RION

| Sound and Vibration | Technical Note |
|---|---|

105

# The Basics of Noise and Vibration

## Chapter I, II, and V

RION CO., LTD.

# The Basics of Noise and Vibration

## Contents

# I. The Characteristics of Sound

## 1. Sound Pressure

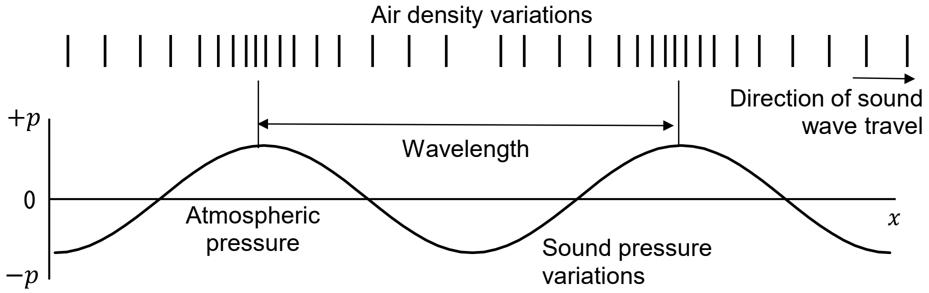
Sound pressure, typically expressed as a root mean square value, refers to the change from the static pressure within a medium caused by sound waves that are transmitted through the medium. The symbol is $p$ or $p_{\mathrm{a}}$; the units are Pa (Pascals). (Reference: Acoustical Society of Japan, *Dictionary of Acoustics,* 2003)

Sound pressure at a specific point in time can be expressed as variations in air density (The horizontal axis in the figure below indicates distance $x$). These microscopic variations in pressure are caused by vibrating air molecules induced by an external force. The vibration transmits variations to adjacent stationary air, causing sound to propagate through the air.

$$p(t) = p_{\mathrm{max}} \sin(2\pi f x \,/\, c)$$

where $p(t)$ is the instantaneous sound pressure (Pa) at the time $t$ (s), $p_{\mathrm{max}}$ is the maximum sound pressure value (Pa), $f$ is the frequency (Hz), $x$ is the distance (m), and $c$ is the speed of sound (m/s).

The minimum distance between identical phase points on a propagating wave is referred to as wavelength. Phase is a quantity indicating the variable position repeated over one cycle for a cyclical phenomenon. For example, $2\pi f x \,/\, c$ in the equation above gives the phase.



Sound wave at a specific point in time

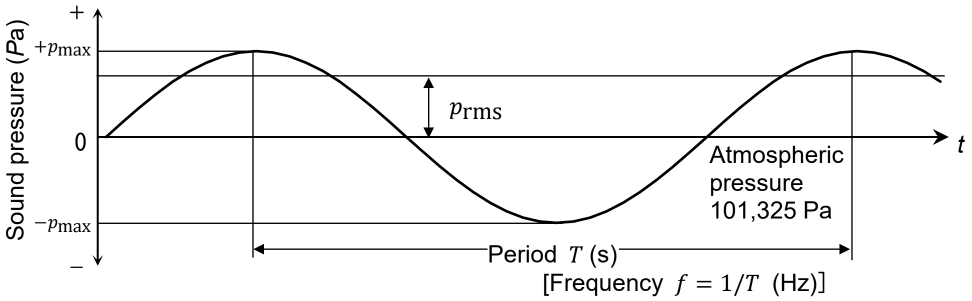
## 2. Sinusoidal Sound Waves

We can express a sound wave observed undulating in a sinusoidal manner at a certain point in a sound field as follows:

$$p(t) = p_{\mathrm{max}} \sin(2\pi f t)$$

The sound pressure state is indicated by the equation above. But we use the root mean square value to indicate the magnitude of sound pressure. The root mean square sound pressure is the square root of the mean of the instantaneous sound pressure squared. The root mean square value, $p_{\mathrm{rms}}$, of a sinusoidal sound wave, will be as follows. ("rms" stands for root mean square.)

$$p_{\mathrm{rms}} = p_{\mathrm{max}} / \sqrt{2}$$



Sinusoidal sound wave

## 3. Sound Intensity

The intensity of sound (acoustic intensity) is the amount of sound energy passing through a unit area per unit time at a certain point within a sound field. The symbol for sound intensity is $I$ or $J$ and is expressed in the units W/m$^2$. (Reference: Acoustical Society of Japan, *Dictionary of Acoustics,* 2003)

The following equation gives the relationship between sound intensity $I$ (W/m$^2$) and sound pressure $p$ (Pa):

$$I = p^2/\rho c$$

where $\rho$ is the density of air (kg/m$^3$), $c$ is the speed of sound in air (m/s) (see next section), $\rho c$ is referred to as the specific acoustic resistance (N·s/m$^3$).

## 4. The Speed of Sound

The speed at which a sound wave propagates through a particular medium is called the speed of sound. (Reference: Acoustical Society of Japan, *Dictionary of Acoustics,* 2003)

The following equation gives the speed of sound in air, $c$ (m/s):

$$c = \sqrt{\gamma P/\rho} = c_0\sqrt{T/273} = 331.5 + 0.61\theta$$

where $\rho$ is the density of air (kg/m$^3$), $\gamma$ is the ratio of specific heat (the ratio of the specific heat at constant pressure and specific heat at constant volume, which is 1.4 for air), $P$ is the atmospheric pressure (Pa), $c_0$ is the speed of sound at 0 °C (m/s), $T$ is the absolute temperature (K), and $\theta$ is the temperature in Celsius (°C). For example, the speed of sound is approximately 344 m/s at 20 °C.

Note that the speed of sound is also referred to as phase velocity. Phase velocity is the velocity in the direction in which a constant phase area propagates when a sinusoidal wave propagates.

The speed of sound in gases

| Substance | Speed of sound $c$ (0 °C, 1 atm) (m/s) | Density $\rho$ (0 °C, 1 atm) (kg/m$^3$) | Specific acoustic resistance $\rho c$ (N·s/m$^3$) |
|---|---|---|---|
| Air (dry) | 331.45 | 1.2929 | 428.6 |
| Oxygen | 317.2 | 1.4290 | 453 |
| Water vapor (100 °C) | 473.0 | 0.5980 | 242 |
| Hydrogen | 1,269.5 | 0.08988 | 114.1 |
| Nitrogen | 337.0 | 1.25055 | 421 |

Reference: Derived from p. 446 of "Chronological Scientific Tables 2020," edited by National Astronomical Observatory of Japan, published 2020 by Maruzen

The speed of sound in liquids such as water generally decreases by between 2 m/s and 5 m/s per degree Celsius. The speed of sound in water increases with temperature, reaching a peak at 74 °C.

The speed of sound in liquids

| Substance | Speed of sound $c$ (m/s) | Density $\rho$ ($10^3$ kg/m$^3$) | Specific acoustic resistance $\rho c$ ($10^6$ N·s/m$^3$) |
|---|---|---|---|
| Water (distilled) (23 °C to 27 °C) | 1,500 | 1.00 | 1.50 |
| Water (seawater) (20 °C) | 1,513 | 1.021 | 1.54 |

Reference: Derived from p. 447 of "Chronological Scientific Tables 2020," edited by National Astronomical Observatory of Japan, published 2020 by Maruzen

The speed of sound in solids can even vary for the same substance, depending on the crystalline state and orientation in the case of metals and the mixture proportions and frequency in the case of substances such as rubber. The speed of sound in solids generally decreases as temperature rises.

The speed of sound in solids

| Substance | Vertical wave speed $c_1$ (m/s) | Horizontal wave speed $c_2$ (m/s) | Bar vertical vibration speed $c_3$ (m/s) | Density $\rho$ ($10^3$ kg/m$^3$) | Specific acoustic resistance $\rho c$ ($10^6$ N·s/m$^3$) |
|---|---|---|---|---|---|
| Aluminum | 6,420 | 3,040 | 5,000 | 2.69 | 17.3 |
| Glass (window pane) | 5,440 | — | — | 2.42 | 13.2 |
| Rubber (natural, 1 MHz) | 1,500 | 120 | 210 | 0.97 | 1.5 |
| Concrete | 4,250-5,250 | — | — | — | — |
| Iron | 5,950 | 3,240 | 5,120 | 7.86 | 46.4 |
| Polyethylene (low-density) | 1,950 | 540 | 920 | 0.90 | 1.75 |

Reference: Derived from pp. 448-449 of "Chronological Scientific Tables 2020," edited by National Astronomical Observatory of Japan, published 2020 by Maruzen

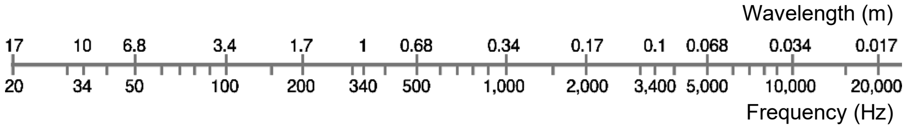
## 5. Frequency and Wavelength

The number of times a cyclical phenomenon repeats within one second is known as its frequency. The symbol is $f$, and values are expressed in units of Hz (Hertz). This value is the inverse of the period $T$ (s) (the minimum time interval that elapses until the same state is repeated).

For periodic wave motion through an isotropic medium, the vertical distance between two wavefronts with a phase difference of just one cycle is referred to as the wavelength. The symbol is $\lambda$, which is expressed in units of m.

The relationship between the speed of sound $c$ (m/s), frequency $f$ (Hz), and wavelength $\lambda$ (m) is as follows:

$$\lambda = c/f$$



Relationship between sound wavelength and frequency

## 6. Level

Level refers to the logarithm of the ratio between a given quantity and a reference quantity. When using common logarithms with base 10, the units are called bels, indicated by the letter B.

Units corresponding to one tenth of a bel, referred to as decibels, are often used. The symbol is dB (JIS Z 8106). The amount of sound measured in decibels is compared against the reference sound power, reference sound intensity, and reference sound pressure, referred to, respectively, as sound power level, sound intensity level (acoustic intensity level), and sound pressure level.

When the base 10 logarithm of $x$ is $z$, the relationship can be expressed as

$$\log_{10} x = z, 10^z = x, \text{and} \log_{10} 10^n = n$$

Since decibels take the form

$$L = 10 \log_{10} \frac{n}{n_0}$$

this produces

$$10^{L/10} = \frac{n}{n_0}, 10^{L/10} \cdot n_0 = n$$

Note that common base 10 logarithms are hereinafter referred to simply as "log."

### 7. Sound Pressure Level

The sound pressure level $L_p$ for sound pressure $p$ (Pa) is defined by the following equation:

$$L_p = 10\log\frac{p^2}{{p_0}^2}$$

where $p_0$ is the reference sound pressure 20 μPa (= 2 × $10^{-5}$ Pa).

### 8. Sound Intensity Level (Acoustic Intensity Level)

The level $L_I$ of sound intensity $I$ (W/m$^2$) in a specified direction is defined by the following equation:

$$L_I = 10\log\frac{I}{I_0}$$

where $I_0$ is the reference sound intensity 1 pW/m$^2$ (= $10^{-12}$ W/m$^2$). Note that the sound pressure and sound intensity levels at a particular point are typically the same.

In the past, due to the technical difficulties in directly measuring sound intensity, the sound intensity was typically approximated by measuring sound pressure. But this quantity ignores the directionality of sound. Nowadays, sound intensity is typically measured for different frequencies using equipment such as FFT analyzers and digital filters to process sound pressure obtained from two adjacent microphones to account for the directionality of sound.

### 9. Sound Power Level

The sound power level $L_W$ of the sound power of a source $P$ (W) is defined by the following equation:

$$L_W = 10\log\frac{P}{P_0}$$

where $P_0$ is the reference sound power of a source 1 pW (= $10^{-12}$ W).

### 10. Sound Energy Level

Sound energy level is used for sporadic or transient sound because sound power level cannot be defined for such sound.

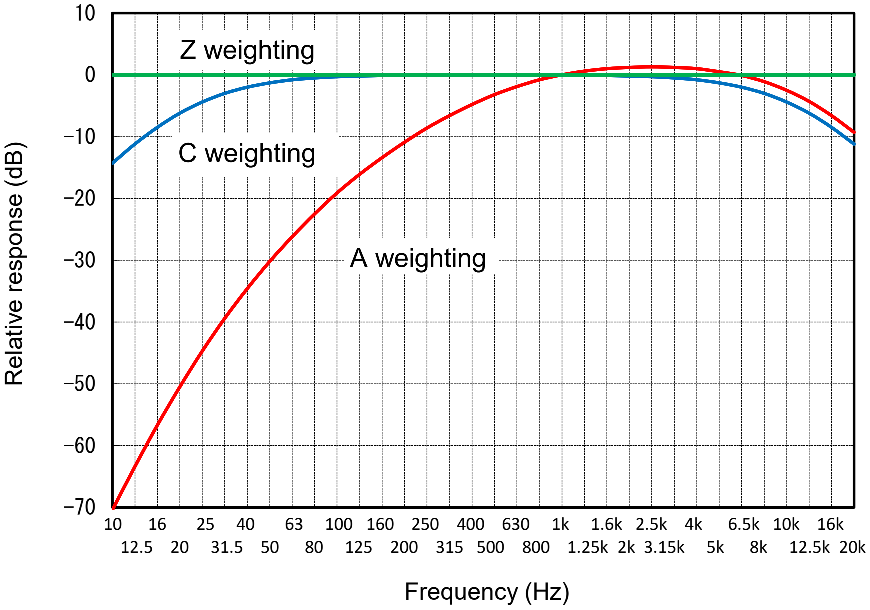
The sound energy level $LJ$ of a sound source with sound energy $E$ (J) is defined by the following equation:

$$LJ = 10\log\frac{E}{E_0}$$

where $E_0$ is the reference sound energy 1 pJ (= $10^{-12}$ J).

### 11. A-weighted Sound Pressure Level

In particular, sound pressure level measured using the frequency-weighted characteristics A as specified in JIS C 1509-1 (Electroacoustics - Sound level meters - Part 1: Specifications) is referred to as A-weighted sound pressure level. The units are decibels, using the symbol dB, and the quantity is indicated by the symbol $L_{p\mathrm{A}}$. The symbol $L_{p\mathrm{A}}$ may be indicated simply as $L_\mathrm{A}$. In the past, A-weighted sound pressure level was measured using the units phons, but this was discontinued following revisions to the Measurement Act.



Frequency weighting characteristics of sound level meters (JIS C 1509-1: 2017)

## 12. Equivalent Continuous A-weighted Sound Pressure Level

If A-weighted sound pressure level varies with time, the continuous steady sound level that gives the same mean square sound pressure within the duration of measurement ( $T = t_2 - t_1$ (s)) is referred to as the equivalent continuous A-weighted sound pressure level. This is expressed in units of dB and indicated by the symbol $L_{\mathrm{Aeq},T}$ . If no confusion may arise, this can be indicated simply as $L_{\mathrm{Aeq}}$ or $L_{\mathrm{eq}}$.

$$L_{\mathrm{Aeq},T} = 10\log\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{{p_{\mathrm{A}}}^2(t)}{p_0^2}\,\mathrm{d}t\right]$$

In other words, the equivalent continuous A-weighted sound pressure level $L_{\mathrm{Aeq},T}$ is a quantity expressing the time mean (rms) value of the total energy of sound (A-weighted sound pressure $p_{\mathrm{A}}(t)$) within a specific time as a level (dB).

Equivalent continuous A-weighted sound pressure level should not be used to evaluate sporadically occurring sound, as it will differ greatly depending on the measurement time used.

## 13. (Single Event) A-weighted Sound Exposure Level

A-weighted sound exposure level refers to the continuous sound over one second with the identical energy to the weighted energy for A-weighting within the duration of measurement $(t_2 - t_1)$ (s). It is also referred to as the single event A-weighted sound exposure level, as it is typically used for evaluating sporadically occurring sound. It is expressed in the units of dB, and indicated by the symbol $L_{\mathrm{A}E}$.

$$L_{\mathrm{A}E} = 10 \log \left[ \frac{1}{T_0} \int_{t_1}^{t_2} \frac{p_{\mathrm{A}}{}^2(t)}{p_0{}^2} \mathrm{dt} \right]$$

where $T_0$ is the reference time (1 s). This normalizes for one second the total sound energy of sporadically or intermittently occurring sound, and is a quantity for calculating the equivalent continuous A-weighted sound pressure level of a specific sound on its own within a specific time.

For calculations of the equivalent continuous A-weighted sound pressure level of a specific intermittent sound occurring within a total length of time monitored *T* (s) (referred to as the observation time), the single sound level can be measured each time it occurs, and the results are used in the following equation to calculate the equivalent continuous A-weighted sound pressure level.

$$L_{\mathrm{Aeq},T} = 10 \log \left[ \frac{T_0}{T} \left( 10^{L_{\mathrm{A}E_1}/10} + 10^{L_{\mathrm{A}E_2}/10} + \cdots + 10^{L_{\mathrm{A}E_n}/10} \right) \right]$$

where $L_{\mathrm{A}E_1}$, $L_{\mathrm{A}E_2}$, … $L_{\mathrm{A}E_n}$ are the single sound levels for each occurrence (dB), and $T_0$ is the reference time (1 s).

## 14. Percentile Sound Level

When the duration for which a sound level is equal to or greater than a particular level accounts for *N* % of the measured time, that level is referred to as the N-percentile sound level. This is expressed in units of decibels (dB). $L_{50}$, the 50-percentile sound level, is referred to as the median value; $L_5$, the 5-percentile sound level, is referred to as the upper end of the 90 % range; and $L_{95}$, the 95-percentile sound level, is referred to as the lower end of the 90 % range.

## 15. Decibel Calculations

### 15.1 Relative Sound Levels

Sound intensity and sound pressure levels are expressed as absolute values with respect to a predetermined datum value. However, when comparing an 80 dB sound against a 90 dB sound, the difference with 90 dB using 80 dB as a datum is 10 dB. In this case, the sound scale is relative. The table on page 8 shows the relationship between energy and decibels for two sounds, with the energy of the reference sound set to 1. For 3 dB, the energy is twice as large; for 10 dB, the energy is 10 times greater. If we remember that energy is 1.25 times and 1.6 times greater for 1 dB and 2 dB, respectively, approximations can be made up to 10 dB by applying 1.25 × 2 = 2.5 for 4 dB (3 dB greater than 1 dB), 1.6 × 2 = 3.2 for 5 dB, and 2 × 2 = 4 for 6 dB etc. Similarly, the energy for 11 dB is ten times greater than for 1 dB; hence 12.5, the energy for 12 dB is ten times greater at 16, the energy for 20 dB is 100, 125 for 21 dB, 1,000 for 30 dB, and 5,000 for 37 dB. Conversely, the energy for -10 dB is 0.1 times greater than for 1dB, 0.125 for -9 dB, and 0.01 for -20 dB.

### 15.2 Summing Decibel Values

On certain occasions, we may want to calculate the combined sound pressure level for two or more sound sources when we know individual sound pressure levels. In such situations, use the following table to convert the individual decibel values to energy (ratios), obtain the sum, then convert this back to a decibel value. For example, to calculate the total decibel value for 76 dB, 81 dB, and 84 dB sound sources, if we set 70 dB as 1, the difference between 76 dB and 70 dB is 6 dB, so the corresponding energy ratio will be 4. Likewise, the energy ratios for 81 dB and 86 dB will be 12.5 and 25, respectively, giving 4 + 12.5 + 25 = 41.5. 10 log 41.5 is approximately 16 (dB), so the result is 70 dB + 16 dB, or approximately 86 dB.

There are several different ways to calculate this mentally. Use the most convenient method.

With scientific calculators, the sum of the sound pressure requires calculating the sum of the energy. This means we calculate the sum of the squared sound pressure.

$$L_1 = 10\log({p_1}^2/{p_0}^2),\ L_2 = 10\log({p_2}^2/{p_0}^2),\cdots,\ L_n = 10\log({p_n}^2/{p_0}^2)$$

where the sum $L$ is given by:

$$L = 10\log\left(({p_1}^2 + {p_2}^2 + \cdots + {p_n}^2)/{p_0}^2\right)$$

We now know $L_1,\ L_2,\ L_n$ (dB), so we can calculate sum $L$ as follows:

$$L = 10\log\left(10^{L_1/10} + 10^{L_2/10} + \cdots + 10^{L_n/10}\right)$$

Note that this calculation applies when the sound is broadband noise. In the case of a pure tone, the sine functions accounting for the phase of individual sound sources must also be added. The characteristic of pure tone addition calculations is that the sum increases 6 dB for two sine waves with the same frequency, amplitude, and phase. Conversely, the sum is zero if the phase difference is 180°. For the sum of sine waves with slightly differing frequencies, the phenomenon of beat waves will occur. The amplitude will vary at intervals corresponding to the difference between the two frequencies.

### 15.3 Averaging Decibel Values

For calculations of the mean of two or more sound pressure levels, the difference between the power mean and arithmetic mean for the decibel value is less than 1 dB if the difference between maximum and minimum sound levels is less than 5 dB. For example, the power mean (decibel value for energy mean) for 80 dB and 85 dB values is (1 + 3.2) / 2 = 2.1, if we set 80 dB as 1, giving 83.2 dB, and the arithmetic mean is (80 + 85) /2 = 82.5 dB, so the difference between the two is 0.7 dB. For 80 dB and 90 dB, the power mean is (1 + 10) / 2 = 5.5, giving 87.45 dB, and the arithmetic mean is (80 + 90) /2 = 85 dB, so the difference between the two is 2.45 dB.

With scientific calculators, the power mean $\bar{L}$ for $N$ levels $L_1,\ L_2,\ldots\ L_n$ (dB) will be

$$\bar{L} = 10\log\left[\frac{1}{N}\left(10^{L_1/10} + 10^{L_2/10} + \cdots + 10^{L_n/10}\right)\right]$$

Note that calculating the power mean for all values measured at constant sampling intervals gives the equivalent continuous A-weighted sound pressure level $L_{\mathrm{Aeq}}$ (dB) for the actual duration of measurement.

Decibel value and energy ratio

| dB | Energy ratio | dB | Energy ratio | dB | Energy ratio | dB | Energy ratio |
|---|---|---|---|---|---|---|---|
| −10 | 0.1 | 0 | 1.0 | 10 | 10.0 | 20 | 100 |
| −9 | 0.125 | 1 | 1.25 | 11 | 12.5 | 21 | 125 |
| −8 | 0.16 | 2 | 1.6 | 12 | 16 | 22 | 160 |
| −7 | 0.2 | 3 | 2.0 | 13 | 20 | 23 | 200 |
| −6 | 0.25 | 4 | 2.5 | 14 | 25 | 24 | 250 |
| −5 | 0.32 | 5 | 3.2 | 15 | 32 | 25 | 320 |
| −4 | 0.4 | 6 | 4.0 | 16 | 40 | 26 | 400 |
| −3 | 0.5 | 7 | 5.0 | 17 | 50 | 27 | 500 |
| −2 | 0.64 | 8 | 6.4 | 18 | 64 | 28 | 640 |
| −1 | 0.8 | 9 | 8.0 | 19 | 80 | 29 | 800 |
| | | | | | | 30 | 1,000 |

Reference: Juichi Igarashi, Mitsuyasu Yamashita: "Noise Control Engineering 58" (Corona, Tokyo, 1988), p.5

Decibel value, energy ratio, and sound pressure ratio

| dB | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 |
|---|---|---|---|---|---|---|---|---|---|
| Energy ratio | 0.01 | 0.03 | 0.1 | 0.32 | 1 | 3.2 | 10 | 32 | 100 |
| Sound pressure ratio | 0.1 | 0.18 | 0.32 | 0.56 | 1 | 1.8 | 3.2 | 5.6 | 10 |

Reference: Juichi Igarashi, Mitsuyasu Yamashita: "Noise Control Engineering 58" (Corona, Tokyo, 1988), p.5

Approximate calculations for sums of two decibel values

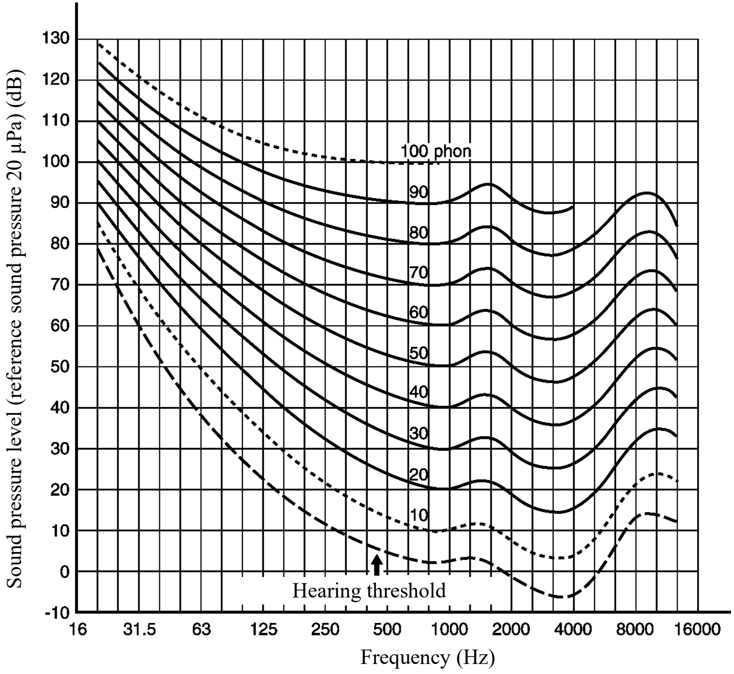
| Difference $\Delta L$ (dB) between two levels $L_1 - L_2 = \Delta L$ $(L_1 \geq L_2)$ | 0, 1 | 2 to 4 | 5 to 9 | 10 or greater |
|---|---|---|---|---|
| Value $a$ (dB) added to larger value | 3 | 2 | 1 | 0 |
| Sum $L = L_1 + a$ (dB) | | | | |

Reference: Juichi Igarashi, Mitsuyasu Yamashita: "Noise Control Engineering 58" (Corona, Tokyo, 1988), p.5

## 16. Loudness Level for a Pure Tone

Human sensitivity to sound depends on frequency and sound pressure level. ISO 226 provides equal-loudness-level contours, which indicate the pressure levels at which different pure tones are sensed as having the same loudness. These curves can be applied to persons between the ages of 18 and 30 with normal hearing. An absolute scale for the sound is established by setting the sound pressure level at 1,000 Hz as the datum. The sound pressure level for each frequency sensed as having the same loudness as that sound pressure level is referred to as the loudness level (sound magnitude level).

For low sound pressure levels, we see that sounds of lower frequency are sensed less easily, while sounds at near 4,000 Hz are sensed most easily.



Equal-loudness-level contours for pure tones (ISO 226:2003)

## 17. Sound Reflection, Transmission, and Absorption

### 17.1 Sound Reflection

When a plane wave is incident on a boundary face between two media, part of the wave is reflected at the boundary face, while part of the wave passes into the medium. For a boundary face between two media with specific acoustic resistance of $\rho_1 c_1$ and $\rho_2 c_2$ respectively, the sound pressure reflectivity for the sound entering this boundary face orthogonal to the $\rho_1 c_1$ side is (sound pressure of reflected wave) divided by (sound pressure of incident wave) and is given by the following equation:

$$\frac{p_r}{p_1} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_1 c_1 + \rho_2 c_2}$$

The reflectivity of the sound energy $r_0$ is given by:

$$r_0 = \left(\frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2}\right)^2$$

The following equation gives reflectivity $r$ of the energy for a plane wave incident at an angle on the boundary face between two media:

$$r = \left(\frac{\rho_2 c_2 \cos\theta_1 - \rho_1 c_1 \cos\theta_2}{\rho_2 c_2 \cos\theta_1 + \rho_1 c_1 \cos\theta_2}\right)^2$$

where $\theta_1$ is the angle of incidence and $\theta_2$ the angle of refraction.

### 17.2 Sound Transmission

Similarly, when a plane wave is incident on a boundary face between two media, the sound pressure transmissivity is (sound pressure of transmitted wave) divided by (sound pressure of incident wave) and is given by the following equation:

$$\frac{p_t}{p_i} = \frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1}$$

The transmissivity of the sound energy $t_0$ is given by:

$$t_0 = \frac{4\rho_1 c_1 \rho_2 c_2}{(\rho_1 c_1 + \rho_2 c_2)^2}$$

The following equation gives transmissivity $t$ of the energy for a plane wave incident at an angle on the boundary face between two media:

$$t = \frac{4\rho_1 c_1 \rho_2 c_2 \cos\theta_1 \cos\theta_2}{(\rho_1 c_1 \cos\theta_2 + \rho_2 c_2 \cos\theta_1)^2}$$

### 17.3 Sound Refraction

A sound wave incident at angle $\theta_1$ at a boundary face between medium 1 and medium 2 for which the speed of sound is $c_1$ and $c_2$, respectively, will propagate into medium 2 with an angle of refraction of $\theta_2$.

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}$$

This relationship is known as Snell's Law. Sound is refracted where differences in temperature or air speed occur within the atmosphere. Atmospheric air temperature varies with height. Air temperature during the daytime typically decreases with altitude, reducing the speed of sound and causing sound emitted from the ground to be refracted upward. For inversion phenomena in which the temperature at ground level is lower than atmospheric air temperature, sound is refracted downward, allowing sound from the ground to travel further. The speed of sound is affected by the presence of wind. Since wind speeds are generally greater at altitude, sound tends to be refracted up when upwind and down when downwind.

### 17.4 Sound Absorption Coefficient and Transmission Loss

A part of the energy of a sound wave is lost at walls and other physical boundary faces. The ratio between the reflected energy $I_\mathrm{r}$ of the remaining sound absorbed and transmitted at the boundary face and the incident energy $I_\mathrm{i}$ is called the sound absorption coefficient $\alpha$. The transmitted energy is expressed as $I_\mathrm{t}$.

$$\alpha = \frac{I_\mathrm{i} - I_\mathrm{r}}{I_\mathrm{i}}$$

The relationship between reflectivity $r$ and sound absorption coefficient is $\alpha + r = 1$.

The degree of transmitted sound is expressed by the transmissivity $\tau$ and transmission loss TL.

$$\tau = I_\mathrm{t}/I_\mathrm{i}$$

$$\mathrm{TL} = 10\log(1/\tau)$$

## 18. Sound Attenuation in Distance

Sound emitted from a sound source spreads out geometrically (in a spherical or semi-spherical pattern), with intensity attenuating over distance. Sound travelling over longer distances, in addition to this geometric attenuation, is also subject to significant attenuation due to absorption by air and the effects of the ground profile. This kind of sound attenuation is called excess attenuation. Meteorological effects are complex. Sound propagation will vary due to factors such as air temperature distribution, wind direction, and wind speed gradient.

### 18.1 Point Sound Sources

If a point sound source with sound power $P$ (W) exists in a free sound field (free space with no reflectors), the following equation gives sound intensity $I$ (W/m$^2$) at a point a distance $r$ (m) from the sound source:

$$I = P/4\pi r^2$$

Similarly, for a hemi-free sound field (such as when the sound source is located on the ground), this is given by the following equation:

$$I = P/2\pi r^2$$

If we express these in terms of sound power level $L_W$ (dB) and sound pressure level $L_p$ (dB), we obtain the following equations:

Free sound field: $L_p = L_W - 20\log r - 11$

Hemi-free sound field: $L_p = L_W - 20\log r - 8$

The sound pressure level, therefore, falls by 6 dB as the distance from the sound source doubles. This is known as the "inverse square law."

These relationships are valid when the sound source is omnidirectional. In reality, the above equations can be used as an approximation if the dimensions of the sound source are sufficiently small compared to the distance.

### 18.2 Linear Sound Sources

If the sound source is an infinitely long axial shape, the sound spreads out in a cylindrical pattern with the linear sound source forming the axis. If a linear sound source with sound power $P$ (W) per unit length of the sound source exists in a free sound field, the following equation gives sound intensity $I$ (W/m$^2$) at a point a distance $r$ (m) from the sound source:

$$I = P/2\pi r$$

Similarly, for a hemi-free sound field (such as when the sound source is located on the ground), this is given by the following equation:

$$I = P/\pi r$$

If we express these in terms of sound power level $L_W$ (dB) and sound pressure level $L_p$ (dB), we obtain the following equations:

Free sound field: $L_p = L_W - 10\log r - 8$

Hemi-free sound field: $L_p = L_W - 10\log r - 5$

The sound pressure level falls by 3 dB as the distance from the sound source doubles.

We can calculate this for linear sound sources of finite length by treating this as continuous nondirectional point sound sources along the finite length. In practice, we use an approximation in which for distances up to approximately $1/\pi$ of the length of the linear sound source, sound is assumed to attenuate by 3 dB as the distance doubles in the same way as with an infinite linear sound source, and for distances greater than this, sound is assumed to attenuate by 6 dB as the distance doubles, as with point sound sources.

Note that this case assumes only energy is added and that phenomena such as sound wave interference can be disregarded for unrelated phase noise emitted from individual sound sources—for example, in a case in which we consider the sound source to be a row of cars.

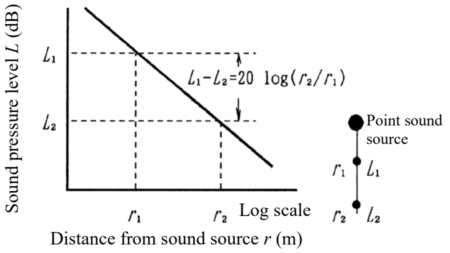
### 18.3 Area Sound Sources

Cases in which the sound source covers a significant area—for example, noise from a large opening or noise emitted after passing through a wall—are referred to as an area sound source. Ideally, these are treated as continuous infinite distributions of point sound sources.

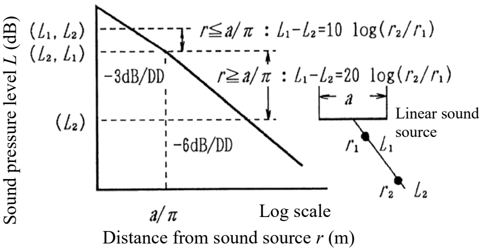
If the area sound source has an infinite area, sound will not attenuate. In the case of an area sound source of a finite area, we calculate the sound attenuation in distance by assuming that phenomena such as interference can be disregarded for unrelated phase noise emitted from individual sound sources. In practice, we use an approximation in which, if the sound source is a rectangular plane, for distances up to approximately $1/\pi$ of the length of the shorter side from the sound source, sound does not attenuate, and from there distances up to approximately $1/\pi$ of the length of the longer side, sound is assumed to attenuate by 3 dB as the distance doubles, in the same way as with linear sound sources. For greater distances from there, sound is assumed to attenuate by 6 dB as distance doubles, as with point sound sources.

### 18.4 Sound Absorption Due to Air

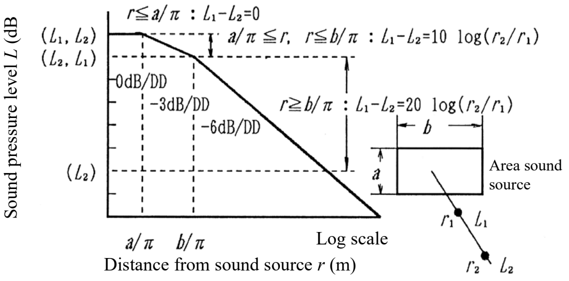
Sound waves propagating through air are primarily attenuated by the expanding wave front. However, over long distances, sound waves are also subject to attenuation by absorption in air. This absorption due to air depends on air temperature and relative humidity as well as sound frequency. Absorption increases for lower temperatures and humidity and for higher sound frequencies.



(a) Point sound source



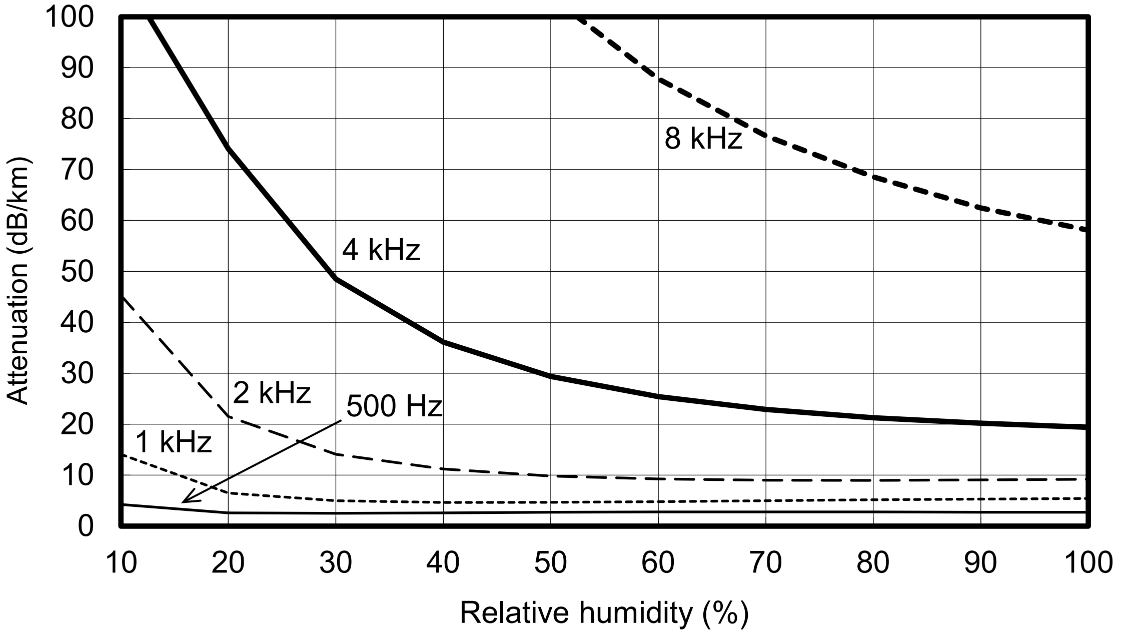
(b) Finite linear sound source



(c) Finite area sound source

Note: dB/DD stands for dB/double distance.

Sound attenuation in distance

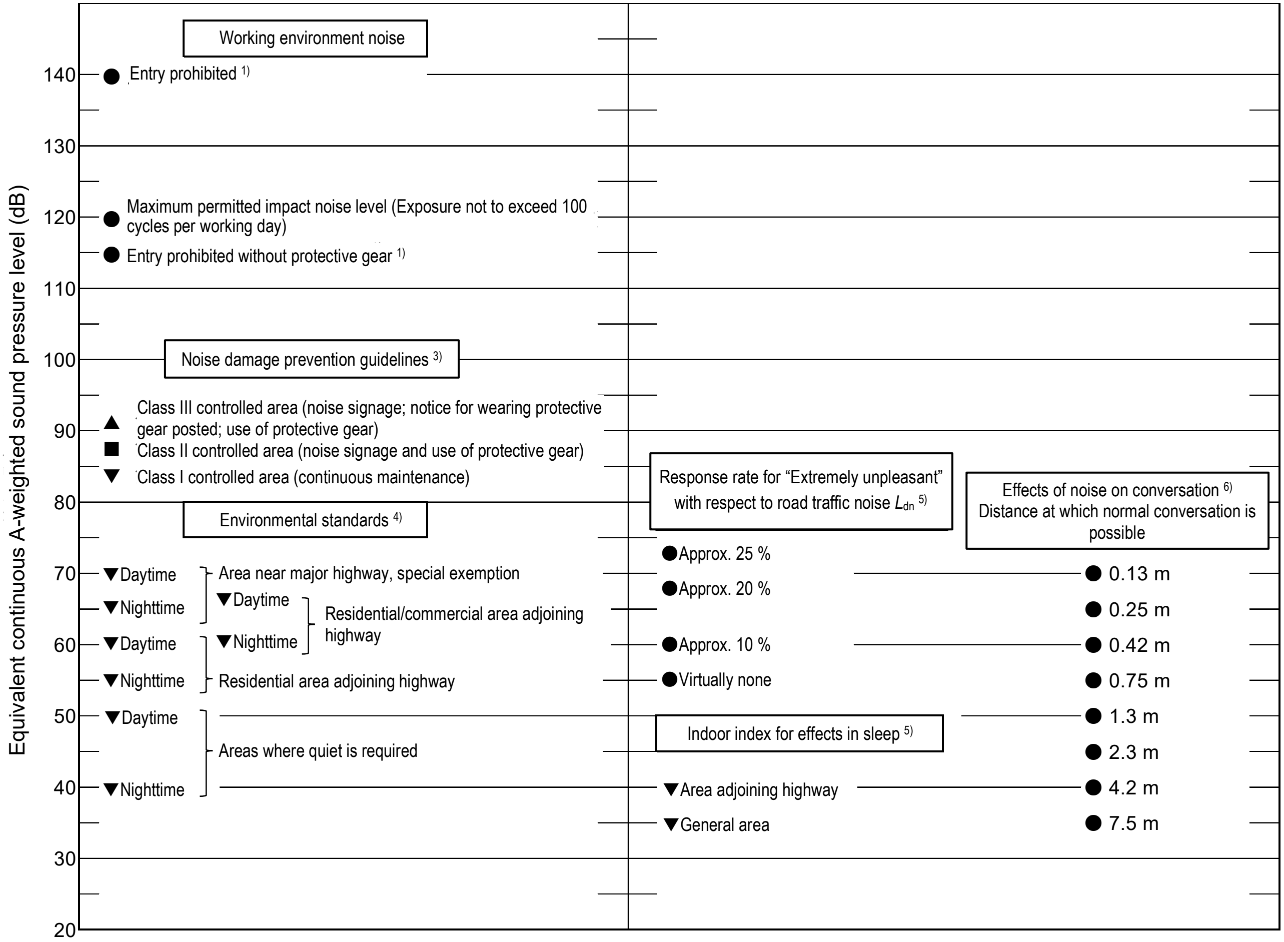


Sound attenuation due to air absorption (ISO 9613-1:1993) Constant temperature 20 °C

## 19. Noise Evaluation

### 19.1 Noise Evaluation Examples

How noise is evaluated depends on the target noise. Several examples are provided here.



Notes:

1) ILO: Protection of workers against noise and vibration in the working environment, third impression (1984)
2) Japan Society for Occupational Health, "Recommendation of Occupational Exposure Limits (2019)," Journal of Occupational Health, 61 (5), p.192, 2019
3) Guideline for the Prevention of Noise-Induced Impairments (October 1, 1992, Labour Standards Bureau Notification No. 546)
4) Environmental quality standards for noise (March 30, 2012, Ministry of the Environment Notification No. 54)
5) Report on "Recommended Environmental Quality Standards for Noise" by the Central Environment Council in Japan (1998)
6) ISO/TR 3352:1974 Acoustics - Assessment of noise with respect to its effect on the intelligibility of speech

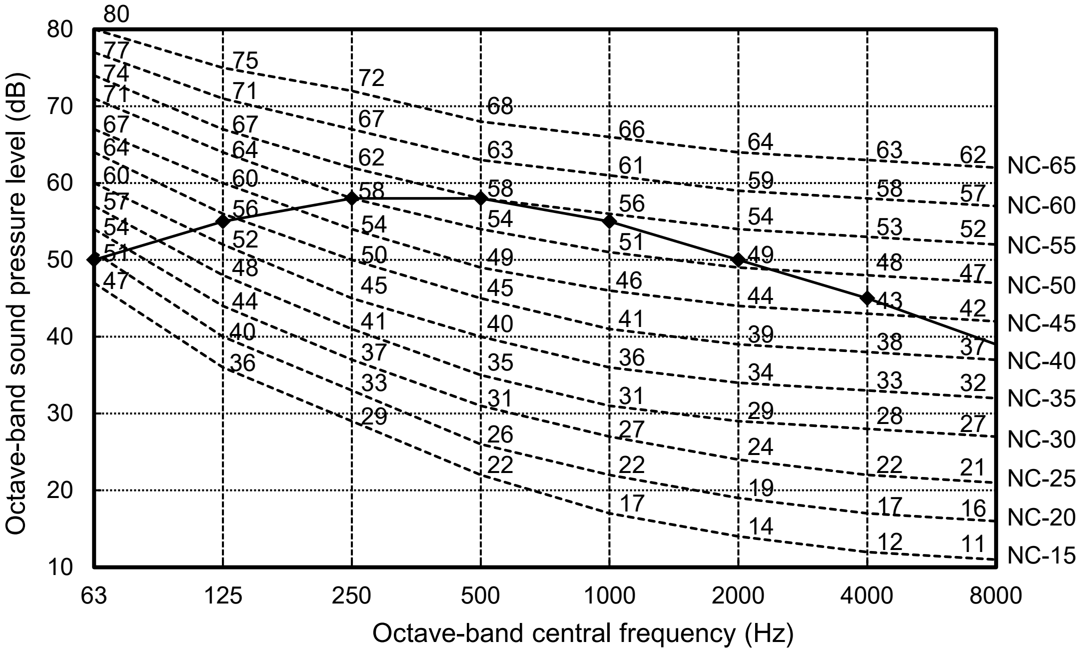
Noise evaluation

### 19.2 Evaluation of Indoor Noise Using NC Curves

NC (noise criteria) curves are widely used to evaluate indoor noise. The method involves plotting sound pressure levels for each octave band of the measured noise on a graph. If sound pressure levels for all bands lie below a particular curve, that NC value is used as the evaluation value. (For more information on octave bands, refer to “II 2.1 Frequency Analyzers.”) For example, if the results of noise octave band analysis are 50 dB, 55 dB, 58 dB, 58 dB, 55 dB, 50 dB, 45 dB, and 39 dB, respectively, from 63 Hz (the solid line on the graph), the evaluation will be NC-55.

If a particular NC value is stipulated—for example, if building construction specifications stipulate “not to exceed NC-20”—sound pressure levels must not exceed the NC-20 curve for any octave band.

With PNC (preferred NC) curves, which are modified NC curves, the value is the same as the NC value for 1,000 Hz, but 4 dB or 5 dB lower for 63 Hz, approximately 1 dB lower for the 125 Hz, 250 Hz, and 500 Hz bands, and approximately 4 dB or 5 dB lower for 2,000 Hz and 4,000 Hz. (The recommended indoor values are the same.)



Reference: Evaluation curves derived from L.L. Beranek (ed): Noise and Vibration Control, (McGraw Hill Publishing, New York, 1971), p. 566

Recommended indoor noise standards and evaluation example using NC curves

Recommended indoor noise standards

| Room type | NC curve | Approximate A-weighted sound pressure level (dB) |
|---|---|---|
| Concert hall, opera house, recital hall (listening to quiet music) | 10 to 20 | 21 to 30 |
| Broadcasting/recording studio (using remote microphone) | 10 to 20 | 21 to 30 |
| Large auditorium, large theater, cathedral (ideal listening conditions) | Not more than 20 | 30 |
| Broadcasting/TV/recording studio (using close microphone) | Not more than 25 | 34 |
| Small auditorium, small theater, music rehearsal room, large conference room (with ideal acoustic conditions) or president's office or 50-person conference room (no amplification required) | Not more than 35 | 42 |
| Bedroom, dormitory, hospital, house, apartment, hotel (for sleeping, rest, and recuperation) | 25 to 40 | 34 to 47 |
| Cubicle (office), small conference room, classroom, reading room (with ideal acoustic conditions) | 30 to 40 | 38 to 47 |
| Living room, house room (listening to conversation or radio/TV) | 30 to 40 | 38 to 47 |
| Large office, banquet hall, store, cafeteria, restaurant (conditions suitable for listening) | 35 to 45 | 42 to 52 |
| Lobby, laboratory, technical office, secretary's office (conditions for clear listening) | 40 to 50 | 47 to 56 |
| Light workshop, office, computer room, kitchen, laundry room (conditions for suitably clear listening) | 45 to 55 | 52 to 61 |
| Store, garage, power station control room, etc. (allowing conversation and telephone calls) NC-60 or higher is not recommended for offices. | 50 to 60 | 56 to 66 |
| Workplaces where conversation or telephone calls are not required (but noise levels do not cause hearing impairment) | 60 to 75 | 66 to 80 |

Reference: Derived from L.L. Beranek (ed.): *Noise and Vibration Control*, (McGraw Hill Publishing, New York, 1971), p. 585

# II. Noise Measuring Techniques

## 1. A-weighted Sound Pressure Level Measurement

### 1.1 Sound Level Meter

A sound level meter is a measuring device that displays a frequency-weighted (A, C, or Z (or FLAT) weighting) or time-weighted (weighted using sound pressure signal quadratic exponential function) “F (fast) or S (slow)” value for sound pressure as a level (sound level or sound pressure level dB value).

Frequency weighting and sensing limits (JIS C 1509-1:2017)

| 1/3 octave-band central frequency (Hz) | Frequency weightings* (dB) | | | Sensing limit (dB) | |
|---|---|---|---|---|---|
| | | | | Class | |
| | A | C | Z | 1 | 2 |
| 10 | –70.4 | –14.3 | 0.0 | +3.0, –∞ | +5.0, –∞ |
| 12.5 | –63.4 | –11.2 | 0.0 | +2.5, –∞ | +5.0, –∞ |
| 16 | –56.7 | –8.5 | 0.0 | +2.0, –4.0 | +5.0, –∞ |
| 20 | –50.5 | –6.2 | 0.0 | ±2.0 | ±3.0 |
| 25 | –44.7 | –4.4 | 0.0 | +2.0, –1.5 | ±3.0 |
| 31.5 | –39.4 | –3.0 | 0.0 | ±1.5 | ±3.0 |
| 40 | –34.6 | –2.0 | 0.0 | ±1.0 | ±2.0 |
| 50 | –30.2 | –1.3 | 0.0 | ±1.0 | ±2.0 |
| 63 | –26.2 | –0.8 | 0.0 | ±1.0 | ±2.0 |
| 80 | –22.5 | –0.5 | 0.0 | ±1.0 | ±2.0 |
| 100 | –19.1 | –0.3 | 0.0 | ±1.0 | ±1.5 |
| 125 | –16.1 | –0.2 | 0.0 | ±1.0 | ±1.5 |
| 160 | –13.4 | –0.1 | 0.0 | ±1.0 | ±1.5 |
| 200 | –10.9 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 250 | –8.6 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 315 | –6.6 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 400 | –4.8 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 500 | –3.2 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 630 | –1.9 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 800 | –0.8 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 1,000 | 0 | 0 | 0 | ±0.7 | ±1.0 |
| 1,250 | +0.6 | 0.0 | 0.0 | ±1.0 | ±1.5 |
| 1,600 | +1.0 | –0.1 | 0.0 | ±1.0 | ±2.0 |
| 2,000 | +1.2 | –0.2 | 0.0 | ±1.0 | ±2.0 |
| 2,500 | +1.3 | –0.3 | 0.0 | ±1.0 | ±2.5 |
| 3,150 | +1.2 | –0.5 | 0.0 | ±1.0 | ±2.5 |
| 4,000 | +1.0 | –0.8 | 0.0 | ±1.0 | ±3.0 |
| 5,000 | +0.5 | –1.3 | 0.0 | ±1.5 | ±3.5 |
| 6,300 | –0.1 | –2.0 | 0.0 | +1.5, –2.0 | ±4.5 |
| 8,000 | –1.1 | –3.0 | 0.0 | +1.5, –2.5 | ±5.0 |
| 10,000 | –2.5 | –4.4 | 0.0 | +2.0, –3.0 | +5.0, –∞ |
| 12,500 | –4.3 | –6.2 | 0.0 | +2.0, –5.0 | +5.0, –∞ |
| 16,000 | –6.6 | –8.5 | 0.0 | +2.5, –16.0 | +5.0, –∞ |
| 20,000 | –9.3 | –11.2 | 0.0 | +3.0, –∞ | +5.0, –∞ |

* Frequency weightings are calculated using the frequency $f$ calculated from $f = f_{\mathrm{r}}[10^{0.1(n-30)}]$, where $f_{\mathrm{r}}$ is 1,000 Hz and n is an integer in the range from 10 to 43. Frequency weightings are rounded to one tenth of a decibel.

### 1.2 Noise Measurement

A-weighted sound pressure levels are typically measured using the methods provided in JIS Z 8731 (Environmental noise measurements).

- Noise shall be measured using sound level meters complying with JIS C 1509-1. A windscreen must always be attached to the microphone of the sound level meter. It minimizes the effects of wind noise occurring if the microphone is exposed to wind.
- Use a Class 1 or Class LS acoustic calibrator complying with JIS C 1515 and of a type indicated in the operating manual of the sound level meter to confirm that both the sound level meter and the integrated microphone function properly.
- Use a level recorder that meets JIS C 1512 requirements.
- When analyzing a sound pressure signal first recorded at the measuring site, the recording device must have the frequency range and dynamic range performance stipulated in JIS C 1509-1. Do not use devices incorporating signal compression.
- When measuring outdoors, noise must be measured at a position at least 3.5 m away from any reflective objects other than the ground. Noise must be measured at a point between 1.2 m and 1.5 m above the ground.
- When measuring around buildings, noise must be measured at a position 1 m to 2 m away from the external walls of the building subject to noise effects. Noise must be measured at a point between 1.2 m and 1.5 m above the building floor level.
- General environmental monitoring measurement shall typically not be conducted indoors.
- Steady noise shall be measured using the time-weighted S weighting reading on the sound level meter. If the reading fluctuates a certain amount, the integral average function of the sound level meter should be used to calculate the equivalent continuous A-weighted sound pressure level for a fixed time.
- For measuring the sound level of a specific steady noise, if the difference in readings is less than 10 dB with and without the noise present, the effects of background noise must be taken into consideration. In such cases, we can estimate the sound level of solely the target noise by adjusting the reading when the target noise is present using the following table. Note that this requires a relatively constant background noise level. (If the difference in readings is 10 dB or greater, the effects of background noise may be disregarded. If the difference is 3 dB or less, the error is likely to be larger.)

Correcting sound level meter reading for the effects of background noise (JIS Z 8731: 2019)

| Difference between readings with/without target noise (dB) | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|
| Correction value (dB) | －2 | | | －1 | | |

- Discrete noise, such as impact noise and intermittent noise, shall be measured by sampling the sound level at intervals not exceeding 100 ms with the sound level meter set to F or S time weighting to calculate maximum values. The type of time weighting must be indicated in the measurement results.

## 2. Noise Frequency Analysis

### 2.1 Frequency Analyzers

Frequency analyzers used to analyze noise and vibration are broadly classified as 1/N octave-band analyzers and FFT (Fast Fourier Transform) analyzers, based on the application. “N” here is a positive integer. The performance of octave-band and 1/3 octave-band analyzers is stipulated in JIS C 1513. These analyzers are widely used for general noise measurements due to the ease of sound frequency analysis and the ease of analyzing corresponding sound level. The filter bandwidth for these analyzers is constant for the 1/N octave ratio. For acoustic measurements, it is recommended to use an octave ratio of $10^{3/10}$ instead of 2.

FFT analyzers analyze frequency through calculations. They include functions to facilitate various calculations and to display the results. The filter bandwidth stays constant over the target frequency range. This type of analyzer is ideal for equipment noise and vibration reduction measures due to the ease in obtaining the data which links noise and vibration to machine operation.

The relationship between the central frequency $f_m$ (Hz), lower cutoff frequency $f_1$ (Hz), and upper cutoff frequency $f_2$ (Hz) for a 1/N octave-band pass filter is as follows:

$$f_m = \sqrt{f_1 \cdot f_2}$$

$$f_1 = f_m \,/\, \sqrt[2n]{10^{3/10}}$$ (Note that $n$ is the N in 1/N.)

$$f_2 = f_m \cdot \sqrt[2n]{10^{3/10}}$$

For octave-band pass filter

$$f_2 = 1.99526 f_1$$

$$f_1 = 0.70795 f_m$$

$$f_2 = 1.41254 f_m$$

For 1/3 octave-band pass filter

$$f_2 = 1.25893 f_1$$

$$f_1 = 0.89125 f_m$$

$$f_2 = 1.12202 f_m$$

Octave-band pass filter passband (lower and upper cutoff frequencies)

| Central frequency (Hz) | Passband (Hz) | | |
|---:|---:|:---:|---:|
| 31.5 | 22.4 | to | 45 |
| 63 | 45 | to | 90 |
| 125 | 90 | to | 180 |
| 250 | 180 | to | 355 |
| 500 | 355 | to | 710 |
| 1,000 | 710 | to | 1,400 |
| 2,000 | 1,400 | to | 2,800 |
| 4,000 | 2,800 | to | 5,600 |
| 8,000 | 5,600 | to | 11,200 |
| 16,000 | 11,200 | to | 22,400 |

1/3 octave-band pass filter passband (lower and upper cutoff frequencies)

| Central frequency (Hz) | Passband (Hz) | | |
|---|---|---|---|
| 20 | 18 | to | 22.4 |
| 25 | 22.4 | to | 28 |
| 31.5 | 28 | to | 35.5 |
| 40 | 35.5 | to | 45 |
| 50 | 45 | to | 56 |
| 63 | 56 | to | 71 |
| 80 | 71 | to | 90 |
| 100 | 90 | to | 112 |
| 125 | 112 | to | 140 |
| 160 | 140 | to | 180 |
| 200 | 180 | to | 224 |
| 250 | 224 | to | 280 |
| 315 | 280 | to | 355 |
| 400 | 355 | to | 450 |
| 500 | 450 | to | 560 |
| 630 | 560 | to | 710 |
| 800 | 710 | to | 900 |
| 1,000 | 900 | to | 1,120 |
| 1,250 | 1,120 | to | 1,400 |
| 1,600 | 1,400 | to | 1,800 |
| 2,000 | 1,800 | to | 2,240 |
| 2,500 | 2,240 | to | 2,800 |
| 3,150 | 2,800 | to | 3,550 |
| 4,000 | 3,550 | to | 4,500 |
| 5,000 | 4,500 | to | 5,600 |
| 6,300 | 5,600 | to | 7,100 |
| 8,000 | 7,100 | to | 9,000 |
| 10,000 | 9,000 | to | 11,200 |
| 12,500 | 11,200 | to | 14,000 |
| 16,000 | 14,000 | to | 18,000 |
| 20,000 | 18,000 | to | 22,400 |

## 2.2 Noise Frequency Analysis

Noise frequency analysis typically involves measuring sound pressure level for a band using Z (or FLAT) or C weighting, then calculating the A-weighted sound pressure level by adding the value of frequency-weighted characteristics A.

In cases in which the emphasis is on reducing A-weighted sound pressure levels—for example when implementing noise reduction measures—A-weighting can be used to directly measure the A-weighted sound pressure level.

Values of frequency-weighted characteristics A (octave band) (JIS C 1509-1:2017)

| Central frequency (Hz) | Weighting value (dB) |
|---|---|
| 16 | –56.7 |
| 31.5 | −39.4 |
| 63 | −26.2 |
| 125 | −16.1 |
| 250 | −8.6 |
| 500 | −3.2 |
| 1,000 | 0 |
| 2,000 | 1.2 |
| 4,000 | 1.0 |
| 8,000 | −1.1 |
| 16,000 | −6.6 |

Values of frequency-weighted characteristics A (1/3 octave band) (JIS C 1509-1:2017)

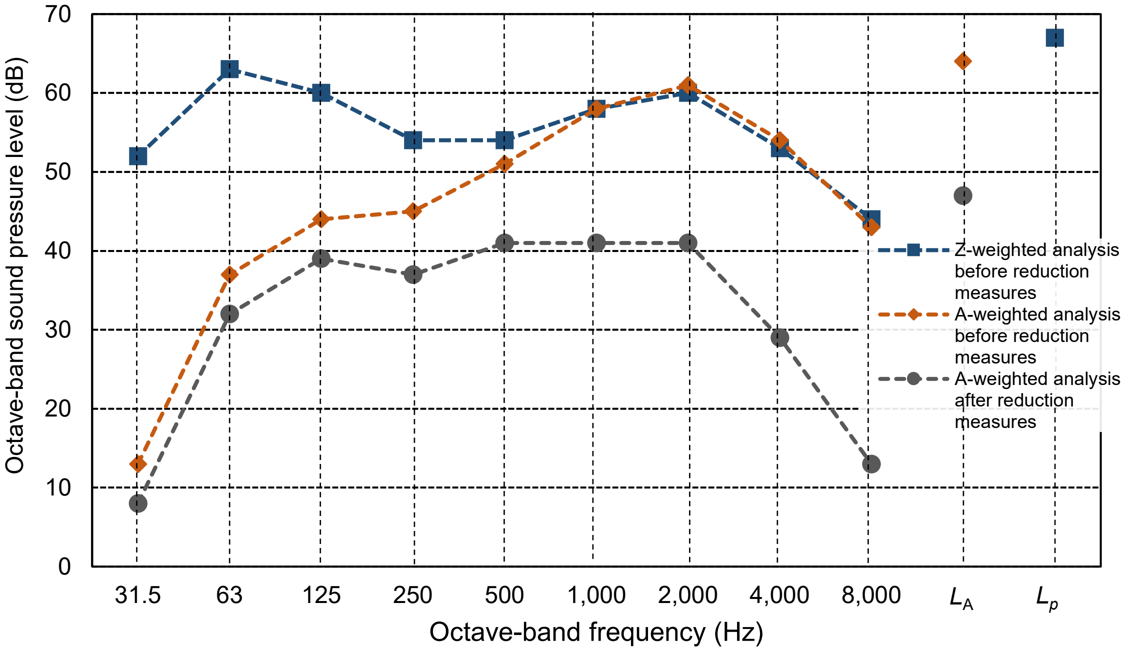
| Central frequency (Hz) | Weighting value (dB) |
|---|---|
| 10 | −70.4 |
| 12 | −63.4 |
| 16 | −56.7 |
| 20 | −50.5 |
| 25 | −44.7 |
| 31.5 | −39.4 |
| 40 | −34.6 |
| 50 | −30.2 |
| 63 | −26.2 |
| 80 | −22.5 |
| 100 | −19.1 |
| 125 | −16.1 |
| 160 | −13.4 |
| 200 | −10.9 |
| 250 | −8.6 |
| 315 | −6.6 |
| 400 | −4.8 |
| 500 | −3.2 |
| 630 | −1.9 |
| 800 | −0.8 |
| 1,000 | 0 |
| 1,250 | 0.6 |
| 1,600 | 1.0 |
| 2,000 | 1.2 |
| 2,500 | 1.3 |
| 3,150 | 1.2 |
| 4,000 | 1.0 |
| 5,000 | 0.5 |
| 6,300 | −0.1 |
| 8,000 | −1.1 |
| 10,000 | −2.5 |
| 12,500 | −4.3 |
| 16,000 | −6.6 |
| 20,000 | −9.3 |

Shown below is an example of octave-band frequency analysis used in noise reduction. This shows the octave-band A-weighted sound pressure level calculated by subtracting the A weighting value from the measured octave-band sound pressure level, as well as the octave-band A-weighted sound pressure level calculated by further accounting for the designed noise insulation level.

Example of octave-band frequency analysis for noise reduction

| Octave-band central frequency (Hz) | Octave-band sound pressure level (dB) | Weighting value (dB) | Octave-band A-weighted sound pressure level (dB) | Designed noise insulation level (dB) | Octave-band A-weighted sound pressure level (dB) |
|---|---|---|---|---|---|
| 31.5 | 52 | −39 | 13 | 5 | 8 |
| 63 | 63 | −26 | 37 | 5 | 32 |
| 125 | 60 | −16 | 44 | 5 | 39 |
| 250 | 54 | −9 | 45 | 8 | 37 |
| 500 | 54 | −3 | 51 | 10 | 41 |
| 1,000 | 58 | 0 | 58 | 17 | 41 |
| 2,000 | 60 | 1 | 61 | 20 | 41 |
| 4,000 | 53 | 1 | 54 | 25 | 29 |
| 8,000 | 44 | −1 | 43 | 30 | 13 |
| A-weighted sound pressure level $L_A$ (dB) | — | — | 64 | — | 47 |
| Sound pressure level $L_p$ (dB) | 67 | — | — | — | — |
| Notes | Z-weighted analysis before reduction measures* | Approximate value | A-weighted analysis before reduction measures | | A-weighted analysis after reduction measures |

Note: *C-weighted analysis may also be applied



Example of octave-band frequency analysis for noise reduction

## 3. Acoustic Intensity Measurements

We can measure acoustic intensity by measuring the intensity of the sound while accounting for sound radiation direction information (see I. 8. Sound Intensity Levels). Acoustic intensity is generally measured using a measuring device that calculates sound pressure and sound particle velocity based on sound pressure measurements between two adjacent points and uses this information to calculate sound intensity.

Known as the two-microphone method, acoustic intensity measurements with two microphones positioned next to each other or a single unit containing two microphones rely on the following principle:

The following equation gives the instantaneous intensity $I_{\text{inst}}$ in the direction of sound wave particle velocity:

$$I_{\text{inst}} = p(t)u(t)$$

where $p(t)$ is sound pressure at time $t$ and $u(t)$ sound particle velocity at time $t$. This time average corresponds to the sound energy passing through a unit area per unit time. This is the acoustic intensity (sound intensity) $I$.

$$I = \frac{1}{T}\int_{t_1}^{t_2} p(t)u(t)\ \mathrm{dt}$$

where $T = (t_2 - t_1)$ is a sufficiently long average time.

To calculate acoustic intensity from the above equation, we must measure $p(t)$ and $u(t)$. When using the two-microphone method, we can calculate particle velocity from the output of the two microphones. Note that in special cases such as for plane waves, the correlation between the particle velocity $u$ and sound pressure $p$ is determined by the specific acoustic resistance $\rho c$ of the medium (where $\rho$ is the density of air and $\mathrm{c}$ is the speed of sound, $p = \rho c u$), thus we can calculate particle velocity directly, by measuring the sound pressure.

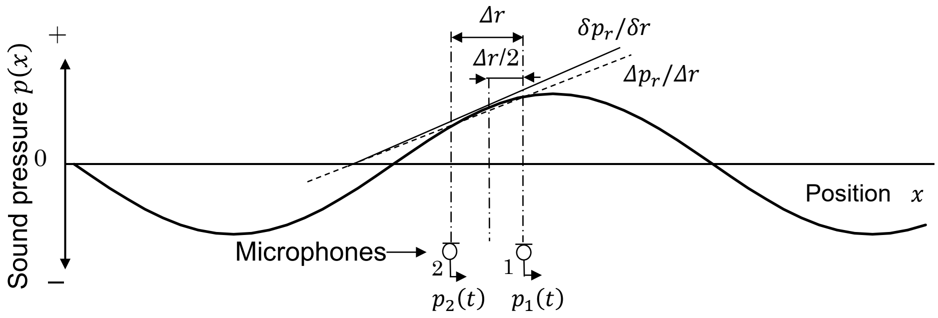
The basic idea of the two-microphone method is to measure sound pressure gradient components using finite difference approximation. We can derive the equation for the relationship between sound pressure gradient (sound pressure spatial differential) and particle velocity time differential from the equation of motion for the fluid medium through which the sound wave propagates. This relationship can then be applied to calculate the particle velocity from the sound pressure gradient.

The sound pressure difference $(p_2 - p_1)$ between microphone 2 and microphone 1 divided by distance $\Delta r$ between the two points is an approximation of the sound pressure gradient component $\Delta p_r$ at the acoustic center between the two microphones in the microphone array direction ($r$ direction). We calculate acoustic intensity by obtaining the particle velocity from this component. There are two ways to do so;

The direct method uses a digital filter to directly integrate the equation described above, replacing $u(t)$ with an equation using $p(t)$. This gives frequency analysis results using 1/3 octave-band or octave-band filters and lets us calculate acoustic intensity with high time resolution using exponential averaging.

The other method, the cross-spectral method, uses the cross spectrum for two points in the r direction using FFT. Using an FFT analyzer achieves high frequency resolution, but entails a trade-off with time resolution. The separation between the microphones in the two-microphone method must be determined carefully; due to finite difference approximation, the upper measurement frequency limit is determined by the microphone separation.

The acoustic intensity measurement devices used with the two-microphone method are stipulated in JIS C 1507. Other standards address sound power levels and sound transmission losses due to acoustic intensity.



Sound pressure gradient from finite difference approximation used in acoustic intensity measurement

## 4. Sound Power Level and Sound Energy Level Measurement

JIS and ISO standards specify the basic methods used to measure sound power level and sound energy level. Numerous other standards address individual devices. All these standards specify numerous stipulations; the reader should refer to the relevant standards as necessary.

### 4.1 Methods for Measuring Sound Power Level and Sound Energy Level in Anechoic and Hemi-Anechoic Rooms (JIS Z 8732)

### 4.1.1 Scope

This standard specifies methods for measuring sound pressure on the measuring plane enclosing a noise source in an anechoic or hemi-anechoic room to calculate sound power level and sound energy level generated by the noise source, as well as methods for obtaining results with Grade 1 accuracy, by determining surface sound pressure level to calculate the sound power level and sound energy level. It also specifies requirements for the test environment and measuring equipment.

### 4.1.2 Calculating Sound Power Level and Sound Energy Level (in Anechoic Room)

The following equation gives the sound power level $L_W$ (dB) and sound energy level $L_J$ (dB) for a sound source in an anechoic room:

$$L_W = L_{p\mathrm{f}} + 10\log\frac{S_1}{S_0} + C$$

$$L_J = L_{pE\mathrm{f}} + 10\log\frac{S_1}{S_0} + C$$

where $L_{p\mathrm{f}}$ is the surface sound pressure level (dB) on the test sphere, $L_{pE\mathrm{f}}$ is the mean surface single sound pressure level (dB) on the measuring sphere, $S_1$ is the area ($4\pi r^2$ if the radius is $r$) (m$^2$) of the test sphere, $S_0$ = 1 (m$^2$), and $C$ is a correction factor for air temperature and atmospheric pressure fluctuations given by the following equation:

$$C = -25\log\left[\left(\frac{427}{400}\sqrt{\frac{273}{273+\theta}}\right)\left(\frac{B}{B_0}\right)\right]$$

where $\theta$ is the air temperature (°C), $B$ is the atmospheric pressure (Pa), and $B_0$ is the standard atmospheric pressure $1.013 \times 10^5$ (Pa).

### 4.1.3 Calculating Sound Power Level and Sound Energy Level (in Hemi-Anechoic Room)

The following equation gives the sound power level $L_W$ (dB) and sound energy level $L_J$ (dB) for a sound source in a hemi-anechoic room:

$$L_W = L_{p\mathrm{f}} + 10\log\frac{S_2}{S_0} + C$$

$$L_J = L_{pE\mathrm{f}} + 10\log\frac{S_2}{S_0} + C$$

where $L_{p\mathrm{f}}$ is the surface sound pressure level (dB) on the test sphere, $L_{pE\mathrm{f}}$ is the mean surface single sound pressure level (dB) on the measuring sphere, $S_2$ is the area ($2\pi r^2$ if the radius is $r$) ($\mathrm{m}^2$) of the test hemisphere, and the other variables are the same as for an anechoic room.

### 4.2 Methods for Measuring Sound Power Level in General Sound Fields (JIS Z 8733)

### 4.2.1 Scope

This standard specifies methods for measuring sound pressure level on a measurement surface surrounding a sound source in hemi-free sound field conditions close to one or multiple reflecting surfaces for calculating the sound power level generated by a single noise source. It also specifies requirements for the test environment and measuring equipment in addition to methods for calculating the surface sound pressure level forming the datum for calculating the sound power level of the sound source.

### 4.2.2 Calculating Sound Power Level (Practical Hemi-Free Sound Field)

The following equation gives the sound power level $L_W$ (dB) of a sound source in a practical hemi-free sound field:

$$L_W = \overline{L_{p\mathrm{f}}} + 10\log\frac{S}{S_0}$$

where $\overline{L_{p\mathrm{f}}}$ is the mean surface sound pressure level (dB) on the measuring hemisphere, $S$ is the area of the measuring surface ($\mathrm{m}^2$), and $S_0$ = 1 ($\mathrm{m}^2$). The following equation gives $\overline{L_{p\mathrm{f}}}$:

$$\overline{L_{p\mathrm{f}}} = \overline{L'_p} - K_1 - K_2$$

where $\overline{L'_p}$ is the mean sound pressure level (dB) on the measuring surface, $K_1$ is the background noise correction factor, and $K_2$ is the environmental correction factor given by the following equation or calculated using the reference sound source:

$$K_2 = 10\log\left(1 + \frac{4S}{A}\right)$$

where $S$ is the area of the measuring surface ($\mathrm{m}^2$) and $A$ is the interior equivalent sound absorption area ($\mathrm{m}^2$). $A$ can be calculated using the following equation:

$$A = \frac{55.3}{c}\cdot\frac{V}{T}$$

where $c$ is the speed of sound in air (m/s), $V$ is the volume of the measuring room ($\mathrm{m}^3$), and $T$ is the reverberation time within the measuring room (s).

If a reference sound source is used, $K_2$ can be calculated using the following equation:

$$K_2 = L_W^{*} - L_{W\mathrm{r}}$$

where $L_W^{*}$ is the sound power level (dB) of the reference sound source in the test sound field, and $L_{W\mathrm{r}}$ is the calibrated sound power level (dB) of the reference sound source.

Note that the reference sound source is defined as "a compact broadband noise source for which the sound power level has been calibrated in accordance with ISO 6926 (JIS Z 8739) and which has sufficient and stable output, flat frequency characteristics, and good omnidirectionality within the frequency measurement range." The sound power level of this sound source is called the reference sound source calibrated sound power level. For more details on reference sound source performance, refer to JIS Z 8739 (Acoustics - Requirements for the performance and calibration of reference sound sources used for the determination of sound power levels).

## 4.3 Methods for Measuring Sound Power Level in Reverberation Rooms (JIS Z 8734)

### 4.3.1 Scope

This standard specifies the direct and comparison methods for calculating the sound power level radiated by a sound source in standard environmental conditions giving a characteristic impedance (specific acoustic resistance) of 400 Ns/m$^3$, requirements for reverberation rooms, general stipulations for sound source position and operating conditions, and measuring equipment and methods for estimating the mean square sound pressure level used in calculating the 1/3 octave-band sound power level of the sound source to Grade 1 accuracy.

### 4.3.2 Calculating Sound Power Level (Reverberation Time)

The following equation gives the sound power level $L_W$ (dB) of a sound source in a reverberation room:

$$L_W = \overline{L_p} + 10\log\left(\frac{A}{A_0}\right) + 4.34\frac{A}{S} + 10\log\left[1 + \frac{S\cdot c}{8\cdot V\cdot f}\right] - 25\log\left[\frac{427}{400}\sqrt{\frac{273}{273+\theta}}\cdot\frac{B}{B_0}\right] - 6$$

where $\overline{L_p}$ is the mean interior sound pressure level (dB), $A$ is the equivalent sound absorption area of the reverberation room (m$^2$), $A_0 = 1$ (m$^2$) , $S$ is the total surface area of the reverberation room (m$^2$), $c$ is the speed of sound (m/s), $V$ is the volume of the reverberation room (m$^3$), $f$ is the central frequency of the measured frequency band (Hz), $\theta$ is the air temperature (°C), $B$ is the air pressure (hPa), and $B_0 = 1.013 \times 10^3$ (hPa) Note that $\mathrm{c} = 20.05\sqrt{273+\theta}$ (m/s).

We obtain equivalent sound absorption area $A$ of the reverberation room as follows for each frequency band:

$$A = \frac{55.26}{c}\left(\frac{V}{T_{\mathrm{rev}}}\right)$$

where $T_{\mathrm{rev}}$ is the reverberation time (s) for each frequency band.

### 4.3.3 Calculating Sound Power Level (Reference Sound Source)

The reference sound source is defined as "a stable and constant noise source that radiates broadband noise with flat frequency characteristics and sufficient sound power level and is operated and calibrated in accordance with ISO 6926 (JIS Z 8739)." We use the following equation to calculate the sound power level $L_W$ (dB) of a test sound source by comparison against the sound power level of a reference sound source:

$$L_W = L_{W\mathrm{r}} + \left(\overline{L_p} - \overline{L_{p\mathrm{r}}}\right)$$

where $L_{W\mathrm{r}}$ is the sound power level of the reference sound source (dB), $\overline{L_p}$ is the interior mean 1/3 octave-band sound pressure level (dB) attributable to the test sound source, and $\overline{L_{p\mathrm{r}}}$ is the interior mean 1/3 octave-band sound pressure level (dB) attributable to the reference sound source.

Note that the calibration value used to calculate the sound power level adjusted to the standard environmental conditions by the comparison method corresponds to the environmental conditions for which the characteristic impedance $\rho c$ = 400 (N·s/m$^3$).

## Methods for Measuring Sound Power Levels of Machines

| Type | Sound pressure methods | | | | | | | Acoustic intensity methods | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Reverberation room methods | | | Anechoic room methods | | | In situ methods | | | |
| | Precision method | Practical comparison method | Practical method | Precision method | Practical method | Simple method | Practical comparison method | As required | Practical/ simple method | Precision method |
| International standard (ISO) | 3741 | 3743-1 | 3743-2 | 3745 | 3744 | 3746 | 3747 | 9614-1 | 9614-2 | 9614-3 |
| Corresponding JIS standard | Z 8734 | — | — | Z 8732 | Z 8733 | — | — | Z 8736-1 | Z 8736-2 | Z 8736-3 |
| Grade | 1 | 2 | | 1 | 2 | 3 | 2, 3 | 1, 2, 3 | 2, 3 | 1 |
| Test environment | Reverberation room | Hard-walled room | Special reverberation room | Anechoic room<br>Hemi-anechoic room | Hemi-free sound field on reflective surface | Outside or indoors | Reverberation room on site | As required | | |
| Test environment suitability standards<br>Room volume $V$ (m$^3$)<br>Total surface area $S$ (m$^2$)<br>Sound absorption coefficient $\alpha$<br>Environmental correction $K_2$ (dB) | $V < 300$<br>$T_{\mathrm{rev}} > V/S$<br>$f_{\min}$ (Hz) / $V_{\min}$ (m$^3$)<br>100 / 200<br>125 / 150<br>160 / 100<br>≥200 / 70<br>$f \geq 3$ (kHz): $V < 200$ | $V \geq 40$<br>$\alpha \leq 0.20$ | $70 \leq V \leq 300$<br>$0.5 \leq T_{\mathrm{nom}} \leq 1$ (s) | $K_2 \leq 0.5$ | $K_2 \leq 2$ | $K_2 \leq 7$ | $K_2 \leq 7$ | Requirements:<br>• External intensity<br>• Wind, air flow, vibration, temperature, air pressure<br>• Surrounding conditions<br>• Sound field index | | |
| Volume of sound source $V_S$ (%) | $V_S \leq 2$ | $V_S \leq 2.5$ | $V_S \leq 1$ | $V_S \leq 0.5$ | — | — | — | — | | |
| Noise type | Constant, broadband, narrowband, discrete frequency sound | As required (except for separate impact sound) | | As required (except for separate impact sound) | | | | Constant over time | | |
| Difference from ambient noise $\Delta L$ (dB)<br>Ambient noise correction factor $K_1$ (dB) | $\Delta L \geq 10$<br>$K_1 \leq 0.4$ | $\Delta L \geq 6$<br>$K_1 \leq 1.3$ | $\Delta L \geq 4$<br>$K_1 \leq 2.2$ | $\Delta L \geq 10$<br>$K_1 \leq 0.4$ | $\Delta L \geq 6$<br>$K_1 \leq 1.3$ | $\Delta L \geq 3$<br>$K_1 \leq 3$ | $\Delta L \geq 6$<br>$K_1 \leq 1.3$ | Determined by sound field index | | |
| Measuring device class<br>Sound level meter<br>Filter<br>Acoustic calibrator<br>Intensity measurement device | Class 1<br>Class 1<br>Class 1<br>— | | | | | Class 2<br>—<br>Class 1<br>— | Class 1<br>Class 1<br>Class 1<br>— | —<br>—<br>0,1,1L<br>1 | —<br>—<br>0,1,0L,1L<br>1, 2 | —<br>—<br>LS,1,LS/C,1/C<br>1 |
| $L_W$ obtained | $L_{WA}, L_{W,\mathrm{oct}}, L_{W,1/3\mathrm{oct}}$ | $L_{WA}, L_{W,\mathrm{oct}}$ | | $L_{WA}, L_{W,\mathrm{oct}}, L_{W,1/3\mathrm{oct}}$ | | $L_{WA}$ | $L_{WA}, L_{W,\mathrm{oct}}$ | $L_{WA}, L_{W,\mathrm{oct}}, L_{W,1/3\mathrm{oct}}$<br>band limits (50 Hz to 6.3 kHz) | | |

## 5. Reverberation Rooms and Anechoic Rooms

### 5.1 Reverberation Rooms

Reverberation rooms are rooms with long reverberation times, constructed to closely approximate diffuse sound field conditions by enclosure in materials with high reflectivity for incident sound from all directions. A diffuse sound field is a sound field with uniform sound energy density in which the flow of sound energy is equally probable in all directions.

In a reverberation room with a sound source placed at one point, the sound pressure level will be more or less constant at any point. Reverberation rooms are used to measure parameters such as the sound absorption coefficient of sound-absorbing materials and the sound reduction index of sound insulation materials. Since the sound field characteristics can be clearly defined, they are also used for sound power level measurements.

Air sound insulation performance test room (JIS A 1416:2000)

| | Type I test room (reverberation room) | Type II test room |
|---|---|---|
| Room volume $V$ | 100 m$^3$ or greater<br>(ideally, 150 m$^3$ or greater) | 50 m$^3$ or greater<br>(The difference between volume of sound source room and the sound receiving room should be at least 10 %.) |
| Reverberation time $T$ | Reverberation time adequate to achieve diffuse sound field conditions | Adjust interior equivalent sound absorption area to ensure<br>$1 \leq T \leq 2\ (V/50)^{2/3}$<br>in low frequency band. |
| Opening | Approx. 10 m$^2$ (ideally, rectangular with short side dimension not less than 2.3 m)<br>10 m$^2$ to 20 m$^2$ for floor construction | |

Reverberation room for reverberation room method sound absorption coefficient measurements (JIS A 1409:1998, ISO 354:2003)

| | | |
|---|---|---|
| Room volume $V$ | 150 m$^3$ or greater<br>Approximately 200 m$^3$ for new construction | |
| Room shape | $l_{\max} < 1.9V^{1/3}$<br>$l_{\max}$: length of longest straight-line interpolating room boundary | |
| Room equivalent sound absorption area $A_1$ | 125 Hz | 6.5 m$^2$ |
| | 250 Hz | 6.5 m$^2$ |
| | 500 Hz | 6.5 m$^2$ |
| | 1,000 Hz | 7.0 m$^2$ |
| | 2,000 Hz | 9.5 m$^2$ |
| | 4,000 Hz | 13.0 m$^2$ |

Reverberation room for sound power level measurements (JIS Z 8734:2000, ISO 3741:2010)

<table>
<tr><td>Room volume</td><td>$V < 300$ m$^3$ ($V_S < 0.001\,V$ for small sound source)
<table>
<tr><th>Minimum 1/3 octave-band central frequency (Hz)</th><th>Minimum reverberation room volume (m$^3$)</th></tr>
<tr><td>100</td><td>200</td></tr>
<tr><td>125</td><td>150</td></tr>
<tr><td>160</td><td>100</td></tr>
<tr><td>200 or greater</td><td>70</td></tr>
</table>
</td></tr>
<tr><td>Reverberation time</td><td>$T > V/S$<br>$S$: Total room surface area</td></tr>
<tr><td>Room interior surface</td><td>Mean sound absorption coefficient not exceeding 0.16 for entire surface<br>However, not exceeding 0.06 for frequencies of $2000/V^{1/3}$ or greater</td></tr>
<tr><td>Allowable standard deviation for mean sound pressure level for each sound source position</td><td>
<table>
<tr><th colspan="2">Central frequency (Hz)</th><th rowspan="2">Maximum allowable standard deviation (m$^3$)</th></tr>
<tr><th>Octave band</th><th>1/3 octave band.</th></tr>
<tr><td>125</td><td>100 to 160</td><td>1.5</td></tr>
<tr><td>250</td><td>200 to 315</td><td>1.0</td></tr>
<tr><td>500</td><td>400 to 630</td><td>1.0</td></tr>
<tr><td>1,000</td><td>800 to 1,250</td><td>0.5</td></tr>
<tr><td>2,000</td><td>1,600 to 2,500</td><td>0.5</td></tr>
<tr><td>4,000</td><td>3,150 to 5,000</td><td>1.0</td></tr>
<tr><td>8,000</td><td>6,300 to 10,000</td><td>1.0</td></tr>
</table>
</td></tr>
</table>

### 5.2 Anechoic Rooms and Hemi-Anechoic Rooms

Anechoic rooms are rooms constructed to satisfy free sound field conditions by enclosure in materials of high sound absorption coefficient for incident sound from all directions. A free sound field is a sound field in which we can disregard the effects of boundaries within an isotropic and homogeneous medium.

Anechoic rooms are rooms designed with sound-absorbing walls, floor, and ceiling (typically using sound absorption wedges) to eliminate sound echoing within the room. Hemi-anechoic rooms are anechoic rooms with a reflective floor surface (typically, concrete floor). The degree of the free sound field is confirmed by sound inverse square law measurement (sound attenuates by 6 dB for every doubling of distance from the sound source).

Anechoic rooms and hemi-anechoic rooms for sound power level measurements
(JIS Z 8732:2000, ISO 3745:2012/Amd 1:2017)

<table>
<tr><th></th><th>Anechoic room</th><th>Hemi-anechoic room</th></tr>
<tr><td>Maximum allowable deviation from inverse square law</td><td>
<table>
<tr><th>1/3 octave-band central frequency (Hz)</th><th>Allowable deviation (dB)</th></tr>
<tr><td>≤630</td><td>±1.5</td></tr>
<tr><td>800 to 5,000</td><td>±1.0</td></tr>
<tr><td>≥6,300</td><td>±1.5</td></tr>
</table>
</td><td>
<table>
<tr><th>1/3 octave-band central frequency (Hz)</th><th>Allowable deviation (dB)</th></tr>
<tr><td>≤630</td><td>±2.5</td></tr>
<tr><td>800 to 5,000</td><td>±2.0</td></tr>
<tr><td>≥6,300</td><td>±3.0</td></tr>
</table>
</td></tr>
<tr><td>Reflective surface dimensions</td><td>—</td><td>Not less than the half-wavelength of the minimum frequency in the target frequency range outside the projection of the reflective surface</td></tr>
<tr><td>Reflective surface sound absorption coefficient</td><td>—</td><td>Not exceeding 0.06 within target frequency range</td></tr>
</table>

# V. Vibration

## 1. Sinusoidal Vibration and Vibration Quantities

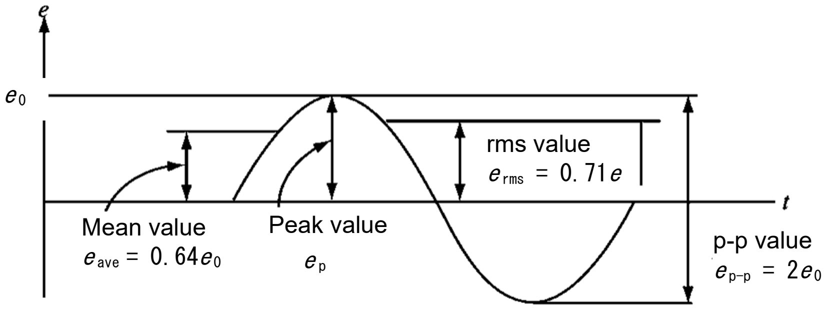
For sinusoidal vibration with maximum amplitude $D$ and initial phase $\phi_0$ for which the instantaneous amplitude is $x(t)$ at time $t$, the following equations describe the relationship between instantaneous amplitude velocity and acceleration values $v(t)$ and $a(t)$ and maximum amplitude velocity and acceleration values $V$ and $A$:

Vibration quantities and unit symbols

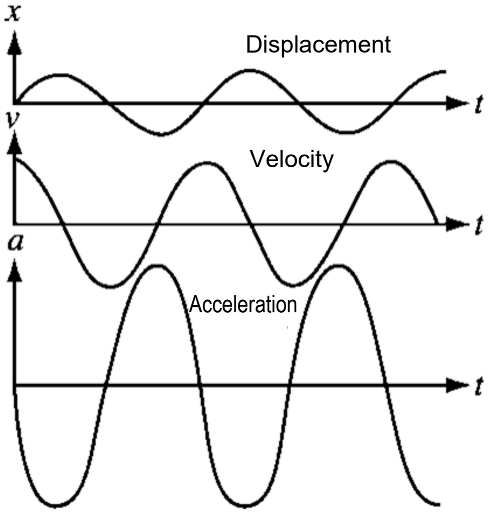
| Vibration quantity | Units | Supplementary units (practical units) | For sinusoidal vibration | |
|---|---|---|---|---|
| | | | Instantaneous value | Maximum value |
| Displacement | m | cm<br>(1 cm = $10^{-2}$ m)<br>mm<br>(1 mm = $10^{-3}$ m)<br>µm<br>(1 µm = $10^{-3}$ mm = $10^{-6}$ m) | $x(t) = D\sin(\omega t + \phi_0)$ | $D$ |
| Velocity | m/s | cm/s<br>(1 cm/s = $10^{-2}$ m/s)<br>mm/s<br>(1 mm/s = $10^{-3}$ m/s) | $v(t) = \frac{dx}{dt}$<br>$= D\omega\cos(\omega t + \phi_0)$ | $V = \omega D$ |
| Acceleration | m/s$^2$ | cm/s$^2$<br>(1 cm/s$^2$ = $10^{-2}$ m/s$^2$)<br>Gal<br>(1 gal = 1 cm/s$^2$) | $a(t) = \frac{d^2x}{dt^2}$<br>$= -D\omega^2\sin(\omega t + \phi_0)$ | $A = \omega^2 D$ |

Reference: Okuma Tsunenobu, "Conversion Chart of Sinusoidal Vibration," Noise Control, Vol. 3 No. 5, pp. 47-48, 1979

### ●Vibration readings



●Vibration displacement, velocity, and acceleration phase



## 2. Whole Body Vibration

### 2.1 Vibration Level

Typically, for nuisance vibrations originating from the vibration of the ground or interior floors of a building, it is impractical to determine a single quantity corresponding to intensity or sound pressure at a specific point. This is because even in the case of ground surface vibration, vertical waves, horizontal waves, and plane waves propagate separately at different velocities, making the phenomenon more complex than with airborne sound waves alone. However, when considering nuisance vibrations, we can consider the entire passing ground surface vibration acceleration without examining the exact wave type.

The vibration acceleration $L_a$ (dB) is expressed as follows using the rms vibration acceleration $a$ (m/s$^2$) and datum value $a_0 = 10^{-5}$ (m/s$^2$):

$$L_a = 10\ log\frac{a_2}{a_{02}}$$

Vibration levels are defined for vibration in the same way as for sound levels. Vibration level $L_\mathrm{v}$ corresponds to vibration acceleration level corrected for vertical or horizontal vibration sensitivity characteristics.

### 2.2 Vibration Level Meter

The measuring devices used to measure vibration levels are defined in JIS C 1510 (Vibration level meters). They have the following characteristics:

(1) The target frequency measuring range is 1 Hz to 80 Hz.

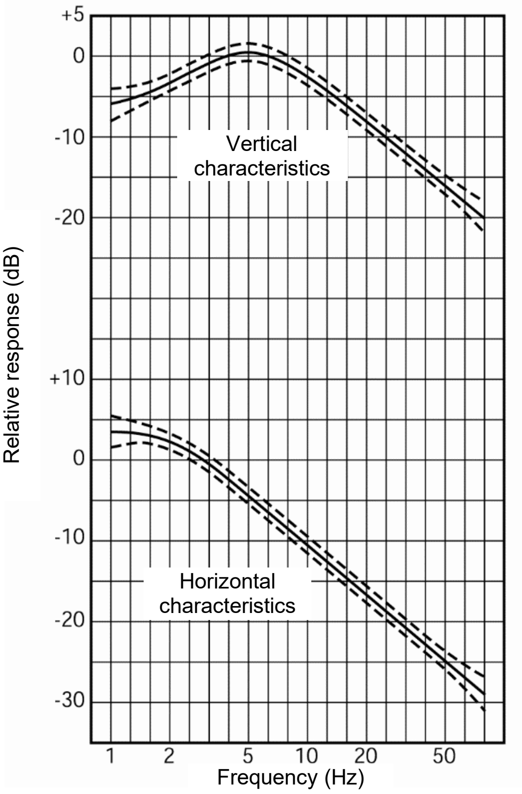
(2) The standard vibration quantity measured is acceleration, indicated in decibels.

(3) The quantity measured is vibration level with vibration sensation frequency corrected.

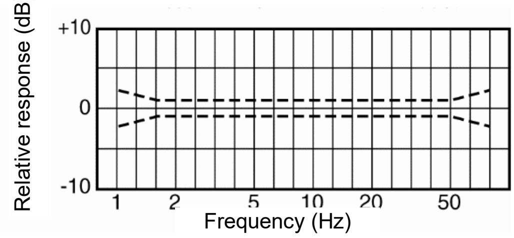
(4) The meter dynamic characteristics are determined to suit the sensation test.

Vibration level meter frequency characteristics (JIS C 1510:1995)

| Frequency (Hz) | Reference response (dB) | | | Tolerance (dB) |
|---|---|---|---|---|
| | Vertical characteristics | Horizontal characteristics | Flatness characteristics | |
| 1 | −5.9 | +3.3 | 0 | ±2.0 |
| 1.25 | −5.2 | +3.2 | 0 | ±1.5 |
| 1.6 | −4.3 | +2.9 | 0 | ±1 |
| 2 | −3.2 | +2.1 | 0 | ±1 |
| 2.5 | −2.0 | +0.9 | 0 | ±1 |
| 3.15 | −0.8 | −0.8 | 0 | ±1 |
| 4 | +0.1 | −2.8 | 0 | ±1 |
| 5 | +0.5 | −4.8 | 0 | ±1 |
| 6.3 | +0.2 | −6.8 | 0 | ±1 |
| 8 | −0.9 | −8.9 | 0 | ±1 |
| 10 | −2.4 | −10.9 | 0 | ±1 |
| 12.5 | −4.2 | −13.0 | 0 | ±1 |
| 16 | −6.1 | −15.0 | 0 | ±1 |
| 20 | −8.0 | −17.0 | 0 | ±1 |
| 25 | −10.0 | −19.0 | 0 | ±1 |
| 31.5 | −12.0 | −21.0 | 0 | ±1 |
| 40 | −14.0 | −23.0 | 0 | ±1 |
| 50 | −16.0 | −25.0 | 0 | ±1 |
| 63 | −18.0 | −27.0 | 0 | ±1.5 |
| 80 | −20.0 | −29.0 | 0 | ±2 |



Vertical and horizontal characteristics



Flatness characteristics

Frequency response and tolerances for vibration sensation characteristics (JIS C 1510:1995)

### 2.3 Vibration Level Measurements

Methods for measuring vibration levels are outlined in JIS Z 8735 (Methods of measurement for vibration level).

### 2.3.1 Measuring Points

The Vibration Control Law specifies points such as site boundary lines for specified factories, boundaries of road sites for measuring traffic vibration, and site boundary lines for specified construction work. For shinkansen railroad vibrations, this is measured at points approved as representative or points considered to pose problems.

### 2.4 Vibration Pickup Installation

Great care is required when installing vibration pickups. The vibration system at the contact surface between the vibration pickup and the ground consists of equivalent springs for the pickup mass and contact point and forms a vibration system with one degree of freedom, which can be described using damping elements. Care is therefore required to ensure the resonance frequency does not lie within the measurement frequency range. It is typically sufficient to install pickups on packed down earth, concrete, or asphalt. Avoid installation on soft soil, turf, or gravel.

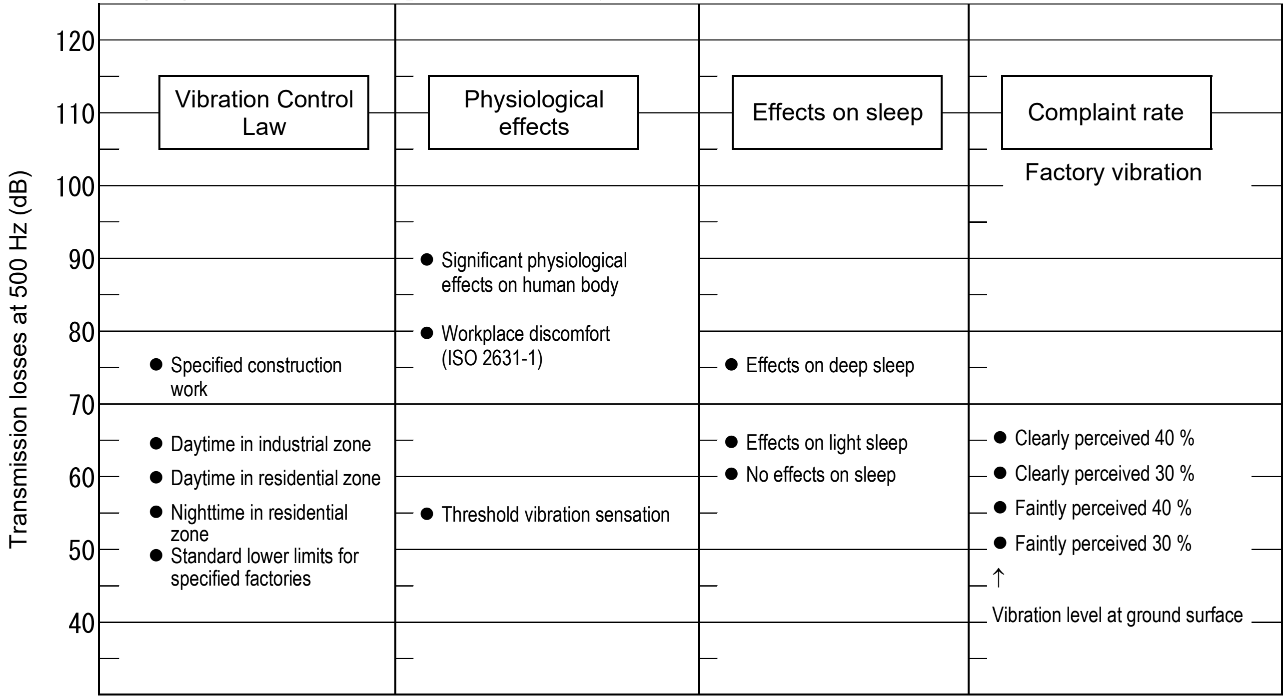
Measurement inside residences on carpets or matting is difficult. Take measurements on hard floor surfaces, such as in hallways or alcoves.

Position vibration pickups with their sensitive axes aligned with the vertical (*z*) and two horizontal (*x*, *y*) axes of vibration.

The horizontal axis may be determined using the vibration source direction as the x axis or using the direction of motion of the vibration source as the *x* axis (such as the direction of motion of machine spindles, roads, and railroads) with the measuring point customarily at the center.

### 2.5 Evaluating Whole-Body Vibration

The following figure shows an example of whole-body vibration evaluation.

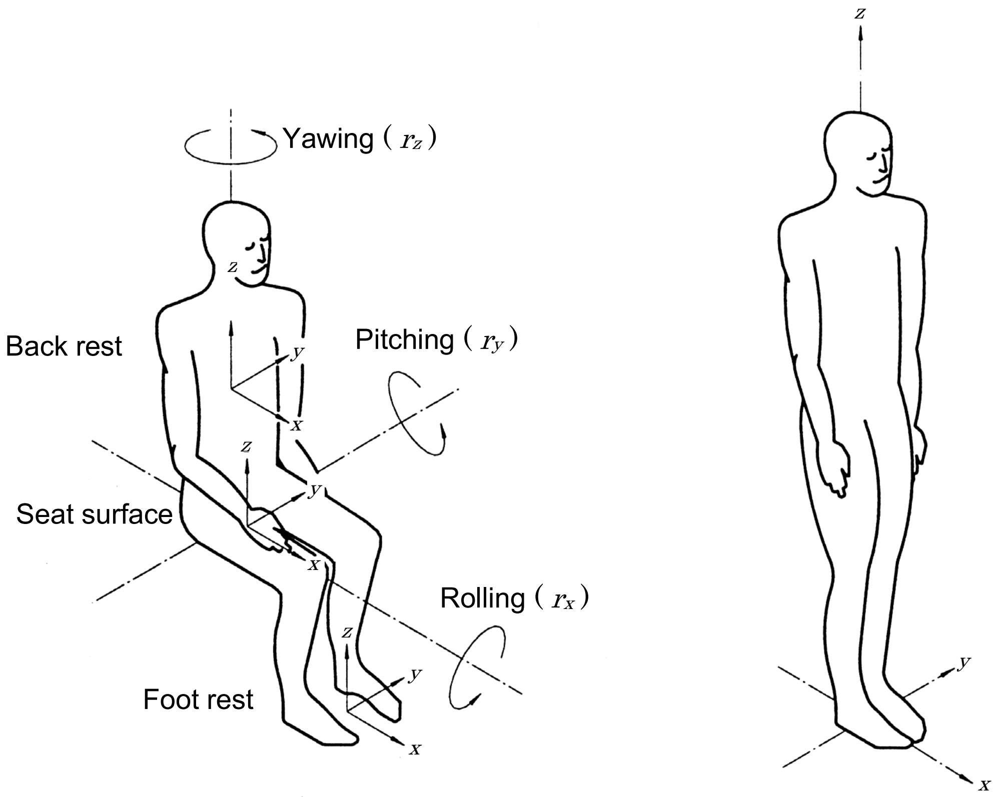


Reference: Derived from environment agency survey overseen by Ministry of International Trade and Industry Industrial Location and Environmental Protection Bureau, *Environmental Pollution Prevention Techniques and Regulations* (Japanese title only) (Maruzen, 1987) pp. 19-20

Example of whole-body vibration evaluation

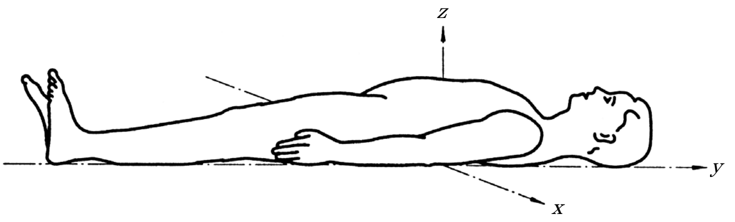
JIS B 7760-2 (Whole-body vibration - Part 2: General requirements for measurement and evaluation method) (ISO 2631-1) addresses measurement and evaluation of whole-body vibration. It describes the evaluation method used to set boundary values. The method quantifies the links between vibration and health, comfort, sensation of vibration, and motion sickness in cases in which humans are exposed to whole-body vibration.

The measured quantities used in the evaluation are the corrected acceleration rms values for each vibration direction.



a) Sitting

b) Standing



c) Supine

Human body bearing surface coordinate system (JIS B 7760-2:2004)

Overview of whole-body vibration measurement and evaluation (JIS B 7760-2:2014)

| | | Health | Comfort | Vibration sensation | Motion sickness |
|---|---|---|---|---|---|
| Frequency range | | 0.5 Hz to 80 Hz | 0.5 Hz to 80 Hz | 0.5 Hz to 80 Hz | 0.1 Hz to 0.5 Hz |
| Measurement point and direction coefficient | Sitting | Seat surface<br>$x$: 1.4<br>$y$: 1.4<br>$z$: 1 | Seat surface $x$: 1<br>$y$: 1<br>$z$: 1<br>Backrest $x$: 0.8<br>$y$: 0.5<br>$z$: 0.4<br>Feet $x$: 0.25<br>$y$: 0.25<br>$z$: 0.4 | Seat surface<br>$x$: 1<br>$y$: 1<br>$z$: 1 | Body support position<br>$z$ |
| | Standing | — | Floor surface $x$: 1<br>$y$: 1<br>$z$: 1 | Floor $x$: 1<br>$y$: 1<br>$z$: 1 | Body support position<br>$z$ |
| | Supine | — | Below pelvis Horizontal: 1<br>Vertical: 1 | Body support point<br>$x$: 1<br>$y$: 1<br>$z$: 1 | — |
| Vector synthesis | | — | Multiply $x/y/z$ weighted rms accelerations by each coefficient to calculate the root sum square value. | — | — |
| Measurement standard | Note: dB values are for reference. The reference acceleration is $10^{-5}$ m/s$^2$. | Warning zone<br>4-hour exposure<br>0.59 m/s$^2$ to 1.16 m/s$^2$<br>(95 dB to 101 dB)<br>8-hour exposure<br>0.46 m/s$^2$ to 0.89 m/s$^2$<br>(93 dB to 99 dB) | Under 0.315 m/s$^2$ (under 90 dB): Not unpleasant<br>0.315 m/s$^2$ to 0.63 m/s$^2$ (90 dB to 96 dB): Slightly unpleasant<br>0.5 m/s$^2$ to 1 m/s$^2$ (94 dB to 100 dB): Somewhat unpleasant<br>0.8 m/s$^2$ to 1.6 m/s$^2$ (98 dB to 104 dB): Unpleasant<br>1.25 m/s$^2$ to 2.5 m/s$^2$ (102 dB to 108 dB): Very unpleasant<br>2 m/s$^2$ or greater (106 dB or greater): Extremely unpleasant | Threshold<br>0.015 m/s$^2$ $_{\text{peak}}$<br>(= 0.01 m/s$^2_{\text{rms}}$ = 60.5 dB) | Levels exceeding 0.5 m/s$^2$ may induce vomiting, depending on exposure duration. |

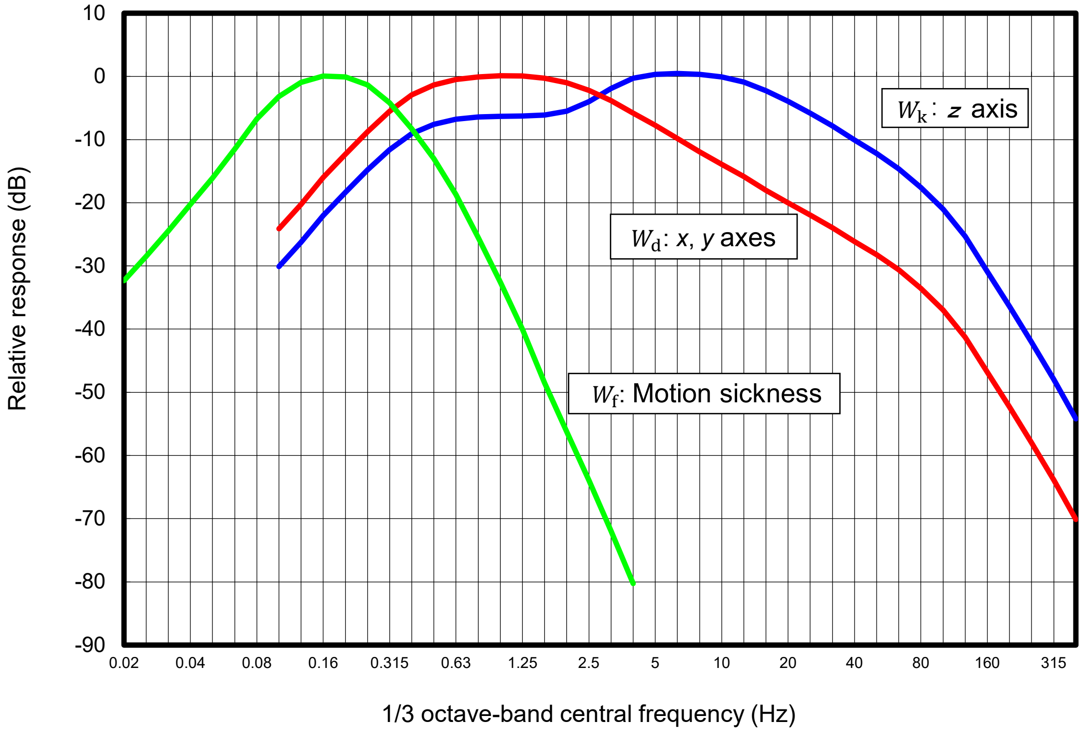
Select the frequency correction coefficient based on the purpose of the evaluation. The correction coefficients typically used are as follows:

$W_k$: Correction coefficient for vertical direction (excluding head) in $z$ direction when supine  
$W_d$: Correction coefficient for horizontal direction in $x$ and $y$ direction when supine  
$W_f$: Correction coefficient for vibration causing motion sickness

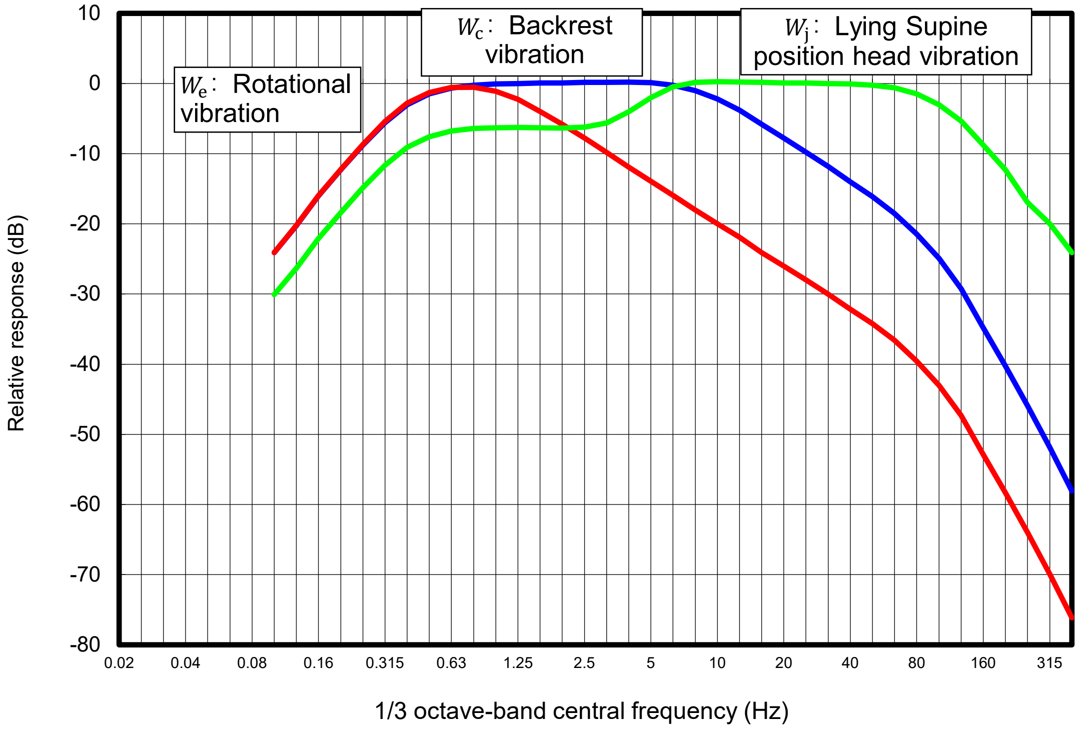
The following supplementary correction coefficients are also used:

$W_c$: Correction coefficient for chair backrest vibration  
$W_e$: Correction coefficient for rotational vibration  
$W_j$: Correction coefficient for vibration at the head support point when supine

These correction coefficients are illustrated in the following figure.



Main correction coefficients (JIS B 7760-2:2004)

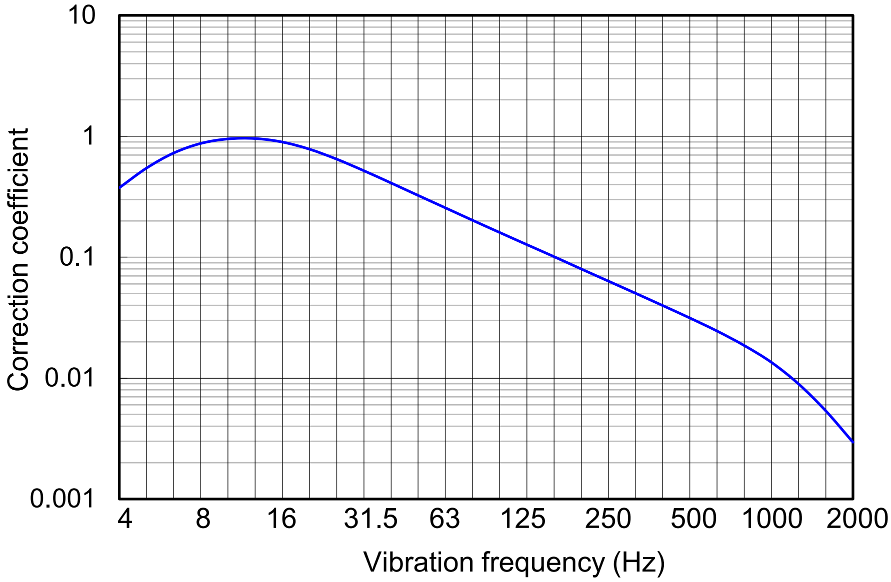


Supplementary correction coefficients (JIS B 7760-2:2004)

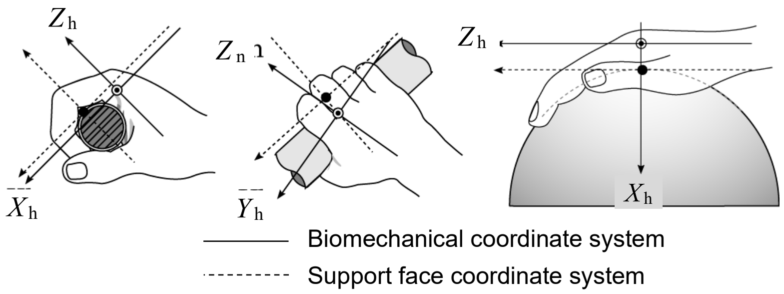
## 3. Hand-Transmitted Vibration Exposure

JIS B 7761-1 (Hand-transmitted vibration - Part 1: Measuring instrumentation) addresses instruments used to measure the vibration of tools and machinery transmitted through the hands. The measured quantities are measured in a way similar to full-body vibration measurements, with a frequency correction value corresponding to the sensitivity of the hand to vibration added to the vibration acceleration.

JIS B 7761-2 (Hand-transmitted vibration - Part 2: Practical guidance for workplace measurements) (ISO 5349-2) provides guidelines for evaluating exposure to hand-transmitted vibration. It describes vibration exposure limits and vibration exposure prevention values based on permissible levels advised by the Japan Society for Occupational Health and in EU directive (2002/44/EC).

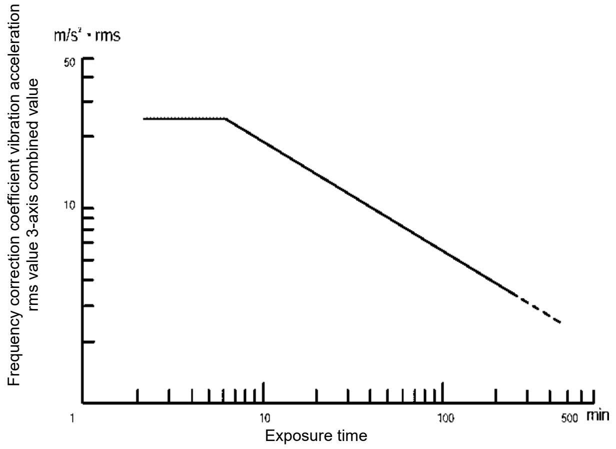


Hand-transmitted vibration frequency correction coefficient $W_h$ (JIS B 7761-1:2004)


a) Handgrip position

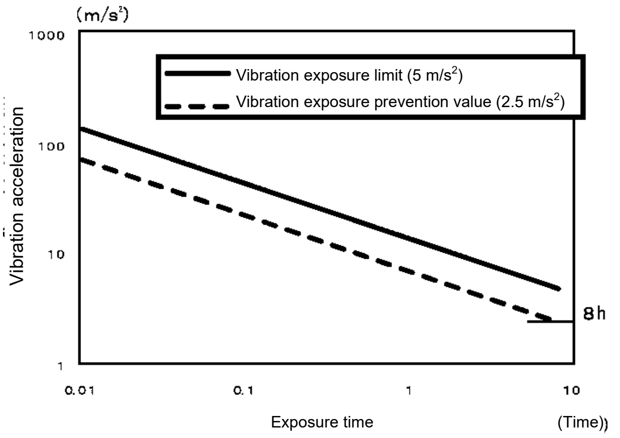
b) Palm position

Hand support face coordinate systems (JIS B 7761-3:2007)



Hand-transmitted vibration permissible levels

(Japan Society for Occupational Health)



Hand-transmitted vibration permissible exposure time

(EU directive)

## 4. Mechanical Vibration

### 4.1 Measuring Mechanical Vibrations

The vibration quantity measured is determined by the purpose of the measurement. If the vibration quantities are stipulated in standards and regulations, use these for measurements.

Typically, vibration displacement, vibration velocity, and vibration acceleration are selected as follows:

(1) Displacement measurement: Indicates the magnitude of vibration with a fundamental frequency corresponding to the rotation speed of rotating machinery. Displacement measurement is also particularly important for positions where vibrating parts must not come into contact with other parts. Displacement measurement is effective at low-frequency ranges where velocity and acceleration are too small to be practically measured.

(2) Velocity measurement: The severity of vibration of a rotating machine depends on the speed. At mid-range frequencies, velocity measurement allows vibration to be measured for which displacement would be too small. It is convenient for understanding the correlation between sound and vibration. This is because sound pressure in the air is proportional to the velocity of a vibrating body surface.

(3) Acceleration measurement: This is ideal for large measurement frequency ranges from low to high frequencies in cases in which we can apply the correlation of the force proportional to acceleration instead of force, load, or stress. Measurement results related to human perception are expressed in terms of acceleration.

### 4.2 Vibration Pickup Mass

The vibration conditions of a vibrating component must remain constant when a vibration pickup is mounted. This depends on various factors, including the mass of the vibration pickup, the material and thickness of the vibration pickup mounting, and the frequency of the vibration. JIS B 0907:1989 (ISO 2954:1975) (Mechanical vibration of rotating and reciprocating machinery - Requirements for instruments for measuring vibration severity) provides a method for checking whether the mass of a vibration pickup is too large when additional weights are added to double the mass of the vibration pickup. Results are considered invalid if the reading differs from the original reading by 12 % or more, indicating that the mass of the vibration pickup is too large. Note that the vibration pickup sensitivity is inversely proportional to the upper limit of the measurement frequency range. Increasing the mass increases sensitivity, while sensitivity decreases for the measurement of high frequencies.

### 4.3 Vibration Pickup Mounting Methods

The stiffness of the contact between a vibration pickup mass and a vibrating body forms a vibration system. Accurate measurements are not possible if the resonance from this vibration system (known as contact resonance) lies within the measurement frequency range.

### 4.4 Vibration Direction

Vibration pickups are typically mounted aligned with sensitive axes in the direction under investigation or a specified direction. The sensitivity when vibration is applied in a direction perpendicular to the sensitive axis is called the transverse sensitivity. The difference between the axial sensitivity and this transverse sensitivity is called the transverse sensitivity ratio. JIS B 0907:1989 (ISO 2954:1975) specifies a transverse sensitivity ratio of less than 0.1 (in practice, approximately 0.05 for piezoelectric acceleration pickups).

### 4.5 Evaluating Mechanical Vibration

#### 4.5.1 Vibration Severity

Vibration severity is defined as the quantity that comprehensively expresses vibration intensity. It is expressed as the maximum, mean, or rms value of the vibration or as another measure related to vibration.

The severity of mechanical vibration was first defined in ISO 2954:1975 as a velocity rms value (mm/s) for vibration in the 10 Hz to 1,000 Hz measurement range. However, the ISO 10816 series subsequently expanded the scope of application; this was later merged with the ISO 7919 series in 2016 to form the ISO 20816 series (Mechanical vibration - Measurement and evaluation of machine vibration). This standard specifies the measurement frequency range according to the machine being measured. The vibration severity specified in ISO 2954 was primarily intended for quality control for new products. In the current ISO 20816 series, it can be applied to the usage and maintenance of machinery.

#### 4.5.2 Vibration Severity Measuring Instruments

A Japanese version of the ISO 2954:1975 standard on measuring instruments for measuring the vibration severity (velocity rms value for vibration between 10 Hz and 1,000 Hz) of rotating and reciprocal machinery exists in the form of JIS B 0907:1989. Note that ISO 2954 was revised in 2012 to include flatness characteristics for vibration severity measuring instruments within the 10 Hz to 1,000 Hz frequency range and -18 dB/octave damping characteristics for frequencies outside this range, as frequency characteristics of vibration severity measuring instruments.

#### 4.5.3 Evaluations Using ISO 20816 Series

ISO 20816-1 is a general standard stipulating basic guidelines for the measurement and evaluation of vibrations measured for rotating parts, non-rotating parts, and non-reciprocating parts of machines.

The general evaluation standards indicate vibration levels related to operations monitoring and acceptance tests as well as operating limits, taking into account factors such as machine warranties, safety, and long-term operation.

The following evaluation zones qualitatively evaluate machine vibration and provide corresponding guidelines:

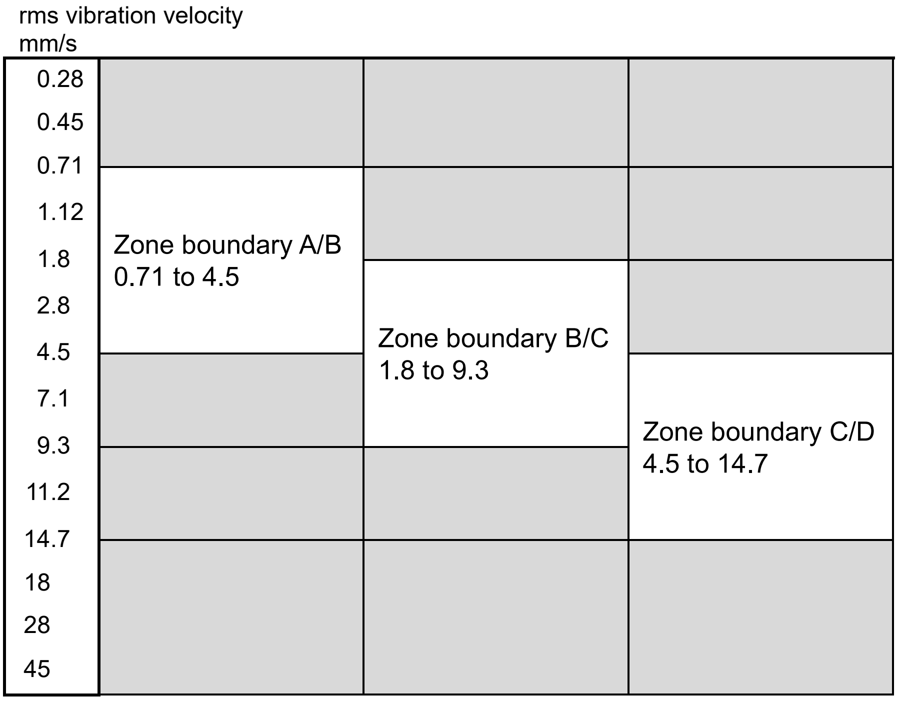
Zone A: The vibration of newly commissioned machines typically falls within this zone.

Zone B: Machines with vibration within this zone are typically considered acceptable for unrestricted long-term operation.

Zone C: Machines with vibration within this zone are typically considered unsatisfactory for long-term continuous operation. Generally, the machine may be operated for a limited period in this condition until a suitable opportunity arises for remedial action.

Zone D: Vibration values within this zone are typically considered to be of sufficient severity to cause damage to the machine.

ISO 20816-1:2016 “Mechanical Vibration - Measurement and evaluation of machine vibration - Part 1: General guidelines” provides the following figure.



Reference: Derived from ISO 20816-1:2016 (Mechanical vibration - Measurement and evaluation of machine vibration - Part 1: General guidelines)

Typical values for the zone A/B, B/C and C/D boundaries for non-rotating parts