Industrial Vibration Accelerometer Performance Considerations: Shear versus Compression Designs

By: David A. Corelli
Category IV Vibration Analyst
Director of Application Engineering
IMI Sensors

Molly Bakewell
Global PR, Advertising & Image Manager
PCB Piezotronics, Inc.
www.pcb.com

The implementation of industrial vibration monitoring sensors and associated signal conditioning as an integral part of industrial predictive maintenance programs has proven for many maintenance and plant engineers to be an effective strategy for reducing downtime and improving overall machinery health. Vibration monitoring technology is widely used because of its ability to detect and diagnose a wide variety of machinery faults, such as bearing faults, gear problems, misalignment, looseness, mass imbalance, and others, on a wide variety of rotating machinery, and its relative ease of integration with portable data collectors, online vibration monitoring systems, PLC's, qne SCADA and Plant Information (PI) systems.

For the proper implementation of sensors into a vibration monitoring program, one must first understand the differences in the two most common designs of industrial piezoelectric sensors, as well as various considerations in selection and mounting. A piezoelectric accelerometer produces a measurable electrical signal when an inertial mass stresses, or applies a force to, its integral crystal sensing element. The two main types of piezoelectric sensor designs most typically used for industrial vibration monitoring applications are shear and compression, which define the actual mode, or crystal axis, in which an inertial mass stresses the piezoelectric crystal. While both types operate in a similar fashion, one of these designs provides much more reliable and repeatable performance when acted upon by certain external influences within the demanding industrial application environment.

Sensor design and performance vary depending on the type of crystal used. Crystalline materials such as quartz and tourmaline are naturally piezoelectric. More commonly used in modern accelerometer designs are ferroelectric ceramic crystals, like lead zirconate titanate, because of their higher electrical output and lower noise levels. Man made ceramics achieve their piezoelectric properties through a process called poling. Poling is a process where a high electrical field is applied to the material at elevated temperatures, producing a net polarization. Each material has unique properties, which offer advantages in particular applications.

This paper shall outline design strengths and challenges associated with both shear and compression-based industrial vibration sensor designs, as well as highlight some sensor selection and mounting considerations.

Shear vs. Compression: What's the Difference?

What is Shear Mode?

As the name implies, shear mode accelerometers stress the internal piezoelectric crystal in a shear, rather than a compressed, manner. In this type of sensor design, crystals are "sandwiched" between a center post and the mass (or masses), depending on the specific type of shear design. They are held in place, either by a preload stud, or a compression ring, as shown in Figure 1A, and the cutaway, shown in Figure 1B.

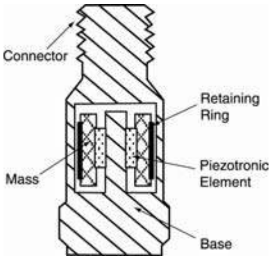

Figure 1A:
Schematic of a shear type piezoelectric accelerometer

Figure 1B: Shear design cutaway of an ICP® tri-shear accelerometer, with integral internal amplifier.

What is Compression Mode?
Compression mode is a fairly simplistic design, in which the crystal sensing element sits between a flat base and an inertial mass. There is typically a preload stud through the center of the mass and crystal to hold it in place, as shown in Figure 2.

Early piezoelectric accelerometers were compression designs, mainly due to the relative ease of manufacturing for this configuration, and subsequent sensor assembly. However, most modern accelerometers now use shear designs, because they have significant performance enhancements over compression types.

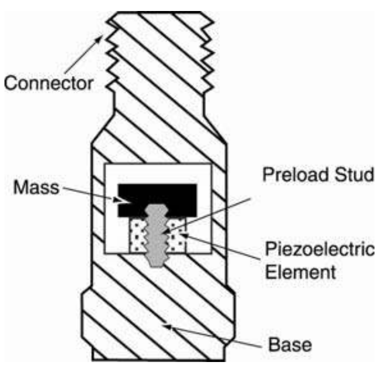

Figure 2: Schematic of a compression type piezoelectric accelerometer

Figure 3: Types of sensors and sensing elements – flexural, tri-shear and compression

How Do These Compare?

In principle, both accelerometers work in a similar fashion. When acceleration is sensed in the vertical axis, the mass exerts a force on the crystal, in accordance with Newton's Second Law of Motion, $F = m \times a$. Thus, the larger the mass, the more force is generated for a given acceleration, and the higher the sensitivity (electrical output) of the accelerometer.

All things being equal, compression designs offer a higher stiffness than shear. This means they have a higher natural (or resonant) frequency, which results in an accelerometer with a slightly higher frequency response (10 to 20%). On the other hand, shear cut crystals produce about 40% more electrical output for the same input force as compression cut crystals. Thus, it takes less mass for a shear cut crystal to produce the same amount electrical output than compression.

Since the natural frequency in Hz (f_n) of a sensor is based on the size of the inertial mass (m) and stiffness of the crystal (k), $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$, the output and frequency response of shear and compression mode accelerometers are very similar for a given package size.

As stated earlier, crystals produce an electrical output when stressed. Thus, anything other than the actual vibration to be measured that stresses the crystal produces unwanted electrical output and errors. The crystals in compression mode sensors are easily stressed by base bending and thermal transients. The output produced can be very significant in structures having a large amount of flexure or when placed in a hot or cold environment and not allowed to thermally stabilize prior to making measurements. This output can be very significant, resulting in large measurement errors, and can cause "ski slope" in the FFT, particularly when integrating the sensor output to velocity.

In shear mode designs, the post to which crystals and masses are attached is essentially isolated mechanically from base bending and thermal stresses. Thus, they are much less sensitive to these errors, and provide readings that are more reliably reflective of the actual vibration to be measured. Most IMI Sensors industrial vibration sensors are manufactured utilising shear mode technology, to offer customers the benefits of increased performance.

Although shear designs are more complex than compression, using modern manufacturing techniques, they also can be easily and economically built. In fact, embeddable piezoelectric shear mode accelerometer units, such as IMI Sensors Series 660 (also referred to as pellets) are able to be mass produced, resulting in very low cost units which may be used in many typical high volume and commercial OEM applications. These include such embedded applications as land surveying equipment; homeland security/border control monitoring devices; and assessing the shock and vibration impact of packages or components. The units also employ field-proven solid state, piezoelectric sensing elements, for durability and broadband performance.

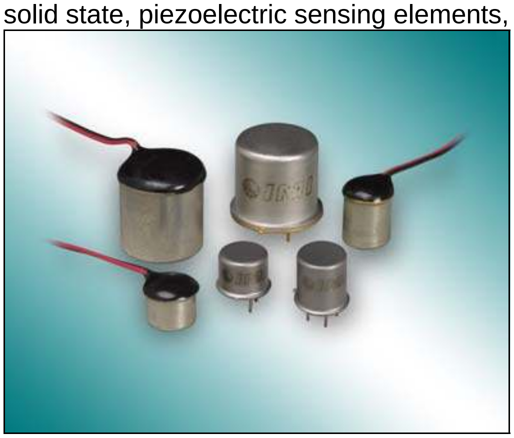

Figure 4: Series 660 embeddable sensors feature shear mode design in a small, durable package

Industrial Vibration Sensor Selection Considerations

When selecting the right piezoelectric vibration sensor for an industrial application, important considerations include frequency response, signal-to-noise ratio and sensor sensitivity, as well as the measurement environment, and its characteristics (e.g., hazardous area operation, temperature, corrosive environments, or submersion in oil, water or cutting fluids).

As stated earlier, selection of connector and cables can have a direct impact on sensor installation, ruggedness and reliability. Erroneous signals can be induced into sensor systems through ground loops or electromagnetic or radio frequency interference (EMI or RFI). Connections to the sensor require two leads, one for the power and signal, and the other for the common and signal return. A loose connector can result in a sensor intermittently turning on and off, causing drift in the DC bias, and resulting in large outputs which are unrelated to the measurement being taken. Another consideration with cables is the termination method of the shield to avoid ground loops. Generally speaking, it is recommended to use a twisted pair, shielded cable for sensors, as this type of cable is less susceptible to noise than a standard coaxial cable, such as RG58. In order to avoid ground loops, it is recommended that the shield be grounded once in the system, typically the analyzer end, and not the sensor end. The shielding of commercial cables manufactured by IMI Sensors is not generally grounded on the sensor end, to avoid ground loop problems. IMI Sensors also provides armored cables, for use in environments where there is risk of cables being cut, such as machine tool cutting applications. Permanent installations require twisted pair shielded cables, to ensure clean vibration signal transmission.

Industrial Vibration Sensor Mounting Techniques

The mounting method used for an industrial vibration sensor directly affects its frequency response. Depending on mounting method utilized, the natural frequency of the sensor system decreases by varying amounts, which significantly lowers the useful frequency range of the sensor. The mounting method chosen should provide flat frequency response throughout the frequency range being studied. Typically, stud mounting on a clean, flat surface with a good finish will provide the highest possible frequency response. The mounted resonant frequency, and thus the sensor system frequency response, decreases progressively when using adhesive and magnetic mountings, and is generally the lowest, with handheld accelerometers with a stinger or probe attached. The useable frequency range depends on many things, including mass of the accelerometer and magnet; magnetic pull strength; thickness of adhesive; and material and length of the probe. “Rule of thumb” tables, such as the one shown below, are only approximate values for typical cases and can vary widely.

Table 1: Approximate frequency spans for 100 mV/g accelerometers, for most typical sensor mounting methods.

Method	Frequency Limit
Handheld	500 Hz
Magnet	2,000 Hz
Adhesive	2,500 - 4,000 Hz
Bees Wax	5,000 Hz
Stud Mounted	6,000 – 10,000 Hz

(Table reprinted with kind permission from the Vibration Institute, www.vibinst.org)

There are specially designed cases, such as the IMI Sensors Model 621B40, where a combination of design parameters are employed, allowing the sensor system to achieve frequencies as high as 30k Hz – even with a magnet.

Figure 5: The Model 621B40 high frequency accelerometer from IMI Sensors operates to 30k Hz, even with a magnet. Because of its wide frequency range, the sensor can be used to diagnose a variety of machinery fault conditions, including bearing and gear problems.

In summary, industrial accelerometers are the predominant workhorse of a sound predictive maintenance and vibration monitoring program. It is imperative that a sensor will meet requirements of the application environment. A vibration analyst must review an application with sensor selection criteria in mind, to help a vibration analyst to select the proper sensor, cabling and mounting for a given application environment. While there are multiple types of sensor technologies available, shear mode designs, such as those offered by IMI Sensors, when used with proper surface mounting techniques and attention to connectors and cabling, will provide reliable, repeatable and accurate performance across a variety of industrial applications.

About the IMI Sensors division of PCB Piezotronics:

The IMI Sensors division of PCB Piezotronics (www.imi-sensors.com) offers a full line of sensors and instrumentation for industrial process monitoring, predictive maintenance, and machinery and equipment protection. IMI Sensors offers high temperature, high frequency, and low-cost versions of its industrial ICP® and charge output accelerometers and 4-20 mA vibration transmitters for route based measurements, permanent installations and affordable 24/7 continuous on-line monitoring. Also offered is a comprehensive selection of electronic and mechanical vibration switches for alarm and shutdown protection of critical machinery, including the patented Bearing Fault Detector, two-wire Smart Vibration Switch, and Reciprocating Machinery Protector.

Local Direct Sales Office Contact:

PCB Piezotronics Limited
7 Paynes Park
Hitchin, Herts
SG5 1EH United Kingdom
Tel: 01462 429710
Fax 01462 429798
Email: info@pcbpiezotronics.co.uk

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About the Authors:

David A. Corelli is Director of Application Engineering for PCB Piezotronics. His nearly 35 years of experience in vibration analysis includes working as a test engineer for the United States Air Force Avionics Laboratory and as a field engineer for Hewlett Packard, Entek and IRD Mechanalysis. A Category IV Vibration Analyst in accordance with ISO 18436-2, Mr. Corelli serves on the Board of Directors for the Vibration Institute, as well as chairman of its Certification Committee. He is the author of dozens of technical papers focused on successful application of industrial vibration monitoring technology.

Maureen (Molly) Bakewell is Global Public Relations, Advertising & Image Manager for PCB Piezotronics, Inc., responsible for guiding the organization's overall strategic corporate marketing and promotional activities within the automotive, aerospace & defense, industrial, test & measurement and power generation markets. With 15 years of expertise in global press and promotions management, Ms. Bakewell has overseen development of more than 300 technical articles worldwide about PCB® sensor technologies and related customer applications.