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Zero Shift in Piezoelectric Accelerometers

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Mechanics Division

September 5, 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

Attempts to measure parameters of severe mechanical shock environments by use of piezoelectric accelerometers are often frustrated by the occurrence of zero shift. This phenomenon defeats measurements by rendering the reference line of the recorded waveform uncertain and perhaps preventing proper operation of recording circuitry as well. Possible causes include improper accelerometer application or recording techniques, as well as the design and material of accelerometer itself. In this study these possibilities have been restricted, so far as possible, to those involving the accelerometer alone, and the reactions of the zero shift phenomenon to variation of several shock parameters observed. Four accelerometers of various materials and constructions have been examined in this way.

Of the two accelerometers which do not exhibit zero shift, one uses a ferroelectric ceramic element in shear mode and with light loading, and the other uses natural quartz in compression mode with moderate loading. Both of the accelerometers which do produce zero shift use ferroelectric ceramics in the compression mode with high loading. High stress on the sensing element is evidently an important factor. Further studies should attempt to explore temperature correlations as well as to separate the effects of element operating mode and stress.

PROBLEM STATUS

This is an interim report on one phase of the problem. Work is continuing on this and other phases.

AUTHORIZATION

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ZERO SHIFT IN PIEZOELECTRIC ACCELEROMETERS

INTRODUCTION

The most widely used electromechanical transducer for general dynamic measurements is the accelerometer, which is essentially a single-degree-of-freedom system operated below its natural frequency. In this region the distortion (motion of the mass relative to the base) is proportional to the acceleration of the base. Provision of a sensing element to furnish an electrical output signal proportional to this distortion results in a device which transduces acceleration input to electrical output. The sensing elements of accelerometers generally used for shock measurements are piezoelectric waiers (which may also function as the spring elements) or strain gage bridges. Each has advantages; the piezoelectric type is capable of much higher natural frequencies, hence good high frequency response, as well as much higher dynamic range. The strain gage types are direct-coupled and may be used with normal strain gage readout apparatus. Accelerometers are usually constructed so that positive acceleration ("into" the base) compresses the sensing element, and polarities are arranged so that compression produces a positive output signal.

One of the most difficult types of motion to measure adequately is that classified as "high-impact shock," such as is encountered in shipboard shock or simulated by the Navy Class H-I Shock Machines. Motion of this type is characterized by a complex waveform encompassing a wide range of frequencies, lasting for a considerable fraction of a second, and involving high levels of acceleration. These characteristics place stringent requirement on the accelerometer and its associated readout equipment. Low frequency response should extend to about 1 cps, high frequency response to around 10 kc, and dynamic range to ±10,000 g. The first requirement is easily met by strain gage types but is difficult to attain with piezoelectric types. These latter are very high impedance charge generators that require high input impedance readout circuitry for long time constants to be realized. The second requirement is at present met only by piezoelectric types which, being essentially undamped, should have a (mounted) first resonance well above the range of frequencies composing the motion at the point of measurement. In practical situations the actual motion at frequencies above about 10 kc may often be seriously altered by the presence of the accelerometer itself. The last requirement, dynamic range, is also met only by piezoelectric accelerometers.

In many cases it may be unnecessary to measure this "raw" shock motion. It may be that the point at which the measurement is to be made is protected by the flexibility of an extended structure and mounting system. More often, it may already be known that only motions with component frequencies lying in a narrow range are important to the investigation. This provides a seductive opportunity to confuse these situations by selecting a measurement setup solely on the basis of the desired measurement. While the motion of interest may contain only a small range of relatively low frequencies having a tractable waveform of fairly low amplitude, it may bear little resemblance to the total actual motion. That part of the motion lying outside the region of interest may well represent an environment with which the accelerometer cannot cope. Thus the accelerometer may display various indications of distress, or may even break up, although the output signal indicates that its ratings are not exceeded.

Accordingly it is advisable that accelerometers with the highest available ratings be used and the region of interest selected by electrical filtering. The disadvantage here is

lack of sensitivity. High ratings (high resonance and high dynamic range) imply low sensitivity from the nature of the single-degree-of-freedom system. In addition, most accelerometers presently available with high ratings use quartz as a piezoelectric material, and while quartz probably remains the best possible material for this purpose, it is singularly insensitive. Since these accelerometers also have low capacitances, the long time constants necessary are difficult to get and sensitivity is further reduced by even a modest length of connecting cable. Both factors contribute to enhancing the importance of cable noise as a component of the measured signal. Because low sensitivity makes high gain essential, filtering should be done at as early a stage as possible to avoid overloads, and care must be taken to keep the noise level as low as possible. The problems of time constant and cable noise can be alleviated by the use of so-called charge amplifiers, but the necessity for filtering before the high gain stages remains. In addition, the operational amplifier input stages of charge amplifiers tend to wander freely at very low frequencies unless a feedback leak is provided. The combination of high gain and low frequency response may not be realizable without degrading the signal-to-noise ratio severely.

The accelerometer should also be evaluated experimentally, since manufacturer's ratings often bear very slight resemblance to actual capabilities. The most common fault seems to be that dynamic range is stated for positive acceleration only, and the number given appears to be derived from an estimated static acceleration field which would strain some element of the accelerometer inelastically. This type of rating may be a source of emotional gratification but is of little practical value. Since H-I shock is double-sided, the accelerometer must have a high dynamic range for negative accelerations as well as for positive. Actual trial shows that many accelerometers succumb (or show signs of distress) at much lower acceleration levels for negative inputs than published ratings for positive inputs.

ZERO SHIFT

One of the most depressing eccentricities of piezoelectric accelerometers exposed to H-I shock is that of zero shift, which is observed as an offset of the zero acceleration line of the recorded trace, generally occurring at an early stage of the shock motion. It may take place in either direction, although some accelerometers have strong preferences for one direction or the other, and it may be of considerable magnitude. It is also a quasi-permanent effect, rolling off at the shortest time constant of the readout circuitry.

The readout circuitry may be a source of zero shift. The full band output of a wide-range accelerometer has a complex waveform containing frequencies beyond the range of interest and probably enriched by the accelerometers own natural frequencies. It is unlikely that the recording channel is arranged to monitor all of this, and the rejected segment may be of much higher amplitude than the recorded signal of interest. These unrecorded components of the original signal may entail signal levels which exceed the linear range of some element in the readout circuitry. Their partial rectification could appear in the record as a sudden dc component. This may be particularly noticeable if the responsible element does not respond equally to positive and negative signals (either in gain or overload characteristics), or if the accelerometer signal is one-sided. Stages preceding filtration are particularly susceptible to overload such as this, as is the filter itself. The filter may also be a source of zero-line uncertainty if its low frequency response is not adequate.

In addition to these electronic mishaps zero shift may originate in the accelerometer. It is common to find that while a value is given for the output of an accelerometer in response to a low cross-acceleration ("crosstalk") no further consideration has been given to the effects of sidewise acceleration inputs. A unit may withstand high accelerations along its sensitive axis (in a positive direction at least) but be damaged by much

lower cross-accelerations. In particular, its component parts may move around physically with resulting changes of capacitance and sensitivity as well as zero shift in its output. This is facilitated by the presence of a high negative acceleration along its sensitive axis coincidentally with the cross-acceleration, since this tends to relieve the preload, which in some cases is all that holds the accelerometer together.

In some instances, dynamic range ratings are so frivolous that an attempt to measure negative accelerations of what would be expected to be a perfectly acceptable level results in gross separation of the accelerometer from the surface when the preload of the hold-down stud is exceeded. Case distortion due to improper torque, angled mounting holes, and rough mounting surfaces may also have internal effects which vary under dynamic conditions, leading to zero shift. A similar source is that in which the accelerometer is mounted properly but to a surface which deforms in motion, such as the top surface of a bending beam. Case distortions resulting from these dynamic strains can be sizable and have much the same result as case distortions arising from improper mounting conditions.

Finally, processes may occur in the piezoelectric sensing material itself. This is usually a ferroelectric ceramic such as $BaTiO_3$ or $PbTiO_3$-$PbZrO_3$ with various impurities. The dissipation factor for the frequencies involved in accelerometry seems to be a largely uncontrolled variable and is usually high. When the high stresses involved in H-I shock measurements are also considered, it seems plausible that repolarization of some sort might take place under extreme dynamic conditions, and this would be revealed by a zero shift.* In this case the onset of zero shift should be strongly affected by temperature. Most of these materials are perovskites and may permit slight structural reorientation as a strain relief mechanism. The charge transfer associated with such a process might also be associated with zero shift. Other possible factors are the presence of impurities, which can be ionized by high stress levels, or changes in the relative importance of surface layer and volume parameters. Whatever the mechanism, it does not produce a significant change in the capacitance or sensitivity of the accelerometer permanently. Much remains to be learned about the behavior of these materials under the conditions which may prevail inside an accelerometer. Perhaps the recent studies of charge release associated with shock wave propagation will provide a clue.

AIMS AND APPARATUS

It was desired to restrict the possible mechanisms for zero shift (as far as possible) to those involving the entrails of the accelerometer only. Care was taken to avoid case distortion and mounting surface deformation, and signal levels were kept well within the linear range of the recording circuitry. Since the present investigation was intended as a preliminary survey, only four arbitrarily selected accelerometers were tested at room temperature (70°F). The primary aims were to determine if zero shift could be produced conveniently and predictably and, hopefully, to see if any definite behavior pattern emerged. It is hoped to extend these investigations to determine the influence of temperature.

The acceleration waveforms were generated by the NRL Drop-Tester Accelerometer Calibrator (Fig. 1), which consists of a hardened steel block (the hammer). The specimen accelerometer is attached to this mass, and both are dropped upon another hardened steel block (the anvil). The hammer can be raised 37 in. above the anvil, giving terminal

*One might also speculate on the effect of measuring an accelerometer's capacitance. The usual bridge may place quite respectable field strengths across the sensitive material at 1 kc for perhaps a few minutes. The resulting temperature rise might well be considerable.

velocities up to 14 ft/sec. The pulse length is varied by insertion of appropriate impact pads between the hammer and anvil. This also adjusts the pulse height. When no impact pads are used, the pulse length is 40 μsec, and accelerations in excess of 20,000 g are obtainable. For these tests, a fixture was fabricated which permitted the use of two accelerometers back to back, and which could be readily inverted to change the sign of the input acceleration. All mating surfaces of this fixture were ground flat and lightly oiled before assembly. The fixture was held together and fastened to the hammer with 1/2 in., 13 Allen screws. These were checked frequently and never found to have loosened.

The specimen mounting blocks form the cross bar of the fixture (see Fig. 1). Several were made to provide the variety of mounting holes required by the specimen accelerometers. In fabrication, these blocks were first drilled through and the hole tapped from one surface to provide for a standard accelerometer. The hole was then enlarged (when necessary) and tapped from the other surface for the specimen, and each surface machine finished perpendicular to the axis of the through hole. Finally, each surface was ground smooth and flat. This routine avoided the more common problems of mounting surface conditions. Considering in addition the dimensions of the mounting block (1-1/4 in. square over an unsupported span of 1-1/4 in.) and that all accelerometers were torqued to 20 in.-lb, it is felt that case distortion effects were minimized as a source of zero shift.

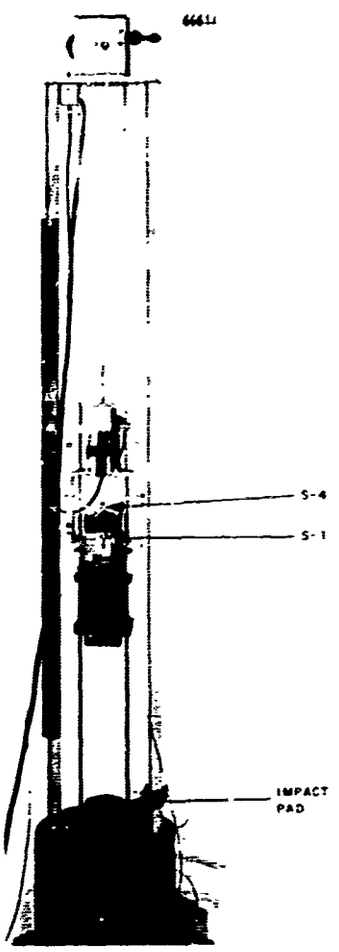


Fig. 1 - NRL Drop-Tester Accelerometer Calibrator showing accelerometer S4 mounted for positive input and S1 for negative input. The impact pad in place provides a pulse length of 10 msec.

The readout circuitry consisted of 10 ft of low-noise cable (about 300 pf) and a cathode-follower with 5000 megohm - 37 pf input impedance feeding paralleled cathode-ray-oscilloscope (cro) and string-oscillograph recording channels (Fig. 2). The input time constant was thus always greater than 2 sec, usually on the order of several minutes. The output circuit of the cathode follower was modified to provide a coupling time-constant of 1 sec with the cro-oscillograph recording combination. Since the cathode-follower itself was essentially flat to about 0.01 cps and the rest of the electronics were direct-coupled, the low frequency limit was set by this 1-sec interstage time constant. The high frequency response was limited to 1 Mc for the cro by the cathode-follower and to 5 kc for the oscillograph by the galvanometers.

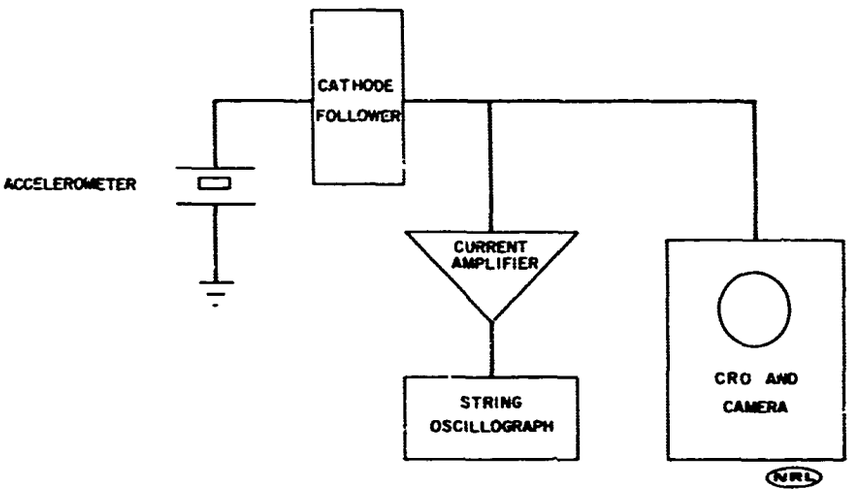


Fig. 2 - Block diagram of readout electronics. Both the cro and the current amplifier-string oscillograph combination are direct-coupled. The shortest time constant of the system is 1 sec, between the cathode follower and the recording units.

SPECIMEN ACCELEROMETERS

Since the behavior of accelerometers under extreme conditions is questionable and is in fact the subject of this investigation, it is perhaps improper to speak of a standard accelerometer. As used here this term refers to a specimen accelerometer which gave the most rational and consistent records. This particular unit had been used for H-I shock measurements for some years, but the other specimen accelerometers were new. It was intended that these tests should be the first use of the specimens (apart from the testings of the manufacturers). The selection of this unit as the standard was arbitrary, although its capabilities were known to be higher than the others. Postfacto justification for the choice comes from comparison of its behavior with theirs.

The characteristics of the specimen accelerometers are listed in Table 1. Two values are given for minimum usable pulse length. The first is from the traditional rule of maintaining a 10:1 ratio between the resonant frequency of the accelerometer and the frequency of the excitation. The second follows from a 3:1 ratio. The choice of minimum usable pulse length depends on how much hash one is willing to tolerate on the output record. Since the amplitude of the transient response varies much more rapidly with frequency than does the magnification ratio, the pulse length may correspond to a frequency region in which the calibration factor of the accelerometer is essentially unaffected,

Table 1
Characteristics of Specimen Accelerometers

Accelerometer	Capacitance (pf)	Sensitivity (pc/g)	Mounted Resonance (kc)	Minimum Pulse Length (μsec)	Maximum Acceleration (g)	Temperature Range (°F)	Mass (+ stud mass) (grams)	Stud Thread (+ material)
S1	666	0.56	60 (nom)	62 to 19	20,000	-65 to +230	12.8 (1.7)	10 to 32 (S.S.)
S2	1,758	51.3	19 (nom)	263 to 79	10,000	-165 to +400	22	1/4 to 28 (S.S.)
S3	118	1.056	36.5	137 to 41	10,000	-320 to +400	19.9 (0.7)	10 to 32 (Be.Cu)
S4	10,547	132	30 (nom)	165 to 50	1,000	-65 to +350	31.2 (1.7)	10 to 32 (S.S.)

while the output pulse signal may be liberally enriched by the natural frequency of the accelerometer.

The piezoelectric materials used in these accelerometers are identified only by registered trade names, except for unit S3 which is described as natural quartz. The sensitivity listed for S2 was derived from the data furnished by the manufacturer, assuming capacitance to be given in picofarads and sensitivity in mv/g, since no units are mentioned. The mounting stud of this unit is integral with its base, while those of the others are removable.

PROCEDURE

The appropriate surface of the mounting block was cleaned with acetone and coated (after drying) with a thin film of light machine oil; then accelerometer S1 was attached with a torque of 20 in.-lb. One of the remaining specimens was similarly attached to the opposite surface, and the mounting block was bolted to the hammer of the drop tester. After connectors of both accelerometers and connecting cables were cleaned with acetone and allowed to dry thoroughly, the cable was attached to the accelerometer. The accelerometers were not removed from the mounting block nor the cables disconnected until the series was completed. Then the cable was disconnected and the torque checked before the accelerometer was dismounted. The cable was disconnected at the cathode-follower end when necessary for calibration of the readout circuitry. When peak signal levels approached the limit of the linear range of the readout, the input was paralleled with extra capacitors (built into the cathode follower), the total capacitance remeasured, new calibration factors calculated, and the readout system recalibrated.

After they had been attached and the system calibrated, the accelerometers were subjected to pulses from 50 g to 10,000 g in amplitude (nominally 1/2-sine wave). Impact pads were changed when required by the limited velocity range available. The two used most provided pulses of 10 msec and 300 μsec, but occasionally 900-μsec and 100-μsec-pads were also substituted. Each time pads were changed a series of blows with the new conditions was performed using pulse heights equal to those of the previous series to reveal possible effects from the change in pulse length alone. The basic series of blows at each level was positive, negative, negative, positive for the specimen accelerometers (and, of course, the opposite for the standard S1).

The oscillograph record was used as the zero shift indicator. Since its bandwidth was limited, its scale factors could be set with regard to the magnitudes of pulse components within this limited band only. Fairly high sensitivities could thus be used without overdriving the galvanometers. The cro record was used to determine pulse parameters and waveform, and its scale factors were set by the requirement to display all components of the pulse waveform. Sensitivities for the cro recordings were consequently much lower than those for the oscillograph recordings.

The pulse parameters were inferred from the cro record of S1. Even this simple fixture and hammer combination behaves in a complex manner when subjected to short, high energy pulses, and a medley of frequencies at the free end is inevitable. The fundamental frequency of the bare hammer (about 20 kc) is excited by the impact and filtered by the structure of the test fixture, which in turn introduces some modes of its own. These will also be dependent on the impedance of the particular accelerometer being tested. The net input to the accelerometer is a wobbly-sided pulse accompanied by much high frequency hash. Consolation may be found in the fact that this is a much better approximation of H-I shock waveforms than is a simple pulse. Since the pulse records were not clean, simple waveforms, their heights (for both standard and specimen) were taken as being the most extreme values legible on the record, the averaged value being about half this reading. The pulse length was also largely a matter of personal preference; a bias was taken towards smaller values. This time interval may be longer than the listed value but is unlikely to be shorter. We excuse this somewhat unorthodox procedure by observing that the recorded pulses are each transmogrified by the inadequately known characteristics of an accelerometer. Since it is not permissible to assign all of the hash to the accelerometer, we have selected the most sensible record as the closest approximation to the input acceleration waveform and have taken extreme values from it. While almost certainly in error, the record of S1 should be reasonably close to reality (due to its high first resonance) and values taken from it establish an acceptable upper limit. A similar procedure for the specimen accelerometer is more easily defended. The extreme peak of its response indicates the extreme peak of its "distortion," hence the maximum strain of its sensing element. This is the parameter, rather than the actual maximum input acceleration, most likely to be associated with zero shift (at a given temperature) if a repolarization mechanism or inelastic behavior is responsible.

The pulse lengths obtained at the accelerometer location for various pulse heights from the above procedure are listed in Table 2. Multiple entries indicate regions of overlap where it is possible to attain a given peak acceleration with more than one impact pad.

Table 2*
Pulse Lengths Obtained at the Accelerometer Location for Various Pulse Heights

Input Pulse Height (g)	Pulse Length (μsec)
50	11,000
100	10,000; 900; 600
200	900; 450
500	450
700	350
1000	330
1500	300
2000	250
4000	250
5000	200
10,000	175

*Multiple entries indicate regions of overlap where it is possible to attain a given peak acceleration with more than one impact pad.

RESULTS

Figure 3 shows the responses of the specimen accelerometers to (nominally) identical inputs. The time scales (horizontal) are 200 μsec/cm for S1, S3, and S4, and 100 μsec/cm for S2; the acceleration scales (vertical) are 1000 g/cm for S1, S3, and S4, and 4000 g/cm for S2. In justice to S2 it should be noted that its natural frequency is nominally 19 kc (and seems to be about 16 kc in actuality), whereas S1, S3, and S4 all indicate a strong component in the neighborhood of 15 kc. In addition, it received a higher pulse than the others due to machine variability. Input pulse parameters (taken from S1's output extreme values) were 1400 g by 320 μsec for S1, 1800 g by 250 μsec for S2, and 1300 g by 320 μsec for both S3 and S4. We might remark that this is an overload for S4 (rated to 1000 g), so the 35 kc garnishing its output may be regarded with a forgiving eye. It will also be noted that S3 deviates from tradition by providing a negative output for a positive input. This may indicate that the manufacturer expects these units to be used with inverting amplifiers.

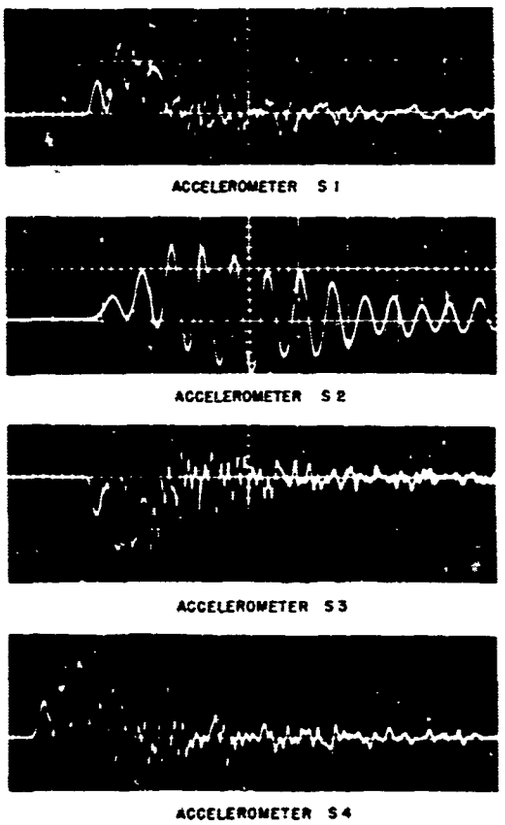


Fig. 3 - Responses of specimen accelerometers to identical inputs. Scale factors are 1000 g/cm and 200 μsec/cm for S1, S3, and S4, and 4000 g/cm and 100 μsec/cm for S2.

The machine variability leading to the pulse parameters variation mentioned above is the result of disturbing a setting and then returning to it. Slight changes in impact pad positioning, etc., make noticeable differences in pulse parameters, which are greatly accentuated by the procedure of taking extreme values of S1's output as indicators. If a setting is not altered, the blow to blow reproducibility is quite good, as Fig. 4 indicates. The accelerometer block was inverted before the last of these three blows, effectively interchanging the locations, but little change occurs in the output waveforms. Scale factors for all of these traces are 500 g/cm vertical, 200 μsec/cm horizontal.

As the pulse height increases, the output waveforms become affected by the pulse polarity. Only S1 retained substantially unchanged waveforms for both positive and negative pulses over the entire range up to 10,000 g. At levels above about 1000 g all the others showed marked differences, as in Fig. 5 (1000 g/cm by 200 μsec/cm). At about this level zero shift made its appearance in the outputs of S2 and S4 (Fig. 6).

Accelerometer S1

This accelerometer remained well behaved throughout the test series, in the course of which it was subjected to as many blows as the rest of the specimens put together (by

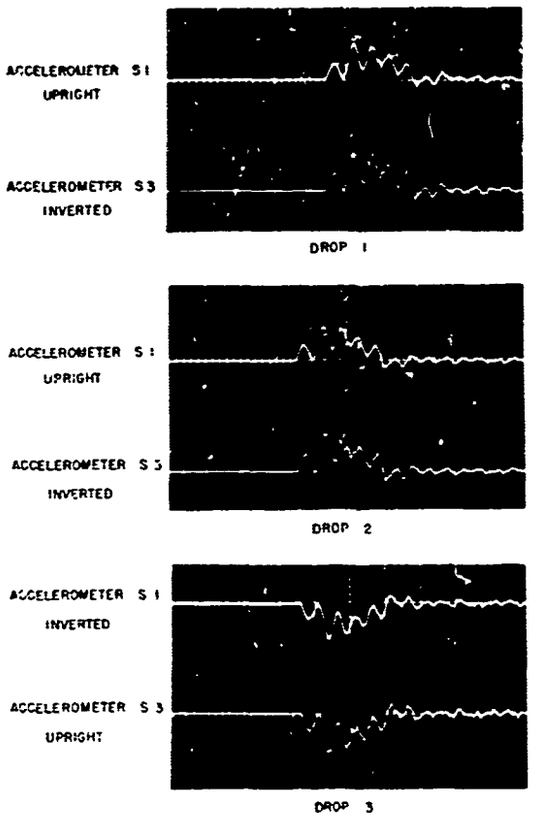


Fig. 4 - Three successive blows with unchanged machine settings. Scale factors are 500 g/cm and 200 μsec/cm. Waveform reproduction is good, even when the accelerometer block is inverted (drop 3).

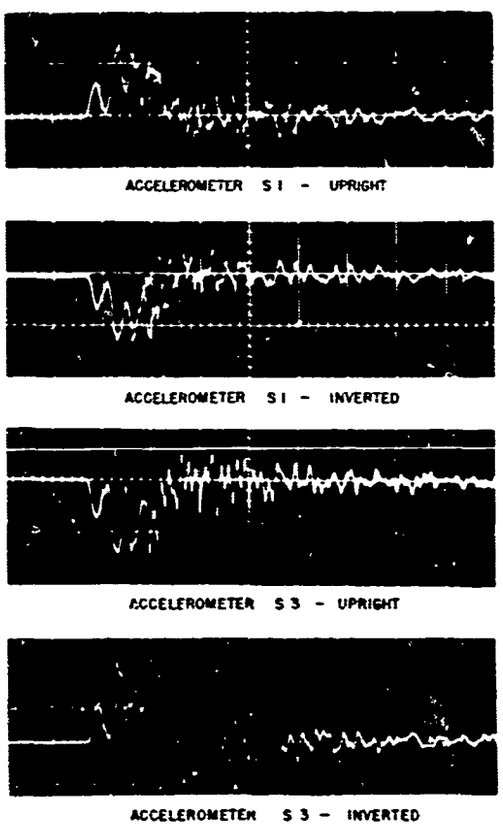
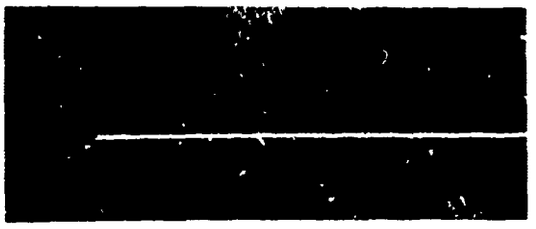
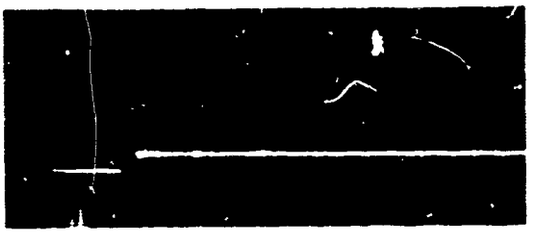


Fig. 5 - Effect of input pulse polarity on output waveform. S1 is changed slightly, S3 considerably. Scale factors are 1000 g/cm and 200 μsec/cm.



ACCELEROMETER S4, POSITIVE INPUT



ACCELEROMETER S4, NEGATIVE INPUT

Fig. 6 - Zero shift of accelerometer S4 for positive and negative 1500-g, 320-μsec inputs. Note that shift is positive for both input polarities. Vertical scale factors are 500 g/cm, horizontal 10 msec/cm. Peak indicated outputs are 1700 g.

virtue of being appointed as a standard). No indications of zero shift were found, and waveforms remained reasonable even for peak outputs up to 20,000 g. Waveform variations were essentially the normal growth of fine structure as input levels increased, and slight variations resulting from polarity reversal may well have been actual due to the inversion of the accelerometer block. From some years of previous use this unit was known to be easily capable of H-I shock measurements, and its natural frequency to be more like 100 kc rather than the 80 kc claimed. This high natural frequency, coupled with its low sensitivity (low even for shear mode $BaTiO_3$) indicate very low operating stresses in the sensitive element, promising high dynamic range. Its sensitivity, like most piezoelectric accelerometers, does increase slightly as input levels increase, but not significantly, being only a few percent higher at 10,000 g than at 100 g.

Accelerometer S2

Figure 7 illustrates the progress of zero shift as the input level is increased. Abscissa values are taken from S1's record. The ordinates show shift magnitude in hundreds of g, taken from S2's oscillograph record, and relative shift in percent of S2's peak output signal, taken from its cro record. Since the shift is only a few percent of the peak output, it is not noticeable on the cro trace, which is scaled to the peak output. However, on the oscillograph record it is very striking. Here the record is restricted to the normal bandwidth of H-I shock measurements, and scaled for the components in this range. The shift becomes noticeable at a level of 750 g, where S2's peak output indicated 1000 g,

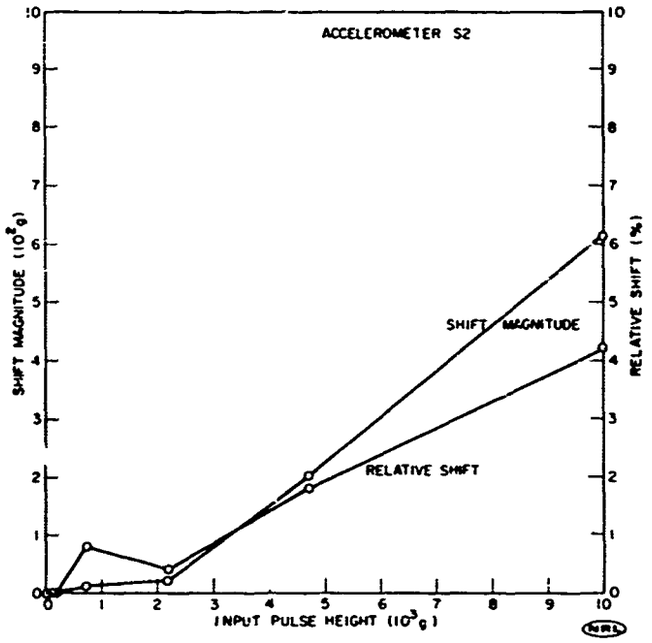


Fig. 7 - Zero shift of S2 as a function of input pulse height. Zero shift is plotted by absolute magnitude read from oscillograph record and the same as a percentage of peak output read from cro record. Abscissas are read from cro records of S1. Each point is the average value for all blows of the same input energy and impact pad.

and becomes progressively worse. Combined with the waveform's variations due to input polarity, it would seem that this unit's peak rating of 10,000 g is somewhat optimistic.

For peak outputs of 1000 to 5000 g the shift is always positive regardless of the polarity of the input pulse. When the peak output exceeds 5000 g, the shift takes on the same polarity as the input pulse. The ordinates of Fig. 7 (and also Figs. 8-10) are averaged absolute values. Abscissa points to which they correspond are also the average values from all blows of common input energy and impact pad.

Figure 8 shows the typical shift pattern resulting from changes in excitation. With repeated 10,000-g input pulses the zero shift becomes progressively less and does not appear at blow 4. A pause of 16 hr (marked +) between blows 3 and 4 does not seem to affect this progress. Decreasing the pulse height to 2500 g (marked ↓, between blows 4 and 5) restores the shift, which again progressively decreases for subsequent blows. Raising the pulse height back to 10,000 g (marked ↑, between blows 7 and 8) again restores zero shift which as before gradually becomes smaller. Finally, reversing the input pulse polarity from +10,000 g to -10,000 g (marked ↕ between blows 12 and 13) restores zero shift to even greater heights.

This accelerometer might be expected to be troublesome for H-I shock measurements from data in Table 1. The low frequency, high capacitance, and high sensitivity all bespeak excessive crystal stresses.

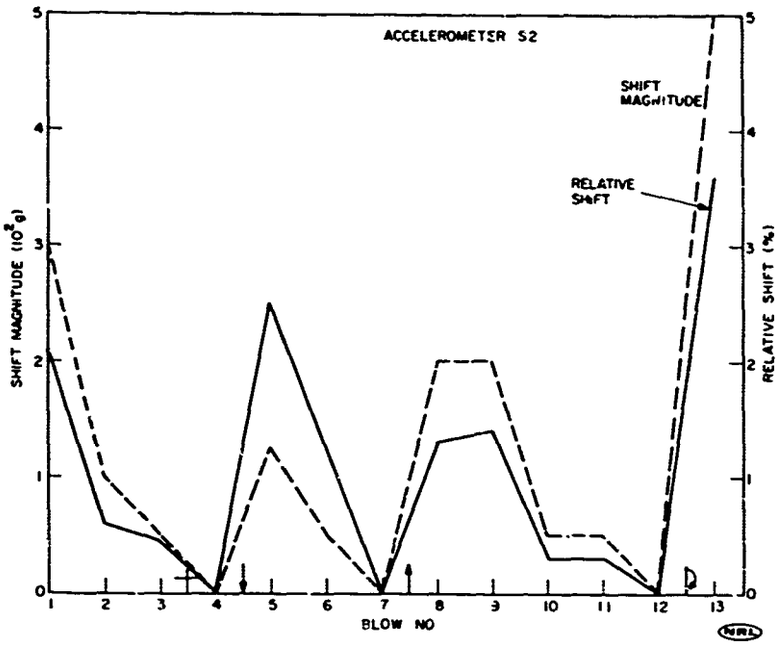


Fig. 8 - Absolute value and percentage of peak output of zero shift from S2 for a series of 13 blows. Repeated blows providing 10,000 g input pulse heights result in progressively less shift. A 16-hr rest period (+) has no effect. Decreasing the pulse height of 2500 g (↓) restores zero shift, which vanishes with additional blows. Raising the pulse height to 10,000 g (↑) once more restores zero shift, which again decreases with additional blows. Changing the input pulse polarity from positive to negative (P) also restores zero shift.

Accelerometer S3

Like S1, this unit showed no signs of zero shift for any input. The piezoelectric component in this instance is natural quartz which is famous for its stability. While satisfactory on the point of zero shift, S3 is unsuited to H-I shock measurements. The claimed natural frequency of 35 kc is adequate, and is not overstated, but output waveforms are seriously different for positive and negative input polarities at peak outputs above 1500 g, and noticeably so above 1000 g. When the peak output exceeds 8000 g for inputs of either polarity, the waveform is considerably distorted in addition. Little confidence therefore could be placed in H-I shock measurements made with S3.

Accelerometer S4

The very high capacitance and sensitivity of S4 (Table 1) indicate correspondingly excessive crystal stresses, in line with its maximum rating of 1000 g. However, it was also tested to inputs up to 10,000 g, since previous versions of this type were rated to this value and were known to exhibit zero shift when exposed to H-I shock. As Fig. 9 indicates, zero shift is substantial when input pulse heights exceed the rated maximum. More disconcerting is the presence of the branch marked A-B. Once zero shift had been initiated by exceeding the accelerometer's rated range it would also occur for inputs well within this range, whereas previously shift had been slight or nonexistent. Another

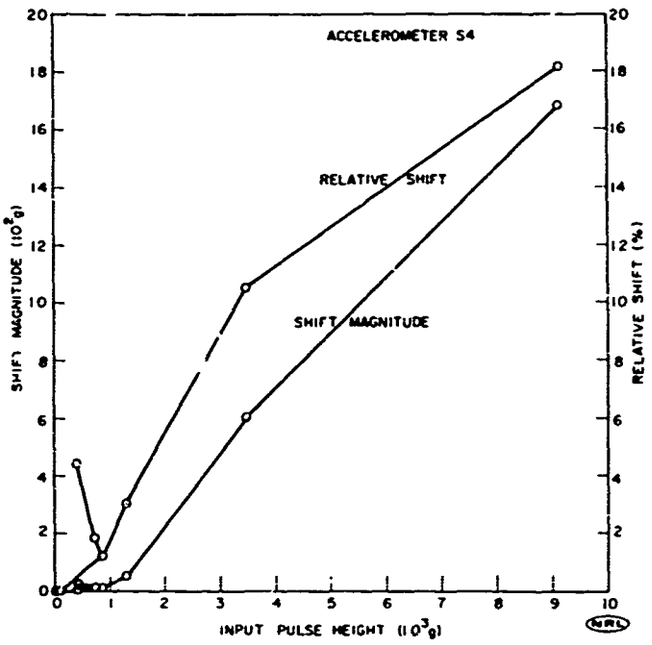


Fig. 9 - Zero shift of S4 vs input pulse height. The shift is plotted by absolute value and as a percentage of peak output. Input heights are taken from S1 records. Each point is the average value for all blows of common input energy and impact pad. The arm A-B indicates that once the shift has been initiated, it will appear at lower input levels where it previously did not.

peculiarity of S4 is that shift was almost invariably positive regardless of the input polarity. On only about a dozen blows (out of 160) was a negative shift observed, also without regard to input polarity and for no discernible reason. All attempts to induce negative shift on later occasions were unavailing, including varying the laboratory temperature over the range 60° to 80°F.

Figure 10 shows the zero shift pattern for a sample run of blows, the event markers having the same meaning as in Fig. 8. As for S2, shift can be reduced by repeated blows and restored by changing the pulse height (750 g to 1500 g) or polarity. In addition, however, rest periods are equally effective in restoring zero shift, which is not the case for S2. Even a rest period of 30 min is adequate.

Output waveforms for positive and negative inputs match quite well up to peak outputs of 10,000 g where the waveforms start to flatten off but are generously embellished with a 30-kc component above the 800-g level.

CONCLUSION

Of the two accelerometers which do not exhibit zero shift, one uses a ferroelectric ceramic element in shear mode and with light loading, and the other uses natural quartz in compression mode with moderate loading. Both of the accelerometers which do produce zero shift use ferroelectric ceramics in the compression mode with high loading. High stress on the sensing element is evidently an important factor. Stress relief

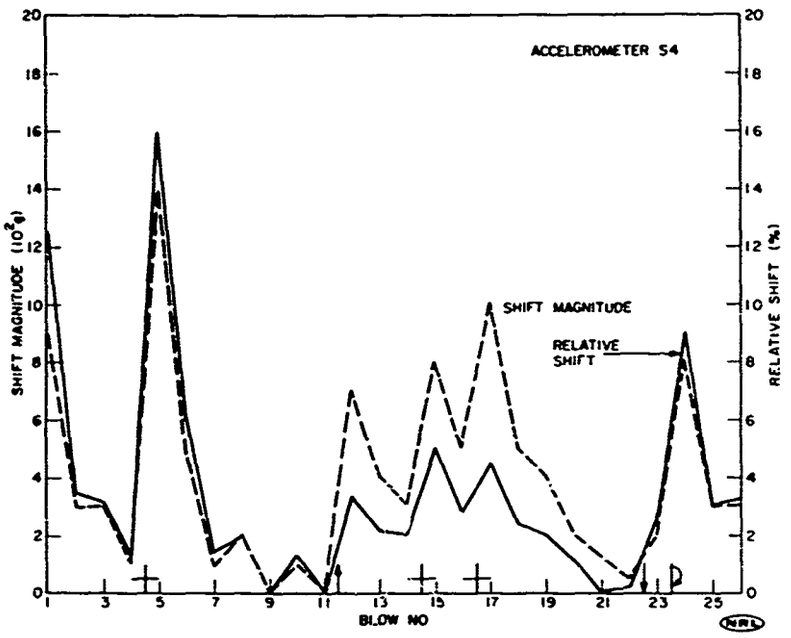


Fig. 10 - Zero shift (absolute magnitude and percentage of peak output) from S4 for a 26 blow series. In addition to the behavior of S2 (Fig. 8), the zero shift is restored by rest periods as short as 30 min. The upper pulse height is 1500 g; the lower pulse height is 750 g.

mechanisms can be envisioned, such as structural realignment and domain wall motion, but since the accelerometer's capacitance and sensitivity do not seem to be affected permanently presumably the gross polarization of the element is not either. Some significance may be attached to the fact that the compression mode of operation aligns the mechanical axis of the sensing element along the pyroelectric axis.

It is possible to condition an accelerometer by repeated application of identical inputs so that its zero will not shift, but zero shift will recur if input level or polarity is changed and perhaps if the accelerometer is allowed to rest. Accordingly, relaxation processes of some description are involved and should be strongly affected by temperature. Further studies should attempt to explore temperature correlations as well as to separate the effects of element operating mode and stress. Very likely an accelerometer of practically any piezoelectric material and construction can be made to show zero shift if hit hard enough and may show a very slight zero shift even at low input levels if sufficiently good measurements can be made.

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13. ABSTRACT

Attempts to measure parameters of severe mechanical shock environments by use of piezoelectric accelerometers are often frustrated by the occurrence of zero shift. This phenomenon defeats measurements by rendering the reference line of the recorded waveform uncertain and perhaps preventing proper operation of recording circuitry as well. Possible causes include improper accelerometer application or recording techniques, as well as the design and material of accelerometer itself. In this study these possibilities have been restricted, so far as possible, to those involving the accelerometer alone, and the reactions of the zero shift phenomenon to variation of several shock parameters observed. Four accelerometers of various materials and constructions have been examined in this way.

Of the two accelerometers which do not exhibit zero shift, one uses a ferroelectric ceramic element in shear mode and with light loading, and the other uses natural quartz in compression mode with moderate loading. Both of the accelerometers which do produce zero shift use ferroelectric ceramics in the compression mode with high loading. High stress on the sensing element is evidently an important factor. Further studies should attempt to explore temperature correlations as well as to separate the effects of element operating mode and stress.

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