ACCELEROMETERS FOR USE IN NUCLEAR REACTOR COMPONENTS

by

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ABSTRACT

Vibrations are known to occur in heat exchangers, rotating equipment and other components used in electric power generating plants. The measurement of these vibrations is very important particularly in the development and testing of nuclear reactors. Certain accelerometer performance characteristics need to be considered in order to make accurate measurements of heat exchanger vibrations. It is also important to select accelerometers which can withstand the severe environments present in the reactor and associated equipment. Piezoelectric and piezoresistive accelerometers have the characteristics necessary for making measurements in these applications. Servo type accelerometers are also suitable for making measurements of small vibrations such as those encountered during seismic excitation of the power plant.

INTRODUCTION

The fluid flow in heat exchangers causes vortex shedding on the tubes. The vortex shedding produces alternating forces at a frequency which is determined by the tube diameter and the component of fluid flow velocity perpendicular to the axis of the tube. Large amplitude vibrations occur when the vortex shedding frequency corresponds to a transverse resonance frequency of the tube. It is important to design the heat exchanger to avoid these vibrations. Failure to do so may result in fretting corrosion and fatigue failures at the tube walls and at the baffle holes. Accelerometers are used to measure the vibrations present and determine whether or not resonances in the heat exchanger are being excited. These measurements are made in the development of heat exchangers as well as at other times during the testing and construction of power plants.

Vibrations occur in other nuclear reactor components. For example, gas-cooled reactors use high velocity circulating blowers to move the gas from the heat exchanger back to the reactor core. These blowers and other rotating equipment produce vibrations as a result of unbalanced forces. Large changes in the amplitude of these vibrations are an indication of wear or faulty operation of bearings and other rotating parts. Vibration monitoring should give an early warning to these equipment failures and permit the orderly scheduling of maintenance work.

Piezoelectric and piezoresistive accelerometers are used for measuring the vibrations in heat exchangers and other nuclear power plant components. The small size of these accelerometers is an important characteristic when measuring vibrations occurring at resonance frequencies in the components. The piezoelectric accelerometers are more suitable for making measurements when extremely high temperatures are present. Recently developed accelerometers are capable of measuring vibrations when exposed to temperatures up to at least 1200 deg F. The piezoresistive accelerometers are most suitable for making very low frequency vibration measurements at room temperature or at moderate temperature extremes. Other important characteristics to consider in using piezoelectric and piezoresistive accelerometers include transient temperature effects, frequency response, strain and pressure effects. Calibrations and tests performed on accelerometers demonstrate their suitability for use in measuring vibrations in nuclear power plant applications.

Servo type accelerometers are used for measuring low amplitude vibrations at frequencies ranging from zero Hz up to several hundred Hz. These accelerometers can be used in a number of power plant applications including the measurement of seismic motions produced by earthquakes as well as man-made vibrations. Some attention must be given to these vibrations because exploratory work[1], [2] has demonstrated that nuclear reactor structures have resonances at low frequencies which can be excited by earthquakes. Possible structural damage resulting from earthquakes may occur in the primary coolant loop and reactor core. The collision of fuel elements and control rods may be possible. Laboratory studies performed with the use of small size accelerometers should help to determine the effects of earthquakes. The servo accelerometer is particularly suitable for monitoring seismic motions.

ACCELEROMETER DESIGNS

The design of accelerometers is based on the mechanical system consisting of simple spring and mass elements. When subjected to motion, the mass element produces infinitesimal deformations in the spring element which usually includes an electromechanical transducing material to produce electrical outputs proportional to the applied acceleration. The accelerometer measures vibrations over a wide range of frequencies. The resonance frequency of the accelerometer is far above its operating range.

Piezoelectric Accelerometers

Piezoelectric accelerometers are frequently designed using the compression or shear mode of operation[3]. Most of these accelerometers measure vibration in the direction of their axis of symmetry as illustrated in Figure 1. When the accelerometer is moved upward, the mass tends to move downward toward the bottom of the accelerometer. Conversely,

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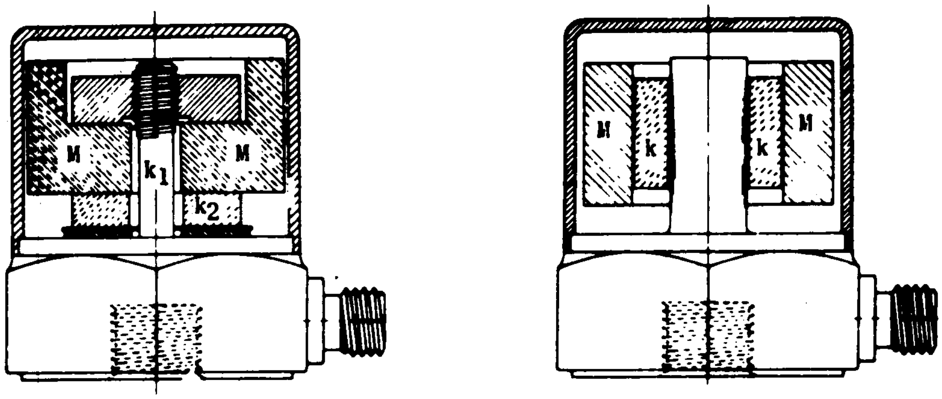

COMPRESSION SHEAR

Fig. 1 Two common types of piezoelectric accelerometers use the piezoelectric ceramic in compression and shear. The motion of the mass element M produces an electric charge on the ceramics k and k_2. Preload is applied by the screw k_1 in the compression accelerometer.

downward motion tends to move the mass element upward. The vibration applies dynamic stress and deforms the piezoelectric ceramic. Both the piezoelectric ceramic and mass elements are cylindrical in shape. The dynamic stress corresponds to a variation in the preload in the compression accelerometer and is a shear stress in the shear accelerometer. An electric charge is generated by the piezoelectric ceramic as a result of the dynamic stress.

The electric charge generated on the ceramic is given by the following equation:

$$Q = d\sigma A$$

where: d = piezoelectric constant of the crystal
A = stressed area on the crystal
σ = stress on the crystal

The numerical value of the piezoelectric constant is determined by the ceramic material. For example, lead-zirconate-titanate and other more recently developed ceramics are used. Quartz is also used in some accelerometers, but has the disadvantage of having a very low piezoelectric constant. Charge amplifiers are used in measuring the output of piezoelectric accelerometers. The output is read with conventional instruments such as voltmeters, oscilloscopes and recorders.

Piezoresistive Accelerometers

The internal construction of a piezoresistive accelerometer is shown in Figure 2. The strain gage elements R1, R2, R3 and R4 are made with piezoresistive materials. The piezoresistive strain gage elements have a high gage factor and the sensitivity of the accelerometer is much higher than that present in accelerometers built with wire strain gages. Also, stiff elements are used to extend the operating range to high frequencies. The strain gages are connected electrically in a Wheatstone bridge. An electrical input is applied to the bridge and the output is measured with conventional signal conditioning instruments. The output is proportional to the acceleration applied to the base of the accelerometer.

Servo Accelerometers

The construction and operating principal of a

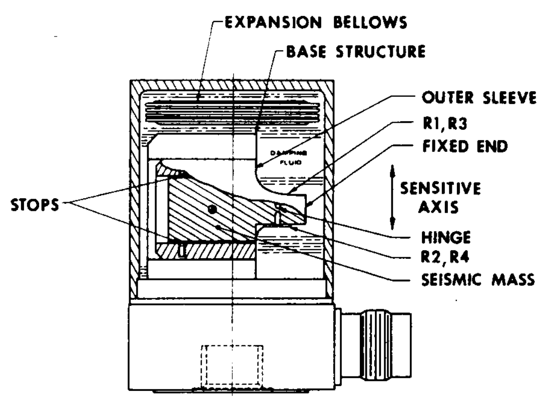

Fig. 2 A piezoresistive strain-gage accelerometer. The seismic mass moves in a fluid medium to change the resistance of the gage elements. Stops are provided to prevent overloading at large accelerations.

servo accelerometer(4) is illustrated in Figure 3. When subjected to motion, the proof mass tends to deflect relative to the base of the accelerometer and the pickoff changes its capacitance as a result of changes in the damping gap. As this occurs, the servo supplies current to the coil which is located in the gaps of the permanent magnets. The resulting force restores the coil to its equilibrium position. The output signal is a measure of the coil current and proportional to the applied acceleration.

Operating Characteristics

The operating characteristics of accelerometers are given in Table 1. These characteristics apply to specific accelerometers presently in wide use. Many other accelerometer models are available with different performance characteristics intended for use in various applications.

The acceleration sensitivity of piezoelectric accelerometers is expressed in pC/g. They are used

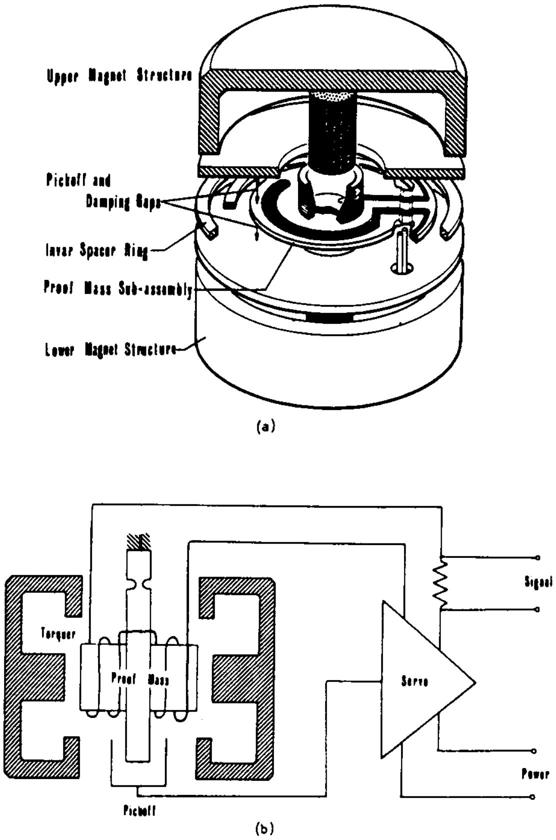

Fig. 3 Exploded view (a) of the servo accelerometer and its operating principal (b) based on the Eyestone-Wilson sensor.

with charge amplifiers having various gain ranges. The accelerometers are suitable for making measurements over a wide range of accelerations. Some of the important characteristics of a piezoelectric accelerometer are its ruggedness and its large acceleration, frequency, and temperature operating ranges.

Piezoresistive and servo accelerometers have a high acceleration sensitivity expressed in mV/g. The piezoresistive accelerometers are used in a large number of applications requiring both low frequency and wide acceleration ranges. The servo accelerometers are most suitable for measuring low frequency and very small amplitude vibrations.

ACCELEROMETER SIZE AND MOUNTING EFFECTS

In many applications, the most harmful vibrations occur at the resonance frequencies of the specimen or structure being tested. At these frequencies the dynamic mass, ratio of force to acceleration, at various locations on the specimen is usually extremely small. This may be true when measuring heat exchanger tube vibrations at attachment points away from the tube supports. Consequently, almost any device which is attached to the specimen will have some effect on the motion of the specimen.

The effect of an accelerometer on the motion of the specimen can be determined by theory. Neglecting the effects of rotary inertia, the motion of the specimen with the accelerometer attached is given by the following equation:

$$A = \frac{A_o M_s}{M_s + M_a}$$

where:

- A = amplitude of motion of the specimen with accelerometer attached
- A_o = amplitude of motion without accelerometer attached
- M_s = point dynamic mass of the specimen at the accelerometer mounting location in the sensitive direction of the accelerometer
- M_a = dynamic mass of the accelerometer in its sensitive direction

The terms in the equation are complex quantities having both a magnitude and a phase angle.

TABLE 1

TYPICAL ACCELEROMETER PERFORMANCE CHARACTERISTICS

Characteristics	Piezoelectric Accelerometer	Piezoresistive Accelerometer	Servo Accelerometer
Sensitivity (pC/g, mV/g)	12	20	250
Frequency Range (Hz)	2 - 5500	0 - 750	0 - 500
Resonance Frequency (Hz)	27,000	2,500	1,000
Amplitude Range (g)	10,000	25	15
Shock Rating (g)	10,000	2,000	250
Temperature Range (^{o} F)	-300 to +500	0 to +200	-45 to +185
Total Mass (gm)	27	28	80

Although the specimen dynamic mass is small at resonance, the presence of reasonably light weight accelerometers may cause only a slight change in the resonance frequency and should not greatly affect the vibration amplitude(5). A general rule is to select accelerometers whose total mass does not exceed about ten times the dynamic mass of the specimen at its resonance frequency. The dynamic mass of the specimen at the accelerometer mounting location can be measured by using force transducers and accelerometers or impedance heads. The dynamic mass of the accelerometer, in its operating frequency range, is equal to its total mass as measured statically.

TEMPERATURE EFFECT ON SENSITIVITY

One of the advantages of piezoelectric accelerometers is their suitability for use at temperature extremes. By careful design of the accelerometer and the piezoelectric ceramic, very small changes in the acceleration sensitivity occur over very wide temperature ranges. The variations in sensitivity with temperature of several accelerometers in common use are shown in Figure 4. The sensitivity of the lead-zirconate-titanate accelerometers varies from -6 percent at about -65 deg F to +10 percent at +350 deg F. This performance is typical for most compression and shear type accelerometers built with this ceramic. The sensitivity of a quartz accelerometer decreases to about -9 percent at +500 deg F. Improved performance is achieved by using special ceramics in compression design accelerometers to extend the operating range from about -450 deg F to +750 deg F. Although the performance of these accelerometers is satisfactory for many applications, recent developmental work on a new design has demonstrated the use of accelerometers at much higher temperatures.

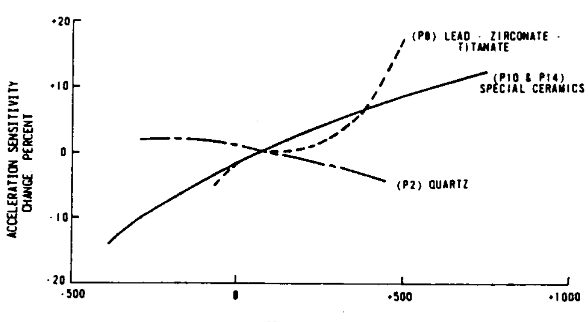

Fig. 4 Typical temperature response characteristics show charge sensitivity changes for accelerometers using different crystal materials.

The performance of accelerometers designed for use at extremely high temperatures is illustrated in Figure 5. The acceleration sensitivity of this accelerometer increases to about +15 percent at about 1000 deg F and then decreases from this value at higher temperatures. This accelerometer is built with a new ceramic material which has good operating characteristics at extremely high temperatures. The accelerometer, subjected to extensive tests, has demonstrated its suitability for use at temperatures up to at least 1200 deg F. In addition to having quite small sensitivity changes at high temperatures,

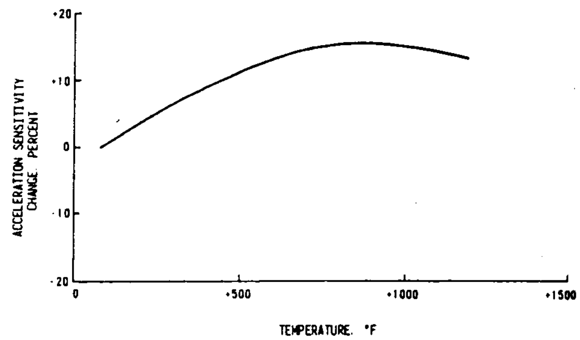

Fig. 5 Typical temperature response characteristics of a recently developed piezoelectric accelerometer.

the accelerometer ceramic maintains relatively high electrical resistance at the highest operating temperatures. It is important to maintain this resistance to avoid degrading the frequency and noise characteristics of the charge amplifier used with the accelerometer.

Although the accelerometer, whose performance is given in Figure 5, was originally designed to meet the requirements for measuring vibrations on jet engines in commercial aircraft, it should also be suitable for use in measuring vibrations in heat exchangers and on other components in nuclear power reactors. This accelerometer has a corrosion-resistant steel-enclosed cable for carrying the electrical output of the accelerometer through extremely high temperature and other severe environments. The steel tubing of this hardline cable is brazed to the accelerometer case to provide a seal against contaminents. This design should make the accelerometer suitable for use in various locations on nuclear reactor components. High temperature gases, water and liquid sodium should not affect the performance of the accelerometer.

The accelerometers whose performance are given in Figure 4 should be suitable for use in more moderate high temperature applications in nuclear reactors. However, these accelerometers are normally supplied with a detachable high temperature cable. Care must be taken to avoid contamination in the connector which may possibly cause intermittent contact and prevent an accurate measurement of the accelerometer output.

ENVIRONMENTAL EFFECTS

Radiation Effects

The effects of radiation environments need to be considered when making acceleration measurements in nuclear reactors. An examination of the effects of transient and steady-state radiation is useful for determining tolerable radiation doses without producing excessive errors or accelerometer malfunctions. Relatively large radiation doses can be experienced without any harmful effects in accelerometers. Piezoelectric accelerometers have been tested at larger radiation doses than is the case for piezoresistive accelerometers.

Battelle Memorial Institute(6) reports that tests have been conducted on a number of piezoelectric accelerometers at a neutron fluence of 10^{16} n/cm^2 and with gamma radiation up to 10^{11} ergs/g (C). Other tests(7) were also performed on piezoelectric accelerometers under actual vibration conditions while being subjected to neutron fluences up to 6 x 10^{14} n/cm^2 with gamma radiation up to 1.6 x 10^7 roentgens. Most of the piezoelectric accelerometers in all of these tests operated normally without displaying any effects due to the radiation environments present. However, some of the accelerometers showed intermittent outputs or no output as a result of immersion in liquid nitrogen, wetting of the accessory electronics, etc. This faulty operation is typical of noisy or shorted connections in the cable and connectors. It has also been reported(6) that piezoelectric ceramics experience no lattice changes at a neutron fluence as high as 10^{18} n/cm^2.

Some semiconductor strain gages and accelerometers suffered damage(6), (8) at exposures of neutron fluence above 10^{13} n/cm^2 and gamma radiation of 10^8 ergs/g (C). However, other tests(9) showed satisfactory performance of semiconductor strain gages at doses of 10^{14} n/cm^2 and 10^8 ergs/g (C). One piezoresistive accelerometer(8) showed no degradation of performance characteristics at radiation doses up to 5 x 10^{15} n/cm^2. Another radiation-hardened piezoresistive accelerometer operated satisfactorily during transient nuclear radiation environments. The accelerometer, while being subjected to vibration, showed no effects except a very short duration transient at time zero. The ability to withstand very high radiation environments depends upon the accelerometer design and the particular semiconductor material and processing used. Some care must be exercised in the selection of piezoresistive accelerometers intended for use in severe radiation environments.

Pyroelectric Effects

Although the piezoelectric accelerometers operate normally when subjected to radiation environments, pyroelectric outputs are produced when transient temperature changes occur in the accelerometer. The magnitude of the pyroelectric output is dependent upon the type of piezoelectric ceramic used as well as the design of the accelerometer.

There are three types of pyroelectric outputs: primary, secondary and tertiary. The primary pyroelectric output is the charge produced as a result of a uniform temperature change throughout the piezoelectric ceramic. Secondary pyroelectric outputs are produced as a result of the piezoelectric 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. The shear design accelerometers have only secondary pyroelectric outputs during uniform heating because the electrodes are put on the radial surfaces parallel to the direction of polarization. Finally, tertiary pyroelectric outputs are produced as a result of dimensional changes in the ceramic when nonuniform heating occurs. All piezoelectric accelerometers exhibit tertiary pyroelectric outputs including those made with quartz. Also, quartz accelerometers may have some output due to differential expansion of the mass element, crystal and other parts of the accelerometer even though the heating is uniform.

Although pyroelectric outputs may be quite large, particularly in compression design accelerometers using ceramics, they usually do not produce significant errors in most applications. This happens because the temperature changes in most applications occur over a long period of time compared to the low frequency time constant of the charge amplifier used with the accelerometer. Accordingly, pyroelectric outputs are usually not measured, but are filtered out by the amplifier. For very severe transient temperature applications, tests(10) may be performed on the specific accelerometer and amplifier of intended use to evaluate pyroelectric effects.

Pressure and Strain Environments

Mechanical forces applied externally to the case of an accelerometer can produce errors in its electrical output. If these forces vary dynamically with time, the error signals are superimposed upon the normal accelerometer output. If static forces are applied, the case is distorted and strains are applied to the sensing element in the accelerometer. Although it is very difficult to determine the exact relationship of some of these forces in terms of error signals, test techniques have been developed to specify the performance of various piezoelectric accelerometer designs relative to each other. This performance characteristic is called the strain sensitivity. The accelerometers are tested by mounting them at the fixed end of a vibrating cantilever beam in accordance with an established procedure(10). Most accelerometers are designed so as to minimize the strain sensitivity. Shear design piezoelectric accelerometers usually have quite low strain sensitivity. Also, special ceramic materials and special case designs are used to minimize the effect in compression type piezoelectric accelerometers. A closely related error source is the case distortion resulting from making vibration measurements while the accelerometer is immersed in presurized gas or liquids.

The effect of external pressures on piezoelectric accelerometers has been carefully analyzed(11) for the presence of high sound fields. If fluctuating pressures were present at accelerometer locations in nuclear power plant applications, similar effects would be present. These include errors due to pressure variations of the gas internally in the accelerometer, errors due to radial strains in the accelerometer base, and acceleration errors due to changing the height of the accelerometer base. It has been demonstrated(11) that these errors are negligible for dynamic pressures corresponding to those present in very severe sound environments.

SUMMARY

Vibration is an important consideration in the design and maintenance of nuclear power plants. Tube vibrations excited by vortex shedding in heat exchangers can cause failures requiring costly repairs. Accelerometers can be used to detect excessive wear and impending malfunction of rotating equipment such as high velocity circulating blowers. Accelerometers are used to measure the vibrations in these components as well as in research and development work on the effects of earthquakes on nuclear reactor components and structures.

Certain performance characteristics are important in the use and selection of accelerometers for making these vibration measurements. For many applications it is necessary for the accelerometer to have a small size and mass in order to make sure that the presence of the accelerometer does not significantly change the vibration motion it is measuring. Particularly in heat exchangers it is important for the accelerometers to have good high temperature operating characteristics. Recently developed accelerometers should be suitable for most of the high temperature applications.

Although piezoelectric accelerometers are most suitable for vibration measurements in severe environments, piezoresistive accelerometers can be used to advantage particularly when very low frequency vibrations are present. In addition, servo accelerometers should be considered for use in the measurement of very small amplitude vibrations present in nuclear reactors such as those caused by seismic motions.

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