Causes of Zero Offset in Acceleration Data Acquired While Measuring Severe Shock

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Abstract

One of the most frustrating aspects of the measurement of severe pyroshock events is the acceleration offset that almost invariably occurs. Dependent on its magnitude, this can result in large, low-frequency errors in both shock response spectra (SRS) and velocity-based damage analyses. Fortunately, recent developments in accelerometer technology, signal conditioning, and data acquisition systems have reduced these errors significantly. Best practices, have been demonstrated to produce offset errors less than 0.25% of Peak-Peak value in measured near-field pyrotechnic accelerations: a remarkable achievement.

This paper will discuss the sensing technologies that have come together to minimize these offsets. More important, it will document the many other potential contributors to them. Included among these are accelerometer mounting issues, cable and connector sources, signal conditioning amplitude range/bandwidth, and digitizing errors (e.g. aliasing), and more.

Introduction

Pyroshock is the decaying, oscillatory response of a structure to high-amplitude and high-frequency mechanical excitation (e.g., explosives, metal to metal impact). The frequencies that comprise this oscillatory response can extend to many thousands of Hertz and beyond. A detailed discussion of the process is presented in Reference 1.

An offset in the recorded acceleration-time record characterizing the pyroshock event can preclude its integral (velocity) from returning to zero. This failure of the recorded acceleration record to integrate to zero is typically viewed as an unfavorable metric on data quality.

A small step in the acceleration record when integrated results in a ramp in velocity. Velocity errors can also result from signal clipping and nonlinearity. For the purposes of this paper, a zero shift is any acceleration artifact that corrupts the velocity record and low-frequency shock response spectrum.

Whenever these errors are found, the performance of the accelerometer measuring the event is automatically questioned. However, there are many other sources of offset in the data error path. To obtain good results, all these contributors must be properly addressed.

Advances in Accelerometer Technology

References 2 and 3 provide a history of the evolution of accelerometer technology. Accelerometers are complex-dynamic systems that have resonances associated with their housing, connector, mount, seismic sensing element, and more. If properly designed and mounted, the lowest resonance of their seismic element (f_n) limits the range of frequencies over which their sensitivity can be treated as constant (typically $f_n/5$). Thus, accelerometers historically used to measure pyroshock have been approximated in terms of a simple, lightly-damped oscillator model.

In 1960 Endevco introduced a 100,000 G piezoelectric (PE) accelerometer with a resonance of 80 KHz. Although pyroshock does not normally approach 100,000 G, out of band energy in the early-time material response always excites the resonance of the accelerometer. Thus, early accelerometers attempting to measure pyroshock had to remain linear over a large amplitude range so that their out of band frequencies could be removed by low-pass filtering. Thisprocess yielded desired pyroshock characterization to frequencies up to 10 KHz. However, it was noted that this resonance excitation typically imparted a high enough stress into the piezoelectric ceramic element of the accelerometer to induce an offset (zero-shift) in the data. An extensive investigation [4] in 1971 determined this offset was due to an inherent limitation in ferroelectric ceramics that were available at that time attributable to dipole reorientation under stress.

As a byproduct of Lawrence Livermore sponsored work performed by Endevco in 1970, the Model 2266 radiation tolerant piezoresistive (PR) accelerometer was introduced with diffused gages (4-wire resistive bridge) in ranges to 30,000 G. Application of this model accelerometer in underground nuclear test environments showed it to perform with less zero shift than had been observed with PE accelerometers. A nonradiation hardened PR accelerometer (Model 2264) soon followed for pyro testing. Again, less zero shift in pyroshock environments was observed by users. Based on this success, in 1983 Endevco introduced the Model 7270A piezoresistive accelerometer in the form of a MEMS device with a resonant frequency of up to 1.2 MHz. It was, and still is, manufactured in ranges to 200,000 G.

The 7270A captured a large portion of the pyroshock market. However, a deficiency was found due to the high amplification of its flexure at resonance because it had almost no damping. Despite its extremely high resonant frequency, it was susceptible to breakage due to out-of-band energy. To compensate for this deficiency, an isolated holder was developed [5] to protect it at high frequencies. While it improved reliability, the isolator's size and mass could potentially modify high-frequency structural response.

Between 2008 and 2010 PCB introduced its MEMS-based PR accelerometers (Models 3991 and 3501) in ranges to 60 KG. These accelerometer models were designed with lower resonant frequencies than the 7270A to enable them to incorporate light damping and mechanical stops. Soon after, Endevco introduced the similar 7280A MEMS accelerometer series. Both PCB's and Endevco's developments improved on the fragility associated with the 7270A.

Having abandoned "hard mounted" piezoelectric accelerometer development for pyroshock based on the knowledge gained in Reference 4, in 1988 Endevco developed a Model 7255A Isotron™ (IEPE) accelerometer. It had a range of 50 KG with built-in mechanical isolation and a 2-pole electrical filter. Although this idea was technically sound, testing over the years has shown this model to be nonlinear. PCB improved the mechanical-isolation strategy, and the release of its models 350CO2 (CY 2005) and 350DO2 (CY 2012) effectively solved the nonlinearity problem.

This design approach uses mechanical isolation to reduce the resonant amplification in the piezoelectric element greatly improving the zero-shift issue. The electronic filter compensates for the transfer function of the elastomeric isolator. Thus, the accelerometer can be thought of as a two-degree of freedom system with the higher frequency resonance of the contained PE element suppressed by a combination of mechanical isolation and electrical filtering.

The single-axis accelerometers from Endevco and PCB appropriate for pyroshock including near field are shown in Table 1 and Figure 1.

Endevco 7270A	60 KG	200mV FS	f_n ~ 600 KHz	1.5 grams
PCB 3991/3501	60 KG	200 mV FS	f_n ~ 130 KHz	1.5 grams
Endevco 7280A/AM4	60 KG	200 mV FS	f_n ~ 130 KHz	1.5 grams
PCB 350DO2	50 KG	5000 mV FS	f_n suppressed	4.5 grams

Table 1. Comparison of Characteristics of Comparable Range Pyroshock Accelerometers

Figure 1. Physical Envelope of Pyroshock Accelerometers, left to right:
7270 A (form also standard for 3991 and 7280A), 3991/3501 with surface mount, 350DO2

Recent Comparative Pyroshock Tests and Results

In CY 2016 a carefully planned sequence of “live pyro” tests was performed to compare the performance of candidate accelerometers. These included those models listed in Table 1 along with a few others. Details of this test and the results can be found as reference 6.

As occurs in most pyro testing, none of the acceleration records were free of zero shift and hence did not integrate to zero. However:

> *One of the remarkable findings of the study was that the acceleration offsets were remarkably small. For most of the records, the offsets were less than 0.25% of the Peak-to-Peak acceleration response. The minimum offset in all testing was 0.02% of the Peak-Peak response. For the MEMS devices, this value corresponded to 20 microvolts.*

Even these tiny errors cause enormous discrepancies in the calculated SRS at frequencies below 100 Hz.

In the more severe tests in this sequence, Peak-to-Peak measured pyroshock was 30 KG. Across five tests, valid data was recorded on 53 of 55 recorded channels. This was a remarkably high data return in such an energetic environment and a testimony to the quality of the testing performed.

In the collective authors’ opinion, these results were as good as could be expected. They represent a threshold as to how well pyroshock data can be recorded today. (All of the small offsets were corrected by post processing and yielded valid test results.)

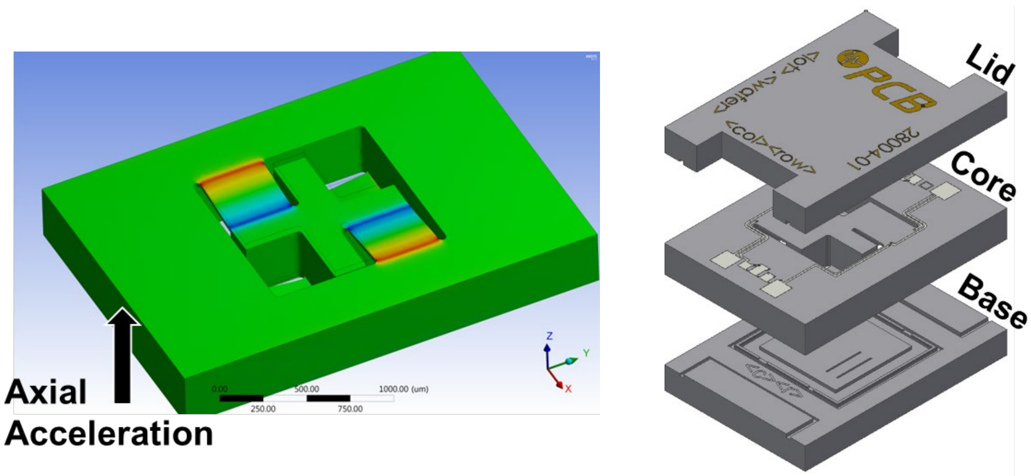
As noted in the Introduction, although the accelerometer performance is usually indicted, many other contributors can be responsible for these small data offsets. The following attempts to identify all the potential sources in the measurement system that can cause these small offsets

Offset Sources Associated with the Accelerometer

Often the offset error from the accelerometer is a result of improper use and not an inherent defect in the accelerometer. Common usage errors include use of the sensor beyond its specified range, inadequate mounting torque, poor mounting surface, inadequate cable strain relief, or insufficient supply current (for ICP® type signal conditioning).

Fundamentally a physical cause of offset error is the transmission of undesired stress into the sensing element [9]. The challenge in accelerometer design is an accelerometer that responds only to acceleration along its sensing axis while rejecting all other mechanical, thermal, and electrical inputs. Pyroshock is a complex environment with acceleration along all axes, large dynamic strain transmitted through the sensor mounting surface, and large inertial forces applied to cable connections.

Zero shift in PR sensors is not inherent to the silicon structure itself (Figure 2a). Rather, it is the result of residual stresses transmitted through various interfaces in the sensor die and packaging (Figure 2b). Silicon is a crystalline linearly elastic material without hysteretic characteristics that might cause a non-return to zero. Piezoresistive gage areas are created by implanting dopants into the silicon resulting in a unitary crystalline structure. When subject to shock below its fracture strength, the silicon structure in isolation cannot permanently deform. However, PR accelerometers can zero shift when shock induced residual stresses are transmitted into the active gage area of the silicon sensing structure. These stresses originate at stressed interfaces such as die bond layers, die packaging, wiring, or at the sensor mounting interface. In designing a PR accelerometer for pyroshock, it is the goal to minimize transmission of residual stress into the active gage area of the silicon structure. Out-of-band high-frequency content and subsequent sensor resonant ringing is another potential source of zero offset resulting in bad data or even permanent damage to the sensor. A successful design strategy to eliminate this influence is a controlled gap between the moving sensing element and the core/lid. The controlled gap provides both viscous air damping and overrange stops that engage when the sensor is subject to shock beyond its specified range.

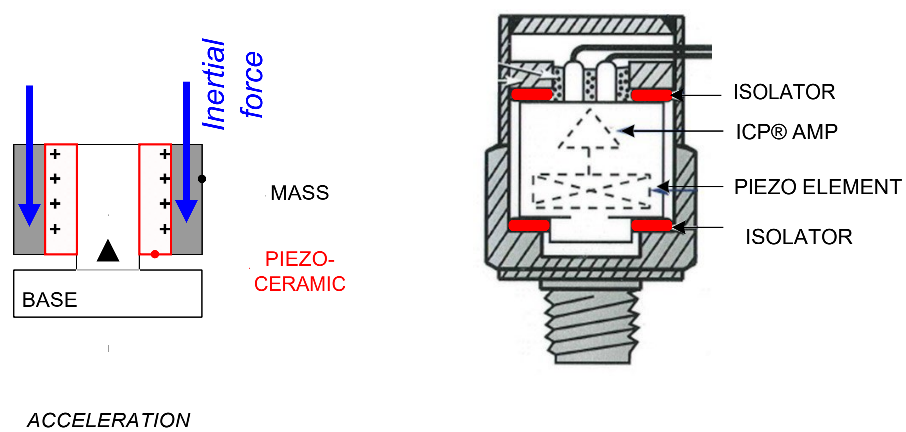


(a) **(b)**

Figure 2. Piezoresistive MEMS element **(a)** and die package **(b)**. Red color on the element indicates an area of high strain and good location for the implanted piezoresistive gage.

Residual stress is also a cause of zero shift in PE accelerometers. Isolation from this residual stress is a challenge because of the large active volume of the piezoceramic element. A typical piezoceramic sensing element may be an annular cylinder with diameter x height of 2 mm x 3 mm (Figure 3). Piezoelectric charge will be generated if stress is applied to any part of this volume. This contrasts with PR silicon element in which the active gages are small structures of approximately 0.1 mm in length.

With PE accelerometers, dipole realignment is an additional source of zero-shift for certain piezoceramic materials [4]. A successful design strategy for PE accelerometers is the incorporation of a built-in mechanical isolator and use of special piezoceramics that do not exhibit the dipole switching phenomenon. The mechanical isolator serves two functions. It filters out of band high-frequency energy and reduces strain transmission into the piezoceramic element. The isolator must be designed to be linear over the sensor operating range so that isolator nonlinearity is not a cause of offset error.



(a) **(b)**

Figure 3. Piezoceramic element **(a)** and packaged sensor **(b)**. Mechanical isolator isolates both the piezoceramic element and ICP® amplifier from out-of-band energy.

Even the best-designed accelerometer will exhibit zero shift when subject to over range. When an accelerometer is subject to acceleration beyond its specified range, the output may become nonlinear, its signal may clip, and under severe conditions the sensor may suffer permanent damage. This error is insidious in that when overrange occurs, the actual peak acceleration level is not always observable in the acquired data record. This may be because the overrange acceleration occurred in a direction transverse to the sensing axis or the bandwidth of the sensor/measuring chain is insufficient to detect it. Pyroshock can have significant high-frequency content, extending to the megaHertz range and this high-frequency energy is typically filtered out by any number of components in the measuring chain.

For undamped PR accelerometers, there is the possibility that high-frequency pyroshock energy may induce excessive sensor ringing. The peak amplitude of the ringing may extend into the nonlinear operating range of the accelerometer or, in cases of sufficient magnitude, fracture the silicon sensing element. Silicon is an extremely low loss material and sensing elements fabricated without intentional damping can have Q (quality factor) well more than 1000. For undamped PR sensors, a mechanical isolator can greatly improve sensor survivability. Good data can be obtained as long as the isolator itself does not introduce signal nonlinearity. Alternatively, "lightly damped" PR sensors with Q values of approximately 30 have been demonstrated to provide improved linearity and survivability without the need for an additional isolator.

Examples of accelerometer offset due to "misuse" are demonstrated using PCB's Hopkinson Bar Calibration System (Figures 4 through 11). The Hopkinson bar is an ideal demonstration platform as the test variables can be well controlled. The sensor under test is mounted on one end of a long slender bar and impacted by a projectile at the opposite end [10]. This produces a stress transient that propagates back and forth in the bar as a series of pulses with peak acceleration levels that can exceed 100,000 G. Integration of the acceleration record (integrated to velocity) produce a series of half sine shock pulses that theoretically returns to zero velocity after each pulse. A metric for "a bad" data record that contains accelerometer offset error is velocity that does not return to zero after the acceleration pulse.

In the first example (Figure 4), an ICP® piezoelectric accelerometer (PCB Model 350D02, contains integral mechanical filter) is mounted to the end of the Hopkinson bar with a 0.003-inch-thick piece of flat solder underneath it, mimicking a surface imperfection such as a thread burr that might be found in field application. With a good mounting surface, the velocity is well behaved, returning to zero after each acceleration pulse (Figure 4b). With debris on the mounting surface, the velocity does return to zero between impacts.

The second example demonstrates the importance of choosing a PE accelerometer with a well-designed mechanical isolator (Figure 5). The integral mechanical isolator must be linear over the full shock acceleration range and the isolator's resonance must be well-beyond the frequency band of interest. In this demonstration, the PCB Model 350D02's velocity properly returns to zero after each impact (Figure 5b). In contrast, the mechanical isolator in the legacy model is not properly designed for the shock environment, exhibiting non-linearity and in-band resonance resulting in zero offset (Figure 5c).

The third example demonstrates the importance of reliable cable connections (Figure 6). Arguably the cable connection is the weak link in the measuring chain and first suspect when bad data is obtained. In this example a 10-32 microdot connector connects the coaxial signal conditioner cable (blue) to the twin lead sensor cable (red and white). The connector assembly is tied down to the Hopkinson bar mimicking cable motion that might be encountered in the field during a shock event. With connector's knurled nuts fully engaged the sensor does not exhibit zero offset (Figure 6b). When one of the nuts is not fully engaged there is movement between the connector pin and socket resulting in zero shift (Figure 6c). It should be noted that the poorly engaged connector only exhibits brief intermittency during the highest levels of shock. Under most conditions the sensor would test acceptably. Because of the intermittent nature, this is something that would be difficult to diagnose in the field.

The fourth example demonstrates the importance of sufficient supply current when ICP® type sensors are used with long cables (Figure 7). Supply current sufficient to drive cable capacitance is required to avoid signal slew distortion [8]. To conserve battery life, most ICP® battery conditioners are set to 2 mA. Of the data acquisition systems that have integral ICP® signal conditioning, many have supply current limited to only 4 mA. In this example, the sensor has a 4000 pF load equivalent to 130 feet of 30 pF/foot cable between sensor and signal conditioner. The sensor does not exhibit zero offset with 10 mA supply current (Figure 7b) but does when supply current is 2 mA (Figure 7c).

The fifth example demonstrates the importance of using the recommended mounting torque (Figures 8 and 9). With proper mounting torque, the sensor does not exhibit zero offset (Figures 8b and 9b). With inadequate mounting torque, the sensor exhibits zero offset (Figures 8c and 9c) as well as ringing (Figure 8c).

The sixth and last example demonstrates the importance of the signal conditioner with gain properly chosen as to not over range (Figure 10). In this example the signal gain is sufficient to clip the peak accelerometer signal, resulting in zero offset in the velocity record (Figure 10c). Clipping in the signal conditioner is insidious in that the clipping in the accelerometer record may be masked by subsequent low pass filter stages.

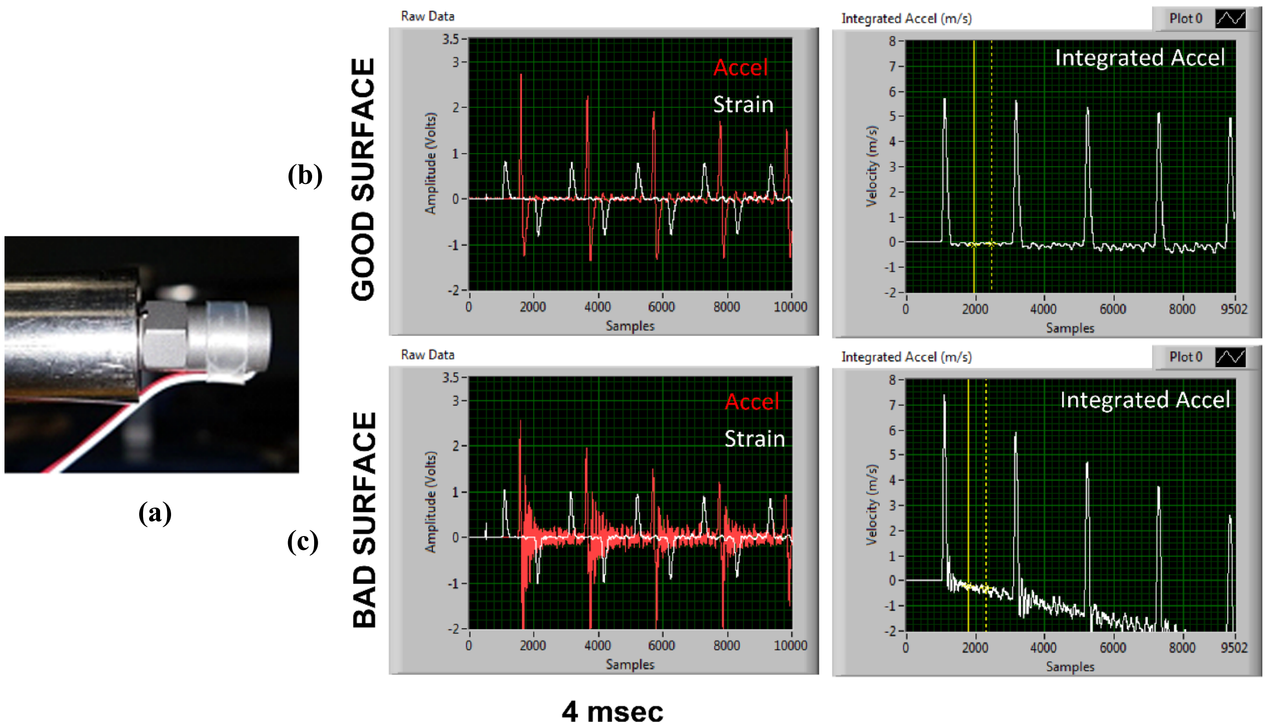


Figure 4. Shock at 25,000G peak with varying surface conditions. PCB Model 350D02 ICP® PE sensor on Hopkinson bar **(a)**; integration to velocity with good mounting surface **(b)**; and integration to velocity with 0.003-inch-thick debris on the mating surface at **(c).**

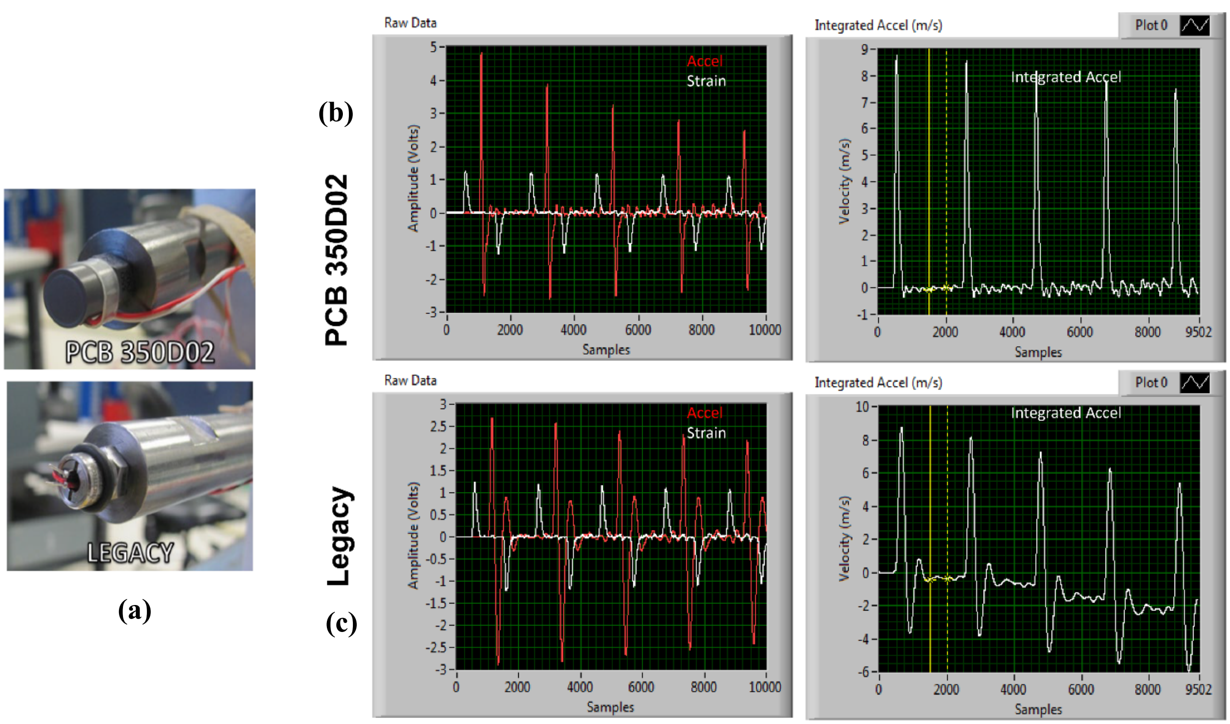


Figure 5. Shock at 50,000G peak with varying sensor models. PE sensor models with integrated mechanical isolators mounted on Hopkinson bar **(a)**; integration to velocity of PCB Model 350D02 PE sensor **(b)**; and integration to velocity of legacy PE sensor **(c)**.

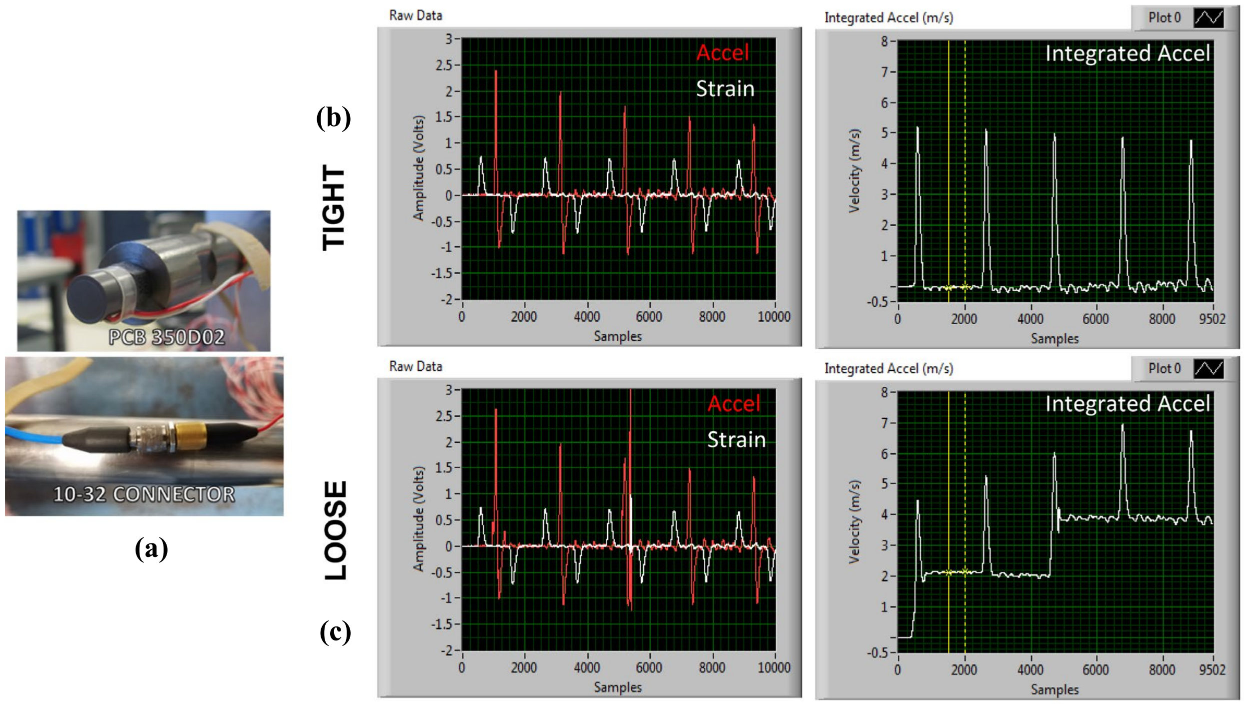


Figure 6. Shock at 28,000G peak with varying connection integrity. PCB Model 350D02 sensor mounted to end and cable/connector attached to the side of Hopkinson bar **(a)**; integration to velocity with connector nuts tight **(b)**; and integration to velocity with one of the nuts not fully engaged **(c)**.

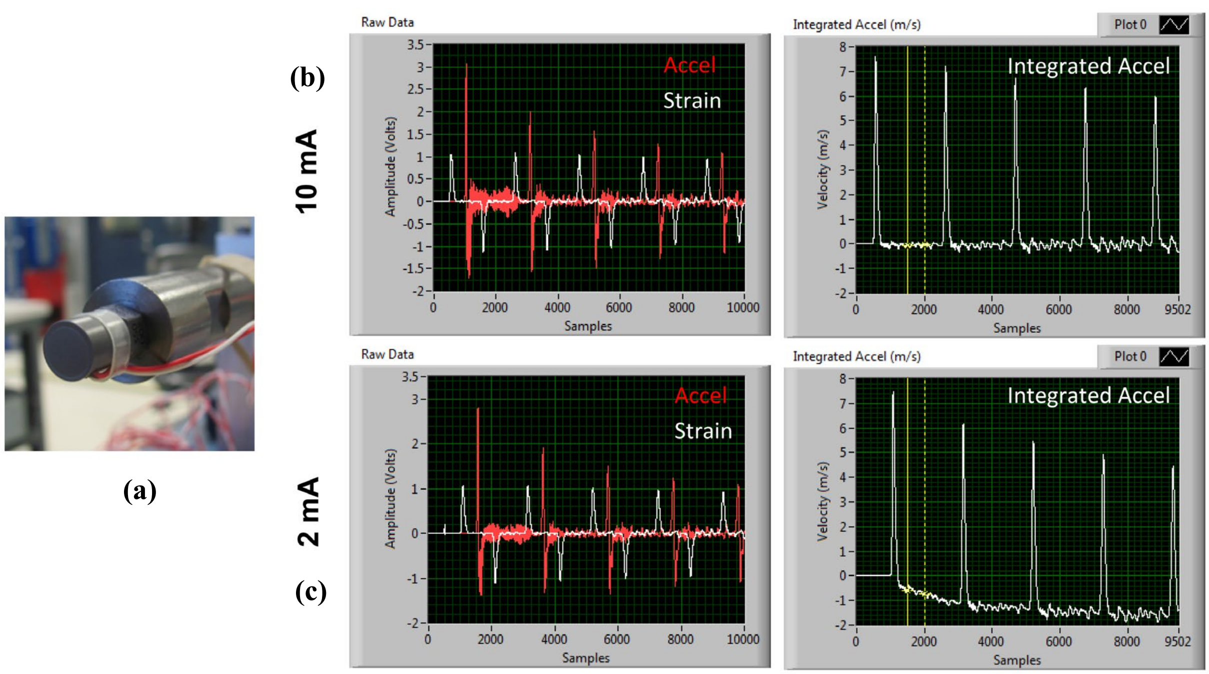


Figure 7. Shock at 60,000G peak with 130-foot long coaxial cable (4000 pF capacitance) and varying ICP® supply current. PCB Model 350B21 ICP® PE on Hopkinson bar **(a)**; integration to velocity with 10 mA supply current **(b)**; and integration to velocity with 2 mA supply current **(c)**.

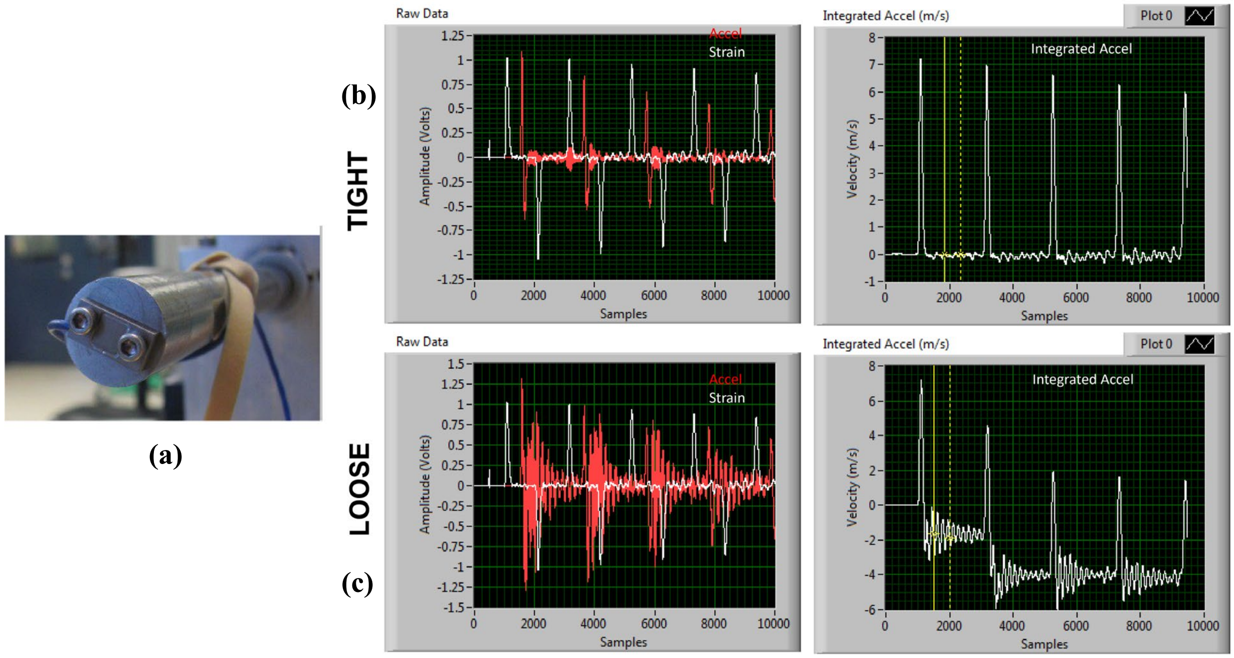


Figure 8. Shock at 50,000G peak with varying mounting torque. PCB Model 3991-60KG PR MEMS sensor mounted to Hopkinson bar **(a)**; integration to velocity with proper mounting torque **(b)**; and integration to velocitywith inadequate torque on one of the two screws **(c)**.

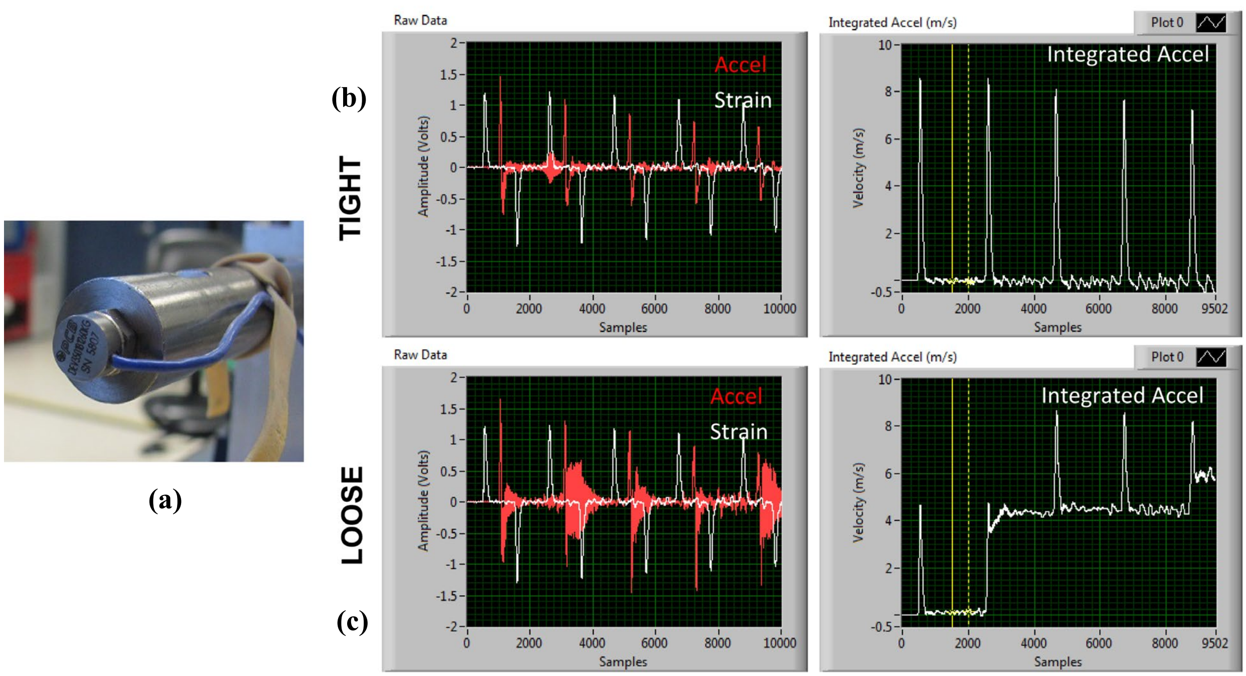
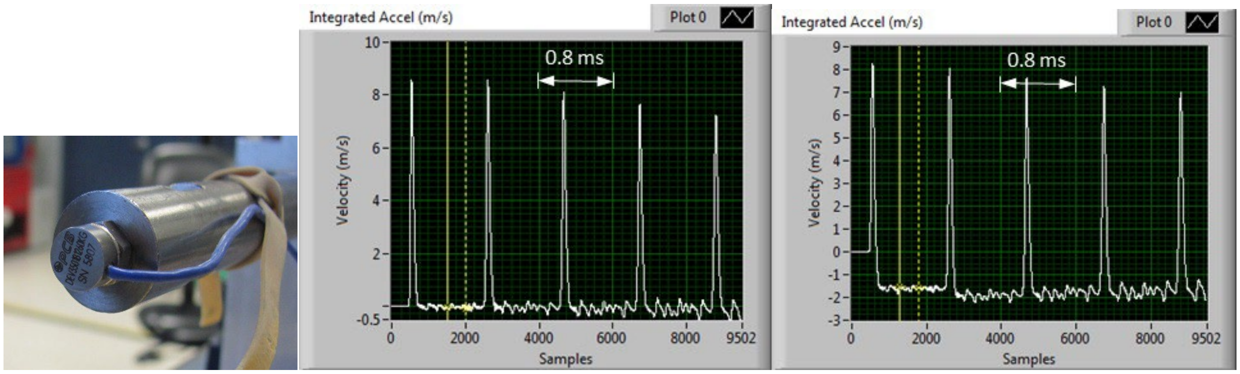


Figure 9. Shock at 50,000G peak with varying mounting torque. PCB Model 3501-50KG PR MEMS sensor mounted to Hopkinson bar **(a)**; integration to velocity with proper mounting torque **(b)**; and integration to velocity with inadequate torque **(c)**.



(a) **(b)** **(c)**

Figure 10. Shock at 60,000G with varying conditioner gain. PCB Model 3501-60KG PR MEMS sensor mounted to Hopkinson bar **(a)**; integration to velocity with adequate ranging of signal conditioner gain **(b)**; integration to velocity with excessive gain causing clipping in signal conditioner **(c)**.

Offset Sources Associated with the Cable

The accelerometer cable can modify the signal passing through it by introducing both unintended filtering and/or internally generated noise. Noise generation within the cable is identified by the term triboelectric effect. This effect will subsequently be discussed after first considering the potential for filtering introduced by the cable.

When using ICP® type accelerometers to measure mechanical shock at frequencies of 10,000 Hz or higher, as noted previously, the capacitance associated with the cable may require higher drive currents than the typically supplied 2-4 milliamp. If required, this increased current would be necessary to eliminate signal amplitude distortion attributable to the cable capacitance. The technical and mathematical justification for increasing current with cable capacitance is provided in reference 7. Readily available charts (reference 8) provide this frequency vs. current relationship for varying values of cable capacitance.

For MEMS accelerometers, the cable capacitance and any additive line resistance, coupled with the resistive bridge source resistance, will result in a low pass RC filter. For example, 5000Ω source impedance (typical for some MEMS sensors) driving 60 feet of coax (e.g., RG58 = 25 pF/foot) will result in -3dB attenuation at 21,000 Hz.

Independent of ICP® or MEMS accelerometer type, early filtering in the cable can result in a data offset by masking the fact that a given accelerometer has exceeded its linear range.

Triboelectric effects result in random noise generation in cables and this noise does not have to be statistically symmetric. Thus, it can result in small zero offsets when averaged. This effect is important to understand when dealing with bridge type sensors providing millivolt level signals or accelerometers without contained electronics (non ICP®). For this effect to occur there must be cable motion. The triboelectric effect (also known as *triboelectric charging*) is a type of contact electrification in which certain materials become electrically charged after they come into contact with a different material and then become separated (such as through rubbing). The polarity and strengthof the charges produced differ according to the material types, surface roughness, temperature, strain magnitude, and other parameters. Thus, this effect is not very predictable, and only broad generalizations can be made about it. Sinceall instrumentation cables are combinations of metal conductors, inner dielectrics, metal shields, and outer jackets of differing materials, it would be expected that any motion of the cable would result in some triboelectric effect (signal generation). This motion can be attributed to cable vibration or, in mechanical impact environments where cables are taped or securely tied down, cable compaction due to traveling stress waves underneath them. The greater the relative motion between the cable constituents, the more charge that is generated. Figure 11 shows one example of this charge generation within a coaxial cable.

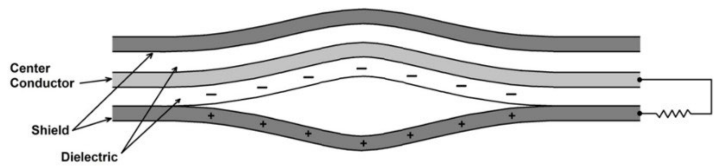


Figure 11. Charge Buildup Due to Cable Motion

Offset Sources and Other Errors Associated with the Signal Conditioning and Data Acquisition Systems (DAQs)

When performing pyroshock testing the objective is normally to provide a good estimate of the shock response spectrum at frequencies up to 10KHz. As noted in the introduction to this paper, the failure of a recorded pyroshock pulse to integrate to zero results in low-frequency errors in the SRS causing data quality to be questioned.

Additional data acquisition faults that may produce offsets and resultant velocity errors include the following bulleted items:

- Zero offset-and low-frequency drift.
  - Small offset errors will seriously affect analysis results.
- Measurement over-range problems.
  - Signal saturation will distort the results and may affect offsets.
  - Signal slew-rate-capability exceedance will cause offsets.
- Inadequate alias protection and sample rate/time resolution.
  - Aliasing of the signal will corrupt all frequencies including the offset (0 Hz).
    - SRS analysis specifications (to be discussed) set the requirement for minimum sample rate.

To provide data to explore the data acquisition challenges, an experiment was performed by Mark Remelman [13] using Spectral Dynamics' explosive test fixture. Two accelerometers, Endevco 7270-20K and PCB 350D02, were tested in a back-to-back configuration and the signals were measured using a Spectral Dynamics VIDAS data acquisition system sampling at 5,000,000 samples/second**.**

The data from the 7270 will be used to demonstrate the effect of the errors listed above. The voltage response has gain applied to make it's time history peak = 1 volt as shown in Figure 12. Pertinent derived parameters are:

- Upper Left Frame: The voltage output (normalized to 1 V).
- Middle Left Frame: Slew rate in Volts/µSecond
- Lower Left Frame: The integral, proportional to velocity, which (correctly) approaches zero after the shock.
- Upper Right Frame: The positive (solid) and negative (dotted) Shock Response Spectrum. The two curves agree well.
- Lower Right Frame: The RMS Spectrum that shows:
  - Significant signal energy out to 700 KHz.
  - The transducer resonance at 415 KHz.

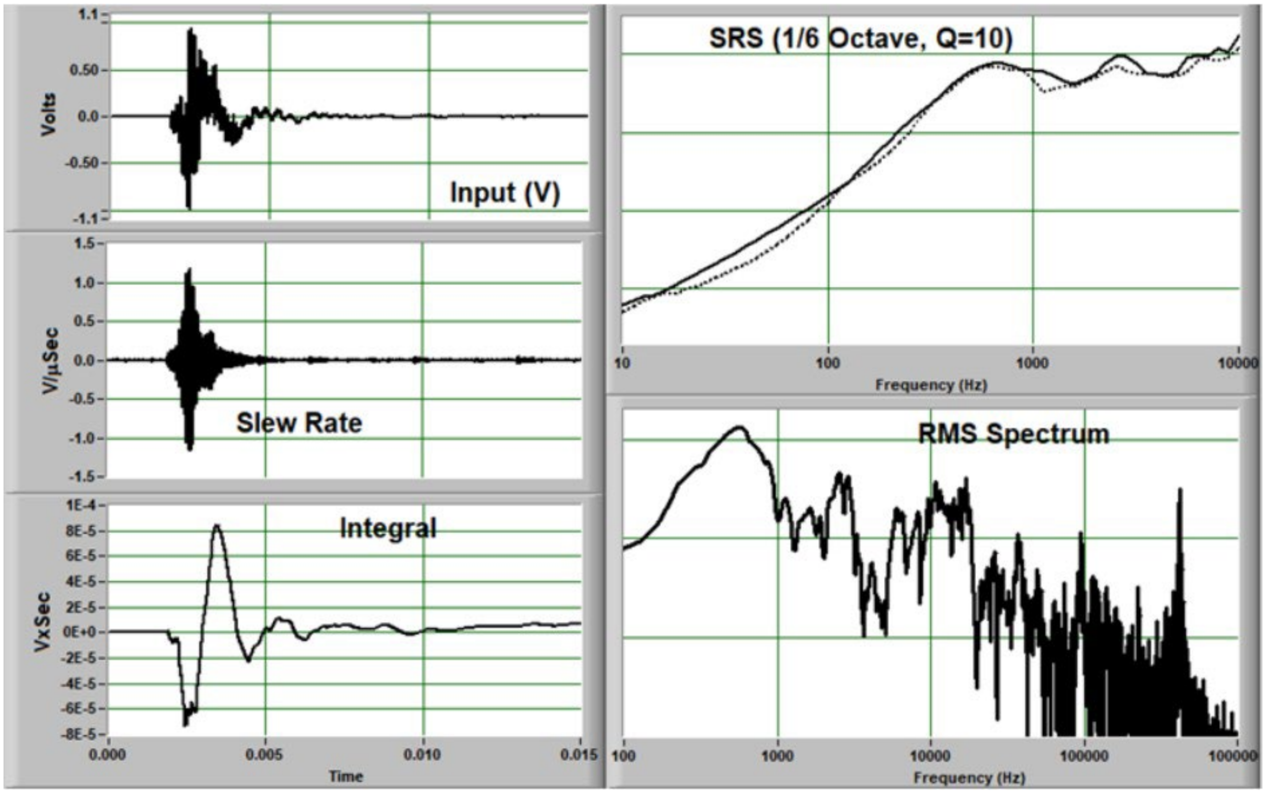


Figure 12. Shock Response Measured with an Endevco 7270
Scaled to 1 Volt Peak

The following four examples use analytically-generated errors to demonstrate their effects on this data set.

1. The Effect of Offset

Figure 13 shows the effect of adding an offset of 1% of the peak value to the data. The integral and low-frequency shock response spectrum (RED) are significantly compromised. In Figures 13-16, BLACK represents the original signal (Figure 12).

In the real world, offsets in the measured data typically occur. The output from MEMS devices can contain offsets due to bridge unbalance and/or any dc acceleration component. The signal conditioning and data acquisition system will also introduce small offsets All of these must be corrected.

As has been noted, this error is typically dealt with in data post processing.

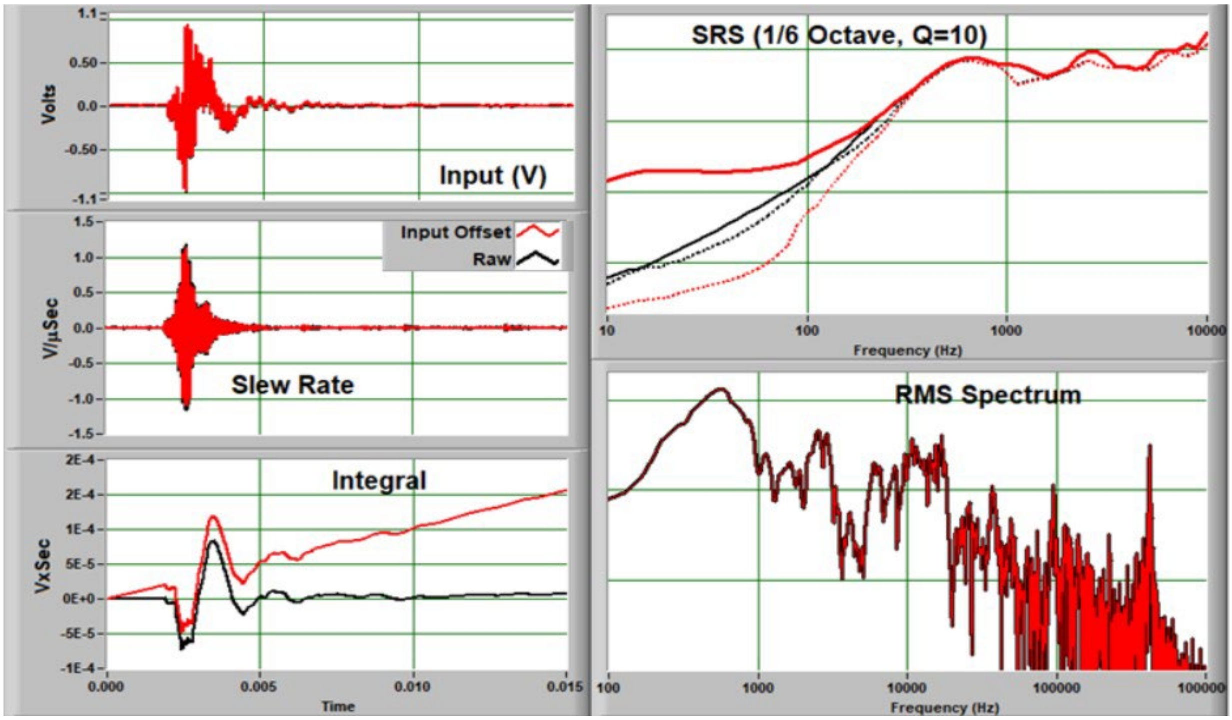


Figure 13. Effect of 1% Offset

2. The Effect of Amplitude Clipping

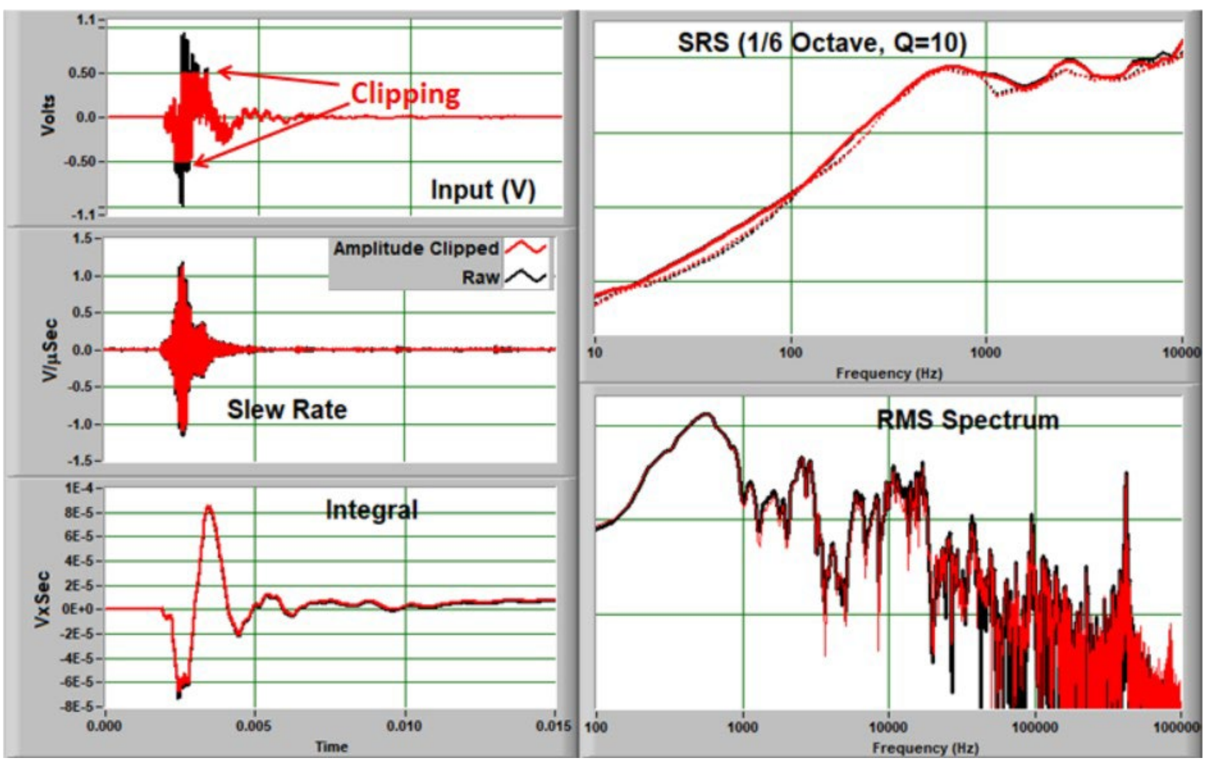


Figure 14. The Effect of 50% Amplitude Clipping

Surprisingly, even drastic clipping, like that shown in Figure 14, does not produce significant offsets (or significant discrepancies in other indications). Only the time record shows the (obvious) error.

Ones sided clipping (as seen in the example in Figure 10) may show more significant errors.

In any case, this data set is corrupt, and the test must be rerun with a wider input range.

3. The Effect of Slew Rate Clipping

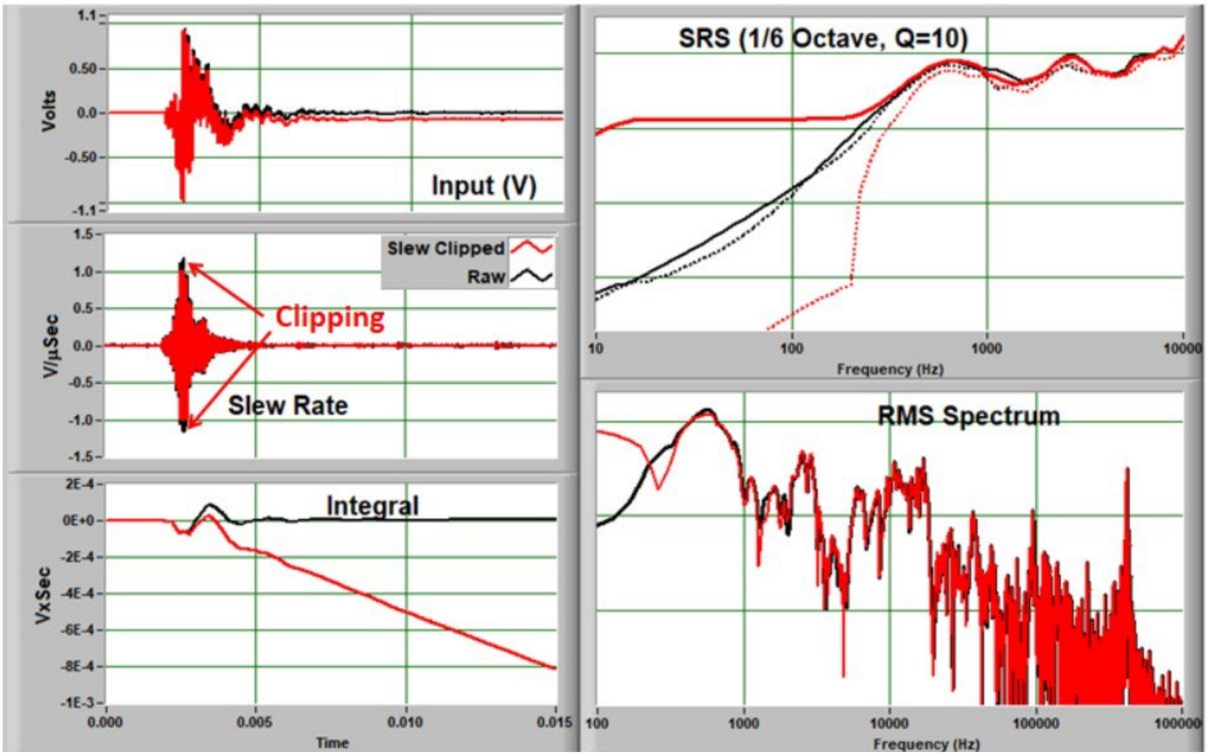


Figure 15. The Effect of Slew-Rate Clipping

Figure 15 shows the effect of a very small clipping on the slew rate. If the amplifier processing this signal is limited to 1 V/µSecond, there are significant offsets. The offset starts at the peak of the slew rate which is also near the peak of the shock. Hence, it looks like an offset error that might be produced by the transducer (discussed above).

Slew rate is an increasingly important consideration when using essentially undamped accelerometers with their associated very high resonant frequencies (e.g. Model 7270). A detailed study of the record in Figure 12 was performed by one of the authors (S. Smith) of this paper. It concluded that when applying gain to the 7270 to acquirethe equivalent signal levels as the 350DO2 to 10 KHz, the slew rate demands on the signal conditioning channel for the 7270 in this instance were 15 times greater than that required for the 350 DO2.

4. The Effect of Aliasing

Aliasing errors corrupt the entire frequency range. If energy is aliased to near zero frequency, offsets will occur as shown in Figure 16.

In this case, the sampled signal in Figure 12 has its digitization rate decimated to 40 KS/S without appropriate anti-aliasing filtering. Thus, all the signal energy content above 20 KHz (i.e., the Nyquist frequency) is folded to lower frequencies. Specifically, data frequency content between 20 KHz and 40 KHz is moved to between 0 and 20 KHz, which results in offset components. In fact, this folding occurs multiple times [12].

Again, this error starts near the shock peak, so it looks like a transducer-shock offset.

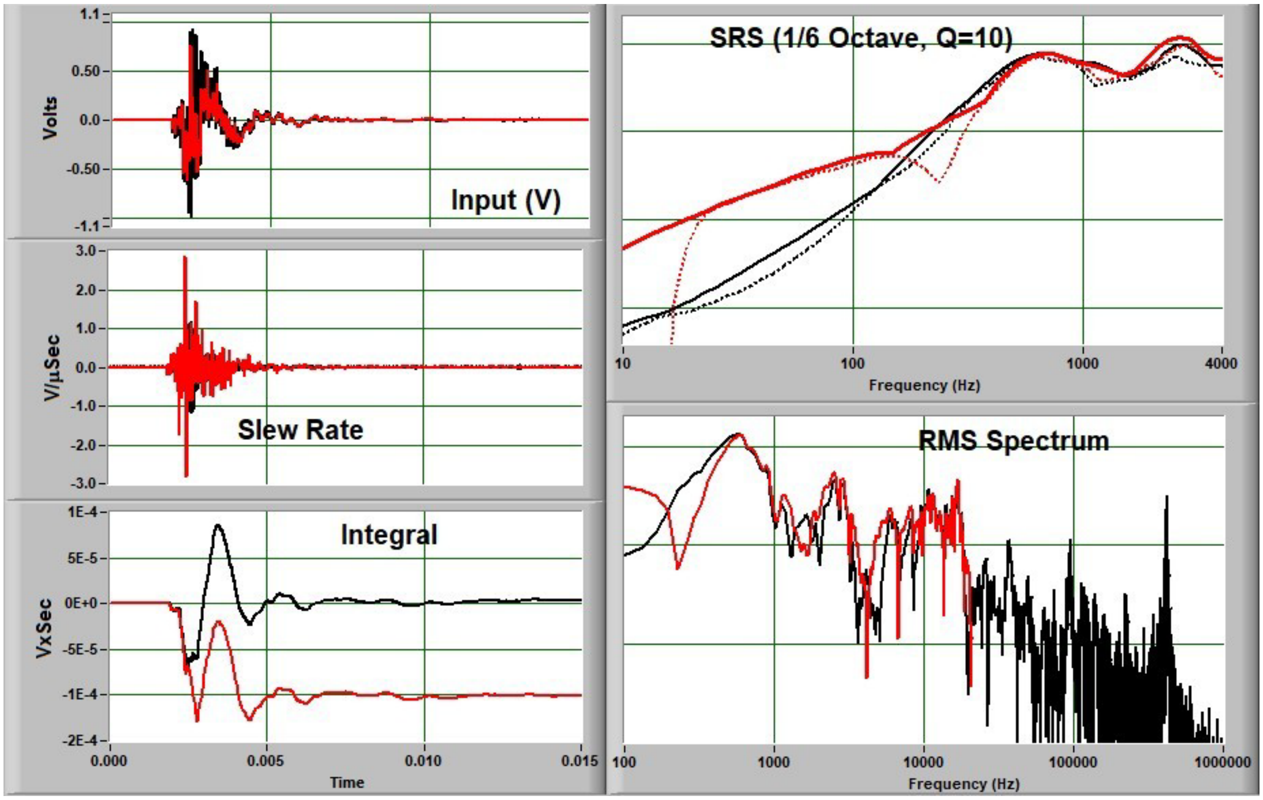


Figure 16. The Effect of Aliasing

Basic Data Acquisition System Requirements

Classical Shock Response Spectrum (SRS) analysis practice requires a minimum of 10 points/cycle at the maximum SRS analysis frequency (normally 10KHz.) which leads to a minimum sample rate of 100KS/S. With this sample rate, appropriate data systems can provide an acquisition bandwidth of 30KHz. Acquisition of ten points/cycle assures that the SRS magnitude estimate (peak SRS band response) will be within 5% of the truth.

Summary and Conclusions

Prior testing in harsh field environments (e.g., pyrotechnic shock) has demonstrated that, for properly designed instrumentation systems, signal offsets from accelerometers can be limited to an extremely small magnitude. The following list summarizes the potential offset contributors that have been discussed in this work.

- Accelerometer related:
  - Residual stress externally induced in the accelerometer during the shock event can result in signal offset. This applies to both MEMS (piezoresistive, i.e., PR) and piezoelectric (PE) accelerometers.
    - Dipole realignment that results in an offset can occur in select ferroelectric ceramic accelerometers. This offset can be minimized or eliminated by assuring that the piezoelectric element operates at low stress levels. The newer design mechanically-isolated, electrically-filtered piezoelectric accelerometers solve this problem.
    - Improper accelerometer mounting torque and/or inadequate mounting surface preparation, as illustrated by examples in this paper, can readily induce stress in the sensing element of the accelerometer resulting in signal offsets.

- Cable related:
  - Motion-related cable interconnect issues can result in offsets in recorded signals through inadvertent electrical grounding and/or intermittency between the cable center pin and its mating receptacle.
  - Triboelectric effects generated within the cable due to vibration or mechanical impact can produce asymmetric acceleration baseline noise resulting in offsets.
- Nonlinearities at any location in the instrumentation system:
  - Improper selection of gain in the signal-conditioning amplifier allowing the data channel to over range will result in a zero offset.
    - Subsequent filtering in the instrumentation system can obscure the fact that this over range condition has occurred. This filtering can even occur attributable to capacitance in interconnect cables.
    - Improper isolator design in a mechanically isolated accelerometer can result in nonlinearities with resultant signal zero offset.
  - Undamped legacy MEMS accelerometers (Endevco 7270A) are particularly susceptible to over range situations due to their high Q. This occurs when the accelerometer resonance is excited by out of band energy. MEMS accelerometers are now available with slightly more damping (Q=30 or less) to help lessen this resonance response. The mechanically-isolated, electrically-filtered PE accelerometers largely eliminate this out of band energy.
  - Slew rate limitations in the electronics are another potential source of nonlinearities and resultant base line offsets.
    - For ICP circuits, inadequate supply current when driving long cables at high frequencies can result in signal slew distortion.
    - The extremely high resonant frequencies (> 500 KHz) of the undamped legacy MEMS accelerometers (Endevco 7270A) can readily create offsets in recorded signals due to slew rate limitations in their signal conditioning electronics.
- Aliasing:
  - Inadequate sampling rate relative to the spectral content of the signal can result in high frequencies in the spectrum being "folded" down to lower frequencies, which can result in a zero offset.

As noted in the introduction to this paper, the recorded signal emanates from an accelerometer and thus it is often blamed for any offsets occurring in the data. However, as has been demonstrated, these offsets can and do occur in all components of the instrumentation system. Critical attention to all these potential contributors is required to make adequate pyroshock measurements. Hopefully the references provided below will also provide additional contributory guidance.

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