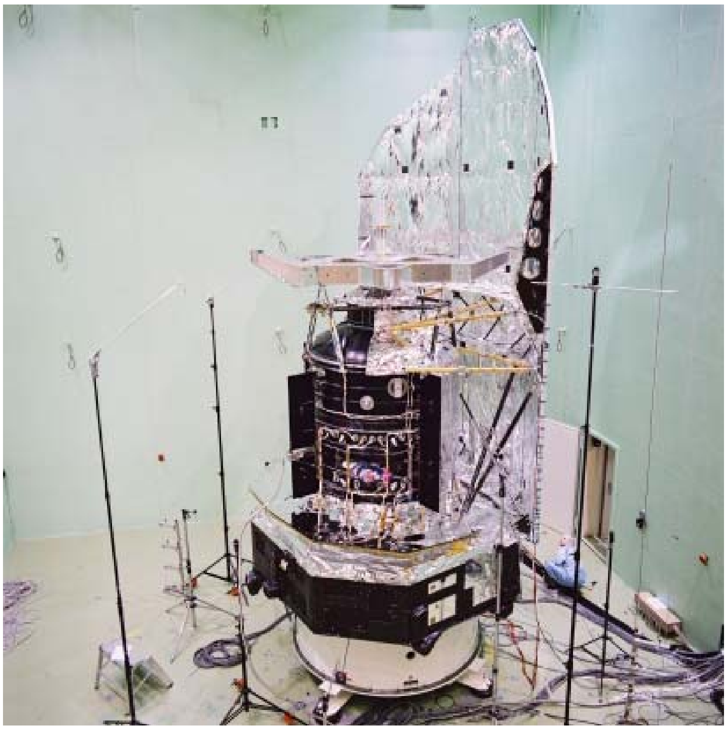
SOUND SENSORS

NTU50235100



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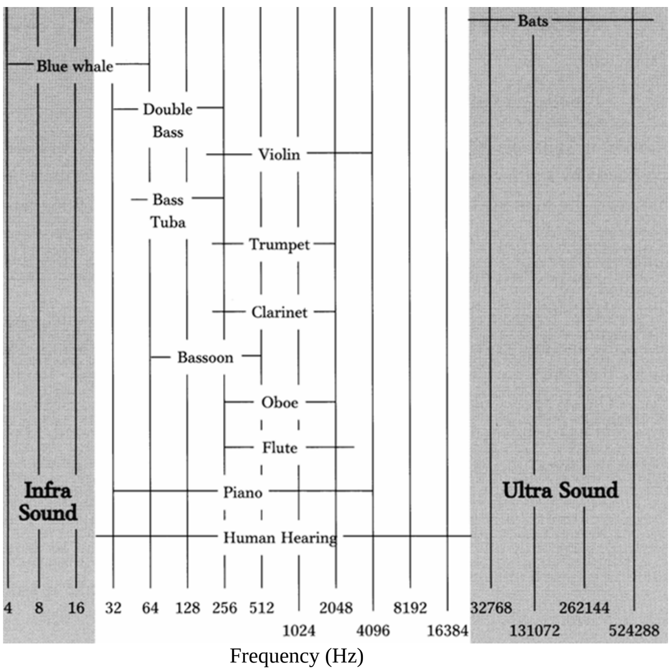
What is Sound?

- The phenomenon of sound in a fluid involves time-dependent changes of density, pressure, temperature, and position of the fluid particles.
- The changes are extremely small in relation to their mean values in the absence of sound.
- Sound propagation involves interplay between pressures generated by elastic reaction to volumetric strain and the fluid inertia that resists these attempts.
- Acoustic disturbances propagate in the form of waves.
- The effectiveness of sound generation is related to the rate of change of flow rather than to the magnitude of the flow.



(C. Taylor, “The Physics of Sound,” SOUND, Edited by Kruth and Stobart, Chap. 2, Cambridge Univeristy Press, 2000.)

Decibel Scales

The audible intensities range from approximately 10^{-12} to 10 W/m^2.

Using a logarithmic scale compresses the range of numbers required to describe this wide range of intensities

It is also consistent with humans judgement of the sound loudness

The *intensity level* IL of a sound is defined by

$$IL = 10\log(I/I_{ref}) \qquad (\text{dB } re\ I_{ref})$$

I_{ref} is a reference intensity

IL is expressed in *decibels referenced to* I_{ref}

progressive plane and spherical waves

$$I = P_e^2/\rho_0 c$$

leading to the sound pressure level

$$SPL = 20\log(P_e/P_{ref}) \qquad \text{dB } re\ P_{ref}$$

If we choose $I_{ref} = P_{ref}^2/\rho_0 c$, then $IL\ re\ I_{ref} = SPL\ re\ P_{ref}$.

CGS units	1 dyne/cm^2	(μbar)
MKS units	1 N/m^2	pascal (Pa)

$$1\ \mu\text{bar} \equiv 0.1\ \text{N/m}^2 \equiv 10^5\ \mu\text{Pa}$$

1 atmosphere (atm) $\equiv 1.01325 \times 10^5$ Pa $= 1.01325 \times 10^6 \mu$bar
1 kilogram/cm^2 (kgf/cm^2) $\equiv 0.980665 \times 10^5$ Pa $= 0.967841$ atm

The reference standard for airborne sounds is

$$I_{ref} = 10^{-12}\ \text{W/m}^2$$

a corresponding effective (root-mean-square) pressure of

$$P_e = P/\sqrt{2} = 20.4\ \mu\text{Pa} \qquad \text{rounded to } 20\ \mu\text{Pa}$$

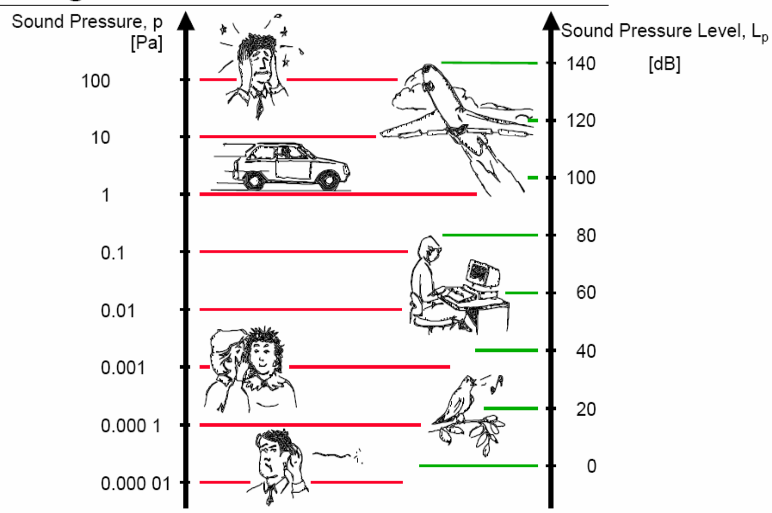
Medium	*Reference*	*Nearly equivalent to*
Air	10^{-12} W/m^2	20 μPa
	20 μPa = 0.0002 μbar	10^{-12} W/m^2
Water	1 μbar = $10^5 \mu$Pa	6.76×10^{-9} W/m^2
	0.0002 μbar = 20μPa	2.70×10^{-16} W/m^2
	1 μPa	6.76×10^{-19} W/m^2

SPL re 1 μbar + 100 = *SPL re* 1 μPa
SPL re 0.0002 μbar − 74 = *SPL re* 1 μbar
SPL re 0.0002 μbar + 26 = *SPL re* 1 μPa

The standard reference pressures in underwater acoustics is 1 μPa.

Source/Environment	Sound pressure level L_p (dB(A))
Launch noise outside rocket payload bay	160
Heavy artillery at gunners' heads	140
Threshold of pain	130
Large jet engine at 30 m; within large symphony orchestra playing fortissimo	120
10 m from loudspeakers at rock concert; 1 m from pneumatic chipping hammer	110
Inside a textile factory; in an old-fashioned underground train	90
Shouted male voice at 1 m; dense, accelerating road traffic at kerbside; inside jet airliner at take-off	80
Dense, free-flowing road traffic at 3 m from kerbside	70
Busy restaurant; two-person conversation	60
Average commercial office	50
Residential, urban neighbourhood, far from main roads, at night; library with no air-conditioning	40
Theatre with full audience just before curtain up	30
Empty recording studio; empty symphony hall	20
Male human breathing at 3 m	10
Average threshold of hearing of 1 kHz tone of normally hearing young persons	*c.* 0

Range of Sound Pressure Levels



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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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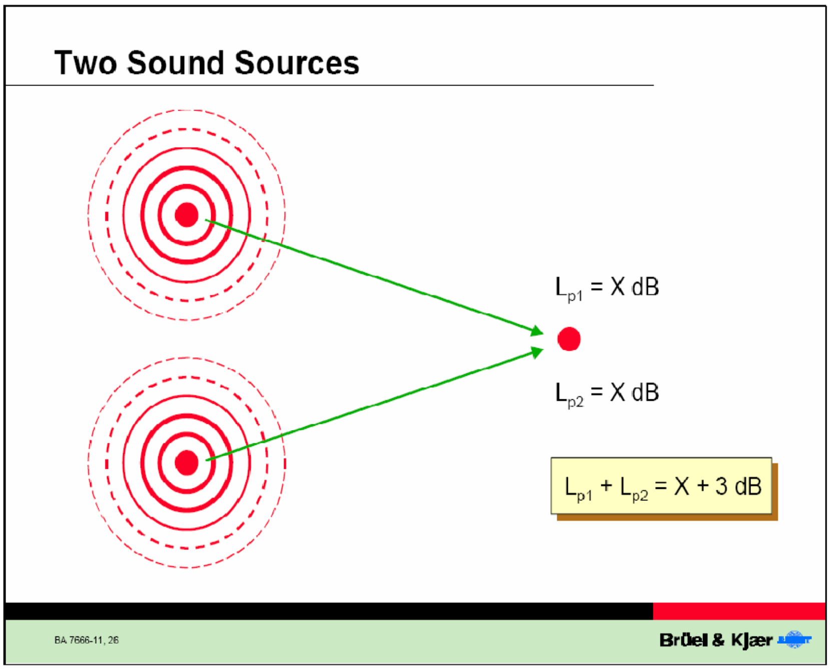

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$$I_1 > I_2$$

$$I_2 = \alpha I_1 \,,\ \alpha < 1$$

$$L_1 = 10\log\frac{I_1}{I_{ref}}$$

$$L_2 = 10\log\frac{I_2}{I_{ref}} = L_1 + 10\log\alpha$$

$$\boxed{\Delta L = L_1 - L_2 = -10\log\alpha}$$

$$I = I_1 + I_2 = (1+\alpha)I_1$$

$$L_t = 10\log\frac{I}{I_{ref}} = 10\log\frac{(1+\alpha)I_1}{I_{ref}} = L_1 + 10\log(1+\alpha) = L_1 + L_+$$

$$\boxed{L_+ = 10\log(1+\alpha)}$$

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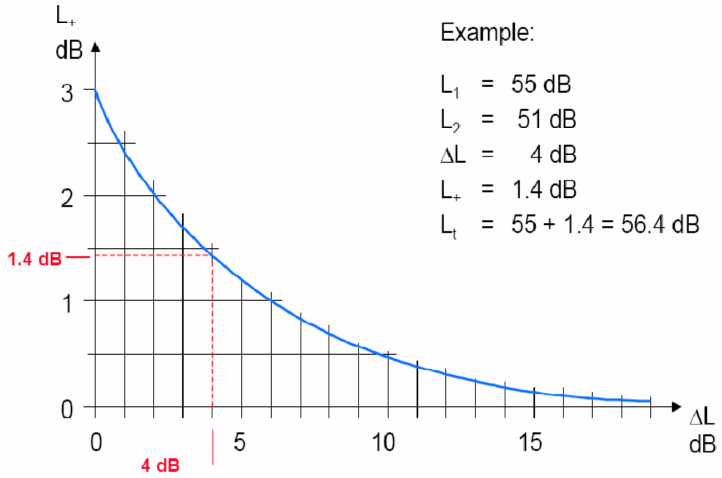
Addition of dB Levels



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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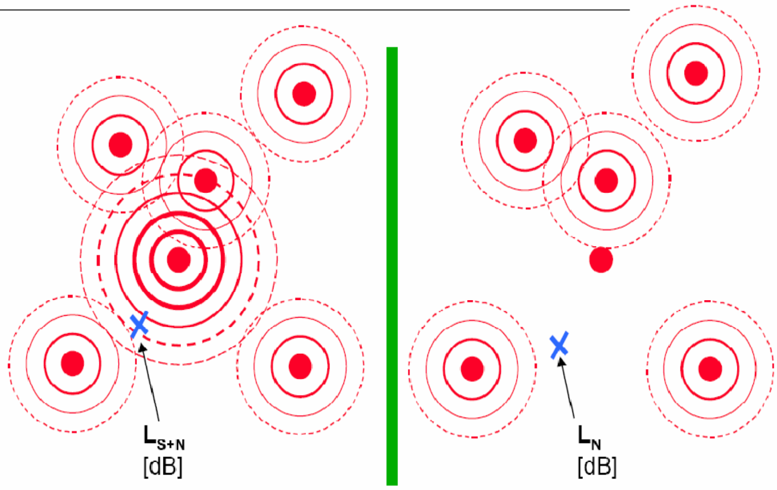
Subtraction of Noise Levels



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$$I_{S+N} > I_N$$

$$I_N = \alpha I_{S+N}\ ,\ \ \alpha < 1$$

$$L_{S+N} = 10\log\frac{I_{S+N}}{I_{ref}}$$

$$L_N = 10\log\frac{I_N}{I_{ref}} = L_{S+N} + 10\log\alpha$$

$$\boxed{\Delta L = L_{S+N} - L_N = -10\log\alpha}$$

$$I_S = I_{S+N} - I_N = (1-\alpha)I_{S+N}$$

$$L_S = 10\log\frac{I_S}{I_{ref}} = 10\log\frac{(1-\alpha)I_{S+N}}{I_{ref}} = L_{S+N} + 10\log(1-\alpha) = L_{S+N} - L_{\_}$$

$$\boxed{L_{\_} = -10\log(1-\alpha)}$$

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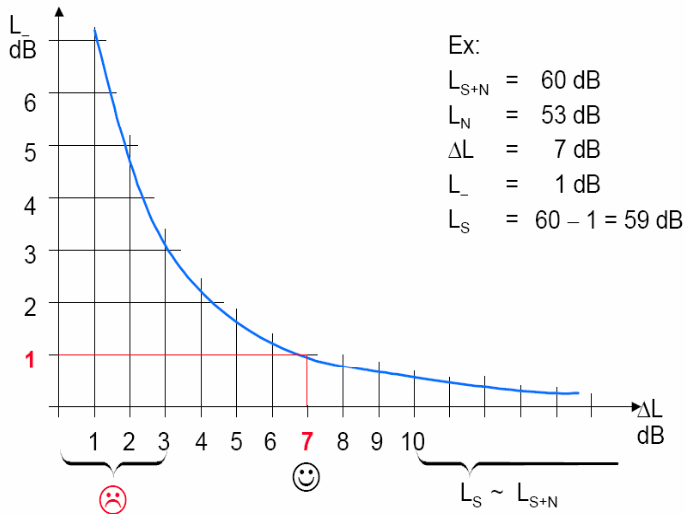
Subtraction of dB Levels



Ex:

L_{S+N} = 60 dB

L_N = 53 dB

ΔL = 7 dB

$L_{\_}$ = 1 dB

L_S = 60 – 1 = 59 dB

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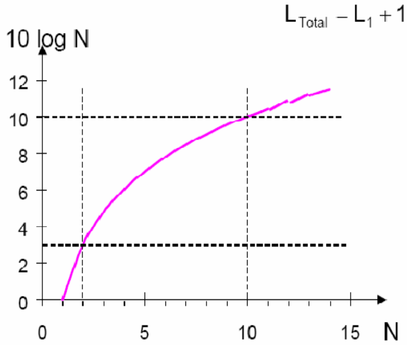
Addition of many dB values

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

For $L_1 = L_2 = L_3 \ldots\ldots = L_N$

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

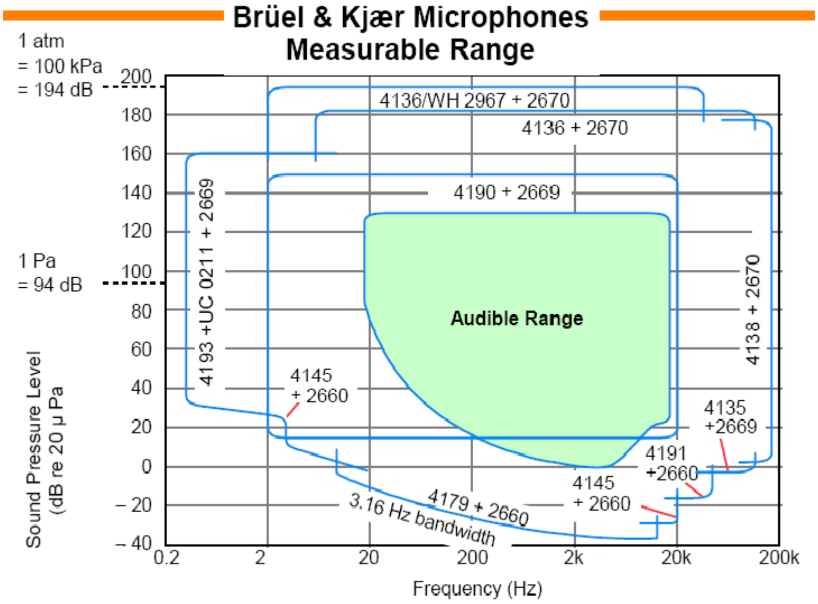


Examples:

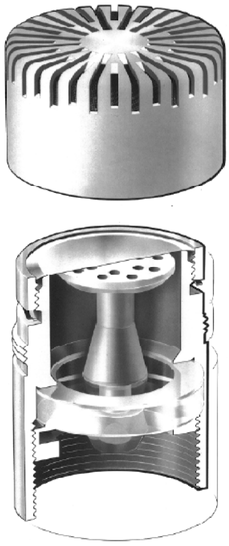
N = 2: $L_{Total} = L_1 + 3$ dB

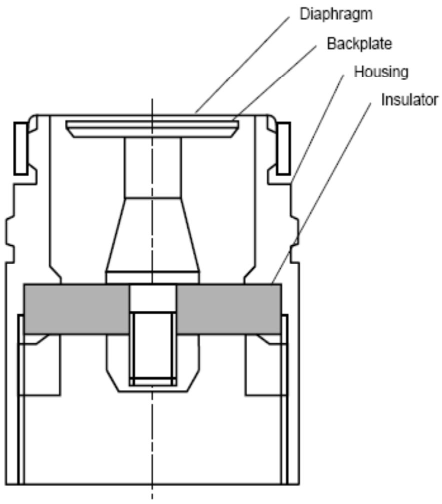
N = 10: $L_{Total} = L_1 + 10$ dB

Microphone



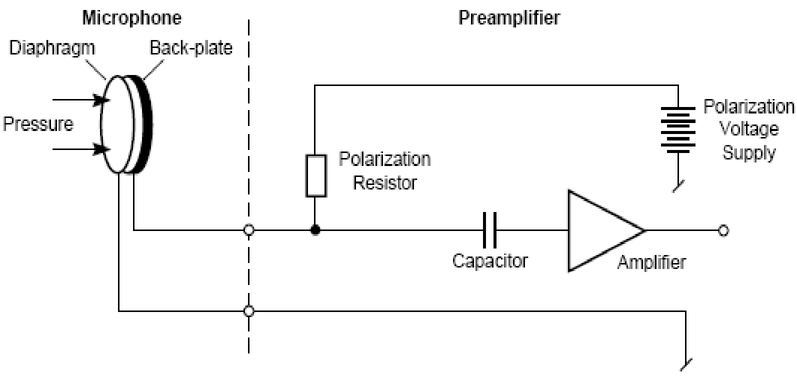
• Condenser measurement microphone





Constant charge principle

• External Polarization Source



The polarization resistance must be so high (1 to 10 GΩ) that it ensures an essentially constant charge on the microphone, even when its capacitance changes due to the sound pressure on its diaphragm.

$$E \cdot C = Q_0$$

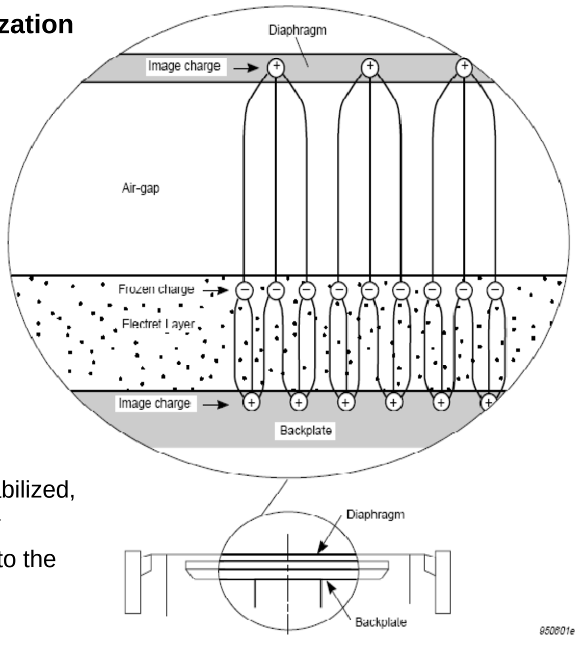
$$(E_0 + e) \cdot \frac{\varepsilon \cdot A}{D_0 + d} = E_0 \cdot \frac{\varepsilon \cdot A}{D_0}$$

$$e = E_0 \cdot \frac{d}{D_0}$$

Movements lead to distance and capacitance changes and to a corresponding AC-voltage across the plates.

A = Area of capacitor plate
C = Instantaneous capacitance between plates
D_0 = Distance between plates at rest position
d = Displacement of moveable plate (diaphragm) from rest position
E = Instantaneous voltage between plates
E_0 = Polarization voltage
e = Voltage change caused by plate displacement
Q_0 = Constant charge on plate capacitor
ε = Dielectric constant of air

• **Electret Polarization**



The electret consists of a specially selected and stabilized, high temperature polymer material which is applied to the top of the backplate.

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

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

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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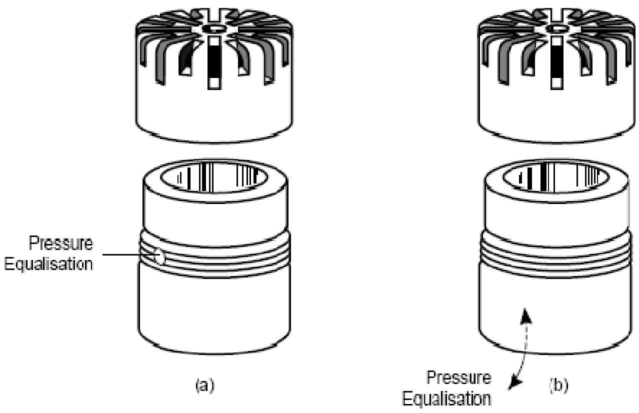
- Static Pressure Equalization



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Two electrical fields are produced in the microphone. One across the air gap and one across the electret. These fields must stay essentially constant during the microphone operation which means that any resistance loading on the microphone must be so high that the voltages produced by the microphone do not lead to any significant interchange of charges.

- Diaphragm and Air Stiffness

$$S(P_s) = S(P_{s,ref}) \cdot \frac{100}{(100 - F) + \frac{P_s}{P_{s,ref}} \cdot F}$$

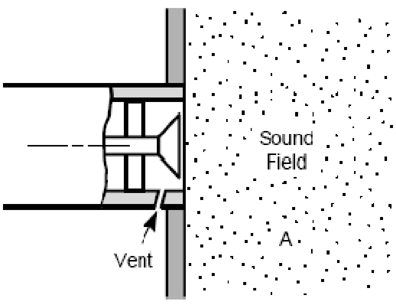
$S(P_s)$ = microphone sensitivity (a function of static pressure)

P_s = static pressure

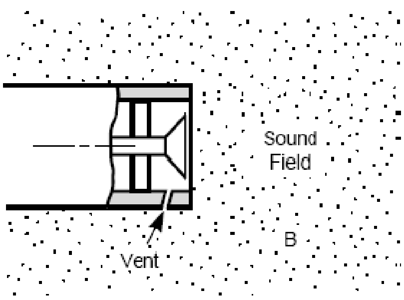
$P_{s,ref}$ = the reference static pressure at which 'F is valid

F = fraction of air stiffness in percent at reference static pressure (ratio between air stiffness and total diaphragm system stiffness)

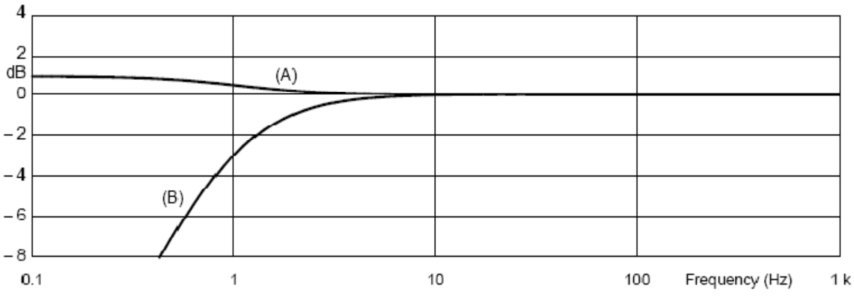
- Low Frequency Response and Vent Position



Inside vent

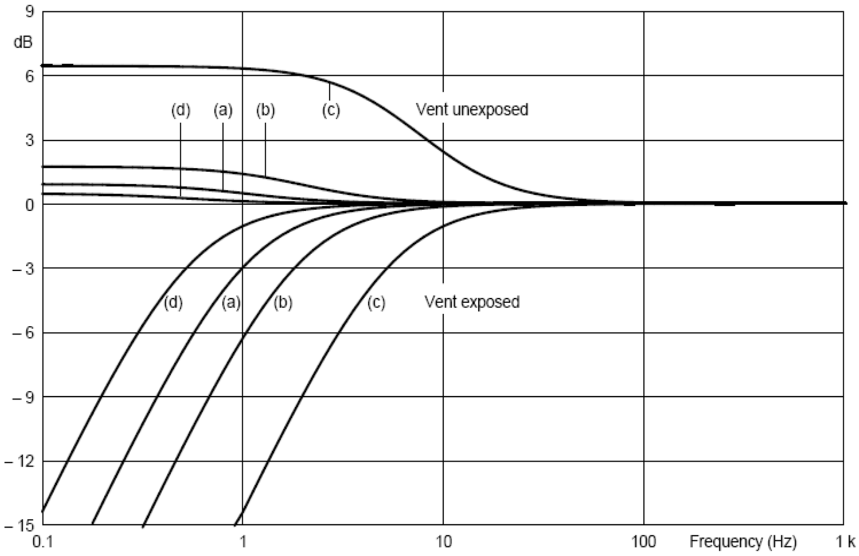


Outside vent

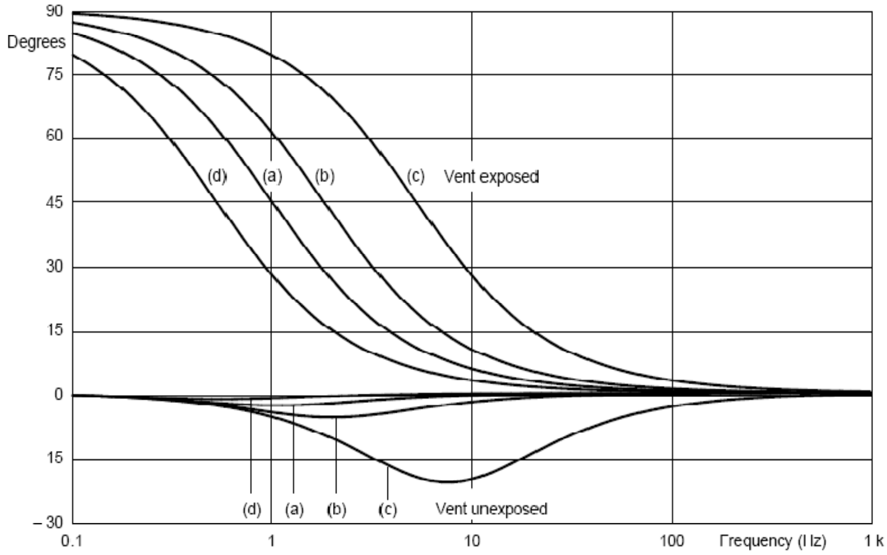


(A) inside vent (B) outside vent

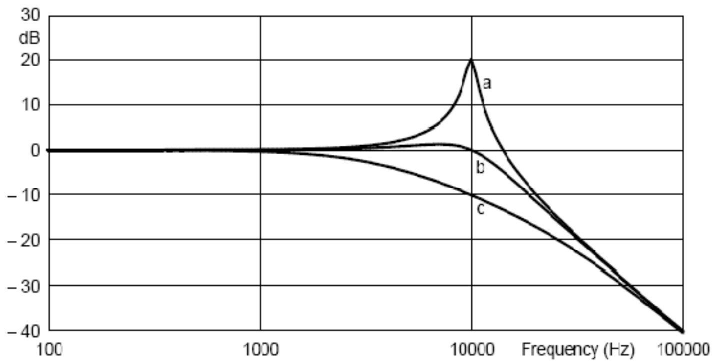
Microphone response is influenced by the ambient pressure



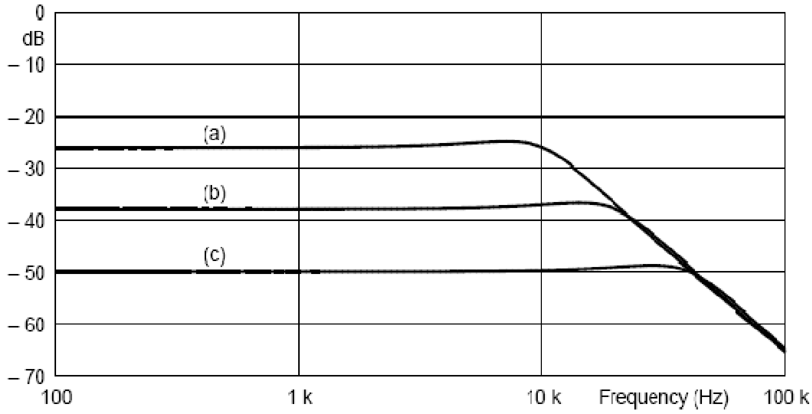
10% air-stiffness at nominal ambient pressure (101.3 kPa):
a) 1 bar, b) 2 bar, c) 10 bar, d) 0.5 bar



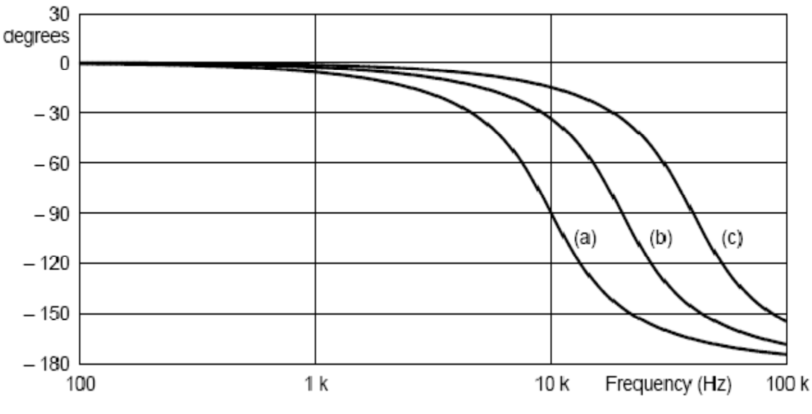
• High Frequency Response



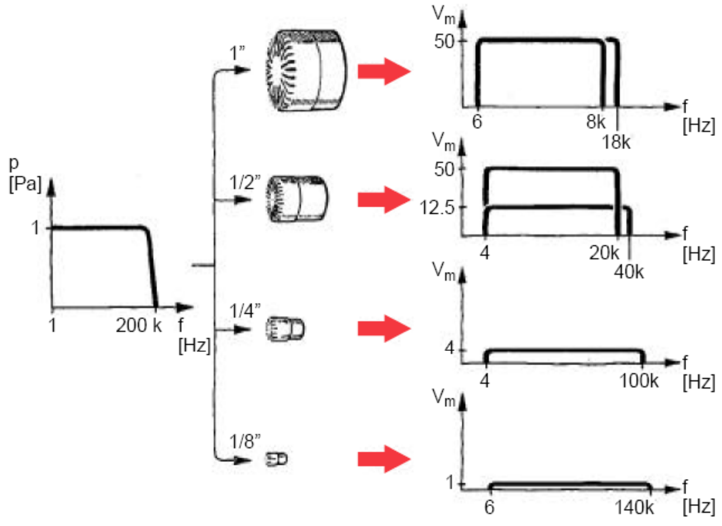
Influence of damping on the high frequency response (magnitude)



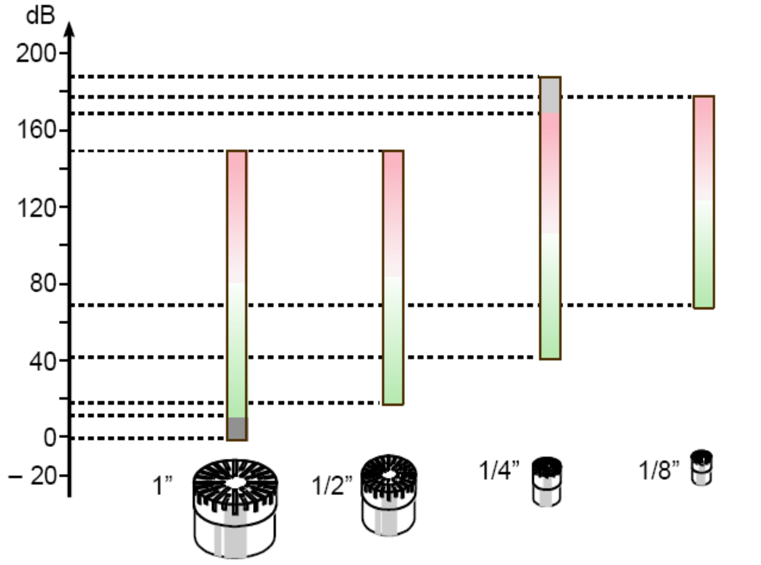
Frequency responses of microphone with critical damping and different diaphragm diameters (relative scale: 1(a), 0.5 (b), 0.25 (c))



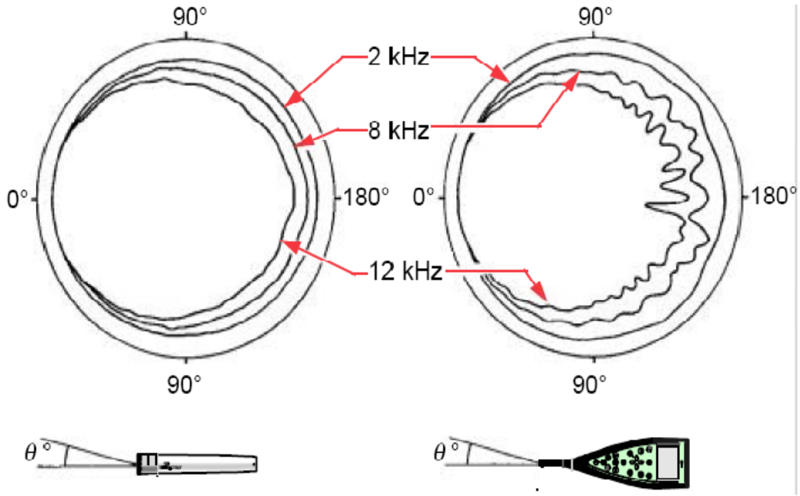
Frequency Range and Sensitivity



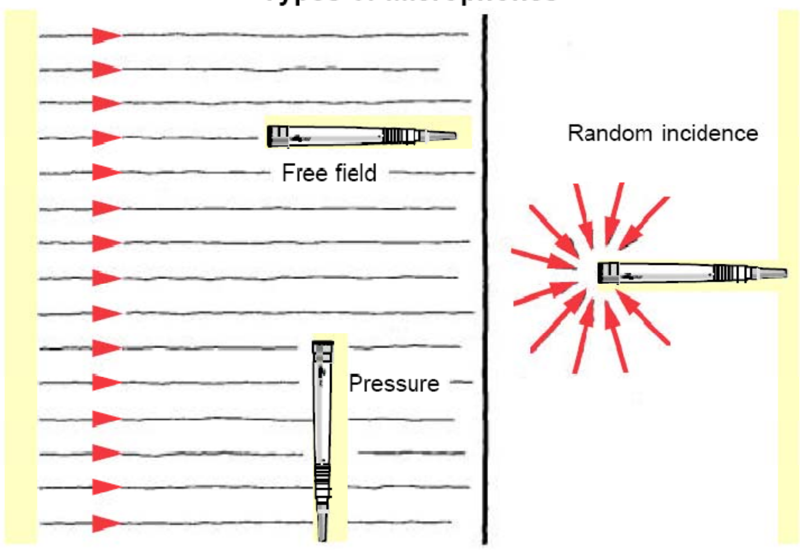
Dynamic Range



Directional Characteristics



Types of Microphones

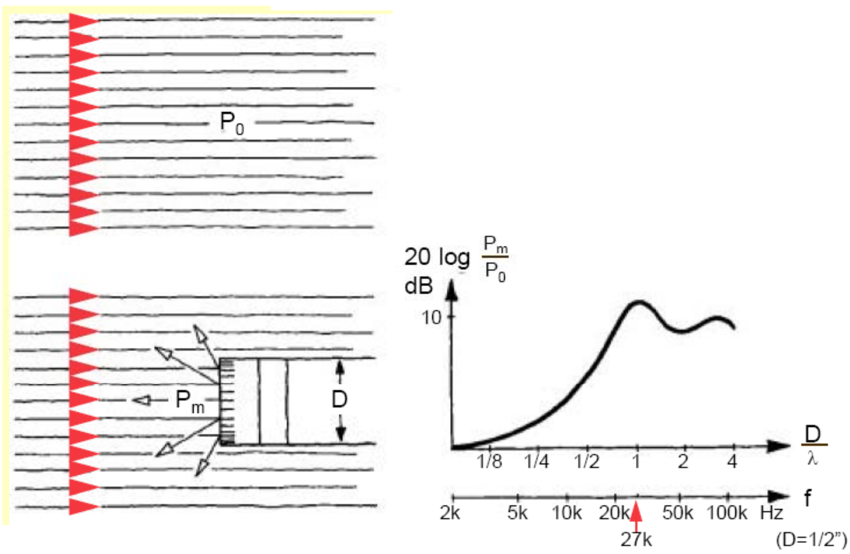


Free field microphones have uniform frequency response for the sound pressure that existed before the microphone was introduced into the sound field. It is of importance to note that any microphone will disturb the sound field, but the free field microphone is designed to compensate for its own disturbing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

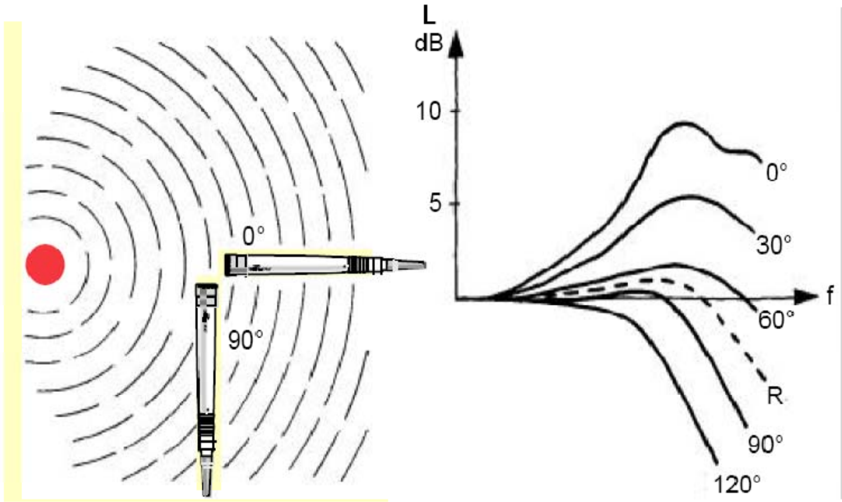
The pressure microphone is designed to have a uniform frequency response to the actual sound level present. When the pressure microphone is used for measurement in a free sound field, it should be oriented at a 90° angle to the direction of the sound propagation, so that the sound grazes the front of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

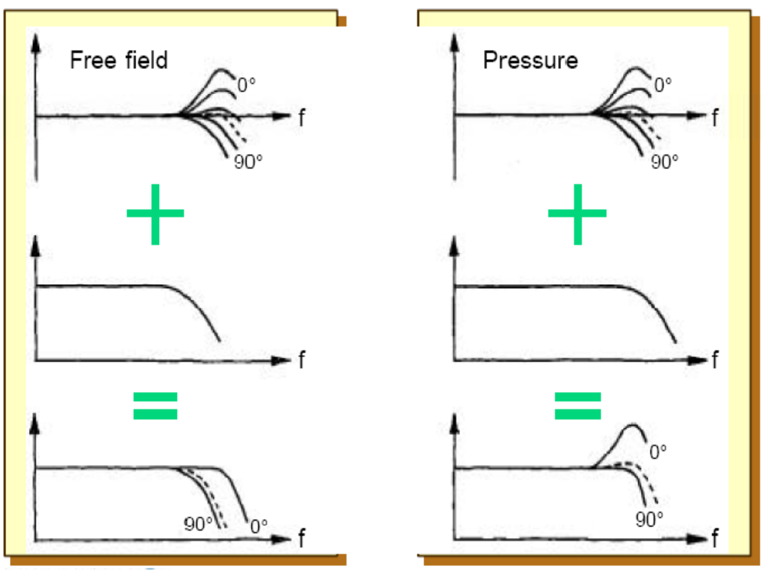
Free Field Correction



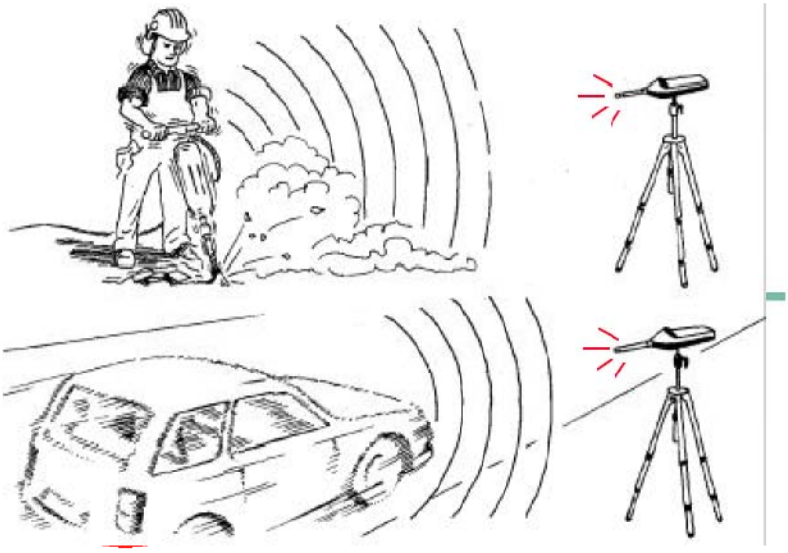
Free Field Correction



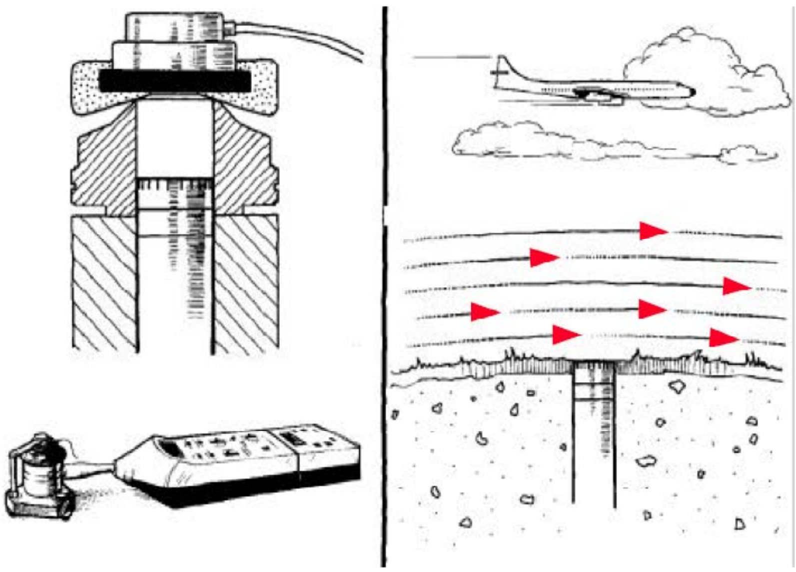
Response of Free Field Pressure Microphones



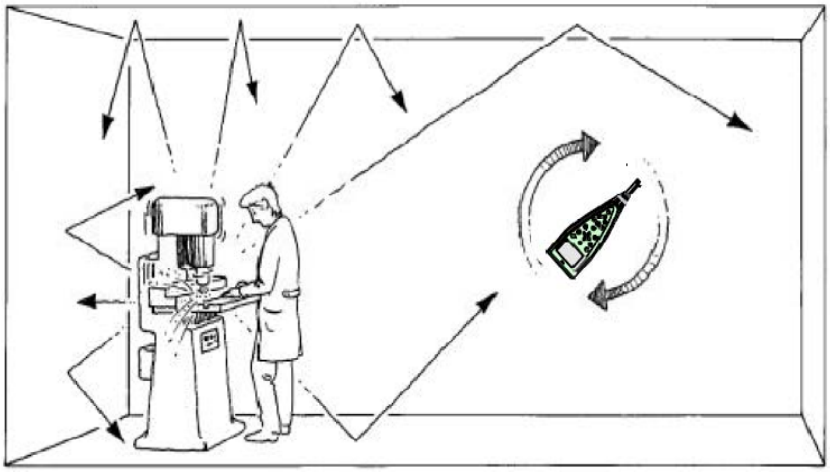
Use of Free Field Microphones



Use of Pressure Microphones



Use of Random Incidence Microphones



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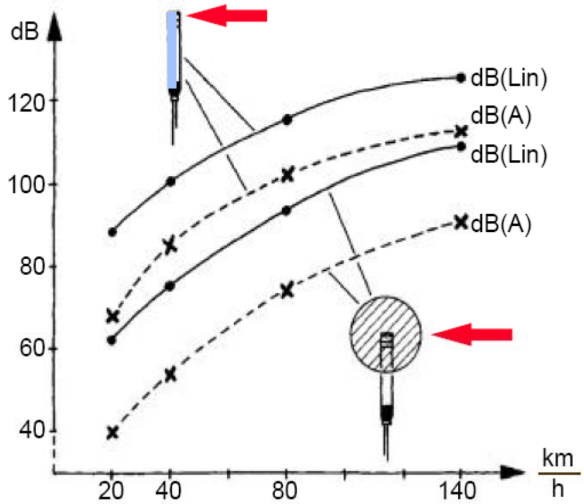
Windscreen



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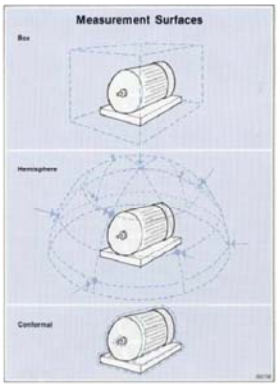
- Sound intensity measurement

Sound power is the cause.

Sound pressure is the effect.

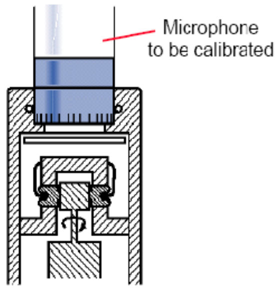
Sound intensity also gives a measure of direction as there will be energy flow in some directions but not in others.



(http://www.bksv.com/license/pdf/Sound_Intensity.pdf)

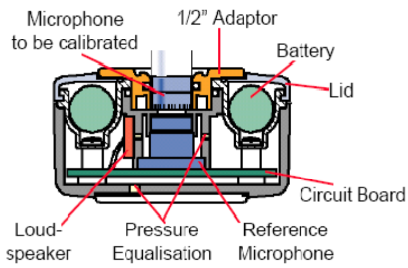
Pistonphone and Acoustical Calibrator

Pistonphone



f = 250 Hz
L = 124 ± Δ L [dB]

Acoustical Calibrator



f = 1000 Hz
L = 94 dB = 1 Pa