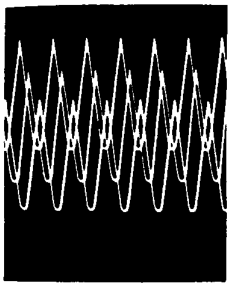
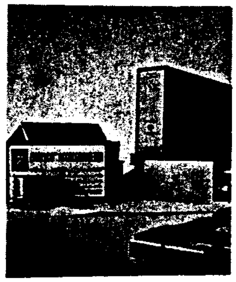
ENDEVCO
AN AMPHENOL COMPANY

Accelerometers for Shock and Vibration Measurements

Technical Paper 243 By
Raymond R, Bouche

ENDEVCO TECH PAPER





TP 243

ACCELEROMETERS FOR SHOCK AND VIBRATION MEASUREMENTS

Raymond R. Bouche, Endevco Corporation

1.0 INTRODUCTION

Piezoelectric accelerometers are used extensively for measuring shock and vibration motions in structures and components. These accelerometers contribute significantly to the development of missiles, aircraft and ocean-going vehicles. The shock and vibration measurements demonstrate the ability of structures to withstand acceleration environments without damage and verify that components will operate while and after being subjected to dynamic motions. Many thousands of piezoelectric accelerometers are used for these measurements.

Piezoresistive accelerometers are used in similar applications. Unlike piezoelectric accelerometers, piezoresistive accelerometers have the advantage that they are useful for measuring constant accelerations (zero frequency). The zero frequency response is an aid for making accurate long duration shock motion measurements. The piezoresistive accelerometers are being used in applications which formerly required the use of wire resistive strain gage accelerometers. The piezoresistive accelerometer has the advantages of higher output and higher frequency characteristics than the resistive strain gage type.

Other accelerometers used in special applications, such as servo accelerometers and navigation guidance accelerometers, are excluded from this discussion even though some of the operating principles are similar.

2.0 SEISMIC ACCELEROMETERS

The seismic accelerometer consists of a case which is attached to a moving part and contains a mass element connected to the case by a sensing element whose stiffness is usually less than the stiffness of the mass element. All these parts possess a slight amount of mechanical damping. The damping in the accelerometer may also be introduced artificially by filling the accelerometer with oil, for example. The parts of the seismic accelerometer are illustrated schematically in figure 3-1.

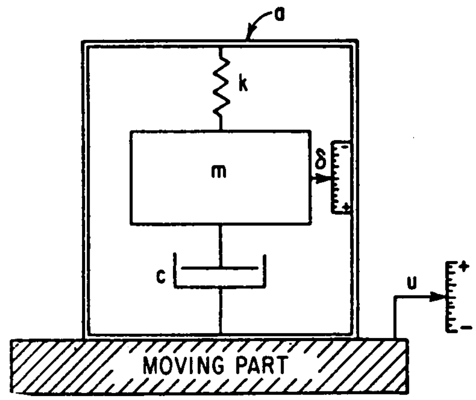


Figure 3-1 Single-degree-of-freedom seismic accelerometer consisting of a mass element M supported by spring K with damping C. The case of the accelerometer is attached to the moving part whose motion is to be measured.

A tungsten alloy is frequently used for the mass element in order to provide

Presented at Northeastern University, March 1967. Lecture course sponsored by Institute of Environmental Sciences, Boston Chapter.

the required mass in the smallest possible volume. The effective spring consists partly of the sensing material used, such as piezoelectric ceramics or piezoresistive strain gages. Sometimes several ceramic crystals are mechanically and electrically connected to each other. Also, the stiffness of several other parts need be considered when designing an accelerometer. However, experiments indicate that the accelerometer responds as if it were made with a single spring as illustrated in figure 3-1.

As indicated in figure 3-1, the accelerometer acts like a lumped system consisting of a mass element, spring and damper. The equation which determines the amplitude of the mass element relative to sinusoidal excitation applied to the accelerometer case is as follows:

$$\frac{\delta}{\ddot{u}} = \frac{\frac{1}{\omega_n^2}}{\left[(1 - \frac{\omega^2}{\omega_n^2})^2 + (2\zeta \frac{\omega}{\omega_n})^2\right]^{1/2}} \quad (3\text{-}1)$$

$$\theta = \tan^{-1} \frac{2\zeta \frac{\omega}{\omega_n}}{1 - \frac{\omega^2}{\omega_n^2}} \quad (3\text{-}2)$$

where
- δ = displacement amplitude of mass element relative to the displacement of the case (housing) of the accelerometer
- $\ddot{u}$ = acceleration amplitude of accelerometer case
- ω = circular excitation frequency, ($\omega = 2\pi f$ where f is expressed in Hz)
- ω_n = undamped natural circular frequency of accelerometer ($\omega_n = 2\pi f_n$ where f_n is usually expressed in Hz)
- ζ = damping in accelerometer expressed as a fraction of critical damping
- θ = phase angle in degrees that the displacement of the mass element lags the acceleration of the case.

Figure 3-2 is a plot of equation 3-1 for different values of damping. The values of damping most frequently used are zero and 0.707.

A damping equal to 0.707 of critical damping is required to produce an accelerometer which would have a flat response, i.e. a constant sensitivity normalized to a value of 1, over the widest frequency range. To achieve this wide frequency range, artificial damping must be provided in the accelerometer. If, on the other hand, the operating frequency range of the accelerometer is limited to less than 20 percent of the natural frequency, the response is independent of damping for all values of damping less than one. More specifically, the sensitivity is constant from that frequency down to zero frequency. Accelerometers should not have more than critical damping because the range of frequency over which the sensitivity is constant is quite limited. It is important to recognize that any artificial damping added in an accelerometer to achieve the 0.7 of critical damping should remain relatively constant over the operating temperature range. If damping changes and it becomes over-damped at some temperature, the usable frequency range is decreased.

Figure 3-3 shows the effect of damping upon the phase shift for different values of damping. Each curve represents a different damping value. With zero damping in an accelerometer, there is 0° phase shift from zero frequency up to the natural frequency where the phase shift changes instantaneously to 180° as indicated by the ordinate scale on the right side. Obviously an accelerometer cannot be built with exactly zero damping because all materials dissipate some energy. However, the inherent damping is so small that accelerometers having no artificial damping will have a phase shift approximating the curve for zero damping. When an accelerometer has 0.707 of critical damping, its phase shift does change with frequency, but up to its natural frequency, the phase shift follows a straight line. For shock measurements, phase shift must be zero or vary linearly with frequency as indicated by the straight line. For intermediate values of damping the phase shift is not linear with frequency and distortion occurs; the electrical output of the accelerometer is not an exact representation of applied input motion.

3.0 PIEZOELECTRIC ACCELEROMETERS

Most piezoelectric accelerometers are of the compression or shear type, see figure 3-4. The accelerometer measures shock and vibration in the direction of

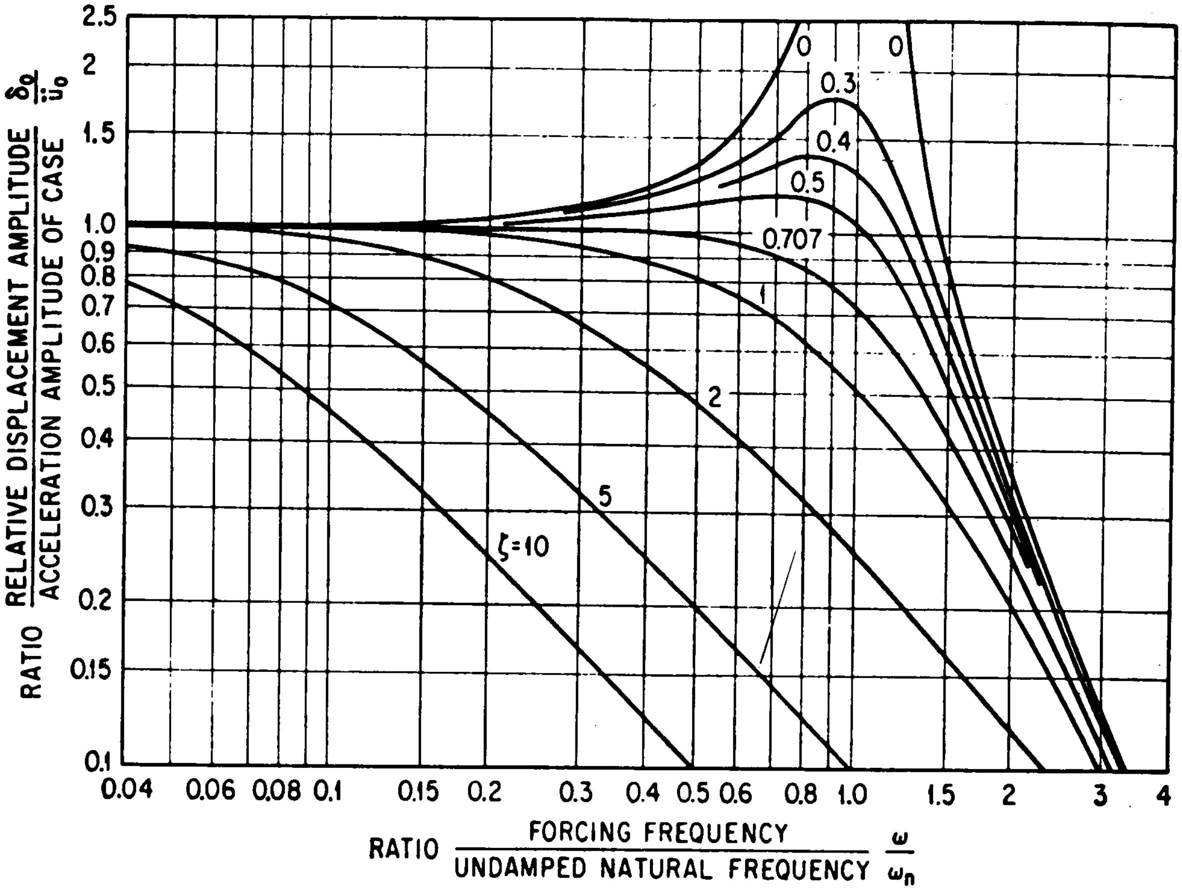


Figure 3-2 Frequency response of an accelerometer subjected to sinusoidal motion. The sensitivity is nearly constant at frequencies up to 1/5 the resonant frequency for accelerometers having near zero damping.

its axis of symmetry which is perpendicular to the bottom of the accelerometer. When the accelerometer is moved upward the mass tends to move downward toward the bottom of the accelerometer. Conversely, downward motion of the accelerometer case tends to move the mass upward, away from the bottom of the accelerometer. For the shear type accelerometer, this upward and downward motion applies a shear stress to the piezoelectric ceramic "k" which is cemented inside the mass element "M". Both the mass element and the piezoelectric ceramic are cylindrical in shape. The ceramic is also attached with cement to the central post which forms a part of the base of the accelerometer. The mass element "M" does not touch the outer case. In this shear accelerometer design, the only stresses applied to the crystal are the dynamic stresses produced when the case is moved as described above.

The compression type accelerometer has a compressive static preload applied to the piezoelectric ceramic k_2. The preload is applied by tightening the nut connected at the top of post k_1. The static tension preload in the post equals the static compression preload in the ceramic. The static preloads are selected so that they greatly exceed the highest dynamic stress produced when the accelerometer case is subjected to a shock or vibration motion. Upward motion of the case produces an inertia force in the mass element which increases the compression stress on the ceramic. Conversely, downward motion decreases the compression stress on the ceramic.

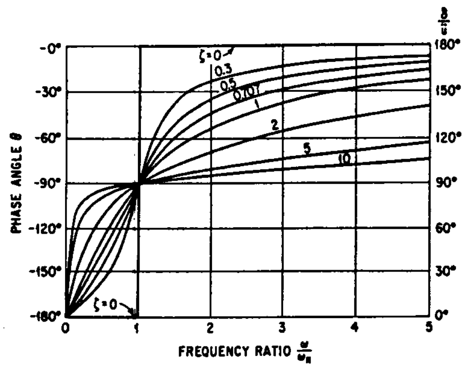


Figure 3-3 Phase angle response of seismic accelerometer indicates the relative displacement, δ, to the applied acceleration, $\ddot{u}$.

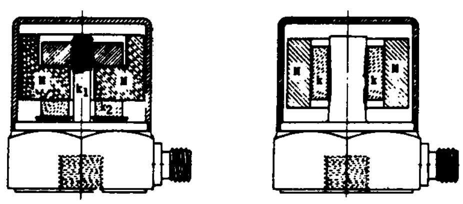


Figure 3-4 Piezoelectric accelerometers showing the compression and shear type constructions.

3.1 BASIC THEORY

Piezoelectric accelerometers are self-generating types; they require no electrical excitation. The electric charge generated on the ceramic is given by the following equations:

$$Q = d\,\sigma A \qquad (3\text{-}3)$$

d = piezoelectric constant of the crystal
A = stressed area on the crystal
σ = stress on the crystal

and

$$Q = C_1\delta \qquad (3\text{-}4)$$

C_1 = constant determined by the above equation and by the specific accelerometer design
δ = deflection of mass element relative to the accelerometer base.

The piezoelectric constant d used depends upon the accelerometer type. Shear type accelerometers use d_{15} and compression type use d_{33} or d_{11}. The numerical values of these piezoelectric constants are determined by the piezoelectric material: quartz, lead-zirconate-titanate and other more recently developed proprietary ceramics. Quartz is a natural crystal and has the lowest piezoelectric constant. Therefore, in most accelerometer designs, it is desirable to use the manufactured ceramics.

It is indicated in equations 3-3 and 3-4 that the charge generated on the crystal is proportional to the deflection of the mass element relative to the accelerometer base. Therefore, the charge Q and the constant C_1 can be substituted for δ in the equation 3-1. The sensitivity of the accelerometer is defined as the generated charge divided by the applied acceleration, and figure 3-2 describes the nominal response. The charge generated and the sensitivity is constant from zero frequency to frequencies up to about 1/5 of the resonant frequency. However, the piezoelectric material is a capacitor and its capacitive reactance is infinite at zero frequency. Therefore, it is practically impossible to measure the charge at zero frequency. However, electric instruments can be used to measure the charge at extremely low frequencies such as 0.03 Hz. These same instruments are suitable also for measuring the charge throughout the entire operating frequency range which sometimes exceeds 10,000 Hz.

3.2 CHARGE AMPLIFIERS

Charge amplifiers are used to measure the output of piezoelectric accelerometers throughout their entire operating frequency range. The operation of charge amplifiers is described in figure 3-5.

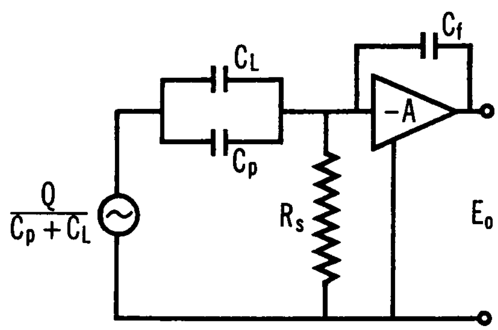


Figure 3-5 Simplified diagram of a charge amplifier.

The output of the charge amplifier is given by equation (3-5):

$$E_o = \frac{-QA}{(C_p+C_L) + (1+A)C_f + 1/j\,\omega R_s} \qquad (3\text{-}5)$$

where

- E_o = charge amplifier output
- Q = charge generated on piezoelectric material
- A = amplifier gain
- C_p = capacitance of the piezoelectric material
- C_L = capacitance of the connectors and cable
- C_f = feedback capacitance used in the charge amplifier
- j = imaginary vector
- ω = circular frequency
- R_s = shunt resistance of the accelerometer and cable

Typical values for accelerometers and charge amplifiers include 1,000 for the amplifier gain and 1,000 pF for the accelerometer and cable capacitance, 1,000 pF for the feedback capacitor and 100,000 ohms for the shunt resistance. Substituting these values in equation (3-5) shows that the output voltage is nearly equal to the charge divided by the feedback capacitor. Accordingly, equation (3-5) is simplified as indicated by equation (3-6):

$$E_o = -\frac{Q}{C_f} \qquad (3\text{-}6)$$

This ratio remains nearly constant even for extremely long cables sometimes used between the accelerometer and the charge amplifier.

The time constant applicable to the schematic in figure 3-5 is given by the equation (3-7):

$$T = 1/2\pi f = R_s\left[C_p+C_L+(1+A)C_f\right] \qquad (3\text{-}7)$$

where

- f = the frequency where the response is down 3db

and the other terms are the same as listed above. Equation (3-7) indicates that the time constant is extremely large and the amplifier response would be normally flat to frequencies much less than 1 Hz. However, it is desirable to eliminate quasi dc outputs which can be produced in the accelerometer due to pyroelectric effects which are discussed in section 3.5.2. For most shock and vibration applications flat frequency response is required only at frequencies down to about 2 Hz. In some applications it is desirable to limit the flat response to frequencies somewhat above 5 Hz. One of the advantages of the charge amplifier is that any desired low frequency response can be easily achieved in the amplifier design. For example, a feedback resistor R_f put in parallel with the feedback capacitor has a time constant of R_fC_f. For applications involving shock motions, this time constant should be long in comparison with the duration of the shock motion pulse.

3.3 VOLTAGE AMPLIFIERS

In the past, only voltage amplifiers and cathode followers were available for use with piezoelectric accelerometers. It is necessary to use the voltage sensitivity, equation (3-8), of the accelerometer with these instruments.

$$E = \frac{Q}{C_p + C_L + C_a} \qquad (3\text{-}8)$$

where

- E = voltage generated across piezoelectric material
- C_a = imput capacitance of the voltage measuring instrument

and the other terms are the same as above. One of the precautions necessary when using voltage measuring instruments on the piezoelectric accelerometer output is that it is difficult to achieve adequate low frequency response for certain applications.

The low frequency response of the cathode follower is determined simply by the product of the frequency in Hz times the input resistance of the cathode follower in ohms times the capacitance of the accelerometer, cable, etc. in farads. The frequency response is flat only when this FRC product is equal to or greater than 1. At frequencies where this product is less than 1, the response decreases. For example, the response is down 3 db when FRC equals about 0.16.

It is also necessary to consider this product when using other voltage amplifiers. However, this product usually is less than 1 only at frequencies below the low-frequency cutoff of the voltage amplifier itself. In this case the low frequency response characteristic of the amplifier is the determining factor. It is important that the frequency where the response is down 3 db, either as a result of the voltage amplifier or the FRC characteristics, occurs at a sufficiently low frequency. For example, in shock motion applications, it is necessary that the reciprocal of the frequency of the 3 db down point have a value which is large compared to the duration of the shock motion pulse.

It is important to know the low frequency characteristics of voltage amplifiers and cathode followers when making sinusoidal and random vibration measurements at frequencies below 50 Hz. When low capacitance accelerometers are used, the response of cathode followers falls off rapidly at low frequencies. In addition to the flat frequency response requirement it is necessary for the phase shift of the amplifier to vary linearly with frequency. This phase shift requirement is not met in voltage amplifiers having poor low frequency response. Accordingly, the amplifier distorts the accelerometer output in random vibration and shock motion measurement applications.

In addition to the low frequency response problem with voltage amplifiers and cathode followers, it is necessary to determine the change in sensitivity when changing cables. The output decreases as the capacitance in parallel with the accelerometer is increased. When cables are changed, it is necessary to compute the new sensitivity from equation (3-8) or recalibrate the accelerometer.

3.4 PERFORMANCE CHARACTERISTICS

Performance characteristics of some piezoelectric accelerometers remain unchanged whether using a charge or voltage amplifier. These characteristics include frequency response, resonant frequency and amplitude linearity for accelerometers manufactured with quartz and certain proprietary ceramic materials. Accelerometers made with lead-zirconate-titanate ceramic have slightly different frequency response and resonant frequency characteristics when using charge and voltage amplifiers. Except for quartz, the temperature response of most accelerometers is somewhat different when using charge and voltage amplifiers.

3.4.1 Acceleration Sensitivity

The typical acceleration sensitivities for various piezoelectric accelerometers are listed in table 3-1. For simplicity the acceleration sensitivities are rounded off to the nearest factor of ten. The acceleration sensitivity depends upon the particular accelerometer design. Accelerometers can be made with various sensitivities simply by using different mass elements in the accelerometer. For example, shear accelerometers using lead-zirconate-titanate ceramics are made with sensitivities of about 1 pC/g and 10 pC/g. Usually the shear accelerometers are made with one or two ceramic elements. Compression accelerometers are frequently made with several ceramic elements connected electrically in parallel. Therefore, the charge sensitivity is determined from the sum of the charge generated by each ceramic element.

The accelerometers made with lead-zirconate-titanate ceramics have the highest capacitance and highest acceleration sensitivity. Accordingly, these accelerometers are used mostly for applications for measuring relatively low accelerations.

The quartz accelerometers have the lowest acceleration sensitivity.

Accelerometers made with Endevco® Piezite® 10 ceramic have capacitances and acceleration sensitivities with values between those obtained with the other two crystal materials. This new material is one of the proprietary ceramics which have excellent performance characteristics for most shock and vibration measurement applications.

TABLE 3-1

Sensitivity of Piezoelectric Accelerometers

Crystal Material	Design Mode	Capacitance	Acceleration Sensitivity Charge	Acceleration Sensitivity Voltage
		pF	pC/g	mV/g
Lead-Zirconate-Titanate	Shear	1000	1-10	1-10
	Compression	1000-10,000	10-100	10-100
Quartz	Compression	100	1	10
Endevco® P-10	Shear	100	.1	1
	Compression	1000	1-10	1-10

3.4.2 Frequency Response

Typical frequency response characteristics of various accelerometers are shown in figure 3-6.

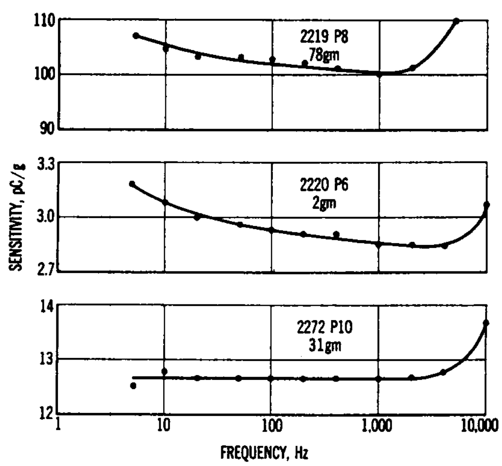


Figure 3-6 Charge frequency response characteristics of piezoelectric accelerometers representing various accelerometer designs and crystal materials.

The charge sensitivity of the accelerometers using P-6 and P-8 ceramic materials decreases about 1% for each octave increase in frequency. This characteristic is typical for lead-zirconate-titanate accelerometers. It happens that the capacitance of these accelerometers has the same frequency characteristic. Therefore, if the voltage sensitivity of the accelerometer is desired, the charge sensitivity at the frequency of the capacitance measurement is divided by the sum of the accelerometer capacitance, cable capacitance, and other capacitances that will be connected across the accelerometer. The use of charge amplifiers eliminates the need for this computation. Accelerometers built with P-10 ceramic material and quartz (not shown in figure 3-6) do not have this frequency characteristic; both the charge and voltage sensitivities are constant at all frequencies up to about one-fifth the resonant frequency. Like all accelerometers, the increase in sensitivity at high frequencies is due to their resonant frequency.

It should be pointed out that the frequency response of all accelerometers is flat in a manner similar to the P-10 curve in figure 3-6 when using voltage amplifiers with extremely small capacitances connected between the accelerometer and the amplifier. With small external capacitances the accelerometer experiences a virtual open circuit condition. However, if the external capacitance including cable capacitance is near or larger that three times the accelerometer capacitance, the accelerometer experiences a virtual short circuit condition. Therefore, with large external capacitance the response of all accelerometers is identical when using either voltage or charge amplifiers and the curves in figure 3-6 apply. If the external capacitance has a value which is between one and three times the accelerometer capacitance, the response of lead-zirconate-titanate accelerometers using voltage amplifiers will be somewhat between that indicated by the two lower curves in figure 3-6. In other words, the sensitivity decreases a fraction of 1% per octave increase in frequency; the fraction being determined by the amount of external capacitance used.

Charge amplifiers are being used for most shock and vibration measurements and the curves in figure 3-6 apply. Corrections for the lack of flat frequency response are usually not made.

It is good practice to consider the accuracy desired and select the accelerometer type and resonant frequency as required in order to make corrections of the data unnecessary.

3.4.3 Resonant Frequency

The resonant frequency of accelerometers changes slightly depending upon the degree of rigidity with which the accelerometer is mounted. Typical variations in resonant frequency are shown in figure 3-7. The most rigid mounting and highest resonant frequency is achieved by using metal studs with lubricated surfaces or by cementing the accelerometer in place. For example, in figure 3-7 the resonant frequency is 34,400 Hz in (a) and

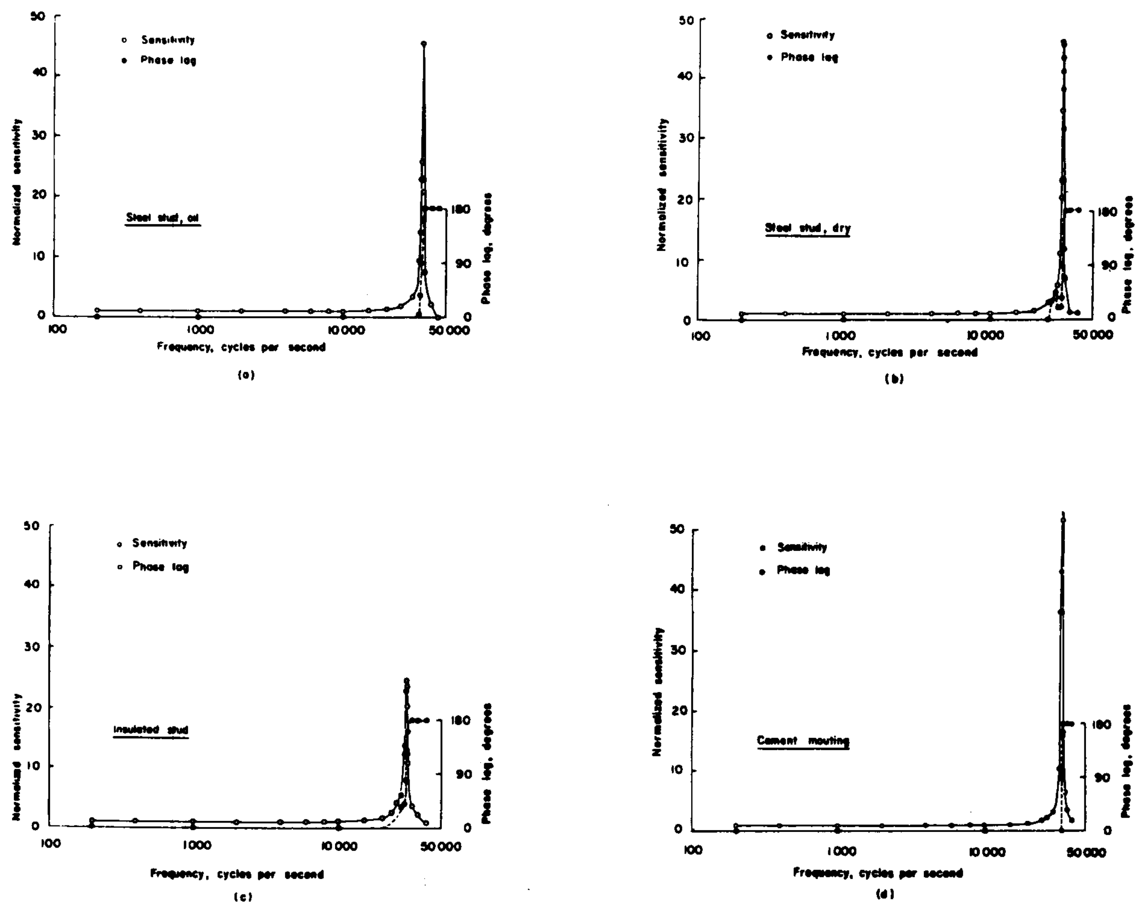


Figure 3-7 Resonant frequency measurements on a piezoelectric accelerometer, determined with different mounting conditions: (a) steel stud using a thin film of light oil, (b) steel stud with a mounting surface degreased, (c) insulated mounting stud, and (d) attached with Eastman 910 cement without any stud.

34,300 Hz in (d). With completely dry surfaces using a metal stud the resonant frequency is decreased to 31,040 Hz, figure 3-7 (b) and further reduced to 29,150 Hz when using an insulated stud, figure 3-7 (c). These variations in resonant frequency are typical of most piezoelectric accelerometers when using different mounting techniques.

The magnification factor at resonance is significantly lower when using an insulated mounting stud, figure 3-7 (c). This is an indication that the effective damping of the accelerometer is increased. The approximate damping is 0.02 when using the insulated stud and 0.01 of critical damping for other types of mounting. For practical purposes the damping of all piezoelectric accelerometers using these mounting methods is sufficiently small so that the damping can be considered nil and the curve marked 0 in figure 3-2 can be used to predict the frequency response characteristics within the operating frequency range.

Some accelerometer designs will have additional resonances occuring at frequencies above the normal operating range, but below the resonant frequency. These additional resonances are called local resonances. They exhibit themselves as perturbations when making resonant frequency measurements similar to figure 3-7. These deviations from normal response occur only over a narrow frequency band at the local resonance and usually do not affect the response at frequencies significantly below or above the local resonance and, therefore, do not affect the response in the operating frequency range. Examples of local resonances include plate and shell resonances when using thin walled cases to house the accelerometer.

Accelerometers are usually selected to have a sufficiently high resonant frequency so that the frequency response can be considered flat throughout the operating frequency range. Accordingly, the accelerometer resonant frequency should be at least five times the maximum frequency of interest. By following this rule slight variations in resonant frequency due to different mounting methods and the possible presence of local resonance can be ignored.

The resonant frequency of accelerometers made with quartz and P-10 materials remains unchanged when used open circuit with voltage amplifiers or with the virtual short circuit condition which is present when using charge amplifiers, see table 3-2. The resonant frequency of accelerometers made with lead-zirconate-titanate ceramic decreases a slight amount when using a charge amplifier. This is an indication that the modulus of elasticity of lead-zirconate-titanate ceramics is less in the short circuit condition. The fact that the decrease in resonant frequency is only 0.6% for one shear accelerometer in table 3-2 is an indication that the ceramic contributed only partly to the effective stiffness of the accelerometer. The differences in magnification factors indicated in table 3-2 are considered insignificant. It is expected that the damping in accelerometers remains unchanged when using charge and voltage amplifiers.

3.4.4 Amplitude Linearity

The sensitivity of piezoelectric accelerometers increases linearly with increasing acceleration. This characteristic is shown in figure 3-8.

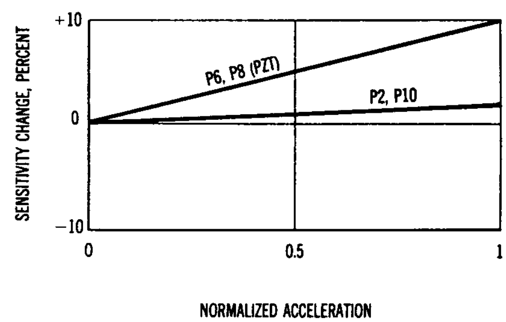


Figure 3-8 Amplitude linearity characteristic of piezoelectric accelerometers shows the sensitivity increasing with acceleration.

The amount of sensitivity increase is dependent upon the piezoelectric material used in the accelerometer and also depends on the design of the accelerometer. Accelerometers designed to have relatively low dynamic stress applied to the crystal will have relatively small sensitivity increases at high accelerations.

TABLE 3-2

Typical Resonant Frequency Characteristics of Piezoelectric Accelerometers Using Voltage and Charge Amplifiers

Accelerometer Type	Crystal Material	Resonant Frequency			Magnification Factor	
		Open Circuit Voltage	Short Circuit Charge	Change	Open Circuit Voltage	Short Circuit Charge
		kHz	kHz	percent		
Compression	Lead-Zirconate-Titanate	30.84	29.65	-3.9	57	33
"	"	15.40	14.92	-3.1	70	62
Shear	"	34.2	33.0	-3.5	38	66
"	"	32.2	32.0	-0.6	35	35
Compression	Quartz	32.2	32.2	0.0	23	24
"	Endevco® P-10	29.6	29.6	0.0	45	47

This is accomplished by using small mass elements in the accelerometer. Similarly, when large mass elements are used the dynamic stresses are relatively large and the increase in the sensitivity at high accelerations is significant for some accelerometers. For example, a lead-zirconate-titanate accelerometer having a charge sensitivity of 10 pC/g increases its sensitivity 1%/250g increment increase in acceleration; whereas, a similar accelerometer having a smaller mass element and a sensitivity of 1 pC/g increases its sensitivity only 1%/2500g. Sensitivity increases of accelerometers made with quartz or P-10 are significantly less as indicated by figure 3-8. Amplitude linearity errors are insignificant in shock and vibration applications provided care is taken to select accelerometers which have low sensitivity when measuring relatively high accelerations.

3.4.5 Temperature Response

The sensitivity of piezoelectric accelerometers changes as a function of temperature. These sensitivity changes can be attributed solely to variations in the piezoelectric constant of the crystal material provided that care is taken in the design of the accelerometer. Typical variations of sensitivities are shown in figure 3-9. The sensitivity changes are quite small for accelerometers made with P-10 ceramic or P-2 quartz. The operating temperature range is highest for accelerometers made with P-10 ceramics. It is difficult to use accelerometers made with quartz at temperatures significantly above 500°F because electrical twinning sometimes occurs. Electrical twinning is domain switching in the crystal and causes a permanent change in the accelerometer sensitivity.

Modulus of elasticity and damping changes in the materials of the accelerometer are relatively small throughout the operating temperature range. For this reason the resonant frequency changes only a very slight amount throughout the operating temperature range. Since accelerometers are used only at frequencies up to one-fifth the resonant frequency the frequency response of the accelerometer remains unchanged at all temperatures.

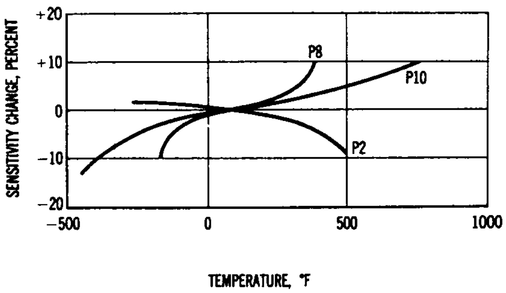


Figure 3-9 Typical temperature response characteristics show charge sensitivity changes for accelerometers using different crystal materials.

Usually it is unnecessary to make corrections to data for changes in sensitivity at various temperatures. It is good practice to select accelerometers which have sufficiently small sensitivity changes throughout the desired temperature range so that this correction is unnecessary. Possible exceptions to this rule concerns measurements below about -300°F and above about 500°F where the changes exceed 5%.

The capacitance of most piezoelectric accelerometers changes with temperature. The capacitance change of good quality accelerometers is about twice the charge sensitivity change as a function of temperature. The voltage sensitivity equals the sensitivity divided by the capacitance. Therefore, when using voltage amplifiers the sensitivity is significantly different when using different amounts of external capacitance. This is one of the reasons why charge amplifiers are preferred for use with piezoelectric accelerometers.

3.5 ENVIRONMENTAL EFFECTS

Environmental effects concern the extremes to which an accelerometer can be exposed without permanent change in the performance characteristics. Also certain environments cause error signals that may be present in the accelerometer output while making shock and vibration measurements. One of the reasons for identifying the characteristics discussed below as environmental effects is that, usually, it is not practical to correct the data for the errors produced by the environment. However, if accelerometers are properly used, the environmental errors should be insignificant. Measurement errors are avoided by being cognizant of the environmental effects and by following certain precautions in the use of accelerometers.

3.5.1 Transverse Sensitivity

The sensitivity axis of the crystal in an accelerometer deviates slightly from being perfectly perpendicular to the mounting surface of the accelerometer. This lack of perfection results from practical limitations in fabricating ceramic materials and in performing the machining required in the various accelerometer parts. In addition static preload stresses are applied to the crystal in some accelerometer designs which tend to change the poled axis of the crystal slightly. These effects combine in the accelerometer so that it produces some output as a result of excitation in a direction parallel to the mounting surface on the accelerometer.

The transverse sensitivity is illustrated schematically in figure 3-10.

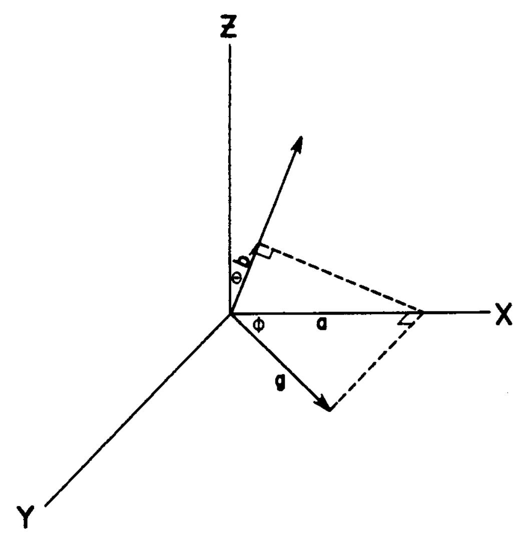


Figure 3-10 Diagram illustrates how transverse and axial accelerations combine to produce outputs along the sensing direction of the accelerometer.

The poled axis of the crystal is represented by a vector in the X-Z plane. The mounting surface of the accelerometer lies in the X-Y plane. An acceleration g applied in the X-Y plane has a component $g \cos \phi$ along the X-axis. This X-axis component has a component $g \cos \phi \sin \theta$ along the poled axis of the crystal. An acceleration g applied perpendicular to the accelerometer mounting surface has a component $g \cos \theta$ along the poled axis of the crystal. The transverse sensitivity of the accelerometer, equation (3-9), is the ratio of the two components along the poled axis:

$$\text{Transverse Sensitivity} = 100 \tan\theta \cos\phi \qquad (3\text{-}9)$$

The factor of 100 is introduced to express the transverse sensitivity as a percent of the axial acceleration sensitivity. For each fabricated accelerometer $\tan\theta$ is a fixed value assuming that no environments are applied to the accelerometer which would tend to change the poled axis of the crystal. The angle ϕ is determined by the direction of the applied motion in the plane of the accelerometer mounting surface. Therefore, the transverse sensitivity varies as the accelerometer is rotated about the Z-axis. This cosine variation in the transverse sensitivity is illustrated in figure 3-11 for various values of the angle ϕ.

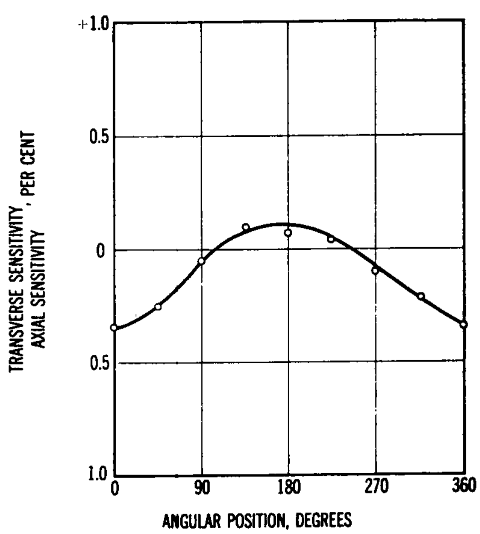


Figure 3-11 Variation in transverse sensitivity as a piezoelectric accelerometer is rotated about its sensitive axis.

(Several experimenters make this plot on polar graph paper). Usually the transverse sensitivity is sufficiently small so that only the maximum value in figure 3-11 need be considered. In other words, the accelerometer is selected so that the maximum transverse sensitivity is sufficiently small so that it produces negligible errors in most shock and vibration measurement applications. The transverse sensitivity provided by the manufacturer is the maximum value of the transverse sensitivity.

In good quality accelerometers, the transverse sensitivity of piezoelectric accelerometers is constant throughout the operating frequency range because care is taken in the design of the accelerometer to assure that all local resonances are above the operating frequency range. Sometimes measurements give a false indication of variations in transverse sensitivity at certain frequencies in the operating range. These variations in output are caused by transverse motion in the shaker used for the measurements or caused by other environmental effects applied to the accelerometer simultaneously while an attempt is made to measure the transverse sensitivity. It is important to make a distinction of one environmental effect from another. For example, errors due to environmental effects, such as certain local resonances, would be present in the output even though no transverse motion were applied to the accelerometer. Responsible accelerometer manufacturers will use extreme care in designing the accelerometer and conduct extensive tests to make sure that all local resonances in the accelerometer are above the operating frequency range. Furthermore, the manufacturer should make sure that all environmental effects are minimized in the accelerometer design.

3.5.2 Transient Temperature Effects

Piezoelectric accelerometers have the characteristic that an output is produced while the temperature of the crystal is being changed. This characteristic is called pyroelectricity. In almost all testing applications, the temperature changes in accelerometers occur gradually over a period of several seconds or minutes. As a result, the pyroelectric outputs are not detected because most amplifiers do not have adequate low frequency response to measure the slowly varying pyroelectric output. The pyroelectric output contains only extremely low frequency components, usually less than 1 Hz. However, these pyroelectric outputs need be considered if the amplifier passes these low frequencies or if the pyroelectric outputs are sufficiently large such that they overload the amplifier input and make it inoperative during the time the pyroelectric output is present. The pyroelectric characteristics of piezoelectric crystals are known and the output for any particular accelerometer-amplifier combination can be experimentally determined under specified temperature conditions.

There are three types of pyroelectric outputs. The primary pyroelectric output is the charge produced as a result of a uniform temperature change throughout the crystal. The secondary pyroelectric output is the piezoelectric charge produced as a result of a dimensional change in the crystal which is caused by a uniform temperature change. The tertiary pyroelectric output is the piezoelectric output of the crystal caused by a temperature gradient across the crystal. Pure primary pyroelectric output occurs when the crystal is constrained to prevent dimensional changes. Conversely, pure secondary and tertiary pyroelectric outputs occur when the crystal is unconstrained. Primary pyroelectric outputs are present only on the crystal surfaces which are perpendicular to the direction of polarization of the crystal; whereas, secondary and tertiary outputs appear on the electrode surfaces of the crystal regardless of the direction of polarization. Shear type accelerometers are designed so that the electrode surfaces are not in the direction of polarization. Consequently, shear type accelerometers do not produce primary pyroelectric outputs and generally are less affected by temperature changes than compression type accelerometers which produce primary pyroelectric outputs. All ceramic crystals produce secondary pyroelectric outputs. However, Piezite® P-2 crystals (quartz) produce only tertiary pyroelectric outputs. Therefore, accelerometers using quartz are preferred when using amplifiers that are designed for use at frequencies near or below 1 Hz. These amplifiers are required for shock motion testing applications when measuring extremely long duration pulses; e.g., pulses of 100 ms duration. In most shock and vibration testing applications, amplifiers which cut off at frequencies near or above 2 Hz are used and no errors due to pyroelectric outputs are present.

3.5.3 Mounting Conditions

The accelerometer tends to alter slightly the motion of the structure or component to which it is attached. This produces a slight error in measuring the actual motion which would exist if the accelerometer were not present. This error is usually insignificant and need be considered only when making measurements on light and flexible structures or components. This effect imposes the requirement that very light accelerometers should be selected for these applications. The specific requirement is that the dynamic mass of the accelerometer must be much less than the dynamic mass of the structure at the point of attachment. Dynamic mass of an object is defined as the ratio of applied force to resultant acceleration; it is similar to mechanical impedance. The magnitude of the dynamic mass of an accelerometer is simply equal to its total weight because accelerometers act as rigid bodies throughout their normal operating frequency range. The dynamic mass of the structure will be sufficiently large if the accelerometer is attached at a point where the cross-sectional dimensions of the structure are large compared to the dimensions of the accelerometer. Applications where the structure's dynamic mass may be relatively small include thin plates and beams, panels and circuit boards, particularly at frequencies at which resonance exists. Accurate measurements can be made even on these structures since piezoelectric accelerometers weighing a fraction of one gram are available.

In some extreme applications, the case of the accelerometer can be distorted significantly when high strains are present in the mounting surface of the accelerometer or structure. These strains may be produced by mechanical loads or by non-uniform heating. The effect of these strains on the performance of accelerometers are determined on beams which are vibrated so that the radius of curvature is 1000 inches and the bending strain is 250 μ in./in. These test conditions are given in standards available from the United States Institute of Standards and the Instrument Society of America. The strain sensitivity of most shear type accelerometers is extremely small and in most test applications the effects of mounting strains can be ignored. The strain sensitivity of compression type accelerometers is sometimes significant. Accelerometers with high performance characteristics; e.g., extremely high resonant frequency and extremely high acceleration rating will usually be more susceptible to output errors from strain environments than other accelerometers. In test applications where the static or dynamic surface strain in the structure is near or above 250 μ in./in., it may be desirable to use insulated studs or rigid fixtures to act as strain filters. This precaution need be considered only when high performance accelerometers are used in testing applications where it is also necessary to measure low accelerations and when excessive strains are expected. A better solution for these applications is to select accelerometers that have high vibration sensitivity and, therefore, also have low strain sensitivity.

3.5.4 Acoustic Sensitivity

Although modern accelerometers produce negligible error signals when exposed to high intensity acoustic sound fields, it is interesting to explore the mechanisms present when gas or fluid pressures are applied to an accelerometer case. The same types of forces are applied to an accelerometer in acoustic fields and when dynamic fluid pressures are present.

When pressure is applied to an accelerometer case, the case deflects and produces a pressure on the crystal due to compression or expansion of the gas in the accelerometer. An approximate calculation on a typical compression type accelerometer indicates that the stiffness of the accelerometer is sufficient to attenuate the pressure about 55 db and an error signal of about 0.003 g/psi of external pressure is produced.

The pressure outside the accelerometer produces radial strains in the accelerometer base. Many designs of compression accelerometers have the crystal mounted on the inner surface of the base and the crystal experiences the same radial strain. As a result the ceramic material produces an output from the d_{31} piezoelectric constant. Typical error signals for compression type accelerometers as a result of the radial strain are about 0.03 g/psi.

For shear type accelerometers the error signals due to the above effects of internal gas pressure and radial strain are much less and can be considered nil.

A third effect is present in all accelerometers. This effect is produced because the external pressure changes the height dimension of the accelerometer base. For dynamic pressures this change in height dimension applies a motion to the accelerometer crystals. The equivalent acceleration at the top surface of the base increases with increasing frequency. For a typical accelerometer the error produced due to this effect is about .04 g/psi at 10,000 Hz and much less at lower frequencies.

All these errors are negligible when the accelerometer is subjected to extremely high intensity acoustic fields. False indications of acoustic sensitivity have been previously reported because of the difficulty in separating the above mentioned outputs from the actual accelerations applied to the mounting surface of the accelerometer as a result of the presence of the acoustic field. In other words, the accelerometer truly measures the acceleration applied to the accelerometer even though this acceleration was produced by the action of the acoustic field on the structure to which the accelerometer is attached.

4.0 WIRE RESISTIVE AND PIEZORESISTIVE ACCELEROMETERS

Wire resistive strain gages have been widely used in a number of applications. The strain gage consists of a fine wire which changes its resistance when its length is changed as strain is applied to a structure to which the wire is attached. Similarly, wire strain gage accelerometers have been used for shock and vibration measurements at moderate accelerations over limited frequency ranges. These accelerometers are built by using the fine wire strain gage element to support a mass element from the case of the accelerometer. These accelerometers have relatively low acceleration sensitivities because the gage factor of the materials used for the wires is limited to a value of about two.

In recent years strain gages have been developed from piezoresistive materials which have a much higher gage factor. The piezoresistive strain gage elements are now used in a variety of accelerometers used for shock and vibration measurements. Because of the high gage factors the piezoresistive accelerometers have higher sensitivities and higher operating frequency range than the wire strain gage accelerometers.

4.1 THEORY OF THE PIEZORESISTIVE ACCELEROMETERS

The gage factor of a strain sensing material is defined as the ratio of its change in resistance to initial resistance divided by its change in length to its initial length. For a piezoresistive material this ratio is given by the equation (3-10).

$$K = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = (1 + 2\mu + E\pi_1) \qquad (3\text{-}10)$$

where

- K = gage factor of resistance element
- ΔR = change in resistance
- R = initial resistance
- ΔL = change in length of resistance element
- L = initial length of resistance element
- μ = Poisson's ratio for the sensing material
- E = modulus of elasticity for the sensing material
- π_1 = piezoresistive coefficient for the sensing material.

The sum of the first two terms, $1 + 2\mu$, is almost 2, which also happens to be the gage factor ordinarily achieved in wire strain gages because π_1 is near zero for the wire strain gage. For piezoresistive materials, the third term $E\pi_1$ can have values that range well above 100 which is about 50 times the gage factor for wire strain gages. This advantage allows construction of accelerometers with high resonant frequency and high sensitivity.

The piezoresistive strain gage element is built into an accelerometer in such a way that the change in length of the gage is proportional to the motion of the mass element in the accelerometer relative to its case. Accordingly, the above equation for the change in resistance can be simplified as follows in equation (3-11):

$$\Delta R = C_2 \delta \qquad (3\text{-}11)$$

- C_2 = constant determined by the specific accelerometer design
- δ = deflection of the mass element relative to the accelerometer base.

Equation (3-11) indicates that the piezoresistive accelerometer will have frequency response characteristics as given by equation (3-1) and (3-2) and by figures 3-2 and 3-3. Many piezoresistive accelerometers have resonant frequencies near and above 30,000 Hz just like the piezoelectric accelerometers already described. It is difficult to introduce artificial damping in these high frequency accelerometers and the curves labeled zero damping in figure 3-2 and 3-3 apply. Accordingly, the normal operating range of these accelerometers is up to about one-fifth the resonant frequency where the sensitivity increase due to the resonant frequency is less than 5%. The important difference in the piezoresistive accelerometer is that its sensitivity is constant to zero frequency. Therefore, the piezoresistive accelerometer is used for measuring constant accelerations as well as for measuring extremely long duration shock motions. Piezoresistive accelerometers are also built with resonant frequencies significantly below 5000 Hz. For these low frequency accelerometers it is practical to introduce artificial damping and the curves labeled .707 in figures 3-2 and 3-3 apply.

A sketch of the internal construction of a piezoresistive accelerometer is shown in figure 3-12.

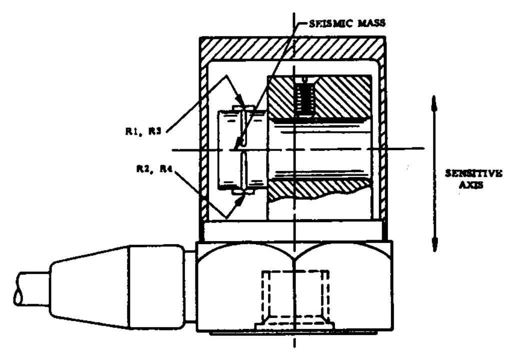


Figure 3-12 Sketch of a piezoresistive strain gage accelerometer.

The piezoresistive strain gage elements are identified as R1, R2, R3 and R4. These strain gage elements are fastened on each side of slots machined in a cylindrical member. When upward motion is applied to the base of the accelerometer along the sensitive axis, the mass element portion of the cylinder bends very slightly toward the base causing the length and resistance of R1 and R3 to increase while the length in resistance R2 and R4 decreases. These piezoresistive strain gage elements are connected electrically in a Wheatstone bridge in a similar way to other resistance strain gage circuits. Direct current voltage excitation is applied to the bridge input and the bridge voltage output varies with time in accordance with the time variation of the acceleration applied to the accelerometer. Frequently this voltage output requires no amplification; it is measured by using the same read-out instruments employed with other accelerometers. If desired, other instruments can be used, such as constant current power supplies and dc amplifiers, which are normally used with strain gage circuits.

4.2 PERFORMANCE CHARACTERISTICS

A summary of performance characteristics of piezoresistive accelerometers is given in table 3-3.

acceleration range. The accelerometers designed for high shock motion measurements have a low sensitivity. The accelerometers with high sensitivities, for example 50 mV/g, are intended for vibration measurement applications at relatively low accelerations up to 25 g. The sensitivity given in table 3-3 applies when the rated excitation voltage is provided at the input of the Wheatstone bridge in the accelerometer.

The amplitude linearity characteristics of piezoresistive accelerometers are quite good. Calibrations performed throughout the operating acceleration range indicate that deviations from constant sensitivity are less than the calibration errors which are 1% for vibration measurements and 5% for shock measurements.

The frequency response characteristics of piezoresistive accelerometers having damping near zero are similar to that obtained with piezoelectric accelerometers. Oil damping is provided in the accelerometer having a resonant frequency of 2700 Hz. The damping is in the range of 0.4 to 0.7 of critical damping at room temperature. With this

TABLE 3-3

Typical Performance Characteristics of Piezoresistive Accelerometers

Characteristic	High Acceleration Model	Low Acceleration Model
Acceleration Range, g	±2500	±25
Sensitivity, mV/g	0.1	50
Excitation, Vdc	10	24
Resonant Frequency, Hz	30,000	2,700
Damping Ratio	0.03	0.4-0.7
Frequency Range, Hz	0-6000	0-750
Temperature Range, °F	-65 to +250	20 to +200
Resistance, ohms	500	1,500
Transverse Sensitivity, %	<3	<3

In addition to the acceleration ranges given in table 3-3 other piezoresistive accelerometers are available with ranges below and above 2500 g. The sensitivity of the accelerometers is related to the damping the sensitivity is nearly constant from zero frequency to 750 Hz. The piezoresistive accelerometer using oil damping is intended for use in the temperature range from 20°F to 200°F.

At the high temperatures the viscosity of the oil decreases resulting in low damping and the viscosity increases at lower temperatures which causes high damping. Accordingly, the frequency response characteristics change as a function of temperature, as illustrated in figure 3-13.

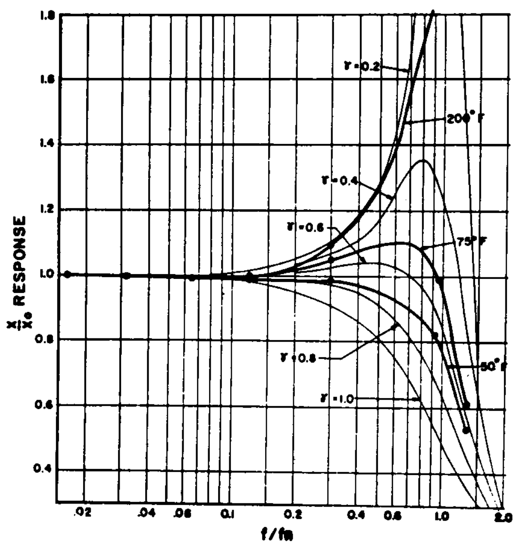


Figure 3-13 Frequency response characteristics of an oil-damped piezoresistive accelerometer.

At 200°F the damping is near 0.2 and at 50°F the damping is about 0.7. For accelerometers using oil damping it is desirable to perform frequency response calibrations throughout the operating temperature range if the accelerometer is normally used at temperature extremes. In addition to the frequency response changes near the resonant frequency at various temperatures, the sensitivity varies as a function of temperature, see figure 3-14, in a manner similar to undamped piezoresistive and piezoelectric accelerometers. This change in the sensitivity is caused by changes in the gage factor and is determined by the temperature characteristics of the modulus of elasticity and piezoresistive coefficient of the piezoresistive sensing element. The sensitivity deviations are minimized, as indicated in figure 3-14, by installing compensation resistors in the bridge circuit within the piezoresistive accelerometer. One final effect present in the accelerometer is that the bridge becomes slightly unbalanced when subjected to temperature changes. This unbalance is due to small differences in resistance changes of the sensing elements as a function of temperature. This change in resistance produces small changes in the dc voltage output of the bridge. Care is taken in the design of the piezoresistive accelerometer to keep the changes in the dc voltage output a small fraction of the output at the maximum rated acceleration of the accelerometer.

4.3 ENVIRONMENTAL EFFECTS

The environmental characteristics of transverse sensitivity and the effect of the accelerometer mass on the motion of the structure is similar in both piezoresistive and piezoelectric accelerometers. The typical values of near or less than 3% for the maximum transverse sensitivity are common for piezoresistive accelerometers. Just as in the case of piezoelectric accelerometers, it is desirable to select piezoresistive accelerometers that weigh significantly less than the mass represented by the cross sectional dimensions of the structure to which the accelerometer is attached. In this way, the presence of the accelerometer will not change significantly the motion of the structure. Frequently, this requirement is satisfied simply by using some care in selecting the mounting location on the structure.

Piezoresistive accelerometers are capable of withstanding shock and vibration accelerations significantly above the rated acceleration range. However, the piezoresistive materials used are quite brittle and it is necessary to limit the applied stresses. In accelerometers designed for high shock motions the moving element can be designed so that excessive stresses are avoided even at the highest shock motions normally encountered. However, some precautions are necessary for piezoresistive accelerometers designed for use at moderately low accelerations. The stresses are minimized in high sensitivity - low acceleration piezoresistive accelerometers by having built-in stops which limit the motion of the mass element to deflections corresponding to applied accelerations of several times the rated acceleration range.

5.0 <u>COMPLEX MOTION MEASUREMENTS</u>

In addition to the above discussion of specific accelerometers, certain general characteristics need be considered which are applicable to both

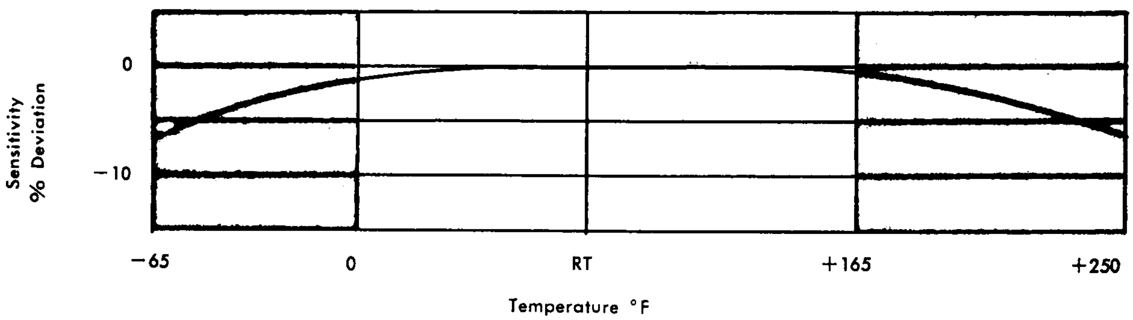


Figure 3-14 Typical sensitivity changes of a piezoresistive accelerometer as a function of temperature.

piezoelectric and piezoresistive accelerometers. The calibrations and evaluation tests on all accelerometers are performed using sinusoidal motion shakers and shock calibrators. However, in practice, the shock and vibration applied to accelerometers are complex wave forms including various frequency components throughout the operating range. Except for extremely short duration shock motions, the significant frequency components are within the operating frequency range since the resonant frequency of the accelerometer is usually at least five times the highest frequency of interest. However, in all random vibrations and shock motion measurements it is necessary to select accelerometers and accessory electronic instruments including filters which have flat frequency and proportional phase response throughout the operating frequency range. Usually the first requirement is satisfied since the accelerometer sensitivity and gain of the accessory electronics are constant throughout the frequency range of interest. However, it is also necessary to verify that all the accessory electronics have a phase shift that is zero degrees or that varies linearly with frequency throughout the operating range. If these requirements are not met the recorded output will not be an exact reproduction of the acceleration wave form applied to the accelerometer.

6.0 SHOCK MOTION MEASUREMENTS

In addition to the flat frequency and proportional phase requirements normally followed for complex motions; certain shock motion measurements impose the additional requirements of extremely low frequency response and good amplitude linearity. For extremely high acceleration - short duration shock motion measurements, it is necessary that certain linearity requirements be met at high frequencies which are beyond the frequency range of interest in other applications.

6.1 FREQUENCY REQUIREMENTS

Figure 3-15 shows the theoretical response of accelerometers which have been subjected to long duration square wave shock motion and illustrates the need for flat response at low frequencies.

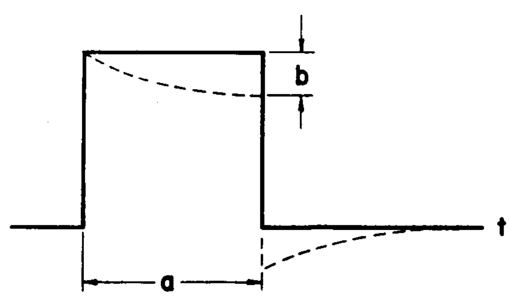


Figure 3-15 Theoretical responses from accelerometers exposed to long-duration square wave shock motions.

With a piezoresistive strain gage accelerometer, the output follows the solid line and would be an exact reproduction of the square wave input because these accelerometers measure all the frequency components down to zero frequency. If the accelerometer has inadequate low frequency response, its output will come up to the peak acceleration, then decay exponentially along the dotted line by an amount, b, and also undershoot zero by an amount, b, when the pulse is terminated, then decay exponentially to zero acceleration. To keep undershoot as small as 3 percent, it is necessary for the reciprocal of 2π times the frequency at which the output is down 3 db to be approximately 10 times the pulse duration "a". For a square pulse this ratio should be at least 20 to achieve less than 5 percent undershoot.

For example, consider a piezoelectric accelerometer with an amplifier which has a frequency response that rolls off at low frequencies. If the output is down 3 db at 1 Hz, the reciprocal of $2\pi(1)$ is about 160 milliseconds. This system is adequate for measuring pulse durations which are 1/10 of that, i.e. 16 milliseconds. The system will faithfully reproduce any pulse which is less than 16 milliseconds duration. If the pulse duration is significantly longer than 16 milliseconds, say 100 milliseconds, the piezoelectric system will no longer have adequate low frequency response and it would be necessary to use the piezoresistive accelerometer.

Frequently shock motion is not a simple pulse, It may be a very short duration-high acceleration pulse followed immediately by a "drag phase", consisting of a low acceleration pulse with a duration of 100 milliseconds. In this situation adequate low frequency response as well as high frequency response is required. There are low frequency components in the "drag phase" so response to zero frequency is needed. Very high frequency components are present because the initial pulse is short. For an accelerometer to adequately measure the entire shock motion it must have flat response from zero frequency to high frequencies. In this particular situation, most piezoelectric accelerometers would not accurately measure the "drag phase" but they would accurately measure the initial high acceleration pulse. Summarizing for this special pulse, a piezoelectric accelerometer will accurately measure the initial acceleration pulse, a wire strain gage accelerometer will measure the "drag phase", and a piezoresistive accelerometer will measure the entire shock motion accurately.

Except for this special shock pulse just mentioned, piezoelectric accelerometers are used extensively for shock measurements. In many applications, perhaps in most, the shock pulses are much less than 100 ms duration. Piezoelectric accelerometers cover a wide range of shock motion applications. They have the advantage of high resonant frequency, e.g. 30 kHz and are extremely rugged and linear which makes them suitable for making measurements near and above 10,000 g. Figure 3-16 illustrates the high frequency requirements.

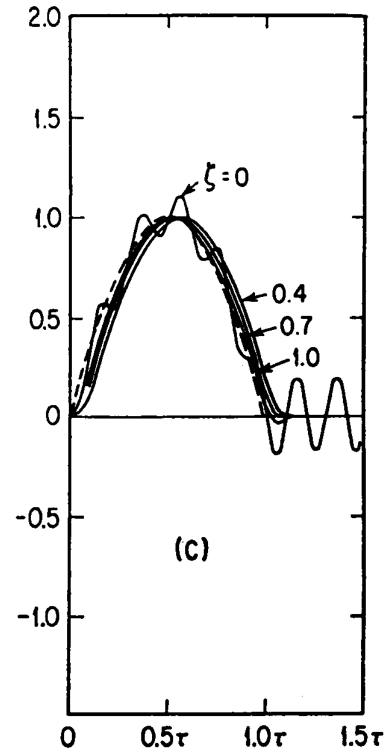


Figure 3-16 Response of accelerometers to short duration half-sine shock pulses.

The dashed line indicates a half sine pulse applied to the base of the accelerometer. The curve marked 0.7 indicates the output of artificially damped accelerometers having linear phase response. Response for other values of damping are shown and the curve marked 0 indicates the accelerometer output for accelerometers having no artificial damping. Except for very special long duration pulses, undamped accelerometers are used. The curves in figure 3-16 apply for pulse durations that are five times the reciprocal of the resonant frequency of the accelerometer. For longer pulse durations the resonant frequency excitation would be less than that indicated in figure 3-16; for shorter pulse durations the resonant frequency excitation would be greater. It is good practice to select an accelerometer which has a high natural frequency, so that its natural period is only one-fifth the pulse duration and resonant frequency excitation will be insignificant. Table 3-4 summarizes this requirement.

TABLE 3-4

Summary of Resonant Frequency Requirements

Pulse Duration	Resonant Frequency
μ sec	kHz
200	25
150	33
100	50
75	67
50	100

To measure a 200 microsecond pulse, a 25 kHz resonant frequency is required. A 50 microsecond pulse requires a resonant frequency near 100 kHz. The requirement is more rigid for pulses that approach a square wave in shape.

6.2 AMPLITUDE LINEARITY AND ZERO SHIFT

The sensitivity of piezoelectric accelerometers increases linearly with applied acceleration as discussed in section 3.4.4. In most shock motion applications the sensitivity increase is significantly less than 5% at accelerations corresponding to the amplitude of the shock pulse. For extremely short duration shock motions of less than 1 ms, it is of some interest to be familiar with the performance characteristics of the accelerometer at accelerations far exceeding the amplitude of the primary shock pulse. In the case of these short durations, resonant frequencies are excited in the structure which sometimes produce ringing or vibrations at frequencies near the resonant frequency of the accelerometer. Accordingly, a quasi-sinusoidal vibration is applied to the base of the accelerometer at the same instant that the primary shock pulse is being measured. Figure 3-2 shows that vibrations applied near the resonant frequency produce outputs which are many times the output that would be present if the vibration occurred in the normal operating frequency range of the accelerometer. This means that the stresses applied to the piezoelectric crystal corresponding to this vibration input are several times greater than the crystal stresses produced by the primary shock pulse.

Figure 3-17 illustrates the sensitivity increase of a piezoelectric accelerometer calibrated up to 100,000 g. This accelerometer is normally used for measuring shock pulse amplitude up to 10,000 g where the sensitivity increase is slightly less than 5%. Figure 3-18 illustrates the accelerometer output at accelerations much higher than 10,000 g. With an applied acceleration of about 60,000 g the output of the accelerometer fails to return to zero immediately at the termination of the pulse. This characteristic is called zero shift. This is an indication of high crystal stresses and the dimensions of the crystal do not return exactly to the original dimensions immediately at the end of the pulse; stress relaxation occurs. A finite period of time is required for the dimensions and stresses to return to their original state. For high stress the time required is longer than for low stresses and the zero shift is observed in the

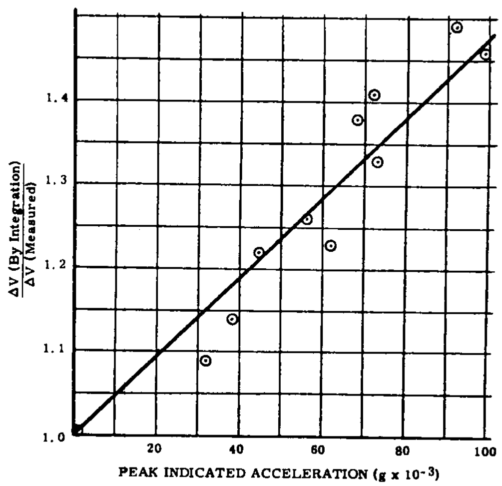


Figure 3-17 Ratio of indicated velocity (by integration) to measured velocity shows how the sensitivity of piezoelectric accelerometers increases with applied acceleration.

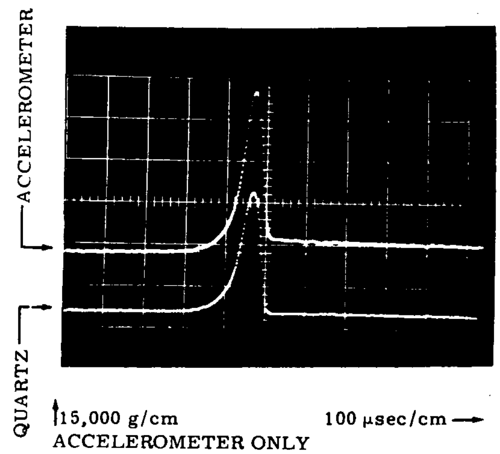


Figure 3-18 Accelerometer shows positive zero shift at 60,000 g.

output. To avoid measurable zero shift, it would be necessary for the pulse amplitude to be less than the maximum rated acceleration for the accelerometer. However, as indicated in figure 3-18, zero shift of about +5% occurs for pulse amplitudes of 60,000 g which is several times the rated acceleration range of the accelerometer. The zero shift is in the same direction as the applied acceleration. For the high frequency vibrations mentioned above, the zero shift may be positive or negative depending on whether most of the vibration amplitude is above or below the zero reference line. Therefore, in actual applications of combined shock and vibration excitation, positive or negative zero shifts will occur if the vibration output of the accelerometer is several times the outputs corresponding to the rated acceleration range of the accelerometer. These zero shifts are minimized simply by selecting accelerometers whose sensitivity increases are less than about 10% at accelerations of several times the amplitude expected in the primary shock pulse. This rule should be followed particularly when measuring shock pulses of durations near 100 us. Generally, accelerometers with low sensitivity are more linear and zero shifts are less likely to occur.

7.0 ACCELEROMETER CALIBRATION

Most laboratory calibrations are performed using sinusoidal motion and shock motion mechanical excitation applied to the accelerometer while measuring the electrical output. Sinusoidal motion calibrations are now performed routinely by the comparison method at frequencies from 5 Hz to 10,000 Hz. Shock motion calibrations are performed up to 10,000 g. Also piezoresistive accelerometers are calibrated on a centrifuge and in the earth's gravitational field.

Field calibrations, as required, are performed by applying an electrical signal to the accelerometer and measuring its electrical output.

7.1 SINUSOIDAL MOTION CALIBRATIONS

Reciprocity calibrations are performed on piezoelectric accelerometers used as standards for vibration and shock calibrations. These reciprocity calibrations are performed by making voltage ratio measurements on the piezoelectric standard output and voltage and current ratio measurements on the driving coil in a sinusoidal shaker. The other measurements required for the reciprocity calibration include mass and frequency. With these reciprocity measurements the sensitivity of good quality piezoelectric accelerometer standards is determined with an error of 0.5%. Once an accelerometer standard is reciprocity calibrated, it is used to perform shock and vibration calibrations on various accelerometers by the comparison method.

Sinusoidal comparison sensitivity and frequency response calibrations are performed at a single acceleration between 1 g and 10 g. Usually, this calibration is sufficient to verify that the performance characteristics of the accelerometer have not changed and that it is in good operating condition. Calibrations are performed by comparing the output of the test accelerometer to the output of the standard accelerometer while both accelerometers are experiencing exactly the same motion. Using this method the sensitivity and frequency response of the test accelerometer can be determined with an estimated error of + 1% at 100 Hz, ± 1.5% at frequencies up to 900 Hz and ± 2.5% above 900 Hz. In order to insure that shock and vibration measurements are free from unnecessary errors, each accelerometer should be comparison calibrated periodically throughout its frequency range of intended use. The time interval between calibrations should not exceed one year. More frequent calibrations should be performed if there is reason to believe that the accelerometer was used at temperatures or accelerations beyond its rated limits.

7.2 SHOCK CALIBRATIONS

Accelerometers used in shock testing applications should be calibrated by shock motion excitation. The exception to this is the case when shock motions measured do not exceed the acceleration used during the sinusoidal calibration and when the frequency components of the shock motion are within the range of the sinusoidal frequency response calibrations of the accelerometer. This happens, for example, when measuring shock motions up to 100 g. The shock calibration need be performed only with one accelerometer of a particular model. If good manufacturing control is maintained, the performance of all accelerometers of a given model will be the same. The calibration should be performed over the acceleration range of intended use. The calibrator frequently used produces short duration pulses. This has the advantage that the performance of the accelerometer is verified experimentally with a shock motion that includes extremely high frequency components which excite resonant frequency response in the accelerometer if it is present.

The absolute shock motion calibrations are performed up to 10,000 g in the primary calibration laboratory. Comparison calibrations are now being performed up to 10,000 g using a recently developed piezoelectric accelerometer standard. The comparison method is recommended for routine laboratory calibrations because of its simplicity and the short time required to perform the calibrations.

7.3 FIELD CALIBRATIONS

Although laboratory calibrations are performed with mechanical excitation applied to the accelerometer, most field calibrations are performed with electrical excitation. Two types of electrical excitation are used.

Field calibrations are performed by using accelerometers designed to provide active internal excitation. The sensor piezoelectric crystals are mechanically excited by including in the accelerometer additional piezoelectric crystals which are used as force generators. A voltage is applied to the crystal used as the force generator. The resulting dimensional change in this crystal produces a force and dimensional change in the sensor crystal. The accelerometer is designed so that a specified voltage input to the force generating crystal produces a voltage or charge output from the accelerometer corresponding to a preselected acceleration. This type of field calibration verifies that the vibration sensitivity of the accelerometer is unchanged. It also performs all the circuit integrity checks obtained in the passive electrical calibration described below.

Another field calibration method is to apply electrical excitation by placing a resistor in series with the crystal in the accelerometer. The resistor is selected so that an AC voltage applied to the resistor will produce a certain output from the accelerometer. For convenience, the selection is made to produce an equivalent acceleration, such as 100 g, at the output terminals of the amplifier used with the accelerometer. Performing the complete system calibration has the advantage that the integrity of the entire electrical circuit is verified. Not only does the calibration insure that there are no misconnections between various accelerometers and amplifiers; but any shorts or open circuits in the accelerometer or between the accelerometer and amplifier are detected. This type of calibration is passive in nature in the sense that the crystal is not mechanically excited and the vibration sensitivity of the accelerometer is not verified. However, a voltage is applied to the crystal and any changes in capacitance are detected. This is a reliable field calibration procedure because it is rare for the accelerometer to experience a change in sensitivity and yet have the capacitance of the accelerometer remain unchanged.

8.0 SUMMARY

Seismic accelerometers have made a significant contribution to the development of space vehicles and high-performance aircraft as well as in other measurement applications. Piezoelectric accelerometers are used to make accurate dynamic measurements of vibration and shock motions throughout the range corresponding to a fraction of gravity to many thousand g's. Piezoresistive accelerometers are now being used in applications which formerly required wire-strain gage accelerometers. The zero-frequency response of these accelerometers is an important characteristic for measuring extremely long-duration shock motions.

9.0 REFERENCES

1. Bouche, R.R., Transducers for Dynamic Measurements, Proceedings, Institute of Environmental Sciences, 1964, pp. 97-110.

2. Bouche, R.R., Characteristics of Piezoelectric Accelerometers, Test Engineering, Oct. 1962, pp. 16-18, 22, 24, 38.

3. Bouche, R.R., Ensuring the Accuracy of Shock and Vibration Measurements, Institute of Environmental Sciences, 1965, pp. 409-415.

4. Peters, R.B., A New Method of Evaluating the Acoustic Response of Piezoelectric Accelerometers, Institute of Environmental Sciences, 1965, pp. 105-112.

5. Butler, R.I. and McWhirter, M., Transducers for Shock and Vibration Measurements, Instrument Society of America, Preprint 16.6-1-66, 1966, 24 pp.

6. Wall, W.E., Piezoresistive Strain Gage Accelerometers with Subcritical Damping and High Overload Capabilities, Instrument Society of America Proceedings, 1966, pp. 269-274.

7. Riedel, J.C., The Accurate Measurement of Shock Phenomena, Institute of Environmental Sciences, 1962, pp. 83-88.

8. Bradley, Jr., W. and Eller, E.E., Introduction to Shock and Vibration Measurements, Shock and Vibration Handbook, McGraw-Hill Book Co., vol 1, Chap. 12, 1961.

9. Bouche, R.R. and Ensor, L.C., Use of Reciprocity Calibrated Accelerometer Standards for Performing Routine Laboratory Comparison Calibrations, Shock and Vibration Bulletin, 34, 4, 1965, pp. 21-29.

10. Bouche, R.R., The Absolute Calibration of Pickups on a Drop-Ball Shock Machine of the Ballistic Type, Institute of Environmental Sciences, 1961, pp. 115-121.

11. Rhodes, J.E., Piezoelectric Transducer Calibration Simulation Method Using Series Voltage Insertion, Environmental Quarterly, vol 8, no. 1, 1962, pp. 30-33,47.

ENDEVCO
AN AMPHENOL COMPANY

10869 NC Highway 903, Halifax, NC 27839 USA

endevco.com | sales@endevco.com | 866 363 3826

TP243-012122