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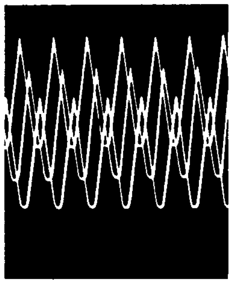

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ACCELEROMETER CHARACTERISTICS USED IN TRANSIENT MOTION AND NUCLEAR APPLICATIONS

by R. R. Bouche and D. E. Lovelace

1.0 INTRODUCTION

Piezoelectric and piezoresistive accelerometers are used in a number of applications for measuring shock motion and transient vibrations. Some of these applications concern the measurement of ground motions produced by nuclear or chemical explosives. Also, high shock motions are measured in pyrotechnic applications.

The amplitude linearity and zero shift characteristics of piezoelectric accelerometers need to be considered if high amplitude and high frequency components are present or if it is desirable to integrate the accelerometer output to measure velocity. Piezoresistive accelerometers are free of zero shifts and have the additional advantage of flat response to zero frequency. These characteristics are important for velocity measurements and for transient motion applications having significant low frequency components.

2.0 AMPLITUDE LINEARITY

It is known that the sensitivity of piezoelectric accelerometers increases linearly with increasing acceleration. The amount of sensitivity increase is dependent upon the piezoelectric ceramic used and on the design of the accelerometer. Accelerometers designed to have relatively low dynamic stress applied to the ceramic will have relatively small sensitivity increases at high accelerations. The amplitude linearity of each accelerometer design can be determined by performing comparison sinusoidal and shock motion calibrations using an accelerometer standard whose characteristics have been previously determined.(1) It is also necessary to accurately establish the amplitude linearity characteristics of piezoresistive accelerometers particularly for those applications where it is desirable to integrate the accelerometer output.

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2.0 AMPLITUDE LINEARITY (continued)

The sinusoidal calibrations are performed at accelerations up to more than 1000 g by attaching the accelerometer and standard at the end of an aluminum rod attached to an electrodynamic shaker. By proper selection of the shaker and dimensions of the rod, it is practical to excite the rod at its resonance frequency to produce high amplitude sinusoidal motion within the normal operating range of the accelerometers.

Accurate shock motion calibrations can be performed at accelerations up to 10,000 g to determine the amplitude linearity at high accelerations and demonstrate the suitability of using accelerometers for shock motion applications. The accelerometer and standard are attached to anvils designed so that the shock pulses produced have little or no resonance frequency excitation throughout most of their operating range.

The results of amplitude linearity calibrations on two accelerometers are shown in Figure 1. These accelerometers are examples of two fundamental designs and show the large differences in amplitude linearity deviations that can occur. The Model 2213E Accelerometer is built with P-8 ceramic in a compression design to provide a high acceleration sensitivity. This accelerometer is quite suitable for general purpose applications at accelerations up to 1000 g. The sensitivity increases

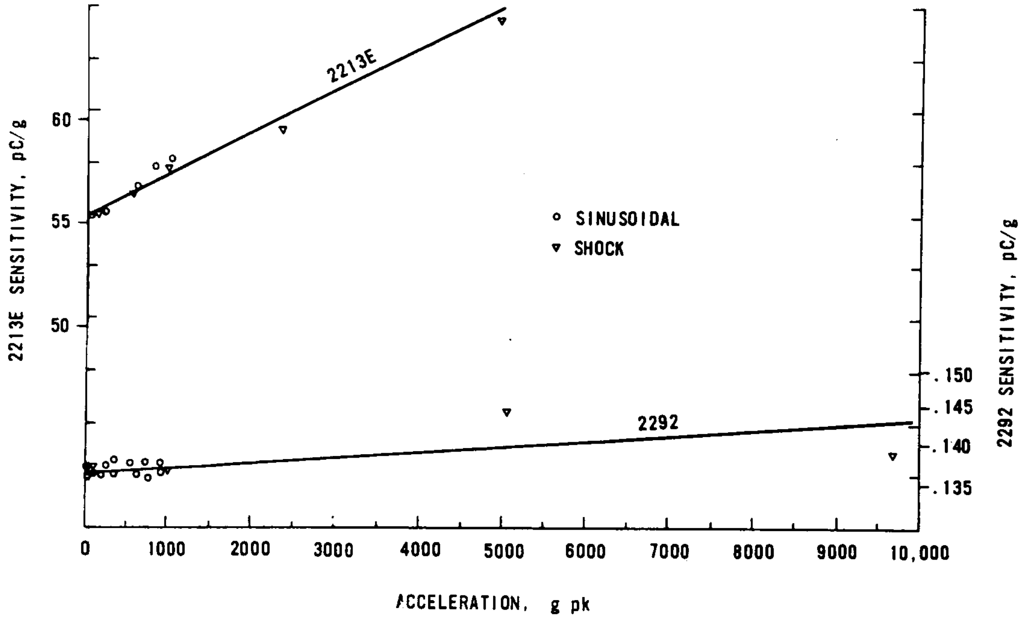


Figure 1.
Sinusoidal and shock motion calibrations demonstrate the amplitude linearity characteristic of piezoelectric accelerometers.

2.0 AMPLITUDE LINEARITY (continued)

approximately 4% per 1000 g. The inner ordinate scale in Figure 1 is 5% per division to indicate the changes in sensitivity. The results of this calibration illustrate the amplitude linearity characteristics of piezoelectric accelerometers and demonstrate that the Model 2213E Accelerometer should not be used for shock motion measurements at high accelerations. The Model 2292 Accelerometer uses the same type ceramic, P-8, in a shear design. Figure 1 demonstrates that the sensitivity increase of this accelerometer is only about 5% in the range from zero to 10,000 g. This performance provides good accuracy for many shock motion measurement applications. However, it should be noted that the sensitivity increases in a linear manner with acceleration which is characteristic of piezoelectric accelerometers.

The results of calibrations on two piezoresistive accelerometers are shown in Figure 2. Although the accelerometers in Figure 2 are used at lower accelerations, the results show that the piezoresistive accelerometers are linear. For convenience, the ordinate scales in Figure 2 are selected so that the percentage changes in sensitivity are similar to the scales used in Figure 1. The deviations from constant sensitivity for the piezoresistive accelerometers are equal to or less than the errors typical for sinusoidal and shock motion calibrations. It is concluded that the piezoresistive accelerometers do not have the sensitivity increases with acceleration as described above for piezoelectric accelerometers. Accordingly, there are certain

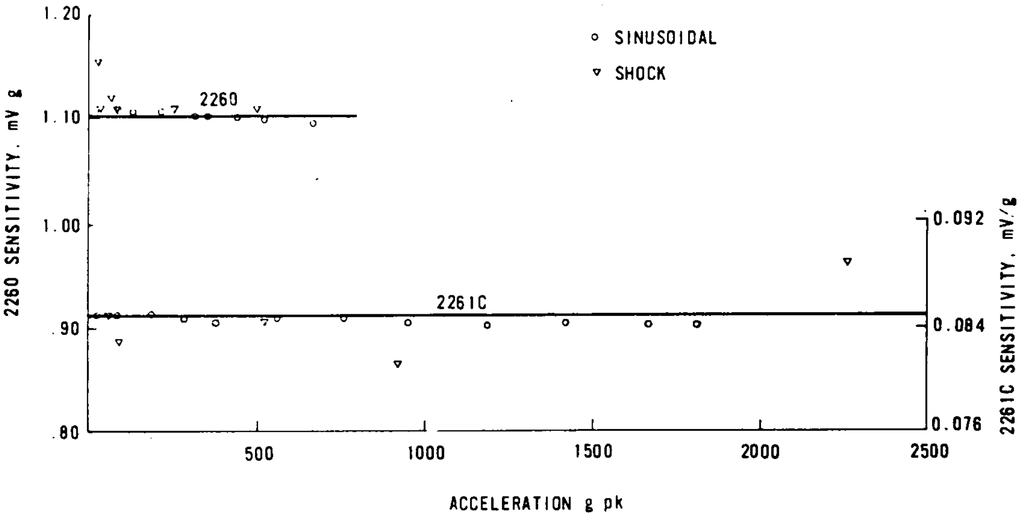


Figure 2.
Calibrations on piezoresistive accelerometers indicate no amplitude linearity deviations.

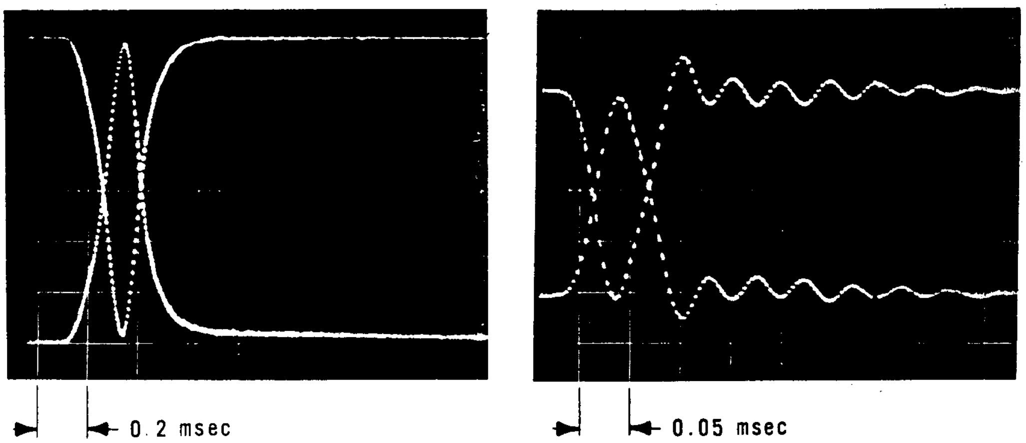
2.0 AMPLITUDE LINEARITY (continued)

applications where it would be advantageous to use piezoresistive accelerometers. One of these is the measurement of shock motions where it is desirable to integrate the output to obtain the velocity change taking place in the medium or structure under test.

3.0 ZERO SHIFTS

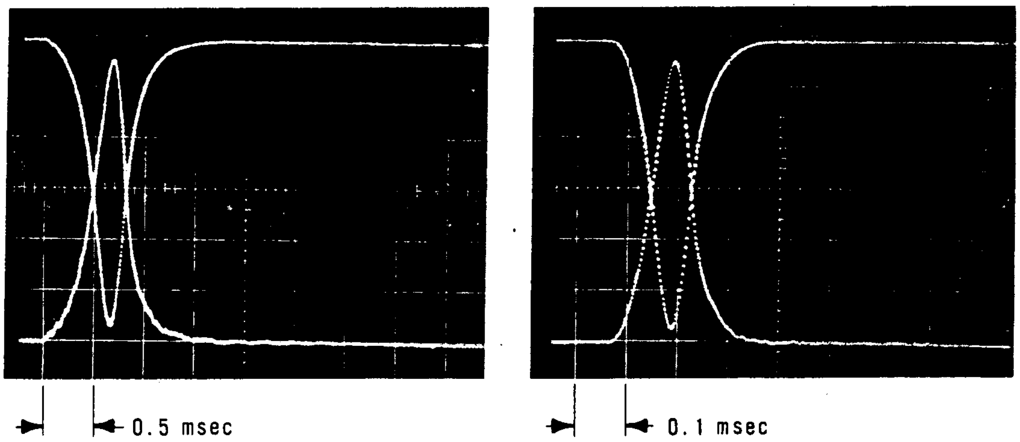
Zero shifts are associated with the amplitude linearity characteristics of piezoelectric accelerometers. Measurable amounts of zero shift occur when high dynamic stresses are applied to the piezoelectric ceramic as a result of shock motions far exceeding the rated range of the accelerometer. High dynamic stresses and zero shifts can also be produced as a result of large amplitude oscillatory frequency components near the resonance frequency of the accelerometer. The zero shift characteristic is studied by calibrating accelerometers known to be significantly nonlinear at accelerations up to 10,000 g. Figure 3A is an example of a calibration on the Model 2213E Accelerometer which is rated for use at accelerations up to 1000 g. It is observed that the output fails to return to zero at the conclusion of a 2500 g shock pulse. The applied acceleration is indicated by the Model 2270 Accelerometer Standard whose output is inverted in Figure 3. The standard shows no zero shift. The zero shift in the Model 2213E is an indication of high dynamic stresses; the dimensions of the piezoelectric ceramic do not return exactly to the original dimensions immediately after the end of the pulse. Stress relaxation occurs. A finite period of time is required for the ceramic material to return to the original dimensions it had prior to the application of the shock motion. The greater that the applied acceleration exceeds the rated amplitude range, the larger will be the amount of zero shift. The zero shift, expressed as a percentage of the peak acceleration, is usually less than the percentage increase in sensitivity at the applied acceleration as indicated in Figure 1. For example, at 2500 g the sensitivity of Model 2213E increases about 10%, whereas the zero shift in Figure 3A is only 6%. Although the peak acceleration for the simple pulse shape in Figure 3A could be corrected from the known amplitude linearity deviations, it is not practical to do so in most test applications because high frequency outputs are usually superimposed upon the pulse. When resonance frequency excitation is present, the zero shifts are sometimes in the negative direction apparently due to high negative stresses being applied to the ceramic. The zero shift also makes it very difficult to perform accurate integration for those applications where the velocity change of the shock motion is desired.

3.0 ZERO SHIFTS (continued)



(a) 2213E, 2500 g

(b) 2292, 10,000 g



(c) 2260, 500 g

(d) 2261C, 2000 g

Figure 3.
Shock motion calibrations indicate measurable zero shifts occur in piezoelectric accelerometers when the indicated acceleration greatly exceeds the rated amplitude range. No zero shifts are present in piezoresistive accelerometers. The inverted pulse is the output from the Model 2270 accelerometer standard.

The obvious solution to the problem of zero shifts when using piezoelectric accelerometers is to select more linear accelerometers which produce smaller zero shifts. At 10,000 g, Figure 3B shows that the Model 2292 Accelerometer does not produce a measurable zero shift. The decay of the resonance frequency excitation ends at the zero line present prior to the application of the pulse. The resonant response is due to the resonance frequency of the mechanical system consisting of the shock calibrator anvil and the Model 2270 Accelerometer Standard. Accordingly, the resonant excitation is equally present in both the 2292 and 2270 accelerometer standard outputs. In actual test applications resonance frequency excitation would be limited to resonances present in the specimen being tested. The resonance frequency of the Model 2292 Accelerometer, 125,000 Hz, may also be excited if sufficiently high frequency components are present. It should be expected that zero shifts will be much less likely to occur when using the Model 2292 Accelerometer than when using other accelerometers having larger amplitude linearity deviations than those indicated in the lower part of Figure 1.

The calibrations in Figures 3C and 3D show that piezoresistive accelerometers produce no zero shifts. It is noteworthy that the piezoresistive accelerometers do not exhibit the amplitude linearity and zero shift characteristics present in piezoelectric accelerometers. The piezoresistive accelerometers are more suitable in shock motion applications for which integration of the accelerometer output is desired. Single and double integration(2) can be performed. Small effects may be present due to thermal zero drift and low frequency noise characteristics of the accelerometers. Piezoresistive accelerometers are also useful for many shock motion applications for measurements within their rated acceleration ranges. These accelerometers have the advantage of zero frequency response which is a requirement for measuring extremely low frequency vibrations and long duration shock motions.

The servo type accelerometers are also used in these applications particularly for measurements at low frequencies and at relatively small accelerations and velocities.

4.0 RADIATION EFFECTS ON ACCELEROMETERS

Accelerometers are being used more frequently for shock and vibration measurements in nuclear radiation environments. In addition to measurements made during underground nuclear explosions, there is an increasing need for acceleration measurements in nuclear reactors used for generating electrical power. 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(3) 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(4) were also performed on piezoelectric accelerometers under actual vibration conditions while being subjected to neutron fluences up to 6×10^{14} n/cm^2 with gamma radiation up to 1.6×10^7 roentgens. Most of the piezoelectric accelerometers 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, etc. This faulty operation is typical of noisy or shorted connections in the cable and connectors. It has also been reported(3) that piezoelectric ceramics experience no lattice changes at a neutron fluence as high as 10^{18} n/cm^2.

Although the piezoelectric accelerometers operate normally when subjected to radiation environments, pyroelectric outputs are produced when transient radiation produces significant temperature changes 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. These outputs appear on the surface perpendicular to the polarized axis of the ceramic. The primary pyroelectric outputs are measured in compression design accelerometers because the electrode leads are normally connected to these surfaces. If the piezoelectric ceramics were constrained to prevent any dimensional changes, only the primary pyroelectric outputs would be present. However, 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 because the electrodes are put on the radial surfaces perpendicular 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.

4.0 RADIATION EFFECTS ON ACCELEROMETERS (continued)

The pyroelectric outputs of several accelerometers are shown in the Table. It should be noted that the compression design accelerometers have larger outputs than the shear design.

TABLE

PYROELECTRIC CHARACTERISTICS OF PIEZOELECTRIC ACCELEROMETERS

Ceramic Material	Accelerometer Design	Acceleration Sensitivity	Pyroelectric Output
		pC/g	g/°F
P-8	Compression	60	300
P-8	Shear	10	30
P-10	Compression	13	2000

This is expected because the primary pyroelectric outputs are greater than the secondary outputs, only the latter being present in the shear design. Although the pyroelectric outputs are large, they usually do not produce significant errors when using accelerometers 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. Accordingly, these outputs are usually not measured, but are filtered out by the amplifier. It is expected that blast radiation environments produce negligible heating in accelerometers. Accordingly, there should be only small errors produced as a result of temperature changes present in nuclear energy shock and vibration measurement applications.

Some semiconductor strain gages suffered damage(3) to the silicon crystals at exposures of neutron fluence above 10^{13} n/cm^2 and gamma radiation of 10^8 ergs/g (C). However, other tests(5) showed satisfactory performance of semiconductor strain gages at doses of 10^{14} n/cm^2 and 10^8 ergs/g (C). The ability to withstand very high radiation environments depends upon the particular semiconductor material and processing used. For example, radiation hardened piezoresistive accelerometers 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. It is felt that no detectable neutron damage occurred during the test and that negligible effects occurred due to gamma rays passing through the accelerometer.

5.0 SUMMARY

Piezoelectric accelerometers have the characteristic of increasing sensitivity with acceleration and zero shifts are produced by dynamic stresses present when accelerometer outputs greatly exceed the rated amplitude range. Significant amplitude linearity errors and zero shifts are avoided simply by selecting piezoelectric accelerometers which have a sufficiently high operating range for the measurement applications. However, errors may be present in shock motion applications, when the accelerometer output is integrated to make velocity measurements. It is preferable to use piezoresistive accelerometers for these velocity measurements.

Tests in nuclear radiation environments demonstrate that piezoelectric accelerometers operate normally without any adverse effects in most shock and vibration measurement applications. Although pyroelectric outputs are produced by transient temperature environments, these outputs are usually not measured because of the operating characteristics of charge amplifiers. Measurable pyroelectric outputs may be produced if significant heating were to occur as a result of burst transient radiation. Tests have demonstrated that negligible effects are produced in piezoresistive accelerometers when exposed to transient radiation and in other motion measurement applications in nuclear radiation environments.

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