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Vibration Instrumentation for Nuclear Reactors

Technical Paper 258

By R. L. Thomas

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VIBRATION INSTRUMENTATION FOR NUCLEAR REACTORS

R. L. Thomas
Endevco, Division of Becton, Dickinson and Company

INTRODUCTION

Many of the malfunctions to which reactors are subject first manifest themselves by changes in vibration levels. The reactor, however, presents one of the most hostile environments in which the sensors could ever by expected to operate. In addition, the consequences of failure, and the difficulty or impossibility of repair and maintenance place an extremely high priority on reliability. Granted, this extreme situation does not apply to all vibration measurements. We could very well consider two categories of measurement. For design verification and modeling tests, maximum emphasis would likely be on broad dynamic range and minimum disturbance of the basic mechanical model, while vibration monitoring on operating reactors might sacrifice some of the finer points as a measurement to gain maximum reliability. If one device could perform both functions, however, it would do much for the confidence in correlation of data.

APPLICABLE TECHNIQUES

This paper will not attempt to treat in depth all possible sensing mechanisms that might be employed in making vibration measurements on nuclear reactors. Rather, it will cover most techniques only in sufficient detail to justify a more thorough look at the best prospects. I will apply four criteria in evaluation of the various prospective techniques.

1. The ability to withstand the expected environment including ambient temperature, radiation and adverse surrounding media such as sodium, water, pressure, etc.
2. Signal conditioning requirements and ability to achieve an acceptable signal-to-noise ratio.
3. Life expectancy and aging phenomena.
4. The efficiency of transformation.[1] This might be looked at as the energy removed from the system under test by the presence of the sensor, or as the product of sensitivity (more appropriately, the inverse of noise floor) and frequency response squared, sometimes referred to as the figure of merit.

It is at least theoretically possible to obtain all the information about the vibration of a structure by measurement of relative displacement or any of its time derivities, since we can integrate or differentiate electronically during data reduction to obtain the desired parameter. In practice, however, we find that integration is far easier to perform than differentiation because of background noise. The most frequently employed forms are acceleration, being proportional to the driving force, and velocity, being proportional to mechanical impedance.

Displacement Sensors

Three displacement measurement techniques in current practice are potentially capable of meeting the temperature, radiation and corrosive media requirements of reactor instrumentation although present standard units are generally limited to the vicinity of 260°C and are not recommended for exposure to radiation. Variable reluctance units sense the proximity of a ferromagnetic structure as a change in the self inductance of a coil. A variation of this technique for non-ferromagnetic materials operates on eddy currents induced in the adjacent material to change reactance as a function of displacement.

Variable capacitance sensors can be used where the media between the reference place and the monitored surface is non-conductive and where independent electrical contact between the two surfaces is possible.

Linear differential transformers (LVDT) employ a moving ferromagnetic mass to vary the coupling between a primary and two differentially connected secondaries as a function of displacement.

All three sensors are used with an externally supplied excitation carrier to provide a frequency or amplitude modulated signal as a function of relative displacement. In either case, the noise rejection is quite good. Adequate sensitivity with the proximity devices requires fairly high frequency carriers, which, in turn make the systems very cable sensitive. This usually prohibits replacement of interconnecting cables without recalibration of the system.

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ENDEVCO DYNAMIC INSTRUMENT DIVISION
801 S. ARROYO PARKWAY · PASADENA, CALIF. 91109 · PHONE (213) 795-0271
AKRON, OHIO · BOSTON, MASSACHUSETTS · CHICAGO, ILLINOIS · PALO ALTO, CALIFORNIA · DETROIT, MICHIGAN · PHILADELPHIA, PENNSYLVANIA · WASHINGTON, D.C. · WEST PALM BEACH, FLORIDA
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From the standpoint of life or aging characteristics, all make a strong showing. Only the LVDT has any moving parts and even there, no moving electrical contact is involved. The common drawback of all displacement measurement techniques for vibration measurements is the small magnitude of displacement involved in meaningful vibration. For example, a vibration magnitude of 1 g at 1 kHz involves a peak to peak displacement of 0.5×10^{-6} meter. This is probably an order of magnitude below the noise floor of the best available system. Displacement signals thus derived are only marginally useful and electronic differentiation is out of the question. Displacement sensors therefore are not normally considered for reactor vibration measurments.

Velocity Sensors

Two velocity measurement techniques are in common use which employ a cylindrical magnet moving inside a solenoidal coil to measure velocity. In one case the magnet takes the form of a probe which is attached to a moving member while the coil is attached to a reference surface. The output signal produced is proportional to the relative velocity between the two surfaces. This technique is only useful for relatively large displacements and can be ruled out for vibration measurements for much the same reasons noted for LVDT's.

In the second technique, the moving magnet is spring suspended within the solenoidal coil. The position of the magnet within the coil is thus a function of the acceleration of the coil and since the voltage induced in the coil is a function of the rate of change of position within the coil, the output signal for frequencies below the resonance of the spring-mass system is proportional to jerk, the time rate of change of acceleration. In practice, these sensors are designed for a resonance frequency below the lowest frequency of interest. The spring-mass system being damped second order, the output above resonance is asymptotic to a rate of 12 dB/octave. This being equivalent to double integrating with respect to time, the output signal in its useful frequency range is directly proportional to inertially referenced velocity.

Commercially available units of the latter type are rated for operation at temperatures to 400°C and presumably could be constructed of materials so that they would not be adversely effected by moderate levels of nuclear radiation. These sensors do tend to have a relatively narrow useful acceleration range, often being limited on the lower end to 1 g due to friction effects and at 50 to 100 g's on the upper end due to structural limitations. They also have a limited life due to wear of bearing surfaces which would probably rule out their use as operational monitors. The output signal is a clear, low impedance voltage that is linear with velocity. Electronic differentiation to obtain acceleration is not recommended however, for the reasons previously mentioned.

Acceleration Sensors

A wide variety of devices are currently being marketed which fall into the general category of acceleration sensors. Keeping in mind the purpose of this paper in describing vibration instrumentation for nuclear reactors, the list can be shortened to three techniques for serious study. These are: strain gage accelerometers, piezoresistive accelerometers, and piezoelectric accelerometers. I have specifically excluded any device which requires electronic circuitry integral to the device as being unsuitable for the hostile environment of the reactor and of significantly lower reliability due to the larger number of active components exposed to the environment. Such devices could well find use external to the reactor however, such as the use of servo accelerometers for seismic studies. Also excluded as unsuitable are potentiometric and variable reluctance types for the reasons noted earlier.

Strain Gage Accelerometers

There really are two types of devices falling under this general description. They are referred to as bonded strain gage transducers and unbonded strain gage transducers. In the bonded type units, a conventional wire of coil gage is bonded to a spring mass system and serves to monitor the deflection of the inertial mass as the transducer is subjected to acceleration forces. This type is generally the less efficient of the two but has a potential advantage of being somewhat more rugged and operable to higher temperatures.

Unbonded units employ strain gage wire wound on a support mechanism which in turn directly strains the wires as a function of the forces on the inertial mass. In essence, the strain gage wires become the major contributor to the spring constant of the spring-mass system. These devices tend to have a significantly higher efficiency and have a higher figure of merit. The drawback of this technique is greater fragility and they must be damped to withstand shock and handling loads. Most types use fluid damping but higher performance units employ air damping which is more constant over the temperature range and useable to wider temperature extremes.

Currently available units are useable to a maximum temperature of approximately 120°C. The potential for higher temperature operation exists through the use of weldable strain gages which are a special version of the bonded gages previously mentioned. Within the useable temperature range, the thermal effects are basically a change in sensitivity as a function of temperature, and a change in static output with temperature. Both of these factors can be passively compensated to a considerable degree by close matching of individual gages and addition of compensating resistors in the bridge circuit. Static output is not really important in vibration measurements and can be effectively disregarded by capacitively coupling the transducer output to its signal conditioning amplifier.

There should be no direct effect from radiation except for possible degradation of cementing materials and insulation. The latter can be quite significant however, since a decreased resistance between signal leads and shield can seriously degrade system noise rejection.

Signal conditioning is straight forward with no special problems. Rather high amplification factors in the conditioning amplifiers are required, however, and the excitation power supply must have very good isolation from the power line. Typical signal levels from strain gage transducers are on the order of 20 to 40 millivolts full scale. This makes it very important that you select a transducer having a full scale acceleration range as near to your expected maximum as possible, to retain an acceptable signal-to-noise ratio.

In relative terms, the efficiency tends to be rather low for strain gage accelerometers, being three or more times more massive and having a figure of merit at least two orders of magnitude lower than either piezoresistive or piezoelectric types.

Piezoresistive Accelerometers

Piezoresistive accelerometers might well have been considered as a special case of the strain gage category except that their unique features seemed to warrant separate treatment. The sensing element generically is a silicon semiconductor strain gage which will have a gage factor up to 100 times that of metalic gages. As in the unbonded strain gage type, the more efficient designs are generally constructed such that the semiconductor element is the major factor in the system spring constant (see Figure 1). Unlike the strain gage units, however, most piezoresistive units have a high enough natural frequency that damping is not required for environmental survivability. Some low g, low frequency units do employ viscous damping to extend their useable frequency range.

Useful maximum temperature for commercially available units is presently 120°C although the technology does exist to extend the range to 260°C. Their behavior in the useful temperature range is much the same as for the strain gage types except they tend to be somewhat harder to compensate due to the non-linear nature of their unstrained resistance versus temperature curve.

Piezoresistive accelerometers appear to be capable of withstanding considerable radiation exposure. Battelle Memorial Institute reports[3] exposure to 6×10^{15} n/cm^2 and 3×10^{10} ergs/gm (C) gamma with satisfactory dynamic performance though undergoing significant changes in unstrained resistance. In another test,[3] satisfactory operation was observed after 5×10^{15} n/cm^2 with negligible change in unstrained resistance. In a similar application,[4] semiconductor strain gage pressure transducers were exposed to 10^{15} n/cm^2 and 10^8 erg/gm (C) with less than 1% change in sensitivity.

The differences in observed susceptibility can be accounted for by the level of dopant used in the silicon. Heavily doped gages have lower resistivity and lower gage factors but are far more resistant to radiation effects. The failure mechanism in radiation damage to piezoresistive devices involves lattice changes in the crystaline structure. It is logical to expect then that any major change in unstrained resistance would also be accompanied by a corresponding change in the piezoresistive constants leaving the dynamic data somewhat suspect as well.

The real forte of piezoresistive accelerometers, however, is their transient handling ability. At very high dose rates such as would be encountered in nuclear weapon detonation, the accompanying electromagnetic pulse (EMP) would effectively block most measurement systems, although the total integrated flux could be relatively small. The combination of a high level signal, low source impedance, potentially good shielding and magnetic field rejection enable a measurement during the period of the transient. In devices designed with this application in mind (see Figure II), all materials used in their construction are selected for low cross section to minimize heating and are further selected to minimize differences in linear coefficients of expansion between the gages and the inertial mass thus assuring minimum perturbation of the primary data.

Signal conditioning of piezoresistive devices is straightforward with much the same considerations as for strain gages except that much lower amplification factors are required. The input impedance of the conditioning amplifiers should be high compared with the gage resistance to avoid source loading, due to their relatively high rate of change of unstrained resistance with temperature. As mentioned for strain gages, the output can be capacitively coupled to the amplifier to eliminate input offset voltage. DC coupling could prove beneficial however, for a check on static resistance if exposure to ratiation is involved.

Piezoresistive accelerometers can be considered to have unlimited life expectancy for dynamic data. Their efficiency is considerably higher than strain gage units although somewhat less than the piezoelectric types. They can also be made quite small if mass loading is a problem and their capability for steady state response is valuable when doing low frequency modal studies on light structures.

Piezoelectric Accelerometers

The sensing element in a piezoelectric transducer is a crystaline structure which causes an electrical charge to exist on its surfaces when opposing forces are applied. In an accelerometer, the forces are provided by a mounting base and an inertial mass. The two most common design approaches[5] are shown in Figure III. Both techniques shown measure vibration in the direction of their axis of symmetry. In the compression mode accelerometer design, the crystal is placed in preload by the central bolt securing the mass and crystal to the base. When the unit is accelerated upward, the inertial mass exerts a reaction force downward increasing the compressive force on the crystal. In the negative direction the mass acts to partially relax the preload resulting in a charge of the opposite polarity. The electrical charge generated on the crystal is given by:

$$Q = d\sigma A$$

where: d = piezoelectric constant of the crystal

A = stressed area of the crystal

σ = stress on the crystal.

Shear mode accelerometer designs operate in much the same way except that the inertial mass acts to create a shear stress in the crystal instead of a compressive stress, and no preload is necessary since the reaction force of the mass is coupled to the crystal in either direction.

The piezoelectric constants referred to are a characteristic of the basic material used and are a function of the direction of stress and direction of measurement of the charge. For compression designs the d_{33} constant is governing. For shear designs the d_{15} constant is used.

Piezoelectric Material Considerations

A great number of crystaline materials exhibit piezoelectric properties although not all have a combination of characteristics that would make them desirable for accelerometer use. Those listed in Table 1 by no means cover the field, but are representative of some of the more common types. Given in the table are: relative dielectric constant compared with free space (e/e_o), the piezoelectric constant of interest in compression mode (d_{33}), the piezoelectric constant of interest in shear mode (d_{15}), and Curie Temperature (T_C). Curie temperature is that point above which the meterial no longer exhibits piezoelectric characteristics. Maximum useful temperature is obviously limited by Curie temperature but for transducer use, the practical limit is considerably lower in most cases due to resistivity decrease with temperature and by the shape of the sensitivity versus temperature curve.

Several different materials of the same generic type (lead zirconate titanate) are listed to illustrate the effect of small quantities of other elements in the material. These materials (called dopants) are added by the manufacturer to alter the basic crystal properties for optimizing one particular constant for a particular use. Meaningful discussion of characteristics then must be in terms of a given manufacturer's product rather than simple generic terms.

Secondary Effects

Another factor not given in the table, but nonetheless of critical importance, is bulk resistivity and resistivity change with temperature. The reason for not listing it is that resistivity is highly variable from manufacturer to manufacturer and from lot to lot for most ceramic materials. Even smaller amounts of foreign elements than are used to alter the crystal constants can have large effects on resistivity. Only in high purity monocrystaline materials is resistivity predictable enough to specify its actual magnitude and temperature variation. The customary practice therefore is to specify a minimum shunt resistance for a finished transducer at its maximum operating temperature.

Specific transducer designs are a compromise of many factors of which maximum operating temperature is one, albiet an important one. Devices are currently available for operation at 760°C although the benefits in increased sensitivity and lower noise make a lower maximum temperature rating desirable when very high temperature limits are not required. Behavior with temperature in the rated range of a piezoelectric accelerometer is a function of ambient temperature and of temperature flux. The sensitivity versus temperature curves of these materials are not linear functions and practical designs must balance the desire for a maximum temperature with a reasonably flat temperature curve.

Pyroelectricity, An Important Consideration

When temperature gradients exist across the transducer another spurious signal source must be considered. This effect is referred to a pyroelectric output and is dependent upon the types of piezoelectric material used as well as the design of the accelerometer.[6]

There are three types of pyroelectric output possible: primary, secondary and tertiary. Primary pyroelectric output is the charge produced by a uniform temperature change throughout the piezoelectric material. Secondary pyroelectric output is the charge generated due to the dimensional change in the ceramic caused by uniform heating. Compression design accelerometers using ceramics exhibit both primary and secondary pyroelectric outputs. Shear designs exhibit only secondary outputs during uniform heating because the electrodes are applied to the radial surfaces parallel to the direction of polarization. Finally, tertiary pyroelectric outputs are produced as a result of dimensional changes in the crystal when non-uniform heating occurs. All piezoelectric accelerometers exhibit tertiary outputs including those using monocrystaline sensing elements.

Since pyroelectric outputs of all types are a function of the temperature gradient across the device, it becomes a function of the thermal time constant of the transducer as well. Through proper design, this phenomenon can be kept slow enough so that it is easily disregarded by high pass filtering of the accelerometer output at a frequency below the normal data band. Only for very large transients with very low frequency data need this be a real problem.

Radiation Effects

As might be expected, the effects of nuclear radiation also vary greatly with the type of piezoelectric material. Under long term exposure to moderate flux levels, the radiation effect, when present, exhibits itself as a decrease in sensitivity and occasionally as a decrease in shunt resistance.

At high rates involving substantial ionization, the deposited charge is inseparable from acceleration induced charge thereby masking data. For this reason, piezoelectric accelerometers are not normally used for monitoring nuclear weapons effects.

Battelle Memorial Institute[2] has tested piezoelectric accelerometers using quartz crystals to levels of 1.8×10^{16} n/cm^2 and 1.3×10^{11} ergs/gm (C) gamma with negligible difference in before and after radiation calibrations.

Lockheed Georgia Nuclear Laboratory[7] conducted tests on samples including quartz and some softer ceramics. In these tests, the accelerometers were excited dynamically and their outputs monitored during exposure. Most of the accelerometers continued to operate throughout exposure to 1.2×10^{15} n/cm^2 and 1.8×10^{5} ergs/gm (C) gamma although some indicated loss in sensitivity was noted. The indicated sensitivity loss as well as the malfunctions are rather inconclusive however, due to water intrusion in the peripheral electronics for these channels.

More recent testing by Aerojet Nuclear Systems[8] showed units employing Endevco Piezite® P14 and P15 elements to be within expected limits for calibration repeatibility after exposure to 2.5×10^{18} n/cm^2 and 4×10^{10} erg/gm (C) gamma. A lead zirconate titanate element transducer included for reference showed a sensitivity decrease of approximately 40%. Aerojet concluded that the apparent change in sensitivity is a function of Curie temperature for the piezoelectric material used.

The failure mechanism involved appears to be depolarization of the piezoelectric material. As would be expected, the "soft" ceramics such as Barium Titanate and Lead Zirconate Titanate tend to be most affected while the "harder" ceramics such as Piezite® P10, P14 and Lead Metaniobate show considerably less susceptibility. Monocrystaline materials such as Piezite® P15, Quartz and Lithium Niobate show no depolarization effects at the levels noted, as might be expected.

Signal Conditioning of Piezoelectric Transducers

Isolation, shielding and grounding are probably the most critical considerations in reactor instrumentation. High level noise is common and the opportunities for multiple grounding points, if one isn't careful, are manifold. It is recommended that all precautions possible be taken whether or not a problem is anticipated.

Triaxial hardline cable has proven to be very beneficial for its 100% shielding and for prevention of multiple grounding points of the signal return. When possible, the signal return lead from the transducer should be isolated from the case although adequate isolation can also be obtained using an isolated input charge amplifier, if transducer constraints do not allow internal isolation.

The use of a charge amplifier is a must for reactor instrumentation. Long lengths of cable and variations in cable length would make calibration problems untenable with a voltage system. For high temperature operation with the attendant low shunt resistance, a charge amplifier is necessary to preserve low frequency response. In a voltage system, the low frequency time constant is determined by the product of source capacitance (transducer plus cable) and shunt resistance. When the shunt resistance is in the giga ohm region, the low frequency cutoff can be held to a few Hertz, but with 10 k ohms shunt resistance, the time constant is so short that you get no low frequency data at all.

Special consideration must be given to the design of a charge amplifier to work with such low source resistances. Most laboratory charge amplifiers are rated for a minimum input shunt resistance of 10 megohms. This is entirely satisfactory for the majority of laboratory applications where the crystal material is operated well below its Curie temperature. It becomes a matter of concern however, when transducer designs begin to push the crystals upper limit of temperature capability. As a general rule, the bulk resistivity of insulators will decrease by a factor of ten for each 100°C increase.[9] A transducer with a comfortable leakage resistance of 1 GΩ at 260°C would show a decrease to 10 kΩ at 760°C. Not all designs will remain stable under those conditions and they tend to be somewhat noisier. The noise in such an amplifier is largely 1/f in nature and can be improved considerably by band limiting, if the very low frequency information is not necessary. The use of two terminal, in line, remote charge converters to reduce the noise effect of cable capacitance can likewise be quite beneficial.

Long Life and an Unexpected Dividend

Extremely long life can generally be expected from piezoelectric sensors. As a matter of fact, a mean time between failure rate in excess of 10^6 hours has been demonstrated under conditions of temperature cycling to 480°C in an aircraft engine monitoring application using Piezite® P14 ceramic. Piezoelectric accelerometers are also the most efficient vibration sensing means available. They have perhaps an order of magnitude higher figure of merit than the next highest technique (piezoresistive) and included in the capability are the lowest mass accelerometers available.

One of the prime attributes of piezoelectric accelerometers is a factor which hasn't been mentioned thus far; that is, dynamic range. Most transducers have a relatively narrow range of physical input over which they are useful, and the user will generally select a range that comes closest to his expected maximum input (plus a little margin for miscalculation). With piezoelectric transducers, the dynamic range (i.e., the region between the lowest level that can be discerned in the output signal and the maximum level the transducer is rated for) is many decades wide. Practical measurements are made to a resolution of 100 μg with an accelerometer rated to 1000 g in a rotating equipment monitoring application.

MECHANICAL CONSIDERATIONS

Operating temperature is certainly a very critical factor in selecting a vibration transducer, but size and mass can be equally important. If it doesn't fit, or if the presence of the transducer distorts the natural modes of the structure to the extent the data is invalid, it is of little value that it is capable of very high temperatures or has a very high sensitivity.

A recent study of vibration modes in prototype fuel rods illustrates the point. Size was an absolute criteria. It had to fit inside the tube. The accelerometer was also required to operate at 650°C to properly prototype the real system and acceleration had to be measured in two perpendicular axes each perpendicular to the axes of the fuel rod. The solution employed Piezite® P15 material in a bolted shear configuration to provide both sensors in a body 5.72 mm diameter by 30.5 mm long (see Figure IV). The sensitivity attained was 2 pC/g.

In a similar application, the combination of a somewhat lower maximum service temperature and a larger allowable size, enabled a sensitivity of 10 pC/g in a housing 9.5 mm diameter by 31.75 mm long while retaining the capability of prolonged operation in a nuclear environment. For the engineering studies in the same program, Piezite® P8 ceramic material was substituted for the Piezite® P15 material for a resultant sensitivity of 75 pC/g in the same housing. Maximum operating temperature for this biaxial unit is 315°C but the unit is not recommended for nuclear exposure.

An example of the isolated and shielded approach recommended is shown in Figure V. This triax cabled, biaxial accelerometer had the additional constraint of operating in a 2200 psi conductive media. The result, using Piezite® P8 ceramic material, is a sensitivity of 16 pC/g with a temperature limit of 315°C in a housing 12.7 mm diameter by 30.5 mm long. This unit provided the additional feature of weldable flanges on each end of its cylindrical housing for welding to the structure under test.

Perhaps the most severe environment that would be encountered in reactor vibration was the challenge for the device in Figure VI. This single axis accelerometer is designed for continuous operation at 650°C with intermittent operation to 760°C in liquid sodium, with nuclear exposure. The liquid sodium exposure imposes some unique problems. No brazing is permitted in the construction and particular attention must be given to surface finish.

The coaxial and triaxial cables shown in the above examples are extruded, solid wall stainless steel (or inconel) with a solid pack magnesium oxide or aluminum oxide dielectric. This cable has proven highly satisfactory for high temperature and nuclear radiation applications having excellent strength and low noise characteristics.

CONCLUSIONS

When compared with the other options available for reactor vibration measurements, piezoelectric accelerometers can be concluded to be, by far, the most suitable. A wide variety of configurations and sensor materials are available enabling specific transducer designs to be optimized for the most important parameter. To assure maximum flexibility in designing for critical parameters, the potential user should specify size, mass, frequency response and maximum service temperature as closely to the known actual requirement as possible to assure best compromise of design tradeoffs.

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TABLE 1

Properties of Typical Piezoelectric Materials

Material	e/e_o	d_{33} (pC/N)	d_{15} (pC/N)	Tc (°C)	Note
PZT2	450	152	440	370	Note 1
PZT5H	3400	593	741	190	Note 1
PZT8	1000	225	330	300	Note 1
HA-11	600	86	125	130	Note 2
HS-21	1150	148	225	120	Note 2
HDT-31	1300	280	360	330	Note 3
G-1500	1700	370	540	360	Note 3
G-2000	250	80	115	400	Note 4
P8	1500	260	460	370	Note 5
P10	170	17.5	22	480	Note 5
P14	150	18.0	22	675	Note 5
P15	84	6	68	1200	Note 5
ZnO	11	12.4	8.6	not ferroelectric	Low resistivity
BeO	7.6	.24	----	very high	expensive
SiO_2 (X cut quartz)	4.5	2.2 (d_{11})	.85 (d_{14})	570	Note 6
$LiGaO_2$	7.0	7.6	-6.1	not ferroelectric	Note 7
$LiNbO_3$	29	20.3	.9	1210	----
$LiTaO_3$	51	8	26	660	----
$PbNb_2O_6$	190	85	----	935	----
Tourmaline	7.1	1.8	3.7	not ferroelectric	Note 8

NOTE
1. Proprietary materials of Vernitron Ltd.,[10] basically lead zirconate titanate.
2. Proprietary material of Gulton Industries,[11] basically barium titanate.
3. Proprietary material of Gulton Industries,[11] basically lead zirconate titanate.
4. Proprietary material of Gulton Industries,[11] basically lead metaniobate.
5. Proprietary material of Endevco, not sold except as part of transducers.
6. T_c listed is not Curie temperature but point at which the material goes through a rather drastic phase change. Practical upper limit is set by a pressure sensitive phenomenon called twinning. Normally assumed maximum is 260°C.
7. Maximum service temperature is approximately 700°C.
8. Maximum service temperature is approximately 800°C.

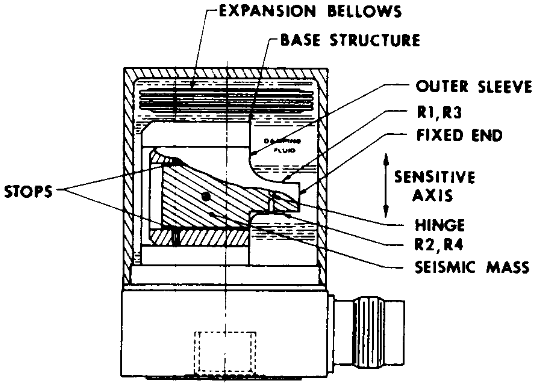


Figure I
Typical Construction of a
Piezoresistive Accelerometer

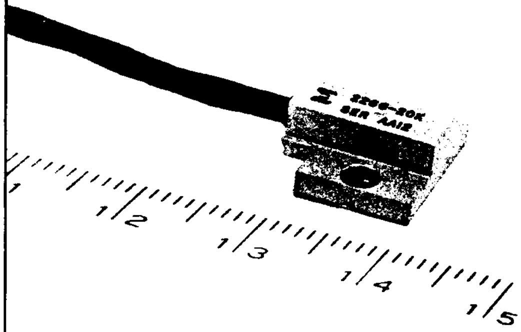
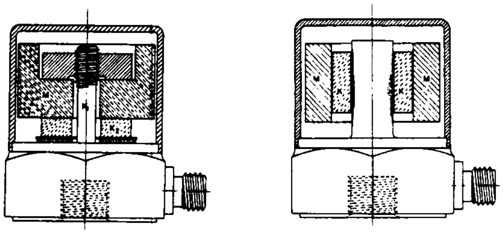


Figure II
A Piezoelectric Accelerometer for Shock
Measurements in a Nuclear Environment



Compression Design Shear Design

Figure III
Typical Piezoelectric
Accelerometer Construction

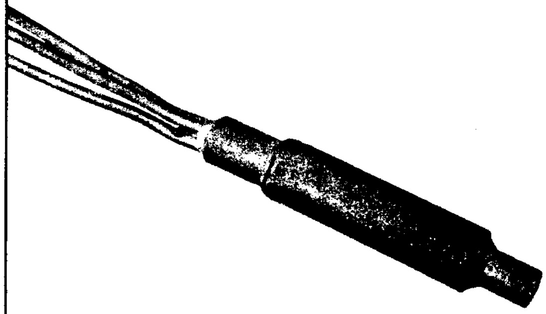


Figure IV
A Piezoelectric Accelerometer for Vibration
Testing of Nuclear Reactor Fuel Rods

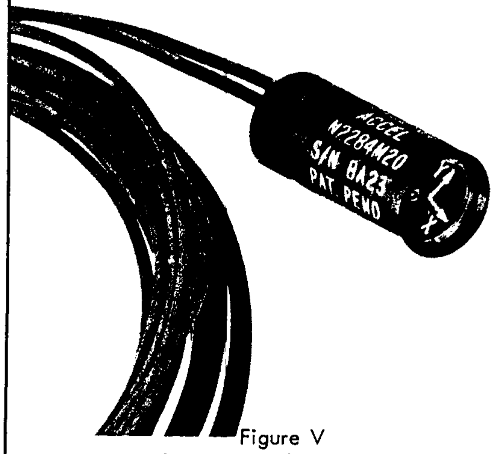


Figure V
A Piezoelectric Accelerometer for Vibration
Measurements in a High Pressure Environment

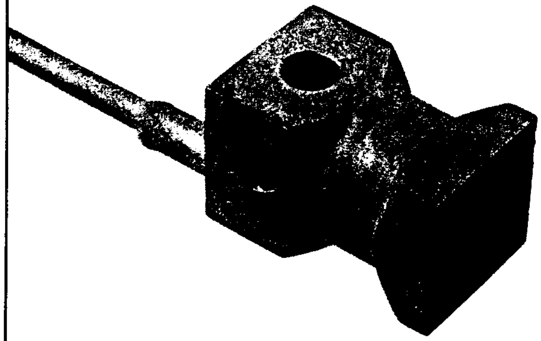


Figure VI
A Piezoelectric Accelerometer for Vibration
Measurements in a Sodium Cooled Reactor

ENDEVCO
AN AMPHENOL COMPANY

10869 NC Highway 903, Halifax, NC 27839 USA

endevco.com | sales@endevco.com | 866 363 3826