CHAPTER 12

VIBRATION TRANSDUCERS

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INTRODUCTION

This chapter on vibration transducers is the first in a group of seven chapters on the measurement of shock and vibration. Chapter 13 describes typical instrumentation used in making measurements with such devices; Chap. 15 covers the mounting of vibration transducers and how they may be calibrated under field conditions; more precise calibration under laboratory conditions is described in detail in Chap. 18. The selection of vibration transducers is treated in Chaps. 15 and 16. This chapter defines the terms and describes the general principles of piezoelectric and piezoresistive transducers; it also sets forth the mathematical basis for the use of shock and vibration transducers and includes a brief description of piezoelectric accelerometers, piezoresistive accelerometers, piezoelectric force and impedance gages, and piezoelectric drivers, along with a review of their performance and characteristics. Finally, the following various special types of transducers are considered: optical-electronic transducers, including laser Doppler vibrometers, displacement measurement systems, fiber-optic reflective displacement sensors, electrodynamic (velocity coil) pickups, differential-transformer pickups, servo accelerometers, and capacitance-type transducers.

Certain solid-state materials are electrically responsive to mechanical force; they often are used as the mechanical-to-electrical transduction elements in shock and vibration transducers. Generally exhibiting high elastic stiffness, these materials can be divided into two categories: the *self-generating type,* in which electric charge is generated as a direct result of applied force, and the *passive-circuit type,* in which applied force causes a change in the electrical characteristics of the material.

A *piezoelectric* material is one which produces an electric charge proportional to the stress applied to it, within its linear elastic range. Piezoelectric materials are of the self-generating type. A *piezoresistive* material is one whose electrical resistance depends upon applied force. Piezoresistive materials are of the passive-circuit type.

A *transducer* (sometimes called a *pickup* or *sensor*) is a device which converts shock or vibratory motion into an optical, a mechanical, or, most commonly, an electrical signal that is proportional to a parameter of the experienced motion.

A *transducing element* is the part of the transducer that accomplishes the conversion of motion into the signal.

A *measuring instrument* or *measuring system* converts shock and vibratory motion into an observable form that is directly proportional to a parameter of the experienced motion. It may consist of a transducer with transducing element, signal-conditioning equipment, and device for displaying the signal. An instrument contains all of these elements in one package, while a system utilizes separate packages.

An *accelerometer* is a transducer whose output is proportional to the acceleration input. The output of a force gage is proportional to the force input; an impedance gage contains both an accelerometer and a force gage.

CLASSIFICATION OF MOTION TRANSDUCERS

In principle, shock and vibration motions are measured with reference to a point fixed in space by either of two fundamentally different types of transducers:

1. *Fixed-reference transducer.* One terminal of the transducer is attached to a point that is fixed in space; the other terminal is attached (e.g., mechanically, electrically, optically) to the point whose motion is to be measured.
2. *Mass-spring transducer (seismic transducer).* The only terminal is the base of a mass-spring system; this base is attached at the point where the shock or vibration is to be measured. The motion at the point is inferred from the motion of the mass relative to the base.

MASS-SPRING TRANSDUCERS (SEISMIC TRANSDUCERS)

In many applications, such as moving vehicles or missiles, it is impossible to establish a fixed reference for shock and vibration measurements. Therefore, many transducers use the response of a mass-spring system to measure shock and vibration. A mass-spring transducer is shown schematically in Fig. 12.1; it consists of a mass m suspended from the transducer case a by a spring of stiffness k. The motion of the mass within the case may be damped by a viscous fluid or electric current, symbolized by a dashpot with damping coefficient c. It is desired to measure the motion of the moving part whose displacement with respect to fixed space is indicated by u. When the transducer case is attached to the moving part, the transducer may be used to measure displacement, velocity, or acceleration, depending on the portion of the frequency range which is utilized and whether the relative displacement or relative velocity $d\delta/dt$ is sensed by the transducing element. The typical response of the mass-spring system is analyzed in the following paragraphs and applied to the interpretation of transducer output.

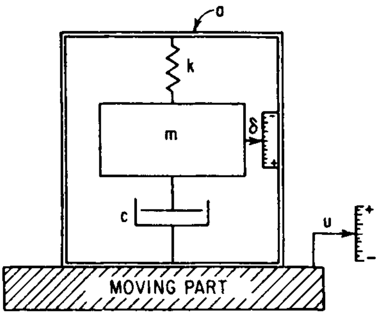


FIGURE 12.1 Mass-spring type of vibration-measuring instrument consisting of a mass m supported by spring k and viscous damper c. The case a of the instrument is attached to the moving part whose vibratory motion u is to be measured. The motion u is inferred from the relative motion δ between the mass m and the case a.[1]

Consider a transducer whose case experiences a displacement motion u, and let the relative displacement between the mass and the case be δ. Then the motion of the mass with respect to a reference fixed in space is $\delta + u$, and the force causing its acceleration is $m[d^2(\delta + u)/dt^2]$. Thus, the force applied by the mass to the spring and dashpot assembly is $-m[d^2(\delta + u)/dt^2]$. The force applied by the spring is $-k\delta$, and the force applied by the damper is $-c(d\delta/dt)$, where c is the damping coefficient. Adding all force terms and equating the sum to zero,

$$-m\frac{d^2(\delta + u)}{dt^2} - c\frac{d\delta}{dt} - k\delta = 0 \tag{12.1}$$

Equation (12.1) may be rearranged:

$$m\frac{d^2\delta}{dt^2} + c\frac{d\delta}{dt} + k\delta = -m\frac{d^2u}{dt^2} \tag{12.2}$$

Assume that the motion u is sinusoidal, $u = u_0 \cos \omega t$, where $\omega = 2\pi f$ is the angular frequency in radians per second and f is expressed in cycles per second. Neglecting transient terms, the response of the instrument is defined by $\delta = \delta_0 \cos (\omega t - \theta)$; then the solution of Eq. (12.2) is

$$\frac{\delta_0}{u_0} = \frac{\omega^2}{\sqrt{\left(\dfrac{k}{m} - \omega^2\right)^2 + \left(\omega\dfrac{c}{m}\right)^2}} \tag{12.3}$$

$$\theta = \tan^{-1}\frac{\omega\dfrac{c}{m}}{\dfrac{k}{m} - \omega^2} \tag{12.4}$$

The undamped natural frequency f_n of the instrument is the frequency at which

$$\frac{\delta_0}{u_0} = \infty$$

when the damping is zero ($c = 0$), or the frequency at which $\theta = 90°$. From Eqs. (12.3) and (12.4), this occurs when the denominators are zero:

$$\omega_n = 2\pi f_n = \sqrt{\frac{k}{m}} \qquad \text{rad/sec} \tag{12.5}$$

Thus, a stiff spring and/or light mass produces an instrument with a high natural frequency. A heavy mass and/or compliant spring produces an instrument with a low natural frequency.

The damping in a transducer is specified as a *fraction of critical damping.* Critical damping c_c is the minimum level of damping that prevents a mass-spring transducer from oscillating when excited by a step function or other transient. It is defined by

$$c_c = 2\sqrt{km} \tag{12.6}$$

Thus, the fraction of critical damping ζ is

$$\zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{km}} \tag{12.7}$$

It is convenient to define the excitation frequency ω for a transducer in terms of the undamped natural frequency ω_n by using the dimensionless frequency ratio

ω/ω_n. Substituting this ratio and the relation defined by Eq. (12.7), Eqs. (12.3) and (12.4) may be written

$$\frac{\delta_0}{u_0} = \frac{\left(\dfrac{\omega}{\omega_n}\right)^2}{\sqrt{\left[1 - \left(\dfrac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\dfrac{\omega}{\omega_n}\right)^2}} \tag{12.8}$$

$$\theta = \tan^{-1}\frac{2\zeta\dfrac{\omega}{\omega_n}}{1 - \left(\dfrac{\omega}{\omega_n}\right)^2} \tag{12.9}$$

The response of the mass-spring transducer given by Eq. (12.8) may be expressed in terms of the acceleration $\ddot{u}$ of the moving part by substituting $\ddot{u}_0 = -u_0\omega^2$. Then the ratio of the relative displacement amplitude δ_0 between the mass m and transducer case a to the impressed acceleration amplitude $\ddot{u}_0$ is

$$\frac{\delta_0}{\ddot{u}_0} = -\frac{1}{\omega_n^2}\left[\frac{1}{\sqrt{\left[1 - \left(\dfrac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\dfrac{\omega}{\omega_n}\right)^2}}\right] \tag{12.10}$$

The relation between δ_0/u_0 and the frequency ratio ω/ω_n is shown graphically in Fig. 12.2 for several values of the fraction of critical damping ζ. Corresponding curves for $\delta_0/\ddot{u}_0$ are shown in Fig. 12.3. The phase angle θ defined by Eq. (12.9) is shown graphically in Fig. 12.4, using the scale at the left side of the figure. Corresponding phase angles between the relative displacement δ and the velocity $\dot{u}$ and acceleration $\ddot{u}$ are indicated by the scales at the right side of the figure.

ACCELERATION-MEASURING TRANSDUCERS

As indicated in Fig. 12.3, the relative displacement amplitude δ_0 is directly proportional to the acceleration amplitude $\ddot{u}_0 = -u_0\omega^2$ of the sinusoidal vibration being measured, at small values of the frequency ratio ω/ω_n. Thus, when the natural frequency ω_n of the transducer is high, the transducer is an accelerometer. If the transducer is undamped, the response curve of Fig. 12.3 is substantially flat when $\omega/\omega_n <$ 0.2, approximately. Consequently, an undamped accelerometer can be used for the measurement of acceleration when the vibration frequency does not exceed approximately 20 percent of the natural frequency of the accelerometer. The range of measurable frequency increases as the damping of the accelerometer is increased, up to an optimum value of damping. When the fraction of critical damping is approximately 0.65, an accelerometer gives accurate results in the measurement of vibration at frequencies as great as approximately 60 percent of the natural frequency of the accelerometer.

As indicated in Fig. 12.3, the useful frequency range of an accelerometer increases as its natural frequency ω_n increases. However, the deflection of the spring in an accelerometer is inversely proportional to the square of the natural frequency; i.e., for a given value of $\ddot{u}_0$, the relative displacement is directly proportional to $1/\omega_n^2$ [see Eq. (12.10)]. As a consequence, the electrical signal from the transducing element may be very small, thereby requiring a large amplification to increase the signal to a level at which recording is feasible. For this reason, a compromise usually is

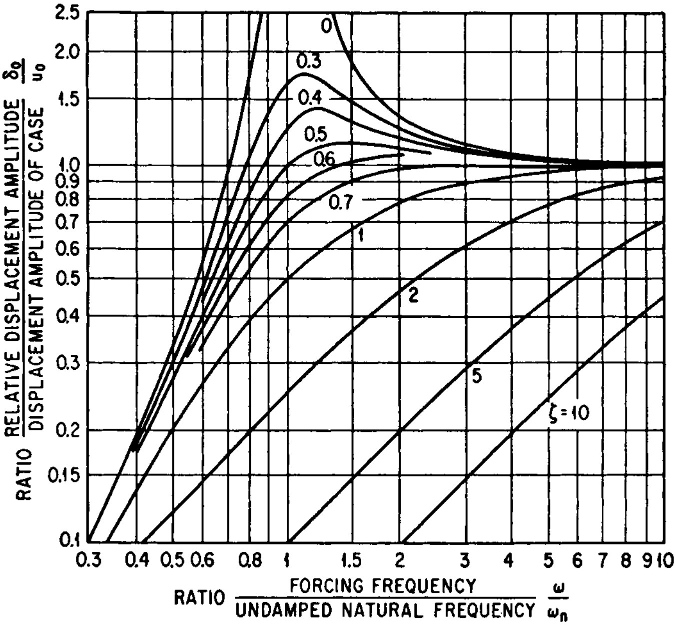


FIGURE 12.2 Displacement response δ_0/u_0 of a mass-spring system subjected to a sinusoidal displacement $\ddot{u} = u_0 \sin \omega t$. The fraction of critical damping ζ is indicated for each curve.

made between high sensitivity and the highest attainable natural frequency, depending upon the desired application.

ACCELEROMETER REQUIREMENTS FOR SHOCK

High-Frequency Response. The capability of an accelerometer to measure shock may be evaluated by observing the response of the accelerometer to acceleration pulses. Ideally, the response of the accelerometer (i.e., the output of the transducing element) should correspond identically with the pulse. In general, this result may be approached but not attained exactly. Three typical pulses and the corresponding responses of accelerometers are shown in Fig. 12.5 to 12.7. The pulses are shown in dashed lines. A sinusoidal pulse is shown in Fig. 12.5, a triangular pulse in Fig. 12.6, and a rectangular pulse in Fig. 12.7. Curves of the response of the accelerometer are shown in solid lines. For each of the three pulse shapes, the response is given for ratios τ_n/τ of 1.014 and 0.203, where τ is the pulse duration and $\tau_n = 1/f_n$ is the natural period of the accelerometer. These response curves, computed for the fraction of critical damping $\zeta = 0, 0.4, 0.7,$ and 1.0, indicate the following general relationships:

1. The response of the accelerometer follows the pulse most faithfully when the natural period of the accelerometer is smallest relative to the period of the pulse. For example, the responses at *A* in Figs. 12.5 to 12.7 show considerable deviation

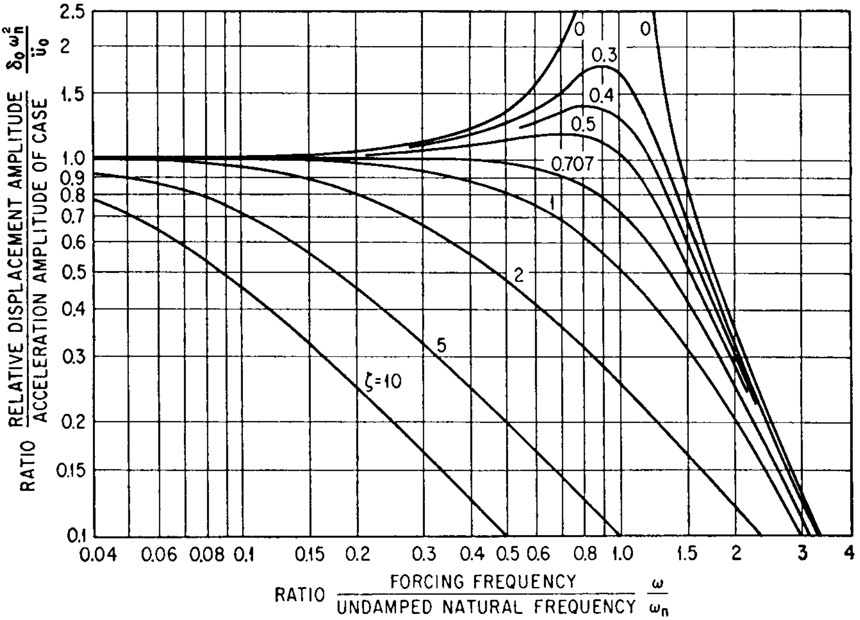


FIGURE 12.3 Relationship between the relative displacement amplitude δ_0 of a mass-spring system and the acceleration amplitude $\ddot{u}_0$ of the case. The fraction of critical damping ζ is indicated for each response curve.

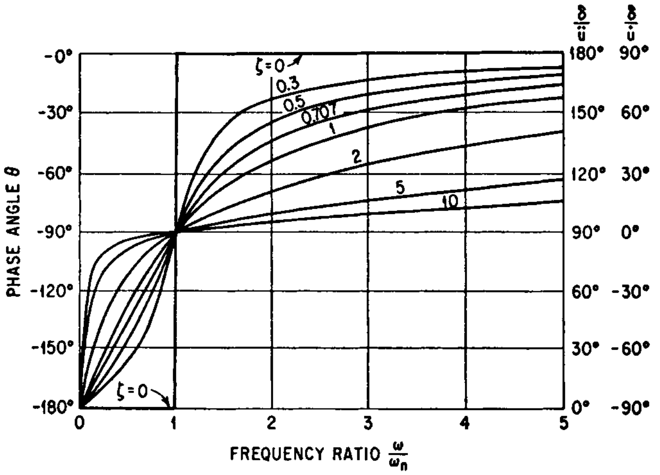


FIGURE 12.4 Phase angle of a mass-spring transducer when used to measure sinusoidal vibration. The phase angle θ on the left-hand scale relates the relative displacement δ to the impressed displacement, as defined by Eq. (12.9). The right-hand scales relate the relative displacement δ to the impressed velocity and acceleration.

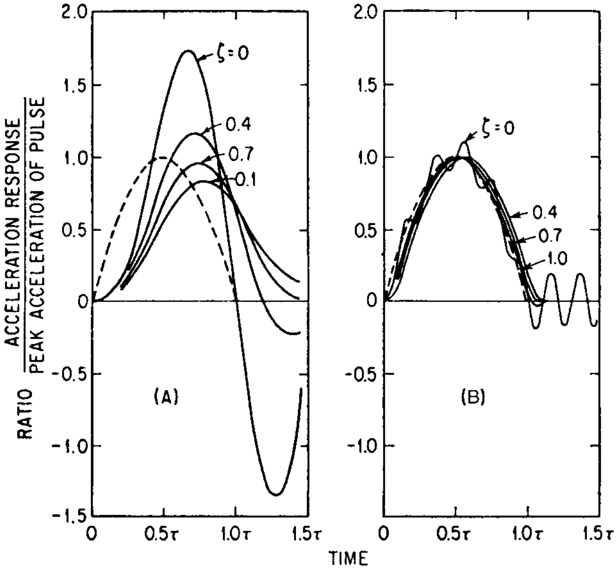


FIGURE 12.5 Acceleration response to a half-sine pulse of acceleration of duration τ (dashed curve) of a mass-spring transducer whose natural period τ_n is equal to: (*A*) 1.014 times the duration of the pulse and (*B*) 0.203 times the duration of the pulse. The fraction of critical damping ζ is indicated for each response curve. (*Levy and Kroll.*[1])

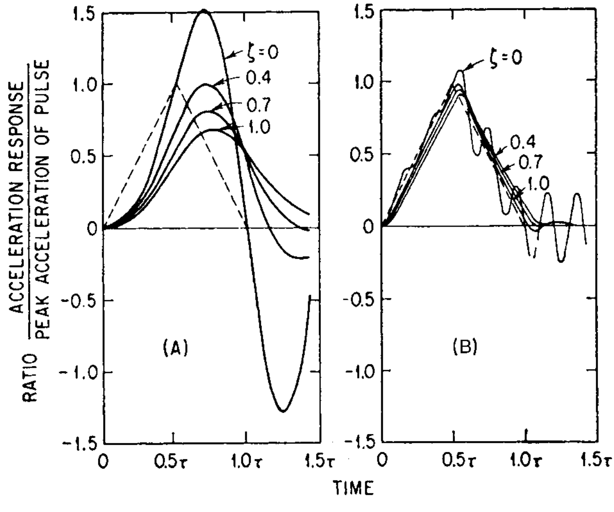


FIGURE 12.6 Acceleration response to a triangular pulse of acceleration of duration τ (dashed curve) of a mass-spring transducer whose natural period is equal to: (*A*) 1.014 times the duration of the pulse and (*B*) 0.203 times the duration of the pulse. The fraction of critical damping ζ is indicated for each response curve. (*Levy and Kroll.*[1])

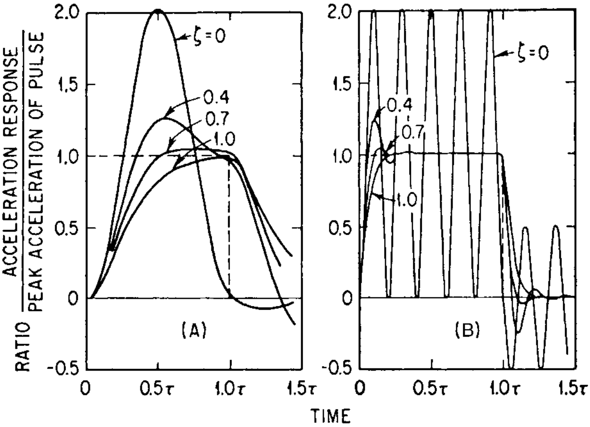


FIGURE 12.7 Acceleration response to a rectangular pulse of acceleration of duration τ (dashed curve) of a mass-spring transducer whose natural period τ_n is equal to: (*A*) 1.014 times the duration of the pulse and (*B*) 0.203 times the duration of the pulse. The fraction of critical damping ζ is indicated for each response curve. (*Levy and Kroll.*[1])

between the pulse and the response; this occurs when τ_n is approximately equal to τ. However, when τ_n is small relative to τ (Figs. 12.5*B* to 12.7*B*), the deviation between the pulse and the response is much smaller. If a shock is generated by metal-to-metal impact or by a pyrotechnic device such as that described in Chap. 26, Part II, *and* the response accelerometer is located in close proximity to the excitation source(s), the initial pulses of acceleration may have an extremely fast rise time and high amplitude. In such cases, any type of mass-spring accelerometer may not accurately follow the leading wave front and characterize the shock inputs faithfully. For example, measurements made in the near field of a high-*g* shock show that undamped piezoresistive accelerometers having resonance above 1 MHz were excited at resonance, thereby invalidating the measured responses. To avoid this effect, accelerometers should be placed as far away as possible, or practical, from the source of excitation. Other considerations related to accelerometer resonance are discussed below in the sections on *Zero Shift* and *Survivability.*

2. Damping in the transducer reduces the response of the transducer at its own natural frequency; i.e., it reduces the transient vibration superimposed upon the pulse, which is sometimes referred to as *ringing.* Damping also reduces the maximum value of the response to a value lower than the actual pulse in the case of large damping. For example, in some cases a fraction of critical damping ζ = 0.7 provides an instrument response that does not reach the peak value of the acceleration pulse.

Low-Frequency Response. The measurement of shock requires that the accelerometer and its associated equipment have good response at low frequencies because pulses and other types of shock motions characteristically include low-frequency components. Such pulses can be measured accurately only with an instrumentation system whose response is flat down to the lowest frequency of the spectrum; in general, this lowest frequency is zero for pulses.

The response of an instrumentation system is defined by a plot of output voltage vs. excitation frequency. For purposes of shock measurement, the decrease in response at low frequencies is significant. The decrease is defined quantitatively by the frequency f_c at which the response is down 3 dB or approximately 30 percent below the flat response which exists at the higher frequencies. The distortion which occurs in the measurement of a pulse is related to the frequency f_c as illustrated in Fig. 12.8.

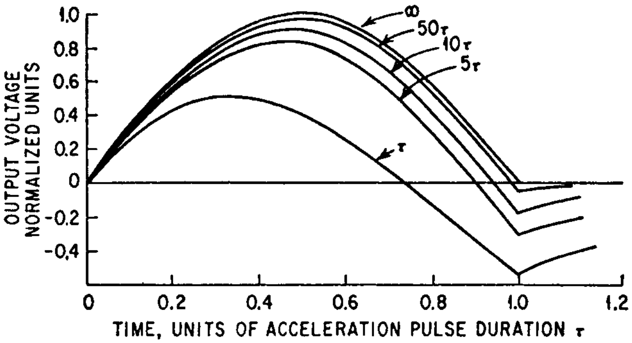


FIGURE 12.8 Response of an accelerometer to a half-sine acceleration pulse for *RC* time constants equal to τ, 5τ, 10τ, 50τ, and ∞, where τ is equal to the duration of the half-sine pulse.[1]

This is particularly important when acceleration data are integrated to obtain velocity, or integrated twice to obtain displacement. A small amount of undershoot shown in Fig. 12.8 may cause a large error after integration. A dc-coupled accelerometer (such as a piezoresistive accelerometer, described later in this chapter) is recommended for this type of application.

Zero Shift. *Zero shift* is the displacement of the zero-reference line of an accelerometer after it has been exposed to a very intense shock. This is illustrated in Fig. 12.9. The loss of zero reference and the apparent dc components in the time history cause a problem in peak-value determination and induce errors in shock response spectrum calculations. Although the accelerometer is not the sole source of zero shift, it is the main contributor.

All piezoelectric shock accelerometers, under extreme stress load (e.g., a sensing element at resonance), will exhibit zero-shift phenomena due either to crystal domain switching or to a sudden change in crystal preload condition.[2] A mechanical filter may be used to protect the crystal element(s) at the expense of a limitation in bandwidth or possible nonlinearity.[3] Piezoresistive shock accelerometers typically produce negligible zero shift.

Survivability. Survivability is the ability of an accelerometer to withstand intense shocks without affecting its performance. An accelerometer is usually rated in terms of the maximum value of acceleration it can withstand. Accelerometers used for shock measurements may have a range of well over many thousands of *g*s. In piezoresistive accelerometers which are excited at resonance, the stress buildup

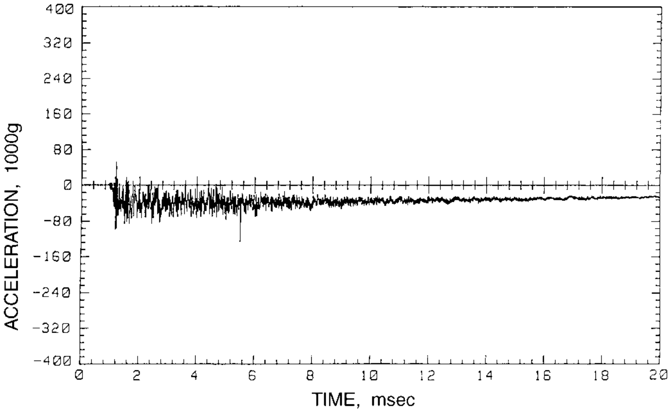


FIGURE 12.9 A time history of an accelerometer that has been exposed to a pyrotechnic shock. Note that there is a shift in the baseline (i.e., the zero reference) of the accelerometer as a result of this shock; the shift may either be positive or negative.

due to high magnitudes of acceleration may lead to fracture of the internal components. In contrast, piezoelectric accelerometers are more robust than their piezoresistive counterparts due to lower internal stress.

IMPORTANT CHARACTERISTICS OF ACCELEROMETERS

SENSITIVITY

The *sensitivity* of a shock- and vibration-measuring instrument is the ratio of its electrical output to its mechanical input. The output usually is expressed in terms of voltage per unit of displacement, velocity, or acceleration. This specification of sensitivity is sufficient for instruments which generate their own voltage independent of an external voltage power source. However, the sensitivity of an instrument requiring an external voltage usually is specified in terms of output voltage per unit of voltage supplied to the instrument per unit of displacement, velocity, or acceleration, e.g., millivolts per volt per g of acceleration. It is important to note the terms in which the respective parameters are expressed, e.g., average, rms, or peak. The relation between these terms is shown in Fig. 12.10. Also see Table 1.3.

RESOLUTION

The *resolution* of a transducer is the smallest change in mechanical input (e.g., acceleration) for which a change in the electrical output is discernible. The resolution of an accelerometer is a function of the transducing element and the mechanical design.

Recording equipment, indicating equipment, and other auxiliary equipment used with accelerometers often establish the resolution of the overall measurement system. If the electrical output of an instrument is indicated by a meter, the resolution may be established by the smallest increment that can be read from the meter. Resolution can be limited by noise levels in the instrument or in the system. In general, any signal change smaller than the noise level will be obscured by the noise, thus determining the resolution of the system.

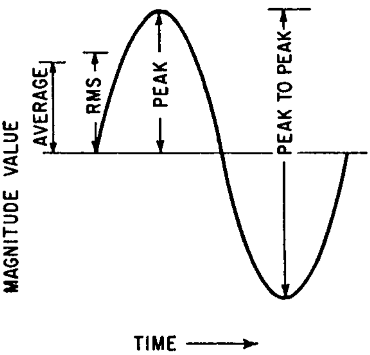


FIGURE 12.10 Relationships between average, rms, peak, and peak-to-peak values for a simple sine wave. These values are used in specifying sensitivities of shock and vibration transducers (e.g., peak millivolts per peak *g*, or rms millivolts per peak-to-peak displacement). These relationships do not hold true for other than simple sine waves.

TRANSVERSE SENSITIVITY

If a transducer is subjected to vibration of unit amplitude along its axis of maximum sensitivity, the amplitude of the voltage output $e_{\max}$ is the sensitivity. The sensitivity e_θ along the X axis, inclined at an angle θ to the axis of $e_{\max}$, is $e_\theta = e_{\max} \cos \theta$, as illustrated in Fig. 12.11. Similarly, the sensitivity along the Y axis is $e_t = e_{\max} \sin \theta$. In general, the sensitive axis of a transducer is designated. Ideally, the X axis would be designated the sensitive axis, and the angle θ would be zero. Practically, θ can be made only to approach zero because of manufacturing tolerances and/or unpredictable variations in the characteristics of the transducing element. Then the transverse sensitivity (cross-axis sensitivity) is expressed as the tangent of the angle, i.e., the ratio of e_t to e_θ:

$$\frac{e_t}{e_\theta} = \tan \theta \tag{12.11}$$

In practice, $\tan \theta$ is between 0.01 and 0.05 and is expressed as a percentage. For example, if $\tan \theta = 0.05$, the transducer is said to have a transverse sensitivity of 5 percent. Figure 12.12 is a typical polar plot of transverse sensitivity.

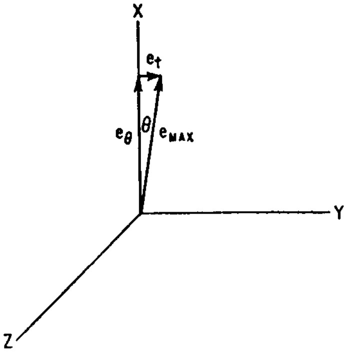


FIGURE 12.11 The designated sensitivity e_θ and cross-axis sensitivity e_t that result when the axis of maximum sensitivity $e_{\max}$ is not aligned with the axis of e_θ.

AMPLITUDE LINEARITY AND LIMITS

When the ratio of the electrical output of a transducer to the mechanical input (i.e., the sensitivity) remains constant within specified limits, the transducer is said to be "linear" within those limits, as illustrated in Fig. 12.13. A transducer is linear only over a certain range of amplitude values. The lower end of this range is determined by the electrical noise of the measurement system.

The upper limit of linearity may be imposed by the electrical characteristics

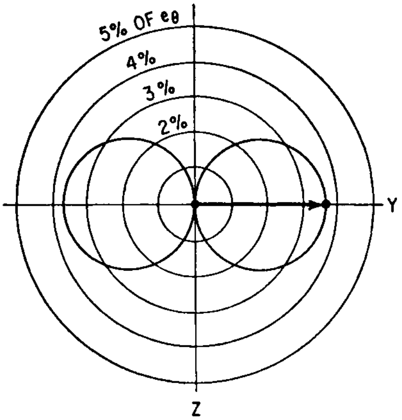


FIGURE 12.12 Plot of transducer sensitivity in all axes normal to the designated axis e_θ plotted according to axes shown in Fig. 12.11. Cross-axis sensitivity reaches a maximum e_t along the *Y* axis and a minimum value along the *Z* axis.

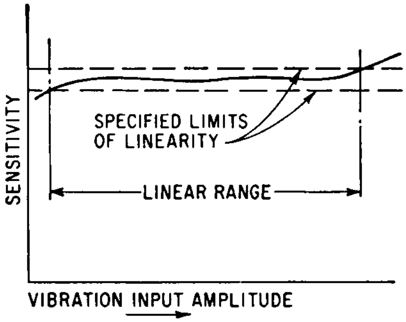


FIGURE 12.13 Typical plot of sensitivity as a function of amplitude for a shock and vibration transducer. The *linear range* is established by the intersection of the sensitivity curve and the specified limits (dashed lines).

of the transducing element and by the size or the fragility of the instrument. Generally, the greater the sensitivity of a transducer, the more nonlinear it will be. Similarly, for very large acceleration values, the large forces produced by the spring of the mass-spring system may exceed the yield strength of a part of the instrument, causing nonlinear behavior or complete failure.[2]

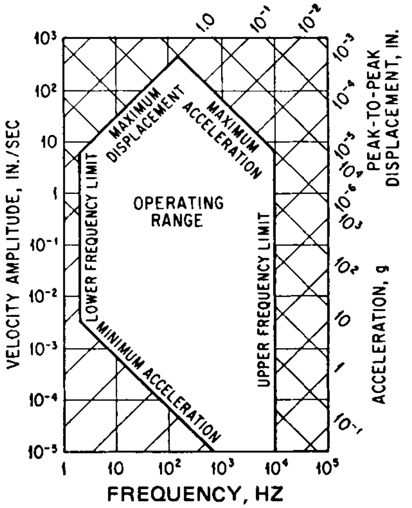


FIGURE 12.14 Linear operating range of a transducer. Amplitude linearity limits are shown as a combination of displacement and acceleration values. The lower amplitude limits usually are expressed in acceleration values as shown.

FREQUENCY RANGE

The operating frequency range is the range over which the sensitivity of the transducer does not vary more than a stated percentage from the rated sensitivity. This range may be limited by the electrical or mechanical characteristics of the transducer or by its associated auxiliary equipment. These limits can be added to amplitude linearity limits to define completely the operating ranges of the instrument, as illustrated in Fig. 12.14.

Low-Frequency Limit. The mechanical response of a mass-spring transducer does not impose a low-frequency limit for an acceleration transducer because the transducer responds to vibration with frequencies less than the natural frequency of the transducer.

In evaluating the low-frequency limit, it is necessary to consider the electrical characteristics of both the transducer and the associated equipment. In general, a transducing element that utilizes external power or a carrier voltage does not have a lower frequency limit, whereas a self-generating transducing element is not operative at zero frequency. The frequency response of amplifiers and other circuit components may limit the lowest usable frequency of an instrumentation system.

High-Frequency Limit. An acceleration transducer (accelerometer) has an upper usable frequency limit because it responds to vibration whose frequency is less than the natural frequency of the transducer. The limit is a function of (1) the natural frequency and (2) the damping of the transducer, as discussed with reference to Fig. 12.3. An attempt to use such a transducer beyond this frequency limit may result in distortion of the signal, as illustrated in Fig. 12.15.

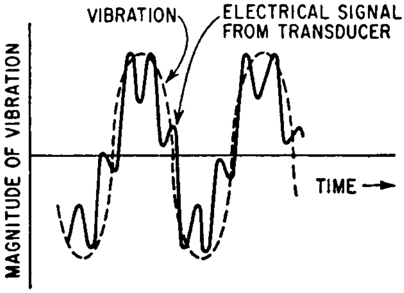


FIGURE 12.15 Distorted response (solid line) of a lightly damped ($\zeta < 0.1$) mass-spring accelerometer to vibration (dashed line) containing a small harmonic content of the small frequency as the natural frequency of the accelerometer.

The upper frequency limit for slightly damped vibration-measuring instruments is important because these instruments exaggerate the small amounts of harmonic content that may be contained in the motion, even when the operating frequency is well within the operating range of the instrument. The result of exciting an undamped instrument at its natural frequency may be to either damage the instrument or obscure the desired measurement. Figure 12.15 shows how a small amount of harmonic distortion in the vibratory motion may be exaggerated by an undamped transducer.

Phase Shift. Phase shift is the time delay between the mechanical input and the electrical output signal of the instrumentation system. Unless the phase-shift characteristics of an instrumentation system meet certain requirements, a distortion may be introduced that consists of the superposition of vibration at several different frequencies. Consider first an accelerometer, for which the phase angle θ_1 is given by Fig. 12.4. If the accelerometer is undamped, $\theta_1 = 0$ for values of ω/ω_n less than 1.0; thus, the phase of the relative displacement δ is equal to that of the acceleration being measured, for all values of frequency within the useful range of the accelerometer. Therefore, an undamped accelerometer measures acceleration without distortion of phase. If the fraction of critical damping ζ for the accelerometer is 0.65, the phase angle θ_1 increases approximately linearly with the frequency ratio ω/ω_n within the useful frequency range of the accelerometer. Then the expression for the relative displacement may be written

$$\delta = \delta_0 \cos(\omega t - \theta) = \delta_0 \cos(\omega t - a\omega) = \delta_0 \cos \omega(t - a) \tag{12.12}$$

where a is a constant. Thus, the relative motion δ of the instrument is displaced in phase relative to the acceleration $\ddot{u}$ being measured; however, the increment along the time axis is a constant independent of frequency. Consequently, the waveform of the accelerometer output is undistorted but is delayed with respect to the waveform of the vibration being measured. As indicated by Fig. 12.4, any value of damping in an accelerometer other than $\zeta = 0$ or $\zeta = 0.65$ (approximately) results in a nonlinear shift of phase with frequency and a consequent distortion of the waveform.

ENVIRONMENTAL EFFECTS

Temperature. The sensitivity, natural frequency, and damping of a transducer may be affected by temperature. The specific effects produced depend on the type of transducer and the details of its design. The sensitivity may increase or decrease with temperature, or remain relatively constant. Figure 12.16 shows the variation of damping with temperature for several different damping media. Either of two methods may be employed to compensate for temperature effects.

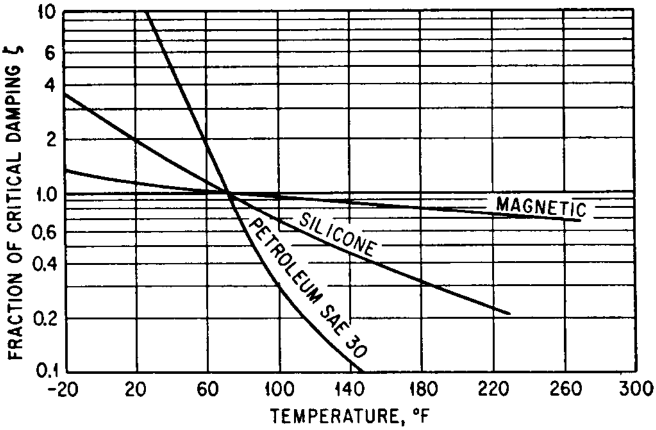


FIGURE 12.16 Variation of damping with temperature for different damping means. The ordinate indicates the fraction of critical damping ζ at various temperatures assuming $\zeta = 1$ at 70°F (21°C).

1. The temperature of the pickup may be held constant by local heating or cooling.
2. The pickup characteristics may be measured as a function of temperature; if necessary, the appropriate corrections can then be applied to the measured data.

Humidity. Humidity may affect the characteristics of certain types of vibration instruments. In general, a transducer which operates at a high electrical impedance is affected by humidity more than a transducer which operates at a low electrical impedance. It usually is impractical to correct the measured data for humidity effects. However, instruments that might otherwise be adversely affected by humidity often are sealed hermetically to protect them from the effects of moisture.

Acoustic Noise. High-intensity sound waves often accompany high-amplitude vibration. If the case of an accelerometer can be set into vibration by acoustic excitation, error signals may result. In general, a well-designed accelerometer will not produce a significant electrical response except at extremely high sound pressure levels. Under such circumstances, it is likely that vibration levels also will be very high, so that the error produced by the accelerometer's exposure to acoustic noise usually is not important.

Strain Sensitivity. An accelerometer may generate a spurious output when its case is strained or distorted. Typically this occurs when the transducer mounting is not flat against the surface to which it is attached, and so this effect is often called *base-bend sensitivity* or *strain sensitivity.* It is usually reported in equivalent g per microstrain, where 1 *microstrain* is 1×10^{-6} inch per inch. The Instrument Society of America recommends a test procedure that determines strain sensitivity at 250 microstrain.[4]

An accelerometer with a sensing element which is tightly coupled to its base tends to exhibit large strain sensitivity. An error due to strain sensitivity is most likely to occur when the accelerometer is attached to a structure which is subject to large amounts of flexure. In such cases, it is advisable to select an accelerometer with low strain sensitivity.

PHYSICAL PROPERTIES

Size and weight of the transducer are very important considerations in many vibration and shock measurements. A large instrument may require a mounting structure that will change the local vibration characteristics of the structure whose vibration is being measured. Similarly, the added mass of the transducer may also produce substantial changes in the vibratory response of such a structure. Generally, the natural frequency of a structure is lowered by the addition of mass; specifically, for a simple spring-mass structure:

$$\frac{f_n - \Delta f_n}{f_n} = \sqrt{\frac{m}{m + \Delta m}} \tag{12.13}$$

where f_n = natural frequency of structure
Δf_n = change in natural frequency
m = mass of structure
Δm = increase in mass resulting from addition of transducer

In general, for a given type of transducing element, the sensitivity increases approximately in proportion to the mass of the transducer. In most applications, it is more important that the transducer be small in size than that it have high sensitivity because amplification of the signal increases the output to a usable level.

Mass-spring-type transducers for the measurement of displacement usually are larger and heavier than similar transducers for the measurement of acceleration. In the former, the mass must remain substantially stationary in space while the instrument case moves about it; this requirement does not exist with the latter.

For the measurement of shock and vibration in aircraft or missiles, the size and weight of not only the transducer but also the auxiliary equipment are important. In these applications, self-generating instruments that require no external power may have a significant advantage.

PIEZOELECTRIC ACCELEROMETERS[5]

PRINCIPLE OF OPERATION

An accelerometer of the type shown in Fig. 12.17*A* is a linear seismic transducer utilizing a piezoelectric element in such a way that an electric charge is produced which is proportional to the applied acceleration. This "ideal" seismic piezoelectric transducer can be represented (over most of its frequency range) by the elements shown in Fig. 12.17*B*. A mass is supported on a linear spring which is fastened to the frame of the instrument. The piezoelectric crystal which produces the charge acts as the spring. Viscous damping between the mass and the frame is represented by the dashpot *c*. In Fig. 12.17*C* the frame is given an acceleration upward to a displacement of *u*, thereby producing a compression in the spring equal to δ. The displacement of the mass relative to the frame is dependent upon the applied acceleration of the frame, the spring stiffness, the mass, and the viscous damping between the mass and the frame, as indicated in Eq. (12.10) and illustrated in Fig. 12.3.

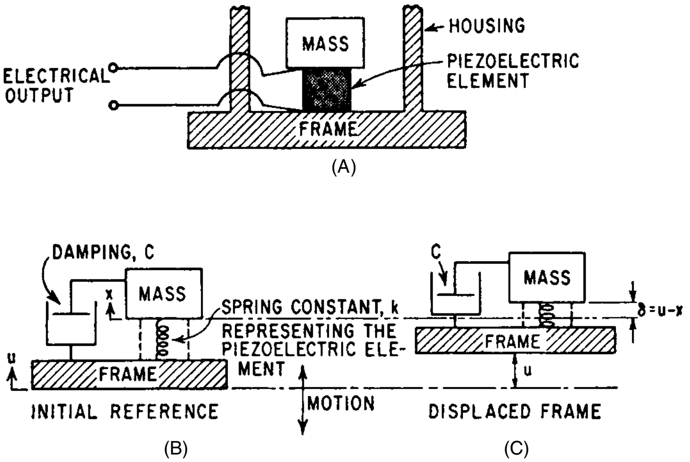


FIGURE 12.17 (*A*) Schematic diagram of a linear seismic piezoelectric accelerometer. (*B*) A simplified representation of the accelerometer shown in (*A*) which applies over most of the useful frequency range. A mass *m* rests on the piezoelectric element, which acts as a spring having a spring constant *k*. The damping in the system, represented by the dashpot, has a damping coefficient *c*. (*C*) The frame is accelerated upward, producing a displacement *u* of the frame, moving the mass from its initial position by an amount *x*, and compressing the spring by an amount δ.

For frequencies far below the resonance frequency of the mass and spring, this displacement is directly proportional to the acceleration of the frame and is independent of frequency. At low frequencies, the phase angle of the relative displacement δ, with respect to the applied acceleration, is proportional to frequency. As indicated in Fig. 12.4, for low fractions of critical damping which are characteristic of many piezoelectric accelerometers, the phase angle is proportional to frequency at frequencies below 30 percent of the resonance frequency.

In Fig. 12.17, inertial force of the mass causes a mechanical strain in the piezoelectric element, which produces an electric charge proportional to the stress and, hence, proportional to the strain and acceleration. If the dielectric constant of the piezoelectric material does not change with electric charge, the voltage generated is also proportional to acceleration. Metallic electrodes are applied to the piezoelectric element, and electrical leads are connected to the electrodes for measurement of the electrical output of the piezoelectric element.

In the ideal seismic system shown in Fig. 12.17, the mass and the frame have infinite stiffness, the spring has zero mass, and viscous damping exists only between the mass and the frame. In practical piezoelectric accelerometers, these assumptions cannot be fulfilled. For example, the mass may have as much compliance as the piezoelectric element. In some seismic elements, the mass and spring are inherently a single structure. Furthermore, in many practical designs where the frame is used to hold the mass and piezoelectric element, distortion of the frame may produce mechanical forces upon the seismic element. All these factors may change the performance of the seismic system from those calculated using equations based on an ideal system. In particular, the resonance frequency of the piezoelectric combination may be substantially lower than that indicated by theory. Nevertheless, the equations for an ideal system are useful both in design and application of piezoelectric accelerometers.

Figure 12.18 shows a typical frequency response curve for a piezoelectric accelerometer. In this illustration, the electrical output in millivolts per *g* acceleration is plotted as a function of frequency. The resonance frequency is denoted by f_n. If the accelerometer is properly mounted on the device being tested, then the upper frequency limit of the useful frequency range usually is taken to be $f_n/3$ for a deviation of 12 percent (1 dB) from the mean value of the response. For a deviation of 6 percent (0.5 dB) from the mean value, the upper frequency limit usually is taken to be $f_n/5$. As indicated in Fig. 12.1, the type of mounting can have a significant effect on the value of f_n.

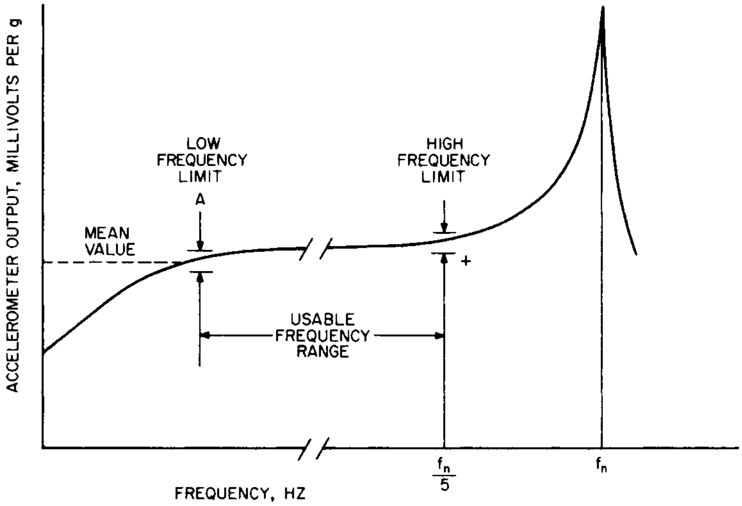


FIGURE 12.18 Typical response curve for a piezoelectric accelerometer. The resonance frequency is denoted by f_n. The useful range depends on the acceptable deviation from the mean value of the response over the "flat" portion of the response curve.

The decrease in response at low frequencies (i.e., the "rolloff") depends primarily on the characteristics of the preamplifier that follows the accelerometer. The low-frequency limit also is usually expressed in terms of the deviation from the mean value of the response over the flat portion of the response curve, being the frequency at which the response is either 12 percent (1 dB) or 6 percent (0.5 dB) below the mean value.

PIEZOELECTRIC MATERIALS

A polarized ceramic called lead zirconate titanate (PZT) is most commonly used in piezoelectric accelerometers. It is low in cost, high in sensitivity, and useful in the temperature range from –180° to +550°F (–100° to +288°C). Polarized ceramics in the bismuth titanate family have substantially lower sensitivities than PZT, but they also have more stable characteristics and are useful at temperatures as high as 1000°F (538°C).

Quartz, the single-crystal material most widely used in accelerometers, has a substantially lower sensitivity than polarized ceramics, but its characteristics are very stable with time and temperature; it has high resistivity. Lithium niobate and tourmaline are single-crystal materials that can be used in accelerometers at high temperatures: lithium niobate up to at least 1200°F (649°C), and tourmaline up to at least 1400°F (760°C). The upper limit of the useful range is usually set by the thermal characteristics of the structural materials rather than by the characteristics of these two crystalline materials.

Polarized polyvinylidene fluoride (PVDF), an engineering plastic similar to Teflon, is used as the sensing element in some accelerometers. It is inexpensive, but it is generally less stable with time and with temperature changes than ceramics or single-crystal materials. In fact, because PVDF materials are highly pyroelectric, they are used as thermal sensing devices.

TYPICAL PIEZOELECTRIC ACCELEROMETER CONSTRUCTIONS

Piezoelectric accelerometers utilize a variety of seismic element configurations. Their methods of mounting are described in Chap. 15. See also Ref. 6. Most are constructed of polycrystalline ceramic piezoelectric materials because of their ease of manufacture, high piezoelectric sensitivity, and excellent time and temperature stability. These seismic devices may be classified in two modes of operation: compression- or shear-type accelerometers.

Compression-type Accelerometer. The compression-type seismic accelerometer, in its simplest form, consists of a piezoelectric disc and a mass placed on a frame as shown in Fig. 12.17. Motion in the direction indicated causes compressive (or tensile) forces to act on the piezoelectric element, producing an electrical output proportional to acceleration. In this example, the mass is cemented with a conductive material to the piezoelectric element which, in turn, is cemented to the frame. The components must be cemented firmly so as to avoid being separated from each other by the applied acceleration.

In the typical commercial accelerometer shown in Fig. 12.19, the mass is held in place by means of a stud extending from the frame through the ceramic. Accelerometers of this design often use quartz, tourmaline, or ferroelectric ceramics as the sensing material.

This type of accelerometer must be attached to the structure with care in order to minimize distortion of the housing and base which can cause an electrical output. See the section on *Strain Sensitivity.*

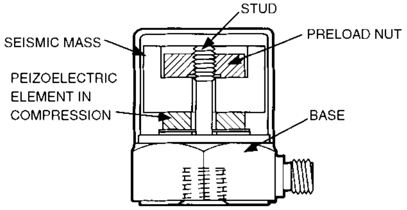


FIGURE 12.19 A typical compression-type piezoelectric accelerometer. The piezoelectric element(s) must be preloaded (biased) to produce an electrical output under both tension forces and compression forces. (*Courtesy of Endevco Corp.*)

The temperature characteristics of compression-type accelerometers have been improved greatly in recent years; it is now possible to measure acceleration over a temperature range of –425 to +1400°F (–254 to +760°C). This wider range has been primarily a result of the use of two piezoelectric materials: tourmaline and lithium niobate.

Shear-type Accelerometers. One shear-type accelerometer utilizes flat-plate shear-sensing elements. Manufacturers preload these against a flattened post element in several ways. Two methods are shown in Fig. 12.20. Accelerometers of this style have low cross-axis response, excellent temperature characteristics, and negligible output from strain sensitivity or base bending. The temperature range of the bolted shear design can be from –425 to +1400°F (–254 to +760°C). The following are typical specifications: sensitivity, 10 to 500 picocoulombs/*g*; acceleration range, 1 to 500*g*; resonance frequency, 25,000 Hz; useful frequency range, 3 to 5000 Hz; temperature range, –425 to +1400°F (–254 to 760°C); transverse response, 3 percent.

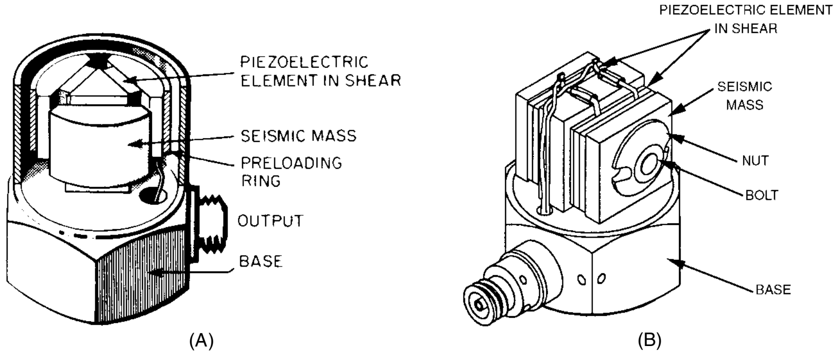


FIGURE 12.20 Piezoelectric accelerometers: (*A*) Delta-shear type. (*Courtesy of Bruel & Kjaer.*) (*B*) Isoshear type. (*Courtesy of Endevco Corp.*)

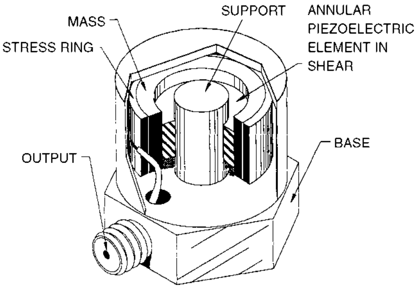
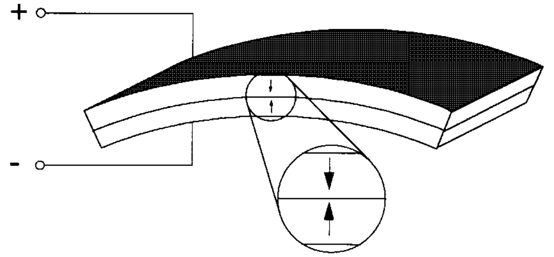


FIGURE 12.21 An annular shear accelerometer. The piezoelectric element is cemented to the post and mass. Electrical connections (not shown) are made to the inner and outer diameters of the piezoelectric element. (*Courtesy of Endevco Corp.*)

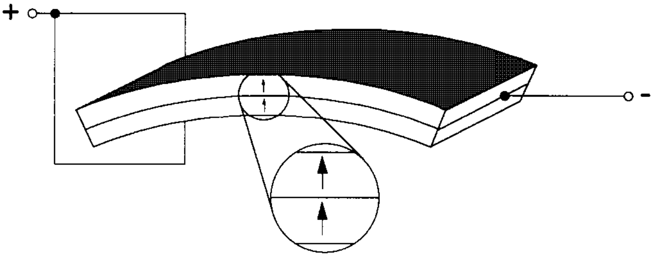
Another shear-type accelerometer, illustrated in Fig. 12.21, employs a cylindrically shaped piezoelectric element fitted around a middle mounting post; a loading ring (or mass) is cemented to the outer diameter of the piezoelectric element. The cylinder is made of ceramic and is polarized along its length; the output voltage of the accelerometer is taken from its inner and outer walls. This type of design can be made extremely small and is generally known as an axially poled shear-mode annular accelerometer.

Beam-type Accelerometers. The beam-type accelerometer is a variation of the compression-type accelerometer.

It is usually made from two piezoelectric plates which are rigidly bonded together to form a beam supported at one end, as illustrated in Fig. 12.22. As the beam flexes, the bottom element compresses, so that it increases in thickness. In contrast, the upper element expands, so that it decreases in thickness. Accelerometers of this type generate high electrical output for their size, but are more fragile and have a lower resonance frequency than most other designs.



(A)



(B)

FIGURE 12.22 Configurations of piezoelectric elements in a beam-type accelerometer. (*A*) A series arrangement, in which the two elements have opposing directions of polarization. (*B*) A parallel arrangement, in which the two elements have the same direction of polarization.

PHYSICAL CHARACTERISTICS OF PIEZOELECTRIC ACCELEROMETERS

Shape, Size, and Weight. Commercially available piezoelectric accelerometers usually are cylindrical in shape. They are available with both attached and detachable mounting studs at the bottom of the cylinder. A coaxial cable connector is provided at either the top or side of the housing.

Most commercially available piezoelectric accelerometers are relatively light in weight, ranging from approximately 0.005 to 4.2 oz (0.14 to 120 grams). Usually, the larger the accelerometer, the higher its sensitivity and the lower its resonance frequency. The smallest units have a diameter of less than about 0.2 in. (5 mm); the larger units have a diameter of about 1 in. (25.4 mm) and a height of about 1 in. (25.4 mm).

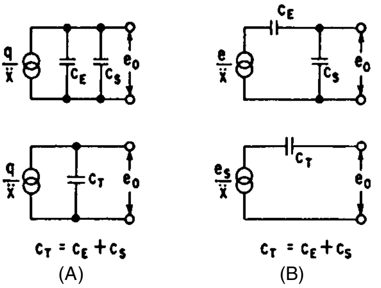
Resonance Frequency. The highest fundamental resonance frequency of an accelerometer may be above 100,000 Hz. The higher the resonance frequency, the lower will be the sensitivity and the more difficult it will be to provide mechanical damping.

Damping. The *amplification ratio* of an accelerometer is defined as the ratio of the sensitivity at its resonance frequency to the sensitivity in the frequency band in which sensitivity is independent of frequency. This ratio depends on the amount of damping in the seismic system; it decreases with increasing damping. Most piezoelectric accelerometers are essentially undamped, having amplification ratios between 20 and 100, or a fraction of critical damping less than 0.1.

ELECTRICAL CHARACTERISTICS OF PIEZOELECTRIC ACCELEROMETERS

Dependence of Voltage Sensitivity on Shunt Capacitance. The *sensitivity* of an accelerometer is defined as the electrical output per unit of applied acceleration. The sensitivity of a piezoelectric accelerometer can be expressed as either a *charge sensitivity* $q/\ddot{x}$ or *voltage sensitivity* $e/\ddot{x}$. Charge sensitivity usually is expressed in units of coulombs generated per g of applied acceleration; voltage sensitivity usually is expressed in volts per g (where g is the acceleration of gravity). Voltage sensitivity often is expressed as open-circuit voltage sensitivity, i.e., in terms of the voltage produced across the electrical terminals per unit acceleration when the electrical load impedance is infinitely high. Open-circuit voltage sensitivity may be given either with or without the connecting cable.

An electrical capacitance often is placed across the output terminals of a piezoelectric transducer. This added capacitance (called *shunt capacitance*) may result from the connection of an electrical cable between the pickup and other electrical equipment (all electrical cables exhibit interlead capacitance). The effect of shunt capacitance in reducing the sensitivity of a pickup is shown in Fig. 12.23.



(A) (B)

FIGURE 12.23 Equivalent circuits which include shunt capacitance across a piezoelectric pickup. (*A*) Charge equivalent circuit. (*B*) Voltage equivalent circuit.

The charge equivalent circuits, with shunt capacitance C_S, are shown in Fig. 12.23*A*. The charge sensitivity is not changed by addition of shunt capacitance. The total capacitance C_T of the pickup including shunt is given by

$$C_T = C_E + C_S \tag{12.14}$$

where C_E is the capacitance of the transducer without shunt capacitance.

The voltage equivalent circuits are shown in Fig. 12.23*B*. With the shunt capacitance C_S, the total capacitance is given by Eq. (12.14) and the open-circuit voltage sensitivity is given by

$$\frac{e_s}{\ddot{x}} = \frac{q_s}{\ddot{x}} \frac{1}{C_E + C_S} \tag{12.15}$$

where $q_s/\ddot{x}$ is the charge sensitivity. The voltage sensitivity without shunt capacitance is given by

$$\frac{e}{\ddot{x}} = \frac{q_s}{\ddot{x}} \frac{1}{C_E} \tag{12.16}$$

Therefore, the effect of the shunt capacitance is to reduce the voltage sensitivity by a factor

$$\frac{e_s/\ddot{x}}{e/\ddot{x}} = \frac{C_E}{C_E + C_S} \tag{12.17}$$

Piezoelectric accelerometers are used with both voltage-sensing and charge-sensing signal conditioners, although charge sensing is by far the most common because the sensitivity does not change with external capacitance (up to a limit). These factors are discussed in Chap. 13. In addition, electronic circuitry can be placed within the case of the accelerometer, as discussed below.

LOW-IMPEDANCE PIEZOELECTRIC ACCELEROMETERS CONTAINING INTERNAL ELECTRONICS

Piezoelectric accelerometers are available with simple electronic circuits internal to their cases to provide signal amplification and low-impedance output. For example, see the charge preamplifier circuit shown in Fig. 13.2. Some designs operate from low-current dc voltage supplies and are designed to be intrinsically safe when coupled by appropriate barrier circuits. Other designs have common power and signal lines and use coaxial cables.

The principal advantages of piezoelectric accelerometers with integral electronics are that they are relatively immune to cable-induced noise and spurious response, they can be used with lower-cost cable, and they have a lower signal conditioning cost. In the simplest case the power supply might consist of a battery, a resistor, and a capacitor. Some such accelerometers provide a velocity or displacement output. These advantages do not come without compromise.[7] Because the impedance-matching circuitry is built into the transducer, gain cannot be adjusted to utilize the wide dynamic range of the basic transducer. Ambient temperature is limited to that which the circuit will withstand, and this is considerably lower than that of the piezoelectric sensor itself. In order to retain the advantages of small size, the integral electronics must be kept relatively simple. This precludes the use of multiple filtering and dynamic overload protection and thus limits their application.

All other things being equal, the *reliability factor* (i.e., the mean time between failures) of any accelerometer with internal electronics is lower than that of an accelerometer with remote electronics, especially if the accelerometer is subject to abnormal environmental conditions. However, if the environmental conditions are fairly normal, accelerometers with internal electronics can provide excellent signal fidelity and immunity from noise. Internal electronics provides a reduction in overall system noise level because it minimizes the cable capacitance between the sensor and the signal conditioning electronics.

An accelerometer containing internal electronics that includes such additional features as self-testing, self-identification, and calibration data storage is sometimes referred to as a "smart accelerometer." During normal operation of the smart sensor, its output is an analog electrical signal. If such a transducer contains a built-in digital identification chip, it can be designed to send out a digitized signal providing such useful information as the calibration of the device and compensation coefficients.[8] Such a device is often called a mixed-mode smart sensor or a mixed-mode analog smart transducer.

Velocity-Output Piezoelectric Devices. Piezoelectric accelerometers are available with internal electronic circuitry which integrates the output signal provided by the accelerometer, thereby yielding a velocity or displacement output. These transducers have several advantages not possessed by ordinary velocity pickups. They are smaller, have a wider frequency response, have no moving parts, and are relatively unaffected by magnetic fields where measurements are made.

ACCELERATION-AMPLITUDE CHARACTERISTICS

Amplitude Range. Piezoelectric accelerometers are generally useful for the measurement of acceleration of magnitudes of from $10^{-6}g$ to more than $10^{5}g$. The lowest value of acceleration which can be measured is approximately that which will produce an output voltage equivalent to the electrical input noise of the coupling amplifier connected to the accelerometer when the pickup is at rest. Over its useful operating range, the output of a piezoelectric accelerometer is directly and continuously proportional to the input acceleration. A single accelerometer often can be used to provide measurements over a dynamic amplitude range of 90 dB or more, which is substantially greater than the dynamic range of some of the associated transmission, recording, and analysis equipment. Commercial accelerometers generally exhibit excellent linearity of electrical output vs. input acceleration under normal usage.

At very high values of acceleration (depending upon the design characteristics of the particular transducer), nonlinearity or damage may occur. For example, if the dynamic forces exceed the biasing or clamping forces, the seismic element may "chatter" or fracture, although such a fracture might not be observed in subsequent low-level acceleration calibrations. High dynamic accelerations also may cause a slight physical shift in position of the piezoelectric element in the accelerometer—sometimes sufficient to cause a zero shift or change in sensitivity. The upper limit of acceleration measurements depends upon the specific design and construction details of the pickup and may vary considerably from one accelerometer to another, even though the design is the same. It is not always possible to calculate the upper acceleration limit of a pickup. Therefore one cannot assume linearity of acceleration levels for which calibration data cannot be obtained.

EFFECTS OF TEMPERATURE

Temperature Range. Piezoelectric accelerometers are available which may be used in the temperature range from –425°F (–254°C) to above +1400°F (+760°C) without the aid of external cooling. The voltage sensitivity, charge sensitivity, capacitance, and frequency response depend upon the ambient temperature of the transducer. This temperature dependence is due primarily to variations in the characteristics of the piezoelectric material, but it also may be due to variations in the insulation resistance of cables and connectors—especially at high temperatures.

Effects of Temperature on Charge Sensitivity. The charge sensitivity of a piezoelectric accelerometer is directly proportional to the d piezoelectric constant of the material used in the piezoelectric element. The d constants of most piezoelectric materials vary with temperature.

Effects of Temperature on Voltage Sensitivity. The open-circuit voltage sensitivity of an accelerometer is the ratio of its charge sensitivity to its total capacitance ($C_s + C_E$). Hence, the temperature variation in voltage sensitivity depends on the temperature dependence of both charge sensitivity and capacitance. The voltage sensitivity of most piezoelectric accelerometers decreases with temperature.

Effects of Transient Temperature Changes. A piezoelectric accelerometer that is exposed to transient temperature changes may produce outputs as large as several volts, even if the sensitivity of the accelerometer remains constant. These spurious output voltages arise from

1. Differential thermal expansion of the piezoelectric elements and the structural parts of the accelerometer, which may produce varying mechanical forces on the piezoelectric elements, thereby producing an electrical output.
2. Generation of a charge in response to a change in temperature because the piezoelectric material is inherently pyroelectric. In general, the charge generated is proportional to the temperature change.

Such thermally generated transients tend to generate signals at low frequencies because the accelerometer case acts as a thermal low-pass filter. Therefore, such spurious signals often may be reduced significantly by adding thermal insulation around the accelerometer to minimize the thermal changes and by electrical filtering of low-frequency output signals from the accelerometer.

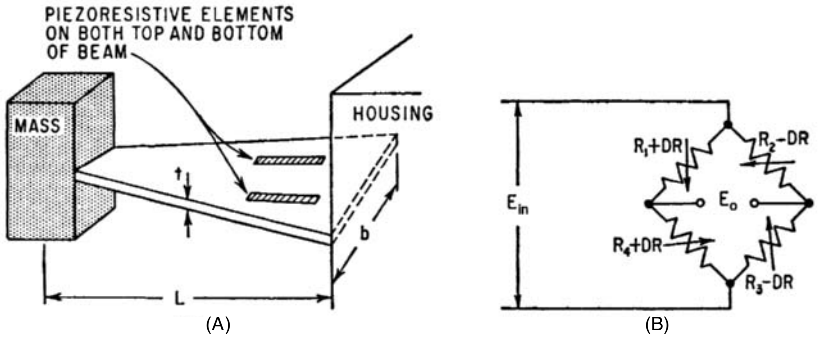
PIEZORESISTIVE ACCELEROMETERS

PRINCIPLE OF OPERATION

A piezoresistive accelerometer differs from the piezoelectric type in that it is not self-generating. In this type of transducer a semiconductor material, usually silicon, is used as the strain-sensing element. Such a material changes its resistivity in proportion to an applied stress or strain. The equivalent electric circuit of a piezoresistive transducing element is a variable resistor. Piezoresistive elements are almost always arranged in pairs; a given acceleration places one element in tension and the other in compression. This causes the resistance of one element to increase while the resistance of the other decreases. Often two pairs are used and the four elements are connected electrically in a Wheatstone-bridge circuit, as shown in Fig. 12.24*B*. When only one pair is used, it forms half of a Wheatstone bridge, the other half being made up of fixed-value resistors, either in the transducer or in the signal conditioning equipment. The use of transducing elements by pairs not only increases the sensitivity, but also cancels zero-output errors due to temperature changes, which occur in each resistive element.

At one time, wire or foil strain gages were used exclusively as the transducing elements in resistive accelerometers. Now silicon elements are often used because of their higher sensitivity. (Metallic gages made of foil or wire change their resistance with strain because the dimensions change. The resistance of a piezoresistive material changes because the material's electrical nature changes.) Sensitivity is a function of the gage factor; the *gage factor* is the ratio of the fractional change in resistance to the fractional change in length that produced it. The gage factor of a typical wire or foil strain gage is approximately 2.5; the gage factor of silicon is approximately 100.

A major advantage of piezoresistive accelerometers is that they have good frequency response down to dc (0 Hz) along with a relatively good high-frequency response.



(A) (B)

FIGURE 12.24 (*A*) Schematic drawing of a piezoresistive accelerometer of the cantilever-beam type. Four piezoresistive elements are used—two are either cemented to each side of the stressed beam or are diffused or ion implanted into a silicon beam. (*B*) The four piezoresistive elements are connected in a bridge circuit as illustrated.

DESIGN PARAMETERS

Many different configurations are possible for an accelerometer of this type. For purposes of illustration, the design parameters are considered for a piezoresistive accelerometer which has a cantilever arrangement as shown in Fig. 12.24*A*. This uniformly stressed cantilever beam is loaded at its end with mass *m*. In this arrangement, four identical piezoresistive elements are used—two on each side of the beam, whose length is *L* in. These elements, whose resistance is *R*, form the active arms of the balanced bridge shown in Fig. 12.24*B*. A change of length *L* of the beam produces a change in resistance *R* in each element. The gage factor *K* for each of the elements [defined by Eq. (17.1)] is

$$K = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\epsilon} \tag{12.18}$$

where ε is the strain induced in the beam, expressed in inches/inch, at the surface where the elements are cemented. If the resistances in the four arms of the bridge are equal, then the ratio of the output voltage E_o of the bridge circuit to the input voltage E_i is

$$\frac{E_o}{E_i} = \frac{\Delta R}{R} = \epsilon K \tag{12.19}$$

TYPICAL PIEZORESISTIVE ACCELEROMETER CONSTRUCTIONS

Figure 12.25 shows three basic piezoresistive accelerometer designs which illustrate several of the many types available for various applications.

Bending-Beam Type. This design approach is described by Fig. 12.25*A*. The advantages of this type are simplicity and ruggedness. The disadvantage is relatively low sensitivity for a given resonance frequency. The relatively lower sensitivity results from the fact that much of the strain energy goes into the beam rather than the strain gages attached to it.

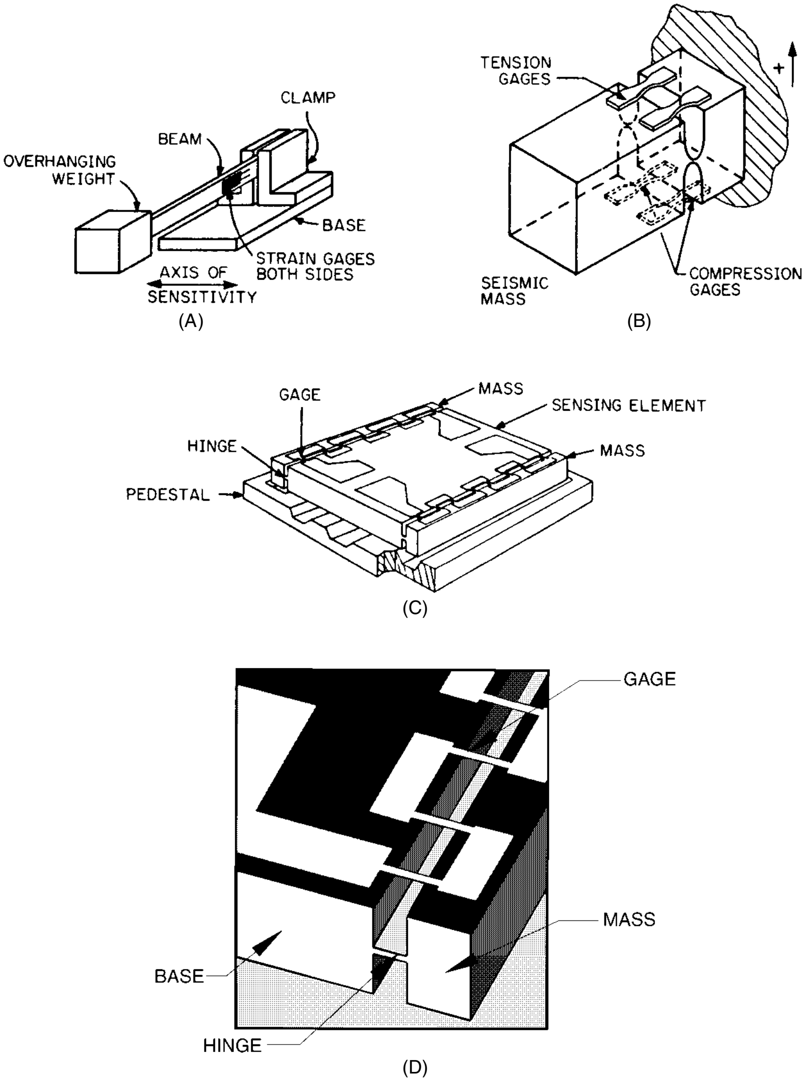


FIGURE 12.25 Three basic types of piezoresistive accelerometers. (*A*) Bending-beam type; the strain elements are usually bonded to the beam. Such an arrangement has been implemented in a micromachined accelerometer either by high-temperature diffusion of tension gages into the beam or by ion implantation. (*B*) Stress-concentrated type; the thin section on the neutral axis acts as a hinge of the seismic mass. Under dynamic conditions, the strain energy is concentrated in the piezoresistive gages. (*C*) Stress-concentrated micromachined type; the entire mechanism is etched from a single crystal of silicon. The thin section on the neutral axis acts as a hinge; the pedestal serves as a mounting base. (*D*) An enlarged view of one corner of the accelerometer shown in (*C*), which has a total thickness of 200 micrometers.

Stress-Concentrated Stopped and Damped Type. To provide higher sensitivities and resonance frequencies than are possible with the bending-beam type, designs are provided which place most of the strain energy in the piezoresistive elements. This is described by Fig. 12.25*B*. This approach is used to provide sensitivities more suitable for the measurement of acceleration below 100*g*. To provide environmental shock resistance, overload stops are added. To provide wide frequency response, damping is added by surrounding the mechanism with silicone oil. The advantages of these designs are high sensitivity, broad frequency response for the sensitivity, and over-range protection. The disadvantages are complexity and limited temperature range. The high sensitivity results from the relatively large mass with the strain energy mostly coupled into the strain gages. (The thin section on the neutral axis acts as a hinge; it contributes very little stiffness.) The broad frequency response results from the relatively high damping (0.7 times critical damping), which allows the accelerometer to be used to frequencies nearer the resonance frequency without excessive increase in sensitivity. The over-range protection is provided by stops which are designed to stop the motion of the mass before it overstresses the gages. (Stops are omitted from Fig. 12.25*B* in the interest of clarity.) Over-range protection is almost mandatory in sensitive piezoresistive accelerometers; without it they would not survive ordinary shipping and handling. The viscosity of the damping fluid does change with temperature; as a result, the damping coefficient changes significantly with temperature. The damping is at 0.7 times critical only near room temperature.

Micromachined Type. The entire working mechanism (mass, spring, and support) of a micromachined-type accelerometer is etched from a single crystal of silicon, a process known as *micromachining*. This produces a very tiny and rugged device, shown in Fig. 12.25*C*. The advantages of the micromachined type are very small size, very high resonance frequency, ruggedness, and high range. Accelerometers of such design are used to measure a wide range of accelerations, from below 10*g* to over 200,000*g*. No adhesive is required to bond a strain gage of this type to the structure, which helps to make it a very stable device. For shock applications, see the section on *Survivability*.

ELECTRICAL CHARACTERISTICS OF PIEZORESISTIVE ACCELEROMETERS

Excitation. Piezoresistive transducers require an external power supply to provide the necessary current or voltage excitation in order to operate. These energy sources must be well regulated and stable since they may introduce sensitivity errors and secondary effects at the transducer which will result in error signals at the output.

Traditionally, the excitation has been provided by a battery or a constant voltage supply. Other sources of excitation, such as constant current supplies or ac excitation generators, may be used. The sensitivity and temperature response of a piezoresistive transducer may depend on the kind of excitation applied. Therefore, it should be operated in a system which provides the same source of excitation as used during temperature compensation and calibration of the transducer. The most common excitation source is 10 volts dc.

Sensitivity. The *sensitivity* of an accelerometer is defined as the ratio of its electrical output to its mechanical input. Specifically, in the case of piezoresistive accelerometers, it is expressed as voltage per unit of acceleration at the rated excitation (i.e., mV/*g* or peak mV/peak *g* at 10 volts dc excitation).

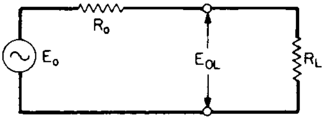


FIGURE 12.26 Loading effects on piezoresistive accelerometers.

Loading Effects. An equivalent circuit of a piezoresistive accelerometer, for use when considering loading effects, is shown in Fig. 12.26. Using the equivalent circuit and the measured output resistance of the transducer, the effect of loading may be directly calculated:

$$E_{oL} = E_o \frac{R_L}{R_o + R_L} \tag{12.20}$$

where R_o = output resistance of accelerometer, including cable resistance
E_o = sensitivity into an infinite load
E_{oL} = loaded output sensitivity
R_L = load resistance

Because the resistance of the strain-gage elements varies with temperature, output resistance should be measured at the operating temperature.

Effect of Cable on Sensitivity. Long cables may result in the following effects:

1. A reduction in sensitivity because of resistance in the input wires. The fractional reduction in sensitivity is equal to

$$\frac{R_i}{R_i + 2R_{ci}} \tag{12.21}$$

where R_i is the input resistance of the transducer and R_{ci} is the resistance of one input (excitation) wire. This effect may be overcome by using remote sensing leads.

2. Signal attenuation resulting from resistance in the output wires. This fractional reduction in signal is given by

$$\frac{R_L}{R_o + R_L + 2R_{co}} \tag{12.22}$$

where R_{co} is the resistance of one output wire between transducer and load.

3. Attenuation of the high-frequency components in the data signal as a result of *R-C* filtering in the shielded instrument leads. The stray and distributed capacitance present in the transducer and a short cable are such that any filtering effect is negligible to frequencies well beyond the usable range of the accelerometer. However, when long leads are connected between transducer and readout equipment, the frequency response at higher frequencies may be affected significantly.

Warmup Time. The excitation voltage across the piezoresistive elements causes a current to flow through each element. The I^2R heating results in an increase in temperature of the elements above ambient which slightly increases the resistance of the elements. Differentials in this effect may cause the output voltage to vary slightly with time until the temperature is stabilized. Therefore, resistance measurements and shock and vibration data should not be taken until stabilization is reached.

Input and Output Resistance. For an equal-arm Wheatstone bridge, the input and output resistances are equal. However, temperature-compensating and zero-balance resistors may be internally connected in series with the input leads or in series with the sensing elements. These additional resistors will usually result in unequal input and output resistance. The resistance of piezoresistive transducers varies with temperature much more than the resistance of metallic strain gages, usually having resistivity temperature coefficients between about 0.17 and 0.95 percent per degree Celsius.

Zero Balance. Although the resistance elements in the bridge of a piezoresistive accelerometer may be closely matched during manufacture, slight differences in resistance will exist. These differences result in a small offset or residual dc voltage at the output of the bridge. Circuitry within associated signal conditioning instruments may provide compensation or adjustment of the electrical zero.

Insulation. The case of the accelerometer acts as a mechanical and electrical shield for the sensing elements. Sometimes it is electrically insulated from the elements but connected to the shield of the cable. If the case is grounded at the structure, the shield of the connecting cable may be left floating and should be connected to ground at the end farthest from the accelerometer. When connecting the cable shield at the end away from the accelerometer, care must be taken to prevent ground loops.

Thermal Sensitivity Shift. The sensitivity of a piezoresistive accelerometer varies as a function of temperature. This change in the sensitivity is caused by changes in the gage factor and resistance and is determined by the temperature characteristics of the modulus of elasticity and piezoresistive coefficient of the sensing elements. The sensitivity deviations are minimized by installing compensating resistors in the bridge circuit within the accelerometer.

Thermal Zero Shift. Because of small differences in resistance change of the sensing elements as a function of temperature, the bridge may become slightly unbalanced when subjected to temperature changes. This unbalance produces small changes in the dc voltage output of the bridge. Transducers are usually compensated during manufacture to minimize the change in dc voltage output (zero balance) of the accelerometer with temperature. Adjustment of external balancing circuitry should not be necessary in most applications.

Damping. The frequency response characteristics of piezoresistive accelerometers having damping near zero are similar to those obtained with piezoelectric accelerometers. Viscous damping is provided in accelerometers having relatively low resonance frequencies to increase the useful high-frequency range of the accelerometer and to reduce the output at resonance. At room temperature this damping is usually 0.7 of critical damping or less. With damping, the sensitivity of the accelerometer is “flat” to greater than one-fifth of its resonance frequency.

The piezoresistive accelerometer using viscous damping is intended for use in a limited temperature range, usually +20 to +200°F (−7 to +94°C). At high temperatures the viscosity of the oil decreases, resulting in low damping; and at low temperatures the viscosity increases, which causes high damping. Accordingly, the frequency response characteristics change as a function of temperature.

FORCE GAGES AND IMPEDANCE HEADS

MECHANICAL IMPEDANCE MEASUREMENT

Mechanical impedance measurements are made to relate the force applied to a structure to the motion of a point on the structure. If the motion and force are measured at the same point, the relationship is called the *driving-point impedance;* otherwise it is called the *transfer impedance.* Any given point on a structure has six degrees-of-freedom: translations along three orthogonal axes and rotations around the axes, as explained in Chap. 2. A complete impedance measurement requires measurement of all six excitation forces and response motions. In practice, rotational forces and motions are rarely measured, and translational forces and motions are measured in a single direction, usually normal to the surface of the structure under test.

Mechanical impedance is the ratio of input force to resulting output velocity. *Mobility* is the ratio of output velocity to input force, the reciprocal of mechanical impedance. *Dynamic stiffness* is the ratio of input force to output displacement. *Receptance,* or *admittance,* is the ratio of output displacement to input force, the reciprocal of dynamic stiffness. *Dynamic mass,* or *apparent mass,* is the ratio of input force to output acceleration. All of these quantities are complex and functions of frequency. All are often loosely referred to as impedance measurements. They all require the measurement of input force obtained with a force gage (an instrument which produces an output proportional to the force applied through it). They also require the measurement of output motion. This is usually accomplished with an accelerometer; if velocity or displacement is the desired measure of motion, either can be determined from the acceleration.

Impedance measurements usually are made for one of these reasons:

1. To determine the natural frequencies and mode shapes of a structure (see Chap. 21)
2. To measure a specific property, such as stiffness or damping, of a material or structure
3. To measure the dynamic properties of a structure in order to develop an analytical model of it

The input force (excitation) applied to a structure under test should be capable of exciting the structure over the frequency range of interest. This excitation may be either a vibratory force or a transient impulse force (shock). If vibration excitation is used, the frequency is swept over the range of interest while the output motion (response) is measured. If shock excitation is used, the transient input excitation and resulting transient output response are measured. The frequency spectra of the input and output are then calculated by Fourier analysis.

FORCE GAGES

A force gage measures the force which is being applied to a structural point. Force gages used for impedance measurements invariably utilize piezoelectric transducing elements. A piezoelectric force gage is, in principle, a very simple device. The transducing element generates an output charge or voltage proportional to the applied force. Piezoelectric transducing elements are discussed in detail earlier in this chapter.

TYPICAL FORCE-GAGE AND IMPEDANCE-HEAD CONSTRUCTIONS

Force Gages for Use with Vibration Excitation. Force gages for use with vibration excitation are designed with provision for attaching one end to the structure and the other end to a force driver (vibration exciter). A thin film of oil or grease is often used between the gage and the structure to improve the coupling at high frequencies.

Force Gages for Use with Shock Excitation. Force gages for use with shock excitation are usually built into the head of a hammer. Excitation is provided by striking the structure with the hammer. The hammer is often available with interchangeable faces of various materials to control the waveform of the shock pulse generated. Hard materials produce a short-duration, high-amplitude shock with fast rise and fall times; soft materials produce longer, lower-amplitude shocks with slower rise and fall times. Short-duration shocks have a broad frequency spectrum extending to high frequencies. Long-duration shocks have a narrower spectrum with energy concentrated at lower frequencies.

Shock excitation by a hammer with a built-in force gage requires less equipment than sinusoidal excitation and requires no special preparation of the structure.

Impedance Heads. Impedance heads combine a force gage and an accelerometer in a single instrument. They are convenient for measuring driving-point impedance because only a single instrument is required and the force gage and accelerometer are mounted as nearly as possible at a single point.

FORCE-GAGE CHARACTERISTICS

Amplitude Response, Signal Conditioning, and Environmental Effects. The amplitude response, signal conditioning requirements, and environmental effects associated with force gages are the same as those associated with piezoelectric accelerometers. They are described in detail earlier in this chapter. The sensitivity is expressed as charge or voltage per unit of force, e.g., picocoulomb/newton or millivolt/lb.

Near a resonance, usually a point of particular interest, the input force may be quite low; it is important that the force-gage sensitivity be high enough to provide accurate readings, unobscured by noise.

Frequency Response. A force gage, unlike an accelerometer, does not have an inertial mass attached to the transducing element. Nevertheless, the transducing element is loaded by the mass of the output end of the force gage. This is called the *end dynamic mass.* Therefore, it has a frequency response that is very similar to that of an accelerometer, as described earlier in this chapter.

Effect of Mass Loading. The dynamic mass of a transducer (force gage, accelerometer, or impedance head) affects the motion of the structure to which the transducer is attached. Neglecting the effects of rotary inertia, the motion of the structure with the transducer attached is given by

$$A = A_o \frac{m_s}{m_s + m_t} \qquad (12.23)$$

where a = amplitude of motion with transducer attached
A_o = amplitude of motion without transducer attached

m_s = dynamic mass of structure at point of transducer attachment in direction of sensitive axis of transducer
m_t = dynamic mass of the transducer in its sensitive direction

These are all complex quantities and functions of frequency. Near a resonance the dynamic mass of the structure becomes very small; therefore, the mass of the transducer should be as small as possible. The American National Standards Institute recommends that the dynamic mass of the transducer be less than 10 times the dynamic mass of the structure at resonance.

PIEZOELECTRIC EXCITERS (DRIVERS)

A piezoelectric element can be used as a vibration exciter if an ac signal is applied to its electrical terminals. This is known as the *converse piezoelectric effect.* In contrast to electrodynamic exciters, piezoelectric exciters are effective from well below 1000 Hz to as high as 60,000 Hz. Some commercially available piezoelectric exciters use piezoelectric ceramic elements to provide the driving force. Other applications utilize the piezoelectric effect in devices such as transducer calibrators, fuel injectors in automobiles, ink pumps in impact printer assemblies, and drivers to provide the antiphase motions for noise cancellation systems.

OPTICAL-ELECTRONIC TRANSDUCER SYSTEMS

LASER DOPPLER VIBROMETERS

The laser Doppler vibrometer (LDV) uses the Doppler shift of laser light which has been backscattered from a vibrating test object to produce a real-time analog signal output that is proportional to instantaneous velocity. The velocity measurement range, typically between a minimum peak value of 0.5 micrometer per second and a maximum peak value of 10 meters per second, is illustrated in Fig. 12.27.

An LDV is typically employed in an application where other accelerometers or other types of conventional sensors cannot be used. LDVs' main features are

- There are no transducer mounting or mass loading effects.
- There is no built-in transverse sensitivity or other environmental effects.
- They measure remotely from nearly any standoff distance.
- There is ultra-high spatial resolution with small measurement spot (5 to 100 micrometers typically).
- They can be easily fitted with fringe-counter electronics for producing absolute calibration of dynamic displacement.
- The laser beam can be automatically scanned to produce full-field vibration pattern images.

Caution must be exercised in the installation and calibration of laser Doppler vibrometers (LDVs). In installing such an optical-electronic transducer system, care must be given to the location unit relative to the location of the target; in many applications, optical alignment can be difficult. Although absolute calibration of the associated electronic system can be carried out, an absolute calibration of the optical system usually cannot be. Thus, the calibration is usually restricted to the range

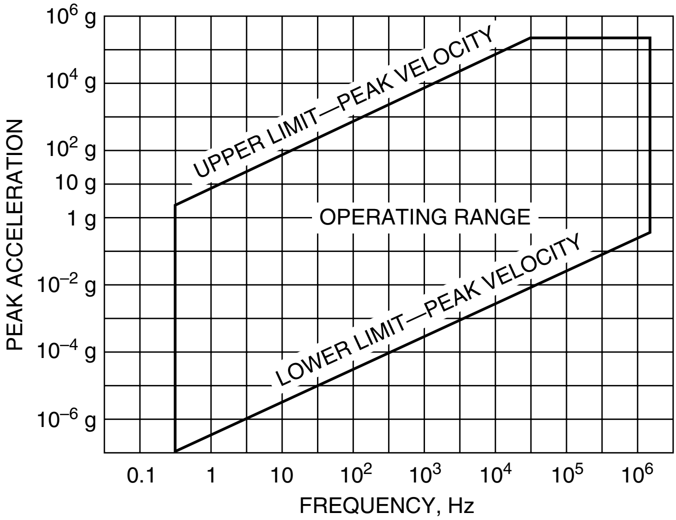


FIGURE 12.27 Typical operating range for a laser Doppler vibrometer. (*Courtesy of Polytec Pi, Inc.*)

of the secondary standard accelerometer used, which is only a small portion of the dynamic range of the LDV; the secondary standard accelerometer should be calibrated against a National Institute of Standards and Technology (NIST) traceable reference, at least once a year, in compliance with MIL-STD-45662A. Since the application of LDV technology is based on the reflection of coherent light scattered by the target surface, ideally this surface should be flat relative to the wavelength of the light used in the laser. If it is not, the nonuniform surface can result in spurious reflectivity (resulting in noise) or complete loss of reflectivity (signal dropout).

Types of Laser Doppler Vibrometers Four types of laser Doppler vibrometers are illustrated in Fig. 12.28.

Standard (Out of Plane). The standard LDV measures the vibrational component $v_z(t)$ which lies along the laser beam. Triaxial measurements can be obtained by approaching the same measurement point from three different directions. This is the most common type of LDV system.

Scanning. An extension of the standard out-of-plane system, the scanning LDV uses computer-controlled deflection mirrors to direct the laser to a user-selected array of measurement points. The system automatically collects and processes vibration data at each point; scales the data in standard displacement, velocity, or acceleration engineering units; performs fast Fourier transform (FFT) or other operations; and displays full-field vibration pattern images and animated operational deflection shapes.

In-plane. A special optics probe emitting two crossed laser beams is directed at normal incidence to the test surface and measures in-plane velocity. By rotating the probe by 90°, $v_x(t)$ or $v_y(t)$ can be measured.

Rotational. Two parallel laser beams from an optics probe measure angular vibration in units of degrees per second. Rotational systems are commonly used for torsional vibration analysis.

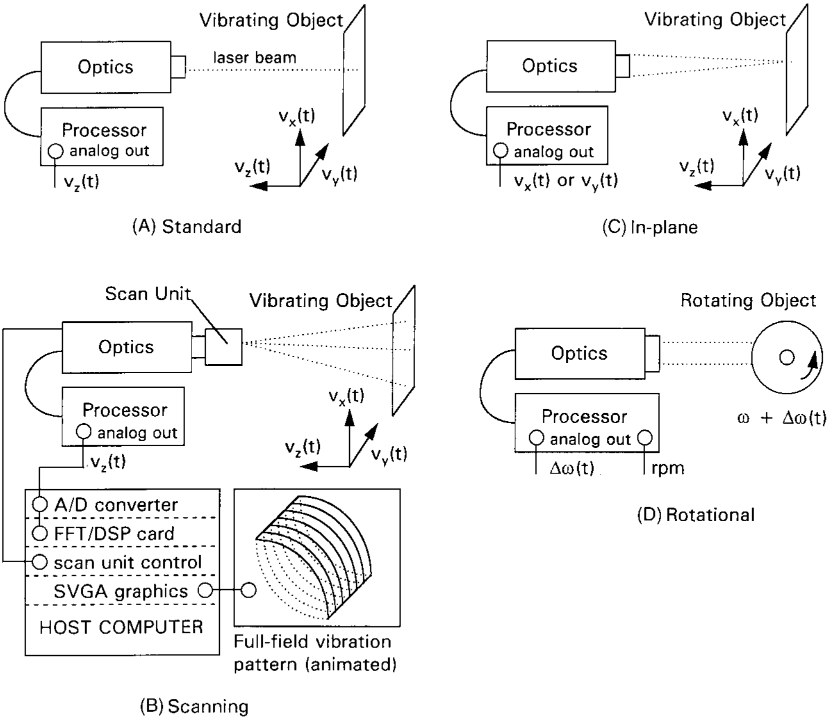


FIGURE 12.28 The four basic types of laser Doppler vibrometer systems. (*Courtesy of Polytec Pi, Inc.*)

DISPLACEMENT MEASUREMENT SYSTEM

The electro-optical displacement measurement system consists of an electro-optical sensor and a servo-control unit designed to track the displacement of the motion of a light-dark target. This target provides a light discontinuity in the intensity of reflected light from an object. If such a light-dark discontinuity is not inherent to the object under study, a light-dark target may be applied on the object. An image of the light-dark target is formed by a lens on the photocathode of an image dissector photomultiplier tube, as shown in Fig. 12.29. The photocathode emits electrons in proportion to the intensity of the light striking the tube, causing an electron image to be generated in real time. The electron image is accelerated through a small aperture that is centrally located within the phototube. The number of electrons that enter the aperture constitute a small electric current that is directly proportional to the amount of light striking the corresponding area on the photocathode. This signal current is then amplified. As the light-dark target moves across the face of the phototube, the output current changes from high (light) to low (dark). When the target is exactly at the center of the tube, the output current represents half light and half dark covering the aperture. If the target moves away from this position, the output current changes. This change is detected by the control unit, which feeds a compensation current back to the optical tracking head. The current that is needed for this deflection is directly proportional to the distance that the image has moved away from the center. Therefore it is a direct measure of displacement.

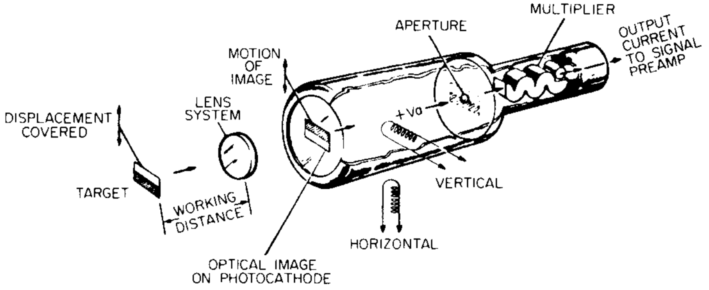


FIGURE 12.29 Image dissector tube of an electro-optical displacement measurement system. (*Courtesy of Optron Corp.*)

The displacement amplitudes that can be measured range from a few micrometers to several meters; the exact value is determined by the lens selected. Systems are available which measure displacements in one, two, or three directions.

FIBER-OPTIC REFLECTIVE DISPLACEMENT SENSOR

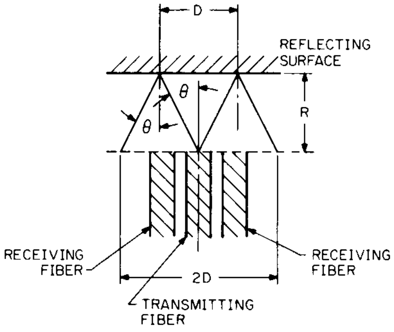


FIGURE 12.30 Fiber-optic displacement sensor. (*Courtesy of EOTEC Corp.*)

A fiber-optic reflective displacement sensor measures the amount of light normal to, and vibrating along, the optical axis of the device. The amount of reflected light is related to the distance between the surface and the fiber-optic transmitting/receiving element, as illustrated in Fig. 12.30. The sensor is composed of two bundles of single optical fibers. One of these bundles transmits light to the reflecting target; the other traps reflected light and transmits it to a detector. The intensity of the detected light depends on how far the reflecting surface is from the fiber-optic probe. Light is transmitted from the bundle of fibers in a solid cone defined by a numerical aperture. Since the angle of reflection is equal to the angle of incidence, the size of the spot that strikes the bundle after reflection is twice the size of the spot that hits the target initially. As the distance from the reflecting surface increases, the spot size increases as well. The amount of reflected light is inversely proportional to the spot size. As the probe tip comes closer to the reflecting target, there is a position in which the reflected light rays are not coupled to the receiving fiber bundle. At the onset of this occurrence, a maximum forms which drops to zero as the reflecting surface contacts the probe. The output-current sensitivity can be varied by using various optical configurations.

While sensitivities approaching 1 microinch are possible, such extreme sensitivities limit the corresponding dynamic range. If the sensor is used at a distance from the reflecting target, a lens system is required in conjunction with a fiber-optic probe. With available lenses, the instruments have displacement measurement ranges from 0 to 0.015 in. (0 to 0.38 mm) and 0 to 5.0 in. (0 to 12.7 cm). Resolution typically is better than one one-hundredth of the full-scale range. The sensor is sensitive to rotation of the reflecting target. For rotations of ±3° or less, the error is less than ±3 percent.

ELECTRODYNAMIC TRANSDUCERS

ELECTRODYNAMIC (VELOCITY COIL) PICKUPS

The output voltage of the electrodynamic pickup is proportional to the relative velocity between the coil and the magnetic flux lines being cut by the coil. For this reason it is commonly called a velocity coil. The principle of operation of the device is illustrated in Fig. 12.31. A magnet has an annular gap in which a coil wound on a hollow cylinder of nonmagnetic material moves. Usually a permanent magnet is used, although an electromagnet may be used. The pickup also can be designed with the coil stationary and the magnet movable. The open-circuit voltage *e* generated in the coil is[2,3]

$$e = -Blv(10^{-8}) \qquad \text{volts}$$

where *B* is the flux density in gausses; *l* is the total length in centimeters of the conductor in the magnetic field; and *v* is the relative velocity in centimeters per second between the coil and magnetic field. The magnetic field decreases sharply outside the space between the pole pieces; therefore, the length of coil wire outside the gap generates only a very small portion of the total voltage.

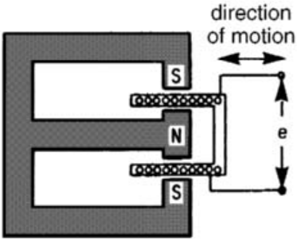


FIGURE 12.31 Principle of operation of an electrodynamic pickup. The voltage *e* generated in the coil is proportional to the velocity of the coil relative to the magnet.

One application of the electrodynamic principle is the velocity-type seismic pickup. Usually the pickup is used only at frequencies above its natural frequency, and it is not very useful at frequencies above several thousand hertz. The sensitivity of most pickups of this type is quite high, particularly at low frequencies where their output voltage is greater than that of many other types of pickups. The coil impedance is low even at relatively high frequencies, so that the output voltage can be measured directly with a high-impedance voltmeter. This type of pickup is designed to measure quite large displacement amplitudes.

DIFFERENTIAL-TRANSFORMER PICKUPS

The output of a differential-transformer pickup depends on the mutual inductance between a primary and a secondary coil. The basic components are shown in Fig. 12.32. The pickup consists of a core of magnetic material, a primary coil, and two secondary coils. As the core moves, a voltage is induced in the secondary coils. When the core is exactly in the center, each secondary coil contains the same length of core. Therefore, the mutual inductances of both secondary coils are equal in magnitude. However, they are connected in series opposition, so that the output voltage is zero. As the core is moved up or down, both the inductance and the induced voltage of one secondary coil are increased while those of the other are decreased. The output voltage is the difference between these two induced voltages. In this type of transducer, the output volt-

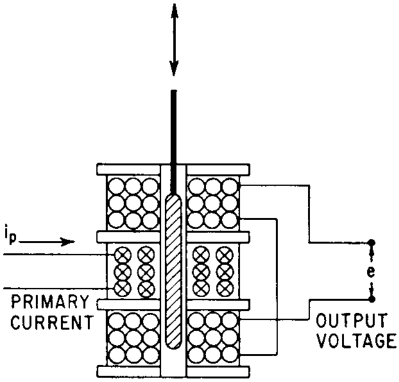


FIGURE 12.32 Differential-transformer principle. The inductance of the coils changes as the core is moved. For constant input current i_p to the primary coil, the output voltage e is the difference of the voltages in the two secondary coils, which are wound in series opposition. (*Courtesy of Automatic Timing and Controls, Inc.*)

age is proportional to the displacement of the core over an appreciable range. In practice, the output voltage at the carrier frequency of the primary current is not exactly zero when the core is centered, and the output near the center position is not exactly linear. When the core is vibrated, the output voltage is a carrier wave, modulated at a frequency and amplitude corresponding to the motion of the core relative to the coils.

These pickups are used for very low frequency measurements. The sensitivity varies with the carrier frequency of the current in the primary coil. The carrier frequency should be at least 10 times the highest frequency of the motion to be measured. Since this range is usually between 0 and 60 Hz, the carrier frequency is usually above 600 Hz.

SERVO ACCELEROMETER

A *servo accelerometer,* sometimes called a "force-balance accelerometer," is an accelerometer containing a seismically suspended mass which has a displacement sensor (e.g., a capacitance-type transducer) attached to it. Such accelerometers can be made very sensitive, some having threshold sensitivities of only a few micro-g. Excellent amplitude linearity is attainable, usually on the order of a few hundredths of one percent with peak acceleration amplitudes up to 50g. Typical frequency ranges are from 0 to 500 Hz. Such devices are designed for use in applications with comparatively low acceleration levels and extremely low-frequency components. Servo accelerometers typically are three to four times the size of an equivalent piezoelectric accelerometer and are usually more costly than other types of accelerometers.

Such accelerometers are of two types: *electrostatic* or *electromagnetic* (where a force is usually generated by a driving current through coils on the mass). The electrostatic type usually has a smaller mass and usually is capable of sustaining higher shocks. Unlike other direct-current response accelerometers whose bias stability depends on the characteristics of the sensing elements, here the bias stability is provided by electronic feedback.

CAPACITANCE-TYPE TRANSDUCERS

DISPLACEMENT TRANSDUCER (PROXIMITY PROBE)

The capacitance-type transducer is basically a displacement-sensitive device. Its output is proportional to the change in capacitance between two plates caused by the change of relative displacement between them as a result of the motion to be measured. Appropriate electronic equipment is used to generate a voltage corresponding to the change in capacitance.

The capacitance-type displacement transducer's main advantages are (1) its simplicity in installation, (2) its negligible effect on the operation of the vibrating system since it is a proximity-type pickup which adds no mass or restraints, (3) its extreme sensitivity, (4) its wide displacement range, due to its low background noise, and (5) its wide frequency range, which is limited only by the electric circuit used.

The capacitance-type transducer often is applied to a conducting surface of a vibrating system by using this surface as the ground plate of the capacitor. In this arrangement, the insulated plate of the capacitor should be supported on a rigid structure close to the vibrating system. Figure 12.33*A* shows the construction of a

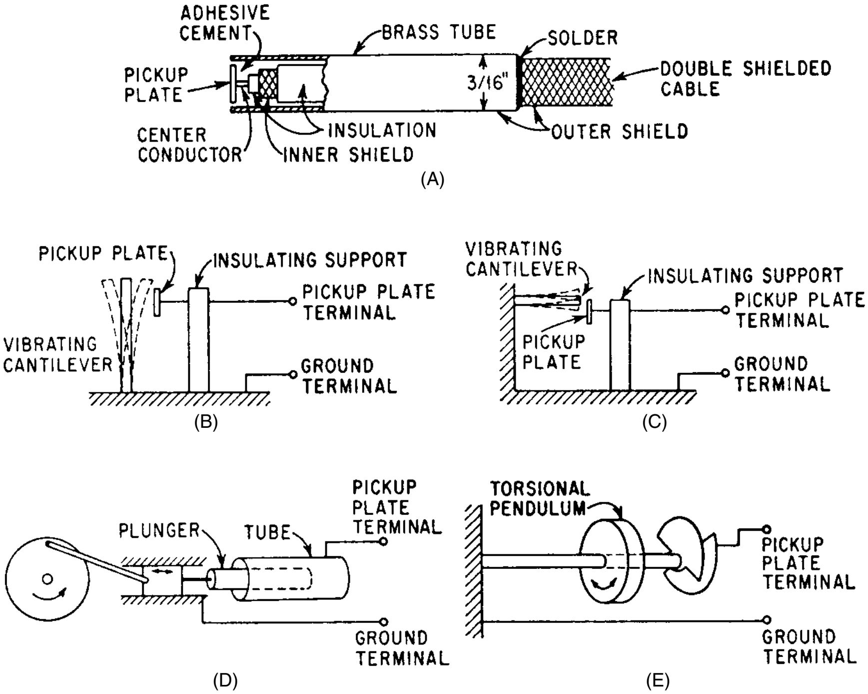


FIGURE 12.33 Capacitance-type transducers and their application: (*A*) construction of typical assembly, (*B*) gap length or spacing sensitive pickup for transverse vibration, (*C*) area sensitive pickup for transverse vibration, (*D*) area sensitive pickup for axial vibration, and (*E*) area sensitive pickup for torsional vibration.

typical capacitance pickup; Fig. 12.33*B, C, D,* and *E* show a number of possible methods of applying this type of transducer. In each of these, the metallic vibrating system is the ground plate of the capacitor. Where the vibrating system at the point of instrumentation is an electrical insulator, the surface can be made slightly conducting and grounded by using a metallic paint or by rubbing the surface with graphite.

The maximum operating temperature of the transducer is limited by the insulation breakdown of the plate supports and leads. Bushings made of alumina are commercially available and provide adequate insulation at temperatures as high as 2000°F (1093°C).

VARIABLE-CAPACITANCE-TYPE ACCELEROMETER

Silicon micromachined variable-capacitance technology is utilized to produce miniaturized accelerometers suitable for measuring low-level accelerations (2*g* to 100*g*) and capable of withstanding high-level shocks (5000*g* to 20,000*g*).

Acceleration sensing is accomplished by using a half-bridge variable-capacitance microsensor. The capacitance of one circuit element increases with applied acceleration, while that of the other decreases. With the use of signal conditioning, the accelerometer provides a linearized high-level output.

In the following example, the microsensor is fabricated in an array of three micromachined single-crystal silicon wafers bonded together using an anodic bonding process (see exploded view in Fig. 12.34). The top and bottom wafers contain the fixed capacitor plates (the lid and base, respectively), which are electrically isolated from the middle wafer. The middle wafer contains the inertial mass, the suspension, and the supporting ringframe. The stiffness of the flexure system is controlled by varying the shape, cross-sectional dimensions, and number of suspension beams. Damping is controlled by varying the dimensions of grooves and orifices on the parallel plates. Over-range protection is extended by adding overtravel stops.

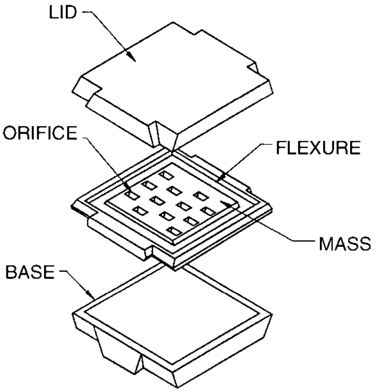


FIGURE 12.34 Exploded view of silicon micromachined variable-capacitance accelerometer. (*Courtesy of Endevco Corp.*)

The full-scale displacement of the seismic mass of the microsensor element is slightly more than 10 microinches. To detect minor capacitance changes in the microsensor due to acceleration, high-precision supporting electronic circuits are required. One approach applies a triangle wave to both capacitive elements of the microsensor. This produces currents through the elements which are proportional to their capacitances. A current detector and subtractor full-wave rectifies the currents and outputs their difference. An operational amplifier then converts this current difference to an output voltage signal. A high-level output is provided that is proportional to input acceleration.

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