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Design, Test, and Evaluation Division
Recommended Practice 011.2

Mechanical Shock and Vibration Accelerometer Selection

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Mechanical Shock and Vibration Accelerometer Selection

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1 SCOPE AND LIMITATION

The purpose of this Recommended Practice (RP) is to provide guidelines for selecting accelerometers to measure shock and vibration in laboratory and field testing environments. Many special applications are not covered (e.g., pyroshock [1,2], consumer products) because of their unique nature and the rapid advancements taking place in their disciplines. Even in applications not specifically addressed, however, these recommendations may be helpful.

There are basically two classes of motion sensors: fixed-reference and mass-spring (relative motion). Non-contact transducers, such as laser interferometric displacement and laser Doppler velocity transducers, are fixed-reference designs. Although they offer some unique properties, these instruments are used to measure shock and vibration only in applications where a fixed reference is available, and where their cost, size, and physical space and geometry requirements are acceptable. Similarly, video and high-speed photographic displacement measurement techniques are becoming more sophisticated, thereby increasingly allowing their application to the motion analysis of structures. These fixed-reference techniques, which have different constraints, are discussed elsewhere [3,4,5]. This RP concentrates on the more common mass-spring type accelerometers, with the sensing element(s) represented by the spring.

The following recommendations apply to dynamic measurements with frequencies ranging from DC (0 Hz) to more than 20 kHz. Only measurements of linear (translational) motion are considered; measurement of angular or rotational motion is addressed as an application at the end of the document.

2 REFERENCES

It is recommended that the user reference manufacturers' specification and application data in the selection and use of equipment. Please see Appendix A: Bibliography for informative resources.

3 TERMS AND DEFINITIONS

accelerometer

A transducer whose instantaneous output is proportional to the instantaneous acceleration input.

acoustic sensitivity

The rated output produced by a non-acoustic transducer in the presence of a specified acoustic field.

back-to-back comparison method

A method of performing a sensitivity/frequency response calibration of an accelerometer by mounting the unit under test to the sensitive surface of a reference standard and comparing the outputs of the two devices.

base strain sensitivity

The rated output produced by an accelerometer in the presence of a specified amount of strain input induced by the bending motion at the mounting interface.

bias voltage

The DC voltage that appears at the output of the accelerometer in quiescent state (its level is determined and preset by the manufacturer); generally interferes with receiving recording devices and normally decoupled by a high value capacitor in series.

charge amplifier (converter)

A preamplifier designed for use with high-impedance piezoelectric transducers, commonly referred to as a “charge amp;” consists of an operational amplifier with a capacitor in its feedback loop; output voltage of the amplifier is proportional to the input charge generated by the transducer and independent of the cable capacitance.

charge sensitivity

The rated output produced by a high-impedance piezoelectric transducer per unit of acceleration input (e.g., pC/g).

closed-loop accelerometer

An accelerometer in which the output generated by deflection in the mass-spring system is used as feedback in a circuit that closes the loop by physically driving the deflected mass back to its equilibrium position.

NOTE: Generally, closed-loop accelerometer designs offer better amplitude linearity than open-loop designs. However, with the use of microprocessors and the ability to correct data at the source, closed-loop accelerometers are finding much less application.

compensation resistor

A resistor placed in parallel or in series with any of the legs of a piezoresistive accelerometer to correct for the imbalance in the bridge circuit or sensitivity errors at temperature, or both.

compliance voltage

The DC supply voltage available to the integral electronics piezoelectric (IEPE) accelerometer circuitry; usually lower than the power supply voltage due to the voltage drop in the constant current device(s).

discharge time constant

The RC time constant determined by the design of a transducer’s circuit topology; time required for the step response to reduce to 37% of its original value.

dynamic range

The ratio of the highest level to the lowest level of signal to be measured, expressed in dB.

electrical isolation

A condition in which the output and ground leads of the accelerometer are electrically isolated from the mounting surface.

electromagnetic rebalancing

A type of closed-loop accelerometer that uses an electromagnetic mechanism to rebalance the deflected mass.

electromagnetic sensitivity

The rated output produced by an accelerometer in the presence of a specified electromagnetic field.

electrostatic rebalancing

A type of closed-loop accelerometer that uses an electrostatic mechanism to rebalance the deflected mass.

ferroelectric

A subset in the piezoelectric-type materials that typically has a high dielectric constant. Example: lead zirconate titanate (PZT).

fixed-reference transducer

A two-terminal transducer in which one terminal is fixed at a point in space as reference and the other terminal is attached to the object in motion.

gage factor

An indicator of efficiency for strain gages, which is the ratio of the relative resistance change to the relative length change.

hermetically sealed

A sealing method used in transducer design; usually accompanied by a welded construction and a glass-to-metal seal in the connector.

integral electronics piezoelectric (IEPE)

A piezoelectric transducer with a built-in preamplifier to convert the high-impedance input into a low-impedance voltage output.

integral mechanically isolated accelerometer

An accelerometer with a mechanical isolator in a single package. In general, the contained isolation material in these instruments can be nonlinear, resulting in errors attributable to extraneous frequencies in their response. Performance documentation and assurance should be requested from their manufacturer. NOTE: External isolators manufactured by the testing organization are also of concern.

laser Doppler velocity transducer

An instrument that uses the Doppler shift of laser light that has been backscattered from a vibrating object to produce a real-time analog signal proportional to instantaneous velocity.

laser interferometric displacement transducer

An instrument that uses an interferometric fringe counting technique for vibration-displacement measurement in low-frequency ranges.

linear variable differential transformer (LVDT)

A variable inductance transducer that provides an AC voltage output proportional to the displacement of a core passing through its internal windings.

linearity (nonlinearity)

The constant (or non-constant) behavior of the ratio of the electrical output of a transducer to the mechanical input; typically stated as a percentage of full scale based on a best-fit straight line, or as a percentage of reading.

mass-loading error

An error in the structural response induced by the added mass of the accelerometer. This is a function not only of the accelerometer mass, but also of the dynamic stiffness of the structure at the mounting location and the frequency range over which measurements are being acquired.

mass-spring (relative motion) accelerometer

An accelerometer that has only one terminal attached to its base and is attached to the object in motion; the motion of the device is inferred from the motion of the mass (of the mass-spring system) relative to the base.

mean time between failure (MTBF)

An established method of calculating and predicting the service life of an instrument.

mechanically isolated accelerometer

An accelerometer with built-in or external mechanical isolation. Substantial documentation should be provided by the manufacturer or other sources to verify that the mechanically isolated accelerometer is appropriate for the intended application (i.e., shock or vibration). This information should include amplitude and frequency performance that is appropriate for the application [6].

mechanically isolated and electrically filtered accelerometer

An accelerometer with mechanical isolation and an electrical filter. Substantial documentation should be provided by the manufacturer or other sources to verify that the mechanically isolated accelerometer is appropriate for the intended application (i.e., shock or vibration). This information should include amplitude and frequency performance that is appropriate for the application [6]. Usually, the electrical filter is included to attenuate the mechanical isolator performance, and the user is advised that these accelerometer additions may mask the shock environment that is to be measured.

micro electro-mechanical systems (MEMS)

A silicon based sensor that uses etching and micromachine fabrication techniques in forming its components; typically less than 1 mm square.

NOTE: MEMS technology can be applied to piezoresistive, variable capacitance, or other types of design.

micromachining

A manufacturing process that produces the entire sensing mechanism from a single piece of silicon by using anisotropic etching or other micro-manufacturing techniques.

noise monitor

A dummy, or placebo, accelerometer that possesses all of the electrical and physical characteristics of a real accelerometer except for dynamic response, usually produced by replacing or desensitizing the sensing element(s); useful in assessing the quality of the output signal in the presence of environmental noise.

noise-treated cable

A type of cable designed to minimize triboelectric noise in a high-impedance piezoelectric accelerometer system; also known as low-noise cable.

open-loop accelerometer

An accelerometer in which the output generated by the deflection in the mass-spring system is used directly to indicate acceleration (cf. closed-loop accelerometer).

overrange capability

The ability of an accelerometer to withstand excessive mechanical input beyond its stated full-scale range without sustaining permanent damage.

picoCoulomb (pC)

A common unit of charge from a PE accelerometer; 10⁻¹² Coulomb.

piezoelectric (PE) accelerometer

An accelerometer that utilizes piezoelectric elements as the spring in its mass-spring system and produces an electric charge proportional to the applied input.

piezoelectric coefficients

The measure of the amount of charge produced per unit of input force; unit is in picoCoulomb per Newton.

piezoresistive (PR) accelerometer

An accelerometer that utilizes piezoresistive elements as a portion of the spring in its mass-spring system, resulting in a change in resistance proportional to the applied input.

piezoresistive elements

Strain gage elements, usually doped silicon ingots, used in a bridge configuration.

pyroelectric effect

The phenomenon in which an electric charge is produced when an accelerometer is subjected to a thermal transient input; relates primarily to piezoelectric accelerometers.

pyroshock

The response of a structure to a high-frequency, high-magnitude shock pulse as a result of an explosive event; also known as pyrotechnic shock.

RAD rating

An indicator used by the nuclear industry to represent the level of integrated gamma radiation.

reciprocity method

A little-used primary vibration calibration method that uses a shaker designed with two coils, one to provide motion, one to measure the motion; the shaker is a reciprocal transducer, able to sense or drive, with a sensitivity factor relating the ratio of the drive current to the ratio of pickup voltage to velocity.

resolution

The lowest level of signal that can be measured by a transducer, usually stated in terms of equivalent engineering unit; other terms, such as residual noise and threshold, are also used to represent the same parameter.

resonance frequency

For undamped accelerometers, the frequency for which the response of a system undergoing forced, steady-state vibration is a maximum. For damped accelerometers, the frequency with 90° phase shift. Damped systems do not have their peak at the resonance frequency. Damped accelerometers may not have a peak in the frequency response curve.

NOTE: The mounted resonance frequency specified by the manufacturer is usually lower than the unmounted resonance (the natural frequency of the device). When an accelerometer is mounted to a structure, the resonance may be lower than the “mounted resonance” as a result of imperfect mounting compliance.

self-generating

A term referring to accelerometers that use only piezoelectric element(s) as the sensing mechanism, thus producing an electrical output without the need for an external power source.

sensing element

An element used in an accelerometer that is responsible for the sensing mechanism; in a piezoelectric accelerometer it is the piezoelectric crystal.

shock response spectrum (SRS)

The plot of the maximum response experienced by a single-degree-of-freedom (DOF) system, as a function of its own undamped natural frequency, in response to an applied shock; may be expressed in terms of acceleration, velocity, or displacement.

slew limiting

The output distortion (nonlinearity errors) resulting from a limit on the rate at which the output voltage can change; occurs when a load requires more current than the finite supply at the last stage of an amplifier, causing the output to adjust to draw only the available current; also known as slew rate limiting.

strain gage

A small measurement device consisting of a piece of very thin foil, fine wire, or semiconductor that exhibits a change in resistance proportional to the mechanical strain imposed on it.

survivability

The ability of an accelerometer to withstand environmental inputs, such as shock and high temperature, without sustaining any damage.

temperature response

An indication of output behavior of the accelerometer over a specified temperature range; also referred to as temperature coefficient.

NOTE: Some manufacturers give a curve showing sensitivity versus temperature; others state it as a number (coefficient) in the specification, assuming a linear relationship. Temperature response should not be confused with thermal transient sensitivity.

thermal transient sensitivity

The output response of an accelerometer when exposed to a defined temperature gradient (transient); usually stated in terms of equivalent engineering unit per degree centigrade.

thermal zero shift

A change in accelerometer zero measurand output caused by a change of ambient temperature.

transducer

A device that converts one form of energy into another. An accelerometer is a transducer that converts the product of inertial force times displacement (mechanical energy) due to the acceleration into electrical energy.

NOTE: The terms “transducer” and “accelerometer” are often used interchangeably with the term “sensor” in industry. The term “sensing element” is used to describe the sensing mechanism inside the transducer or sensor.

transducer electronic data sheet (TEDS)

Transducer information stored inside a digital memory chip defined by IEEE 1451.4 [33]; typically located inside the transducer, the digital ID chip contains permanent information (model number, serial number) and temporary information (sensitivity, date of calibration) provided by the manufacturer or calibration facilities.

transmissibility

The non-dimensional ratio of the response amplitude of a system in steady-state forced vibration to the excitation amplitude; ratio may be one of forces, displacements, velocities, or accelerations.

transverse sensitivity

The output response of an accelerometer when excited by a transverse motion perpendicular to its sensitive axis; stated in percent of the nominal output.

triboelectric noise

The output generated by a coaxial cable in motion due to the momentary separation of its dielectric material from its shield.

variable capacitance (VC) accelerometer

An accelerometer that uses a bridge-type variable capacitance microsensor as the sensing element; the capacitance of one circuit element increases with applied motion, while that of the other decreases.

velocity coil

A transducer that converts an input velocity to an electrical output proportional to the input velocity; uses an electrodynamic (or moving coil) sensing mechanism.

voltage sensitivity

The rated output produced by an accelerometer at the specified level of acceleration; in a high-impedance piezoelectric device: open circuit voltage output sensitivity (charge sensitivity divided by source capacitance plus cable capacitance); in an IEPE device: output sensitivity; in a PR or VC device, output sensitivity.

Wheatstone bridge

A four-element circuit arrangement that is one of the most precise methods for measuring small changes in resistance; widely applied in transducer design.

zero measurand output (ZMO)

In a bridge circuit, the small offset or residual DC voltage at the output due to slight differences in resistance between each arm; expressed in millivolts at full rated excitation; also known as zero balance or zero offset.

zeroshift

The apparent shift from the zero-reference line of an accelerometer output due to an intense shock from mechanical, electrical, or thermal causes; all accelerometer types exhibit some degree of zeroshift under high-shock load.

4 BACKGROUND AND PURPOSE

Shock and vibration environments are seldom measured directly. The structural response of an item is normally obtained using measurements of acceleration, velocity, displacement, or dynamic force.

Except for a few unique cases, acceleration is the preferred measurand of motion. However, acceleration is a quantity that cannot be measured directly in practice. As a result, strain or displacement in a mass-spring motion transducer is used to obtain acceleration information indirectly.

To understand why acceleration is the preferred measured parameter, consider the following.

The nature of mechanical systems is such that appreciable displacements occur only at low frequencies. Displacement measurements, due to their limited bandwidth, are of little value for most structural measurements. Also, displacement sensors, such as linear variable differential transformer (LVDT) displacement transducers, tend to be large, heavy, and limited to frequencies below 500 Hz.

Most practical velocity sensors, such as velocity coils, are based on the electrodynamic principle. This type of transducer is designed to be used at frequencies above its natural frequency, and is not very useful at frequencies above several thousand Hz due to its inherent design characteristics [3,4,5]. Most velocity coils, therefore, are used on industrial rotating machineries where vibration frequencies are relatively low. One uniquely fabricated velocity coil has been designed to measure intense shock up to 100 kHz, but it is not commercially available [40]. In general, a single wide-band measurement of a signal in a shock and vibration environment often requires transducers with much broader bandwidth.

With modern accelerometers, satisfactory acceleration measurements can be made from steady state (DC) to over 10 kHz. Many of these new designs offer more than 100 dB signal-to-noise ratio, giving the accelerometer a definite edge over displacement and velocity transducers in regard to bandwidth and signal/noise ratio. In addition, with a suitable accelerometer, velocity and displacement information can be derived from acceleration data by single- and double-integrating the signals during post-processing.

This RP makes recommendations in terms of performance characteristics rather than instrument construction, brand, or model number. Various sensing technologies are discussed in detail to provide a good understanding of design trade-offs. It is assumed that instrument suppliers provide accurate performance specifications, enabling users to select the optimum available instrument. In a few instances, advice or precautions are provided for interpreting manufacturer specifications. In general, manufacturers and users should use the referenced ANSI and ISA specifications [22,23].

5 ACCELEROMETER TYPES FOR SHOCK AND VIBRATION

This section concentrates on several different accelerometer types; other types of transducers will be addressed in future RPs.

The most common mass-spring accelerometer types for shock and vibration measurements are:

- Piezoelectric (PE)—high-impedance charge output
- Integral electronics piezoelectric (IEPE)—low-impedance voltage output
- Piezoresistive (PR)
- Variable capacitance (VC)

Each type has its own strengths and weaknesses and serves in different applications. Piezoelectric sensors (both PE and IEPE types) are the most commonly used accelerometers for shock and vibration measurements. The following sections describe each type and address issues that affect the measurement.

5.1 Piezoelectric (PE) type

5.1.1 PE materials

Many natural and man-made materials display PE characteristics, usually in the form of crystals or ceramic, although some PE materials are polymers. All such materials have a regular crystalline molecular structure with a net charge distribution that changes when strained. One property all PE materials share is that they have no center of symmetry in the unit cell of the structure [21,41]. Deforming a symmetric cell does not produce electric fields.

PE materials may also have a dipole (the net separation of positive and negative charge along a particular crystal direction) when unstressed. With these materials, such as ferroelectric and polymer, fields can be generated by deformation from stress or temperature, causing PE or pyroelectric output, respectively. The effects are reciprocal. The PE sensor can be made to distort with the application of a field or temperature. PE materials without a dipole (such as quartz) are not pyroelectric.

Pyroelectric outputs can be very large unwanted signals, generally occurring over the long time periods associated with most temperature changes. The outputs might not be noticed if the signal conditioner does not respond to those low frequencies, but they can be very large as thermal rates and gradients increase. (Polymer PE materials have such high pyroelectric output that they were originally used as thermal detectors.) There are three pyroelectric effects, discussed in detail in section 7 on environmental characteristics.

Charges are not “generated,” just displaced. (Like energy and momentum, charge is always conserved.) What is generated is an electric field along the direction of the dipole. Metallic electrodes on faces at the opposite extremes of the gradient provide mobile electrons, which move from one face, through the signal conditioning, to the other side of the sensor to cancel the generated field. The quantity of electrons depends on the voltage created and the capacitance between the electrodes. A common unit of charge from a PE accelerometer is the picoCoulomb (pC), or 10^{-12} Coulomb, which is approximately 6 million electrons.

Piezoelectric materials consist of ions oriented in a crystal cell. When the cell is strained, a net change in the separation of the positive and negative charges occurs. The direction of the separation (which, depending on the crystal, is not necessarily in the direction of the applied force) defines the surfaces on which the electrical signal appears. In Figure 1, compression sensitivity is shown on the left (an example of a linear DOF). This example would not develop a net charge on the sides for the given strain. The result of shearing stresses (a torsional DOF) is shown on the right.

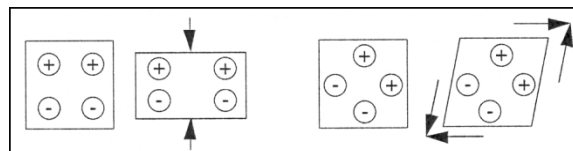


Figure 1. Compression and shear crystal strains.

The position of the electrodes depends on the crystal orientation and the type of stress to be sensed. A given material may be sensitive to several directions and types of strain. (The two simplified examples in Figure 1, showing compression and shear strains corresponding, respectively, to linear and rotational DOFs, are for the same crystal

material, simply rotated 45°.) The alignment of the sensitive axis of the accelerometer (affecting cross-axis sensitivity) is only as good as the net alignment of the dipoles with respect to the faces for ferroelectric ceramics, or to the cut of crystal relative to its crystallographic axes for natural crystals.

Many types of PE materials are used, with the choice being a trade-off of charge sensitivity, dielectric coefficient (which, with geometry, determines the capacitance), thermal coefficients, maximum temperature, frequency characteristics, and stability. The best signal-to-noise ratios generally come from ferroelectric ceramics with the highest PE coefficients. Best output stability, on the other hand, comes from natural crystals with the lowest PE coefficients (Figure 2).

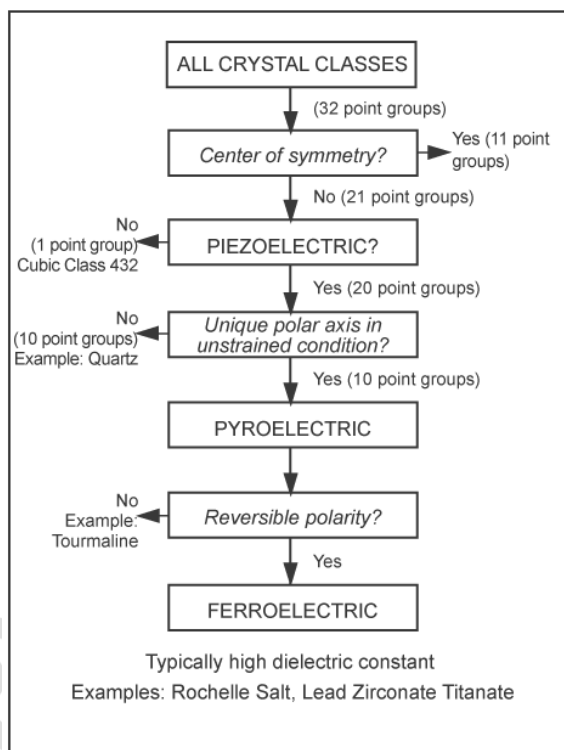


Figure 2. Classifications of crystal types.

Naturally occurring PE crystals, such as tourmaline or quartz, generally have low charge sensitivity, approximately 1% of the more commonly used ferroelectric materials. Allowing smaller size for a given sensitivity, ferroelectric materials are usually man-made ceramics in which the crystalline domains (regions in which dipoles are naturally aligned) are themselves aligned by a process of artificial polarization.

A center of symmetry exists at a point in a crystal cell if all atoms have an exact twin an equal distance on the other side of the point. Crystals with centers of symmetry are not PE. A dipole is formed by a net separation of the center of the negative charges with respect to the center of the positive charges within the unit cell of the crystal. If the dipole exists in the unstrained state, the unit will have pyroelectric sensitivity. Ferroelectric materials are defined as those in which the direction of the dipole can be reversed.

Polarization usually occurs at temperatures much higher than operating temperatures, to speed the process of alignment of the domains. Depolarization, or relaxation, can occur at lower temperatures (but at much lower rates) and can also occur with applied voltages and preload pressures. Depolarization always results in temporary or permanent loss of sensitivity. Exposing a polarized ceramic element to very high temperature will permanently depolarize it. Tourmaline is a natural crystal that does not suffer such depolarization, used particularly at very high temperatures. Under extreme shock loading, common ceramic crystal may exhibit zershift errors due to temporary depolarization, but the crystal usually recovers in a matter of seconds. This subject is discussed in section 10.3.

5.1.2 PE – High-impedance charge output

PE accelerometers use the PE effect of the sensing element(s) to produce a charge output. This type of accelerometer is also considered “self-generating” because it does not require an external power source for operation. This mode of operation, however, usually requires the use of a charge amplifier to convert the high-impedance output from the crystals to a low-impedance voltage signal usable for subsequent processing. The “spring” sensing elements provide a given number of electrons proportional to the amount of applied stress (*piezien* is a Greek word meaning “to press”).

Nothing comes free in nature, of course; PE sensors transduce mechanical strain energy in the PE crystal into electrical energy in the circuit (hence the generic name “transducer”), actually drawing a small amount of energy (needed to squeeze the element) from the mounting surface.

An important consequence of this property is that PE accelerometers cannot be used to measure steady-state accelerations or force. Steady-state acceleration or force would put a fixed amount of energy into the crystal (a one-way squeeze) and therefore a fixed number of electrons at the electrodes. Conventional voltage measurement would bleed electrons away, as does the internal resistance of the sensor. (High temperature or humidity in the accelerometer worsens the problem by reducing the resistance value.) Energy would be drained and the output would decay despite the constant input acceleration or force. Some quartz force sensors, however, are designed to have discharge time constant of more than 1000 sec, allowing for quasi-static measurements.

The PE accelerometer is effectively a voltage source driving a series capacitor C_a , producing a charge Q across its plates according to $V = Q/C_a$. Making a measurement, however, requires connecting the sensor to a readout device through cable(s). The total capacitance C_c of the cable is in parallel with the accelerometer. Under this mode of operation, the voltage output of a PE accelerometer is therefore $V_a = Q/(C_a + C_c)$. Consequently, factory calibration of the voltage sensitivity of a PE accelerometer always includes the cable supplied with the accelerometer. If a different cable is used, a new voltage sensitivity should be determined for that combination. With the IEPE type, discussed in section 5.1.3, cable capacitance is not an issue due to its built-in impedance conversion.

Measuring voltage output of PE accelerometers externally is not recommended. This practice requires special attention to the cable’s dynamic behavior and the input characteristics of the preamplifier. Because cable capacitance directly affects the signal amplitude, excessive movement of the cable itself during measurement may cause changes in cable capacitance and should be avoided. Close attention should also be paid to the input impedance of the preamplifier. The input impedance should be on the order of 1000 M Ω or higher to ensure sufficient low-frequency response. Most acceleration measurements are made using a charge amplifier or an IEPE system.

In practice, PE accelerometers are normally used in the charge mode, which requires the use of a charge amplifier (converter). As shown in Figure 3, a charge converter/amplifier is a high-impedance operational amplifier with a capacitor as its feedback. The output of the amplifier is proportional to the charge at the input and the feedback capacitor only, and is nearly unaffected by the input capacitance of the accelerometer or attached cables. The high-pass corner frequency (-3 dB point), or the discharge time constant, is set by the feedback capacitor and resistor in a charge converter, not by the accelerometer characteristics. (The accelerometer resistance changes noise characteristics, not the frequency response.)

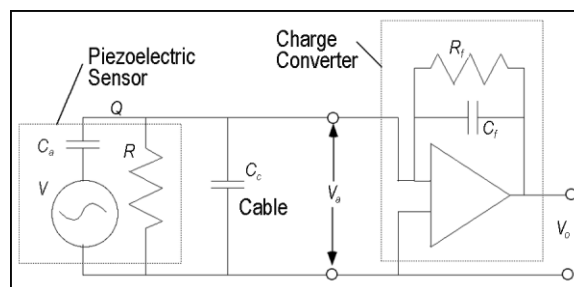


Figure 3. Equivalent circuit of a PE sensor and a charge amplifier.

The charge amplifier may be located remotely from the PE accelerometer, or an amplifier may be integrated with the PE sensing element(s) into the IEPE accelerometer. Each of these configurations has its unique advantages and limitations.

For example, a remotely located charge amplifier can be protected from severe environments, such as extreme temperatures, while the PE accelerometer is expected to simultaneously measure the dynamic environment under these extremes. The high-impedance coaxial cable connecting the PE accelerometer with the remote charge amplifier, including its connections, will probably be exposed to environmental extremes similar to the PE accelerometer, plus possible contamination from dust, lint, and fluid corrosion.

As noted previously, the charge output of a sensor is equivalent to a voltage source driving a series capacitor. The parallel internal resistance of the sensor drains off the electrons, preventing DC response. The low-frequency response of a charge amplifier system is governed by the feedback circuit of the charge converter (R_f and C_f in Figure 3). Because the net output of the sensor is charge, the voltage output is shunted by the parallel capacitance of a cable. A charge converter is not affected by such input capacitance. A charge converter is a high-impedance operational amplifier that drives a feedback capacitor with a charge equal to $-Q$ (balancing the input Q , since effectively no current flows into the input node), resulting in output voltage $V_o = Q/C_f$.

For PE accelerometers, there are four general types of external charge amplifier, some of which are designed to handle more than one type or category of accelerometer.

1. Bench-top, laboratory—This type of charge amplifier is designed for lowest noise operation, for use with most PE accelerometers. This amplifier usually has variable gain adjustment, a bandwidth from 0.1 Hz to 100 kHz, and optional functions such as filtering and integration.
2. Electrostatic—In addition to the functions of a typical charge amplifier, this general-purpose design has a very long input time constant to permit short-term static (quasi-static) measurement and calibration with quartz-based pressure sensors and accelerometers. The time constant is usually selectable on the unit by the user to suit different applications.
3. Low source resistance—This type of charge amplifier is designed to operate with low source resistance (below $1\text{M}\Omega$) presented by high-temperature PE accelerometers at above 200°C (392°F). Ordinary laboratory charge amplifiers would not function properly with these input conditions.
4. In-line charge converter—Also known as remote charge converter, this is a category of miniature, fixed-range charge amplifiers intended to be mounted near the PE accelerometer to act as a line-driver in long cable applications. The use of an in-line amplifier improves signal-to-noise ratio. These converters generally operate from a constant current power source similar to those used with IEPE accelerometers. The converters can be designed to operate with low source resistance, high-temperature accelerometers.

As with PE accelerometers, charge converter outputs are AC or capacitively coupled (where “AC” is alternating current; i.e., they do not pass steady-state DC direct current values). At very low frequencies there are significant attenuation and phase shifts. Depending on the application, this is not necessarily a limitation. Practically speaking, only gravitational acceleration lasts indefinitely. If time constants of the system are long enough, such as with the electrostatic type charge amplifier, frequency response of the system can approach 0 Hz.

Another limitation of high-impedance output PE accelerometers is the requirement that they be used with “noise-treated” cables. Otherwise, motion in an untreated cable can displace triboelectric charge, which adds to the charge measured by the charge amplifier. This type of measurement error is known as triboelectric noise [4,5,7]. To minimize triboelectric errors, manufacturers of PE accelerometers typically have included noise-treated cables as standard equipment.

Most PE accelerometers are extremely rugged. Various shapes and sizes are available, each with different performance compromises. The most common types are the compression and shear designs (Figure 4). The shear design offers better isolation from environmental effects, such as thermal transient and base strain. The beam type design, a variation of the compression design, is also very popular due to its lower manufacturing cost. But the beam design is more fragile and has limited bandwidth [4].

In Figure 4, arrows represent the directions of the forces on the crystal element(s) when accelerated motion is introduced at the base of the unit.