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Accelerometers Developed for Vibration Measurement at High Temperature

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ACCELEROMETERS DEVELOPED FOR VIBRATION MEASUREMENT AT HIGH TEMPERATURE

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ABSTRACT

This paper reviews the development of several piezoelectric accelerometers designed for measuring vibration at temperatures exceeding 750°F (400°C). The measurement system design considerations, including cable, connector, and signal conditioner characteristics, are examined as they interrelate with the accelerometer. To provide the high temperature transduction element it was necessary to develop the high temperature piezoelectric materials. The critical characteristics of these materials and the resulting accelerometer designs are discussed. One of the accelerometers, with a temperature range to 1400°F (760°C), weighs only 0.6 ounce (18 grams). The methods used to evaluate the vibration, shock, and accuracy capabilities at high temperature are discussed, and the results of tests are presented.

INTRODUCTION

Accelerometers are used in a wide variety of applications for structural vibration measurements. Along with the vibration, other severe environmental conditions are usually present; often one of these is high temperature. Typical applications encompass vibration measurements on power generating and handling equipment such as gas turbines, pumps, and heat exchangers. Although accelerometer temperature ranges have increased in the past, the temperatures were limited to about 750°F because of piezoelectric material and electronic signal conditioning limitations. Developmental efforts in the last two to three years have increased temperature ranges substantially. Temperature ranges to 900°F are now routine and ranges to 1400°F have more recently been accomplished.

These new developments are the subject of this report. Several high temperature accelerometers have evolved from this development; the highest temperature version uses the newly developed PIEZITE® P-15 piezoelectric element.* An example of the accelerometer designed is the 1400°F Endevco Model 2285 shown in Figure 1. This design is extremely small and light; the weight is 18 grams. Development of new piezoelectric materials, new system and electronic circuit designs, and new cabling has been required to achieve this. These factors are discussed herein, along with procedures and test data for the accelerometers developed.

PIEZOELECTRIC MATERIALS FOR HIGH TEMPERATURE USE

There are many uses for piezoelectric materials. The requirement for high temperature operation is a need somewhat peculiar to the transducer application. Critical factors for high temperature operation include:

1. Stability of piezoelectric output with time at low and high temperature, and with temperature cycling.
2. Small variation of the piezoelectric output with temperature change.
3. High charge and voltage piezoelectric strain constants.
4. High resistivity.

In the past the maximum temperature for transducers has primarily been limited by the ferroelectric Curie temperatures and crystal phase changes. Typical Curie temperatures for ferroelectrics are shown in Table 1. Quartz, which is often used, is limited to about 500°F because of material twinning, a premature alpha to beta phase change. High piezoelectric strain constants are extremely important to provide adequate transducer output and small size. Accelerometers must be small and light to minimize their effect on the structure's motion. High bulk resistivity is also critical since the resistance of insulating materials decreases exponentially with temperature increase. A general rule is that resistance drops by a factor of ten for each 100°C increase. Thus with a temperature increase from 20°C (70°F) to 720°C (1330°F), the resistance would drop by a factor of 10,000,000. Bulk resistivity of typical insulation and piezoelectric materials is plotted versus temperature in Figure 2.

* PIEZITE® is a trade name for proprietary piezoelectric materials from Endevco.

PIEZITE® P-15 piezoelectric material which has recently been developed provides these desirable characteristics. Curie temperature is above 1750°F (950°C). Charge sensitivity varies little from room temperature to at least 1500°F (820°C). The strain constant (charge sensitivity) is about equivalent to those of materials now used in accelerometers at lower temperatures. Finally, bulk resistivity at 1500°F (820°C) is 10^4 ohm-cm. During the research phase of this program and before the full development of P-15, a thorough search of possible piezoelectric materials was completed, and four piezoelectric materials were experimentally evaluated.

VIBRATION SYSTEM DESIGN

With the above piezoelectric material characteristics in mind, the accelerometer and signal conditioning system design can be evaluated. The low frequency response of a voltage amplifier is a function of the time constant of the circuit at the amplifier input. For high temperature accelerometer systems this would be the RC product of the accelerometer shunted by any cabling. Frequency response of -5% at 10 Hz requires RC to equal .05 ohm-farad. If resistivity is 10^4 ohm-cm the relative dielectric constant would need to be greater than 10^7 to provide this response. Such dielectric is 10^4 times greater than that for our lead zirconate titanate material and is unreasonably large.

Within design limits the low frequency response of a charge amplifier is controlled by the time constant of the conditioner alone. Thus lower input resistance is acceptable. The typical laboratory charge amplifier will function within its specification with input resistances as low as 10-50 megohms. At temperatures above about 750°F this resistance limit has proven to be too high when other accelerometer design requirements are considered. As a result, a new charge amplifier circuit has been developed which accepts input resistances to as low as 10,000 ohms. Performance of this circuit is equivalent to that of our standard laboratory charge amplifiers with input resistances as low as 100,000 ohms. With lower resistance the amplifier noise begins to increase with significant 1/f contribution and response at low frequency (3-10 Hz) decays. Noise is within 1 pC rms and response within -5% at 10 Hz with 10,000 ohms input. In short, this charge amplification technique provides the needed system concept.

One other system consideration significant to the accelerometer design is the method employed to eliminate noise from electrostatic potentials and ground currents. If this is ignored the odds are great that noise will interfere with the measurement signal in most applications. Use of accelerometer insulating studs is common at lower temperatures. Several other new and interesting approaches have recently evolved and are in use with higher temperature accelerometers.

One of these is the accelerometer-amplifier combination used for the engine vibration monitoring system on the Boeing 747 aircraft. This system uses two Endevco Model 6233 Accelerometers on each engine. This accelerometer operates continuously to 900°F. The piezoelectric element is electrically isolated from the accelerometer case and the two signal leads are fed through shielded twisted pair cabling to a differential charge amplifier. The cable lengths are about 150 feet, and the wires are fed through multipin connectors. Effects of frame voltage and stray electromagnetic fields are minimized by the use of this differential circuit technique. Figure 3 shows a simplified block diagram of this measurement system.

Another system approach has been designed for use with the 1400°F Model 2285 Accelerometer. The piezoelectric element in this accelerometer is grounded to the case which provides an electrostatic shield. The signal lead is fed through single wire shielded cable (Coax). The signal conditioner contains an isolation amplifier which eliminates the ground loop which normally exists between the input and output, thus providing the noise rejection. This system permits simpler cabling and connectors, and the elimination of insulation from within the accelerometer. Because of the lower resistivities of insulators at high temperature and because of the need to retain high insulation resistance, the size of those insulators would be significant. Their elimination permits a smaller accelerometer design with better overall performance. Figure 4 shows a block diagram of this system approach. In most applications for high temperature accelerometers this approach is likely the optimum choice, and as such forms the system concept for the accelerometer discussed below.

ACCELEROMETER DESIGN

After the mechanical and electrical interface requirements were established, and the proper piezoelectric material was developed, the accelerometer was designed. Although an accelerometer often appears simple, the development of such an item is a specialized endeavor. Requirements are multifold, and accuracy needs are stringent. In general, the development of high temperature accelerometers is similar to that of low temperature accelerometers with a few noteworthy exceptions.

As outlined in the previous section, the accelerometer resistance is one of the controlling factors. Resistance of a piezoelectric or insulator disc is equal to the bulk resistivity times the disc thickness and divided by the disc area. For a resistivity of 10^4 ohm-cm at 1400°F and an element resistance requirement of 10 kohm, the size would be about .1 inch thick by .25 inch diameter (assuming shape is a disc). If the temperature limit is only 1200°F the size could decrease, for example, to .01 inch thick. If the resistivity however is only 10^3 ohm-cm at 1400°F, the size would increase resulting in crystal thickness of 1 inch. From this one can see that the resistivity in combination with the inherent sensitivity of the piezoelectric material controls the size of the accelerometer (sensitivity is the piezoelectric strain constant multiplied by the weight of the internal mass element).

In addition to the above dimensional design, the accelerometer accuracy factors such as resonance, strain sensitivity, and transverse sensitivity required design solution. The temperature span of 1500°F (minimum range to maximum range) requires analysis and experimentation to maintain proper stress levels and sensitivity stability. A 2×10^{-6} in/in/°F expansion unbalance results in about .001 inch dimensional change within the accelerometer, or possible strains of up to 4000 microstrains. Typical high temperature materials and ceramics have expansion differences of this magnitude. The metals were naturally chosen for their high temperature characteristics. We are usually using inconel for parts with the use of precious metals for electrical conduction paths within the unit. Both welding and brazing are employed for metal joining.

The principal accelerometer resulting from this development is pictured in Figure 1. Both the case and the integral cable sheath are inconel with the cable attached by a braze alloy. Other similar accelerometers with lower temperature ranges have also been designed in order to provide higher sensitivity in the same space and still maintain the 10,000 ohm minimum resistance at its maximum temperature range. Since the cable is fixed to the unit, a single mounting bolt hole is provided. This enables the accelerometer to be mounted without chance of cable misalignment. Resulting size and weight is within .5 inch x .5 inch x .9 inch and 18 grams; sensitivity is 2.5 pC/g, and maximum operating temperature is 1400°F.

CABLING DESIGN

The cabling shown attached to the 2285 Accelerometer is sheathed in a metal tube; we call it hardline. This is fabricated by swaging or extruding tubing over refractory oxide insulation, thus crushing the insulation and capturing the internal parts, preventing relative motion. Triboelectric noise is maintained low. Our tests have shown it to be about the same level as that from Endevco 3090A Cable (a TFE cable used up to 500°F). The cable bend radii may be as small as two times the diameter which permits its use in small, restricted installations. Although the cable on the Model 2285 is coaxial with a diameter of .093 inch, various configurations and sizes have been produced. See Figure 5. Since the wiring is totally confined, the historic problems of contamination with environmental exposure and insulation deterioration with temperature and vibration cycling have been reduced. Special manufacturing precautions must be taken since the oxide insulation is hygroscopic. Problems from this are minimized by treating the ends with proprietary fluids such as Conoseal (product of Continental Sensing), or Aeroseal (product of American Standard), and by high temperature baking just prior to sealing the assembly.

Since the cable does not contain organic insulation, such as Teflon in 500°F cabling, the material has little internal damping. Because of this, additional care must be taken with the cable dressing and clamping. Unsupported lengths can be excited into resonance if sufficient energy exists at the critical frequencies (it should be pointed out, however, that sustained resonance excitation is unlikely). The fundamental resonant frequency of a supported cable length can be expressed as follows:

$$\text{Fundamental Resonant Frequency} = \frac{\text{constant X cable dia.}}{\text{unsupported length}^2}$$

The constant lumps material characteristics and beam constraints. High resonance frequency also results in a higher acceleration input capability for equivalent fatigue life. Amplification factors at resonance have been shown by our tests to vary from about 4 to 20. Clamping at short distance is therefore advisable. In addition, tests have shown clamping with devices which distribute the load (reduce the stress concentration) greatly reduces chance of fatigue. We have used, with good success, clamps with TFE or silicone rubber liners to 550°F and clamps with woven metal liners to higher temperatures.

The housing for the 2285 Accelerometer does not have an electrical connector in order to keep the unit small and light, and to also eliminate problems inherent in present day high temperature connectors. Oxidation of contact systems, galling of parts, and the loss of any environmental seal, limit the utility of high temperature connectors. The coaxial connector at the end of the cable is rated to 900°F where these problems are not so severe. The connector system is fabricated of inconel. Thread lubricants, such as Antionic Compound, Kern Chemical KC24 and Fel-Pro C5-A, Felt Products Manufacturing Company, Skokie, Illinois, have been successfully used on the threaded shell.

TEST RESULTS

Considerable test data has been accumulated on accelerometers of the design reported above. Three different versions have been produced, the Model 6236M3-6 and 6237M1, both rated to 1200°F and Model 2285 rated to 1400°F. Although the data documented here is primarily that for the 2285, others have been included where applicable. Basic accelerometer characteristics have been tested and are shown in Table 2. Test procedures are in accordance with ISA-RP37.2, Guide for Specification and Test for Piezoelectric Acceleration Transducers for Aerospace Testing; therefore, further discussion on the procedures does not seem necessary. However, several of the high temperature tests are special and those procedures and the test data are presented below.

A. Resistance

High temperature accelerometer resistance has been measured with the accelerometers placed

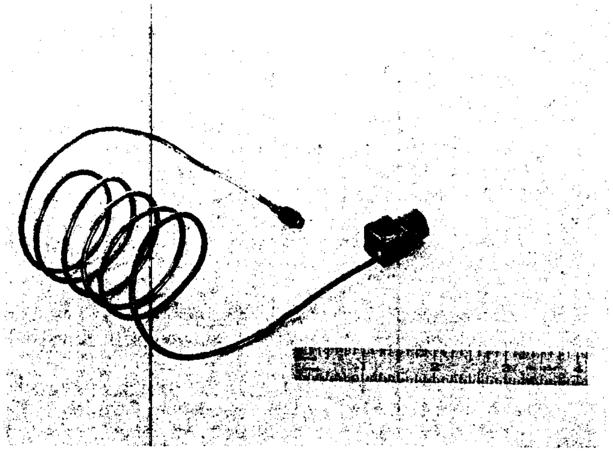

Figure 1. Endevco 1400°F Accelerometer, Model 2285

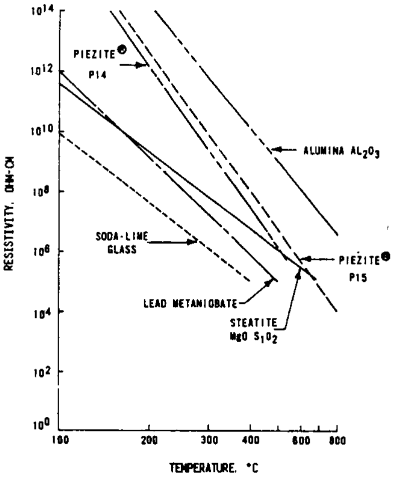

Figure 2. Resistivity versus Temperature of Typical Insulation and Piezoelectric Materials

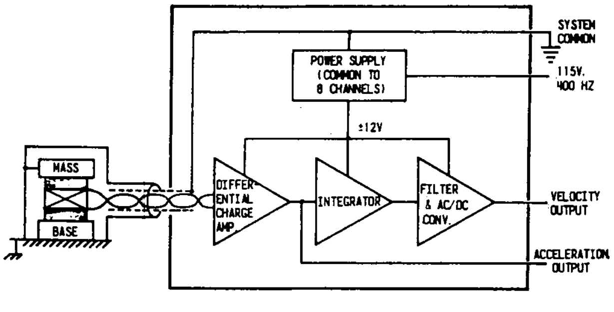

Figure 3. Simplified Block Diagram of Accelerometer-Signal Conditioner System used for EVM on Boeing 747 Aircraft

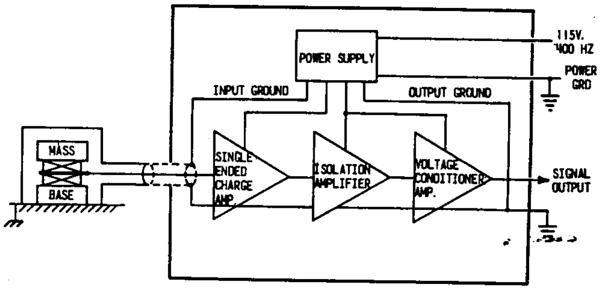

Figure 4. Simplified Block Diagram of Vibration System With Grounded Accelerometer and Noise Isolation Amplifier

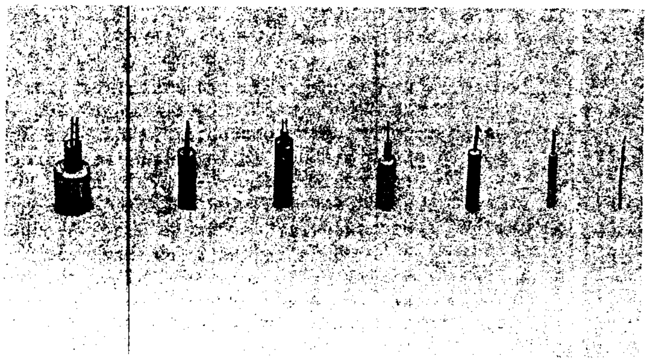

Figure 5. Metal Sheathed Cables With Outside Diameters if 0.015 to 0.25 in. and With Various Internal Configurations

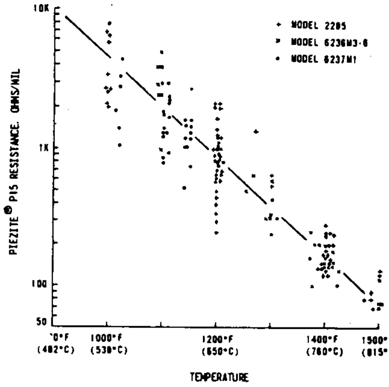

Figure 6. Resistance versus Temperature for Various Endevco High Temperature Accelerometers

in a natural convection electric furnace. Thirty minutes is allowed for thermal stabilization. We have found that if the chamber temperature profile is not well understood, a thermocouple should be placed on the accelerometer. Temperature gradients in these ovens at high temperature can vary over 100°F. We have also found that resistance measurements with DC voltages of over about 10 volts at temperatures exceeding 400°C results in erroneous data. This is thought to be caused by changes in the conduction mechanism of the insulation materials. At high voltage the resistance increases with applied time with polarity in one direction, and resistance drops with the polarity in the other direction. Valid measurements have been made with low voltage using a Hewlett-Packard Model 412A Ohmmeter. Resistance of three accelerometer models is plotted in Figure 6. Since the crystal thickness varied for these units, the plot shows resistance divided by element thickness.

B. Acceleration Sensitivity at High Temperature

Temperature response at Endevco can be measured with the accelerometer placed in forced convection ovens to temperatures of 1000°F. At temperatures above that a test console using an electric furnace is employed. These can be seen by Figures 7 and 8. Both are comparison systems with the standard accelerometer outside the temperature chamber and the test accelerometer in the chamber; Figure 9 shows a block diagram for both test consoles. Test data for 32 accelerometers are all plotted on Figure 10.

C. Frequency Response and Resonance Characteristics

Response of the 2285 Accelerometer to Sinusoidal vibration above 500 Hz is tested on the Ling/Endevco System 50. Calibration below 1500 Hz is performed on an air bearing vibration exciter. The air bearing shaker is used to keep the motion rectilinear in the presence of forces due to resonances of the hardline cable. Other shakers could also be used for low frequency vibration calibration, assuming they have a massive moving element and a low transverse motion characteristic.

Figure 11 shows a typical plot of the frequency response and resonant frequency characteristics for the 2285 Accelerometer. Both plots are comparison calibrations using a standard accelerometer in the moving element of each shaker. The accelerometer does have two resonances; the lower is caused by the case structure and the higher by the internal mechanism.

Resonant characteristics at high temperature are tested by shock excitation techniques. An accelerometer is placed on one end of a Hopkinson Shock Bar; the other end is impacted by a pendulum. This test has shown no measurable difference in the resonance from laboratory temperature to 1400°F. This same equipment is also used to check the shock environmental limits over the temperature range of the accelerometer.

D. Life

In addition to the environmental shock testing mentioned above, tests are also being conducted to establish output stability and service life under conditions of high temperature vibration and temperature cycling. Time alone at high temperatures is achieved by storage of the accelerometers in a furnace. Model 6236M3-6 Accelerometers have been exposed to 1000 hours at an average temperature of 1200°F with sensitivity shifts of less than 5%. A total of 15,000 hours has been accumulated on 58 samples of various models. Sensitivity changes were encountered on early prototypes because of creep and chemical changes. These factors have been eliminated in the final design.

Temperature and vibration are applied simultaneously with the test equipment pictured in Figure 12. This is an MB C-10 Vibration Excitor System vibrating an inconel structure surrounded by electric furnaces. The system does vibrate accelerometers and cables combined. Over 4,000 hours have been accumulated on this equipment for this program. Considerable work has been done to establish the fatigue strength of the cable material alone.

Hardline cable with 304L sheath, which is used extensively on a 900°F system, has been shown to have about 27 k psi fatigue strength up to 900°F (fatigue strength is defined as no failure for over 10^7 stress reversals). Tests with the inconel sheath at 1400°F are still in process as are tests with the 2285 Accelerometer. Test results on cable terminations are briefly discussed in the previous Cable Design Section. Temperature and vibration cycling completed to date has shown no degradation of performance of the accelerometers, including several 2285 Accelerometers which have been vibrated continuously for over sixteen hours at 500 pk g, 2000 Hz.

CONCLUSIONS

Small piezoelectric accelerometers for vibration measurement at temperatures to 1400°F (760°C) have been developed. Because the electrical resistance of piezoelectric materials decreases with temperature, and is as low as 10,000 ohms in these accelerometers at their maximum rated temperature, special electronics are required for proper operation. To provide environmental protection for the cabling, metal sheathed cable is used. To reject noise from ground loops, ground isolation has been included in the remote signal conditioner.

The results from this development program are only briefly discussed in this report; individual

TABLE 1

Material	Curie Temperature
Barium Titanate	240°F
Lead Zirconate-Lead Titanate	Typically 700°F
Lead Metaniobate	1050°F
Endevco PIEZITE® P-10	930°F
Endevco PIEZITE® P-14	1250°F
Quartz	(Phase change) 1070°F

TABLE 2 - TEST DATA

Test		Results		
		Model 2285-36	Model 6236M3-6	Model 6237M1
Sensitivity, pC/g	No. units tested	20	15	12
	Average	2.50	5.0	5.0
	Maximum	2.62	5.2	5.3
	Minimum	2.20	4.9	4.7
Transverse Sensitivity ratio, percent	No. units tested	20	15	12
	Average	1.3	2.0	2.5
	Maximum	3.0	3.0	4.8
	Minimum	0.5	1.5	1.0
Amplitude Linearity, percent increase up to 1000 g	No. units tested	15	1	2
	Average	<2	2	2
Base Strain Sensitivity, Equivalent g at 250 microstrains	No. units tested	9	-	3
	Average	1.4	-	2.6
	Maximum	2.4	-	3.0
	Minimum	0.9	-	1.7
Capacitance, pF with 3 ft. cable	No. units tested	15	-	-
	Average	345		
	Maximum	400		
	Minimum	330		
Resonance Frequency, Hz *Two resonances present	No. units tested	9*	15*	1*
	Average	12 k, 33 k	14 k, 25 k	14 k, 33 k
	Maximum	14 k, 37 k	15 k, 25 k	
	Minimum	10 k, 26 k	13 k, 20 k	
Weight, grams	Without cable	18	45	17
	With 3 ft. cable	45	85	44
Resistance at temperature, ohms	No. units tested	20	15	8
	Average	14 k (1400°F)	50 k (1100°F)	14 k (1200°F)
	Maximum	30 k (1400°F)	100 k (1100°F)	20 k (1200°F)
	Minimum	10 k (1400°F)	20 k (1100°F)	9 k (1200°F)
	Average	100 k (1200°F)	100 k (1000°F)	100 k (1000°F)

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