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Accelerometer Characteristics Utilizing Natural and Ferroelectric Crystals

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By Len Maier

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ACCELEROMETER CHARACTERISTICS UTILIZING NATURAL AND FERROELECTRIC CRYSTALS

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By Len Maier, Manager of Product Engineering, ENDEVCO

ABSTRACT

Piezoelectric accelerometers are manufactured with both natural and ferroelectric crystals. The choice of which type to use depends on the environment and system characteristics as well as the inherent properties of the piezoelectric materials. This paper reviews the characteristics of natural and ferroelectric piezoelectric materials and compares the design features of acceleration transducers utilizing both. Comparison data of bismuth titanate and tourmaline accelerometers under varying conditions on a gas turbine engine is also presented.

INTRODUCTION

Piezoelectric accelerometers have been used to make difficult vibration measurements for many years. Accelerometer designs vary considerably from micro-miniature (0.14 grams) for modal testing to relatively large, rugged designs weighing up to one kilogram for seismic measurements. The transducer designer is confronted with many design choices depending on size, temperature and figure of merit requirements. Yet, the success of any design may hinge on the proper selection of system components rather than the choice of crystal material. For example, the effects on resonant excitation are often neglected in vibration measurement systems. When high output accelerometers with relatively low resonance are used in complex vibration environments, resonant excitation of the accelerometer can often cause saturation of the charge converters in the vibration amplifier, resulting in an apparent failure. Insertion of a simple, low pass filter before the charge converters is usually all that is required to avoid this problem. Low frequency transient phenomena such as pyroelectric output and base strain can be avoided by employing steep high pass filtering. If the frequency of interest is below 1 Hz, then the selection of piezoelectric materials becomes more important with natural crystals generally favored. The connection system is often the least considered component and consequently the most important for successful vibration measurement.

NATURAL AND FERROELECTRIC CRYSTALS

Within the context of accelerometer design, natural crystals refer to piezoelectric materials which occur naturally, and those which are grown in the laboratory and are inherently piezoelectric. That is, they do not require poling to become piezoelectric. The most common natural piezoelectric materials used in accelerometers are quartz and tourmaline. Quartz can be found in both the natural and man-made form with the man-made form preferred in accelerometer design. Tourmaline, on the other hand, is available only in its naturally occurring form. There have been some attempts to grow tourmaline in the laboratory with no known success. Bismuth Germanium Oxide (BGO) is another natural crystal material which is grown in the laboratory by the Czochralski pulling technique. All of the natural crystals mentioned are unique in that they have very low pyroelectric output, making them ideal for very low frequency measurements in the presence of thermal transients.

Ferroelectric crystals refer to polycrystalline dielectric materials generally known as ceramics. These materials are not naturally or inherently piezoelectric, but are capable of becoming electrically active. Ceramic materials require the application of a high dc electric field for dipole arrangement and inducement of the piezoelectric effect. These polarizable ceramic materials have properties analogous to ferromagnetic materials and have become known as "ferroelectrics". The most common ferroelectric ceramics used in accelerometer designs are lead zirconate titanate and bismuth titanate. Ferroelectric ceramic crystals are known for their very high sensitivities which provide extended frequency range and smaller size for equivalent output compared to natural crystals.

A comparison of accelerometer characteristics using natural and ferroelectric materials is shown in Table 1.

PYROELECTRIC CHARACTERISTICS

All piezoelectric accelerometers whether they use natural or ferroelectric crystals produce a pyroelectric response. Materials such as quartz and BGO which do not possess a pyroelectric axis and are, therefore, non-pyroelectric yield an apparent output which is sometimes referred to as false pyro. This phenomena is attributed to the fact that pyroelectric response consists of three types of outputs; primary, secondary and tertiary. The primary component is the result of a uniform temperature change in the crystal when constrained and occurs on surfaces perpendicular to the axis of polarization. Compression accelerometers using ferroelectrics have a large primary component. Ferroelectric shear accelerometers which have electrode surfaces parallel to the axis of polarization do not produce a primary pyroelectric response and are comparable to natural crystal accelerometers in pyroelectric response. The secondary component is caused by thermal deformation of the crystal from uniform heating. Natural crystals that are pyroelectric such as tourmaline, have a relatively large secondary component, but still small compared to ferroelectrics. The tertiary component applies to all accelerometers and is caused by a temperature gradient across the crystal due to non-uniform heating. The tertiary component is highly dependent on the mechanical design, polarization axis and electrode orientation as opposed to the specific crystal material.

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TABLE 1

MATERIAL	PIEZOELECTRIC COEFFICIENT dxx10-¹²C/N	MAXIMUM USE TEMP. °C	RESONANT FREQUENCY at 50 pC/g in Hz	FIGURE OF MERIT SENS. x fn² x10⁹
Natural				
Quartz	2.2	250	7 000	2.45
Tourmaline	1.8	600	7 000	2.45
Bismuth Germanium Oxide	22	350	8 000	3.20
Ferroelectric				
Bismuth Titanate	20	500	15 000	11.25
Lead Zirconate-Titanate	280	260	25 000	31.25
Lead Zirconate-Titanate (Shear)	450	300	23 000	26.45

Laboratory tests were conducted comparing the pyroelectric output of natural and ferroelectric crystals under varying amplifier responses starting with dc using an electrometer, single pole high pass filtering at 0.73 Hz and 30 Hz, and 3 pole high pass filtering at 3.7 Hz. The units were of comparable compression design and sensitivity except the lead zirconate-titanate shear unit which was of shear construction and significantly smaller. The units were subjected to an instantaneous temperature change by immersing in a 120°C oil bath with the outputs recorded on an X-Y plotter. The pyroelectric output in equivalent g's per 100°C is shown in Table 2.

TABLE 2

MATERIAL	PYROELECTRIC OUTPUT (g/100°C) LOW FREQUENCY ROLL-OFF 3 POLE 3.7 Hz	1 POLE 30 Hz	1 POLE 0.73 Hz	DC
QUARTZ	0.0010	0.0014	0.068	21
BGO	0.0010	0.0020	0.094	26
LEAD ZIRCONATE TITANATE S	0.0010	0.0090	0.43	440
TOURMALINE	0.0010	0.010	0.43	.12
BISMUTH TITANATE	0.0010	0.040	1.7	5150
LEAD ZIRCONATE TITANATE C	0.0010	0.68	2.8	1200

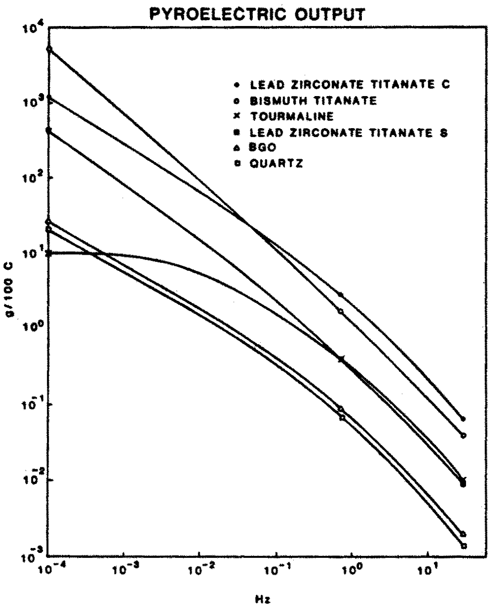


Figure 1

The results indicate that as you approach dc, the natural crystals are significantly better than ferroelectric crystals as expected. With the introduction of high pass filtering, the difference between natural and ferroelectric crystals decreases significantly. At 0.73 Hz, the response of lead zirconate-titanate shear is identical to tourmaline compression. With 3 pole high pass filtering at 3.7 Hz, the pyroelectric response for both natural and ferroelectric crystals is negligible. Tourmaline has a lower pyroelectric output at dc than quartz and BGO which may be attributable to the cancelling affects of the secondary and tertiary components. A graphical representation of the pyroelectric output is shown in Figure 1.

ACCELEROMETER CHARACTERISTICS

The design of an accelerometer will vary significantly depending on the piezoelectric material used. Configuration is primarily a function of the piezoelectric charge coefficient, resistivity, and maximum use temperature. Table 1 lists the main characteristics for 50 pC/g designs using natural and ferroelectric materials.

Figure of merit is a function of sensitivity times the resonant frequency squared and is a measure of efficiency of a design. The higher the figure of merit the more efficient which means greater frequency range for equivalent sensitivities. Ferroelectric accelerometers are generally more efficient than natural crystal accelerometers due to their significantly higher charge coefficients with lead zirconate-titanate designs the most efficient. In addition high figure of merit designs provide significantly reduced size and weight for equivalent sensitivities. Figure 2 illustrates the relative size of three accelerometer designs utilizing lead zirconate-titanate in shear, bismuth titanate in compression, and tourmaline in compression. It is quite apparent that ferroelectric designs provide significant advantage in size and weight over natural crystal designs.

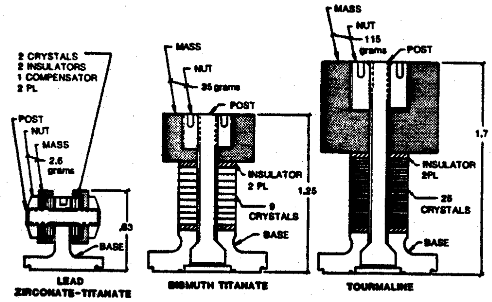
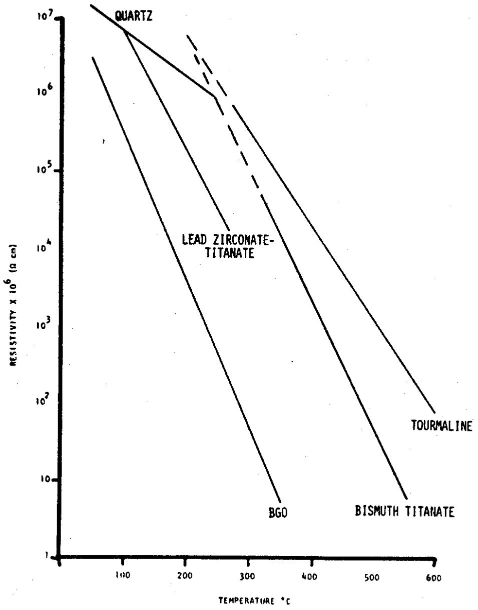


Figure 2

The maximum use temperature is determined either by the Curie point, characteristic of ferroelectrics, or the temperature at which the source resistance equals 100 000 ohms for a 50 pC/g design. Above 300°C resistivity plays an important part in accelerometer design (reference Figure 3). Tourmaline can be used above 600°C with a concomitant reduction in sensitivity or output resistance. Although quartz has a Curie, or inversion, temperature at 573°C its maximum use temperature is limited to 250°C due to electrical twinning. This phenomena increases with stress and is quite pronounced above 250°C rendering the material useless. BGO does not have a Curie point but has a relatively low resistivity limiting its usefulness to approximately 350°C. Lead zirconate-titanate has a Curie point at 370°C limiting its temperature range to approximately 300°C. Bismuth titanate is the highest temperature ferroelectric material successfully employed in accelerometer designs and can be used up to 500°C.

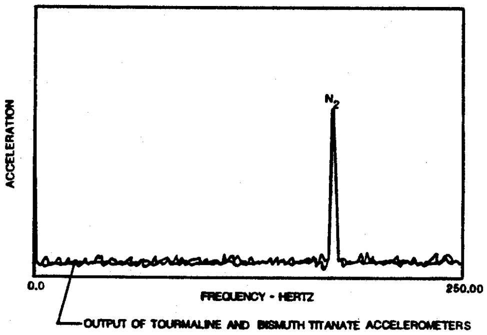
GAS TURBINE COMPARISON DATA

A "real world" evaluation of ferroelectric and natural crystal accelerometer designs was completed by comparing their responses at identical locations on a gas turbine engine in a test cell. The designs were the same or similar to those used to generate the data in Tables 1 and 2, and are typical of engine vibration monitoring accelerometers. The engine tests were limited to a bismuth titanate ferroelectric design and a tourmaline natural crystal design. All units were mounted at the turbine mid-frame location on a T-bracket. Standard test cell vibration amplifiers with filtered acceleration and velocity outputs were used. The data presented is in relative terms to illustrate comparative responses of ferroelectric and natural crystal designs, but is typical of test cell data at turbine mid-frame locations and respective power level. Figures 4a and 4b are representative of the responses obtained when the installation, which includes cable tie down and connector tightening, was performed correctly. The acceleration and velocity responses for ferroelectric and natural crystal designs are nearly identical.



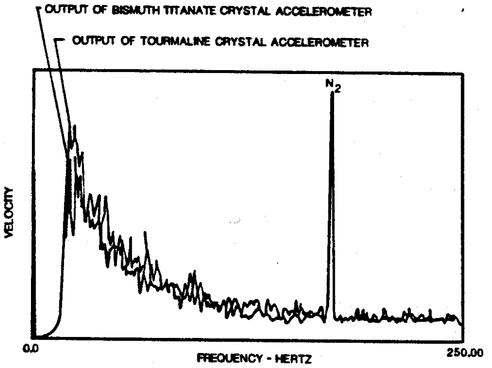
RESISTIVITY vs TEMPERATURE

Figure 3



MOUNTED AT TURBINE MID-FRAME LOCATION ON 50,000 LB. THRUST ENGINE

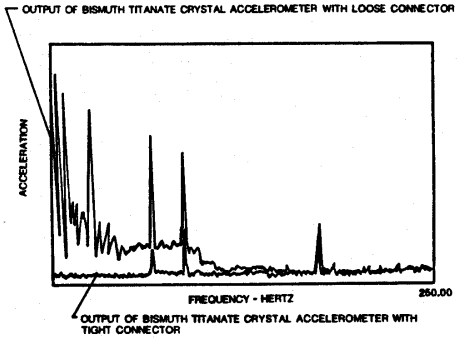
Figure 4a



MOUNTED AT TURBINE MID-FRAME LOCATION ON 50,000 LB. THRUST ENGINE

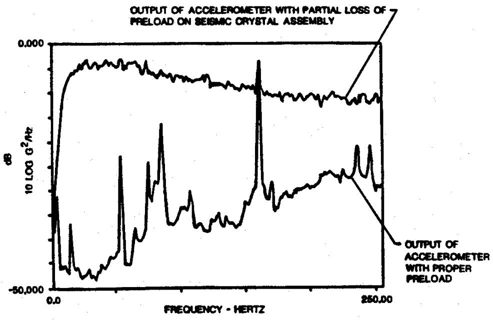
Figure 4b

As previously stated, the connection system is often the least considered component in a vibration monitoring system and very often the source of erroneous data. During the course of engine testing, some data anomalies developed which were traced to the connectors. The high level low frequency response shown in Figure 5a was the result of a loose coupling nut at the transducer cable interface. After tightening the coupling nut and re-running the engine under identical conditions a normal response was obtained. Figure 5b shows the effect of loose contact pins at the firewall interface. The mating plug had rear insertable pins which were loose due to improper assembly. The response returned to normal after correcting the connector deficiency. Figures 5a and 5b indicate that good or bad data can be obtained irrespective of the crystal material with the integrity of all system components necessary for valid data.



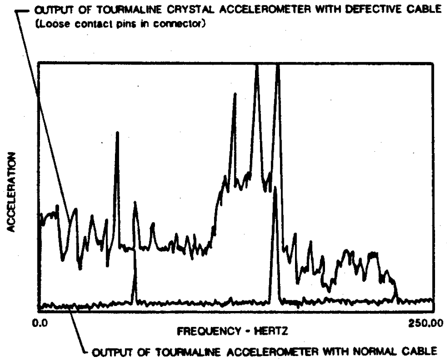
MOUNTED AT TURBINE MID-FRAME LOCATION 50,000 LB. THRUST ENGINE

Figure 5a



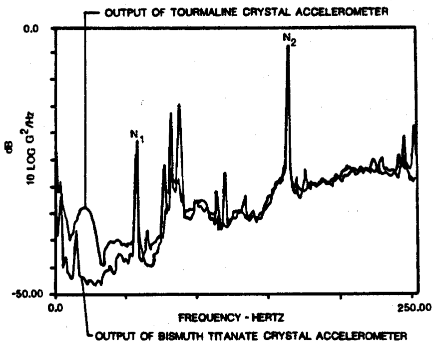
BISMUTH TITANATE-TYPE ACCELEROMETERS MOUNTED AT TURBINE MID-FRAME LOCATION ON 50,000 LB. THRUST ENGINE

Figure 6a



MOUNTED AT TURBINE MID-FRAME LOCATION ON 40,000 LB. THRUST ENGINE

Figure 5b



MOUNTED AT TURBINE MID-FRAME LOCATION ON 50,000 LB. THRUST ENGINE

Figure 6b

A problem slightly more esoteric than loose connectors is illustrated in Figure 6a. The response appears as valid data but is significantly higher than expected and occurs only at high power levels. The solution to this phenomena took several months to resolve and was attributed to preload loss on the seismic assembly as a result of yielding of the compression bolt during assembly processing. Standard calibration at relatively low g levels gave no indication of the problem. Subsequent laboratory testing at higher g levels in the transverse mode produced high level readings compared to normal units. The bolt was changed to a high strength super-alloy type and the unit re-run on a gas turbine engine with expected results. A comparison of ferroelectric bismuth titanate and natural tourmaline with proper preload is illustrated in Figure 6b.

CONCLUSION

Ferroelectric crystal accelerometers have higher figures of merit providing either greater sensitivity or frequency response than natural crystal accelerometers.

Natural crystal accelerometers are less sensitive to thermal transients (lower pyroelectric output) than ferroelectric designs especially at frequencies less than 1 Hz. With adequate high pass filtering the pyroelectric response of both ferroelectric and natural crystal accelerometers is negligible.

At temperatures above 500°C Tourmaline offers advantages in resistivity and long term exposure. At 500°C and below the choice of material is significantly greater with ferroelectrics providing advantages in size and weight, frequency range and sensitivity.

Erroneous vibration data is more dependent on the connector interface than the piezoelectric material used. More attention should be given to the connector design with emphasis on integral cable assemblies.

Insufficient seismic preload is also a source of erroneous vibration data. New calibration procedures at higher energy levels should be used on all engine monitoring accelerometers.

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REFERENCES

Ballman, A.A., "Growth of Piezoelectric and Ferroelectric Materials by the Czochralski Technique." J. American Ceramic Society, 48 (2) P112 (1965).

Goodman, G., "Ferroelectric Ceramic Composition." United States Patent No. 2,731,419 (1956).

Lang, S.B., "The Pyroelectric Thermometer: A Sensor for Measuring Extremely Small Temperature Changes or Rates of Temperature Change," Source Unknown.

Bhalla, A.S. and Newman, R.E., "Primary and Secondary Pyroelectricity," Office of Naval Research, Contract No. N00014-78-C-0291 November, 1981.

Bouche, R.R., "Calibration of Shock and Vibration Measuring Transducers," Shock and Vibration Information Center, U.S. Department of Defense, P53 (1979).

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