106

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

# Mechanical Vibration Measurement

## Chapter 1 and 2

RION CO., LTD.

# Contents

**Mechanical Vibration Measurement** .......... 1
1. Definition of Vibration and Measurement Quantities .......... 1
   1.1 Mechanical Vibration .......... 1
   1.2 Sinusoidal Vibration .......... 1
   1.3 Selecting Vibration Quantities According to Measurement Purpose .......... 4
   1.4 Displaying Vibration Quantities .......... 5
   1.5 Decibel Display of Vibration Quantities .......... 6
2. Selecting Measurement Methods .......... 7

# Mechanical Vibration Measurement

The measurement of mechanical vibration spans a broad field. A wide range of different measuring methods are available. Current measuring methods include highly advanced practical methods used in their respective fields.

This note introduces the basic points of general mechanical vibration measurements.

## 1. Definition of Vibration and Measurement Quantities

### 1.1 Mechanical Vibration

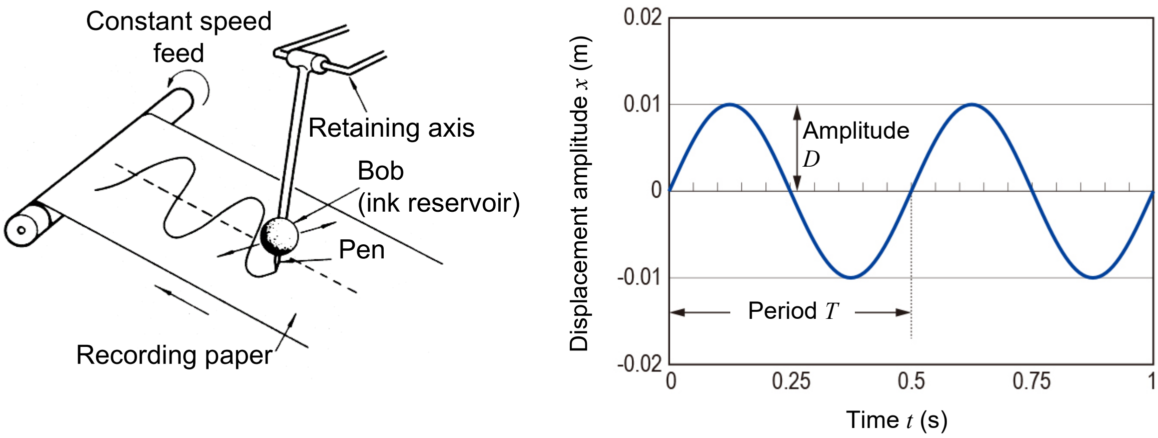
Mechanical vibration is defined in JIS B 0153 (Glossary of terms used in mechanical vibration and shock) as “the repeated fluctuation of the size of the quantity expressing the movement or position of a mechanical system with time alternately between a large state and a small state about a particular mean or datum value.”

### 1.2 Sinusoidal Vibration

Simple vibration performing harmonic movement periodically in the simplest form of movement is defined as “movement expressed by the sine function about time.” This is generally called sinusoidal vibration. Consider a pendulum consisting of an ink reservoir as a bob with a pen attached to its tip as shown in Fig. 1.1 (1). We will assume that the support for this pendulum has minimal friction and that the pendulum is sufficiently long.

If we pull the pendulum away to an angle then release it while feeding the recorder paper at a constant speed, a sinusoidal waveform will be recorded, as shown in Fig. 1.1 (2).

The time taken to make one cycle here is called the period. The number of cycles per second is called the number of vibrations. In other words, the period $T$ is the inverse of vibration frequency, while the vibration frequency $f$ is the number of cycles per unit time.




(1) Pendulum motion　　(2) Sinusoidal vibration

Fig. 1.1 Pendulum motion

Vibration frequency is also called frequency (the term *frequency* is used in acoustic engineering).

$$T = \frac{1}{f} \quad [\text{s}] \qquad (1.1)$$

$$f = \frac{1}{T} \quad [\text{Hz}] \qquad (1.2)$$

If the distance traveled by the bob from the stationary point in time $t$ (s) is called the instantaneous displacement $x$ (m) and the maximum distance moved is called the maximum displacement $D$ (m), the displacement of the sinusoidal vibration can be expressed as follows:

$$x = D\sin\omega t \qquad (1.3)$$

where $\omega$ is the angular frequency corresponding to the vibration frequency (rad/s) related to the angle when an object moves, and is $2\pi$ times the frequency.

$$\omega = 2\pi f \quad [\text{rad/s}] \qquad (1.4)$$

Next, consider the velocity of the pendulum. Velocity is a change in distance per second. But, as the pendulum displacement varies continuously, in such cases we calculate the velocity $v$ (m/s) by differentiating the displacement $x$ (m).

$$v = \frac{dx}{dt} = D\omega\cos\omega t \qquad (1.5)$$

Similarly, the acceleration $a$ (m/s$^2$) corresponds to a change in velocity per second. We can calculate this by differentiating the velocity $v$ (m/s) (i.e., displacement is differentiated twice).

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2} = -D\omega^2\sin\omega t \qquad (1.6)$$

The expressions $\sin\omega t$ and $\cos\omega t$ in equations (1.3), (1.5), and (1.6) express the phase of the sinusoidal vibration, i.e., the position of sinusoidal vibration at time $t$ as it varies over one cycle. We see a phase difference of 90° between $\sin\omega t$ and $\cos\omega t$. The velocity phase of sinusoidal vibration is 90° ahead of displacement, while the acceleration phase is 90° ahead of velocity and 180° ahead of displacement. Fig. 1.2 shows the velocity and acceleration waveforms with respect to the displacement waveform for sinusoidal vibrations (with the maximum displacement of 1 cm and frequency of 2 Hz). Note that the scales on the vertical axes increase by a factor of 10.

In typical vibration measurements, we disregard the phase of vibration waveforms and apply relationships like those described in the following equations:

Displacement amplitude $\quad D = \frac{V}{\omega} = \frac{V}{2\pi f}$

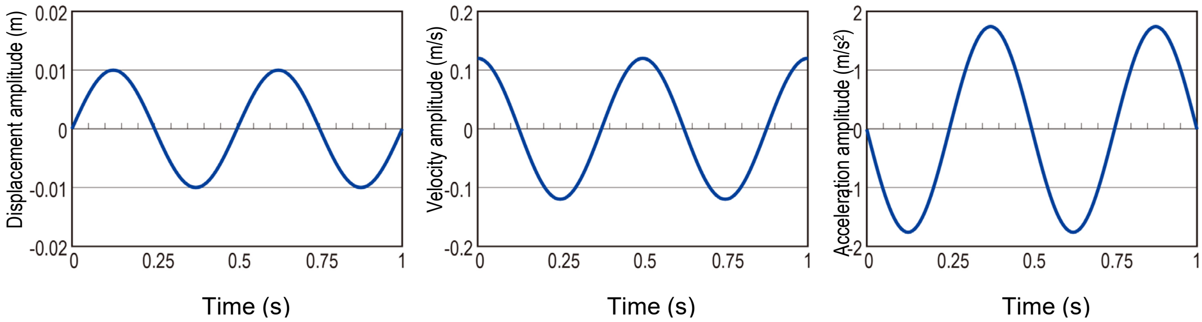
$$= \frac{A}{\omega^2} = \frac{A}{(2\pi f)^2} \qquad (1.7)$$

Velocity amplitude $\quad V = \omega D = 2\pi f D$

$$V = \frac{A}{\omega} = \frac{A}{2\pi f} \qquad (1.8)$$

Acceleration amplitude $\quad A = \omega^2 D = (2\pi f)^2 D$

$$= \omega V = 2\pi f V \qquad (1.9)$$




(1) Displacement waveform (2) Velocity waveform (3) Acceleration waveform

Fig. 1.2 Sinusoidal vibration

The MKS (SI) unit system is typically used for vibration quantities. The units shown in Table 1.1 may also be used in practice. While the gal is a non-SI unit, it is approved by the Japanese measurement act for use only in measuring the acceleration due to gravity and seismic vibration acceleration.

Note that equations (1.7), (1.8), and (1.9) are valid only for sinusoidal vibration and cannot be applied directly to complex vibration (conversion is possible with complex vibration if frequency analysis results are used).

Table 1.1 Unit symbols for vibration quantities

| Vibration quantity | Units | Supplementary units (practical units) | Instantaneous value | Maximum amplitude |
|---|---|---|---|---|
| Displacement | m | cm (1 cm = $10^{-2}$ m)<br>mm (1 mm = $10^{-3}$ m)<br>µm (1µm = $10^{-3}$ mm = $10^{-6}$ m) | $x(t) = D\sin(\omega t + \varphi_0)$ | $D$ |
| Velocity | m/s | cm/s (1 cm/s = $10^{-2}$ m)<br>mm/s (1 mm = $10^{-3}$ m/s)<br>kine (1 kine = 1 cm/s) | $v(t) = dx/dt$<br>$= D\omega\cos(\omega t + \varphi_0)$ | $v = \omega D$ |
| Acceleration | m/s$^2$ | cm/s$^2$ (1 cm/s$^2$ = $10^{-2}$ m/s$^2$)<br>Gal (1 Gal = 1 cm/s$^2$)<br>G (1 G = 9.80665 m/s$^2$) | $a(t) = d^2x/dt^2$<br>$= -D\omega^2\sin(\omega t + \varphi_0)$ | $A = \omega^2 D$ |

Up to this point, we derived velocity and acceleration by differentiating the displacement for sinusoidal vibration, but if we base our calculations on acceleration, we can express velocity and displacement as integrals. Fig 1.3 shows the relationship between vibration displacement, velocity, and acceleration.

$$a = A\sin(\omega t + \varphi_0) \tag{1.10}$$

$$v = \int a\mathrm{d}t = -\frac{A}{\omega}\cos(\omega t + \varphi_0) \tag{1.11}$$

$$x = \iint a\mathrm{d}t = -\frac{A}{\omega^2}\sin(\omega t + \varphi_0) \tag{1.12}$$

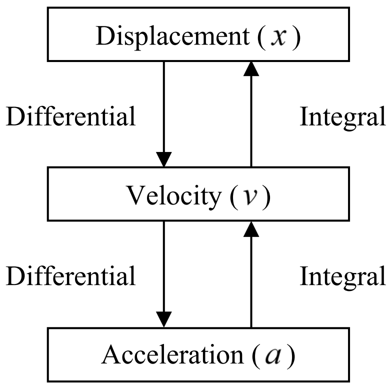



Fig. 1.3 Relationship between vibration displacement, velocity, and acceleration

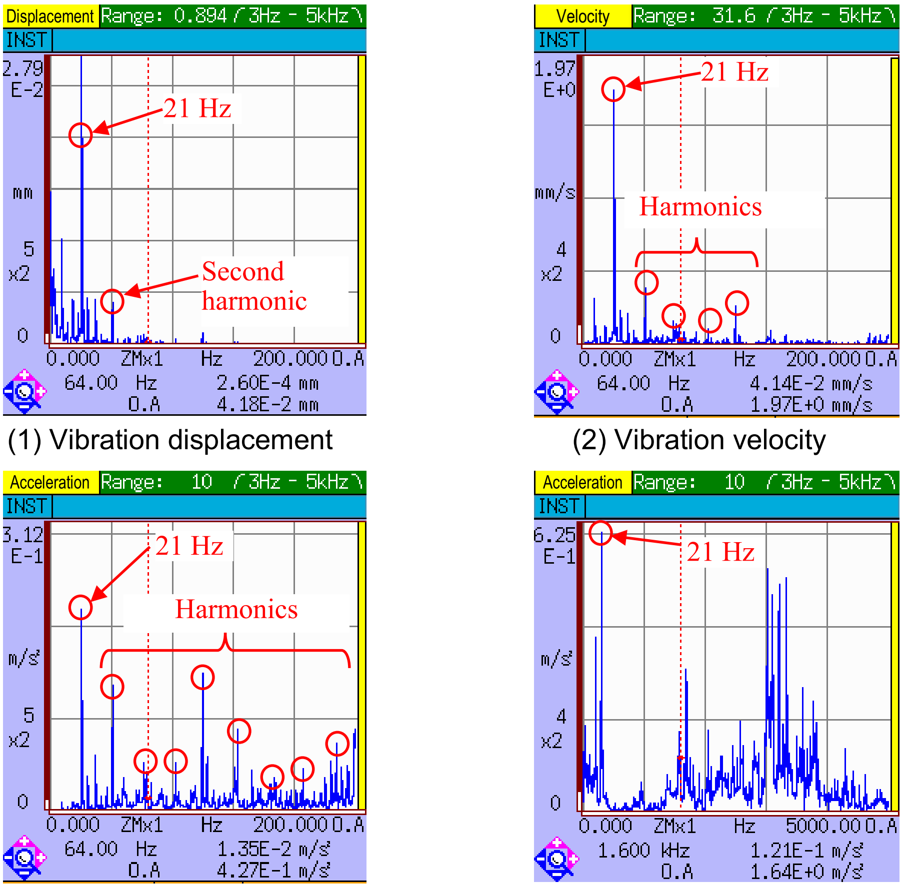
## 1.3 Selecting Vibration Quantities According to Measurement Purpose

The vibration quantities used in measurements are selected based on the purpose of the measurement. If quantities are stipulated by standards, regulations, or specifications, use these instead. In other cases, select measurement quantities in accordance with the purposes and features listed in Table 1.2.

Table 1.2 Measurement quantity selection

| Measurement quantity | Purpose/features |
|---|---|
| Vibration acceleration | ① Large output is obtained at high vibration frequencies<br>② When a proportional relationship between force and acceleration can be used instead of force, load, and stress<br>③ For human response related measurements |
| Vibration velocity | ① When displacement is too small for mid-range vibration frequencies<br>② Vibration severity measurement for machines<br>③ Measurement for solid sound and sound radiation |
| Vibration displacement | ① When displacement amplitude is especially important (such as contact dangers and machining accuracy) |

Fig. 1.4 shown below is the results of vibration frequency analysis using each vibration quantity for the same mechanical vibration.




(1) Vibration displacement

(2) Vibration velocity

(3) Vibration acceleration (0 Hz to 200 Hz)

(4) Vibration acceleration (0 Hz to 5 kHz)

Fig. 1.4 Vibration frequency analysis results using different vibration quantities for the same vibration

Fig. 1.4 shows the vibration detected using an acceleration pickup on the bearing of a fan. However, the vibration displacement in (1) only allows us to observe up to the second harmonic of the fundamental vibration frequency of 21 Hz corresponding to the rotation speed. The vibration velocity in (2) lets us observe up to the fifth harmonic. The vibration acceleration in (3) lets us observe up to the ninth harmonic, and in (4) with the vibration frequency range expanded, we can observe components up to 5 kHz.

## 1.4 Displaying Vibration Quantities

The vibration quantity for the sinusoidal vibration in Fig. 1.1 (2) is displayed using amplitude (peak value) but can also be displayed using peak to peak (p-p) or root mean square (rms) values. (Table 1.3)

Peak values were conventionally used to display quantities. Now, the norm in Japan is to use rms values due to the use of rms vibration velocity for mechanical vibration and rms vibration acceleration for human body related vibration in ISO standards.

For sinusoidal vibrations, quantities can be displayed either as peak or rms values, but in the case of vibration with asymmetrical waveforms, rms values express the overall vibration, as they are the time-mean of the energy within that time, whereas peak values indicate the instantaneous maximum value within a specified time interval. While peak values cannot be added for non-sinusoidal vibration, rms values can be added even for non-sinusoidal vibration.

The following equation gives the rms value $A_{\mathrm{rms}}$ for the instantaneous amplitude of α at a period $T$ :

$$A_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T a^2 dt} \qquad (1.13)$$

In practice, one period is too brief; a suitably longer time is assumed.

The rms value $A_{\mathrm{rms}}$ for the sinusoidal vibration with peak value $A$ becomes:

$$A_{\mathrm{rms}} = \frac{A}{\sqrt{2}} \qquad (1.14)$$

We calculate the sum of $n$ rms values $A_{\mathrm{rms}1}, A_{\mathrm{rms}2}, \cdots A_{\mathrm{rms}n}$ using the square root of the sum of the squares.

$$A_{\mathrm{rms}} = \sqrt{A_{\mathrm{rms}1}^2 + A_{\mathrm{rms}2}^2 + \cdots + A_{\mathrm{rms}n}^2} \qquad (1.15)$$

Table 1.3 Vibration quantities for sinusoidal vibration

| | |
|---|---|
| Peak value | Maximum value within an obtained interval (equivalent to amplitude for sinusoidal vibration) |
| RMS value | Root mean square of the instantaneous value<br>For sinusoidal vibration, the rms value = peak value / $\sqrt{2}$ ≒ 0.707 × peak value |
| Peak to peak value (p-p value) | The maximum of the representative difference between vibration peaks (difference between maximum and minimum) within the specified interval |

Fig. 1.5 shows the relationship between peak values, rms values, and p-p values for sinusoidal vibration and random vibration. In the case of random vibration, rms value × $\sqrt{2}$ is called the equivalent peak value. This is equivalent to the peak value when converted to sinusoidal vibration with an identical rms value.

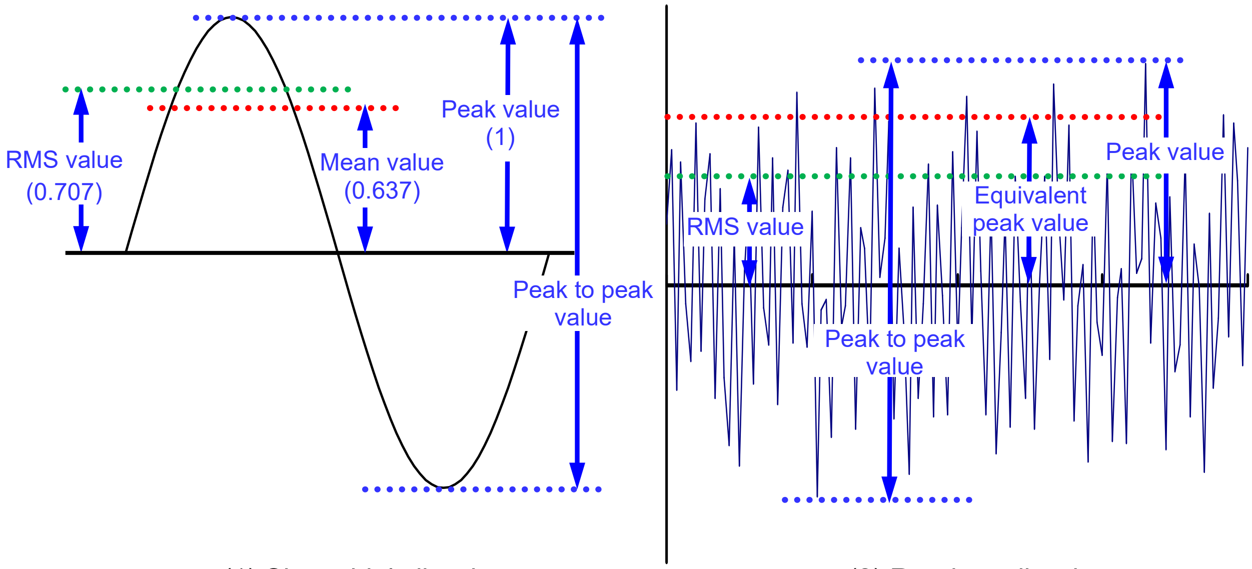



Fig. 1.5 Quantities indicating vibration magnitude

## 1.5 Decibel Display of Vibration Quantities

In Japan, vibration quantities related to vibration nuisance are displayed as vibration levels (vibration sensation adjusted acceleration level) using decibels (dB). The decibel is a quantity expressing the ratio with a datum as a logarithm and is widely used in acoustic fields. In the case of mechanical vibrations, no standards specify the use of decibels. Nevertheless, it may be convenient to handle measurements over a wide range using decibels. When defining decibels for mechanical vibration, it can be defined as follows except the above vibration levels:

Vibration acceleration level $$L_a = 10\log_{10}\frac{a^2}{{a_0}^2} \text{ [dB]} \quad (1.16)$$

where $a$ is the rms vibration acceleration (m/s$^2$) and $a_0$ is the reference vibration acceleration ($10^{-5}$ m/s$^2$ in Japan[1)] based on relationship with vibration level, and $10^{-6}$ m/s$^2$ = 1 μm/s$^2$ in ISO[2)]).

Vibration velocity level $$L_v = 10\log_{10}\frac{v^2}{{v_0}^2} \text{ [dB]} \quad (1.17)$$

where $v$ is the rms vibration velocity (m/s) and $v_0$ is the reference vibration velocity ($10^{-9}$ m/s = 10 nm/s). In the case of measurements[2), 3)] examining the correlation of sound radiation with vibration from structures such as solid sounds from structures, the reference vibration velocity is set as $5 \times 10^{-8}$ m/s (= 50 nm/s). This index is derived from the fact that the sound pressure of the air immediately in front of the vibration face is proportional to the vibration velocity.

References:

1) JIS C 1510:1995 Vibration level meters

2) ISO 1683:2015 Acoustics – Preferred reference values for acoustical and vibratory levels

3) ISO/TR7849:1987 Acoustics –Estimation of airborne noise emitted by machinery using vibration measurement

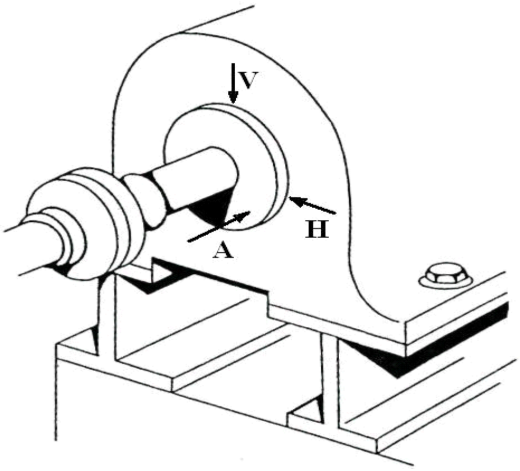
Values may sometimes be read as positive and negative values about a specific decibel datum value, even when not defined in this way—for example, -X dB when setting the maximum reading on a measuring instrument scale as 0 dB. If measurements give rms decibel values, $L_1, L_2, \cdots, L_n$, the sum $L$ of these can be calculated using the following equation:

$$L = 10\log(10^{L_1/10} + 10^{L_2/10} + \cdots + 10^{L_n/10}) \quad [\text{dB}] \qquad (1.18)$$

## 2. Selecting Measurement Methods

One purpose of vibration measurement is to evaluate whether or not a machine is operating in an ideal state. In such cases, the measuring method and measuring instrument used will often differ depending on the type of machine being evaluated, the location being measured, and the required measurement quantity.

Fig. 2.1 shows typical measurement quantities and measuring directions for fault diagnosis. Vibration velocity is measured in the case of unbalance and misalignment, and vibration acceleration is measured in the case of bearing defects. Measurements should ideally be made in three directions, but for the sake of efficiency, they are sometimes made only in the directions in which phenomena are likely to occur.




| Fault mode | Vibration velocity | Vibration acceleration |
|---|---|---|
| Unbalance | H/V directions | |
| Misalignment | H/V/A directions | |
| Bearings | | H or V direction |

Fig. 2.1 Typical measuring directions and measurement quantities for fault diagnosis

When planning mechanical vibration measurements, the overall plan is drawn up and the measuring system is determined based on factors such as the type of machine being measured and the purpose of measurement or evaluation. Since few standards related to measuring instruments apply to mechanical vibrations, the tester in charge specifies the required measuring instrument performance and selects the appropriate measuring instrument. Fig. 2.2 shows the main points to note when measuring mechanical vibration.

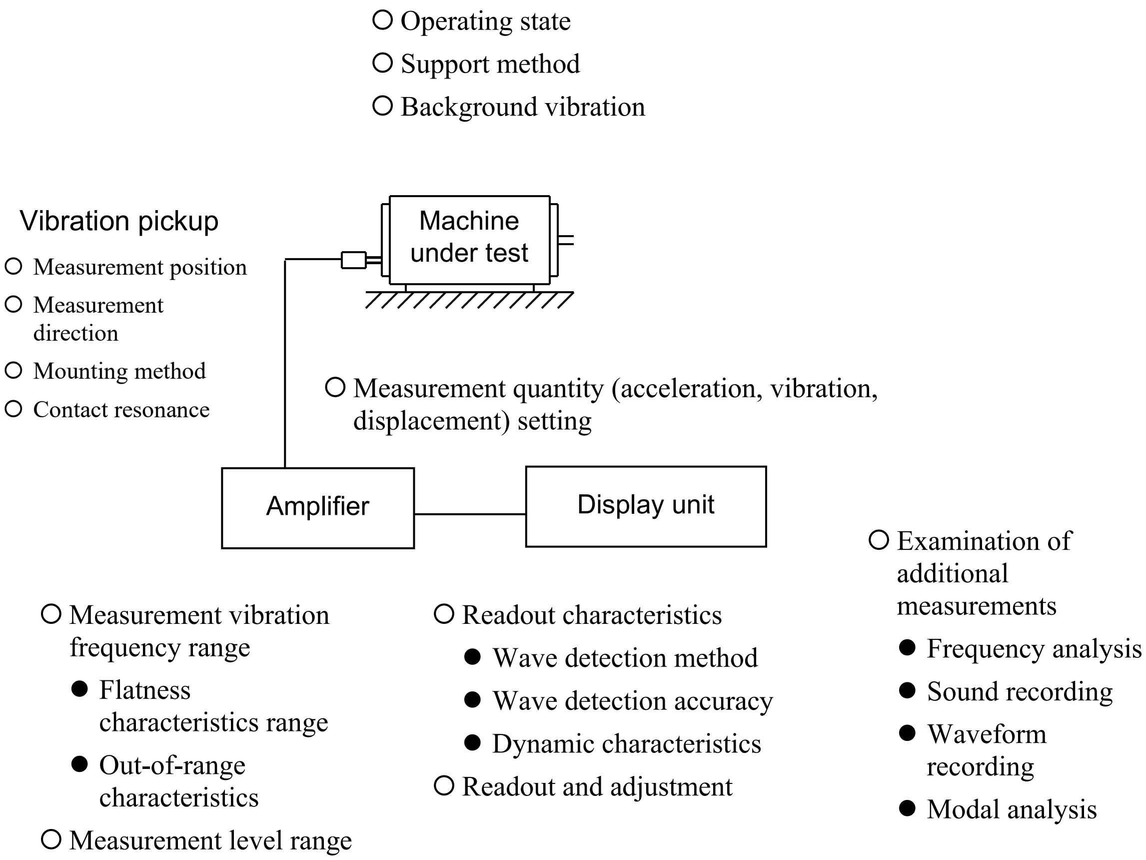



Fig. 2.2 Main points to note when measuring mechanical vibration

Vibration encompasses a wide range of phenomena. It is typically not possible to detect all of these using a single type of vibration pickup. Many different vibration pickups have therefore been developed for use. Here we will describe the measurement method with the piezoelectric acceleration pickup widely used for mechanical vibration measurements.

Once the measurement quantities and acceleration pickup have been selected, this enables the vibration meter consisting of the amplifier and display unit to be determined.

We next examine the vibration frequency of the vibration occurring to understand its characteristics. The state of vibration can be assessed by comparing these vibration frequency components against factors such as rotation speed and load conditions that are considered as being related to the occurrence of machine vibration. In such cases, frequency analysis will also be required in addition to using a vibration meter.

For example, Fig. 2.3 shows the results of frequency analysis on vibration from a fan bearing rotating at 1,860 rpm. We can confirm the 31 Hz frequency corresponding to the rotation speed of 1,860 rpm. The overall vibration velocity value is extremely high at 4.55 mm/s, and as there are few harmonics, it can be surmised that a potential unbalance exists.

Fig. 2.4 shows the data for a different fan also rotating at 1,860 rpm. There are a large number of harmonics of the frequency (31 Hz) corresponding to the rotation speed. The second harmonic in particular is notably elevated. This suggests the possibility of misalignment.

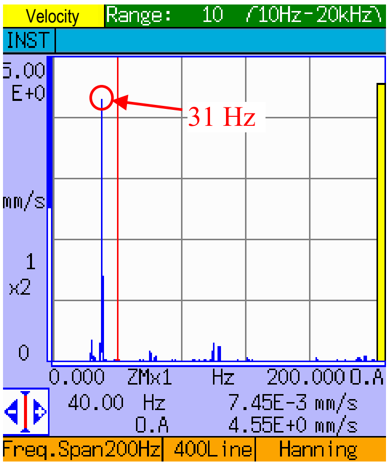



Fig. 2.3 Unbalance example (1,860 rpm)

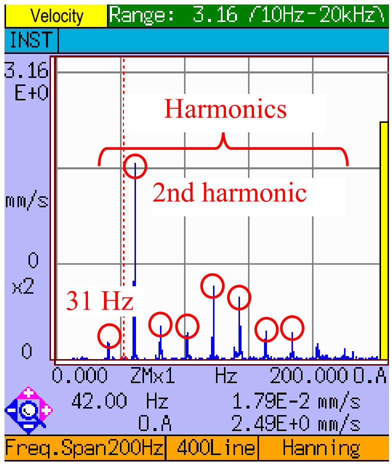



Fig. 2.4 Misalignment example (1,860 rpm)

If we wish to examine aspects such as the vibration characteristics of a machine structure or location of a vibration source, in addition to knowing the vibration frequency, we can subject the machine to a known vibration, measure the machine's response to that vibration, and use the results to estimate the various qualities of the machine vibration. The methods used to achieve these goals include methods for determining resonance curves using a vibration exciter to subject the machine to forced vibration and methods for determining the transfer function for the vibration system from the input (excitation force) and output (vibration response) when an impulse is applied with an impulse hammer.

No.65670