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Latest technology in piezoelectric vibration- and pressure sensors and their benefits for measurement

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Abstract

To measure on turbines, engines and equipment at high temperatures vibrations or pressures, the sensors must meet extremely high demands. Special materials in the sensor design, for sensor housing and cable as well as the sensor element itself, is necessary to achieve extremely high operating temperatures. The new piezoelectric crystal UHT-12™ (Ultra High Temperature 1200°F/650°C) allowed an operating temperature of up to 700°C for sensors with charge output.

In addition, the measurement results are highly accurate, low noise (no popcorn noise) and temperature stable. Using this special synthetic crystal, also ICP® vibration sensors with extremely low temperature coefficients have been developed.

The result is reflected in an improvement in the accuracy of the amplitude response of the entire measurement chain over the entire temperature range from 29% down to 4% .

This is a significant improvement in measurement uncertainty compared with sensors that use ferroelectric ceramics as measuring material.

With a clever choice of materials and manufacturing technologies are now also ICP® vibration sensors up to a working temperature of 180°C possible.

This challenge has been implemented in a miniature triaxial accelerometer with a weight of 1 gram.

Integrated low-pass filter in ICP sensors find increasing popularity because it reduced the chance of amplifier saturation and increase the useable frequency range.

It saves so much trouble in applications where the sensor does not just see periodic signals, but also transient events or strokes.

Against amplifier saturation by acoustic emission we can also integrate mechanically filters.

Key Words

ICP, UHT-12™, Low Temperature Coefficient (LTC), Ferroelectric Ceramics, Piezoelectric Materials, Spurious Noise, Popcorn Noise,

Material Selection

Piezoelectric sensors are made from both naturally piezoelectric crystals and artificially polarized polycrystalline ferroelectric ceramics. The choice of sensing material 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 range and the lowest (or zero) pyroelectric output. However, ferroelectric ceramics offer extended frequency range and smaller size for equivalent charge output. Table 1 organizes material types ranked by temperature and pyroelectric susceptibility.

Natural versus Ceramic Crystals					
Material	**Natural Piezoelectric Single Crystals**	**Ferroelectic Ceramic, Piezoceramics**	**Piezoelectric Coefficient pC/N**	**Maximum Useable Temp °C**	**Pyroelectric**
UHT-12 shear	X		12	650	No
UHT-12 compression	X		6	650	No
Quartz shear	X		4	250	No
Quartz compression	X		2.2	200	No
Tourmaline shear	X		3.5	650	Yes
Tourmaline compression	X		1.8	650	Yes
Bismuth Titanate		X	21	500	Yes
Bismuth Titanate derivates		X	14	600	Yes

Table 1
Examples of Piezoelectric Material

Single, natural crystals, such as quartz and tourmaline, are inherently piezoelectric. Most natural occurring single crystals that are used for sensors are 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 has enabled development of new, higher performance variations. The exception is tourmaline, only available through mining, and thus the supply chain is uncertain and the cost becomes prohibitive for use in sensors.

Ferroelectric ceramic materials are not inherently piezoelectric because upon chemical formulation they are in a random polycrystalline orientation. For the ceramic to become piezoelectric the individual dipoles of each crystalline structure must be aligned. The alignment process involves applying a high voltage to the material to align polar-regions within the ferroelectric ceramic element. After the artificial polarization process is complete, known as poling, the crystal may undergo a pre-aging process and then can be used in a sensor.

Ferroelectric ceramics exhibit significantly higher sensitivity or charge output per imposed unit force. A commonly used high temperature sensor material, BiTi (Bismuth Titanate), has an output three to four times its natural crystal counterpart, quartz. BiTi 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. Drawbacks of BiTi include the requirement for a carefully controlled environmental condition inside the sensor and for a perpetually stabilized partial pressure level of Oxygen to preserve its operational characteristics.

The new UHT-12™ crystal is quite happy in any atmosphere and these sensors are backfilled with inert gas such as Argon or Nitrogen. UHT-12™ crystal does not exhibit any pyroelectric output and provides for reliable operation at temperatures approaching 1200 °F (650 °C). While the raw charge output of this material is not as high as commonly used BiTi, additional benefits of the material include a relatively low capacitance and higher insulation resistance at operating temperature, which results in a low noise operation when used with a differential charge amplifier.

One often overlooked comparison of BiTi and UHT-12™ is the ability to use the material in a sensing element configuration for use in a shear orientation. Physical and process limitations prevent BiTi from operating in a shear mode and thus legacy high temperature sensors are still manufactured with compression mode sensing elements. On the other hand, UHT-12™ may be used in a shear configuration if properly prepared. The benefits and characteristics of these two sensing element configurations are discussed further.

Insulation Resistance

Very low IR (insulation resistance) may produce signal output drift in a charge amplifier; however, this is not usually a problem in a properly designed accelerometer meeting product specifications and when used with a properly designed charge amplifier. Existing accelerometers with ferroelectric ceramics may have IR values around 100k Ohm at 905 °F (485 °C), whereas the UHT-12™ crystal will have values approximately ten times larger at the same temperature. While the noise in any charge amplified system depends on a number of factors, the larger IR value in UHT-12™ is an important benefit, as the system noise gain is a function of the feedback resistor in the charge amplifier and the input resistance. Larger IR values reduce system noise gain.

It is shown in Figure 1 below that the resolution of the new 10 pC/g sensor is comparable to that of a traditional higher sensitivity 50 pC/g BiTi based sensor for this reason. In addition to being a factor in determining the inherent resolution of the measurement system, the system noise gain also has the characteristic of amplifying externally imposed noise (as with RFI, for example) and therefore is an important characteristic. The new UHT-12™ accelerometers will have a susceptibility to externally imposed noise which is approximately 8 dB (2.5x) less than a comparable system based on ferroelectrics ceramic.

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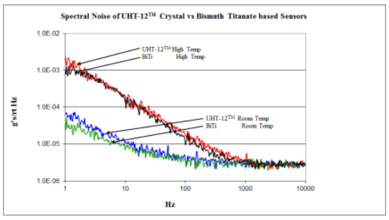

Figure 1
Noise Comparison of UHT-12^{TM} 10 pC/g Accelerometer vs. BiTi 50 pC/g

Spurious Noise Sources

When subjected to temperature gradients, compression element assemblies will experience differential expansions/contractions of the various mating surfaces and the preload bolt. When differential expansion is large enough, the sensor may create a corresponding electrical output as stress is released and the parts instantaneously slip against each other. In addition, ferroelectric ceramic as well as tourmaline elements are pyroelectric, which means charge is created simply due to changes in temperature. In the time domain, the output from these two spurious noise sources may appear as a step output that decays at a rate governed by the signal conditioner's time constant. Example data is shown in Figures 2 for a compression accelerometer design.

The data reveals positive going spike output of approximately 13 g's during the ramp up to 900 °F, at time 1170 minutes. When integrated to velocity the result is 100 in/sec pk-pk. The spiking phenomenon repeats during the cool down phase, in the negative direction with a greater rate, yet at slightly lower amplitude per occurrence.

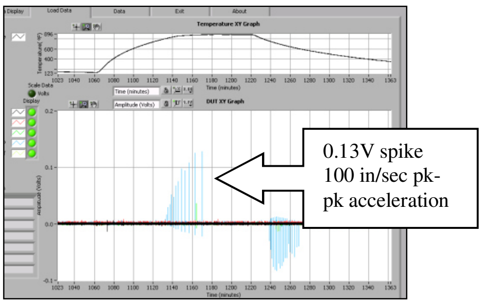

Figure 2
Typical Noise Data from Compression Mode Accelerometer during Temperature Change

The new UHT-12™ shear design, which only responds to shear stress, is significantly more tolerant of thermal changes because those changes occur in the primary axis of the accelerometer, and the sensing element is oriented 90 degrees to the primary axis of vibration. The shear mode UHT-12™ accelerometer consistently shows low amplitude spike levels. The fact that the UHT-12™ also has no pyroelectric output is an additional advantage during thermal transient events. An example data set for the thermal response of the new UHT-12™ shear design is shown in Figure 3.

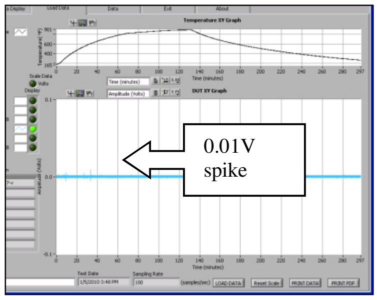

Figure 3
Typical Noise Data from Shear Mode Accelerometer during Temperature Change

To engine balance instrumentation, a step output from an accelerometer will look like a large low frequency signal. The problem occurs during or soon after a change in temperature, such as going from idle to full power for take-off.

Piezoelectric Sensors with new single crystal Material UHT-12™

UHT-12™ is a new crystal designed for more accurate, low noise measurements during temperature variations. UHT-12™ reduces the effect of temperature variation. Pyroelectricity phenomenon may occur during large temperature fluctuations, generating "spikes" and disrupting behavior of the accelerometer and the test results. Accelerometers made with UHT-12™ technology have improved data quality.

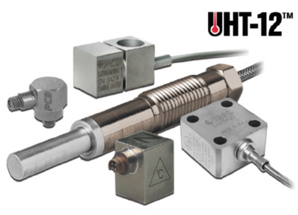

Figure 4
Vibration- and Pressure Sensors with UHT-12™ Technology

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Solution to improve measurement uncertainty

For certain applications, it is necessary to know the accuracy of the overall vibration measurement chain. It will be noted that the largest percentage of inaccuracy is supplied by the sensor. The reason is the transformation of the physical quantity in the electric and many other environmental factors including the temperature.

The influence of temperature on a vibration sensor describes the temperature coefficient. The temperature coefficient describes the relative change of a physical property with a given change in temperature, with respect to a specified reference temperature. The quantity of interest is mostly a material property. In piezoelectric sensors is that the sensing material. As discussed, there are a wide range of piezoelectric materials for different applications available.
An outstanding advantage for sensors with ICP technology can be achieved through the use of UHT-12™. The temperature coefficient is improved compared with ferroelectric materials by a factor of 10. Practically this results in an improvement of the amplitude response over the entire temperature range from 29% down to 4% (Figure 5).

The LTC-Series (Low Temperature Coefficient) sensors are designed for wide operating temperature, and good broadband measurement resolution, making ideal for powertrain development and powertrain NVH application, or for any vibration measurement requiring tight control of amplitude sensitivity over wide thermal gradient.

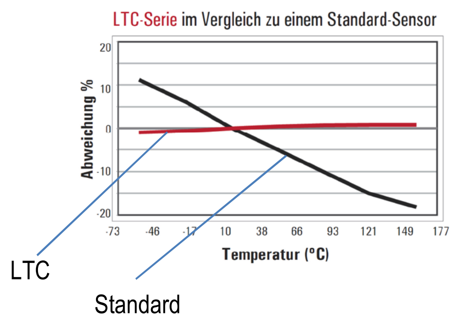

Figure 5
Low Temperature Coefficient (LTC) vs. Standard ICP®-Vibration Sensors

Figure 6
Selection of Accelerometers with LTC (UHT-12™)

Progressive miniaturization and + 180 ° C continuous use for ICP technique.

For most sensors for vibration measurement technology, the advantages of the ICP technique have prevailed. They cannot, however, be used where the ambient temperature exceeds the capability of the built-in circuitry. These are for special versions (HT) + 162°C.
With the model HT456B01 the +180 ° C limit is reached. In addition, extreme miniaturization is achieved.
This triax vibration sensor is unique. The 6,3 mm cube weighs 1 gram only.
A step in the right direction for climate chamber tests and measurements on engines or exhaust system.

Figure 7
Triaxial ICP® Accelerometer Model HT356B01 (+180°C)

What's wrong with my Piezoelectric Accelerometer

A frequently asked question about measurements made with piezoelectric (PE) vibration sensors is related to the measurement parameters. After completing a test and evaluating data, test engineers may observe obvious signs of problems within the data that was collected.
Many factors can affect the data from a PE accelerometer including measurement range, the measurement input amplitude, the measurement input frequency content, and the data acquisition sample rate. For example, input amplitude levels that are greater than the sensor's measurement range will saturate the amplifier. Input frequency content at or near the sensor's resonant frequency may also saturate the amplifier. The high Q-factor at resonance will cause the sensor to enter an overload recovery state and no meaningful data can be acquired (even with post-process filtering in your DAQ). Data of

saturated amplifier will appear as illustrated in Figure 8 and 9.

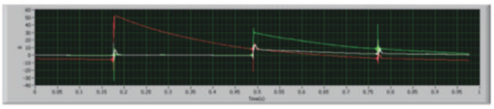

Figure 8
Input amplitude saturate amplifier

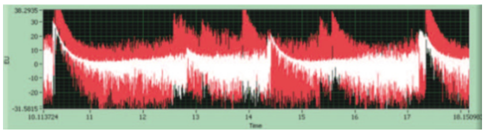

Figure 9
Input frequency near the sensor's resonant frequency saturate amplifier

Sensors with single or two-pole low pass filters will decrease the chance on amplifier saturation and increase the useable frequency range. Low pass filters will attenuate (suppress) signal generation at or near the resonance frequency of the sensor. This counteracts the gain (high-Q) factor caused by the sensor's mechanical resonance. See figure 10.

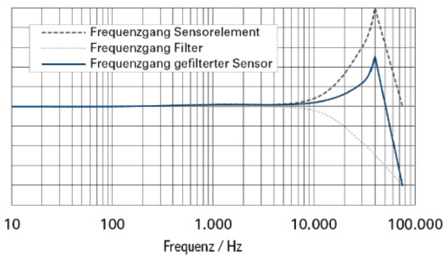

Figure 10
Unfiltered and Filtered Sensor Response

ICP®-Accelerometer with integrated low pass filters (in extracts)

Model 355M102: 10 mV/g, LP-Filter, LTC, isolated, 8 Gram

Model 356A61: 10 mV/g, Triax miniature, LP-Filer, 4 Gram

Models 339A30/A31:10 mV/g, Triax, LP-Filter, LTC, 5,5 / 4 Gram

Conclusion

- High Temerature Sensors with UHT-12™ Sensing Material are Temperature stable, has a low noise output and can used up to 700°C.
- The new crystal shows NO pyroelectric spikes in temperature change (Popcorn Noise).
- ICP®-Sensors with UHT-12™ have an extremely low temperature coefficient. It has a particularly positive effect on the accuracy and temperature stability of the measuring chain.
- UHT-12™ sensors in shear sensing element configuration, limits susceptibility to environmental influence such as temperature transients, base strain and transverse sensitivity errors.
- ICP®-Technology reached +180°C Operation Temperature, sub miniature triax available.
- Integrated low-pass filter protect the sensors for saturation and generate high signal quality.

References

Bob Metz, PCB Piezotronics, Inc "Design and Selection Criteria of High Temperature Accelerometers for Aerospace Propulsion".