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ZEROSHIFT OF PIEZOELECTRIC ACCELEROMETERS IN PYROSHOCK MEASUREMENTS

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ZEROSHIFT OF PIEZOELECTRIC ACCELEROMETERS IN PYROSHOCK MEASUREMENTS*

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Zeroshift, a common measurement error in piezoelectric shock accelerometry, is any spurious output baseline shift which occurs after a pyroshock event. In this paper, all components of the shock measurement system are analyzed for sources of zeroshift, and preventive practices are presented to aid in equipment selection, setup, and operation.

INTRODUCTION

In acceleration data, zeroshift refers to any spurious baseline shift which occurs in response to a transient acceleration. This effect has been documented since the early 1950's. In 1971, Plumlee [1] and Davis [2] of Sandia Corporation published technical studies in which contributions to zeroshift from high-g shock effects in the ferroelectric ceramics were examined at great length. These reports, however, did not treat the contributions of other sources in the total measurement system. Recently, Schelby [3] published recommendations for measuring high-level, short-duration shock waveforms, and summarized them into an overall system specification.

Early research at Endevco indicated that zeroshift effects can be created in the accelerometer, the cable, and/or the electronics. This paper presents the results of a recent reevaluation of zeroshift causes, considering all the components of the measurement system. The study indicates that, in addition to effects within the ferroelectric material, other sources such as slippage of internal parts, cable noise, straining of sensing element, inadequate system low frequency response, and overloading of electronic circuits can also lead to zeroshift. This paper shows that, for most shock measurements, zeroshift can be minimized or eliminated through proper component selection and instrumentation system setup.

BACKGROUND

High level transient acceleration or shock response of an object under test is commonly measured by a piezoelectric accelerometer, which converts sensed motion into electrical signals for recording and analysis. Any differences between the accelerometer output and the actual input acceleration represent errors which may invalidate the test results. Zeroshift is commonly defined as failure of the electrical output of a piezoelectric accelerometer to return to its original zero baseline after an acceleration transient. This shift can be of either polarity and of unpredictable amplitude and duration.

Samples of two similar acceleration-time histories are shown in Figures 1A and 1B. Figure 1A shows an accurate measurement of a pyroshock event, with a maximum amplitude of about 50,000g peak. The high frequency ringing is superimposed on a baseline which is unchanged from the preshock level. Figure 1B shows a similar pyroshock waveform, but the high frequency components are superimposed on a baseline which has shifted by nearly -40,000 g from the preshock level. The step change in output in Figure 1B appears to indicate that the test specimen has suddenly experienced a constant negative acceleration of 40,000g. Such large zeroshifts are normally detected during the test run and recognized as spurious because they represent impossible accelerations. Correction of the problem and retest, however, can be a costly undertaking and can result in unintentional overtest of the specimen. Lower levels of zeroshift often go unnoticed and create errors in subsequent data processing. Integrating an acceleration-time history with zeroshift yields unrealistic velocity and displacement results, and zeroshift can introduce errors in the low frequency portion of the shock response spectrum. Compensating for zeroshift requires making assumptions and interpretations, which can then be the source of unacceptable errors. The best approach to the zeroshift problem is prevention.

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*This paper was presented in the Pyrotechnic Shock Workshop at the 57th Shock and Vibration Symposium.

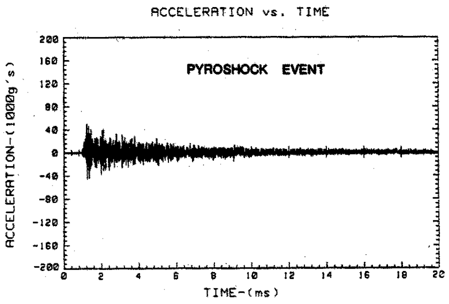

FIGURE 1A PYROSHOCK TIME HISTORY

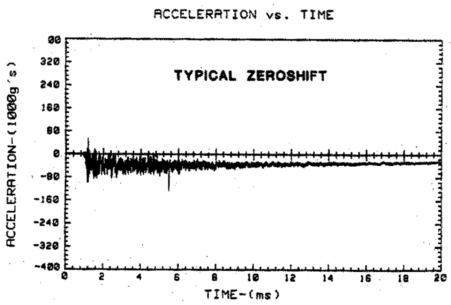

FIGURE 1B TYPICAL ZEROSHIFT

CAUSES OF ZEROSHIFT

Efforts to prevent zeroshift must be based on an understanding of all causes of zeroshift. In this study, each known cause of zeroshift has been separately investigated, insofar as possible. Testing was conducted using shock wave generated by Hopkinson bar, hammer drop, and flexible charge (pyrotechnic) cord. The causes of zeroshift that were investigated are:

(1) Overstress of sensing elements,
(2) Physical movements of sensor parts,
(3) Cable noise,
(4) Base strain induced errors,
(5) Inadequate low frequency response, and
(6) Overloading of signal conditioner.

A detailed treatment of each cause of zeroshift is presented in the following sections. In some instances, there are component choices or system configurations which minimize or eliminate a particular cause of zeroshift. Experience has shown, however, that no one cause dominates as a major source of zeroshift. Therefore, to minimize the actual zeroshift in a given test, all of the causes must be minimized or eliminated.

1. Overstress of Sensing Elements

The piezoelectric materials used for the sensing elements in acceleration transducers may be divided into two basic classes; ferroelectric ceramics (such as Lead Zirconate Titanates and Bismuth Titanates), and single crystals (such as Tourmaline and synthetic and natural Quartz).

Ferroelectric materials are made up of many individual crystaline regions or domains, hence the term polycrystalline ceramics. These individual domains are piezoelectric, but are randomly oriented after the material is formed. To produce a usable piezoelectric effect, it is necessary to align the majority of domains so that their piezoelectric axes point in the same direction. This polarization process is typically performed in a strong electric field, and is analogous to the magnetization of iron in a magnetic field [4] [5]. In a well-polarized and stabilized ferroelectric ceramic, piezoelectric charge output is linearly proportional to the amount of tension or compression in the material. However, if the element is overstressed, some of the polarized domains will switch back to their original positions, generating spurious additional output. These switched domains will eventually return to their former positions and as a result, produce no detectable sensitivity change in the accelerometer.

Because piezoelectric accelerometers normally have amplification factors (Q) well over 30dB at resonance, resonant ringing in response to pyroshock inputs will often cause higher element stresses than expected. The resulting domain switching [6] will generate zeroshift. Ferroelectric accelerometers with high effective mass and low resonant frequency are particularly susceptible to this effect.

The amount of domain switching due to a given stress during a transient acceleration depends on the formulation of the ferroelectric material, its polarization processing and its post-polarization stabilization, the pre-stress on the ceramic element, and the ambient temperature. Experiments [1] [2] have shown that the domain orientation seeks a new equilibrium condition for every new combination of stress, E-field, and temperature.

There are two broad classes of ferroelectric ceramic formulations, which differ in their polarization characteristics.

> Low Coercivity materials, such as Lead Zirconate Titanates, which polarize at relatively low voltages. These materials also have high charge coefficients (charge/stress) which result in accelerometers with high output sensitivity. When subjected to a strong mechanical impulse or temperature transient, however, these materials exhibit domain switching rather easily, causing zeroshift at the output.
>
> High Coercivity materials, such as Bismuth Titanates, which require a much higher polarization potential (usually three to four times that of low coercivity materials) to align the crystal domains. These ceramics are much more stable under a wide range of environmental conditions. Consequently, high coercivity materials exhibit considerably less domain switching than low coercivity materials at the same stress/field level. The low charge coefficient, however, limits the output sensitivity of the seismic system, and the low signal level may be more susceptable to other causes of zeroshift, such as cable motion. Most of these effects can be eliminated by using high coercivity material in conjunction with built-in electronics.

Single crystal materials, which include natural quartz, synthetic quartz, tourmaline, etc., do not exhibit the problem of domain switching due to the entire element being one crystal domain. However, since natural crystals cannot be shaped to achieve optimum configurations for use in accelerometers, they are only produced in configurations which are susceptible to other causes of zeroshift, as described below.

2. Physical Movements of Sensor Parts

The stress on the piezoelectric element of an accelerometer is created by the reaction of a seismic mass to the input acceleration. Obviously, any slippage between the mass and the element will result in an output error. In addition, if the accelerometer design utilizes a preload on the piezoelectric element, any slippage will result in the material not returning to its original preload. This step change in preload will show up as a spurious step acceleration on the transducer output.

Current piezoelectric accelerometer designs utilize a variety of construction techniques to support the sensing elements. Some of these designs are intrinsically more complicated than others, and consequently have more internal moving parts. Figure 2A and 2B depict the components of two common shock accelerometer designs.

Figure 2A shows a compression type shock accelerometer, in which preload is required for the crystal to produce linear output in tension. The preload is usually provided by some form of threaded stud in the assembly. When the unit experiences high-g shock, the stress wave travels through the base into the seismic assembly, and the tension portion of the wave can exceed the clamping force. In this relaxed condition, minute relative movements can occur between adjacent components. These slippages can result in spurious output which appears as zeroshift. In applications where the shock wave can impinge on the accelerometer from an off-axis direction, the preload compression construction is even more vulnerable.

Figure 2B shows an annular shear type shock accelerometer, in which no preload is required. The ferroelectric ceramic is secured to the transducer base (and to the seismic mass, if used) with high strength epoxy. This type of design is inherently free from parts movement unless the survival limit of the accelerometer is exceeded. It is equally robust to shock waves impinging from any direction.

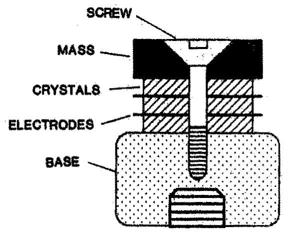

FIGURE 2A COMPRESSION DESIGN

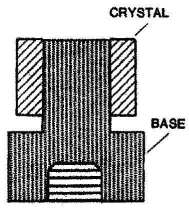

FIGURE 2B SHEAR DESIGN

3. Cable Noise

The direct piezoelectric output of an accelerometer is generated at high impedance, and generally requires the use of coaxial cable for its shielding and constant capacitance characteristics. However, because the output signal is at low amplitude, the coaxial cable itself can be a source of zeroshift. A poorly supported cable can flex sufficiently to produce spurious signals during high-g shocks. This noise generating mechanism is known as the triboelectric effect [7].

When a coaxial cable is physically distorted, as shown in Figure 3, a localized separation between the cable dielectric and the outer shield around the dielectric may occur. As the outer shield separates from the dielectric, the steady state charge distribution becomes unbalanced at the interface. Charges on the dielectric are trapped due to its low conductivity. Charges on the shield, however, are mobile and are neutralized by flowing to the center conductor through the input impedance of the electronic amplifier. This momentary current flow is sensed as a signal by the amplifier input. When the cable distortion is relieved, dielectric and shield are joined together and the formerly trapped electrons now flow into the shield, resulting in a second pulse of opposite polarity.

A typical cable motion induced zeroshift is shown in Figure 4. This experiment was conducted on the Endevco Compression Wave Shock Calibrator with a half-sine input pulse. A high-quality coaxial cable connected the high impedance accelerometer to the charge amplifier. Since the cable was allowed to flex during the shock event, spurious output was generated which appeared as a zeroshift.

4. Base Strain Induced Errors

Base strain or base bending sensitivity is defined as the output from an accelerometer caused by deformation of the surface to which it is mounted. This effect can cause a zeroshift error in some transducer designs. Compression accelerometers require preload for their operation, and usually display a high sensitivity to base strain. In addition to this direct base strain output, it has been demonstrated that mild strain (less than 250 micro-strain) can vary the preload and allow internal part movement which results in a sizable zeroshift.

To demonstrate this effect, several compression and shear accelerometers were tested. Each transducer was mounted near the fixed end of a long steel beam of rectangular cross section. (The details of this apparatus is described in the ISA tentative recommended practice ISA-RP 37.2, Section 6.6.) The units were mounted at their specified mounting torque, and the associated electronics was DC-coupled where possible. The free end of the beam was deflected to produce a 300 micro-strain impulse at the transducer location, as measured by strain gages. The strain step input was maintained for 0.5 second, which created a negligible acceleration at the mounting location.

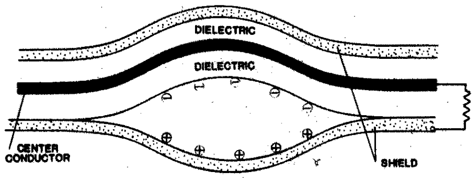

FIGURE 3
TRIBOELECTRIC EFFECT

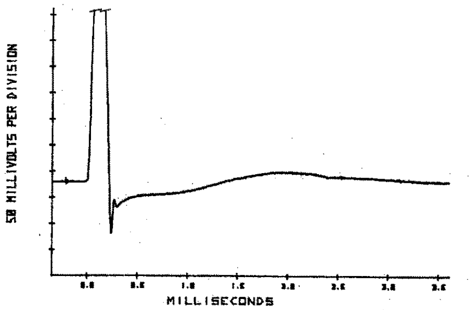

FIGURE 4
ZEROSHIFT DUE TO CABLE MOTION

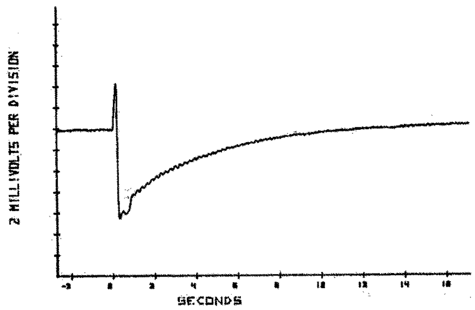

FIGURE 5A
COMPRESSION DESIGN UNDER STRAIN

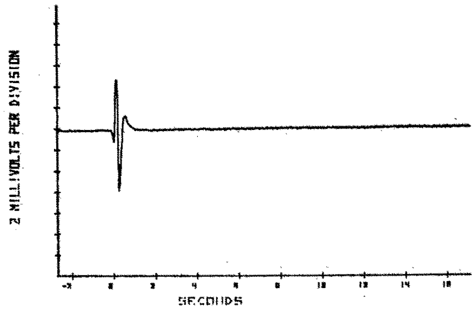

FIGURE 5B
SHEAR DESIGN UNDER STRAIN

Figure 5A shows the output from one of the compression (single crystal Quartz) accelerometers and Figure 5B shows the output from one of the shear (Ferroelectric) accelerometers. Momentary strain outputs were apparent on all units, as indicated by the spikes. The compression accelerometers also produced noticable amount of DC shift after the transient, however. This DC offset returned to zero following the RC time constant of the electronic signal conditioner. The shear accelerometers recovered immediately from the momentary transient, and no hysteresis effect was detected after the transient.

An accelerometer which produces a base strain output within its specification, and is free from DC offsets due to base bending, can nonetheless generate an output which resembles zeroshift. A shock event may contain low frequency bending waves, which may take a long time to die out. A base strain sensitive accelerometer will superimpose a signal due to this low frequency bending input upon the normal pyroshock acceleration signal. Because flexural waves can be at very low frequencies, the resultant data is usually mistaken for zeroshift, even though the accelerometer is operating within its stated specification.

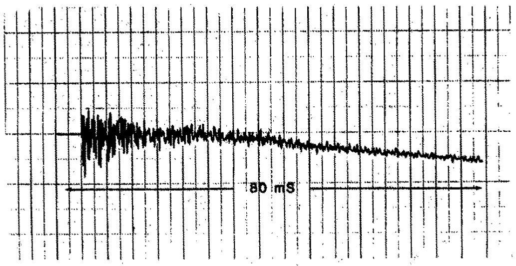

FIGURE 6A

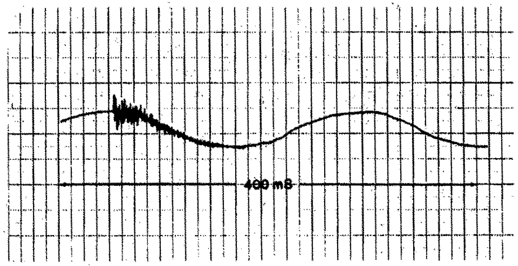

FIGURE 6B

Figure 6A shows the time history of a shock event with a viewing window of 80 milliseconds. By looking at the last portion of the shock recording, one may easily conclude that the transducer has zeroshifted. However, if one were to look at a longer viewing window, as shown in Figure 6B, it is obvious that the shock time history is superimposed on some low frequency signals. These base strain induced low frequency components can be at times larger in amplitude than the real shock data, confusing the operator during data reduction.

5. Inadequate Low Frequency Response

Zeroshift can also be created in the associated electronics. Inadequate low frequency response will result in failure to accurately reproduce the shock pulse. The nature of this distortion can be shown in Figure 7, which shows the theoretical response of an amplifier to a halfsine input pulse. The set of curves indicates the effect of varying the ratio of the RC time constant to the duration of the half-sine input.

As the time constant to pulse width ratio is reduced, amplitude error and post-transient offset become significant. This offset, or "undershoot", is opposite in polarity to the applied pulse. This type of zeroshift is usually associated with low frequency measurements, such as ground movements from explosion, where the pulse is assymetrical and long in duration. Sine-wave frequency response measurements may not provide a valid indication of the low end characteristics of a shock measurement system. For example, a shock calibration system which measures -3dB at 1Hz in a sinusoidal test might exhibit a significant amount of amplitude distortion and undershoot when subjected to a 100 mS half-sine pulse.

6. Overloading of Signal Conditioner

The spectrum of a pyroshock event may contain frequencies far above the passband of the measurement system. This undesired mechanical input can generate signals with higher amplitudes than those in the passband, causing the electronic circuitry to overload. This problem is aggravated by the effect of accelerometer resonance. Although most shock accelerometers have their resonant frequencies above 100 kHz, they can still be excited by pyroshock inputs. These inputs are amplified by the mechanical Q of the seismic system, resulting in very high, out-of-band electrical signals. When a signal conditioner attempts to process this signal, one of its stages is driven into saturation. No only does this clipping distort the in-band signals momentarily, but the overload can partially discarge capacitors in the amplifier, causing a long time-constant transient.

Figure 8 shows the output of a charge amplifier under overload conditions. The output exhibits undershoot which is determined by the discharge rate of its feedback capacitor and resistor when overloaded with an asymmetric input pulse. The severity of zeroshift of a particular signal conditioner depends on its clipping characteristics (whether it reacts equally to positive and negative inputs), recovery time, and the nature of the acceleration signal.

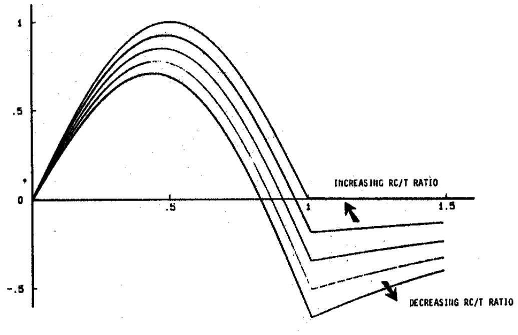

FIGURE 7
ZEROSHIFT DUE TO FREQUENCY RESPONSE

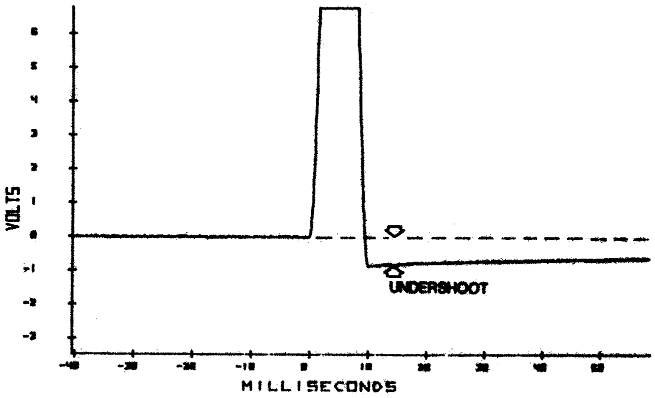

FIGURE 8
ZEROSHIFT DUE TO OVERLOADED ELECTRONICS

GUIDELINES TO MINIMIZE ZEROSHIFT

Since the various sources of zeroshift can generate a similar signature, it is extremely difficult to solve zeroshift problems by inspecting the output data. Therefore, all feasible precautions should be taken against each potential cause of zeroshift. Suggested guidelines are provided in the following paragraphs.

1. Transducer Design Considerations

   Avoid using shock accelerometers with elements of low-coercivity ferroelectric ceramics, to minimize domain switching (avoid Lead Zirconate Titanates).

   Avoid using shock accelerometers that use piezoelectric elements in a bolted preload configuration, to minimize physical movement of sensor parts (avoid compression design, which include all single crystal accelerometers).

   Choose accelerometers which have the highest resonant frequency. The higher the resonant frequency, the harder it is to excite the ceramic, hence less crystal domain switching. Transducers which utilize the weight of the crystal itself as the seismic mass reduce the effective stress even further and are, therefore, highly desirable.

   Shear type, high-coercivity ferroelectric accelerometers with minimum effective mass are recommended for pyroshock measurements.

2. Signal Transmission Considerations

   Use low impedance accelerometer designs which feature built-in impedance conversion. They provide:

   a) Reduced noise pick-up -- with low output impedance, the output signals are less susceptible to external noise sources when traveling through the long transmission line.

   b) Elimination of the coaxial cable -- regular hook-up wires can be used in place of coaxial cables because signals are low impedance. Hook-up wires are generally less expensive and more manageable than coaxial cables. In addition, hook-up wires does not exhibit triboelectric effect under motion as with coaxial cable.

   c) More options in connector design -- a bulky, shielded connector can actually induce strain to the sensing elements and produce spurious output. Simple arrangement such as solder pins will reduce the possibility of strain, plus have the advantage of field repairability.

If high impedance transducers must be used, great care should be taken when installing the connecting coaxial cable. It has been demonstrated that flapping and flexing of coaxial interconnects can generate zeroshift like signals. Therefore, it is necessary to prevent the cable from moving. Taping or gluing the cable on the mounting surface is highly recommended. Since the cable essentially experiences the same shock level as the sensor, miniature shielded interconnects should be used to reduce the moving mass under high-g acceleration. Noise treated coaxial cables should be used to minimize triboelectric output caused by cable motion. Consideration should be given to strain relieving the cable at the accelerometer, especially top-connector models (see Figure 9).

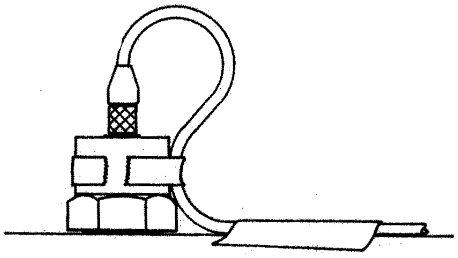

FIGURE 9
CABLE MOUNTING FOR MINIMUM STRAIN

3. Base Strain Considerations
Avoid compression type accelerometers if the mounting surface is suspected to have high strain. Base strain sensitivity is tested at fairly low strain levels, and is normally quite non-linear with strain levels. While the base strain specification of a compression design may seem acceptable, extrapolation to the expected test levels may not be valid. Accelerometers with the lowest possible strain sensitivity should be selected to provide the maximum margin against base strain errors. Furthermore, above a critical level of strain, a compression unit may produce zeroshift due to variations in the preload. Shear designs that do not require crystal preload are a better choice in high strain environment.

Shock accelerometers that incorporate base strain isolation in their design can effectively reduce strain motion to the sensing elements. This is presently accomplished by allowing sufficient clearance around the crystal assembly which concentrates the stress at a non-critical location. Correctly design, strain isolation groove and channel will not lower transducer resonance.

Another base strain reduction method is to use external isolator. Shaped like spacers and washers, these devices isolate the accelerometer from the mounting surface mechanically and minimize effective strain to the sensor. However, external isolators usually alter the resonance of the transducer which is not always desirable.

A longer time recording of the shock event will enable the user to distinguish real zeroshift from low frequency bending signal due to base strain sensitivity of the accelerometer. If this problem occurs, a lower base strain sensitivity accelerometer must be selected.

4. Frequency Response Considerations
All signal conditioning circuits should have sufficient time constant for handling long duration shock pulses, to avoid distortion related zeroshifts. As a rule of thumb [4], for a half-sine long duration pulse, the time constant to pulse width ratio ought to be at least 7 to obtain 5% accuracy. Low end frequency response of the signal conditioner should, therefore, be determined based on the input pulse width and output accuracy. Subsequent electronics, such as digital oscilloscope and waveform analyzer, should also be compatible in low end response. Attempting to use high pass filtering to remove zeroshift actually compounds the problem due to low frequency distortion.

5. Overload Considerations
To prevent electronics overload due to seismic resonance, a low pass filter may be employed before the very first input stage. Placing a low pass filter after the input stage may not prevent zeroshift because saturation can have already occurred. A shock accelerometer with built-in input low pass filter and impedance converter seems to be a logical solution [3]. Filter type should be carefully chosen to avoid excessive ringing, phase shift, and distortion due to group delay [8]. Select appropriate roll-off corner frequency to reject only unwanted information.

Select accelerometer sensitivity to suit a particular application; use lower output devices for large dynamic range. For safety measure, a factor of 2 should be used when estimating maximum acceleration level. When making measurement for one-time (non-repeatable) event, use two or more accelerometers of different ranges to allow for unexpected results.

For transducers with integral electronics that operate in constant current mode, increasing compliance voltage (within specification limits) will allow more headroom (swing) in the positive direction.

A MINIMUM ZEROSHIFT SHOCK ACCELEROMETER

One approach to an optimal shock accelerometer is shown in Figure 10.

Ideally, the sensing element should be inherently free of domain switching effects, and be used in a simple design which does not require preload. At the present state of the art, however, such a device is not available. An accelerometer which demonstrated the least amount of compromise in performance used high coercivity ferroelectric ceramics in the shear mode with minimum effective mass. Surrounding the sensing element is a strain isolation groove to minimize base strain errors due to low frequency bending motion. In this device, the output of the piezoelectric element is fed directly to an integral microelectronic package which includes an input low pass filter and an impedance converter. The low impedance output signal is then transmitted through the solder terminals and small gage hook-up wire to subsequent processing or recording equipment.

This accelerometer provides the following performance:

Output Sensitivity	0.05 mV/g
Output Impedance	< 100 Ohms
Dynamic Range	100,000 g
Zeroshift	Less than 0.1%
Resonant Frequency	270 kHz
Low-Pass Input Filter	Two-Pole
Electrical Configuration	Case Isolated

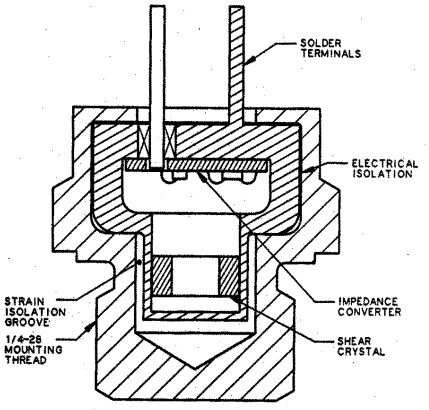

FIGURE 10
OPTIMAL SHOCK ACCELEROMETER

SUMMARY

Causes of zeroshift in piezoelectric accelerometers are:

- Overstress of sensing elements
- Physical movement of sensor parts
- Cable noise
- Base strain induced errors
- Inadequate low frequency response
- Overload of signal conditioner

Guidelines to minimize the occurrence of zeroshift errors are:

TRANSDUCER DESIGN - Use high coercivity material in bonded shear design with minimum mass loading.

SIGNAL TRANSMISSION - Use low impedance accelerometers.

BASE STRAIN - Use no-preload shear design with low base strain sensitivity.

FREQUENCY RESPONSE - Provide sufficient time constant in the electronics for long duration pulses.

OVERLOAD - Use input low pass filter, include safety factor when estimating maximum acceleration level.

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