PCB PIEZOTRONICS
AN AMPHENOL COMPANY

Selecting the Correct High Sensitivity Piezoelectric Accelerometers for Infrastructure Monitoring (SHM)

Includes an Accelerometer Selection Guide and Application Case Studies

Written By
PCB Piezotronics, Inc.

pcb.com | 1 800 828 8840

High Sensitivity Piezoelectric Accelerometers for Infrastructure Monitoring

First System to Detect Tremors

Some historians suggest that technology to sense low-frequency vibrations originated in China when Zhang Heng invented an accurate seismograph in 132 AD. This device was an urn of bronze construction and contained an inverted pendulum. Slight tremors caused the pendulum to move. When the pendulum moved it tapped a ball that fell. When the ball fell it landed in the mouth of a sculptured frog at the bottom of the urn (Rigg, 2021).

An attempt at a working replica (Science & Society Picture Library via Getty)

Members of the court (Han Dynasty) thought the device failed when the ball fell one day and they felt nothing. Doubt turned to astonishment a few days later when a messenger arrived from a town many miles away to report that it experienced an earthquake.

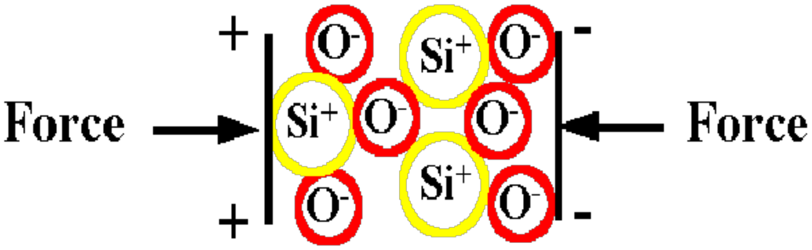
Modern Applications

Centuries later, vibration monitoring of earth tremors evolved into the monitoring of buildings, monuments, and critical infrastructures. High-sensitivity accelerometers installed in these structures provide real-time data used for trending, analyzing, and alerts. When structural motion approaches safety thresholds, warnings are sounded.

Sensor Technology

PCB® Piezotronics' high sensitivity dynamic accelerometers use the same technology as their popular general-purpose ICP® accelerometers. These sensors rely on the piezoelectric effect to generate a useful signal. "Piezo" is a Greek term that means "to squeeze." External forces produce strain on piezoelectric elements. This creates an electrical charge on opposing surfaces. Figure 1 shows the displacement of the electrical charge. The displacement, in this case, is due to the deflection of the lattice in the piezoelectric material. The larger circles represent silicon atoms. The smaller ones represent oxygen.

Figure 1: Displacement of Electrical Charge



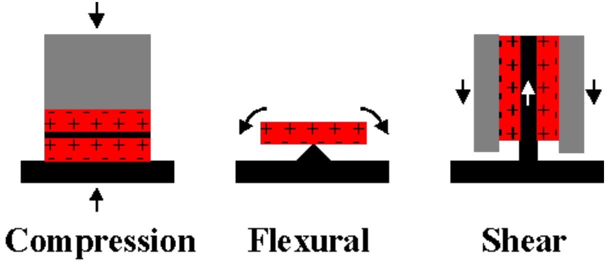
PCB® uses primarily two types of piezoelectric materials: quartz and polycrystalline, piezoceramics.

Table 1: Comparison of Piezoelectric Materials

Quartz Crystal	Polycrystalline Ceramic
naturally piezoelectric material	artificially polarized
high voltage sensitivity	high charge sensitivity
stiffness comparable to steel	unlimited availability of sizes and shapes
exhibits excellent long term stability	materials available which operate at 1000 °F (540 °C)
non-pyroelectric	output due to thermal transients (pyroelectric)
low-temperature coefficient	characteristics vary with temperature

Piezoelectric sensors use many different sizes and shapes of piezoelectric materials (Figure 2). Red represents the piezoelectric elements. The arrows show the direction of stress. Gray represents the seismic mass. The compression design features high rigidity. Its disadvantage is that it is somewhat sensitive to thermal transients and base strain. The simplicity of the flexural design is offset by its narrow frequency range. It also has low over shock survivability. The shear configuration has a wide frequency range and low off-axis sensitivity. It also exhibits low sensitivity to base strain and temperature.

Figure 2: Material Configurations



Piezoelectric materials produce a high output with very little strain. They have no deflection. This makes piezoelectric sensors rugged and their signal linear over a wide amplitude range. Potentially, an accelerometer can measure acceleration levels as low as 0.0001 g's. Piezoelectric materials can only measure dynamic or changing events. Static events will cause an initial output. But, the signal will slowly decay.

Piezoelectric Charge Mode (PE) Accelerometers

PE accelerometers generate a high-impedance, electrostatic charge output in response to mechanical stress applied to its piezo-ceramic, or crystal, sensing element. PE accelerometers operate through a low-noise cable into a high input impedance charge amplifier. The amplifier converts the charge signal into a usable low-impedance voltage signal for acquisition purposes. The charge amplifier provides for signal impedance conversion, normalization, and gain/range adjustment. Options may include filtering, integration for velocity and/or displacement, and adjustment of the input time constant, which determines the low-frequency response. Modern charge amplifiers are designed with more effective low-noise circuits and may incorporate simplified LCDs and digital controls.

The main advantage of the laboratory PE (charge system) is the flexibility of adjusting and controlling the electrostatic charge output of the accelerometer. PE accelerometers can also operate to higher temperatures.

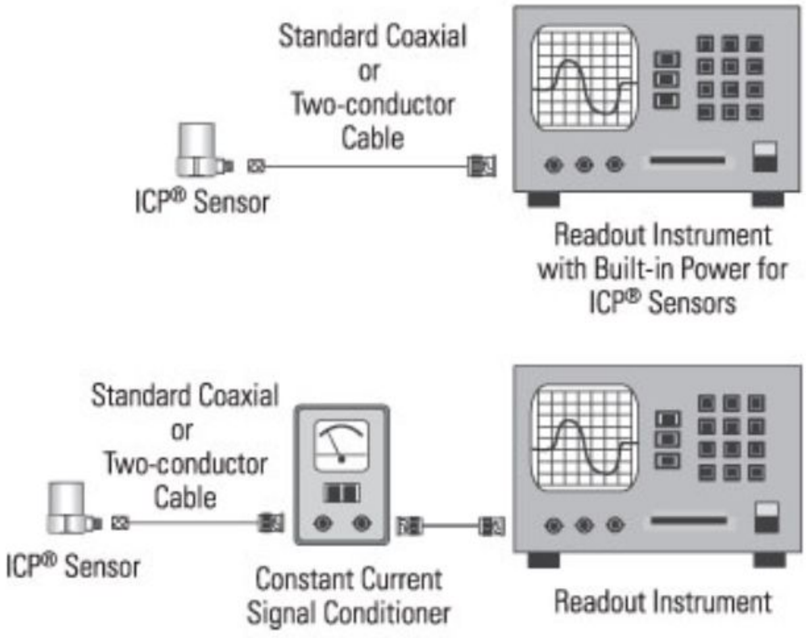
Piezoelectric ICP® Accelerometers

ICP® accelerometers incorporate a built-in microelectronic charge or voltage amplifier. This functions to convert a high impedance electrostatic charge from the PE sensing element into a low impedance voltage signal. In hermetically welded designs, all high impedance circuitry is sealed and electrically shielded inside the accelerometer.

ICP® accelerometers operate from a constant-current power source. The circuit is only two wires. Signal/power is carried over one wire and the other wire serves as ground. The cable can be ordinary coaxial or ribbon wire. A Low-noise cable is not required for ICP® sensors. This can reduce setup and operating costs and simplify

operating the measurement systems as there is no chance of triboelectric output. Constant current to operate the accelerometer comes from a separate power unit or it may be incorporated inside a readout instrument such as an FFT analyzer or Data Collector (Figure 3). Although most ICP® integrated electronic accelerometers operate from 2 to 4 mA constant current, some operate from as little as 0.5 mA for low power consumption. PCB® offers different types of ICP® signal conditioners that provide 2 to 20 mA of current at a DC voltage level of +18 to +30 volts.
Do not power ICP® sensors with commercially available power supplies. The unregulated current will damage and destroy internal electronics.

Figure 3: Instrumentation for ICP® Sensor



Choosing whether to use a PE or an ICP® accelerometer involves several trade-offs as there are advantages and disadvantages of each (Table 2). Generally, ICP® accelerometers are easier to use but PE is the unit of choice for high-temperature applications.

Table 2: Considerations for Selecting Charge Mode PE & ICP® Accelerometers

Charge mode PE SENSOR	ICP® SENSOR
Advantages	**Advantages**
Flexibility in adjusting accelerometer electrical output characteristics properly	Simplified operation-less operator attention, training and expertise
Wide dynamic range	Uses standard coaxial cable
Higher temperature operation	Drives long cables without noise increase or loss of resolution
Interchangeability in existing charge systems Extended low-frequency response	Operates from low-cost constant current power source
More durable due to simplicity, longer MTBF	
Limitations	Connects directly to many readout instruments High output miniature designs reduce mass loading
Requires training and expertise to understand and operate high impedance circuits	Low impedance systems have greater resistance to contamination and electrical interference
Capacitive effects from accelerometer and cable increases noise and reduces the resolution	Better system reliability
	Dynamic range typically > 100,000 to 1
High impedance circuitry must be kept clean and dry.	Range and resolution are data sheet specifications
Requires special-purpose low-noise cable to minimize triboelectric noise	Bias monitor detects cable faults - shorts/open circuits
High impedance systems are more susceptible to electrical and RF interference	Can incorporate self-identification "TEDS" circuit and steep filtering
Accelerometer size and sensitivity are directly related. A sensitivity/size/mass loading consideration	Lower cost per channel than charge mode PE type
Higher cost per channel than ICP® type (due to required low-noise cable and charge amplifier)	**Limitations**
	Electrical characteristics, sensitivity, range, and discharge time constants are fixed within the sensor
	Limited temperature range
	It may not be interchangeable in the system if power requirement is not the same

ICP® High Sensitivity Accelerometers - Structural Applications

The high sensitivity ICP® accelerometers share the same advantages and disadvantages as the lower sensitivity ICP® accelerometers.

There are many different sensor offerings available. Some models are designed to be smaller, lighter weight, and focused on Test applications. Other models are designed for more rugged, long-term industrial applications. Single and 3 axis devices are available. Ceramic sensing elements are most common. These designs offer low-noise, signal conditioning circuitry for the greatest measurement resolution. Units vary by housing type - titanium, anodized aluminum, or stainless steel. Stud mount designs dominate while quartz sensing and compression configurations are not favored.

Table 3: Overview of High Sensitivity ICP® Accelerometers

Model	Category	Design	Axis	Sensitivity mV/g	Mounting	Sensing Element	Case Isolated
333B50	Test	Shear	3	1000	Stud	Ceramic	No
333B52	Test	Shear	3	1000	Stud	Ceramic	No
352B	Test	Shear	1	1000	Stud	Ceramic	No
356B18	Test	Shear	3	1000	Epoxy	Ceramic	No
356M98	Test	Shear	3	1000	Stud	Ceramic	No
393A03	Test	Shear	1	1000	Stud	Ceramic	Yes
393B04	Test	Flexural	1	1000	Stud	Ceramic	No
393B05	Test	Flexural	1	10000	Stud	Ceramic	No
393B12	Test	Shear	1	10000	Stud	Ceramic	Yes
393B31	Test	Flexural	1	10000	Stud	Ceramic	Yes

REMINDER: ICP® devices and will not measure or respond to uniform acceleration (also known as static or DC acceleration). If uniform acceleration is applied, the output signal will decay.

Many high-sensitivity ICP® accelerometers include TEDS functionality as an option. A sensor incorporating a Transducer Electronic Data Sheet (TEDS) has a built-in read/write memory. This memory contains information about the sensor and its use. It includes information about the manufacturer, specifications, and calibration, defined by IEEE standard 1451.4. This gives it the ability of “plug-and-play” self-identification within a measurement system. Using the same two-wire design of traditional piezoelectric with internal charge amplifier transducers, the TEDS sensor can flip between analog and memory modes.

A TEDS sensor can be connected to any ICP® sensor signal conditioner. Only a TEDS-capable ICP® signal conditioner and data acquisition equipment support the digital communication mode. Mounting pads, multi-conductor signal cables, and patch panels all help to control and organize the cable bundles of sensor arrays. This helps to minimize set-up time and potential errors that are often the result of large cable bundles needed for high channel count systems.

Unique Features of High Sensitivity ICP® Designs

There are five unique features of the high sensitivity designs not found together in the more general-purpose ICP® configurations.

1. **Sensitivity** - the ratio of the change in transducer output to a change in the value of the measurand (e.g., mV/g)

Structural applications require higher sensitivities to capture the smaller forces on the structure. These sensitivities are 1,000 mV/g or greater. The sensitivity of each accelerometer is found on the datasheet and the calibration sheet shipped with each unit.

2. **G Range** - g is the range of gravitational force an accelerometer can measure. 1 g equals 9.80665 m/s^2.

The smaller the range the more sensitive the reading one obtains from the accelerometer. High sensitivity accelerometers will have ranges from <1 to 5 g's. See examples below.

Model 352B has a sensitivity of 1000 mV/g and a range of ±5 g's peak.
5 g's X 1000 mV/g = 5000 mV = 5 volts

Model 393B05 has a sensitivity of 10,000 mV/g and a range of ±.5g's peak.
.5 g X 10,000mV/g = 5000 mV = 5 volts

3. **Frequency Range (Hz)** - the upper and lower frequencies for accelerometer operation.

Larger structures exhibit lower frequencies. Consequently, high sensitivity accelerometers are designed to operate in the lower frequency ranges from 0.01 to <4000 Hz.

4. **Mass -** A physical property, dynamically computed as acceleration/force. Statically computed as W (which can be measured on a scale)/g. Ordinary structures are not pure masses as they contain reactive elements, i.e. springs and damping.

The larger ICP® high sensitivity accelerometers are 5 to 100 times the mass of the smallest ICP® accelerometer.

5. **Low Spectral Noise** - Noise is the signal output that does not represent vibration. Spectral noise is a measure of noise per an equivalent output such as g. It is often expressed at different frequencies.

General-purpose accelerometers will have a higher Spectral Noise specification than that of a high sensitivity accelerometer.

A general-purpose ICP® accelerometer that measures +/- 50g's with a sensitivity of 100 mV/g might have a spectral noise specification of 11 ug/Hz at 10 Hz.

A high sensitivity ICP® accelerometer with a range of +/- 5.0 g with a sensitivity of 1000 mV/g might have a spectral noise specification of 0.5 ug/Hz at 10 Hz.

Note: 1 Micro-g (ug) =0.000001 g.

Applications

There are thousands of ICP® accelerometers in use worldwide. Many of the high-sensitivity applications have already been alluded to. Below are a few specific examples.

Examples of ICP® Accelerometer High Sensitivity Applications

- Ballast Track
- Beamline
- Bolt Loosening Detection
- Borehole Research
- Bus Traffic
- Canal Bridge
- Column Crash
- Concrete Slabs
- Dams
- Deep Foundation Piles
- Earthquake Prediction
- Elevated Water Tanks
- Embankments
- Flow Rates
- Footstep Detection
- Highway Bridge
- Interstate Bridge
- Linear Accelerator
- LNG Storage Tank
- Load Characteristic
- Lock Gate
- Masonry Arches
- Masonry Dome
- Office Floors
- Oil Platform
- Pedestrian Bridge
- Pipe Structures
- Railroad Bridge
- Railway Viaduct
- Retaining Wall
- Road Vibration
- Roadbed
- Seismic Surveying
- Soil Structure Analysis
- Sonic Boom Exposure
- Steel Tanks
- Telescope Structure
- Theatre Stage
- Train Vibration
- Tsunami Detection
- Tunnels
- Viaduct Decks
- Volcanoes
- Wind Turbine Blades
- Wind Turbine Tower

Application Examples

The following three research applications presented below provide some insight on how professionals conducting tests approach high sensitivity accelerometer applications.

Application 1: The Maratona Tower

After experiencing recent seismic activity, Italian authorities have been reviewing large structures for susceptibility to seismic forces. Their focus started with structures that hosted large social functions and events, such as stadiums.

The Artemio Franchi Stadium in Florence was first built in the 1930s and has been updated and modernized over the years as various activities, including World Cup matches, required. The stadium has a reinforced concrete structure with 24 stands, a cantilever roof, and a 50-meter tower (Maratona). The challenge was to collect data from two instruments (accelerometer and interferometric radar) to corroborate the frequencies of the tower in wind conditions.

The attic in the tower contained a **Model 393B31** PCB® accelerometer. A distant stadium entrance housed the interferometric radar.

The researchers (Miccinesi et al., 2019) were happy with the results. Natural frequency data from the accelerometer matched well with the data obtained from the interferometric radar, and researchers were able to show how both are viable options for monitoring structures.

Application 2: The Labado Dance

Researchers at the Gdansk University of Technology in Poland (Grębowski et al., 2019) were called in to review the excessive vibration of a motorbike stadium. The research examined fan behavior as it affected the structure of the Swiss Krono Arena motorbike speedway stadium in Zielona Góra (Poland). Fans at this stadium cheer by performing the Labado dance. "In this dance, the fans put their hands on their neighbor's shoulders and in the rhythm of the animator's drumming, they jump simultaneously to the song."

This dance risks damage to the structure and excessive vibration was observed during past events. Fans jumping together could cause resonant vibrations. This might cause the stands to collapse.

Nine triaxial accelerometers (**Model 356B18**) monitored vibration. Both the stand and the roof structure were instrumented. Dynamic characteristics of the structure were identified through numerical simulations. Validation was carried out by comparing the numerical model with the results obtained in the field.

After the validation of the numerical model, the identification of the jump load dynamic function was determined. The researchers were able to prove that the fan's "Labado Dance" generated forces at frequencies dangerously close to the resonant frequency of a portion of the stadium structure. Researchers recommended structural tuning to reduce the vibration during the fan's ritual.

Application 3: The Fish Ladder

The Dalles Dam in Oregon, USA, provides hydroelectric power from the Columbia River to the surrounding communities. The Dam is located in an important location for Salmon spawning and includes a large fish ladder to mitigate the impact o the dam on Salmon migration. The Fish Ladder Auxiliary Water System required some construction work. Vibration data from the support columns were monitored during construction. Daily reports informed dam operators of vibration conditions (Deng et al., 2018).

When vibration levels became excessive the operators did a forced spill. This encouraged the salmonids to continue to navigate the ladder. Otherwise, the vibrations may have prevented the salmonids from attempting the navigation.

Three triaxial accelerometer arrays (**Model 393A03**) were placed on the inner wall of the fish ladder. The baseline data was obtained before construction. This provided researchers with a basis for comparison during construction. Each day the vibration data was compared to the established threshold. On five construction days, the threshold was exceeded.

References

Deng, Z. D., Zang, X., Martinez, J. M., Mueller, R. P., & Lu, J. (2018). (rep.). *The Dalles Dam Fish Ladder Auxiliary Water System Vibration Monitoring*. BATTELLE. Retrieved October 20, 2021, from http://pweb.crohms.org/tmt/documents/FPOM/2010/FFDRWG/TDA%20back-up%20AWS/TDA_Fishway_vibration_report_FINAL_12312018.pdf.

Grębowski, K., Rucka, M., & Wilde, K. (2019). Non-destructive testing of a sport tribune under synchronized crowd-induced excitation using vibration analysis. *Materials*, *12*(13), 2148. https://doi.org/10.3390/ma12132148

Miccinesi, L., Pieraccin, M., Terenzi, G., Costoli, I., Spinelli, P., & Mazzieri, G. (n.d.). 5th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. In *Structural Health Monitoring of Artemio Franchi Stadium in Florence, Italy: Measurement Using Interferometric Radar*. Potsdam. Retrieved October 20, 2021, from https://www.ndt.net/search/docs.php3?id=24901.

Rigg, J. (2021, May 13). *The Ancient Earthquake Detector That Puzzled Modern Historians*. Engadget. Retrieved October 20, 2021, from https://www.engadget.com/2018-09-28-backlog-zhang-heng-seismoscope.html.

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

3425 Walden Avenue, Depew, NY 14043 USA

pcb.com | info@pcb.com | 800 828 8840 | +1 716 684 0001

WPL_87_1121