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Transducers for Dynamic Measurements

Technical Paper 227
By Dr. R.R. Bouche

TRANSDUCERS FOR DYNAMIC MEASUREMENTS

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R.R. Bouche

Dr. Bouche received a BME degree from Marquette University and MS and Ph.D. from the University of Maryland. He was at the National Bureau of Standards for nine years. In addition to research work on force and strain measuring devices, he developed standards for the calibration of shock and vibration transducers. Since 1959, he has been associated with Endevco Corporation. As Transducer Engineering Manager, his responsibilities include work on shock and vibration instrumentation including pressure transducers and microphones. He has written a number of papers in this field.

In addition to his IES membership, Dr. Bouche is active with several other professional societies.

INTRODUCTION

A transducer is a device for converting strain, force, pressure, and shock or vibratory motions into an electrical signal that is proportional to the applied mechanical stimulus. Although some of the transducers described below measure constant mechanical stimulus, i.e. zero frequency, this tutorial paper is directed toward their use for dynamic measurements. The mechanical stimulus varies with time and usually does not remain constant for periods any longer than a fraction of one second.

The terminology in this paper is frequently used by environmental engineers. Definitions of the terms used are found in references 1 and 2 of the selected bibliography.

SEISMIC TRANDUCERS

Most dynamic transducers are used by making a mechanical connection to the structure providing the stimulus. Seismic transducers are used extensively for shock and vibration measurements. These transducers incorporate a transducing element as a part of a simple spring mass single-degree-of-freedom system.

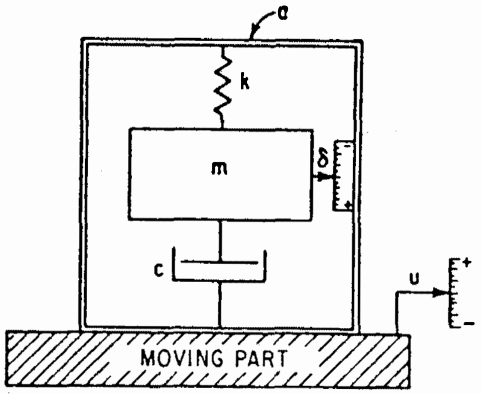

Figure 1 Single-degree-of-freedom seismic transducer consisting of a mass m suspended by spring k and viscous damper c. The case a of the transducer is attached to the moving part whose vibratory motion is to be measured. (After W. Bradley Jr.[1])

The seismic transducer consists of a case or moving part which contains a mass element connected to the case by a spring and damping medium, Figure 1. The equations which determine the amplitude of the mass element relative to sinusoidal excitation of the case are as follows:

$$\frac{\delta}{u} = \frac{\delta\omega}{\dot{u}} = \frac{\dfrac{\omega^2}{\omega_n^2}}{\left[\left(1 - \dfrac{\omega^2}{\omega_n^2}\right)^2 + \left(2\zeta\dfrac{\omega}{\omega_n}\right)^2\right]^{1/2}} \qquad (1)$$

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

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

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where δ = displacement amplitude of mass element relative to the displacement of the case (housing) of the transducer

u = displacement amplitude of transducer case

u = velocity amplitude of transducer case

$\ddot{u}$ = acceleration amplitude of transducer case

$\dddot{u}$ = jerk amplitude of transducer case

ω = circular excitation frequency, ($\omega = 2\pi f$ where f is usually expressed in cycles per second)

ω_n = undamped natural circular frequency of transducer ($\omega_n = 2\pi f_n$ where f_n is usually expressed in cycles per second)

ζ = damping in transducer expressed as a fraction of critical damping

θ = phase angle in degrees that the motion of the mass element lags the motion of the case.

Displacement and velocity transducers are usually designed to have a low natural frequency, e.g. 10 cps, and their frequency response is described by equation (1) and Figure 2. The transducer is a displacement pickup if the transducing element selected produces an electrical output proportional to its displacement, δ. It is a velocity pickup if the transducing element selected produces an electrical output proportional to its velocity, $\delta\omega$. The sensitivity of these pickups is constant, i.e. their frequency response is flat, at all frequencies above three times their natural frequency. Examples of these transducers are capacitive displacement pickups and electrodynamic velocity pickups.

Acceleration transducers are usually designed to have a high natural frequency, e.g. 30,000 cps, and their frequency response is described by equation (2) and Figure 3. The transducing element produces an electrical output proportional to its displacement or deformation, δ. It is called an accelerometer since its sensitivity ratio of electrical output divided by applied acceleration, $\ddot{u}$, is constant at all frequencies up to one-fifth the natural frequency. Typical accelerometers utilize piezoelectric, piezoresistive, differential transformer, and variable reluctance principles.

It is interesting to note that a high natural frequency jerk transducer can be built if the transducing element selected produces an electrical output proportional to the velocity motion (time rate of change of the deformation) of the element, $\omega\delta$. Its sensitivity, $\omega\delta/\dddot{u}$, is constant at all frequencies up to one-fifth the natural frequency as indicated by equation (2). An example of this transducer is the magnetostrictive jerk pickup.

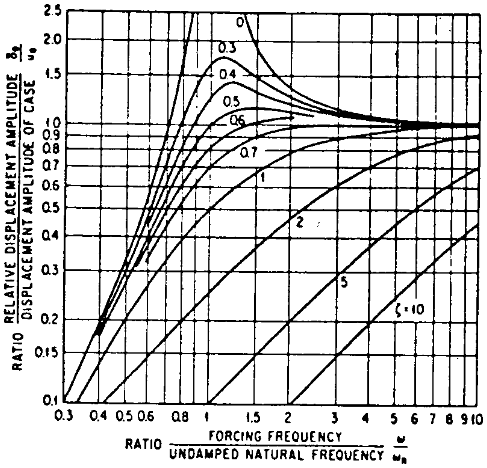


Figure 2 Frequency response of displacement and velocity transducer subjected to sinusoidal motion. The sensitivity is nearly constant at frequencies above resonance for transducers having less than critical damping, $\zeta < 1$. (After W. Bradley Jr.[1])

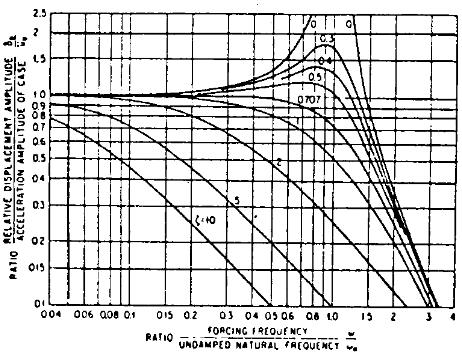


Figure 3 Frequency response of an accelerometer subjected to sinusoidal motion. The sensitivity is nearly constant at frequencies up to 1/5 the resonance frequency for accelerometers having less than critical damping, $\zeta < 1$. (After W. Bradley Jr.[1])

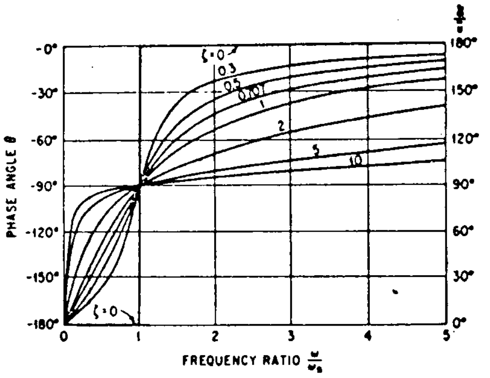


Figure 4 Phase angle response of seismic transducer. When used to measure sinusoidal vibration, the left hand scale relates the relative displacement, δ, and velocity, $\delta\omega$, to the applied displacement and velocity, respectively. The right hand scale relates the relative displacement, δ, to the applied acceleration. (After W. Bradley Jr.[1])

Equation (3) and Figure 4 describes the phase lag response of all the transducers. Throughout their operating frequency ranges, the phase lag of the accelerometer and jerk pickup is less than 90 degrees; the phase lag of displacement and velocity pickups is greater than 90 degrees. For zero damping the phase lag is constant throughout the frequency range at 0 or 180 degrees.

The response of the seismic transducer subjected to a shock motion depends upon the high and low frequency characteristics. The natural period of the accelerometer should be small compared to the pulse duration of the motion. For example, for half-sine wave pulses, an accelerometer is selected so its natural period is less than 1/5 the pulse duration. For accurate reproduction of the shock motion, it is also necessary that an accelerometer have good low frequency response. Accurate measurements are obtained for half-sine pulses of duration τ if $T_c > 16\tau$. The value T_c is $1/2\pi f_c$ where f_c is the frequency where the response is down 3 db. If the low frequency response is poor, undershoot distortion in the accelerometer output occurs. For shock motion measurements, it is also necessary for the phase lag response to be a linear function of frequency over the frequency range of Fourier components of the motion. This condition is satisfied for transducers that have damping values near zero or 0.7 of critical damping.

VARIABLE RESISTANCE TRANSDUCERS

Wire Strain Gages

Although other types of transducers may be used for measuring dynamic strains in structures, the most practical way is with wire resistance strain gages.

The resistance strain gage uses the principle that a piece of wire changes its resistance when strain is applied to it. If a wire is stretched its resistance increases. Conversely, if a compressive load is applied to shorten a wire, its resistance decreases. Within the linear range for the wire, this characteristic is defined by

$$\frac{\Delta R}{R} = k \frac{\Delta L}{L} \tag{4}$$

where k = gage factor

ΔR = resistance change

R = initial wire resistance

ΔL = length change, and

L = initial wire length.

Resistance strain gages that are in common use are Constantan (Ni 0.45, Cu 0.55), which has a gage factor of approximately +2.0 and Iso-elastic (Ni 0.36, Cu 0.08, Fe 0.52 and Mo 0.005), which has a gage factor of about +3.5. Later in this paper, piezoresistive materials that have a much higher gage factor are discussed.

Bonded strain gages are usually mounted on a paper backing. The paper backing is cemented to the structure at the point where the strain measurement is made. The gages are factory made with the grid of wire or foil formed on the paper backing. The grid is formed in such a way so that the change in resistance due to strain in a direction transverse to the length direction is only about 4 percent of that corresponding to an axial strain. This is called the transverse sensitivity of the gage. For shock and vibration applications, the stress concentration at the point of attachment of the lead wire to the gage wire is critical. To prevent fatigue failures, special gages are available which have a short length of intermediate size wire between the lead wire and gage wire. The effect of temperature on the resistance of the gage is usually not a problem in shock and vibration testing because measurements are made over a very short period of time. However, for special applications, temperature compensated gages are available.

Bonded strain gages are used also in pressure transducers. The gages are cemented to a diaphragm which is deflected due to pressure changes. The diaphragm is attached to the body of the transducer.

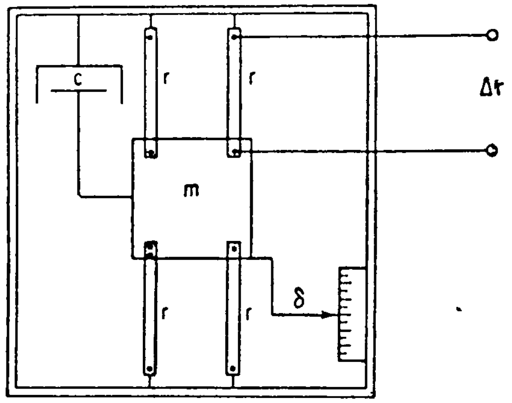


Figure 5 Unbonded wire resistance strain gage accelerometer.

Unbonded gages are used in seismic accelerometers, Figure 5. A fine wire of suitable gage factor supports a rigid mass element and acts as the spring element in the accelerometer. The stiffness of the wire and weight of the mass are selected to obtain the desired accelerometer resonance frequency. A typical wire-resistance strain gage accelerometers has its resonance frequency at 1000 cps, Figure 6. Such an accelerometer has low sensitivity and is suitable for shock measurement applications. Its use is limited to long duration shock measurements where the significant Fourier frequency components of the motion are near or below the resonance frequency.

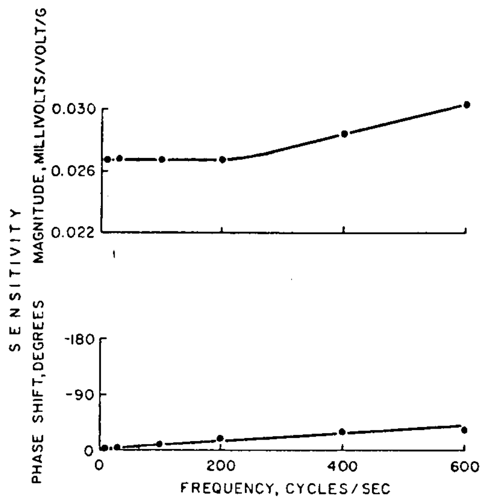


Figure 6 Calibration of an unbonded wire resistance strain gage accelerometer. (After R.R. Bouche[15])

Both bonded and unbonded gages are usually arranged electrically to form a Wheatstone bridge. The bridge input is energized by dry batteries or commerical power supplies. The output is measured with an oscilloscope or oscillographic recorder.

In shock and vibration applications where the strain applied to the gage is very rapid, magnetostrictive effects should be considered. Self-generated voltages due to rapid loading may be as much as several millivolts.

Potentiometer Accelerometers

Variable resistance potentiometers are used in accelerometers. A wire is wound on a hollow tube. The slider which makes contact with the wire is attached to the mass element in the accelerometer. The wire is energized with batteries or power supplies and the output connection is made to the slider.

Like the strain gage accelerometer, the potentiometer accelerometer may be used for measuring constant accelerations (zero frequency) as well as vibrations below the resonance frequency. A typical resonance frequency for a potentiometer accelerometer is 20 cps.

VARIABLE CAPACITANCE TRANSDUCERS

The air-gap capacitor is used in microphones and in certain types of vibration transducers for special applications.

The capacitance of an air-gap capacitor is

$$C = \frac{K}{3.6\pi} \frac{A}{d} \qquad (5)$$

where C = capacitance, picofarads

K = dielectric constant, unity for air

A = area, square centimeters

d = gap length, centimeters.

This equation can be approximated by:

$$\Delta C \cong C \frac{\Delta d}{d} \qquad (6)$$

where ΔC and Δd are changes in the capacitance and gap, respectively. The nonlinearities which characterize this transducer result from (1) the capacitance being inversely proportional to the air-gap, d, (2) fringing effects, and (3) the characteristics of the electric circuit used with the transducer.

Even though this transducer is inherently non-linear, it is useful in special vibration applications where even the smallest seismic vibration transducer would alter the motion of certain structures. It is used as a proximity pickup. One of the capacitor plates is placed near to the vibrating body which is used as the second plate.

In a microphone, one of the plates of the capacitor is a diaphragm which deflects due to a change in sound pressure. The corresponding change in capacitance produces a signal that is proportional to the sound pressure when a polarizing voltage is applied to the capacitor through a very high resistance. The frequency response of the microphone rises significantly at the upper audio frequencies. A typical condenser microphone has a capacitance of 50 pf, which has a capacitive reactance of 160,000,000 ohms at 20 cps. In order to obtain high outputs, the pre-amplifiers used have very short input cables.

VARIABLE INDUCTIVE TRANSDUCERS

The principal advantages of inductive transducers are: 1) high voltage outputs at low frequencies eliminate the need for pre-amplifiers and, 2) low electrical output impedances permit the use of long cables. Their principal disadvantages include 1) high mechanical impedance preventing their use on light structures and 2) low resonance frequency and/or low outputs at high frequencies. These characteristics restrict their use to vibration measurements below 2000 cps and to shock motions of long durations.

Seismic electrodynamic, differential-transformer and variable reluctance transducing elements are used in velocity pickups and accelerometers. Other inductive transducers utilizing eddy-current, magnetostrictive, electromagnetic, and mutual inductance principles are infrequently used and not discussed here.

Seismic Electrodynamic Transducers

The electrodynamic velocity transducer is one of the more common inductive types. The transducer weight varies from 2 ounces to about 20 pounds. Usually, the sensitivity of the transducer is higher as its weight increases. The transducer consists of a cylindrical coil located in the gap of a permanent magnet. The open-circuit voltage generated in the coil is

$$E = -BLV\,(10^{-8}) \qquad (7)$$

where E = generated output, volts

B = flux density, gausses,

L = total coil wire length in the magnetic field

V = relative velocity between coil and magnet, cm/sec.

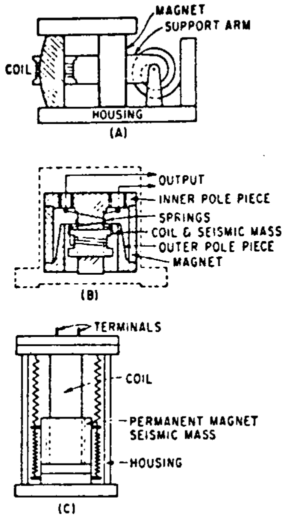


Figure 7 Electrodynamic velocity pickups. (After R.R. Bouche[1])

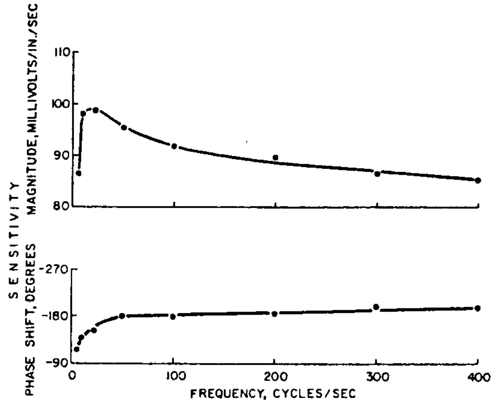


Figure 8 Calibration of an electrodynamic velocity pickup. (After R.R. Bouche[15])

This electrodynamic principle is used in a seismic velocity pickup, Figure 7. It is designed to have its resonance frequency near or below 10 cps. Its sensitivity, voltage output divided by applied velocity is nearly constant at frequencies above its resonance frequency, Figure 8. At frequencies near or above 2000 cps, the voltage output of most velocity pickups is extremely small and it is difficult to use them to measure acceleration levels below 10 g. Oil, air, and eddy-current damping are used in these pickups.

The electrodynamic principle is also used in microphones. The coil is attached to a thin diaphragm and a permanent magnet is attached to the microphone case. The low frequency response of these microphones is poor.

Seismic Differential-Transformer Reluctance Transducers

Unlike electrodynamic velocity transducers, differential-transformer and variable reluctance transducers are not self-generating. They require an input exciting voltage. Their output is a function of the input exciting voltage and the relative displacement between two parts of the magnetic circuit.

The differential transformer output depends upon the mutual inductance between the primary and secondary coils. The voltage induced in each secondary coil is given by

$$E = M\omega i_p \tag{8}$$

where E = induced secondary voltage, volts

M = mutual inductance, henries,

ω = circular frequency, radians/sec

i_p = the alternating current in the primary coil, amperes.

When the core is moved, the voltage in one secondary coil increases as the other decreases. The secondary coils are connected in series opposition so that the output voltage is the difference of the two secondary coil voltages. In seismic transducers, the coils are rigidly attached to the transducer case and the core is mounted on springs.

The variable reluctance principle is also used in seismic transducers. A coil is wound on a permanent magnet which is rigidly attached to the transducer case, Figure 9. A movable armature is mounted on springs. The inductance of the coil is given by

$$L = \frac{4\pi n^2 S\ (10^{-9})}{\ell} \tag{9}$$

where L = coil inductance, henries

S = area of the air-gap perpendicular to the direction of flux flow, cm^2

ℓ = air gap thickness, cm

n = total number of coil turns.

Over an appreciable range, the inductance is nearly proportional to the change in air-gap thickness. In most transducers, more than one coil is used. They are arranged as a dual or E-core magnet. The coils are used as part of a Wheatstone bridge in an electric circuit.

The outputs of both the differential transformer and reluctance seismic transducers are proportional to the relative displacement between the spring mounted core or armature and the case of the transducer. Such a seismic transducer operates as an accelerometer. Its acceleration sensitivity is nearly constant from zero cps up to about two-thirds of the resonance frequency, Figure 10. The resonance frequency is usually below 1000 cps. Like other inductive pickups, its use is limited to the measurement of relatively low frequency vibrations and long duration shock motions.

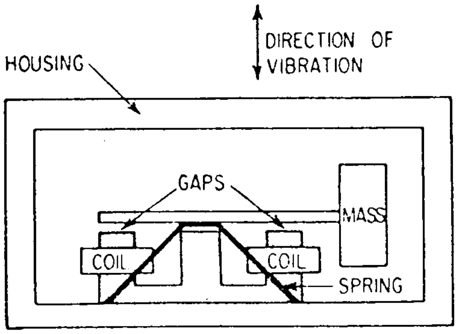


Figure 9 Wiancko variable reluctance accelerometer. The inductance of the coils changes as the gaps vary when the accelerometer is vibrated. (After R.R. Bouche[1])

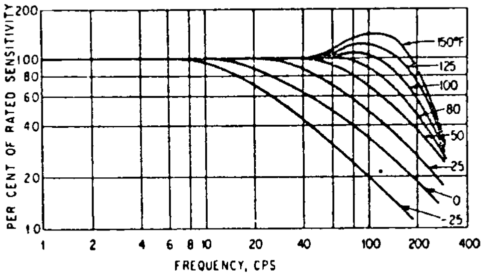


Figure 10 Combined temperature and frequency response of CEC Model 4-260 variable reluctance accelerometer. The operating frequency range within which the sensitivity is constant is reduced at low temperatures, by an increase in the internal damping. (After R.R. Bouche[1])

PIEZOELECTRIC TRANSDUCERS

Piezoelectric materials are used extensively in accelerometers and microphones. As a self-generating sensing material, it produces a large output for its size and is useful to extremely high frequencies. Piezoelectric transducers have low-mechanical impedance. Therefore, their effect on the motion of most structures is negligible. Another important characteristic is the extreme stability that results from proper aging and curing. For these reasons high quality piezoelectric accelerometers make excellent vibration standards.

Piezoelectric materials produce an electric charge proportional to the amount it is deformed.

$$Q = d_{xx}\sigma A \qquad (10)$$

where Q = crystal charge, coulombs
d_{xx} = piezoelectric coefficient, coulombs/newton
σ = crystal stress, newtons/meters^2,
A = crystal surface area, meters^2.

The trend is to use charge amplifiers with piezoelectric transducers. The voltage output from the amplifier is proportional to the charge output on the crystal. The transfer function and frequency response of the system remain unchanged for cable lengths up to one mile.

When using voltage amplifiers, the system output depends upon the capacity attached to transducer. The equivalent circuit consists of parallel capacitances and resistances which results in the following equation,

$$E = \frac{d_{xx}\sigma A}{C}\left[1 + (1/\omega RC)^2\right]^{-1/2} \qquad (11)$$

where E = amplifier input voltage, volts
C = total capacity, farads
ω = frequency, radians/second
R = total resistance, ohms

and the other terms are the same as in equation (10). The total capacity includes the capacity of the crystal, connecting cable and amplifier input. Likewise the resistance includes the parallel combination of the leakage resistance of the crystal and amplifier input resistance. The total resistance is usually at least 10^8 ohms. The capacitance of most transducers is in the range from 100 to 10,000 picofarads. Therefore, the practical low frequency limit of using piezoelectric materials is near 1 cps except when using an electrometer. At higher frequencies, the exponential term in equation (11) approaches unity and the output is proportional to crystal stress or deformation.

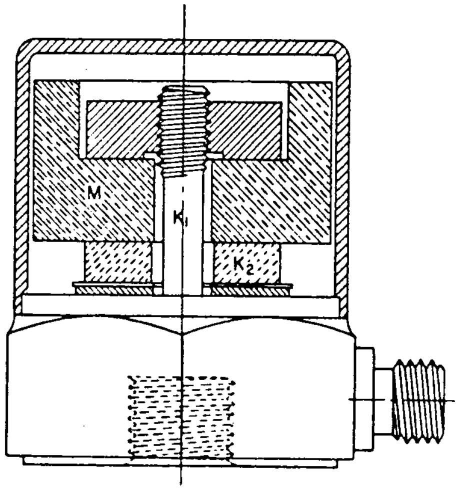


Figure 11 Piezoelectric accelerometer using the crystal in compression. Accelerometer designs using the crystal in shear or bending are also frequently used. (Courtesy of Endevco Corporation)

Piezoelectric Accelerometer

In a seismic accelerometer, Figure 11, the crystal displacement (deformation) is proportional to the applied acceleration at frequencies up to one-fifth the accelerometer resonance frequency. Therefore, the upper frequency limit is determined by the design of the accelerometer. Piezoelectric accelerometers are designed to have their resonance frequency in the range from 1,000 cps to 100,000 cps. As an example, the sensitivity constant, output voltage divided by applied acceleration, of an accelerometer with a 12,000 cps resonance frequency is 300 mv/g. Such an accelerometer would be best suited for measuring extremely small motions at frequencies up to 2000 cps. Many accelerometer designs have their resonance frequency in the range from 25,000 cps to 50,000 cps. These are intended for general purpose use in most vibration and shock measurement applications. Their sensitivity constant is in the range from 5 mv/g to 100 mv/g. Finally, at least one accelerometer design with a resonance frequency of 80,000 cps is available. It is intended primarily for very high acceleration shock motions. Because of its very high frequency range, it is suitable for measuring very short duration shock motions, e.g. a 75 microsecond half-sine wave pulse.

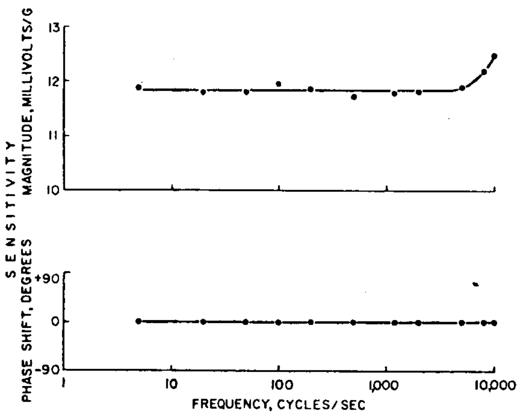
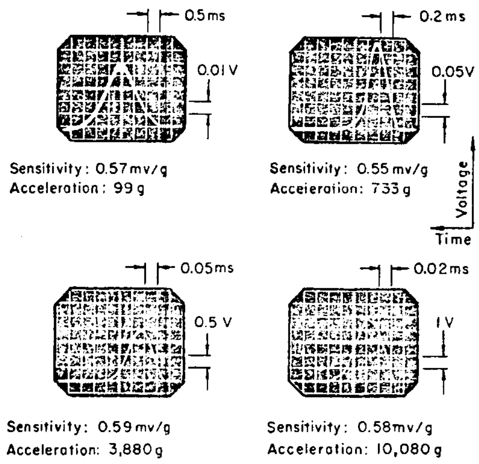


Figure 12 Calibration of a piezoelectric accelerometer. (After R.R. Bouche[15])



Sensitivity: 0.57mv/g
Acceleration: 99 g

Sensitivity: 0.55 mv/g
Acceleration: 733 g

Sensitivity: 0.59 mv/g
Acceleration: 3,880 g

Sensitivity: 0.58mv/g
Acceleration: 10,080 g

Figure 13 Shock motion amplitude linearity calibration performed on a piezoelectric accelerometer. (After R.R. Bouche[15])

Piezoelectric materials have very low internal damping, 0.01 to 0.04 of critical. Therefore, the response for an ideal accelerometer is constant throughout its frequency range with a rise in sensitivity of nearly 5 percent at one-fifth its resonance frequency, Figure 12. Piezoelectric accelerometers are available with nearly flat response from near 1 cps to 15,000 cps. This response is necessary for accurate measurements in many shock motion applications, Figure 13. Also, piezoelectric accelerometers are used in most vibration measurement applications. These vibrations frequently include significant frequency components up to 5,000 cps and sometimes 10,000 cps.

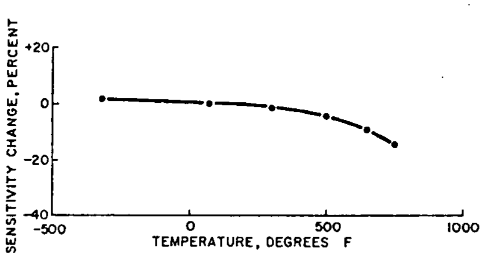


Figure 14 Temperature response calibration of a piezoelectric accelerometer. (After R.R. Bouche[15])

Another important characteristic of piezoelectric accelerometers is the effect of temperature on their performance, Figure 14. Extensive development work on piezoelectric materials has resulted in accelerometer designs that maintain good characteristics from -450°F to 750°F. By careful design, it is possible to maintain the voltage or charge output relatively constant over very wide temperature ranges. Another parameter affected by temperature is the leakage resistance of the accelerometer. The resistivity of piezoelectric materials decreases as the temperature increases. It may decrease to 500 megohms at the upper temperature limit. This resistance value affects the time constant and reduces the accelerometer response at very low frequencies when using voltage amplifiers. Charge amplifiers are preferred for extremely high temperature and low frequency measurements.

Relative humidity atmospheres greater than 50 percent also decrease the insulation resistance of piezoelectric materials. In some applications it is necessary to select accelerometers that are hermetically sealed.

Piezoelectric Impedance Head

Most mechanical impedance measurements are made with piezoelectric impedance heads, Figure 15. The head has a built-in accelerometer and a force-gage. The head measures the force transmitted to the structure and the resulting acceleration at the point of attachment. Impedance heads are designed for use at frequencies from 5 cps to 5000cps. The other performance characteristics of the head are similar to those for piezoelectric accelerometers.

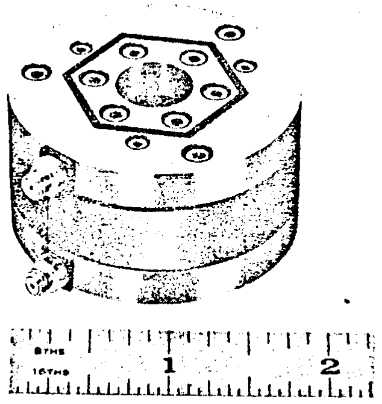


Figure 15 Impedance head with built-in piezoelectric accelerometer and piezoelectric force gage. (Courtesy of Endevco Corporation)

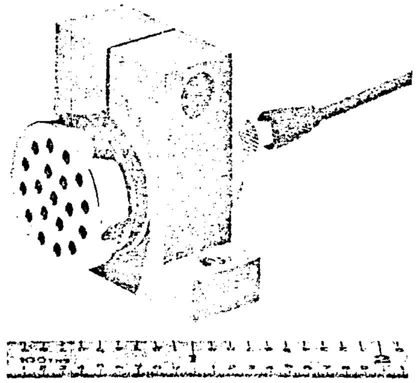


Figure 16 High intensity piezoelectric microphone with mounting bracket. (Courtesy of Endevco Corporation)

Piezoelectric Microphone

Piezoelectric materials are used in microphones, Figure 16, by attaching one side of the crystal to the diaphragm. In addition to having an output proportional to the sound pressure on the diaphragm, an output proportional to the vibratory acceleration of the microphone case is produced. This latter output can be minimized by building an accelerometer within the microphone case and connecting it electrically in series opposition with the microphone crystal. Since the built-in accelerometer is not exposed to the sound pressure, high-intensity piezoelectric microphones are available that are unaffected by the ambient vibration environment. The other performance characteristics of piezoelectric microphones are similar to those for piezoelectric accelerometers.

PIEZORESISTIVE TRANSDUCERS

Piezoresistive materials are semi-conductors whose resistivity changes with applied stress. As a thin rod or bar the gage factor is

$$K = \frac{\Delta R/R}{\Delta L/L} = 1 + 2\mu + E\pi_1 \qquad (12)$$

where K = gage factor
R = resistance of bar
L = length of bar
μ = Poisson's ratio
E = Young's modulus, dynes/cm^2
π_1 = longitudinal piezoresistive coefficient, cm^2/dyne.

The operation of the piezoresistive transducer is similar to the wire strain gage except that the gage factor is between 10 and 100 times larger. Therefore, it is used in applications where extremely small strain measurements require increased sensitivity. The low electrical impedance permits piezoresistive transducers to be used for static measurements, zero frequency, in addition to dynamic measurements at relatively high frequencies. The auxiliary instruments used with piezoresistive transducers are similar to those used with wire resistance strain gages.

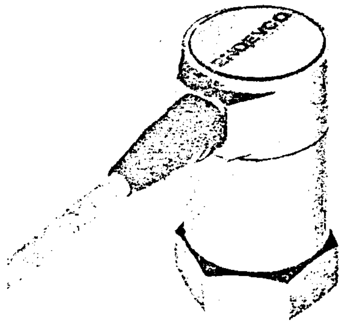


Figure 17 Piezoresistive accelerometer. (Courtesy of Endevco Corporation)

Accelerometers, Figure 17, using piezoresistive transducing elements have recently become available. Like the strain-gage accelerometer, the piezoresistive element is used as the spring in a spring-mass system. The change in resistance of the element is proportional to the acceleration applied to the accelerometer case at frequencies up to one-fifth the resonance frequency. The piezoresistive accelerometer can be designed with its resonance frequency above 10,000 cps. In addition to its high resonance frequency, the sensitivity of piezoresistive accelerometers is much higher than wire-resistance strain gage accelerometers. The piezoresistive accelerometer is used for sinusoidal and long duration shock motion measurements which require zero frequency response.

CALIBRATION METHODS

Strain Gage Calibration

Wire resistance gages used for strain measurements on structures are expendable items. Therefore, it is usually not possible to calibrate the same gage that will be used in a test. Sample gages are calibrated from a given manufacturing lot to determine the nominal gage factor for all gages in the lot. All gages in the lot are fabricated at the same time by a single operator to assure this is an accurate process. The calibration is performed by cementing the sample gages to a carefully machined beam loaded by dead weights. The gage factor is calculated from the beam formula which gives the theoretical value of the strain at the gage location.

In addition to calibrating the gage itself, it is necessary to calibrate the auxiliary readout instruments. Usually, built in calibrating circuits are used which adjust for the variation in gage factors from one package of gages to another.

Microphone Calibration

The absolute calibration of microphones is performed by the reciprocity method. Two microphones and a sound source are required. One of the microphones must be reversible. First the relative response of the two microphones is measured when both are exposed to exactly the same sound pressure. The reversible microphone is then used as a loudspeaker and its input current and the output voltage from the other microphone are measured. The sensitivities of the two microphones are determined by computations on these measurements. Reciprocity calibrations are performed at low sound pressure levels.

An absolute calibration of high-intensity microphones is performed with a pistonphone. The microphone is placed in a closed cavity. The sound pressure is computed from the measured piston motion and the dimensions of the cavity. Pistonphone calibrations are performed at frequencies up to at least 100 cps.

A comparison calibration of microphones is more easily accomplished. Pressure calibrations are performed in a closed chamber. An anechoic chamber is used to obtain free-field conditions. Both microphones, one at a time, are placedin the same position in the chamber. Having the standard previously calibrated at a qualified laboratory, the sensitivity of the second microphone is determined from their relative responses. Care should be taken to obtain a pure tone from the loudspeaker and that both microphones are exposed to exactly the same conditions. Free-field calibrations are performed at sound pressure levels up to about 130 db and frequencies up to 15,000 cps. Pressure calibrations have been performed up to 160 db and 10,000 cps.

Shock and Vibration Transducer Calibration

There has been a considerable advancement in shock and vibration calibration techniques during recent years. Even though calibrations at frequencies up to 2000 cps suffice for many laboratories, accurate calibrations can be performed from zero frequency (constant acceleration) up to 10,000 cps. Qualitative measurements can also be performed up to 50,000 cps.

Only sinusoidal calibrations are required if performed throughout the frequency and acceleration ranges of intended use. Shock motion calibrations are required if the Fourier spectrum of the motion contains frequency components not included in the sinusoidal calibration. Also, shock motion calibrations are required for measurement applications in excess of 100 g. It is sometimes difficult to calibrate at sinusoidal accelerations as high as the peak accelerations reached in the shock motion test.

Constant Acceleration

Zero frequency calibrations are performed either on a tilting support or centrifuge.

A tilting support, Figure 18, can be built to position an accelerometer at a known angle relative to the earth's gravitational field. Calibrations up to ±1 g can be performed with errors of ±0.0003 g.

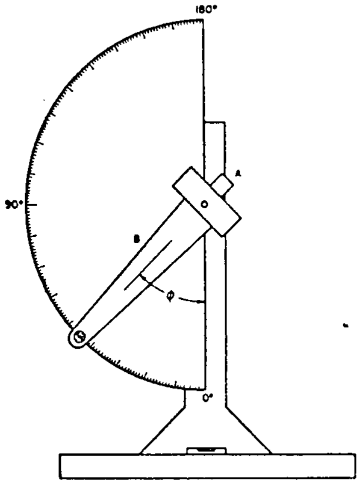


Figure 18 Tilting support used to calibrate accelerometers in the earth's gravitational field at constant acceleration. (Courtesy of American Standards Association[2])

A centrifuge consists of a rotating disk on which the accelerometer is placed off-center. The applied acceleration is

$$a = r\omega^2/g \qquad (13)$$

where a = acceleration, g's

r = distance from center of disk to mass element in the accelerometer, inches

ω = circular speed of disk, radians/sec

g = acceleration of gravity, 386 inches/sec^2.

This method can be used at accelerations up to 60,000 g with errors of ±1 percent.

The tilting support and centrifuge may be used to calibrate accelerometers utilizing variable resistance and inductive principles. In addition to performing one of these zero frequency calibrations, a sinusoidal motion calibration should be performed if other than constant acceleration measurements will be made.

Sinusoidal Calibrations

Electrodynamic vibration exciters are available for use from 5 cps to 50,000 cps. Absolute calibrations are performed by the reciprocity method, direct-viewing optical method, and by the interferometric method. Absolute methods are used at NBS and other primary standards laboratories. Almost all laboratories should use the comparison method. The possible exception to this, is that some laboratories will want a microscope on the shelf in order to make an occassional optical check on working standards at a low frequency.

The reciprocity method can be performed at frequencies from 10 cps to 5,000 cps. The calibration is performed by permanently mounting a standard electrodynamic velocity pickup or piezoelectric accelerometer to the exciter. The driving coil in the exciter is used as the reversible transducer. First the ratio of the driving coil current to the standard voltage output is measured with several known weights attached to the exciter. Then, at the same frequency, the exciter is driven by a second exciter and the ratio of the standard voltage output and open circuit driver coil voltage in the first exciter is measured. These measurements are repeated at each frequency a calibration is desired. The sensitivity of the standard pickup is calculated using the appropriate equations developed in the reciprocity theory. The errors in this calibration do not exceed 1 percent up to 900 cps and 2 percent up to 2000 cps.

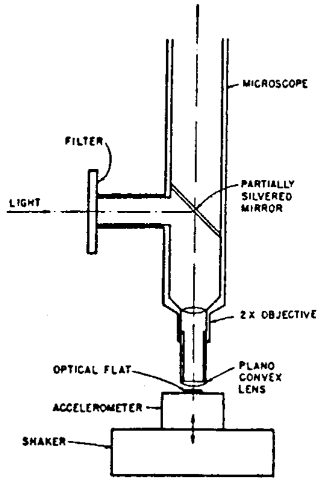


Figure 19 Interferometric calibrator for absolute sensitivity and frequency response calibrations. (After S. Edleman[16])

The fringe disappearance interferometric method is used at frequencies from 2,000 cps to at least 10,000 cps with estimated errors of 2 percent. This calibration is usually performed at one fringe disappearance which is a double displacement amplitude of 8 microinches. This corresponds to an acceleration of about 2 g at 2000cps and about 40 g at 10,000 cps. Below 2000 cps, one fringe disappearance occurs at too low an acceleration to be suitable for calibrating some accelerometers. The fringe disappearance is viewed in a telescope, Figure 19, which includes matched optically flat dividing and compensating plates through which passes an incident light beam from a mecury vapor lamp. The light beam is reflected from two optically flat mirrors. One of the mirrors is fixed to the vibrating surface. The pattern observed in the telescope which depends on the amplitude of the vibrating mirror is given by

$$I = K \left[1 + J_o\left(\frac{2\pi d}{\lambda}\right) \cos\left(\frac{2\pi x}{h}\right)\right] \qquad (14)$$

where I = light intensity for 50 percent transmission through the plates

K = illuminating intensity

J_o= Bessel function of zero order

λ= light wave length, 5461 x 10^{-8} cm for mercury

d = double displacement amplitude

h = separation of bands in fringe pattern

x = lateral displacement from point midway between two bands.

When the double displacement amplitude of the mirror is 8.18 microinches, J_o becomes zero and the fringe pattern disappears. Only the illuminating intensity K is present. At this amplitude the output voltage from the accelerometer mounted adjacent to the vibrating mirror is measured. Calculating the applied acceleration from

$$a = 0.0511\ f^2 d \qquad (15)$$

completes the calibration.

An optical calibration may also be performed by direct viewing with a microscope. A scotch-lite reflecting tape target is attached to the exciter. It is easy to focus on an illuminated bead on the tape and measure the applied displacement. This type calibration is usually performed at 10 g and 50 cps. The corresponding double-displacement amplitude calculated from equation (15) is 0.0783 inches. The displacement error is usually near 0.0005 inches. Using special techniques, the absolute voltage output measurement error can be controlled so that the probable calibration error does not exceed 1 percent. In order to keep the displacement error as small as possible, this method is not frequently performed at frequencies above 100 or 200 cps.

The comparison calibration method, Figure 20, is best suited for making routine laboratory calibrations over wide frequency ranges. A standard velocity coil or piezoelectric accelerometer is used. The standard is previously calibrated by (a) the reciprocity method, (b) by the interferometric method, or (c) by the comparison method itself. Piezoelectric accelerometers are frequently used as standards because of their high frequency characteristics, low mechanical impedance, and long-time stability. The comparison calibration is performed by subjecting both standard and test transducers to the same motion and measuring the ratio of their outputs. At frequencies above several hundred cps, it is necessary to mount both test and standard transducers in close proximity to assure both transducers have exactly the same motion. This is easily accomplished at frequencies up to 2000 cps. Above 2000 cps, special back-to-back fixtures or exciters with built-in standard accelerometers should be used. Using care, calibrations up to 10,000 cps may be performed. The comparison calibration method errors are 1.5 percent at frequencies up to 900cps, 2.5 percent up to 4000 cps, and 3 percent up to 10,000 cps. This includes the error of the standard accelerometer previously calibrated at NBS.

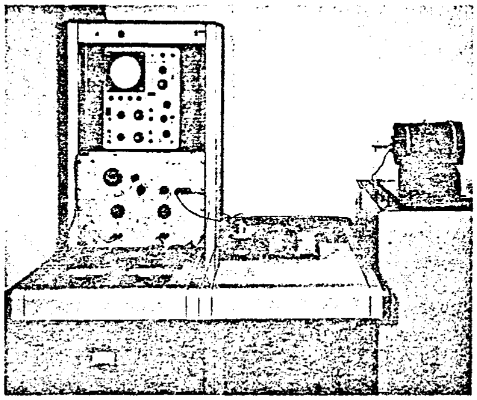


Figure 20 Sinusoidal calibrator used for comparison sensitivity and frequency response calibrations from 5 cps to 10,000 cps and for resonance frequency measurements up to 50,000 cps. (After R.R. Bouche[17])

Shock Calibrations

Absolute shock motion calibrations are now routinely performed, Figure 21. The calibration is performed on a drop-ball shock calibrator of the ballistic type. A steel ball is permitted to fall and impact an anvil to which the test transducer is attached. The velocity of the anvil due to impact is measured while the output from the transducer is photographed on an oscilloscope. For an accelerometer, the sensitivity is determined from the area under the oscilloscope trace and the measured velocity. The calibrator is capable of applying accelerations from 100 g to 15,000g with corresponding pulse durations of 3 milliseconds to 50 microseconds. The pulse duration depends upon the acceleration applied. The approximate pulse shape usually applied is a half-sine wave. The pulse duration applied should be more than 5 times the natural period of the accelerometer being calibrated. For this reason calibrations are most frequently performed in the range from 100 g to 10,000 g where the shortest pulse duration is near 100 microseconds. The calibration errors for this method are less than 5 percent.

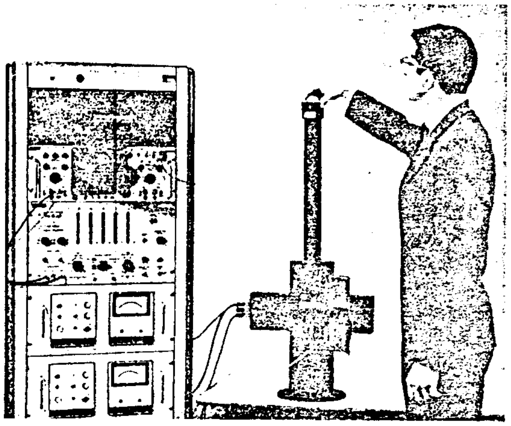


Figure 21 Ballistic shock motion calibrator used for comparison calibrations up to 5000 g and absolute calibrations up to 10,000 g. (Courtesy of Endevco Corporation)

Force and Pressure Pickup Calibration

The dynamic calibration of force and pressure pickups can be performed on sinusoidal vibration exciters. A standard accelerometer is used to measure the applied acceleration. A known weight is attached on top of the pickup. The output from the pickup is measured with and without the weight attached while the acceleration is maintained constant. The sensitivity of the force pickup is the change in output divided by the product of the weight and applied acceleration. For a pressure pickup, the output is also multiplied by the contact area of the weight on the pickup. This method can be used at amplitudes up to at least 10 psi and 100 pounds on pressure pickups and force pickups, respectively.

For higher loads, a transient calibration can be performed on a hydraulic loading apparatus. Bourdon tube pressure gages indicate a static force or pressure applied to the pickup. A quick-acting valve is used to reduce the load to zero in a fraction of a second. An oscilloscope is used to measure the resulting change in output voltage from the pickup.

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