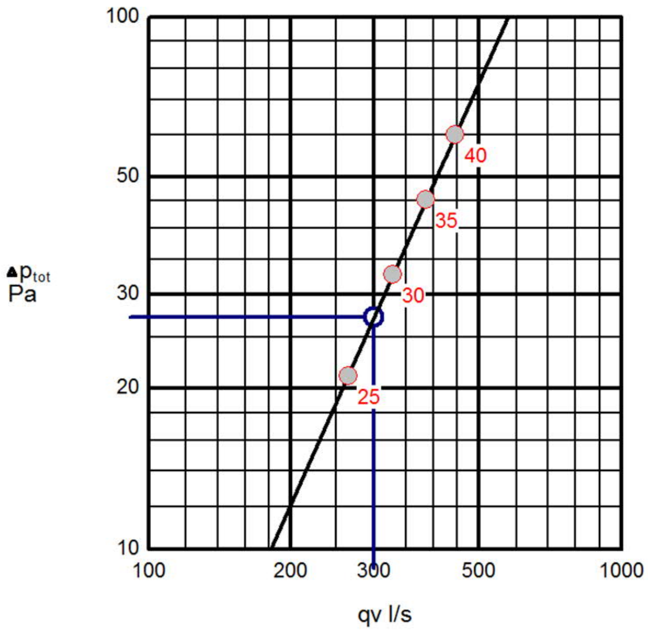
With duct size of 315 @ 35 dB(A), it means max. airflow rate of 400 L/s



Example of Diffuser Noise



DFB/A-18-18							
Supply							2007.02
qv=300 l/s						Δp_{tot}=27 Pa	
L_pAre 10m²sab=28 dB(A)					NR/NC=20/19		
L_w dB							
63 Hz	125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz
53	31	34	29	23	16	3	3



The sound pressure level in the space has been calculated taking into account the room attenuation D_{Lr} = 4 dB based on the 10 m2 sab total absorption.

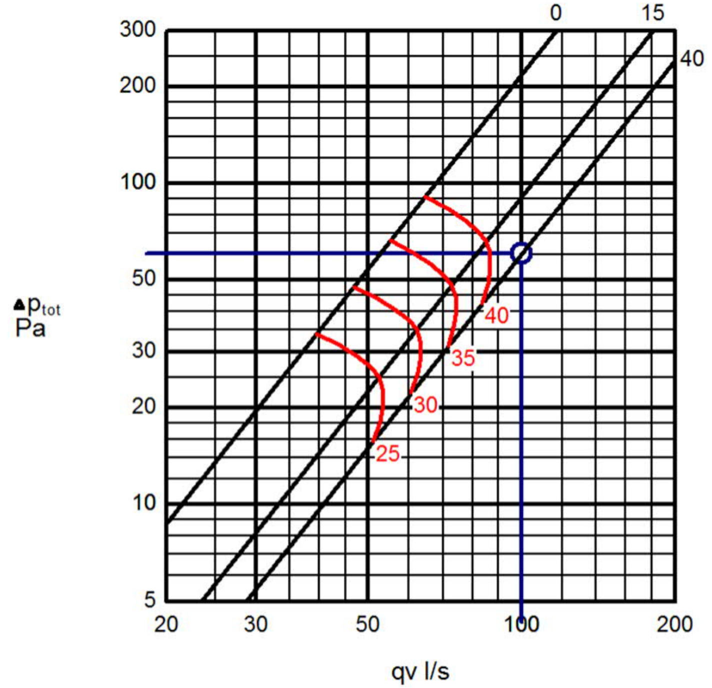
Room attenuation is varying between 4-10 dB depending on the different standards.

Example of Diffuser Noise and Attenuation

Supply

DCS/C-200-160-S1 (Supply)							2008.10
qv=100 l/s				Δp_{tot}=61 Pa		a=40.0	
L_pAre 10m²sab=46 dB(A)					NR/NC=41/41		
L_w dB							
63 Hz	125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz
50	57	49	49	44	39	21	15

DCS/C-200-160-S1 (Supply / Attenuation)							2008.10
ΔL dB							
f Hz							
63	125	250	500	1000	2000	4000	8000
23	16	27	25	16	15	13	13

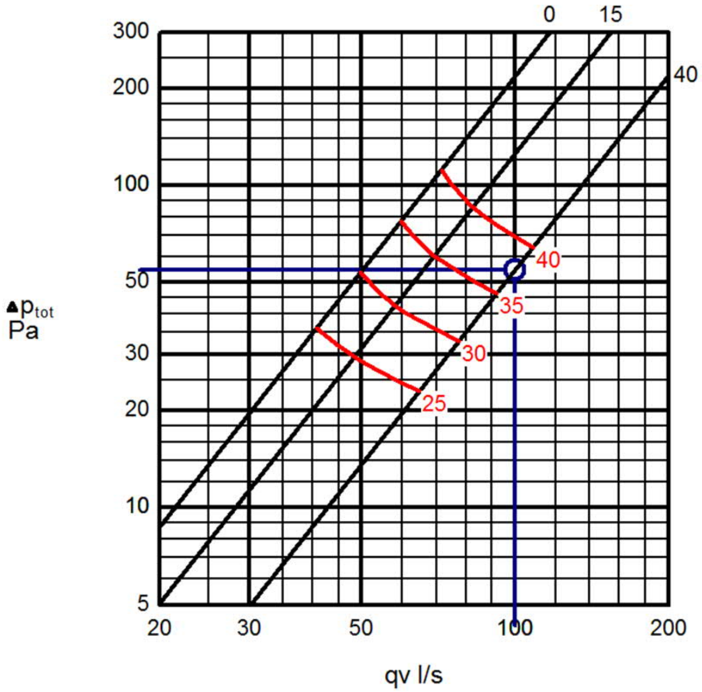


Example of Diffuser Noise and Attenuation

Exhaust

DCS/C-200-160-E1							
Exhaust							2008.08
qv=100 l/s				Δp_{tot}=55 Pa		a=40.0	
L_pAre 10m²sab=38 dB(A)					NR/NC=33/31		
L_w dB							
63 Hz	125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz	8k Hz
47	51	43	37	37	29	17	14

DCS/C-200-160-E1							
Exhaust / Attenuation							2008.08
ΔL dB							
f Hz							
63	125	250	500	1000	2000	4000	8000
23	16	27	25	16	15	13	13



Sound Attenuator

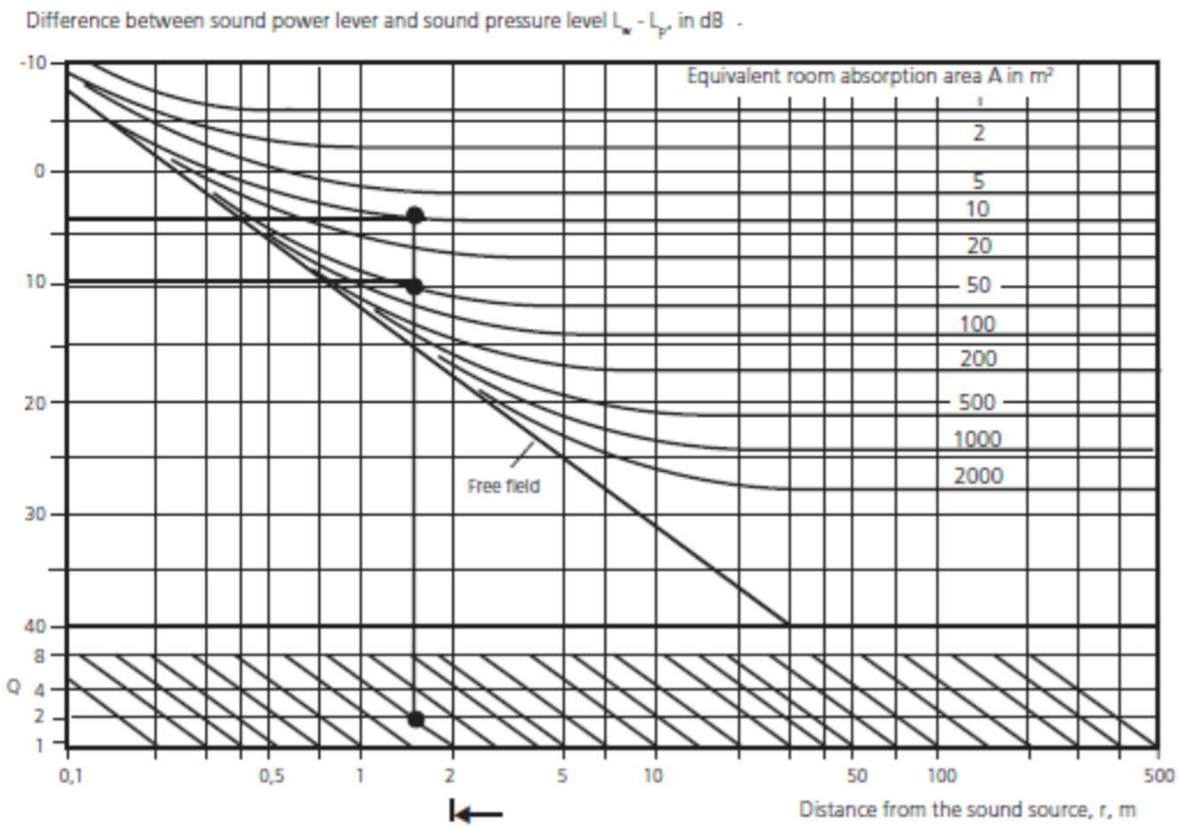
- Sound Attenuators (silencers) are commercially available devices that allow the passage of air while restricting the passage of sound generated from air distribution equipment.
- They subdivide the airflow into several passages each lined with perforated sheet backed by mineral wool or glass fibre.
- A silencer usually has a cross section greater than the duct in which it is installed such that noise induced by high air flow velocity passing through the silencer can be avoided.
- They are specified by the sound power level reduction in decibels (dB) in each octave band, so that the sound power level of combined noise source (e.g. fan) and attenuator can be calculated.
- The other important parameter is the pressure loss i.e. resistance to airflow.

Sound Attenuation due to End Reflection

- Attenuation due to the end reflection at some typical duct dimensions with sharp ends and different frequencies are indicated below:

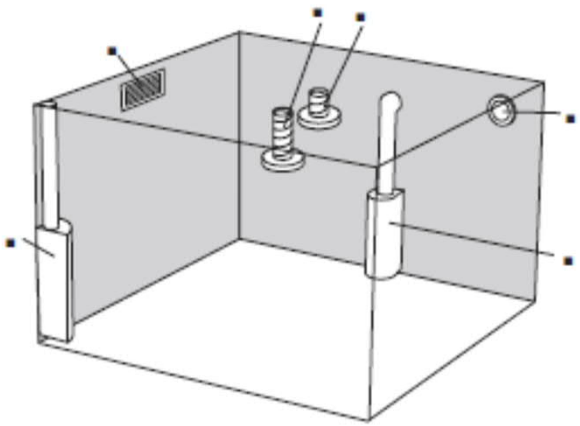
Attenuation (dB)						
Duct Dimension[1)] (mm)	Octave Band Center Frequency (Hz)					
	63.5	125	250	500	1000	2000 and higher
125	17	12	8	4	1	0
250	12	8	4	1	0	0
500	8	4	1	0	0	0
1000	4	1	0	0	0	0
2000	1	0	0	0	0	0

Noise in room



$$L_p - L_w = 10 \ \mathrm{Log}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right)$$

where Q = direction factor
r = distance from sound source (m)
R = the room constant

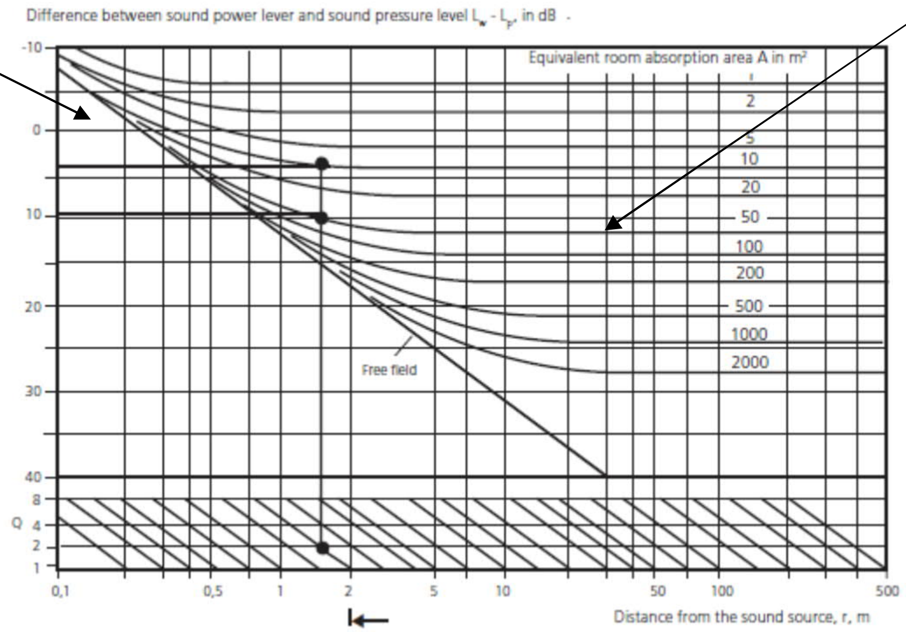


Q = 1 Middle of room. free supply air
Q = 4 Wall near ciling
Q = 2 Wall or ceiling
Q = 8 Corner position

Direct and reverberant effects

Descendingt line:
direct effect

Constant line:
reverberant effect



Room constant and absorptio

The room constant, R, is often encountered in the literature as a variable that characterises the room absorption. As mentioned previously it is same as the equivalent sound absorption (A). It is defined as:

$$R = A = \frac{S\bar{\alpha}}{1-\bar{\alpha}} \approx S\bar{\alpha} \ where \bar{\alpha} \leq 0.15$$

where S is the total surface area of the room (m^2),
α is average statistical sound absorption coefficient,
R is measured in Sabines (m^2).

The relationship between the room constant (R or A) and reverberation time is given by:

$$A = R = \frac{0.161V}{T}$$

where V is the volume of the room (m^3),
T is the reverberation time of the room (s).

Noise in room II

The total sound pressure at any point is the combined effect of the direct and reverberant sound field and is given by:

$$L_p = L_W + 10\lg\left(\underbrace{\frac{Q_\theta}{4\pi r^2}}_{direct} + \underbrace{\frac{4}{A}}_{reverberant} \right) \quad \text{dB}$$

where A is the equivalent sound absorption area (m^2), also known as the room constant R where $A = S\alpha$
α is average absorption coefficient for the room,
S is room surface area (m^2),
Q_θ is directivity factor of source in direction θ,
r is distance from source (m),
L_W is the sound power (dB).

The pressure level in the diffused field is where only reverberant plays the most important role:

$$L_{pd} = L_W + 10 \lg [4/A]$$

Thank you