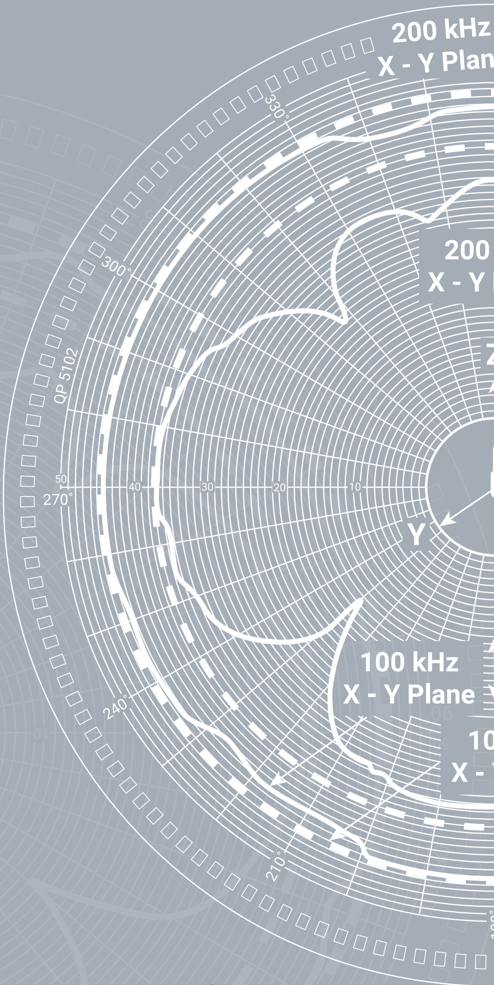
HBK HOTTINGER BRÜEL & KJÆR



SOUND AND VIBRATION

Pocket Handbook

SOUND AND VIBRATION

Pocket Handbook

Contents

UNDERWATER ACOUSTICS

VIBRATION

FREQUENCY ANALYSIS

SHOCK RESPONSE

Units of measurement

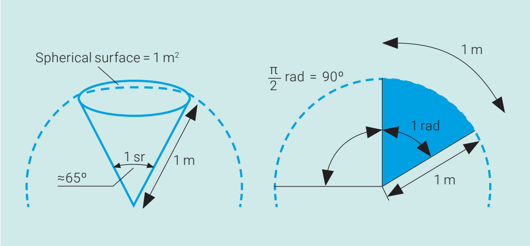
International System of Units (SI)

BASIC UNITS

	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric Current	ampere	A
Thermodynamic Temperature	kelvin	K
Amount of Substance	mole	mol

SUPPLEMENTARY UNITS

Plan Angle	radian	rad
Solid Angle	steradian	sr



DERIVED UNITS (SELECTED LIST)

Quantity	Name	SI Symbol	Formula
Acceleration	metre per second squared	m/s^2	–
Area	square metre	m^2	–
Celsius temperature	degree Celsius	°C	K
Density, mass density	kilogram per cubic metre	kg/m^3	–
Electric capacitance	farad	F	A·s/V
Electric inductance	henry	H	V·s/A
Electric potential difference	volt	V	W/A
Electric resistance	ohm	Ω	V/A
Quantity of electricity	coulomb	C	A·s
Energy	joule	J	N·m
Force	newton	N	$kg \cdot m/s^2$
Frequency	hertz	Hz	1/s
Magnetic field strength	ampere per metre	A/m	–
Magnetic flux	weber	Wb	V·s
Magnetic flux density	tesla	T	Wb/m^2
Power	watt	W	J/s
Pressure	pascal	Pa	N/m^2
Velocity, speed	metre per second	m/s	–
Volume	cubic metre	m^3	–

PREFIXES

Multiple		Prefix	Symbol
10^1	ten times	deca	da
10^2	hundred times	hecto	h
10^3	thousand times	kilo	k
10^6	million times	mega	M
10^9	milliard times	giga	G
10^{12}	billion times	tera	T
10^{15}	billiard times	peta	P
10^{18}	trillion times	exa	E
10^{-1}	tenth part	deci	d
10^{-2}	hundredth part	centi	c
10^{-3}	thousandth part	milli	m
10^{-6}	millionth part	micro	µ
10^{-9}	milliardth part	nano	n
10^{-12}	billionth part	pico	p
10^{-15}	billiardth part	femto	f
10^{-18}	trillionth part	atto	a

Conversion Table
(*indicates exact conversion)

LENGHT

Name	Symbol	Multiply	to obtain
angstrom	Å	10^{-10}	m*
micrometre	µm	10^{-6}	m*
inch	in	2.540	cm*
foot	ft	30.48	cm*
yard	yd	0.9144	m*
fathom	fm	1.829	m
mile (statute)		1.609344	km*
mile (nautical)		1.852	km*
light year		$9.461 \cdot 10^{15}$	m

AREA

square inch	in^2	6.4516	cm^2*
square foot	ft^2	$9.290 \cdot 10^{-2}$	m^2*
square yard	yd^2	0.8361	m^2*
acre	ac	4047	m^2*
square mile	–	2.590	km^2*

VOLUME

cubic inch	in^3	16.39	cm^3
cubic foot	ft^3	28.32	m^3
litre	L	10^{-3}	m^3*
quart liq. (US)	qt	0.9464	L
gallon (US)	US gal	3.785	L
gallon (UK, Imperial)	UK gal	4.546	L
fluid ounce (fluid, US)	fl oz	29.57	cm^3
fluid ounce (fluid, UK)	fl oz	28.48	cm^3

MASS

grain	gr	$6.480 \cdot 10^{-2}$	gram
ounce	oz	28.35	gram
pound = 16 oz	lb	453.6	gram
Stone (UK)	–	6.35	kg
long hundredweight	cwt	50.80	kg
tonne, metric ton	t	1000	kg

FORCE

dyne	dyn	10^{-5}	N*
pound – force	lbf	4.448	N
kilogram – force	kgf	9.807	N

TORQUE

Name	Symbol	Multiply	to obtain
dyne centimetre	dyn cm	10^{-7}	N·m
ounce-force inch	ozf · in	$7.062 \cdot 10^{-3}$	N·m
pound-force inch	lbf · in	0.1130	N·m
pound-force foot	lbf · ft	1.356	N·m

PRESSURE

atmosphere (normal)	atm	$1.013 \cdot 10^{5}$	Pa
bar		10^{5}	Pa*
dyne per sq centimetre	dyn/cm^2	0.1	Pa*
inch of water (4°C)		249.1	Pa
millimetre of mercury (0°C)	mmHg	133.3	Pa
pound-force per square foot	lbf/ft^2	47.88	Pa
pound-force per square inch	lbf/in^2	6.895	Pa

VELOCITY

foot per minute	ft/min	$5.080 \cdot 10^{-3}$	m/s*
foot per second	ft/s	0.3048	m/s*
inch per second	in/s	$2.54 \cdot 10^{-2}$	m/s*
knot		0.5144	m/s*
knot		1.852	km/h
mile per hour (international)	mi/h	1.609	km/h

ACCELERATION

acceleration of gravity (standard)	g	9.807	m/s^2

ANGLE

cycle (360°)		6.283	rad
degree		$1.745 \cdot 10^{-2}$	rad
hertz		6.283	rad/s
revolution per minute	rpm	$1.047 \cdot 10^{-1}$	rad/s
revolution per second	rps	6.283	rad/s

ENERGY

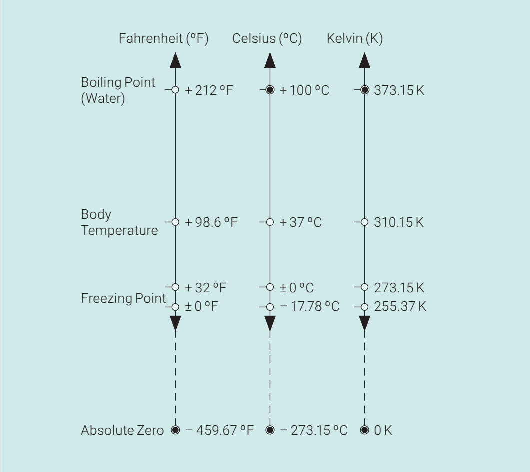
British thermal unit (IT)	Btu_{IT}	$1.055 \cdot 10^{3}$	J
calorie (IT)	cal_{IT}	4.187	J
erg		$1.000 \cdot 10^{-7}$	J*
watt hour	W · h	$3.600 \cdot 10^{-3}$	J*
foot-pound force	ft · lbf	1.356	J

POWER

Name	Symbol	Multiply	to obtain
British thermal unit per hour (IT)	Btu_{IT}/h	$2.931 \cdot 10^{-1}$	W
horsepower (electric)		$7.46 \cdot 10^{2}$	W*
erg per second	erg/s	$1.000 \cdot 10^{-7}$	W*
calorie per second (thermochemical)	cal_{th}/s	4.184	W*

TEMPERATURE

Celsius to Kelvin	K = °C + 273.15
Fahrenheit to Celsius	°C = (°F – 32)/1.8
Fahrenheit to kelvin	K = (°F + 459.67)/1.8



Decibel Formulas and Notation

(ISO 1683)

Quantity	Symbol	Formula	Reference Level[a]
Sound pressure level	L_p	$20 \log(p/p_0)$ dB	20μPa (in air) 1μPa (in other media)
Acceleration level	L_a	$20 \log(a/a_0)$ dB	1 μm/s²
Velocity level	L_v	$20 \log(v/v_0)$ dB	1 nm/s
Force level	L_F	$20 \log(F/F_0)$ dB	1μN
Power level	L_W	$10 \log(P/P_0)$ dB	1pW
Intensity level	L_I	$10 \log(I/I_0)$ dB	1pW/m²
Energy density level	L_w	$10 \log(w/w_0)$ dB	1pJ/m³
Energy level	L_E	$10 \log(E/E_0)$ dB	1 pJ

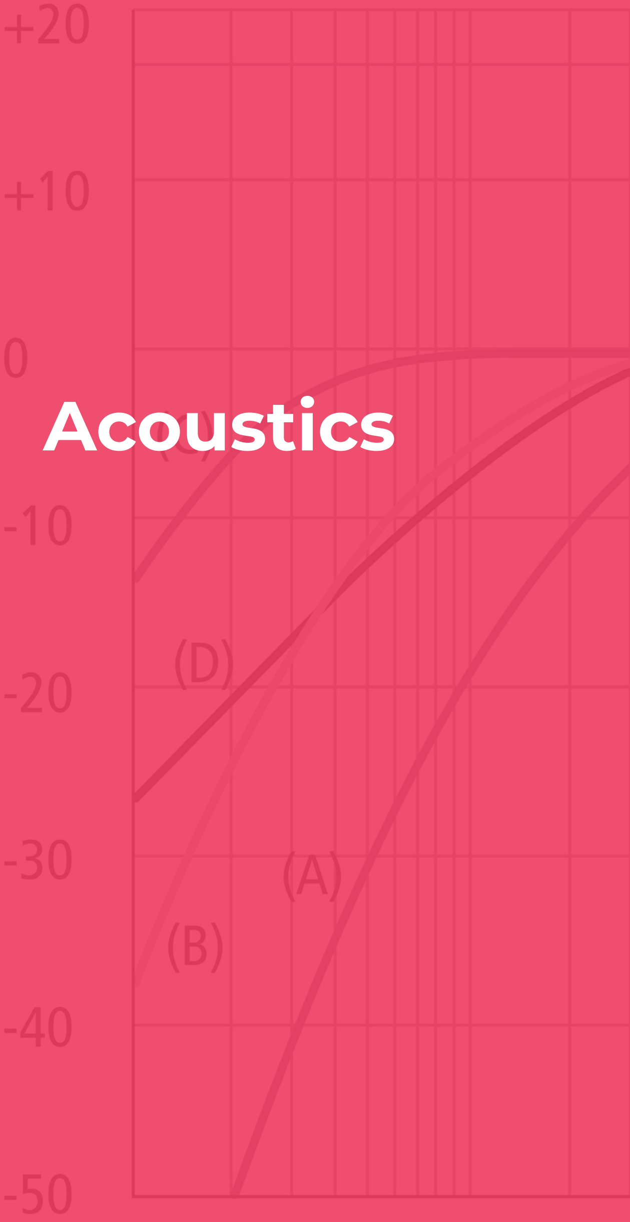
a. p_0, a_0, ...

dB to Pressure Ratio

Pressure Ratio	−dB+	Pressure Ratio	Pressure Ratio	−dB+	Pressure Ratio
1.000	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	8	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	0.158	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	31.620
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}
0.565	5.0	1.778	10^{-5}	100	10^{+5}

dB to Power Ratio

Power Ratio	−dB+	Power Ratio	Power Ratio	−dB+	Power Ratio
1.000	0.0	1.000	0.251	6	3.981
0.977	0.1	1.023	0.200	7	5.012
0.955	0.2	1.047	0.158	8	6.310
0.933	0.3	1.071	0.126	9	7.943
0.912	0.4	1.096	0.100	10	10.000
0.891	0.5	1.122	0.0631	12	15.849
0.871	0.6	1.148	0.0398	14	25.119
0.851	0.7	1.175	0.0251	16	39.811
0.832	0.8	1.202	0.0158	18	63.096
0.813	0.9	1.230	10^{-2}	20	10^{+2}
0.794	1.0	1.259	10^{-3}	30	10^{+3}
0.708	1.5	1.413	10^{-4}	40	10^{+4}
0.631	2.0	1.585	10^{-5}	50	10^{+5}
0.501	3.0	1.995	10^{-6}	60	10^{+6}
0.398	4.0	2.512	10^{-8}	80	10^{+8}
0.316	5.0	3.162	10^{-10}	100	10^{+10}



Acoustics

Glossary of Acoustic Terms

ABSORPTION
The conversion of sound energy into another form of energy, usually heat, when passing through an acoustical medium.

ABSORPTION COEFFICIENT
Ratio of sound absorbing effectiveness, at a specific frequency, of a unit area of acoustical absorbent to a unit area of perfectly absorptive material.

ACOUSTICS
The science of the production, control, transmission, reception and effects of sound and of the phenomenon of hearing.

AMBIENT NOISE
All-pervasive noise associated with a given environment.

AMPLITUDE DISTRIBUTION
A method of representing time-varying noise by indicating the percentage of time that the noise level is present in a series of amplitude intervals.

ANECHOIC ROOM
A room whose boundaries effectively absorb all incident sound over the frequency range of interest, thereby creating essentially free-field conditions.

AUDIBILITY THRESHOLD
At a specified frequency, the sound pressure level above which persons with normal hearing begin to perceive sound.

BACKGROUND NOISE
Noise from all sources other than the noise source under test. Background noise includes contributions from airborne noise, structure-borne vibration noise and electrical noise in the instrumentation.

CUMULATIVE DISTRIBUTION
A method of representing time-varying noise by indicating the percentage of time that the noise level is present above (or below) a series of amplitude levels.

DAMPING (1)
The action of frictional or dissipative forces on a dynamic system causing the system to lose energy and reduce the amplitude of movement.

DAMPING (2)
Removal of echoes and reverberation by the use of sound-absorbing materials.

DECIBEL SCALE
A linear numbering scale used to define a logarithmic amplitude scale, thereby compressing a wide range of amplitude values to a small set of numbers.

DIFFRACTION
The scattering of radiation at an object smaller than one wavelength and the subsequent interference of the scattered wavefronts.

DIFFUSE FIELD
A sound field in which the sound pressure level is the same everywhere and the flow of energy is equally probable in all directions.

DIFFUSE SOUND
Sound that is completely random in phase; sound which appears to have no single source.

DIRECTIVITY FACTOR
The ratio of the mean-square pressure (or intensity) on the axis of a transducer at a certain distance to the mean-square pressure (or intensity) that a spherical source radiating the power would produce at that point.

FAR FIELD
Distribution of acoustic energy at a significantly greater distance from a sound source than the linear dimensions of the source itself, and where the sound pressure level obeys the inverse-square law (the sound pressure level decreases 6 dB with each doubling of distance from the source).

Also, in this region the sound particle velocity is in phase with the sound pressure. In the far field, the sound waves can be considered planar.

FREE FIELD
An environment in which there are no reflective surfaces within the frequency range of interest.

HEARING LOSS
An increase in the threshold of audibility due to disease, injury, age or exposure to intense noise.

HERTZ
The unit of frequency measurement, representing cycles per second.

IMPEDANCE, ACOUSTIC
The complex ratio of dynamic pressure to particle velocity at a point in an acoustic medium, measured in rayls (1 rayl =1 Ns/m^3).

INFRASOUND
Sound at frequencies below the audible range, that is, below about 16 Hz. It is sometimes referred to as low-frequency sound.

ISOLATION
Resistance to the transmission of sound by materials and structures.

LOUDNESS
Subjective impression of the intensity of a sound. Equal-loudness contours are a measure of sound pressure over the frequency spectrum, for which a listener perceives a constant loudness when presented with pure steady tones. Equal-loudness contours are defined in ISO 226.

MASKING
The process by which the threshold of audibility of one sound is raised by the presence of another (masking) sound.

NEAR FIELD
That part of the sound field, usually within about two wavelengths from a noise source, where there is no simple relationship between sound level and distance.

NEWTON
The force required to accelerate a 1 kg mass at 1 m/s^2. Approximately equal to the gravitational force on a 100 g mass.

NOISE EMISSION LEVEL
The dB(A) level measured at a specified distance and direction from a noise source, in an open environment, above a specified type of surface. Generally follows the recommendation of a national or industry standard.

NOISE REDUCTION COEFFICIENT (NRC)
The arithmetic average of the sound absorption coefficients of a material at 250, 500, 1000 and 2000 Hz.

NOY
A linear unit of noisiness or annoyance.

PARTICLE VELOCITY
The velocity of air molecules about their rest position due to a sound wave.

PASCAL (Pa)
A unit of pressure corresponding to a force of 1 newton acting uniformly upon an area of 1 square metre. Hence 1 Pa = 1 N/m^2.

PHON
The loudness level of a sound. It is numerically equal to the sound pressure level of a 1 kHz free progressive wave that is judged by reliable listeners to be as loud as the unknown sound.

PINK NOISE
Broadband noise whose energy content is inversely proportional to frequency (–3 dB per octave or –10 dB per decade).

POWER SPECTRUM LEVEL
The level of the power in a band one hertz wide referred to a given reference power.

RANDOM NOISE
Noise whose instantaneous amplitude is not specified at any instant of time. Instantaneous amplitude can only be defined statistically by an amplitude distribution function.

REVERBERATION
The persistence of sound in an enclosure after a sound source has been stopped. Reverberation time is the time, in seconds, required for sound pressure at a specific frequency to decay 60 dB after a sound source is stopped.

ROOT MEAN SQUARE (RMS)
The square root of the arithmetic average of a set of squared instantaneous values.

SABINE
A measure of sound absorption of a surface. One metric sabine is equivalent to 1 m^2 of a perfectly absorptive surface.

HEMI-ANECHOIC FIELD
A free field above a reflective plane.

SONE

A linear unit of loudness. The ratio of loudness of a sound to that of a 1 kHz tone 40 dB above the threshold of hearing.

SOUND

Energy that is transmitted by pressure waves in air or other materials and is the objective cause of the sensation of hearing. Commonly called noise if it is unwanted.

SOUND INTENSITY

The rate of sound energy transmission per unit area in a specified direction.

SOUND INTENSITY LEVEL

The fundamental measure of sound intensity. Defined as:

$$L_I = 10 \log (I/I_0) \text{ dB}$$

where I is the rms value of sound intensity in W/m^2 and I_0 is $I_p W/m^2$.

SOUND LEVEL

The level of a sound measured with a sound level meter and one of its weighting filters. When A-weighting is used, the sound level is given in dB(A).

SOUND LEVEL METER

An electronic instrument for measuring the rms and peak levels of sound in accordance with an accepted national or international standard, such as IEC 61672.

SOUND POWER

The total sound energy radiated by a source per unit time.

SOUND POWER LEVEL

The fundamental measure of sound power. Defined as:

$$L_W = 10 \log (P/P_0) \text{ dB}$$

where P is the rms value of sound power in watts and P_0 is 1 pW.

SOUND PRESSURE

A dynamic variation in atmospheric pressure. The pressure at a point in space minus the static pressure at that point.

SOUND PRESSURE LEVEL

The fundamental measure of sound pressure. Defined as:

$L_p = 20 \log (p/p_0)$ dB

where p is the rms value (unless otherwise stated) of sound pressure in pascals, and p_0 is 20 µPa for measurements in air.

SOUND TRANSMISSION CLASS (STC)

A single-number rating for describing sound transmission loss of a wall or partition.

SOUND TRANSMISSION LOSS

Ratio of the sound energy emitted by an acoustic material or structure to the energy incident upon the opposite side.

SOUNDSCAPE

A description of the human perception of sounds heard in an environment.

SOUND QUALITY

The rating of perceived sound in terms of quality.

STANDING WAVE

A periodic wave having a fixed distribution in space that is the result of interference of progressive waves of the same frequency and kind. Characterized by the existence of maxima and minima amplitudes that are fixed in space.

ULTRASOUND

Sound at frequencies above the audible range, that is, above about 20 kHz.

WAVELENGTH

The distance measured perpendicular to the wave front in the direction of propagation between two successive points in the wave that are separated by one period. Equals the ratio of the speed of sound in the medium to the fundamental frequency.

WEIGHTING FILTER

An electronic filter in a sound level meter that approximates, under defined conditions, the frequency response of the human ear. The A-weighting filter is the most commonly used.

WHITE NOISE

Broadband noise having constant energy per unit of frequency.

Community Noise Criteria

L_{AeqT} (L_{Aeq})
Equivalent continuous sound level. The steady dB(A) level that would produce the same A-weighted sound energy over a stated period of time as the specified time-varying sound.

$L_{Ar,Tr}$ RATING LEVEL
The A-weighted equivalent continuous noise level (L_{AeqT}) during a specified time period with specified adjustments for tonal or impulsive noise, and for time of day and type of source.
$L_{Ar,Tr} = L_{AeqT} + K_I + K_T + K_R + K_S$

L_{den}
A Rating Level based on the 24-hour L_{AeqT} with a 5 dB adjustment for levels during evening (for example, 18:00 – 22:00) and 10 dB for levels during the night (for example, 22:00 – 07:00). Often used to determine dose-response realtionships to determine community noise limits.

L_{dn}
A 24-hour L_{AeqT} except 10 dB is added to all levels measured at night, typically defined as being between 22:00 – 07:00.

L_{AE}
Sound Exposure Level (also known as SEL) Single Event Noise Exposure Level. The dB(A) level that, if it lasted for one second, would produce the same A-weighted sound energy as the actual event.

L_N ($L_{AFN,T}$)
The dB(A) level exceeded N% of the time. For example, L_{90}, the level exceeded 90% of the time, is commonly used to estimate the ambient (background) noise level while L_5 or L_{10} is used to indicate the levels of noise events.

L_{EPN}
Effective Perceived Noise Level. A complex rating used to certify aircraft types for fly-over noise. Includes corrections for pure tones and for duration of the noise.

L_{NP}

Noise Pollution Level. A variation of L_{AeqT} that accounts for short-term variability in noise level. For a gaussian distribution of dB(A) level, it is defined as:

$L_{NP} = L_{eq} + (L_{10} - L_{90})$

NEF

Noise Exposure Forecast. A complex criterion for predicting future noise impact of airports. The computation considers Effective Perceived Noise Level of each type of aircraft, flight profile, number of flights, time of day, etc. Generally used in plots of equal NEF contours for zoning control around airports.

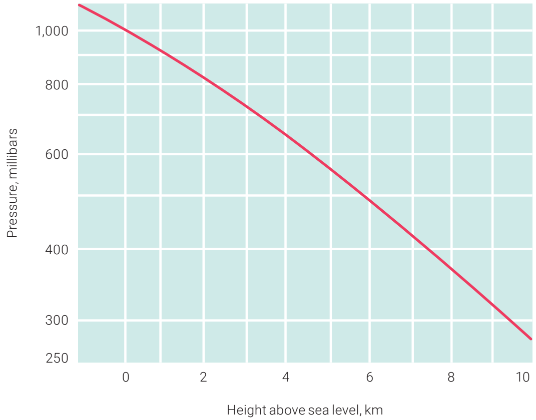
Speed of Sound in Various Media

Medium	Speed of Sound (m/s)
Air, 21°C	344
Alcohol	1213
Lead	1220
Hydrogen, 0°C	1269
Water, fresh	1480
Water, salt, 21°C	1520 (3.5% salinity)
Human body	1558
Plexiglas	1800
Wood, soft	3350
Concrete	3400
Mild steel	5050
Aluminium	5150
Glass	5200

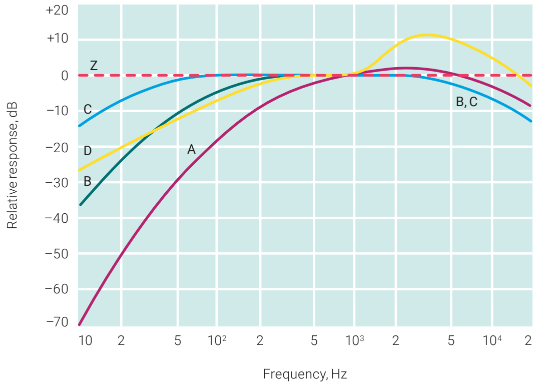
Wavelength

$$\lambda = \frac{\text{speed of sound}}{\text{frequency}}$$

Static Pressure vs Altitude

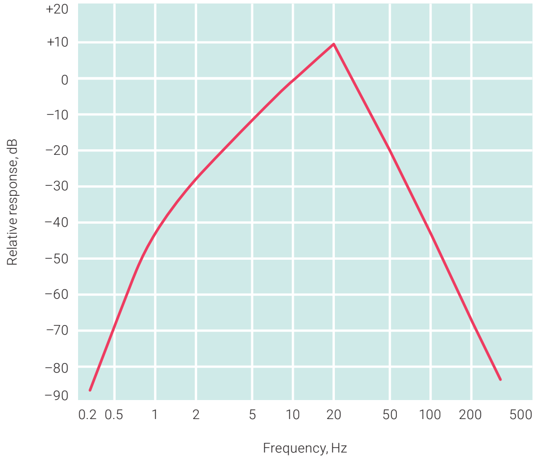


Sound Level Meter Weighting Filters

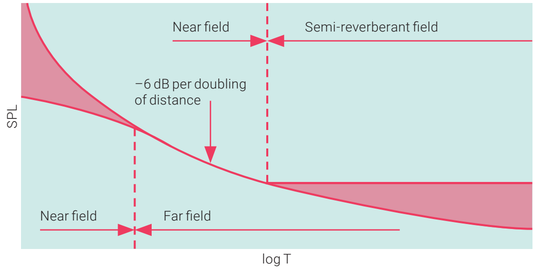


Note: The current sound level meter standard uses A, C and Z-weighting.

'G' Infrasound Weighting Filter

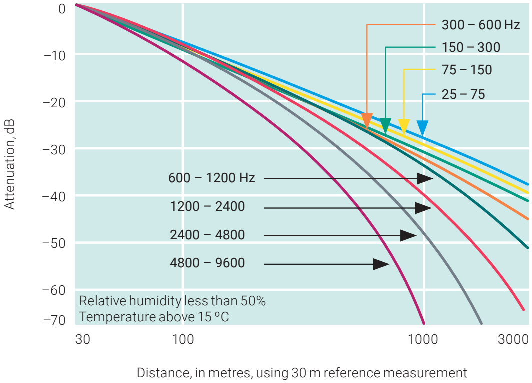


Sound Fields



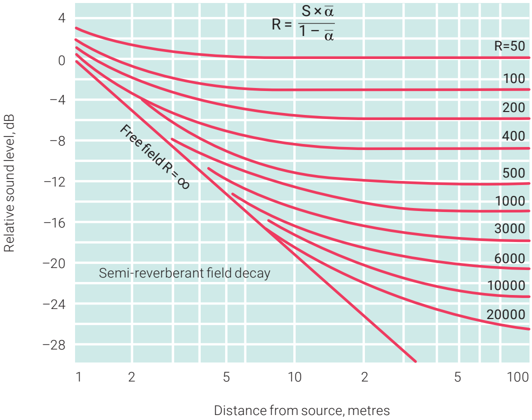
The graph above illustrates the fundamentals of noise generation and propagation that must be kept in mind when measuring noise emission. In the near field, the darker area shows that noise emission cannot be measured reliably. But further away, in the far field, measurements are reliable and the level decreases with 6 dB per doubling of distance (spherical spreading due to inverse-square law) as long as the environment is effectively free field. When the environment becomes semi-reverberant due to reflections that add to the level of the direct sound wave, noise emission measurements again become unreliable.

Sound Attenuation in Air



Approximate correction for air attenuation including the inverse-square law.

Predicting Sound Level in Semi-reverberant Fields



Relative sound level with respect to source level in a semi-reverberant field

Acoustic Formulas

NOISE REDUCTION AND TRANSMISSION LOSS

$$NR = L_{p1} - L_{p2}$$

$$TL = L_{W1} - L_{W2}$$

where:

subscript 1 represents the source and
subscript 2 the receiver

In free field: NR = TL
For wall in source room:

$$NR = TL - 10 \log \left[\frac{1}{4} - \frac{A}{R_2} \right] dB$$

where:

A is the area the wall and
R_2 is the room constant of the receiving room

PREDICTING SOUND PRESSURE LEVEL FROM SOUND POWER LEVEL

In a free field:

$$L_p = L_W + 10 \log Q - 20 \log r - 10.8 \text{ dB}$$

Over a hard reflecting plane:

$$L_p = L_W + 10 \log Q - 20 \log r - 7.8 \text{ dB}$$

In a reverberant room:

$$L_p = L_W - 10 \log R + 6.2 \text{ dB}$$

where:

r is distance in metres
Q is directivity factor of the sound source
R is the room constant in square metres

ROOM CONSTANT

$$R = \frac{S_t \times \overline{\alpha}}{1 - \overline{\alpha}}$$

where:

R is the room constant in square metres
S_t is the total area of the room in square metres
$\overline{\alpha}$ is the average absorption coefficient

$$\overline{\alpha} = \frac{\alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n}{S_1 + S_2 + \ldots + S_n}$$

where:

α_n is the absorption coefficient of component surface S_n
S is the area of the surface in square metres

or

$$R = \frac{S_t}{\frac{T \times S_t}{0.161\ V} - 1} \qquad \frac{0.161\ V}{T}$$

where:

T is the reverberation time in seconds
V is the room volume in cubic metres
S_t is the total area of the room in square metres

Sound Intensity and Acoustic Imaging

Glossary of Sound Intensity Terms

SOUND INTENSITY

The time-averaged rate of energy flow per unit area. The real part of the complex intensity and the propagating part of the sound field (sometimes called the active part).

COMPLEX INTENSITY

Complex intensity is the combined active and reactive intensity, as real and imaginary parts.

REACTIVE INTENSITY

Reactive intensity is the amplitude of the non-propagating part of the sound field.

ACTIVE SOUND FIELD

A sound field in which the particle velocity is in phase with the sound pressure. All acoustic energy is transmitted, none is stored. A plane wave propagating in a free field is an example of a purely active sound field and constitutes the real part of the complex sound field.

REACTIVE SOUND FIELD

A sound field in which the particle velocity is 90º out of phase with the pressure. An ideal standing wave is an example of this type of field, where there is no net flow of energy, and constitutes the imaginary part of a complex sound field.

PHASE MISMATCH

The relative phase mismatch between the two channels in an intensity measuring system.

PRESSURE-INTENSITY INDEX

In a given direction at a point, the difference between the sound pressure level and the sound intensity level. In practice, F_{pI} is normally positive.

Note: The pressure-intensity index is an important indicator of the character of the sound field as it is measured and is used for evaluating the accuracy of sound intensity measurements.

RESIDUAL INTENSITY

The sound intensity level measured when the same signal is fed to both channels of a sound intensity measuring system.

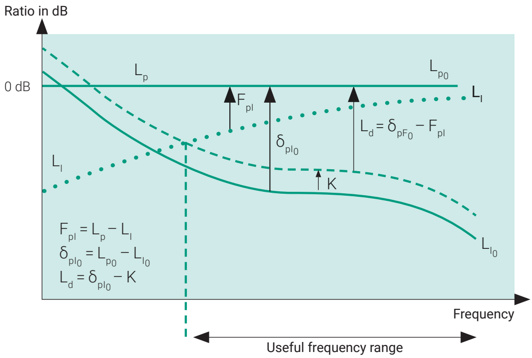
PRESSURE-RESIDUAL INTENSITY INDEX, δ_{pI_0}

The pressure-residual intensity index for a given measurement system is defined as the difference between the measured sound pressure level and the indicated intensity level when the intensity probe is placed in a zero intensity sound field. It is expressed in decibel and the index will normally be positive.

DYNAMIC CAPABILITY, L_d

The dynamic capability of an intensity measurement system is determined by substracting K which is 7 dB (survey grade) or 10 dB (engineering and precision grades) from the pressure-residual intensity index, $L_d = \delta_{pI_0}$ -K.

The relationship between sound field and measurement system indicators for a given microphone spacing Δr using the two pressure microphone method is shown below.



L_P = Sound pressure level of the sound field

L_I = Sound intensity level of the sound field

F_{pI} = Pressure intensity index for the sound field

L_{P_0} = Sound pressure level measured with an intensity measuring system during calibration

L_{I_0} = Sound intensity level measured with an intensity measuring system during calibration

δ_{pI_0} = Pressure-residual intensity index for the measuring system

Basic Formulas

In a medium without mean flow, the intensity vector equals the time averaged product of the instantaneous pressure and the corresponding instantaneous particle velocity at the same position:

$$\vec{I} = \overline{p(t) \cdot \vec{u}(t)}$$

where:

$\vec{I}$ is the sound intensity

$p(t)$ is the instantaneous sound pressure

$\vec{u}(t)$ is the instantaneous particle velocity

The sound intensity can be measured directly according to the above definition by use of the formula:

$$\hat{I}_r = \overline{p \cdot u_r} = \frac{1}{2\rho\Delta r} \cdot \overline{(p_A + p_B) \int (p_A - p_B)\, dt}$$

where:

$\hat{I}_r$	is the estimated sound intensity in direction r
p	is the sound pressure at the measuring position
u_r	is the particle velocity at the measuring position in direction r
ρ	is the density of the medium
Δr	is the transducer separation (typically 0.012 m)
p_A, p_B	are the sound pressures at the two transducer positions

The sound intensity can also be estimated using a dual-channel analyzer (frequency domain formulation), from the imaginary part of the cross-spectrum:

$$\hat{I}_r = -\frac{1}{\omega\rho\Delta r} \text{Im}\, G_{AB}$$

where:

ω	is the angular frequency
$\text{Im}\, G_{AB}$	is the imaginary part of the cross-spectrum

In a purely active sound field (that is a plane wave propagating in a free field), the actual intensity is given by:

$$|\vec{I}| = \overline{p \cdot u} = \overline{p^2 / \rho c} = p^2_{rms} / \rho c$$

where ρc is the impedance of the medium

Under standard conditions (20°C and 1013 mbar):
Where c = 343.2 m/s and ρ = 1.204 kg/m^3

$$L_I = L_p - 0.146 \text{ dB}$$

where

L_I is the sound intensity level measured in the direction of propagation
L_p is the sound pressure level

The relationship between the various quantities in which intensity can be expressed is given by:

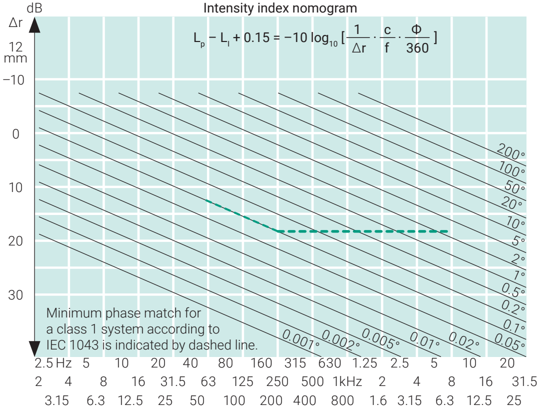
$$\text{Intensity} = \frac{\text{Power}}{\text{Area}} = \frac{\text{Energy}}{\text{Area} \cdot \text{Time}} = \frac{\text{Force} \cdot \text{Distance}}{\text{Area} \cdot \text{Time}}$$

$$= \text{Pressure} \cdot \text{Velocity}$$

Practical Measurements

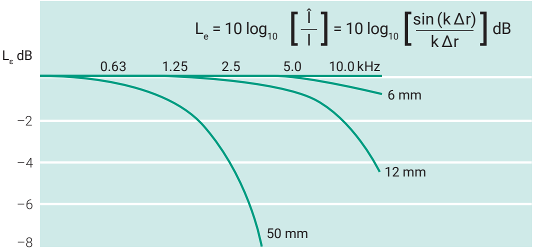
CALIBRATION

Calibration of a sound intensity analysis system involves a pressure amplitude calibration of the two channels, a phase match check and phase compensation. The phase match is checked by measuring the pressure-residual intensity index of the system. Knowledge about microphone spacing and density of the medium are also required.



HIGH-FREQUENCY LIMITATIONS

The two-microphone technique imposes limitations at high frequencies due to the approximation of the pressure gradient by the finite pressure difference. The high-frequency approximation error is given below.

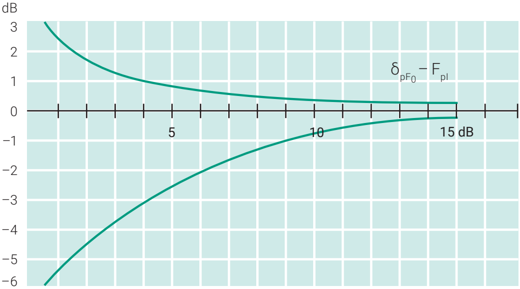


Approximation error, L_ε, at high frequencies for various spacers

Note: The high-frequency limit can be raised by an octave by compensating for the resonance phenomenon between the spacer and the microphones at high frequencies.

LOW-FREQUENCY LIMITATIONS – PHASE MISMATCH

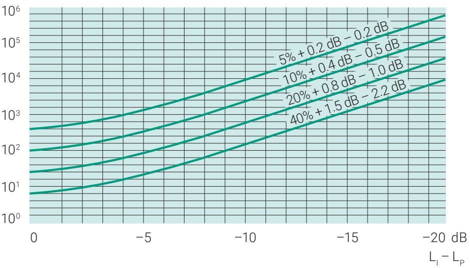
At low frequencies, the phase mismatch of the system becomes comparable with the actual phase to be measured. Therefore, an intensity error is introduced in the measurement. This error can be expressed directly as a function of the difference between the pressure-residual intensity index (measured during calibration) and the pressure-intensity index of the sound field at the measuring position and direction. If phase compensation is available in the systems, the phase mismatch can be minimized.



RANDOM ERROR

When measuring in reactive environments, a higher BT product is necessary to obtain the same confidence level as in active sound fields. The relationship between the reactivity index of the sound field and the BT product for a given confidence level is given below.

Random Error (68% Confidence Level)



Glossary of Array Acoustic Terms

ACOUSTIC HOLOGRAPHY

A method that is used to estimate the 3D sound field (pressure, particle velocity and intensity) near a source by measuring acoustic parameters on a surface away from the source via an array of pressure and/or particle velocity transducers.

ACOUSTIC CAMERA

A common term for an array system which can superimpose measured acoustical data onto a photograph.

ARRAY

A microphone array is any number of microphones arranged in a known configuration operating together. There are many applications. For noise source identification, a typical array consists of 18 to 150 microphones arranged in a 2D (single or double layer) or 3D grid.

BEAMFORMING

Noise source identification using an array at medium to long distances to resolve sound incidence from different directions. A set of different algorithms exist for establishing the directionally sensitive 'beam pattern', characterized by a main lobe in the focus direction and side lobes in other directions. A narrow main lobe will provide high directional resolution. The side lobes produce unwanted sensitivity in other directions than the selected focus direction, so the side-lobe level should be minimized.

COMBO ARRAY

An array that can be used for a combination of beamforming and acoustic holography techniques in order to measure over a wide frequency range. Examples are sector rectangular and sector wheel arrays.

CONFORMAL MAPPING

Conformal mapping provides a map of sound field quantities directly on the actual surface geometry of an arbitrary shaped object. Conformal maps are easier to interpret and more understandable than 2D maps to non-acousticians. Typically measured with a small hand-held array by means of SONAH or ESM algorithms.

DELAY AND SUM (DAS)

DAS is the most common algorithm for beamforming. The various microphone signals provided by the array are computationally delayed in a way to align in time the signal components coming from the focal point. Subsequent summation will cause these signal components to add up coherently, while suppressing signals from other points. The algorithm can also be implemented in the frequency domain.

EQUIVALENT SOURCE METHOD (ESM)

Acoustic holography method where the sound source is modelled by a number of monopoles behind the surface of the source. ESM is typically used in conformal mapping and in wideband holography applications.

FILTER AND SUM (FAS)

Filter and Sum is used for spherical beamforming, having some similarity to Delay and Sum. It provides better suppression of side lobes, that is, larger dynamic range, than the SHARP algorithm.

GRID ARRAY

An array with a fixed distance in both x and y directions between transducers. Examples are single-layer and double-layer hand-held arrays.

NOISE SOURCE IDENTIFICATION (NSI)

Noise source identification is typically performed using either a single sound intensity probe in combination with a (manual or automatic) positioning system or array techniques such as beamforming and/or acoustic holography.

NEAR-FIELD ACOUSTIC HOLOGRAPHY (NAH)

A technique for establishing a model of the sound field by applying a 2D spatial Fourier Transformation to the measured array signals. This is the classical implementation of holography and requires a regular grid array.

MOVING SOURCE BEAMFORMING

A planar beamforming technique that continuously adjusts the focal direction in order to track moving targets, such as moving cars, trains and airplanes or the blades of wind turbines.

REFINED BEAMFORMING

Also called deconvolution beamforming. A beamformer has a finite spatial resolution given by the width of its main lobe. Compensating for the width of the main lobe by deconvolution techniques results in beamforming results with an improved resolution.

PLANAR BEAMFORMING

Beamforming performed with a planar array.

SHARP, SPHERICAL HARMONIC ANGULAR RESOLVED PRESSURE

A spherical beamforming technique where the sound field is decomposed into spherical harmonics.

STATISTICALLY OPTIMISED, NEAR-FIELD ACOUSTIC HOLOGRAPHY (SONAH)

SONAH establishes a model of the sound field by applying correlation techniques to the measured array signals. Avoids the leakage and windowing artefacts of the 2D spatial Fourier Transform as used in NAH.

SPHERICAL BEAMFORMING

Beamforming performed with a spherical array.

SPATIAL TRANSFORMATION OF SOUND FIELDS (STSF)

An older HBK but now obsolete term for near-field acoustic holography combined with Helmholtz integral equation formulation for far-field calculations.

WIDEBAND HOLOGRAPHY (WBH)

Holography based on ESM techniques and enforcing sparsity in the source model. It covers a wide (full) frequency range as opposed to traditional holography which covers low to medium frequencies and traditional beamforming which covers medium to high frequencies.

WHEEL ARRAY

An array consisting of a set of identical line arrays arranged as spokes on a wheel, also known as Spoke Wheel Array. The typical application is DAS or Refined Beamforming. For many applications such as vehicle pass-by or in wind tunnels, a half wheel array is used, placed on a reflective mirror ground.

Electro-acoustics

Glossary of Electroacoustic and Communication Audio Terms

COMB FILTERING
In signal processing, a comb filter adds a delayed version of a signal to itself, causing constructive and destructive interference. The frequency response of a comb filter consists of a series of regularly spaced spikes, giving the appearance of a comb. In room acoustics, comb filtering results from reflected sound (or multiple speakers) arriving at the listener at a delayed time from the direct sound and the combination results in a similar effect at the listener.

CRITICAL DISTANCE
The distance at which the level of the direct sound is equal to the level of the diffuse sound

DBM
Power level in decibels, relative to a power of 1 mW (milliwatt).

DISTORTION
The alteration of the waveform of a signal in amplitude and/or spectral characteristics.

DUT
Device Under Test.

DRUM REFERENCE POINT (DRP)
A point located at the end of the ear canal, corresponding to the eardrum position.

EAR REFERENCE POINT (ERP)
A virtual point for acoustic and geometric reference located outside the entrance to the ear canal. The exact location is specified for each type of ear simulator.

FREQUENCY RESPONSE
Electrical, acoustic, or electroacoustic sensitivity (output/input), or gain, as a function of frequency.

FULLBAND (FB)
Nominally 20 – 20,000 Hz. Usually refers to a device or transmission channel.

HAAS EFFECT

A binaural psychoacoustic effect, where a sound is followed by another sound separated by a sufficiently short time delay (below the listener's echo threshold), so that the listener perceives a single 'fused' auditory image; its perceived spatial location is dominated by the location of the first-arriving sound (the first wave front). The lagging sound also affects the perceived location. However, its effect is suppressed by the first-arriving sound.

HARMONIC DISTORTION

The simplest form of Non-linear Distortion where some part of the energy of the input signal is translated to harmonics (integer multiples) of the input signal frequency.

INTERMODULATION DISTORTION

Amplitude modulation of one signal by another signal, caused in an electroacoustic system where its amplification varies with level (that is, it is non-linear) so that one signal causes another signal being reproduced to vary in level at a rate determined by the 'modulating' frequency. This effect expresses itself as 'sidebands' (sums and differences) of the signal and modulating signal around the higher frequency.

LINEAR DISTORTION

Time- and frequency-dependent characteristics of the amplitude and phase response of the transfer function, for example, an ideal equalizer. This occurs with no changes in the frequency content of the input signal such that one frequency at the input results in only one frequency at the output.

MOUTH REFERENCE POINT (MRP)

A point on the axis of the mouth simulator, 25 mm in front of the centre of the external lip plane.

NARROWBAND (NB)

Nominally 100 – 4000 Hz. Usually refers to a device or transmission channel.

NON-LINEAR DISTORTION

Changes in the frequency content of the input signal such that energy is transferred from one frequency at the input to more than one frequency at the output. Non-linear distortion products usually have a fixed frequency relationship to the excitation frequency.

RUB AND BUZZ

A type of harmonic distortion found in some dynamic systems such as loudspeakers, often caused by the voice coil rubbing against the pole piece or other mechanical component. Manifested at high harmonics, it is a very audible form of distortion.

SUPERWIDEBAND (SWB)

Nominally 50 – 16,000 Hz. Usually refers to a device or transmission channel.

SENSITIVITY

The ratio of the output to the input of a transducer or system. For example, a loudspeaker will have a sensitivity of Pa/V (acoustic pressure it produces as a function of the voltage provided) or dB re 1 Pa/V. Often specified at a 1 metre distance.

SIMULATED FREE FIELD

A family of techniques to provide approximate anechoic measurements without the need of an anechoic chamber. Also known by the acronyms TSR (Time Selective Response), TDS (Time Delay Spectroscopy) or other terms, they use advanced mathematical techniques to 'time-window' the direct energy from the DUT and thereby eliminate the effect of reflections from surfaces in the test room.

TOTAL HARMONIC DISTORTION (THD)

A measurement of distortion as the ratio of the power sum of the harmonics to the power sum of the harmonics and the fundamental.

TRANSDUCER

A device for converting one form of energy to another. In electroacoustics, it is typically an electromechanical device for converting electricity to sound (loudspeaker) or sound to electricity (microphone).

WIDEBAND (WB)

Nominally 100 – 8000 Hz. Usually refers to a device or transmission channel.

Communication Systems Acronyms and Terminology

1G, 2G, 3G, 4G	Terms used to describe the various generations of mobile terminals or mobile phones and the supporting networks.
Active speech level	Long-term average speech level that does not include pauses or silences. It is the time integral of the instantaneous power over the active time, divided by active time, in decibels relative to the appropriate reference. See ITU-T P.56 for details.
Active time	Time during which the speech in question is present, excluding pauses or noises below a defined threshold.
AMPS	Advanced Mobile Phone Service. Analog FDMA cellular system used in North America. (Legacy)
CDMA	(General): Code Division Multiple Access. Digital transmission using spread-spectrum techniques.
CELP	Code Excited Linear Prediction. A class of digital voice coding schemes using LPC for voiced speech and codebooks for unvoiced speech. Coefficients and codes are transmitted instead of speech.
Codec	'Code-Decode.' A combination of analogue-to-digital encoder and digital-to-analogue decoder operation in opposite directions of transmission within the same equipment.
dBm0	Power level in dBm, relative to a reference point called the zero transmission level point, or 0 TLP. A signal level of X dBm at the 0 TLP is designated X dBm0. In a codec, 0 dBm0 is specified in relationship to the full-scale digital level or saturation. However, digital saturation is generally not 0 dBm0. For µ-law codecs 0dBm0 is 3.17 dB below digital full scale. For A-law codecs 0 dBm0 is 3.14 dB below digital full scale. For the L16-256 wideband codec, 0dBm0 is 3.17 dB below digital full scale.

Double-talk (DT)	Two talkers speaking simultaneously in opposite transmission directions.
FDMA	Frequency Division Multiple Access. Transmission allowing many users to access a group of bands without interference.
GSM	Groupe Speciale Mobile (Global Standard or System for Mobile) – Pan-European digital cellular system using FDMA+TDMA techniques
ISDN	Integrated Services Digital Network
Listener sidetone	The signal present at the receiver due to sound in the environment where the terminal is used.
LR	Loudness Rating. Usually refers to international loudness ratings defined in ITU-T P.79.
LSTR	Listener Sidetone Masking Rating – a measure for how much of the noise in a room is transmitted to the person listening. (Legacy)
MOS	Mean Opinion Score. A subjective measurement giving score of 1 – 5.
MOS-LQO	MOS – Listener Quality Objective
OLR	Objective Loudness Rating. Usually refers to legacy North American loudness ratings defined in IEEE-661. (Legacy)
PCM	Pulse Code Modulation. Technology used for coding in digital phones.
PESQ	Perceptual Evaluation of Speech Quality. An objective method for end-to-end speech quality assessment of narrowband telephone networks and speech codecs.
P.OLQA	Perceptual Objective Listening Quality Assessment
POTS	Plain Old Telephone System. Refers to corded analogue telephones.

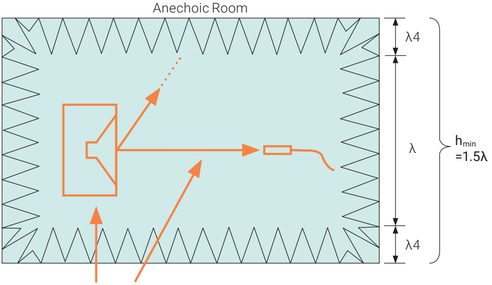
PSQM	Perceptual Speech Quality Measurement – a means for objective assessing how much the quality of speech has been degraded by a Telephone Network. (Legacy)
PSTN	Public Switch Telephone Network. Technology used for transmission in analogue corded phones.
RLR	Receive Loudness Rating. A measure of loudness loss in the receiving direction. (International)
Send	Speech transmission from mouth to the network.
Sidetone	Speech transmission path from the microphone to the receiver of the handset or headset. See definitions for listener sidetone (LSTR) and talker sidetone (STMR).
SLR	Send Loudness Rating. A measure of loudness loss in the sending direction. (International)
STMR	Sidetone Masking Rating. A measure of loudness loss in the sidetone path. (International)
Talker sidetone	The direction of speech transmission from mouth to ear of the terminal user.
TCLw	Weighted Terminal Coupling Loss
TCLt	Temporally Weighted Terminal Coupling Loss
TDMA	(General): Time Division Multiple Access Digital transmission allowing many users to access a single channel without interference by multiplexing in the time domain
UMTS	Universal Mobile Telecommunications System
VoLTE	Voice over Long Term Evolution – speech transmission using packet speech in true 4G mobile network

Relationship Between Electrical and Acoustical Quantities

Electrical			Electroacoustic efficiency			Acoustical		
Power W	Level dBW	Voltage V	Impedance Ohms	%	Power mW	Level dBSPL	Pressure Pa	Impedance Rayls*
1	0	2	4	3	30	94	1	407
2	3	√2 2	4	3	60	97	√2	407

* Units of $N\ s/m^3$ for plane wave, free-field, standard atmosphere.

Dimensions for Anechoic Room Design



$d_{total} = h_{min} + d_{object} + d_{test}$
(about 6.5 m for small objects tested at 1 m)

Underwater Acoustics

Speed of Sound in Water

The speed of sound in seawater is very complex. The simple formula below was given by Medwin in 1975 and is accurate within a few tenths of a m/sec in the temperature range 0 to 22 °C, salinity less than 35 ppt and ocean depth down to 1000 m.

$$c = 1449.2 + 4.6 \cdot T - 0.055 \cdot T^2 + 0.00029 \cdot T^3 + (1.34 - 0.01 \cdot T) \cdot (s - 35) + 0.016 \cdot z$$

where:

c is the speed of sound in m/s
T is the temperature in °C
S is the salinity in parts per thousand (ppt)
Z is the depth in m

Wavelength

At 20°C and 3.5% salinity:

$$\lambda = \frac{c}{f} = \frac{1521.5\ \text{m}}{f}$$

where:

f is the frequency in Hz

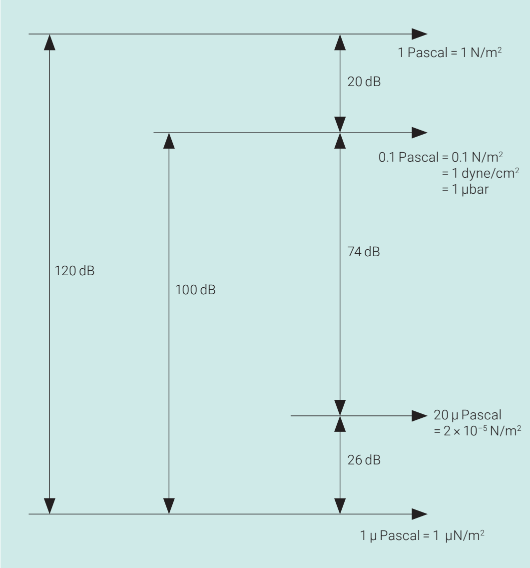
Note: The speed of sound in water is about 4.4 times its speed in air. Therefore, the wavelength in water will be 4.4 times the wavelength in air at any given frequency.

Intensity Comparison to Air

$$\frac{I_{water}}{I_{air}} = \frac{(p^2 / \rho c)_{water}}{(p^2 / \rho c)_{air}} ; \quad \frac{(\rho c)_{air}}{(\rho c)_{wate}} = \frac{1}{3570}$$

For an identical source intensity in water and air, the acoustic pressure generated in water will be about 60 times greater than in air (ρ is the density).

Reference Pressure

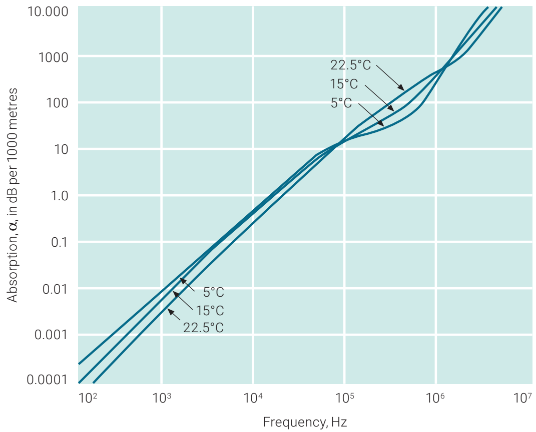


Pressure vs Depth for Fresh Water 4°C

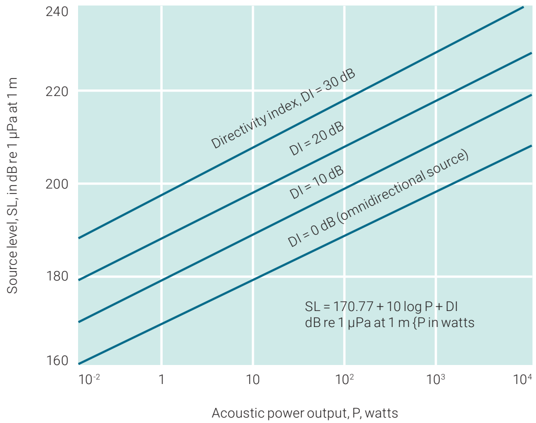
Pressure \ Depth (m)	10	20	30	50	100	1000
kg/cm^2	1	2	3	5	10	100
Atmospheres	1	2	3	5	10	100
psi	15	30	45	75	150	1500

The density of seawater is typically 2.7% higher than that of fresh water and the pressure correspondingly higher.

Sound Absorption in Seawater

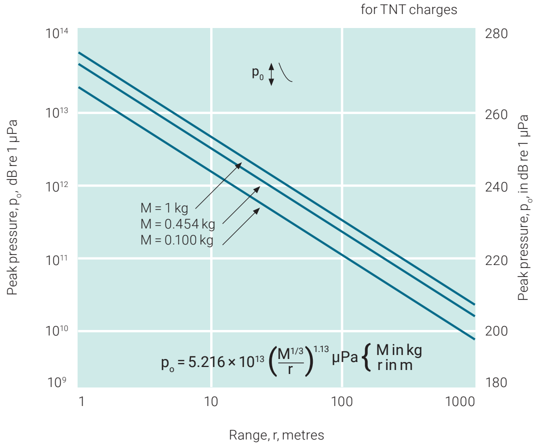


Source Level as a Function of Radiated Power

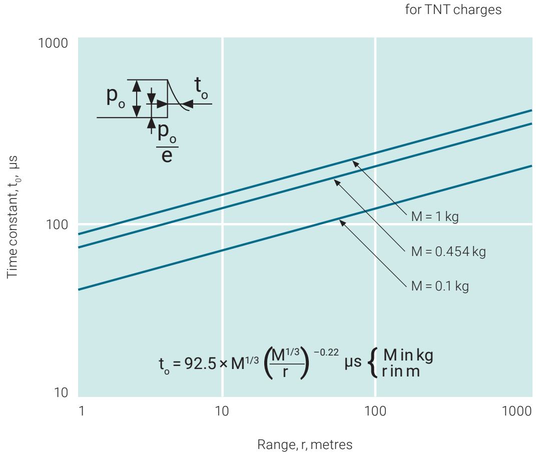


SL = 10logW + DI + 170.77 dB re 1 μPa, where W is the power in Watts. DI is the directivity index.

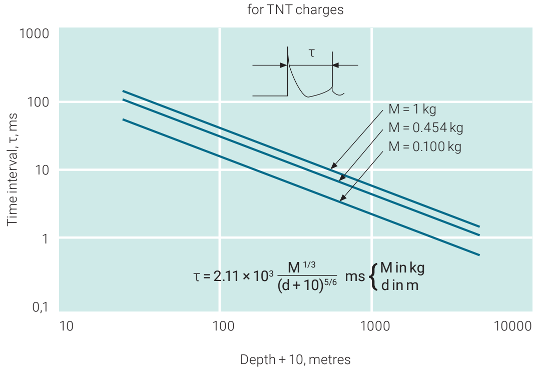
Peak Pressure as a Function of Explosive Charge



Time Constant of Shock Waves



Time Interval from Shock Wave to First Bubble Pulse



Glossary of Hydrophone Terms

Definitions partly from IEC 60565:2006

FREE-FIELD SENSITIVITY OF A HYDROPHONE

Paragraph 3.15. Ratio of the open-circuit voltage of the hydrophone to the sound pressure in the undisturbed free field in the position of the reference centre of the hydrophone if the hydrophone were removed.

Note 1: The unit is volt per pascal, VPa^{-1}
Note 2: The pressure is sinusoidal
Note 3: The term 'response' is sometimes used instead of 'sensitivity'

PRESSURE SENSITIVITY OF A HYDROPHONE

Paragraph 3.22. Ratio of the output voltage to the actual sound pressure existing over the region of the hydrophone designed to receive sound.

Note: The unit is volt per pascal, VPa^{-1}

TRANSMITTING RESPONSE TO CURRENT OF A PROJECTOR

Paragraph 3.28. Ratio of the sound pressure at a reference distance from the reference centre of a projector (at a given frequency and in a specified direction), multiplied by the reference distance, to the current flowing through the electrical terminal.

Note 1: Reference distance is 1 m
Note 2: The unit is pascal metre per ampere, $Pa \cdot m \cdot A^{-1}$

TRANSMITTING RESPONSE TO VOLTAGE OF A PROJECTOR

Paragraph 3.29. Ratio of the sound pressure at a reference distance from the reference centre of a projector (at a given frequency and in a specified direction), multiplied by the reference distance, to the voltage across the electrical terminals.

Note 1: Reference distance is 1 m
Note 2: The unit is pascal metre per volt, $Pa \cdot m \cdot V^{-1}$

DIRECTIONAL RESPONSE

Paragraph 3.5. Description, generally presented graphically, of the response of an electroacoustic transducer, as a function of the direction of propagation of the radiated or incident sound in a specified plane through the reference centre and at a specified frequency.

TRANSMITTING DIRECTIVITY INDEX

A ratio measurement, at a point on the axis of the beam pattern, between the intensity generated by the projector and the intensity that would be produced by a nondirectional projector radiating the same acoustic power.

Vibration

Glossary of Vibration Terms

Definitions partly from ISO 2041

ACCELERATION
Rate of change of velocity.

ACCELEROMETER
A sensor whose electrical output is proportional to acceleration.

CHARGE AMPLIFIER
An amplifier whose output voltage is proportional to the output charge from a piezoelectric transducer. Has the advantage that the charge output is not affected by the length of the connecting cable to the transducer.

COMPLIANCE
Reciprocal of Stiffness.

CRITICAL DAMPING
For a single-degree-of-freedom system, the amount of damping that corresponds to the limiting condition between an oscillatory and a non-oscillatory transient state of free vibration.

DISPLACEMENT
Time-varying quantity that specifies the change in position of a point on a body with respect to a reference frame.

DAMPING
Dissipation of energy with time or distance.

DAMPING RATIO
Ratio of the actual damping coefficient to the critical damping coefficient.

DEGREES OF FREEDOM
Minimum number of generalized coordinates required to completely define the configuration of a mechanical system.

DYNAMIC MASS
Complex ratio of force to acceleration.

DYNAMIC MODULUS
Complex ratio of stress to strain under vibratory conditions.

EXCITATION
External force (or other input) applied to a system that causes the system to respond in some way.

FORCE
Dynamic influence that changes a body from a state of rest to one of motion or changes its rate of motion.

IMPACT
Single collision of two bodies.

IMPULSE
Integral with respect to time of a force taken over the time during which the force is applied.

INTEGRATOR
An electrical frequency filter used to convert a vibratory acceleration signal to one whose amplitude is proportional to velocity or displacement.

JERK
Rate of change of acceleration.

MECHANICAL IMPEDANCE
Complex ratio of force to velocity at a specified point and degree-of-freedom in a mechanical system.

MOBILITY
Complex ratio of the velocity, taken at a point in a mechanical system, to the force, taken at the same or another point in the system.

MODAL ANALYSIS
Vibration analysis method that characterizes a complex structural system by its modes of vibration, that is its natural frequencies, modal damping and mode shapes, and based on the principle of superposition.

NATURAL FREQUENCY
Frequency of free vibration of an undamped linear vibration system.

PERIODIC VIBRATION
Vibration where the values of the vibration parameter recur for certain equal increments of the independent time variable.

RANDOM VIBRATION
Vibration where the instantaneous value cannot be predicted. Pseudo, periodic and burst random are all special forms.

RESONANCE
State of a system in forced oscillation when any change, however small, in the frequency of excitation causes a decrease in a response of the system.

RESPONSE
Output quantity of a system.

SHOCK
Sudden change of force, position, velocity or acceleration that excites transient disturbances in a system.

SIMPLE HARMONIC VIBRATION
Periodic vibration where the values of the vibration parameters can be described as sinusoidal functions of the independent time variable.

STIFFNESS
Ratio of change of force (or torque) to the corresponding change in translational (or rotational) deformation of an elastic element.

TRANSMISSIBILITY
Non-dimensional complex ratio of the response of a system in forced vibration to the excitation.

VELOCITY
Rate of change of displacement.

VIBRATION ISOLATOR
Isolator designed to attenuate the transmission of vibration in a frequency range.

VIBROMETER
Instrument with one or more outputs (typically voltage) that are proportional to either displacement or velocity.

VIBRATION SEVERITY

Value, or set of values, such as a maximum, average or rms value, or other parameters that are descriptive of the vibration, referring to instantaneous values or to average values.

VOLTAGE PREAMPLIFIER

A preamplifier that produces an output voltage proportional to the input voltage from a piezoelectric accelerometer. The input voltage depends on cable capacitance.

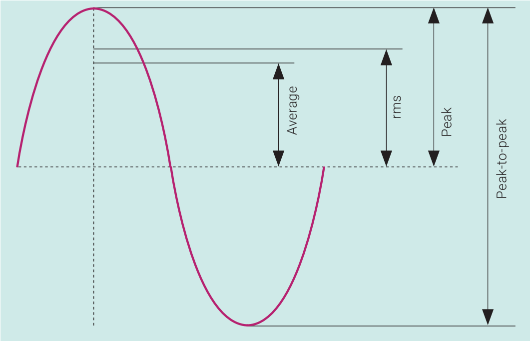
WHITE FINGERS

A disorder of the hands caused by using hand-held tools such as chainsaws and jackhammers. Results in reduction of the hand's ability to feel or to regulate its temperature. May also result in numbness and excessive sensitivity to low temperatures. Called Raynaud's disease.

WHOLE-BODY VIBRATION

Vibration of the human body as a result of standing on a vibrating floor or sitting on a vibrating seat. Often encountered near heavy machinery and on construction equipment, trucks and buses.

Amplitude Relationships (Sinusoids)



$$\text{rms} = \frac{\pi}{2\sqrt{2}} \times \text{average} = \frac{1}{\sqrt{2}} \times \text{peak}$$

rms = 1.1 × average = 0.707 × peak

peak = 1.57 × average = 1.414 × rms

Average = 0.9 × rms = 0.637 × peak

peak-to-peak = 2 × peak

Crest Factor = Peak/rms

Form Factor = rms/Average

Displacement, Velocity, Acceleration Relationships (Sinusoids)

displacement	$= d_0 \sin 2 \pi ft$
where	d_0 = peak displacement
	f = frequency in Hz
velocity	$= 2 \pi f d_0 \cos 2 \pi ft$
	= 2 π f × displacement (90° phase shift)
acceleration	$= -(2 \pi f)^2 d_0 \sin 2 \pi ft$
	$= -(2 \pi f)^2 \times$ displacement

Dynamic Measurements

MECHANICAL IMPEDANCE

$$Z = \frac{F}{v} = \frac{F}{\omega d} = \frac{\omega F}{a}$$

having units of $\frac{\text{lb·sec}}{\text{inch}}$ or $\frac{\text{newton·sec}}{\text{metre}} = \frac{\text{Ns}}{\text{m}}$

dynamic mass: $Z^a = \frac{F}{a}$ dynamic stiffness: $Z^d = \frac{F}{d}$

where all terms are phasors, having a magnitude and direction.

MOTION OF A SINGLE-DEGREE-OF-FREEDOM SYSTEM

natural frequency: $f_n = \frac{\omega}{2\pi} = \frac{1}{2}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{g}{\delta_{st}}}$

where: δ_{st} = static deflection
ω = angular frequency in radians/second

$$k = \frac{\text{force}}{\text{deflection}} = \frac{m\,a}{d}$$

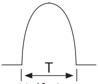
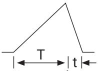
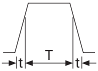
transmissibility: (undamped) $T = \frac{1}{1 - \omega^2/\omega_n^2} = \frac{1}{1 - f^2/f_n^2}$

critical damping: $C_C = 2\sqrt{km}$

damping ratio: $\zeta = \frac{c}{c_C} = \frac{c}{2\sqrt{km}}$

amplification factor: (at resonance) for $\zeta < 0.1$, $Q = \frac{1}{2\zeta}$

TRANSIENT MEASUREMENTS

Pulse Shape	Minimum $\frac{RC}{T}$ (1)	Minimum $\frac{RC}{T}$ (2)	Minimum Resonance Frequency HZ (3)	Minimum Low Frequency Response, f_5 HZ (4)
 Half-sine	16	7	$\frac{5}{T}$	$\frac{0.03}{T}$
 Sawtooth	16	7	$\frac{2.5}{t}$	$\frac{0.03}{T}$
 Square	50	20	$\frac{2.5}{t}$	$\frac{0.01}{T}$

where: RC = low-frequency time constant in seconds

$$= \frac{1}{2\pi f_c} \approx \frac{1}{2 f_5}$$

f_c = frequency for –3 dB response
f_5 = frequency for –5% response
T = pulse duration in seconds
t = rise or fall time in seconds

(1) for 2% accuracy in peak amplitude
(2) for 5% accuracy in peak amplitude
(3) for transducer (based on ratio indicated peak to actual peak approximately 1.1 maximum)
(4) for signal conditioner or associated electronics, for 2% accuracy in amplitude

SPRING CONSTANT OF MATERIALS

$$k = \frac{E\,A}{t}$$

where: E = elastic modulus
A = area of material
t = thickness of material

VELOCITY CHANGE DURING IMPACT

$$\Delta v = \int_{t_1}^{t_2} a\,dt = (2\,g\,h_1)^{1/2} + (2\,g\,h_2)^{1/2}$$

for half-sine pulse	: $\int a\,dt = 0.636\,a\,dt$
for sawtooth pulse	: $\int a\,dt = 0.5\,a\,dt$
where	: h_1 = height of drop
	h_2 = height of rebound
	a = peak acceleration
	$t_2 - t_1$ = duration of pulse

RANDOM EXCITATION

$$a = \sqrt{B\,a_0}$$

where: a = rms level (m/s^2)

B = frequency bandwidth in Hz

a_0 = acceleration density ($(m/s^2)^2/Hz$)

$$\text{crest factor} = \frac{\text{peak magnitude}}{\text{rms magnitude}}$$

RESONANCE FREQUENCY OF FIRST BENDING MODE

(unloaded beams)

$$f_n = C\sqrt{\frac{E\,I\,g}{L^4\,W}}$$

where:

C = constant, function of method of support

E = elastic modulus

I = moment of inertia of cross section

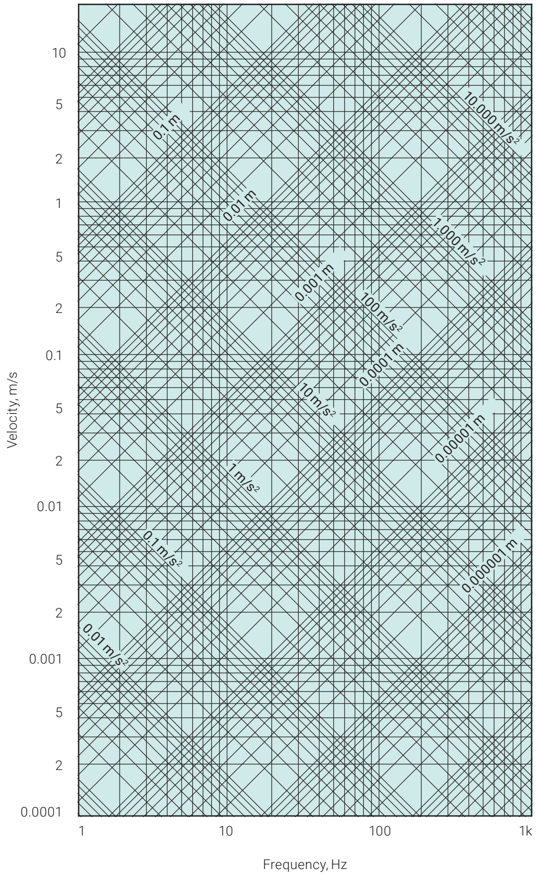
g = acceleration of gravity

L = length

W = weight per unit length

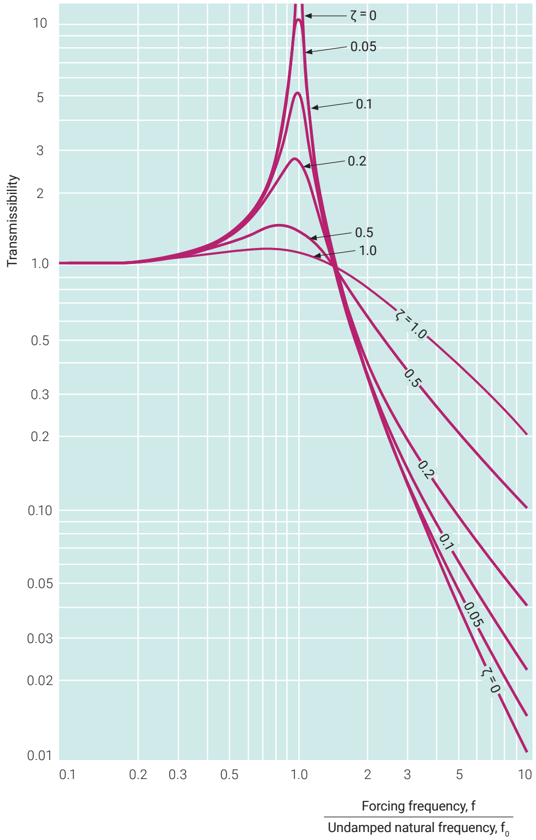
Support Method	C
Cantilever	0.56
Point support each end	1.57
Both ends fixed	3.56
Totally unsupported	3.56

Vibration Nomogram



Frequency, acceleration, velocity, displacement nomogram (for rms, peak-to-peak, or peak values)

Transmissibility Curves



To produce isolation, select vibration isolators with f_0 such that the lowest machine forcing frequency is greater than 1.4 f_0. High damping ratio, ζ, protects best against vibration transmission as a machine passes through isolator resonance to attain operating speed. Low damping ratio gives best protection at high forcing frequencies.

MACHINE VIBRATION MONITORING

Many defects in rotating machinery manifest themselves in specific vibration patterns or signatures. Spectrum analysis of running vibration can give important clues to causes within the machinery. A recorded spectrum (signature) taken on the new (presumably non-defective) machine is extremely helpful for later analysis and diagnosis.

Frequency	**Possible Cause**
1 × operating speed	Imbalance Misalignment Bent shaft Looseness Electrical
2 × operating speed	Misalignment Bent shaft
Harmonics of operating speed	Loose mounts or bearing caps
Subharmonics of operating speed	Oil whirl Bearing cage defects
Non-integer multiples of operating speed	Rolling element bearings Gears Belts Blades or vanes
Powerline frequency harmonics	Electrical

BLADES OR VANES

Missing or cracked blades can cause an imbalance that produces vibration; a large number of harmonics around the blade passing frequency (operating speed × number of blades) indicates a broken or missing blade.

ELECTRICAL

Vibration components at 2 × powerline frequency, or sidebands around the operating speed at 2 × slip frequency often indicate a shortened stator or broken rotor bar. Induction motors normally produce frequency components at the number of poles times the operating speed.

GEARS

Gear mesh frequencies (gear rotational speed × number of teeth) are always present to some extent. Gear defects cause these components to greatly increase in amplitude. Also, sidebands around the gear mesh frequency often appear at the rotational speed of the defective gear.

IMBALANCE

A large component at operating speed is usually considered to indicate an imbalance condition. Severe imbalance can also cause harmonics. Load variation and pump cavitation can also cause similar symptoms.

MISALIGNMENT

Large component at 2 × operating speed accompanied by high-level axial vibration characterizes misalignment.

OIL WHIRL

Fluid film bearings experiencing oil whirl exhibit components at around 0.45 × operating speed.

ROLLING ELEMENT BEARINGS

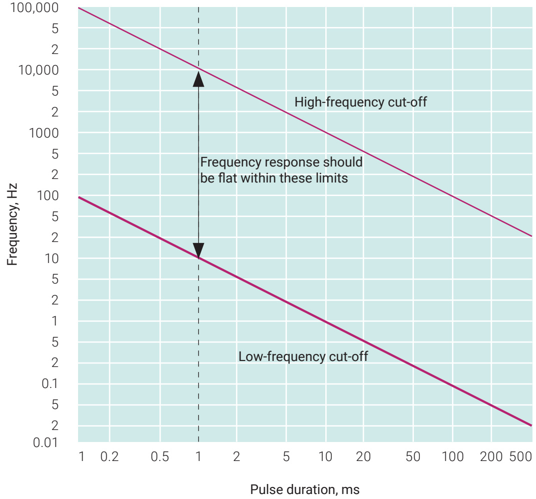
Ball or roller bearings can produce many frequency components, depending on the design of the bearings. These are functions of the number of rolling elements, pitch diameters, ball or roller diameters, and operating speed. They are often accompanied by harmonics and operating speed sidebands. Formulas commonly used are given below.

P = Pitch diameter
D = Rolling element diameter
f = Frequency

N = Number of rolling elements
C = Contact angle
S = Operating speed (rpm)

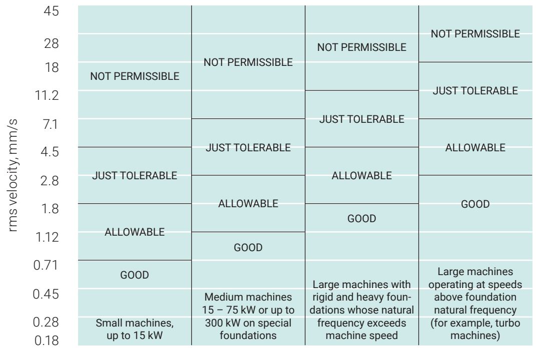
Outer Race	$f = (\frac{N}{2})(\frac{S}{60})$	$(1 - \frac{D}{P} \cos C)$
Inner Race	$f_n = (\frac{N}{2})(\frac{S}{60})$	$(1 + \frac{D}{P} \cos C)$
Ball Defect	$f_n = (\frac{P}{2D})(\frac{S}{60})$	$\left[1 + (\frac{B}{D})^2 \cos C^2\right]$
Fundamental Train (Worn cage)	$f = (\frac{1}{2})(\frac{S}{60})$	$(1 - \frac{B}{D} \cos C)$

Frequency Range for Shock Measurements



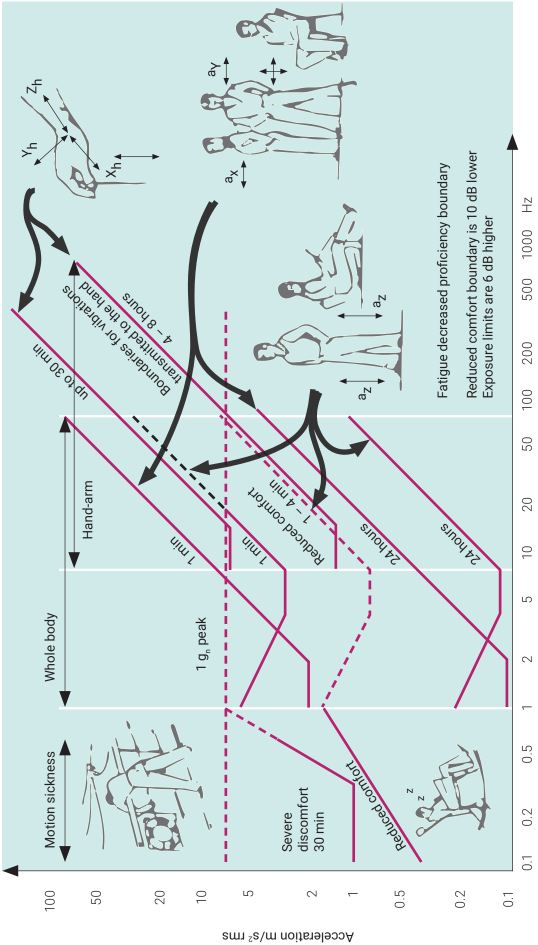
Suggested instrument frequency range for measuring shocks of known pulse duration

Machine Vibration Severity



Vibration criteria, from VDI 2056, for rotating machines

Tolerances for Human Body Vibration



Frequency Analysis

Glossary of Frequency Analysis Terms

ALIASING ERROR
An error in digital sampling in which two frequencies cannot be distinguished. Caused by sampling at less than twice the maximum frequency in the signal.

BANDWIDTH (–3 dB)
The spacing between the frequencies at which a filter attenuates by 3 dB. Normally expressed as frequency difference for constant bandwidth filters and as percentage of centre frequency for constant percentage bandwidth filters.

BANDWIDTH (EFFECTIVE NOISE)
The bandwidth of an ideal filter that would pass the same amount of power from a white-noise source as the filter described. Used to define bandwidth of third-octave and octave filters and for calculation of PSD.

CENTRE FREQUENCY
The arithmetic centre of a constant bandwidth filter, or the geometric centre (midpoint on a logarithmic scale) of a constant percentage bandwidth filter.

CONSTANT BANDWIDTH FILTER
A filter that has fixed frequency bandwidth, regardless of centre frequency.

CONSTANT PERCENTAGE BANDWIDTH (CPB) FILTER
A filter whose bandwidth is a fixed percentage of centre frequency.

DEGREES OF FREEDOM, STATISTICAL
A measure of the statistical reliability of random signal data.

DISCRETE FOURIER TRANSFORM
A version of the Fourier transform applicable to a finite number of discrete samples.

ENERGY SPECTRAL DENSITY (ESD)

An energy spectral density scale is the correct scale to use for displaying spectral content of transient signals. Power has no meaning in relation to transient signals, since the signal only lasts for a short period of time. However, the energy of transient signals is meaningful. What is actually measured is the ESD, which is the energy of the transient as a function of frequency, normalized both for analysis bandwidth and the duration of the record length. ESD is measured in units squared times seconds per hertz.

EXPONENTIAL WEIGHTING

Used in impact testing on lightly damped systems or for system analysis using burst random excitation when the signals do not decay sufficiently within the time records. A decaying exponential weighting function specified by a starting point and a time constant.

FAST FOURIER TRANSFORM (FFT)

A fast method for computing the discrete Fourier transform.

FLAT-TOP WEIGHTING

A smooth, narrow time-weighting function that is zero at the beginning and end of the time record and is used for calibration measurements. Named for the low ripple (0.01 dB) in the passband of ±½ line of the centre frequency. Low ripple gives only small errors in amplitude measurements. The maximum picket-fence error is 0.01 dB, which gives very high amplitude accuracy in analysis of discrete frequency components.

FOURIER TRANSFORM

A mathematical operation for decomposing a time function into its frequency components (amplitude and phase). The process is reversible, and the signal can be reconstructed from its Fourier components.

HANNING WEIGHTING

An amplitude weighting of the time signal. Used in FFT analysis of continuous signals to give them a smooth onset and cut-off in the FFT record in order to reduce the generation of side lobes in their frequency spectrum. The maximum picket-fence error is 1.4 dB.

IDEAL FILTER

A filter having a rectangularly shaped characteristic, unity amplitude transfer within its passband and zero transfer outside its passband.

KAISER-BESSEL WEIGHTING

This is a smooth weighting function similar to Hanning. It is zero at the beginning and end of the time record. Compared to Hanning it has better selectivity but a wider effective noise bandwidth. The maximum picket-fence error is 1.0 dB.

OCTAVE FILTER

A filter whose upper-to-lower passband limits bear a ratio of 2. Relevant standards include IEC 1260, DIN 45651, ANSI S1.11 and ISO 266.

ORDER ANALYSIS

A form of frequency analysis, used with rotating machines, where the amplitude of the signal frequency components is plotted as a function of multiples of the rotating frequency.

PASSBAND

The range of frequencies between the filter cut-off frequencies.

PINK NOISE

Broadband noise whose energy content is inversely proportional to frequency (–3 dB/octave or –10 dB/decade).

PREFERRED FREQUENCIES

A set of standardized octave and third-octave centre frequencies.Relevant standards include ISO 266, IEC 1260 and ANSI S1.11.

POWER SPECTRAL DENSITY (PSD)

A power spectral density scale is the correct scale to use for displaying spectral content of random signals. Since random signals have continuous spectra, the amount of power transmitted by the analysing filter will depend on the filter bandwidth. Hence, it is usual to normalize the measurement with respect to the analysis bandwidth, and measure PSD. PSD is measured in units squared per hertz.

POWER (PWR)

A power scale is useful for displaying stationary deterministic signals. The power of a signal is the mean value of the squared signal. This is the square of the rms value.

ROOT MEAN SQUARE (RMS)

A root mean square (rms) scale is useful for displaying deterministic signals. Deterministic signals are frequently described in terms of their rms amplitude as a function of frequency. For a voltage signal, the rms is measured in volts (V). The rms is the square root of the averaged power.

SAMPLING THEOREM

A theorem that states that a signal is completely described if it is sampled at a rate twice its highest frequency component.

THIRD-OCTAVE FILTER

A filter whose upper-to-lower passband limits bear a ratio of $2^{1/3}$. Relevant standards include IEC 1260, DIN 456551, ANSI S1.11 and ISO 266.

TRANSIENT WEIGHTING

Used when performing impact testing to apply a transient window to the excitation force pulse. The transient window is uniform and all samples outside the window are set to zero. This has the effect of improving the signal-to-noise ratio for the measurement.

UNIFORM WEIGHTING

Also known as rectangular, flat or box-car. It has unity value within the record length and zero value outside. The time record remains unchanged.

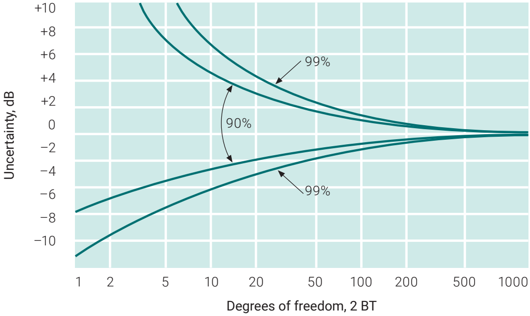
WHITE NOISE

Broadband noise having same power spectral density at all frequencies.

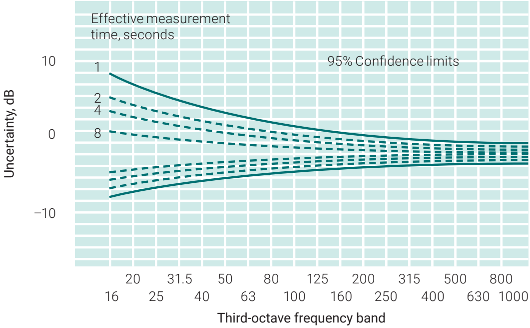
Confidence Limits

Confidence limits describe the uncertainty in measuring the level of random signals in finite periods of time. Confidence limits are a function of the number of statistical degrees of freedom, 2BT, where B is the filter bandwidth and T is the effective measurement time (integrating time or recording duration, whichever is shortest) in seconds.

Assume a bandwidth of 5 Hz and an integrating time of 1 s, that is 10 degrees of freedom. The graph below shows that there will be 99% confidence that the measured value is within about +6/–4 dB of the true rms level, or 90% confidence that it is within about +4/–3 dB. For ±0.5 uncertainty, 200 degrees of freedom are required at 90% confidence.



Confidence limits as a function of degrees of freedom



Confidence limits for third-octave analysis

Third-octave and Octave Passbands

Band No.	Nominal Centre Frequency (Hz)	1/3-octave Passbands (HZ)	Octave Passbands (Hz)
1	1.25	1.12 – 1.41	
2	1.6	1.41 – 1.78	
3	2	1.78 – 2.24	1.41 – 2.82
4	2.5	2.24 – 2.82	
5	3.15	2.82 – 3.55	
6	4	3.55 – 4.47	2.82 – 5.62
7	5	4.47 – 5.62	
8	6.3	5.62 – 7.08	
9	8	7.08 – 8.91	5.62 – 11.2
10	10	8.91 – 11.2	
11	12.5	11.2 – 14.1	
12	16	14.1 – 17.8	11.2 – 22.4
13	20	17.8 – 22.4	
14	25	22.4 – 28.2	
15	31.5	28.2 – 35.5	22.4 – 44.7
16	40	35.5 – 44.7	
17	50	44.7 – 56.2	
18	63	56.2 – 70.8	44.7 – 89.1
19	80	70.8 – 89.1	
20	100	89.1 – 112	
21	125	112 – 141	89.1 – 178
22	160	141 – 178	
23	200	178 – 224	
24	250	224 – 282	178 – 355
25	315	282 – 355	
26	400	355 – 447	
27	500	447 – 562	355 – 708
28	630	562 – 708	
29	800	708 – 891	
30	1000	891 – 1120	708 – 1.41 k
31	1250	1120 – 1410	
32	1600	1410 – 1780	
33	2000	1780 – 2240	1.41 k – 2.82 k
34	2500	2240 – 2820	
35	3150	2820 – 3550	
36	4000	3550 – 4470	2.82 k – 5.62 k
37	5000	4470 – 5620	
38	6300	5620 – 7080	
39	8000	7080 – 8910	5.62 k – 11.2 k
40	10 k	8910 – 11200	
41	12.5 k	11.2 – 14.1 k	
42	16 k	14. 1 – 17.8 k	11.2 k – 22.4 k
43	20 k	17.8 – 22.4 k	

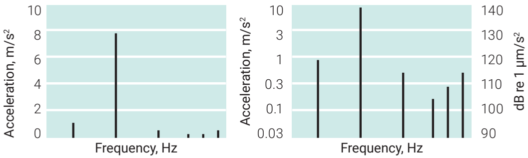
Preferred Frequencies

Octave and third-octave filters are centred at preferred frequencies defined in ISO 266. Although nominal frequencies are used to identify the filters, the true centre frequencies of third-octave filters are calculated from $10^{n/10}$, where n is the band number.

Band No.	Exact Frequency (Hz)	Band No.	Exact Frequency (Hz)
0	1	6	3.9811
1	1.2589	7	5.0119
2	1.5849	8	6.3096
3	1.9953	9	7.9433
4	2.5119	10	10
5	3.1623	11	12.589

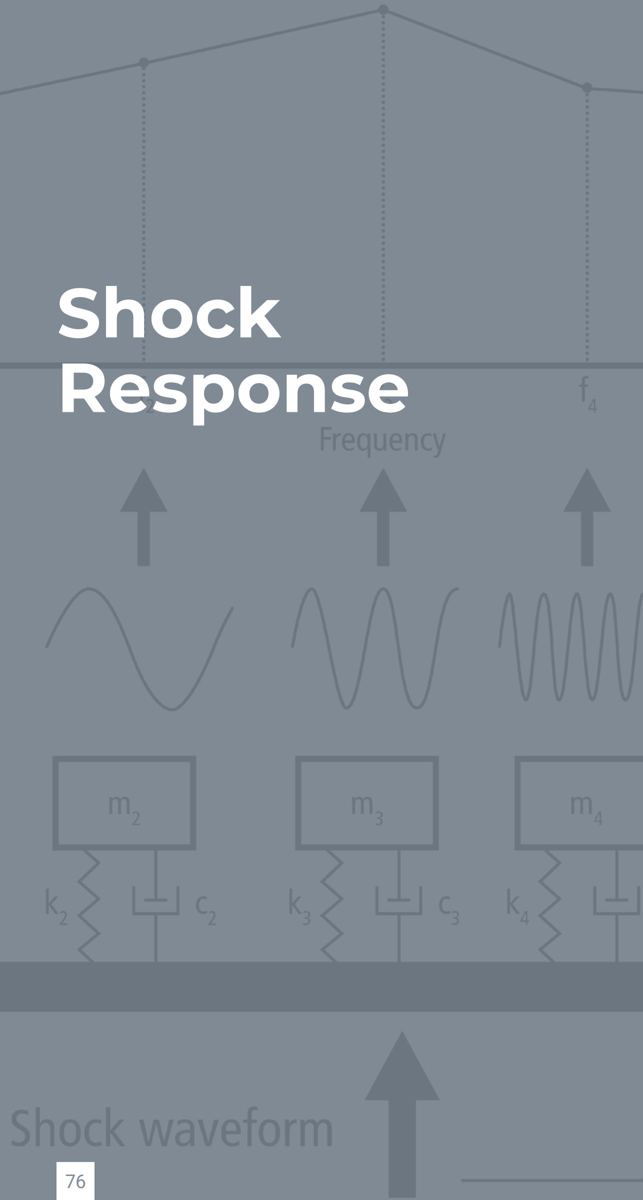
Because of the way their centre frequencies are generated, third-octave filters are often referred to as one-tenth decade filters. Octave filters are successive sets of three third-octave filters, starting with bands 2 – 4.

Why a Logarithmic Amplitude Scale?



Critical vibration components can occur at low amplitudes compared to the rotational frequency vibration. These components are not revealed on a linear amplitude scale because low amplitudes are compressed at the bottom of the scale. But a logarithmic scale shows prominent vibration components equally well at any amplitude. Moreover, percentage change in amplitude can be read directly as a dB change. Therefore, noise and vibration frequency analyses are usually plotted on a logarithmic amplitude scale.

Shock Response



Glossary of Shock Response Terms

COMPOSITE SHOCK RESPONSE SPECTRUM
Envelope of the primary and residual shock response spectra.

CRITICAL DAMPING
Critical damping is the minimum viscous damping that will allow a displaced system to return to its initial position without oscillation.

DAMPING RATIO
The fraction of critical damping for a system with viscous damping. It is the ratio of the actual damping coefficient c to the critical damping coefficient.

DRIFT
Acceleration can also contain a drift that can be estimated from data obtained after the shock when the acceleration should have returned to zero. This drift can be mathematically removed from the input data prior to computing the shock response. This technique does not consider the shock itself and is not influenced by asymmetric shocks like the half-sine.

EQUIVALENT STATIC ACCELERATION
A quantity computed from the relative displacement response by multiplying it by the square of the angular natural frequency. It has the dimensions of acceleration.

FREE VIBRATION
Free vibration is the vibration that occurs after the removal of an excitation or restraint.

MECHANICAL SHOCK
Mechanical shock is a non-periodic excitation of a mechanical system that is characterized by a suddenness and severity. It usually causes significant relative displacements in the system.

NEGATIVE SHOCK RESPONSE SPECTRUM (NEGATIVE SRS)
SRS where the maximum value is taken in the negative direction of the response.

POSITIVE SHOCK RESPONSE SPECTRUM (POSITIVE SRS)
SRS where the maximum value is taken in the positive direction of the response.

PRIMARY SHOCK RESPONSE SPECTRUM (PRIMARY SRS)
SRS where the maximum value is taken during the time of the shock (looking at the forced response of the structure). Also called the initial shock response spectrum.

PSEUDO ACCELERATION
See Equivalent Static Acceleration.

PSEUDO VELOCITY
A quantity computed from the relative displacement response by multiplying it by the angular natural frequency. It has the dimensions of velocity.

RESIDUAL SHOCK RESPONSE SPECTRUM (RESIDUAL SRS)
SRS where the maximum value is taken after the shock has taken place. The structure is in free vibration. Also called the secondary shock response spectrum.

SINGLE DEGREE OF FREEDOM SYSTEM (SDOF)
Single Degree of Freedom is used for a simple mechanical system for which the motion can be described with a single coordinate. This system is characterized by a lumped mass m, a linear spring with stiffness, k, and a viscous damper with damping coefficient, c.

SHOCK RESPONSE
Response of a mechanical system to a shock. The response can be acceleration, velocity or displacement depending upon the model selected.

SHOCK RESPONSE SPECTRUM (SRS)
The maximal response of the SDOF system subject to a given shock. It is computed as function of the resonance frequency of the system, usually for a fixed damping value. The resulting table or plot is the shock response spectrum. The response can be expressed in terms of acceleration, velocity or displacement.

VELOCITY SHOCK

Velocity shock is a particular type of shock motion characterized by a sudden velocity change of the base of a structure.

VISCOUS DAMPING

Viscous damping is the dissipation of energy that occurs when a particle in a vibration system is resisted by a force with a magnitude proportional to the magnitude of the velocity of the particle and direction opposite to the moving direction of the particle.

ZERO SHIFT

The quality of accelerometer data can be adversely affected during shock events. The sensing elements can be overstressed, which may lead to a zero shift in the acceleration time history. This in turn distorts the low-frequency region of the shock response spectrum. This should be avoided in the data acquisition stage, but a DC offset from the acceleration input can still be removed before computing the shock response spectrum. When this is desired, the input to the SRS should contain some data before the shock starts. The average of these first samples provides an estimate of the DC offset.

ZERO VELOCITY CHANGE

For pyroshock applications, it can be desirable to force the end velocity of the input to zero before computing the shock response. The velocity is computed by integrating the acceleration signal over the total record. If there is a residual velocity, it is forced to zero by adjusting the average acceleration.

Sound and vibration are critical to our quality of life. They affect us every day, from the smartphones we use and the cars we drive to the aircraft we fly in and the environment in which we all live.

At HBK, we produce the world's most accurate and advanced technology for measuring and managing the quality of sound and vibration.

Having led the industry for over 75 years, today we are able to help our customers from supplying quality components to monitoring their compliance.

We measure, analyze, test and optimize sound and vibration to accelerate business growth; whether this helps you ensure or enhance product performance or improve environmental quality.

And we can help you at every stage of your product life cycle, by applying our deep knowledge and experience to support your design and development right through to your deployment and operation.

Discover how HBK can accelerate your business growth, delivering value that goes beyond measure.

www.hbkworld.com