PCB PIEZOTRONICS
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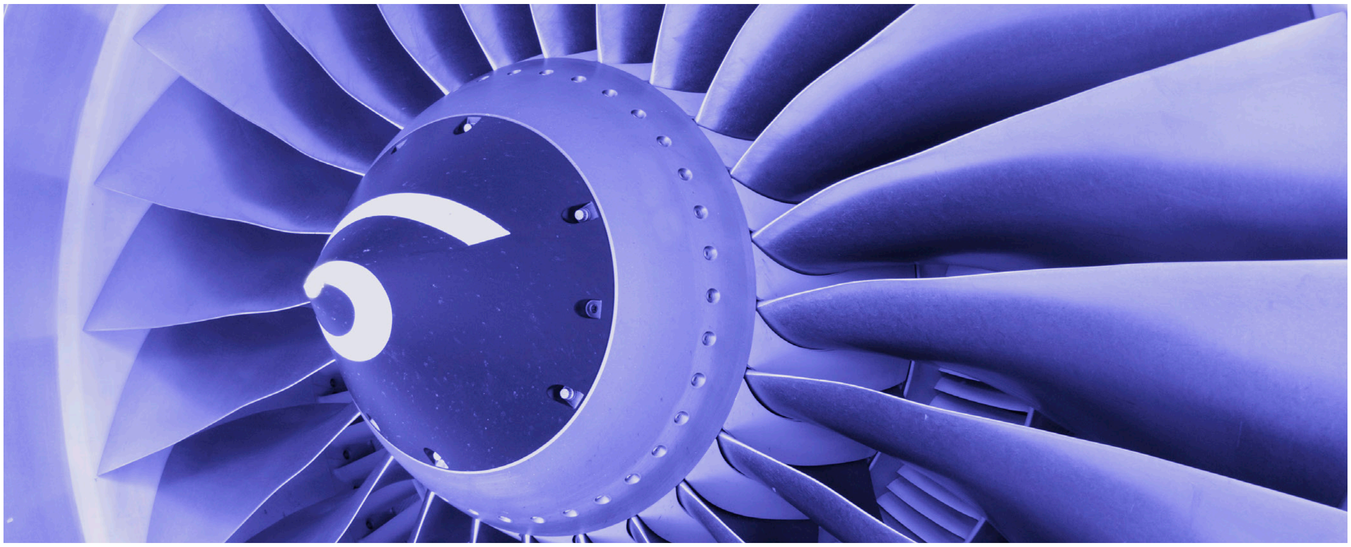

Recent Design Updates and Selection Considerations

For High Temperature and Cryogenic Aerospace

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Recent Design Updates and Selection Considerations for High Temperature and Cryogenic Aerospace Sensors

Accelerometers and Pressure sensors for measurement in extreme environments require special consideration during design and manufacturing processes. Specialized applications frequently require use of a single sensor model, which must be capable of operating over significantly wider temperature ranges, for example, -420 to +1200°F (-251 to +649°C), while providing high accuracy, stability, and reliability. Typical applications for high temperature aerospace sensors include measurement on gas turbine engines both in-flight and in test cells, as well as rocket motors and thruster assemblies. The same sensor might be required to withstand radiation and be used in monitoring vibration inside a nuclear power plant or on a space vehicle, or the cryogenic conditions of liquid propellants. These environments present a multitude of measurement challenges. Materials and construction must be optimized, not only to enhance high-temperature performance, but also to allow operation in the presence of gamma and neutron radiation without degradation.

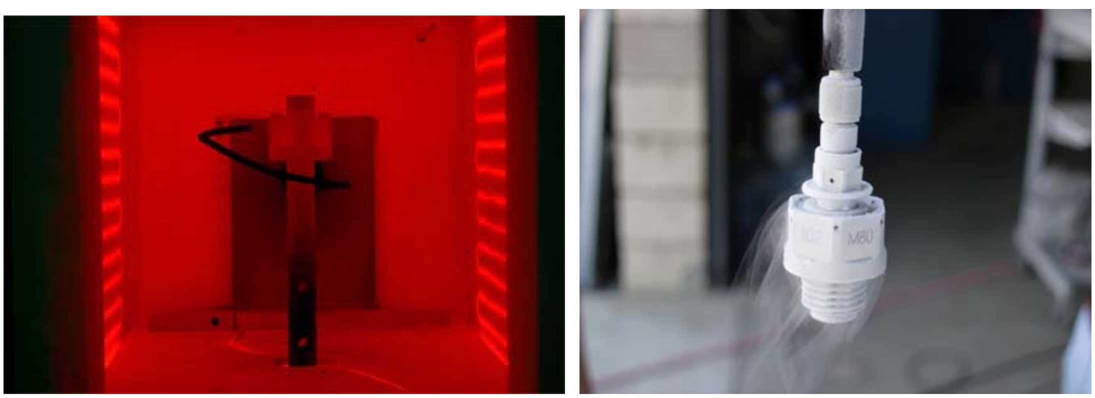

Photo on left shows a high-temp accelerometer on stinger test in thermal chamber at 1200°F (649°C).
Photo on right shows a cryogenic pressure sensor after soak in liquid Hydrogen at -420°F (-251°C)

Figure 1
Temperature extremes with piezoelectric sensors

Material Selection

Piezoelectric sensors are made from both natural and ferroelectric ceramic crystals. The choice of crystal depends on environmental and performance requirements. Each material has unique features and advantages, which characterize its performance in various applications. Natural crystals tend to provide the highest temperature ranges and the lowest pyroelectric outputs. However, ferroelectrics ceramics offer extended frequency ranges and smaller sizes for equivalent charge output (see Figure 2).

Figure 2
Examples of Quartz, Tourmaline, and Ceramics

Single, natural crystals, such as quartz or tourmaline are inherently piezoelectric. Most natural materials are single crystals grown in laboratories rather than mined, resulting in consistent quality with reduced risk of supply. In addition, the man-made aspect of a 'natural crystal' enables development of new, higher performance variations.

Ferroelectric ceramic materials on the other hand are not inherently piezoelectric. A ceramic is composed of many crystals in random orientation. For the ceramic to become piezoelectric the dipoles must be aligned. The alignment/polarization process involves applying a high voltage to the material to align polar-regions within the ferroelectric ceramic element. This process is known as 'poling' and is shown pictorially in Figure 3.

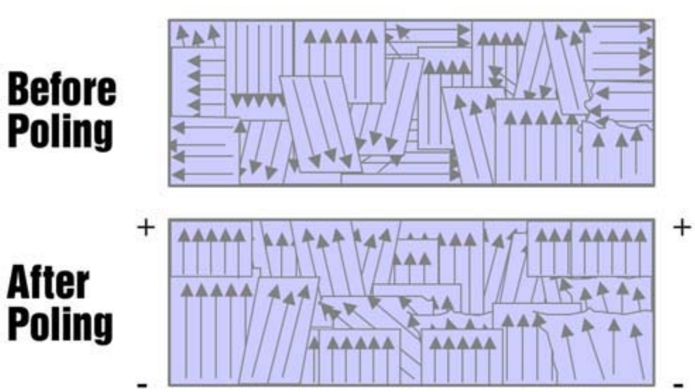

Fig 3

Ferroelectric ceramics exhibit significantly higher sensitivity or charge output per imposed unit of force. The most common material, bismuth titanate, has an output ten times the most common high temperature natural crystal, tourmaline. Bismuth titanate can be used to temperatures as high as +950°F (+510°C). Various compounds may be added to the ceramic material to alter sensor characteristics but high temperature ranges come at the expense of sensitivity.

A natural single-crystal material can be employed in either shear or compression mode. In compression mode, the material creates an electric charge in the same direction as the applied force. Lead zirconate titanate (PZT) is a ceramic material that is widely used in temperature environments as high as +550°F (+288°C). In shear mode, the material creates a charge in the direction perpendicular to the applied force. PZT can be designed into sensors using both shear and compression mode, but is most efficient in the shear since it has a higher charge output and upper temperature range. Typically, shear mode configurations are more efficient than compression because there is greater bandwidth and higher output with smaller size. In addition, since the required preload force that holds the crystal in place is perpendicular to the polarization axis, a shear design has extremely stable output over time. This enables extensive design flexibility and performance optimization (see Figure 4).

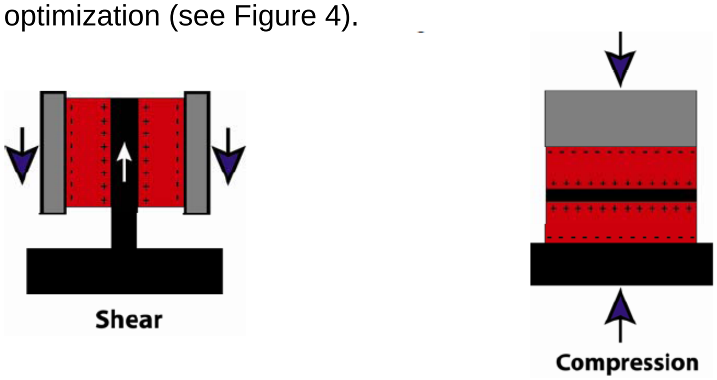

Figure 4

There are numerous temperatures, bandwidth, mounting and other tradeoffs that must be considered in high-temperature applications. Temperature effects exist beyond the limitation of the operating environment. Temperature changes may produce extraneous outputs and may change the sensitivity and other parameters. Piezoelectric sensors cannot produce an output in response to a constant temperature, as they cannot produce an output in response to a constant input: they are self-generating. They can produce an output in response to a change in temperature.

The piezoelectric element itself is often pyroelectric; that is it generates an output in response to temperature. In addition, temperature or temperature gradients may change the pre-load stress on the element because of thermal expansion. Temperature change inside a sensor, where output would be affected, is relatively slow due to the thermal transfer. Therefore, thermal outputs are at low frequencies where they are attenuated by the low frequency response of the system. For this reason, thermal output is not usually a problem. Sometimes piezoelectric sensors can show sharp spikes in their output after a large temperature change; this can be related to electrostatic surface discharge of pyroelectric fields. Spikes which continue after a pyroelectric discharge can be related not only to the piezoelectric material but to the design of the individual components and processing of the sensor.

A design that utilizes ferroelectric ceramic material in compression mode will have a greater pyroelectric output that that of a piezoelectric shear design or one using a natural crystal.

This is because of two effects:

- In compression mode accelerometers, piezoelectric material is directly coupled to the environment through the base of the sensor
- The ferroelectric material is sensitive to uniform temperature changes on those surfaces perpendicular to the axis of polarization.

However, pyroelectric output is a very low frequency phenomenon that is typically well below frequency ranges of interest and can be avoided by the use of high-pass filtering within measurement system electronics.

Challenges

The maximum operation temperature of sensors is controlled by two design challenges. First is a property of the piezoelectric material alone and is, termed the "Curie' temperature in piezoceramics, or 'twinning' temperature in natural materials. This is the temperature at which the material loses its piezoelectric properties.

The second design challenge is a sensor's insulation resistance, which significantly decreases with temperature. A low insulation resistance charge amplifier and charge converters must be specifically designed to operate with sensors having low insulation resistance values. If the charge output is being measured, the frequency response will not be affected, but the low frequency noise will tend to increase. And some charge measuring equipment will not tolerate low input resistance and will clip the output signal. Ordinarily the leakage resistance of a sensor is understood and the appropriate signal conditioning is used, thus there will be no noticeable effects.

Whenever a sensor is exposed to temperature changes, other parameters such as sensitivity and sensor capacitance also change. Changes should be predictable and repeatable however, and are influenced not only by the crystal material, but with each component and every process associated with building the sensor. Manufacturers should test every high-temperature sensor at its maximum operating temperature in order to assure consistency and quality.

Successful Measurements

Successful high-temperature measurements require more that just good sensor design. Cabling and electrical connections are critical to the acquisition of good quality data. A loose connector can result in the generation of a high-level, low frequency signal, unrelated to the measurement. Over time, reliability of connectors can degrade at temperatures over +900°F (+482°C) due to oxide formation on pin to socket contacts and potential loss of pin retention. The result can show up as a roll-off in the output of the sensor at higher frequencies.

Sensors designed for temperature of up to +1200°F (+649°C) are therefore fitted with integral cables, which also are mechanically isolated from the seismic system to avoid base and cable strain effects. Cables provided might use magnesium oxide or silicone dioxide insulation. The later is preferred since it is non-hydroscopic and exhibits excellent high-temperature electrical characteristics. Figures 5 and 6 show examples of removable and attached cables.

Figure 5
+900°F (+482°C) Accelerometer and Pressure Sensor with Removable Cable

Figure 6
+1200°F (+649°C) Accelerometer and Pressure Sensor with Attached Cable

Careful selection of cable material and use of protective over-braid facilitates ease of handling and allows bend forming during installation while maintaining cable integrity. The braid provides ‘flex’ to rigid cables and protects it from getting nicked or damaged. Cables should not be bent under 2.5 times the diameter of the cable as it may damage internal insulation or affect dielectric properties. Cables on accelerometers should be clamped at approximately 8-inch (20 cm) intervals to prevent excessive flexing during vibration. It’s important to provide clearance between cables and other components on the structure to prevent abrasion during vibration.

An accelerometer must be coupled to the surface it is measuring. As a result, bending of the structure or mounting bracket can cause distortion, producing unwanted output called base-strain sensitivity. If brackets must be used, care must be taken to avoid introducing dynamic response problems due to bracket resonances within or near the operational frequency range. A thorough understanding to the modes of mounting brackets and adaptors is important for good data and it must be verified that test item resonance, bracket resonances and sensor resonances do not overlap. Figure 7 shows a typical bracket accelerometer.

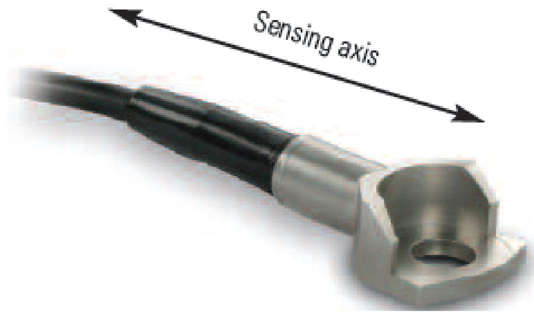

Figure 7
Bracket Mount Accelerometer

Piezoelectric sensors will operate normally when subjected to radiation environments. Pyroelectric outputs will be produced when transient radiation produces significant temperature change, but this is no greater than that produced within the standard temperature range. The magnitude of pyroelectric output depends on the type of piezoelectric ceramic used as well as the design. There should only be small errors produced as a result of temperature changes present in nuclear shock and vibration applications typical as a result of Gamma radiation. Neutron radiation could cause change to the molecular structure but only at severe extraordinary levels. Adverse reactions to radiation include a reduction of piezoelectric material output and deterioration of various materials that are intolerant to radiation such as Teflon. Generally, higher temperature crystals are more resistant to the effects of radiation.

High temperature sensor designs are driven mainly by the purpose for which they are used. In test and measurement applications single ended designs are used to minimize mass and size. Because of the wide array of test and measurement environments and associated conditions, high temperature sensors feature numerous mounting and cable/connector configurations. With a single ended system, the accelerometer has an inherent capacitance between the case and the signal side of the crystal. It would normally be susceptible to electrostatic pickup without the use of an insulating base.

A general category of high temperature is intended for use in permanently mounted condition monitoring applications. This type of accelerometer is often referred to as a ‘bill of material’ or OEM sensor because it is integrated into a customer’s product line. These accelerometers are almost exclusively designed for each application. Unlike their test and measurement counterparts, the housings of these sensors are almost always electrically isolated from the measurement circuit and the charge output of the sensor is differential. Differential signal output is used, where the capacitance balance between signals is important since the structure it is mounted to is used as an electrical ground return. Capacitance balance allows differential charge amplifiers to distinguish between common mode signal (noise) and differential signal which is the true measure of the dynamic acceleration. Differential output is preferred when signals must be routed through multipin connectors where individual shielding of conductors is not feasible. A typical monitoring accelerometer is shown in Figure 8.

Figure 8
Differential 900 °F (482 °C) Accelerometer for Turbine Engine Monitoring

Conclusion

Whether used in aircraft engines, space vehicles, or power generation stations, these sensors must provide high levels of accuracy, stability and reliability. Therefore instruments used in extreme environments such as cryogens and high-temperature require special consideration during the design and manufacturing process.

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