UEI App Notes:

Using Accelerometers in a Data Acquisition System

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Using Accelerometers in a Data Acquisition System

Accelerometers are widely used in industry for measuring vibration in rotating machinery, moving vehicles, aircraft, and in structures. Virtually all accelerometer devices use the force generated by moving a seismic mass to measure acceleration of the mass. The displacement of the mass or the force developed by the motion of the mass is detected and measured by a very wide range of sensors, such as electromagnetic, electrostatic, magnetic reluctance, inductive (LVDT), piezoelectric, piezoresistive, potentiometric, capacitance, strain gauge, servo force-balance and motion-balance, and micromachined semiconductors (MEMS).

New types of accelerometers and integrated sensor systems are now replacing more traditional vibration sensors for a number of reasons such as lower cost, better performance, rugged design, and smaller size. The new devices offer increased sensitivity, a wider range of operating frequencies, and much wider range of application in industry.

This paper describes the most popular and widely used types of accelerometers now in common industrial use, compares their typical performance specifications, shows how they are used in typical data acquisition applications, and points the reader to sources of more detailed reference information.

Popular Types of Accelerometers

The most common types of accelerometers or vibration sensors in use today are:

- Piezoelectric accelerometers (ICP and charge output devices)
- Piezoresistive accelerometers (ICP and IEPE output devices)
- Strain gauge accelerometers (bridge output devices)
- MEMS accelerometers (PWM, high impedance analog voltage, and bridge output devices)

Piezoelectric Sensors

Piezoelectric sensors use Newton's Second Law (F=ma) and the piezoelectric effect to measure acceleration of a mass. A piezoelectric accelerometer contains a “seismic mass” mounted so that the force applied to the mass by movement of the housing “squeezes” or stresses a natural quartz crystal or man-made piezoelectric ceramic measuring element. The pressure on the measuring element produces an electrical charge within the material that is proportional to the force applied — the piezoelectric effect. This force, in turn, is proportional to acceleration (F=ma). The charge output is a high impedance signal that can be measured directly or amplified and conditioned by other electronic circuits. When supplied without additional signal conditioning circuits, the unit is called a “charge sensor”. It is characterized by a very high inner impedance, low output signal, and no steady-state response. When the device is supplied with built-in preamplifier/impedance converter, it is called an Integrated Electronic Piezo-Electric sensor (IEPE sensor). Integrated vibration sensors supplied by PCB Piezotronics, Inc. use a registered trademark, ICP. The signal conditioning circuits may also be designed to convert the measurement from acceleration to velocity or to displacement.

Because the charge eventually bleeds off through the internal insulation resistance, piezoelectric sensors are not suited for true static measurements. They can, however, function accurately at very low frequencies, depending on the characteristics of the piezoelectric material used. The typical range of frequencies of a piezoelectric sensor is illustrated in **Figure 1**.

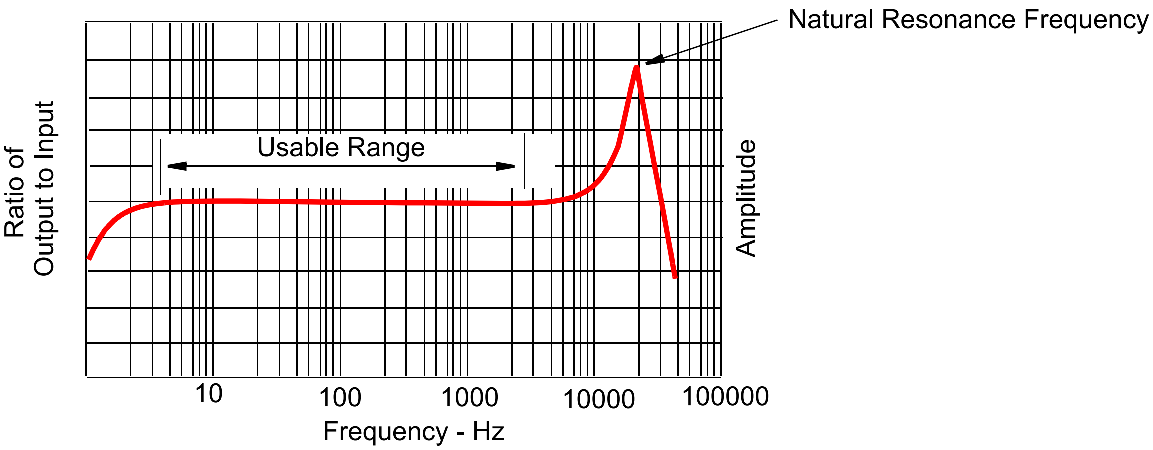


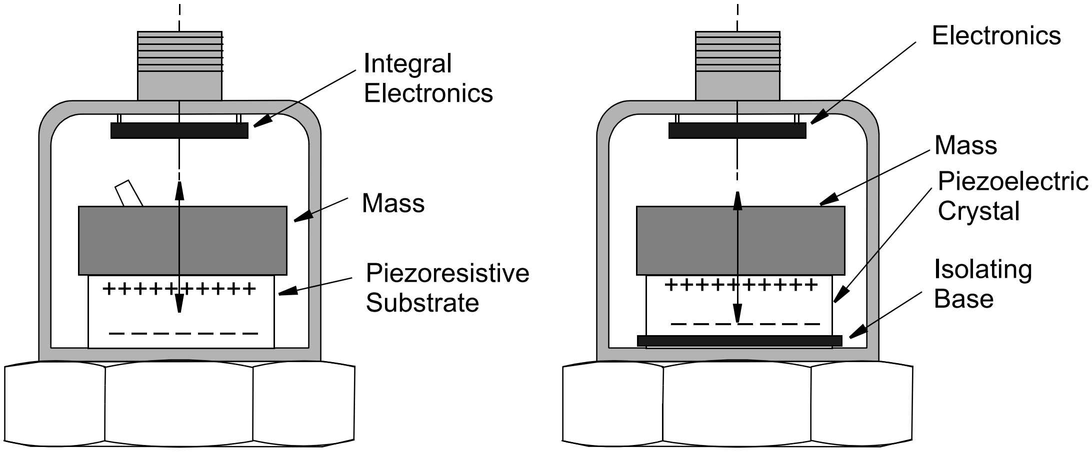
Figure 1. Typical Response Curve of a Piezoelectric Vibration Sensor

The piezoelectric units use natural quartz crystals or man-made ceramic elements to meet varying performance requirements, as shown in the following table, which compares characteristics of quartz and ceramic crystals.

Table 1. Ceramic Crystals vs. Quartz Crystals

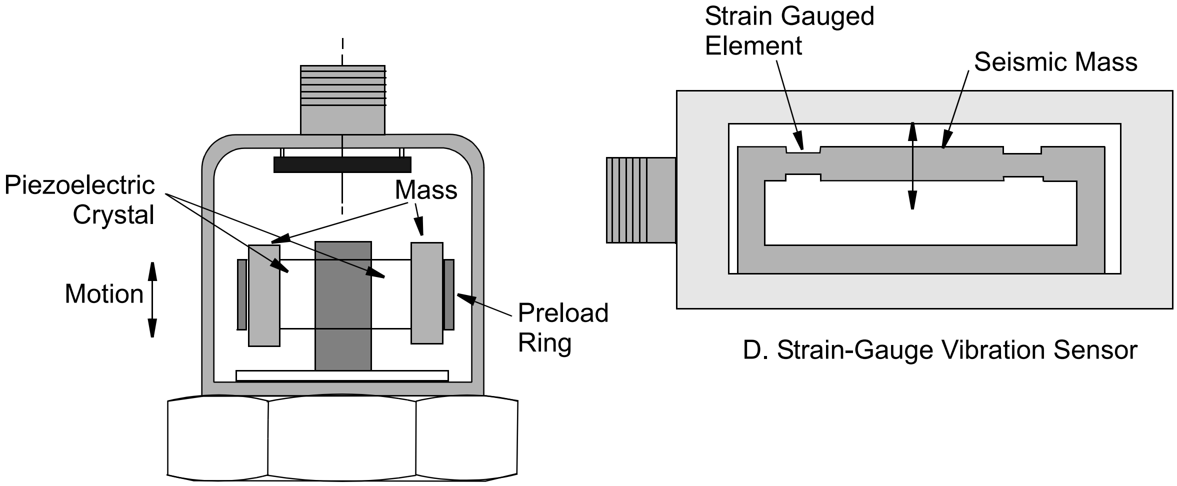
Ceramic Crystals	Quartz Crystals
Man made crystals	Natural Crystals
High Output Sensitivity	Low Output Sensitivity
Less Expensive	More Expensive
Higher pyroelectric effect at high temperatures	Lower pyroelectric effect at high temperatures
Higher crystal decay rates at high temperatures	No crystal decay rate with time or temperature
Lower temperature of operation	Higher temperature operation

Mounting Types



A. Single-ended Piezoresistive Compression Sensor

B. Isolated Piezoelectric Compression Sensor



C. Shear-type Piezoelectric Sensor

D. Strain-Gauge Vibration Sensor

Figure 2. Typical Constructions of Commonly-Used Accelerometers

Piezoresistive Sensors

Piezoresistive accelerometers use a piezoresistive substrate instead of a piezoelectric crystal as shown in Figure 2A. The force generated by the seismic mass changes the resistance of strain gauge elements of a Wheatstone bridge that are etched onto the substrate, which outputs a signal proportional to acceleration. A major advantage of a piezoresistive sensor compared to a piezoelectric sensors is that it can be used to measure acceleration accurately at zero frequency, a true static measurement.

Isolated Piezoelectric Sensors

Compression accelerometers can sometimes be affected by strain on the housing. To prevent this from happening, the crystal can be mounted on an isolating washer that isolates the crystal from the base, as illustrated in Figure 2B.

Shear-type Piezoelectric Sensors

Shear-type accelerometers mount the seismic mass so that the direction of motion of the mass produces a shear load on the crystal instead of a compressive load. This type of construction is recommended for applications such as flexible structures or those subject to extreme base distortion or thermal changes.

Strain Gauge Sensors

A modern strain gauge accelerometer typically uses a silicon or foil strain gauge deposited on or bonded to an element that flexes or deforms with movement of a seismic mass, as shown in Figure 2D. The strain is detected by a bridge circuit. Like piezoresistive sensors, strain gauge type sensors may also be used for static measurements at zero Hz.

MEMS Sensors

The MEMS sensor (not shown in Figure 2), a relatively new type of sensor developed within the last 15 years for automotive airbag applications, is by far the largest selling and lowest cost type of sensor in use today. Analog Devices, Inc. recently reported selling more than 200-million MEMS sensors for automotive use. Freescale Semiconductor is also a large supplier of MEMS accelerometers for industry.

A MEMS sensor is produced by using micromachining techniques to form minute springs, seismic masses, and motion or force sensing elements from a silicon wafer. When the body of the accelerometer is moved by an externally applied force, the motion of the seismic mass is detected by differential capacitive, piezoresistive, or other types of sensing elements. The signal produced is amplified, conditioned, and filtered by circuit components mounted inside the same IC package. The output signal from a MEMS accelerometer can be any of several signal types, such as an analog voltage, a digital PWM signal, or an SPI serial pulse train. The digital signals eliminate the need for an A/D converter in the data acquisition system.

MEMS sensors, which are available in many different types and ranges, may be used for inertial, vibration, and tilt (DC response) measurement applications. The major advantages of using a MEMS accelerometer are low cost and small size, although some types can be very expensive.

Velocity and Displacement Sensors

For some applications such as monitoring of the health of a rotating machine, velocity or displacement measurement are preferred over acceleration sensing. Since velocity is the first derivative of displacement vs. time, and acceleration is the derivative of velocity, both measurements can be calculated from acceleration by integrating the signal once or twice or by using the logarithmic relationships between acceleration, velocity, and displacement as illustrated in **Figure 3**.

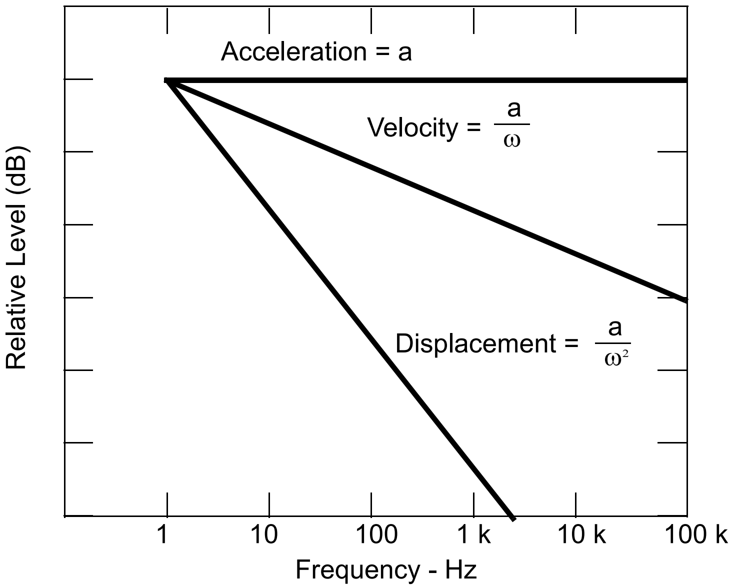


Figure 3. Logarithmic Relationship Between Acceleration, Velocity, and Displacement

Charge Sensors

A piezoelectric sensor supplied without integral signal conditioning circuits is called a charge sensor. It produces a charge output and has a high impedance. A charge sensor is typically required in high temperature or high radiation applications that could damage signal conditioning components.To overcome this problem, the signal amplifier and associated components are mounted in a safe area at a distance from the charge sensor.

IEPE and ICP Accelerometers

IEPE sensors have built-in signal conditioning circuits that have low impedance output electronics compatible with a two-wire constant current supply providing a DC voltage bias. IEPE sensors are very popular in most industrial applications except those with special requirements such as static (zero Hz) sensing, high temperature applications, or process control applications requiring 4-20 mA current outputs.

ICP sensors are “integrated circuit piezoelectric” sensors supplied by PCB Piezotronics, Inc. under the trademark, ICP, and are basically the same as IEPE sensors.

The output of an 2-wire IEPE accelerometer is an AC voltage on a DC voltage bias. The DC bias can be removed by inserting a capacitor in series with the output signal. The IEPE unit also requires a constant current supply. A typical circuit is shown in the figure below.

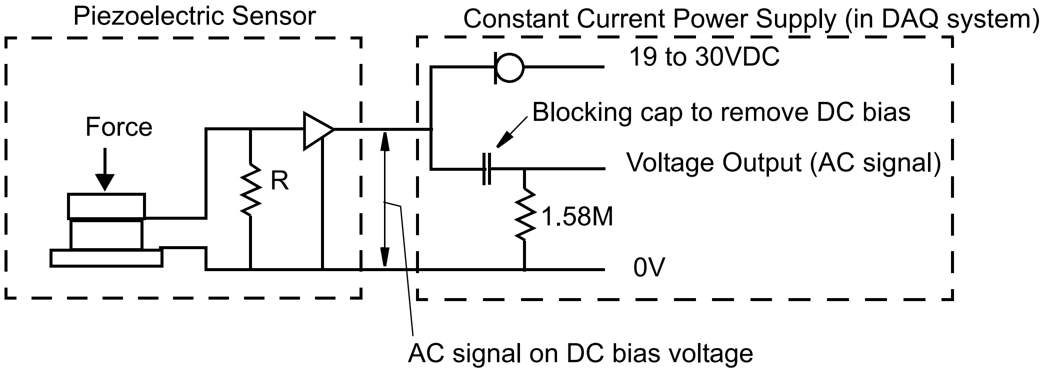


Figure 4. IEPE Sensor Output Circuit and Constant Current Source

In its DNA-AI-211 analog input board for use with 2-wire IEPE accelerometers, UEI provides a user-adjustable constant current source for each of its four input circuits. The currents supplied to each sensor are generated by user-settable DACs, amplified, continuously measured and feedback controlled, and monitored by an A/D converter to detect abnormal operation such as a short or open. The current to each sensor can also be switched off independently, enabling that circuit to be used as a standard analog voltage input.

Parameters

This section discusses some of the common parameters that must be considered when choosing an accelerometer for an application.

Frequency Content of Measured Signal

It is very important to know what range of frequencies is present in your measured signal. Use of Fast Fourier Transform algorithms to convert time domain data to frequency domain is a very useful analytical tool. When that information is available, you can make logical decisions about which sensor to specify and what filtering you should add to the measurement signal.

Usable Range

The frequency response curve of a typical accelerometer is shown in Figure 1. The usable frequency range of a sensor is the flat section of the curve from about 5 Hz up to 1/3 to 1/2 of the natural resonance frequency.

Natural Frequency

The equation that defines the natural frequency of an accelerometer is:

$$f_N = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

where f_N is the natural frequency, K is the stiffness, and M is the mass.

From the equation, it is clear that to increase the frequency, you should either increase the stiffness or decrease the mass. Since decreasing mass also decreases sensitivity, increasing stiffness is preferable. In most cases, a combination of the two approaches is required.

The natural frequency of an accelerometer is the point of the frequency response curve where the output to input ratio is highest. At this point the curve is highly non-linear, which makes a reading difficult to interpret. It is therefore best not to operate near the natural frequency of the device.

Linearity

Linearity of a sensor is typically in the range of 1%. This parameter defines the accuracy of the sensor as the frequency to which it is subjected increases from minimum to maximum. The output of an IEPE sensor typically ranges from a low of 100 micro-g to a maximum of 500 g.

Sensitivity – how to choose

Sensors supplied with integral electronics produce a voltage output that typically ranges from 4 to 8 volts. A unit with a sensitivity of 80mV/g and a maximum output voltage of 5V has a dynamic range of 80 x 5 = ± 400g. If the highest g level expected is G_{max}, the maximum sensitivity you should use for your sensor should be $5/G_{max}$.

The resolution of an accelerometer device in many cases can be improved through the use of digital signal processing techniques, such as oversampling to improve resolution of the sensor, adding digital filters, and automatically calculating/correcting bias offsets and scale errors.

Mounted Natural Frequency

The natural frequency of an unmounted sensor is different from that of a mounted sensor, because the mounted sensor has a stiffness determined by the stiffness of the structure in which it is mounted. Cementing, bolting, or magnetically attaching the sensor to a structure can lower the natural frequency by a substantial amount.

Sensitivity to Mounting Strain

Bending, twisting, mechanical or thermal stresses in the base of an accelerometer can cause errors in its measurement output because these stresses can distort a piezoelectric crystal just as an acceleration force does. Single-ended compression sensors are most susceptible to errors caused by strain on the base; shear-type sensors are the least affected. Adding an isolation base to a compression sensor rather than specifying a shear-type sensor is often the best design compromise for most applications.

Triboelectric Effect

The triboelectric effect is the generation of an error signal in a charge output sensor whenever its attached cable is physically moved. The only effective way to eliminate this error signal is to clamp the cable as close to the accelerometer as possible.

Triaxial Sensors

Triaxial sensors detect and measure acceleration in all three axes at once. Some units incorporate three separate sensors in a package and others detect 3-axis motion with a single sensor. Separate output signals are provided for each axis of motion.

Tilt Sensors

Measuring tilt is a static sensing task measuring the acceleration of gravity. It requires zero Hz (DC) accuracy and is commonly found in pitch and roll measurements in aircraft or similar applications. To achieve the highest resolution per degree of tilt, the accelerometer should be mounted with its sensitive axis parallel to the plane of movement where the most sensitivity is desired. Such applications usually use 2- (biaxial) or 3-axis (triaxial) accelerometers.

Signal Conditioning

The signal conditioning normally used in an IEPE accelerometer is a low noise regulated constant current source to supply a bias voltage to power the sensing device. A blocking capacitor is usually inserted in the output line to remove the DC bias from the sensor signal. The signal fed to the data acquisition system is an AC voltage with amplitude proportional to the amplitude of vibration and a frequency the same as the frequency of vibration. Additional signal conditioning may be introduced for computing RMS or peak-to-peak measurements, for analyzing the frequency domain spectral content, or for performing snap shot time domain analysis

Low Pass Filter

Typically, a low pass filter is used to remove unwanted frequencies present in the sensor signal, such as the natural resonant frequencies of the accelerometer itself.

Ground Isolation

Caution must be exercised to prevent ground loops, especially when signal levels are low or where the signal is not amplified. Ground loops may either be eliminated by hard wiring electrical grounds together or prevented by electrically isolating sensors with isolating washers, studs, or bases. Note that use of an isolating mounting may change the natural frequency of the accelerometer.

Choosing a Sensor Type.

The following table lists some factors to consider in choosing an accelerometer:

Type of Accelerometer	Advanages	Disadvantages
Single-ended Compression	Robust Highest natural frequency High shock resistance	Poor base strain performance
Isolated Base Compression	Robust High natural freqency	Better base strain performance
Shear	Best base strain performance Best temperature transient immunity Smallest size	Less robust Lower shock resistance
Charge output	High Temperature Operation Suitable for radiation environments Small size	Requires local charge amplifier Susceptible to triboelectric effect
Piezoresistive	Measures down to zero Hz.	Limited high frequency response
Strain Gauge	Measures down to zero Hz. High shock resistance.	Limited high frequency response

Some typical questions to ask in choosing a sensor are listed below:

- ☑ Will you be measuring an AC variable such as vibration or a DC parameter such as gravity or a constant acceleration?
- ☑ What is the maximum range you expect to measure?
- ☑ What is the smallest signal you need to detect?
- ☑ What is the maximum frequency you need to measure?
- ☑ What level of sensitivity is required for your sensor?
- ☑ What power consumption is acceptable?
- ☑ What type of mounting will be used?
- ☑ What size limitations do you have?

The answers to these questions should provide you with information needed to specify and choose the best accelerometer for your application.

References

The following is a list of websites that contain information about accelerometers of various types and useful guides to the application of such devices.

www.omega.com
www.coleparmer.com
www.wilcoxon.com
www.endevco.com
www.pcb.com
www.sensormag.com
www.vibrametrics.com
www.sensotec.com
www.analog.com