5. Mechanical Vibration and Measurement

5.1 Vibration Monitoring

5.1.1. Introduction

Monitoring, by definition, is an act of extracting information from a specific system by means of appropriate observations or information carriers, in the form of acoustics, temperature, lubricant, electric current, vibration, etc. As such, they may carry information about exciting forces (internally or externally generated) and about the structural path through which the signals propagate to the sensing elements.

Compared with other information carriers such as acoustic signals, temperature or lubricant data, vibration monitoring has some unique features that make it a viable monitoring tool. Firstly, vibration signals are usually easy to measure by the use of off-the-shelf instrumentation systems. Secondly, it is non-intrusive in measurement and monitoring. It is thus possible to acquire information about inaccessible sources under normal operating conditions. In this sense, we may consider vibration monitoring as one kind of non-destructive testing.

Some of the difficulties encountered in vibration monitoring can be traced to these same features. Vibration sensors are sensitive to noises from other vibratory sources, where acoustic monitoring is superior in this aspect. It is worthwhile to note that in our context (and actually in any context), “noise” is to be understood as that part of the signal not carrying information of interest to us.

5.1.2 Application of vibration monitoring

Vibration monitoring is used both as a maintenance tool and as a production quality control strategy for machinery systems. Vibration monitoring as a maintenance tool, often called condition monitoring, enables the establishment of a maintenance program based on an early warning. This can be of great value in cases involving critical machinery in which an unexpected shutdown can have serious economical or environmental consequences. We thus often deal with the case involving the monitoring of a single (or a few) system where continuing operation is imperative. As a quality control tool, a reliable monitoring system can recognize machinery defects at their early stage before they reach some critical level so as to prevent machinery performance degradation, malfunction or even some catastrophic failures. On the other hand, costs can be further reduced in maintenance operations by quickly identifying the faulty components without inspecting all of the mechanical parts in a machine. The sensing features of vibration monitoring make it a viable quality control tool, especially where other practical tools are unavailable.

Another advantage is the fact that an unviable state of a system may be recognized, even when there is no faulty component at hand, for example, the monitoring of mounted gyroscope bearings in which improper preloading will change the vibration signature. The recognition of such a state enables the prediction of a reduced component life, even though no fault has yet developed.

In both types of monitoring as described above, information about the state of a system is needed. For maintenance, a prediction well ahead of failure is sought. Figure 5.1 illustrates a typical machinery deterioration-time curve.

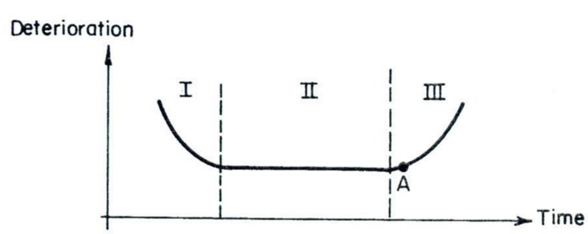


Figure 5.1. Deterioration-time curve for machinery.

Three stages can usually be identified: stage I: the run-in period; stage II: the normal operation period; and stage III: failure development. Figure 5.1 is an overall description with no sharp separation between phases. State *A* enables an early failure prediction, and is the one sought by the monitoring scheme. A longer lead-time will enable a better planning of a maintenance schedule. The early recognition of this state is critical for predictive maintenance.

The recognition of point *A* necessitates the identification of the state of a system, based on the parameter(s) monitored. It has no knowledge to theoretically identify state *A*, and usually continuous or regular measurements are performed during operations. For trend monitoring, the change of monitoring parameters is used for recognizing point *A*. Trend monitoring thus necessitates a *baseline signature*. Due to complex machinery conditions and limitations in today's technologies, we still have to limit ourselves to the mode of trend monitoring.

5.1.3 Procedures for vibration monitoring

Machinery vibration is a complex combination of signals caused by a variety of internal sources of vibration. Consider the example as shown in Figure 5.2, vibration is produced by residual imbalance of the rotor (the white spot), a bearing defect, and meshing of gears – each occurring at a unique frequency. The condition monitoring task takes four steps: (1) converting the vibration to an electrical signal using appropriate transducers; (2) examining the components in the signal by using FFT; (3) correlating those spectral components with machine parts based on the knowledge of characteristic frequencies for different machinery component and by applying appropriate filtering processes; and (4) analyzing the results. The recognition of a faulty machine or component is actually a classification task. Usually, a faulty situation is recognized when the value of a monitoring parameter (index) exceeds a predetermined threshold.

The detailed issues related to instrumentation selection and measurement considerations to improve the signal-to-noise (S/N) ratio will be discussed in the following sections.

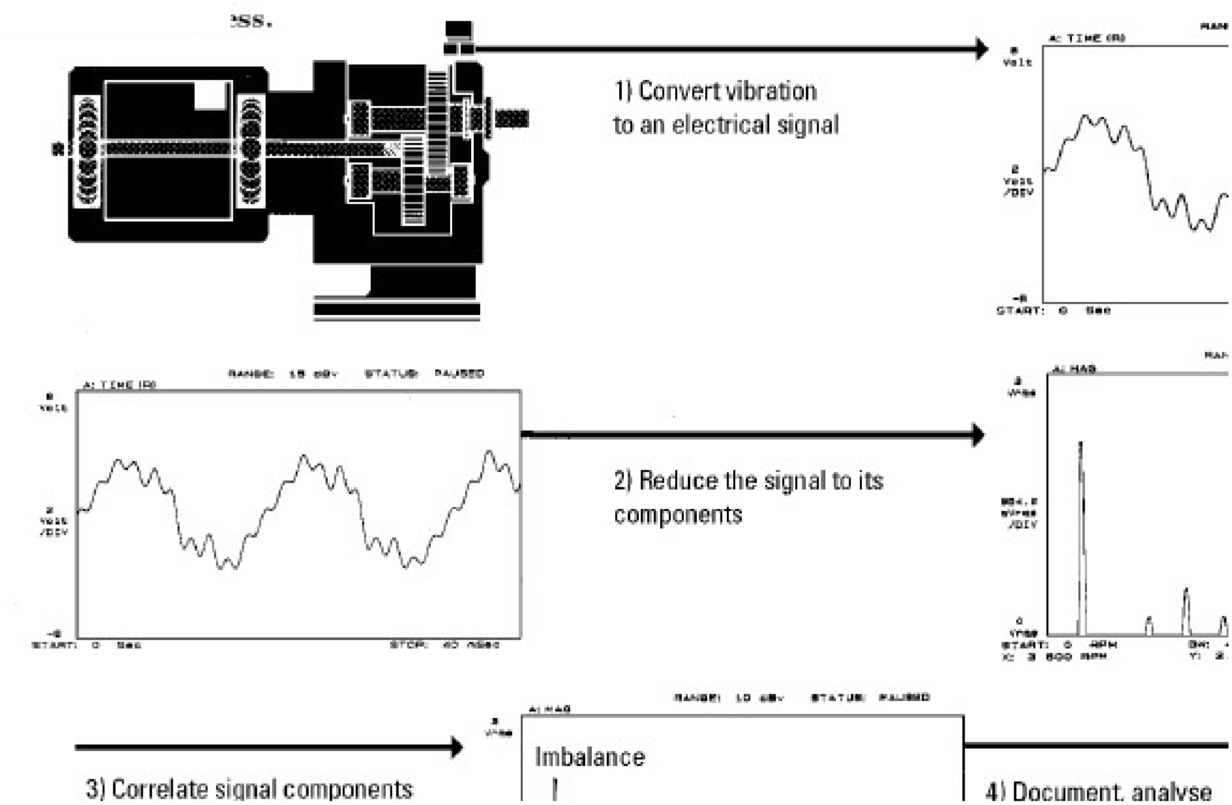


Figure 5.2. The process of machinery vibration monitoring.

5.2 Basics of Vibration

Before starting our discussion of vibration-based fault detection, it is important to review some basic concepts in vibration theory.

Vibration parameters: Using commercially available transducers, we can measure the displacement, velocity, and acceleration of vibration. Selecting the right parameter is critical for effective analysis.

Mechanical impedance: What we can measure with transducers is the response of the machine to vibration forces, not the forces themselves. The mechanical impedances of the machinery shaft/rotor and housing determine how they respond to vibration forces, which can alter significantly the characteristics of the signal we measure. These characteristics are often nonlinear in nature.

Natural frequencies: When a structure is excited by an impact, it will vibrate at one or more of its natural frequencies (or resonances). These natural frequencies are important because they are often associated with critical speed of the machine. They can cause large changes in the vibration response and are often associated with critical operation conditions.

5.2.1 Vibration parameters

We will start our discussion of vibration parameters by examining the vibration produced by a simple imbalance. Referring to the machine rotor in Figure 5.3, the heavy spot produces a rotating force that appears sinusoidal from any fixed reference position. At points A and C, the force in the direction of reference is zero. At points B and D, it is at positive and negative maximum, respectively.

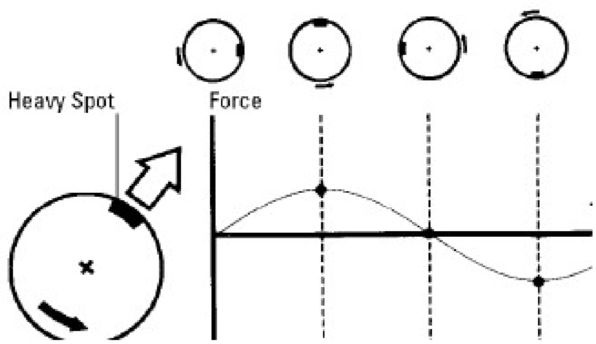


Figure 5.3. A heavy spot on a machine rotor results in a sinusoidal rotating force vector.

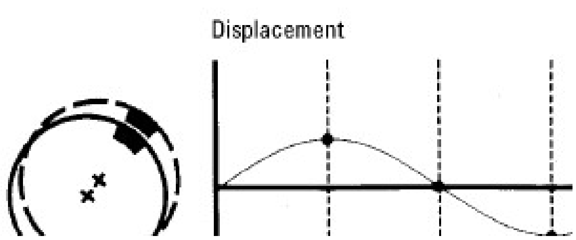


Figure 5.4. The imbalance force produces a vibration.

The response of the rotor to such a force vector is a displacement, which moves the center of rotation away from the geometric center, as shown in Figure 5.4. A displacement measurement performed on the rotor results in approximately the same waveform as the force, with the signal amplitude approximately proportional to the magnitude of the force. They are not exactly the same because rotor dynamics will affect the response.

The velocity and acceleration parameters of the vibration are offset in phase relative to displacement – an important consideration when using phase for analysis. Phase relationships are shown in Figure 5.5. Velocity, for example, is offset from displacement by 90º. At point B when displacement is minimum, the velocity is zero. At point C when displacement is zero, the velocity is maximum. Similarly, acceleration is offset 90º from velocity, and thus 180º from displacement.

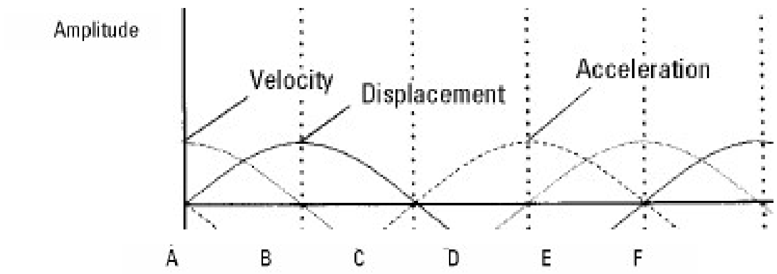


Figure 5.5. Velocity and acceleration of the vibration are offset 90º and 180º in phase from displacement.

The amplitudes of the vibration parameters also vary with rotation speed f_r (in Hz) – an important consideration in transducer selection. Velocity increases in direct proportion to frequency, while acceleration increases with the square of frequency. These relationships can be illustrated by using the following example with a simple sine wave:

Displacement: $x(t) = A\sin(2\pi f_r t)$

Velocity: $\frac{dx(t)}{dt} = 2\pi f_r A\cos(2\pi f_r t) = 2\pi f_r A\sin(2\pi f_r t + \pi/2)$

Acceleration: $\frac{d^2x(t)}{dt^2} = -(2\pi f_r)^2 A\sin(2\pi f_r t) = (2\pi f_r)^2 A\sin(2\pi f_r t + \pi)$.

These three vibration parameters are closely related and, in fact, can be derived from each other. One of these parameters could supply the necessary information for vibration analysis.

Figure 5.6 illustrates the impact of variations in amplitude with shaft rotation speed for a low-speed fan and a high-speed gear system, respectively. It can be noted from these two cases that: 1) displacement and acceleration levels differ widely, and 2) velocity is relatively constant.

(a) (b)

Figure 5.6. (a) 600 rpm fan: displacement: 10 mils pk-pk, velocity: 0.3 in/sec, acceleration: 0.1 g.
(b) 15 KHz gear mesh: displacement: 1.2 mils pk-pk, velocity: 0.12 in/sec, acceleration: 30 g.

From the above example, it is seen that frequency considerations are important in selecting a vibration parameter. Acceleration is not a good choice for very low frequency analysis, while displacement is not a good indicator for high frequency analysis. It should be noted that these properties are associated with the limitations of the vibration parameters not the transducers. In addition, frequency range limitations of transducers are also an important consideration in parameter selection, which will be discussed later.

Velocity is a parameter that is relatively independent of machine speed, or the vibration limit can be set independent of frequency. Velocity remains constant with damage level because it is proportional to the energy content of vibration. But the upper frequency limitation of velocity transducers can be a problem for high-speed system analysis (e.g., gears).

5.2.2 Mechanical impedance

As is illustrated in Figure 5.7, the measured vibration is the response of the machine to vibration forces, not the forces themselves. Thus the response characteristics of the machine – its mechanical impedance – have a direct impact on the measured vibration signal. The two key results of this are: (1) if the response is small, the vibration will be difficult to analyze, and (2) if response changes drastically with frequency, changes in running speed can produce misleading information in measurement. These are important considerations in selecting and installing transducers.

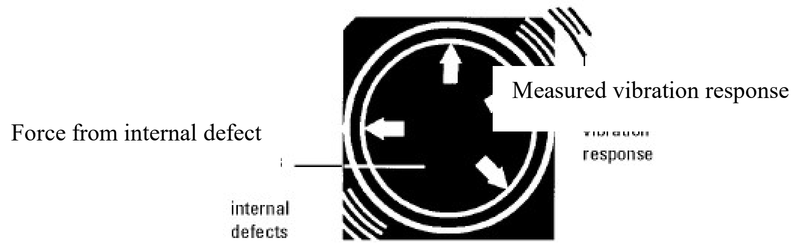


Figure 5.7. Vibration measured on a machine is the response to defect force, not the defect itself.

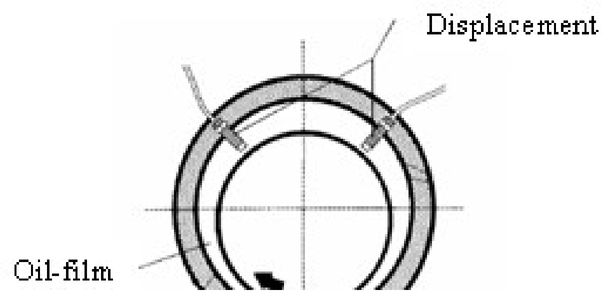


Figure 5.8. A relatively light shaft turning in fluid-film bearings transmits little vibration to the machine housing.

For the cases with low-level responses, such as machines with light rotors turning in fluid-film bearings, very little shaft vibration can be transmitted to the casing. Shaft vibration must be measured directly, as illustrated in Figure 5.8. Rolling element bearings are much stiffer than most fluid-film bearings, and can transmit shaft vibration to the bearing case well.

5.2.3 Natural frequencies

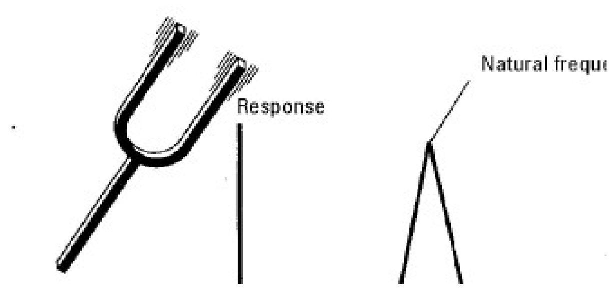


Figure 5.9. When excited by an impact, a tuning fork vibrates at its natural frequency.

In a vibration response plot, the response peaks usually occur at the natural frequencies. A good illustration of natural frequency-related vibration is a tuning fork as shown in Figure 5.9, which is designed to vibrate at a specific frequency when excited. When a vibration force is applied at a natural frequency, the structure will resonate, or respond with a large amplitude vibration.

Natural frequencies are related to machinery vibration analysis in three aspects: 1) resonances of the structure can cause changes in vibration level, 2) the dynamics of rotating shafts change significantly near natural frequencies, and 3) resonances of transducers will limit the operating frequency range of the measurement. Changes in vibration response with frequency are illustrated in Figure 5.10.

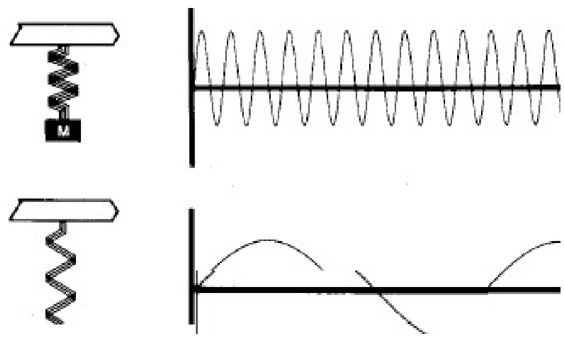
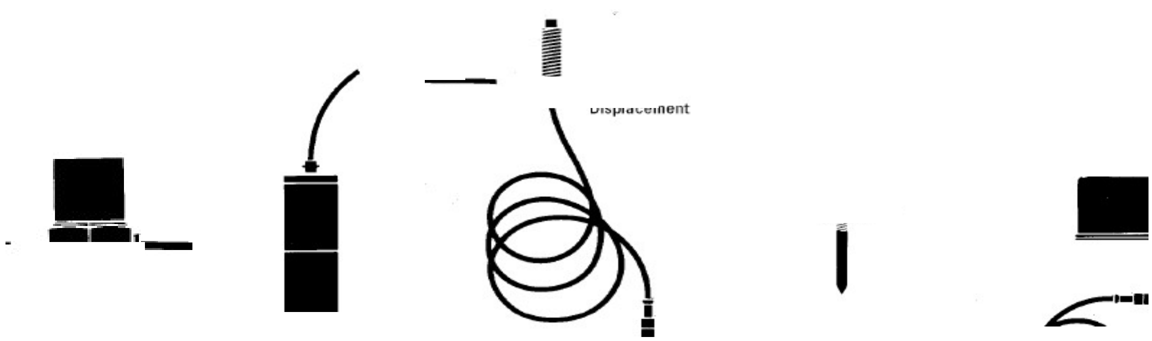


Figure 5.10. Vibration is related to natural frequency which varies with mass and stiffness.

5.3 Instrument and Measurement

5.3.1 Introduction

In measurement, vibration must be converted to an electrical signal – a task performed by vibration transducers (sensors). The key considerations in obtaining a signal that accurately represents the vibration are: 1) selecting the right type of transducer, and 2) locating and installing it correctly. The four types of transducers commonly used for vibration measurement are shown in Figure 5.12. They are differentiated by the parameter measured (i.e., displacement, velocity, or acceleration), and by the machine component measured (i.e., shaft or housing). Transducer selection depends on the characteristics of the machine of interest and its expected faults. Installation requires correct placement, secure mounting, and proper signal conditioning.



(a) (b) (c) (d)

Figure 5.11. Four types of commonly used transducers in vibration measurement for:
(a) acceleration; (b) velocity; (c) displacement; (d) tachometer

In addition to motion transducers, for some measurements, a tachometer can be used to measure the operating speed of the shaft, which produces a pulse type signal as opposed to the analog data normally found in motion transducers. The tachometer usually produces a fixed number of “pulses” per revolution, which is in turn converted to a rotation speed by a frequency counter. Common types of tachometers are the displacement probes and optical or magnetic sensors.

In the following subsections, we will briefly discuss the properties of different types of transducers and their common applications.

5.3.2 Displacement transducers

Noncontacting displacement transducers (also known as proximity probes), like the one as shown in Figure 5.11(c), can be used to measure relative shaft motion directly. A high frequency oscillator is used to set up eddy currents in the shaft without actually touching it. As the shaft moves relative to the sensor, the eddy current energy changes, modulating the oscillator voltage. This signal is demodulated, providing an output voltage proportional to displacement, as illustrated in Figure 5.12.

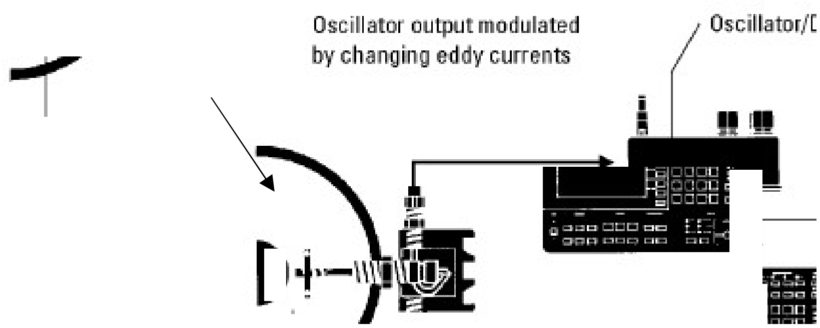


Figure 5.12. Schematic diagram of a typical noncontacting displacement transducer installation.

In practice, noncontacting displacement probes can be used on turbo-machinery because their flexible bearings (fluid film) and heavy housings result in small external responses. Some gas turbines, especially those used on aircraft, use relatively stiff rolling element bearings; and then housing-mounted acceleration and/or velocity transducers can be used for data collection. Some key characteristics of displacement transducers are listed as follows:

a) Displacement transducers measure relative motion between the shaft and the mount that is usually the machine housing. Thus, vibration of stiff shaft/bearing combination is difficult to measure using displacement transducers alone.

b) Signal conditioning is usually included in the electronics. Typical outputs are 200 mv/mil or 8 mv/micron (1 mil is 0.001 inches, 1 micron is 0.001 millimeters). Technically, the frequency response of displacement probes is up to 10,000 Hz (or 600,000 rpm), but in practice, the displacement levels at these frequencies are so low that the actual useful frequency range of proximity probes is up to 500 Hz.

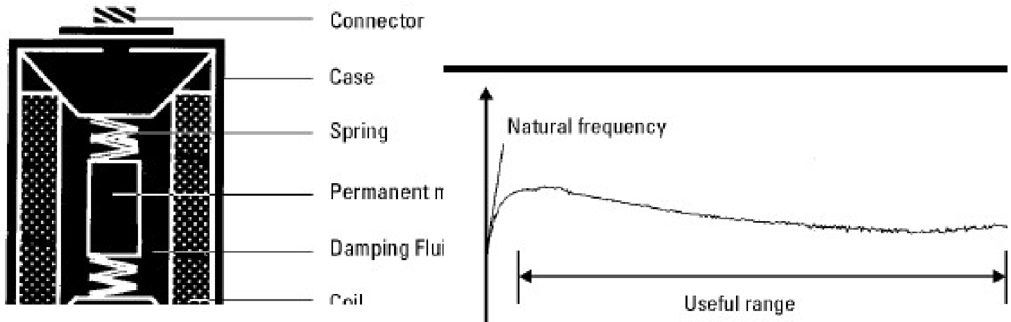
c) Shaft surface scratches, out-of-roundness, and variation in electrical properties will produce signal errors. Surface treatment and run-out subtraction can be used to solve these problems.

d) Sometimes it may be difficult to install displacement transducers, which often requires a hole to be drilled in the machine housing.

e) The output voltage usually contains a DC offset of 6 – 12 volts, requiring the use of AC coupling for sensitive measurements. AC coupling is a feature to block the DC quantities. On the contrary, DC coupling keeps both AC and DC components in the signal.

5.3.3 Velocity transducers

Velocity transducers were the first vibration transducers, and most early work in vibration measurement was done using velocity criteria. Velocity transducer construction is illustrated in Figure 5.13(a). The vibrating coil moving through the field of the magnet produces a relatively large output voltage; therefore it does not require signal conditioning. The amplitude of the voltage is directly proportional to the velocity of the vibration. As shown in Figure 5.13(b), the spring-mass-damper system is designed for a natural frequency of 8 to 10 Hz, which allows the magnet to stay essentially fixed in space. This establishes a lower frequency limit of approximately 10 Hz. The upper frequency limit is 1000 to 2000 Hz, determined by the inertia of the spring-mass-damper system.



(a) (b)

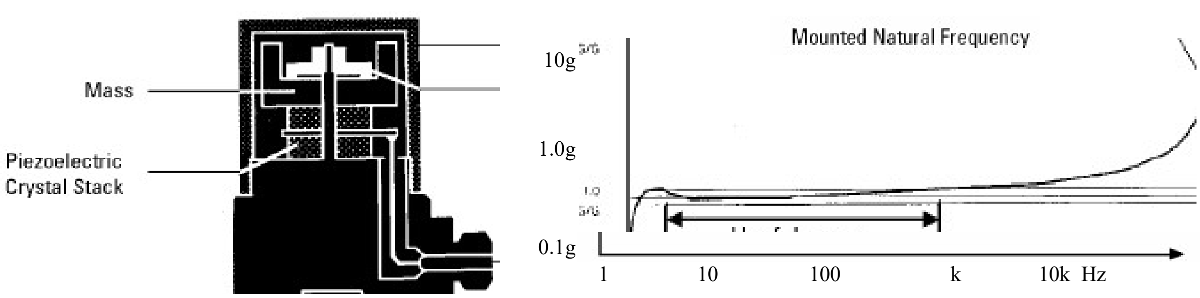
Figure 5.13. A typical velocity transducer: (a) structure; (b) frequency response.

Historically, the velocity transducer was widely used in vibration measurements. But in recent years most transducer manufactures have replaced this technology with accelerometers that have electrically integrated outputs to provide the same functionality as velocity probes but with wider frequency range and better stability.

5.3.4 Accelerometers

Accelerometers are the most popularly used vibration transducers. They are constructed using a number of different technologies. But for general purpose applications, the design is the piezoelectric quartz accelerometer, as illustrated in Figure 5.14(a). The vibrating mass applies a force on the piezoelectric crystal that produces a charge proportional to the force and thus to the acceleration. The frequency response of a typical accelerometer is shown in Figure 5.14(b). Note that the natural frequency is above the operating range of the transducer (unlike the velocity transducer). Operation should be limited to about 20% of the natural frequency.

Accelerometer sensitivity is largely dependent on the size of the mass: the larger the mass, the more output. High output is especially important for increasing the usability of accelerometers at low frequencies. However, as in our previous discussion of natural frequency, natural frequency decreases as mass increases. Thus, increase sensitivity will lead to decrease operating frequency range and increase physical size.



(a) (b)

Figure 5.14. A typical acceleration transducer: (a) structure; (b) frequency response.

Accelerometer output is a low-level, high-impedance signal, which requires special signal conditioning. The traditional method is to use a separate charge amplifier. However, special accelerometers are available with built-in signal condition electronics that require only a simple current-source supply. Such type of accelerometer, sometimes referred to as ICP (integrated circuit piezoelectric), can be directly connected to most data acquisition systems. Another advantage of the ICP accelerometer is that expensive low-noise cable required for normal piezoelectric accelerometers is not needed. This can be especially important when long or multiple cables are required.

The following summarizes the key characteristics of accelerometers:

a) Accelerometers offer the broadest frequency coverage of the three transducer types. Their weakness is related to their low frequency response, where low levels of acceleration result in small output voltages. This can be overcome by those models with built-in integrators to give velocity output, or by added extra signal processing functions.

b) The low frequency response of piezoelectric accelerometers is limited to approximately 5 Hz. This can be improved by using special accelerometers with special low frequency characteristics.

c) Accelerometers are very sensitive to mounting condition. Generally, accelerometers should be securely mounted using a threaded stud, high strength magnet, or industrial adhesive. The mounting surface should be flat and smooth – preferably – machined. Frequently, special mounting studs are bonded or welded in place where repeated measurements are to be made.

5.3.5 Tachometers

Tachometers are devices used to measure the rotation speed of a machine shaft. Tachometers differ from motion transducers in the fundamental variable measured. They measure the timing of an event; that is, the passing of a reference, such as a keyphasor. They are useful in determining operating speed. The transducer itself normally provides a pulse of some fixed amplitude at a rate related to rotation speed (typically once per revolution). We will discuss two common types of tachometers: proximity probes and optical tachometers.

The proximity probe is the same as previously discussed, however, it cannot be used to get accurate displacement information in this mode. It is commonly used to detect the presence of something such as a keyway slot (often referred to as a keyphasor) or gear tooth. Figure 5.15(a) illustrates a proximity probe detecting a keyway to provide a once-per-revolution signal. This transducer has many of the limitations as previously described.

Another common type of tachometer transducer is the optical sensor. It generally consists of either an optical or an infrared light source and a detector, as shown in Figure 5.15(b). Optionally, a lens is provided to focus the beam. The beam is trained on the rotation shaft to detect the presence of a reflective indicator (usually a piece of tape or reflective paint). On multi-channel measurement, the tachometer signal is fed into one channel of the measurement. This is useful in obtaining valuable phase information about the response channels.

(a)

(b)

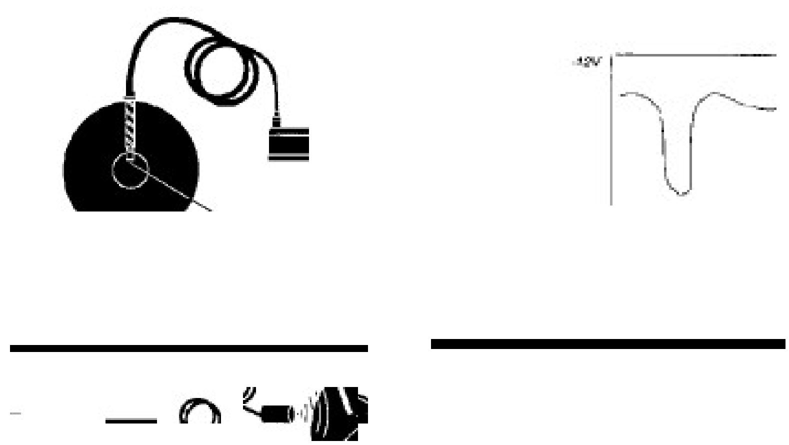


Figure 3.15. Two types of tachometers: (a) the proximity probe, (b) the optical tachometer.

5.3.6 Transducer selection

The following summarizes the process in selecting the right transducer for an application:

Step 1: The parameter of interest. If you are interested in monitoring a critical clearance or relative displacement, the only choose is a displacement transducer. Although acceleration and velocity can be converted to displacement, a displacement probe will provide an absolute measurement, rather than the relative measurement. If the parameter is a quantity other than a clearance or relative displacement, go on to the next step.

Step 2: Mechanical impedance considerations. If the vibration is not well transmitted to the machinery casing (e.g., a flexible rotor-bearing system), you must use a displacement transducer to measure the shaft run-out directly. If the shaft is not accessible (e.g., the internal shaft in a gearbox), or if the rotor-bearing system is stiff, you should use a casing mounted velocity or acceleration transducer. If Steps 1 and 2 indicate a displacement transducer, it is the one that will provide the best results. If a housing-mounted acceleration or velocity transducer is indicated, go on to Step 3.

Step 3: Frequency considerations. If the frequency of the expected vibration is greater than 1000 Hz, you must use an accelerometer. If the vibration is in the range of 10 to 1000 Hz, either velocity or acceleration transducers can be used; generally, an accelerometer will be the choice in these cases. The important thing to consider is the individual specifications of the accelerometer related to the frequency range and vibration level anticipated. Figure 5.16 illustrates the general performance of different types of transducers. In many cases for low frequency (<10 Hz) measurement or applications where the overall level is important to machinery health condition monitoring, a velocity output is required. This can be achieved using either a velocity transducer or more commonly an accelerometer with integrated output proportional to velocity.

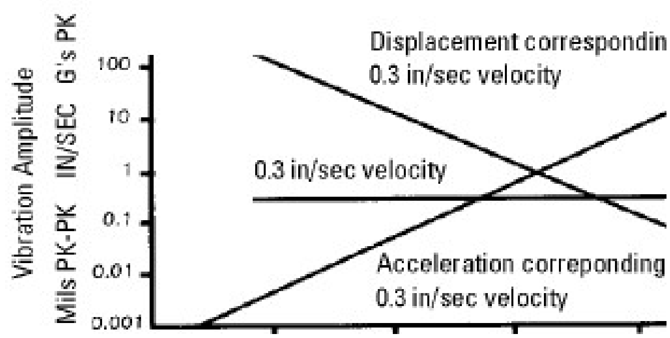


Figure 5.16. Performance comparison of different transducers.

5.3.7 Installation guidelines

After the transducer has been selected, it must be properly installed for reliable measurement. Figure 5.17 shows an example of a machine combination (i.e., a small motor and pump, or a steam turbine and generator). In general, the number of transducers used on a machine combination depends on the purpose of the measurement. Table 5.1 summarizes a guide for the application of transducers to machinery measurement applications.

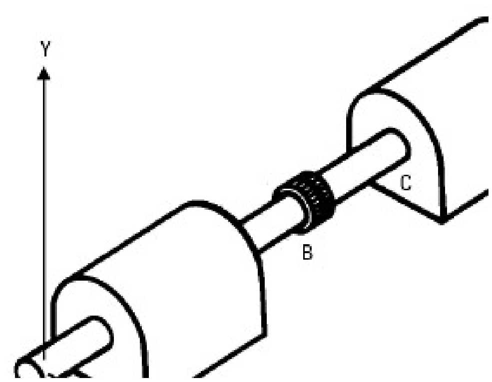


Figure 5.17. Transducer locations referenced in Table 5.1

Table 5.1. Transducer application summary

Machine Description	**Transducer Variable**	**Location**
Steam turbine/large pump or compressor A, B, C, D, with fluid-film bearings	Displacement	Radial horizontal at redundant axial at A and D
Gas turbine or medium size pump	Displacement	Radial horizontal and vertical at A and B
	Velocity	Radial horizontal or vertical at A and B
Motor/fan both with fluid-film bearings	Displacement or velocity	One radial at each bearing. One axial displacement to detect thrust wear
Motor/pump or compressor with fluid film bearings	Velocity or acceleration	One radial at each bearing. One axial, usually on motor, to detect thrust wear
Gearbox with rolling element bearings	Acceleration	Transducers mounted as close to each bearing as possible.
Gearbox with fluid film bearings	Displacement	Radial horizontal and vertical at each bearing. Axial to detect wear.

When troubleshooting a vibration problem, it is critical to get information on vibration of key components in the principal directions. The inclusion of phase information may be helpful in diagnosing machine dynamics problems. A few points should be kept in mind in designing a vibration measurement: the ultimate goal in measurement, careful transducer selection, transducer specification, and proper mounting of the transducer. One particular caution: the transducer should never be mounted to a sheet metal cover, because resonances may easily be in the operating speed range, which can mask the real objective of the measurement.