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INSTRUMENTATION FOR THE MEASUREMENT OF VIBRATION IN SEVERE ENVIRONMENTS SUCH AS NUCLEAR REACTORS

T.K. Bierney

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ABSTRACT

Measurement of vibration and pressure (including acoustic levels) in hostile environments such as those found in generation of nuclear power presents many special problems. Transducers may be required to operate in combined environments of high temperature, high pressure, high acoustic levels, high radiation exposure and a corrosive atmosphere. These hostile environments can present a challenge to the transducer designer in terms of materials to be used and the mounting of the transducers. The challenge extends further as the transduced signal must be transmitted to monitoring equipment outside the hostile environment.

The signal conditioning of transducers used at high temperature also requires careful design to obtain useful data. For example, conventional charge amplifiers may be unusable with transducers at high temperature due to the sensing element of the transducer undergoing severe changes in its characteristics.

This paper will discuss the types of vibration transducer for a nuclear reactor environment, the design of suitable piezoelectric transducers and the signal transmission and conditioning.

INTRODUCTION

Measurement of vibration in severe environments, as found in nuclear power- generation, presents special problems. Each type of reactor presents its own significant environmental requirements. The advanced gas reactor (AGR) has a relatively low-temperature and pressure environment, but often creates high intensity sound. The pressurized water reactor (PWR) presents a relatively low temperature and noise intensity, but high-pressure environment. The high-temperature gas reactor (HTGR) does not appear to be receiving much research effort at this moment. The fast-breeder reactor (FBR) appears to be the reactor of the future; it presents many new problems regarding measurement at high temperature and material compatibility due to the sodium environment.

The reactor presents one of the most hostile environments in which sensors could ever be expected to operate. The consequences of failure of instrumentation can make it difficult or impossible to repair and maintain equipment. This places an extremely high priority on reliability. Many types of transducers, predominantly accelerometers, have been built for companies in the nuclear industry and have proved most successful. Several devices are available as stock items and will now be discussed in more detail.

VIBRATION SENSORS

Vibration may be measured using several different types of sensor. Some utilize acceleration as the measured quantity; others use velocity or displacement. The selection among these depends on such factors as the required frequency response, necessary physical characteristics, and suitability to the ambient environment.

Displacement Sensors

These types of sensor are usually used in conjunction with an externally supplied excitation carrier. To achieve adequate sensitivity very high-frequency carriers are employed, which tend to make the system very cable-sensitive. This usually prohibits replacement of interconnecting cables without recalibration of the system. The common drawback of displacement techniques for vibration measurement is the small magnitude of displacement involved, resulting in very low-level output signals. Capacitive-type displacement systems have been successfully used in AGR in the UK where it is essential to monitor absolute

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displacement, which is not possible with devices such as accelerometers.

Velocity Sensors

Two types of velocity measurement sensors are in common use; these both employ moving components. These would normally be used for monitoring large displacements; but I consider that their reliability, because of moving components, does not meet the requirement of environments such as the nuclear generation industry.

Acceleration Sensors

A wide variety of acceleration sensors is currently being marketed. These devices may be strain-gauge, piezoresistive or piezoelectric accelerometers. Strain-gauge accelerometers tend to be low in efficiency and several times more massive than other types. They usually have a figure of merit at least two orders of magnitude lower than either the piezoresistive or piezoelectric type. Piezoresistive accelerometers, unlike strain-gauge units, can have a high natural frequency. The usual maximum temperature for commercially available units is approximately 120° C, although the technology exists to extend this to 260°C.

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

The differences observed can be accounted for by the level of dopant. Heavily doped gauges have lower resistivity and lower gauge factors, but are more resistant to radiation effects. The failure mechanism in radiation damage to piezoresistive devices involves lattice changes in the crystalline structure. The real forte of piezoresistive accelerometers is their transient-handling capability at very high dose rates, as encountered in nuclear-weapon detonation. The accompanying electromagnetic pulse would effectively block most measurement systems, although the total integrated flux could be relatively small.

Piezoresistive accelerometers can be considered to have unlimited life expectancy for dynamic data. Their efficiency is considerably higher than strain-gauge units, although somewhat less than piezoelectric types. With their higher efficiency, signal conditioning is more straightforward in that they require lower amplification factors. They can also be made quite small if mass loading is a problem and, together with their capability for steady-state response, provide useful devices for applications such as low-frequency modal studies on light structures.

PIEZOELECTRIC ACCELEROMETER DESIGN AND PERFORMANCE CONSIDERATIONS

Piezoelectric Materials

Fundamental to the design of a piezoelectric transducer is the choice of sensor material. Not all piezoelectric materials act alike. What may be a good material for one application may not be for another. Material properties important to performance include stability, piezoelectric strain constant, bulk resistivity and change of output with temperature.

Stability of output with time is mandatory. Some piezoelectric materials can provide excellent conversion of energy: either mechanical to electrical, or electrical to mechanical. However, the stability of the electromechanical properties may not be the best. When using piezoelectricity for measurement of vibration, the material is optimized for stability of properties. Also, the energy levels are held to a small fraction of that feasible with the material. For example, the mechanical stress in the piezoelectric material caused by the vibration is less than 100 lb/in^2 for the subject accelerometers.

The piezoelectric strain constant is important, as it controls sensitivity. The electrical charge generated is a function of the product of this strain constant and the input force. Therefore, the higher the strain constant, the lower the force must be for a given output. The need for lower force results in a smaller and lighter accelerometer with higher resonance frequency ($F=ma$). This electrical charge is fed into charge amplifiers (not voltage amplifiers) for most of today's measurement systems. These devices are not restricted to applications where they must be located close to the transducer. They may be located 1000 ft or more distant. Sometimes a charge-sensing line driver is placed nearer the sensor to convert to low impedance.

For proper operation, charge-sensing electronics require a minimum input resistance. This resistance is the parallel sum of the piezoelectric element resistance and any shunt resistance from cables and connectors. The bulk resistivity of the piezoelectric material is important because it decreases with increasing temperature. (Generally resistivity of insulators decreases.) This decrease can be substantial when extending the operating temperature range to more than 200°C. A general rule is that the resistance drops by at least a factor of 10 for each 100°C increase; therefore, to extend operation to 600°C from 200°C, the resistance can decrease by a factor of approximately 10,000.[11] See Fig. 1. Even with the best piezoelectric materials, special electronics are required when the ambient temperature is above about 400°C. These circuits permit lower input resistance than in the past (discussed in greater detail later). Another property varying with temperature is vibration sensitivity itself (Fig. 2). Because charge-sensing electronics are used, the sensitivity change is dependent on the change in the material's piezoelectric strain constant with temperature. This, in combination with the resistivity and stability factors, determines the maximum temperature range for the sensor.

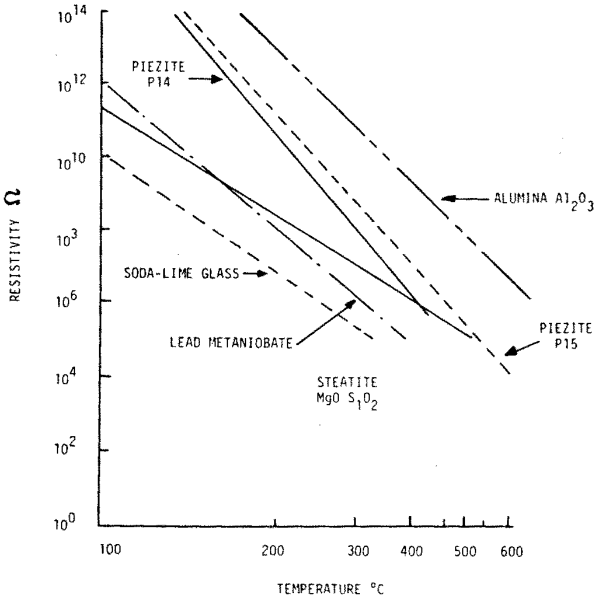


Fig. 1. RELATIONSHIP BETWEEN INSULATOR RESISTIVITY AND TEMPERATURE

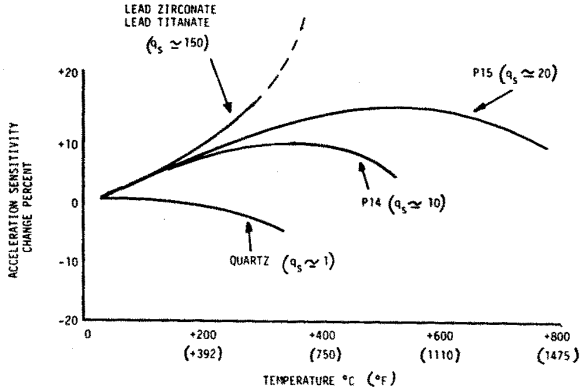


Fig. 2. CHARGE TEMPERATURE RESPONSE CHARACTERISTICS OF ACCELEROMETERS USING PIEZOELECTRIC MATERIALS - HIGH TEMPERATURE ONLY

The basic material property which controls temperature span for ferroelectrics is the Curie temperature; defined as that temperature at which permanent and complete loss of piezoelectric activity occurs. For crystals, which are naturally polarized, the maximum temperature is limited by material phase transformations. The maximum operational temperature must also be held well below any of the limits of other materials used in the transducer construction, bearing in mind migration of one material with another at elevated temperatures.

To determine which piezoelectric material could be used, Endevco completed measurements on materials which they generally felt might function well. These materials and some of their pertinent properties are listed in Table 1.[9,10] For the subject accelerometer design we found three of the materials included in Table 1 to be of prime interest and are therefore employing them to the greatest extent. The workhorse material is a special lead zirconate--lead titanate composition (P-8)*. It has the highest sensitivity of those shown in but also has a rather limited temperature capability.

Table 1. Simple Comparison of Piezoelectic Materials (Approximate Values Only).

Material	Dielectric Constant	Piezoelectric Strain Constant (pC/N)	Curie Temperature (°C)
Lead zirconate--lead titanate composition (P-8)	1600	300	370
Barium sodium niobium	30	--	560
Quartz	4.5	2	570 (Phase transition)
Lead metaniobate	200	75	540
Zinc oxide	9	12	
Tourmaline	7	2	
P-14 ceramic	20	20	680
Lithium niobate (P-15)	40	68	1 200

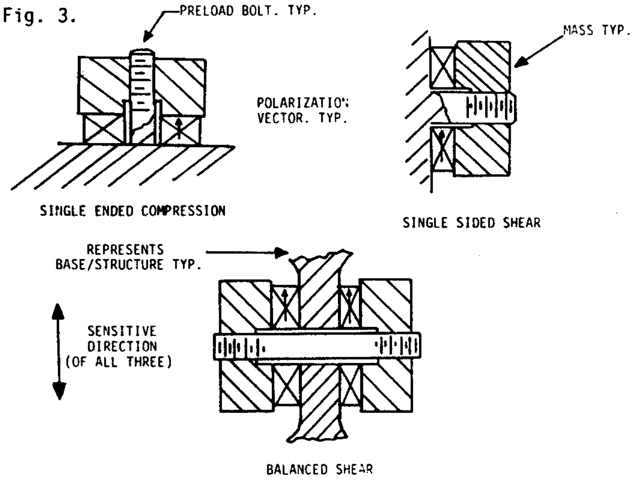
* P number denotes trademark of the manufacturer (Endevco) for the material.

The cost of P-8 material is lower than the alternatives, and its stability can be made adequate for many applications. Temperatures within operating heat exchangers and power systems preclude the use of this material if they exceed approximately 315°C. A second material used is a special ceramic (P-14) having a higher Curie temperature and a lower sensitivity. This is usually used in compression-mode accelerometers up to 540°C using several slabs in a stack to increase the charge output. The cost is fairly low, but higher than P-8, and the output stability is excellent. Lithium niobate (P-15), the third material in use, is employed in the highest-temperature situations. This material can be used in various modes; it has excellent sensitivity, but the cost is high. It is a single-crystal, single-domain ferroelectric, and as such it is not subject to the domain-switching and ageing characteristics of the ceramic ferroelectrics. Thus stability is excellent. Operating temperatures up to 760°C have been achieved.[11]

Mechanical Design Alternatives

After considering possible piezoelectric materials, application requirements and design alternatives, two basic types of transducer design were chosen, the compression mode and thickness-shear mode. Their piezoelectric elements are flat discs formed, in one case to provide output when squeezed between two parallel surfaces, and in the other case to provide output when a shearing force is applied between the parallel surfaces.[2] To hold these disc-shaped elements to the accelerometer structure, a preload bolt is used. This is a standard technique used for many lower-temperature accelerometers, and eliminates adhesives, which are of little value for attaching parts at higher temperatures.

Fig. 3.



DIAGRAMS OF THE TYPES OF ACCELEROMETER DESIGNS EMPLOYED - SIMPLIFIED

The mechanical approaches employed for these designs are shown in Fig. 3. Note that two different styles of the shear design have been used, one having a single-shear element and the other having two matching elements on each side of a web. This double-sided or balanced approach is used when high-frequency response is critical. Response is improved because eccentric loading on the support is eliminated along with resultant resonance modes. In general the compression design accelerometer is the most rugged and is best for high frequencies, while the shear design tends to better isolate against strain and thermal inputs. The response accuracy to high-frequency vibration inputs depends on how closely the piezoelectric element is coupled to the structure. Any spring elements placed between the structure and the crystal reduce resonance frequency. For the subject accelerometers the compliance of the case structures and mounting designs are more dominant than that of the piezoelectric element. The seismic mass, attached to the crystal, is the predominant mass element.

Rejection of Noise Inputs

Noise on an accelerometer signal can emanate from many sources. The difference between good and bad vibration data is often a function of the accelerometer design approach to noise rejection. Several of the more important of these considerations are briefly outlined.

Electrical/Magnetic Inputs

In general, complete shielding of the signal is necessary, and multiple grounding should be avoided. Either single-ended or differential-sensing circuitry can be used, although single-ended is preferred for reasons of simplicity and reliability. Resistive isolation at all points except systems ground is not enough. Capacitance coupling to the signal leads can be a significant source of noise. For example, if there is a 1 pF capacitance between the positive terminal of an electrically isolated single-ended accelerometer and the structure, a 1 pC signal would result for each volt of alternating potential on the structure referenced to system ground. With an accelerometer having a sensitivity of 10 pC/g the noise sensitivity would represent 0.1 g/V. Differential circuitry can be employed to advantage, but the system must be well balanced. Sometimes this type of system is used if the signal must be routed through commercial multi-pin connectors, where individual shielding of conductors is not feasible.[4] Differential circuits can also be helpful in certain magnetic field situations. However, the accelerometer internal design is usually the limiting factor. To maintain low magnetic sensitivity, low-permeability materials are used.

The approach taken to design for noise rejection required several new mechanical techniques. Because the ambient temperatures can be too high for organic insulation, ceramic or glass-type materials are used. A triaxial-style metal-sheathed mineral-oxide-insulated cable has been used to ensure that the shield is isolated from the structure. In severe environments the accelerometer cases are designed to be fully hermetic and the sensing element insulated from ground. Without these precautions multiple grounding would occur.

Thermal Inputs

The classical pyroelectric effect of materials and transducers is discussed in other literature.[5,3] In short, the shear-mode designs discussed herein have very little primary pyroelectric output--much less than that of standard compression-mode accelerometers. For both types we have found that, with fast changing temperatures, spurious noise (not classical pyroelectrical output) can result from discrete material and interface shifts. This is different from output caused by strains from differential temperatures and material expansions within the transducer. Start-up, or fast power changes, on light-weight gas turbines is a typical application example where such a situation might arise (i.e. 250°C/min change). The classical pyroelectric phenomenon tends to cause a low-frequency output wander or oscillation. The spurious noise effect appears as transient, sharp, low-level spikes. Both normal pyroelectric and spurious noise effects are reduced by placing a thermal resistance between the case and the piezoelectric material.

Physical Inputs

Forces transmitted to the piezoelectric element as a result of other force inputs can cause spurious signals. These inputs might result from strain at the mounting surface of the accelerometer, displacements of the cable close to the accelerometer, or acoustic/hydrostatic pressure fluctuations on the accelerometer case. These considerations can become paramount when measuring the motions of elastic systems vibrating in bending modes, or when the accelerometer is surrounded by liquids with a high fluctuating pressure (e.g. 550°F H_2O, 2000 (±20) lb/in^2). The basic design approach is to provide sufficient strain isolation to the case structure. The trade-off is reduction of frequency response.

ENVIRONMENTAL FACTORS

Temperature

As previously discussed, the maximum temperature rating of piezoelectric accelerometers must be held below that temperature which causes permanent shift of piezoelectric properties. At the higher temperatures (about 400°C), signal conditioning considerations also become important since the accelerometer resistance decreases with increasing temperature. Special "front-end" electronics are required which function with lower input resistance than those commercially acceptable in the past. Circuits are now available which accept $10^5\,\Omega$ input shunt resistance, and even down to $10^4\,\Omega$ input or less.

Nuclear Radiation

Test units have been produced and subjected to radiation by others. A few of the test reports have been released to industry. Considering only some of the data, the exposure levels and results are very briefly described:

(a) Irradiating P-14 and P-15 accelerometers with 2.7×10^{18} neutrons/cm^2 ($E>1.0$ MeV) had no discernible effect on calibration.[1]

(b) A specimen of lithium niobate showed no measurable change after irradiation with 4×10^9 erg/g of ^{60} Co-gamma rays, half of the dose being accumulated at 281°C, the remainder at 537°C.[7]

(c) Several piezoelectric accelerometers were irradiated with 10^{16} neutrons/cm^2 integrated dose and 10^{11} erg/g of ^{60}Co-gamma radiation.[6]

It appears that the piezoelectric materials with high-temperature capabilities are the more stable, and function at high radiation levels.

Surrounding Media

The fluids surrounding the accelerometers may not only have corrosive properties, but are often at extreme temperatures and pressures. The choice of materials for accelerometer cases has been based on published compatibility data and specific customer requests. Where high pressure surrounds the unit the cases may be made much thicker than usual. As previously discussed, the signals from accelerometers are transmitted through integral stainless-steel or Inconel-sheathed cables, brazed or welded to the accelerometer case. The cable insulation is a compacted metal oxide, usually MgO. One interesting design of a cable exit is shown in Fig 4. This reflects an all-welded assembly and a cable exit with a horn-shaped strain relief. We have found that such exits extend the bend life of the cable by about 5-10 times. We have also found that brazing and welding are extremely critical. All units are leak-tested at their maximum rated case pressure as a normal quality check.

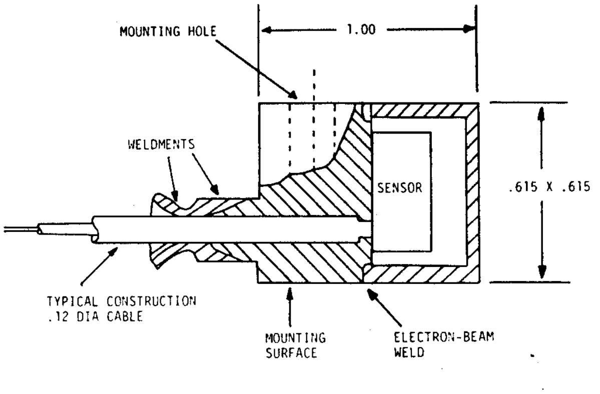


Fig. 4. INTERNAL CONSTRUCTION OF DESIGN B ACCELEROMETER WITH WELDED CABLE EXIT

HARDWARE RESULTS

Single-Axis Accelerometer; Typical Examples

Both compression- and shear-mode accelerometers have been produced for severe environments. Two units are described to point out typical design solutions. The first is a compression design rated at 540°C (1 000°F) using the P-14 element. The need was for a hermetic accelerometer having a low base and low case-strain sensitivity and low transient-temperature sensitivity. It was also important that the unit withstand considerable physical punishment. The accelerometer is shown in Fig 5. Basic performance results are displayed in Table 2 (design A).

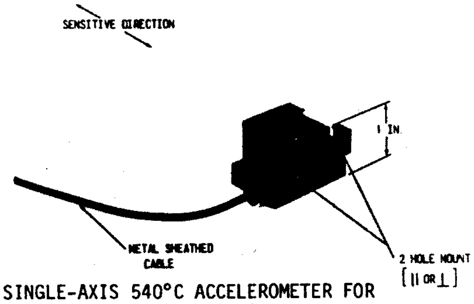


Fig. 5. SINGLE-AXIS 540°C ACCELEROMETER FOR LIQUID SODIUM APPLICATIONS

Table 2. Performance Results For Various Accelerometer Designs.

Accelerometer Characteristic	A Single Axis P-17 Compression	B Single Axis P-15 Shear	C Sub-mini P-15 Shear	D Biaxial P-8 Shear
Charge sensitivity (pC/g)	10	10	1.5	16
Frequency response *(Hz)	3 000	3 000	7 000	1 500
Maximum operating temperature (°C)	540	650	400	315
Base strain output (equivalent g at 250 μstrain	0.01	0.5	4.0	Low; dependent on mounting
Maximum pressure (lb/in^2)	2 000	2 000	--	2 500
Sensor volume (mm^3)	20	5.6	0.9	3.9
Sensor weight (g)	120	45	4	22

* Upper limit of the frequency range in which the response is flat to within 5%.

The second design achieves maximum temperature rating. This unit is designed for 650°C (1200°F) service in either pressurized H_2O or liquid Na, and uses P-15 with the element isolated by alumina insulators. The cable is a triaxial metal-sheathed cable terminated at the accelerometer through welds. This design is shown in Fig 4, and its performance results are shown in Table 2 (design B). The intent of both designs is to measure low acceleration (0.1 g-100 g) at moderately low frequency (10-2000 Hz) with good fidelity.

Subminiature High-Temperature Accelerometer

The objective for this design was to provide the smallest feasible unit consistent with a need to measure a few g on a plate type of structure at frequencies up to 10 kHz, and in the presence of surface strains and temperatures to 704°C (1300°F). The design approach utilized the balance-shear mode and P-15 element. Frequency response is flat within 10% to 10 kHz. To provide minimum size, weight, and cable mass loading, electrical circuit isolation was omitted. For this application the accelerometer is welded (see Fig 6).

Multi-Axis Accelerometers

In general this design may have outputs for each of three orthogonal axes. It is packaged in a cylinder with all cables leaving one end. By doing this, the accelerometer lends itself to mounting within heat exchanger tubes. Designs have been completed having diameters of 5.6 mm

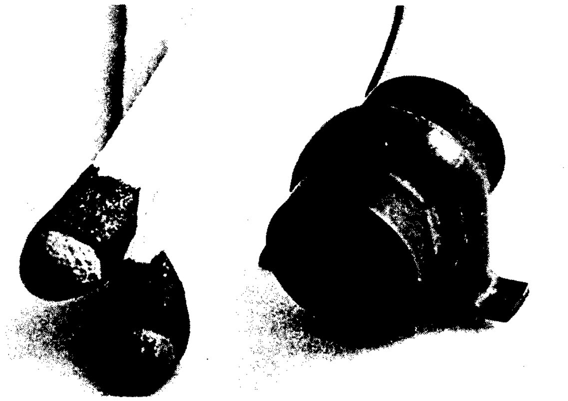


Fig. 6. SUB-MINIATURE 700°C ACCELEROMETER

(0.22 in) to 14 mm (0.56 in) and with temperature ranges of 315°C (600°F) and 650°C (1200°F). Both P-8 and P-15 piezoelectric materials have been used.

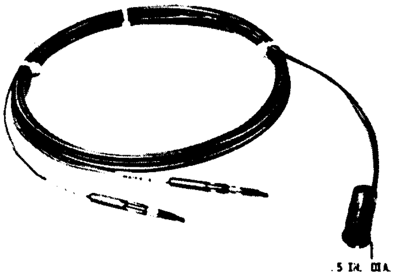


Fig. 7. BIAXIAL ACCELEROMETER SHOWING HARD-LINE CABLES AND TERMINATING CONNECTORS

Fig 7 shows a 315°C P-8 biaxial accelerometer. The overall size is 13 mm (0.50 in) diameter by 31 mm (1.20 in) long, with ends suitable for welding to its intended structure. Performance factors are included in Table 2 (design D). Another design includes a novel method for installation in tubes. As can be seen from Fig 8, the base section of the accelerometer is tapered so that a clamp-shell two-section clamp can be squeezed between the unit and the tube. This clamp is tightened by threading the bolt which holds the clamp to the accelerometer, thus pulling the clamp and accelerometer together and expanding the diameter. A special socket wrench and accelerometer-holding tool, which can be quite long, is used to install the accelerometer deep into tubes. Material selection for strength and expansion coefficient is critical for holding the system tight over wide temperature ranges. When the cylindrical case of the accelerometer is rigidly clamped, the frequency response is flat within 5% to 1.5 kHz. Using the special clamp system, the response was not degraded. The optimum configuration to reduce strain inputs is to hold the accelerometer by the base end only.

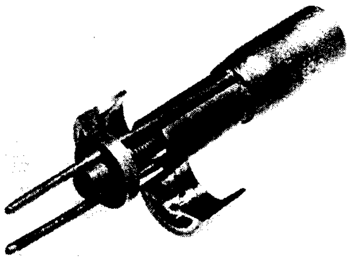


Fig. 8. BIAXIAL ACCELEROMETER SHOWING CLAMP DESIGN

Charge Amplifier Noise and Effects of Source Resistance

Specifications of some charge amplifiers restrict the input to capacitive devices only, yet it is not unlikely that the input may be shunted by the leakage resistance of the transducer, cables and input connectors. Accelerometer leakage resistance at normal temperatures is normally very high (1 GΩ). The decrease in resistance produced at elevated temperature can introduce factors which severely derate system performance. Source resistances as low as 10 kΩ are not uncommon with transducers designed to operate at 540°C. Some charge amplifier designs may cease to operate with input shunt resistances less than several megohms, due to significant changes of quiescent constant-voltage biasing. This problem may be overcome with proper design.

In a practical charge amplifier the relationship between amplifier feedback resistor R_f, and source resistance R_s must be considered in order to determine the system noise figure. Noise gain at low frequencies will be governed by the ratio $(R_f + R_s)/R_s$ (assuming that it does not approach the open-loop gain of the amplifier).

Fig 9 illustrates the noise gain increase (at a 20 dB per decade rate) for various ratios of R_f to R_s. For a fixed feedback resistance R_f, noise gain increases with increasing transducer temperature, due to the falling source resistance. Unfortunately this rise in noise gain manifests itself at low frequencies where noise distribution is already dominated by the 1/f noise increase. Low source resistances may also alter low-frequency roll-off characteristics of the amplifier.

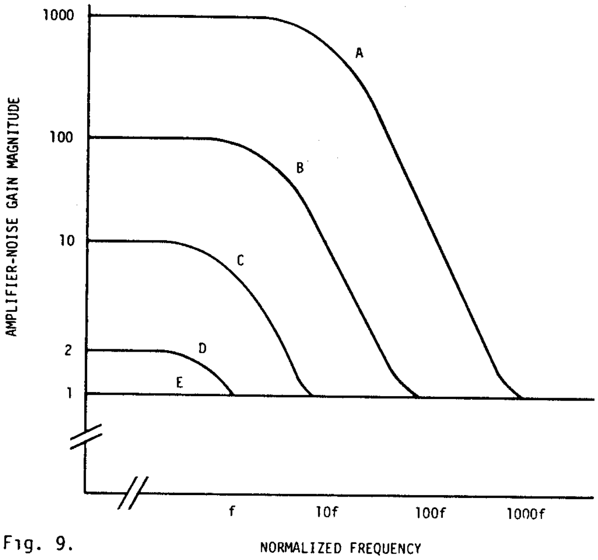


Fig. 9.

It is possible to optimize amplifier characteristics for operation with normally high or extremely low source resistance. Fig 10 illustrates two characteristics: one where input noise is minimized for low source resistance, the second for high source resistance. The correct choice is required for the relevant application.

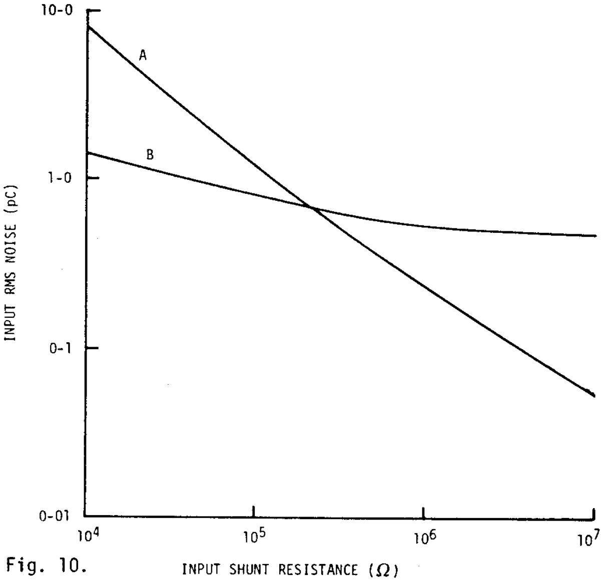


Fig. 10.

CONCLUSION

A reliable and precise vibration- or pressure-monitoring system (typical example is shown in Fig 11) may be achieved by the application of transducers based on sound engineering design, correct selection of signal conditioning equipment and careful selection and installation of the interconnecting cable.

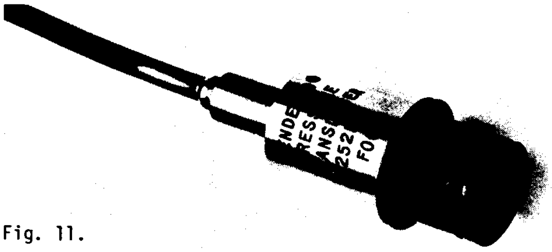


Fig. 11.

ACKNOWLEDGEMENTS

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