Gunfire Measurements with Broadband Triaxial Piezoresistive Accelerometers

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Gunfire simulations are important for evaluating new mobile and fixed weapon systems and components with realistic survivability testing criteria. With field component failures of sophisticated accessories, there are increasing demands for better testing regimens. The data necessary to develop a database to accurately quantify this pyroshock environment are being measured for two automatic weapons. Recent live gunfire measurements were made using the highest fidelity measurement techniques available. Single live gunfire and multiple live gunfire measurements (single and three round burst) have been evaluated according to MIL-STD-810G Method 516.7 for Shock. These data highlight the requirements for validating model against live gunfire data.

INTRODUCTION

With the increasing spectrum of sophisticated electronic weapons augmentation systems being fielded, there are new demands on the testing and survivability evaluation processes. It is just not practical to throw 2 or 3 thousand rounds down range to test an electronics payload, switch to another device and do it again. Yet this is currently the only available proof of a device's field worthiness. This type of testing is very expensive, and is not without risk. When hand held weapons were limited to mechanical or lens based optics, the major testing concerns focused on impacting shock and dust intrusion which compromised their field life. The shocks transmitted to these devices by repeated firing events were of less concern that the shocks absorbed by the weapon from environmental factors, such as a weapon stock-butt slam on a hard surface to clear a jam, or the impact of the weapon on a hard surface as the bearer drops for cover. Today's sophisticated electronics and electro-optical systems are even more at risk, and far more costly to procure and repair. Their failure in the field puts lives at risk. These severe shock, real world events are still of concern, and do need to be addressed, but are beyond the scope of this paper.

This paper will address some of the apparent discrepancies associated with the historical failure to collect valid live fire data and then subsequent testing which has been based on these data. It is important that we gain an understanding of the pyroshock and mechanical events and interactions which make up these live-fire high speed shock events. It is not just the frequencies and energy that result from these shocks that create testing issues. It is their repetitive nature and the inherent difficulties in trying to faithfully reproduce these events in a testing environment.

The data for this paper were collected using three high frequency responses (broadband), piezoresistive (PR) accelerometers in a tri-axial mounting block configuration. The goal is to measure the shocks imparted to the electronics mounting point that are not only complex in nature; they are extreme in three DOF simultaneously. Since gunfire simulations will be developed from the data, it is important to determine the bandwidth of the pyroshock and mechanical shock environments. Specifically, it must be determined if there is frequency content at and above 10 KHz that must be included for simulation development.

To make the point of out of band energy saturation, raw broadband data plots will be shown, with the subsequent low pass filtering of that same data. The lack of proper aliasing protection against these large magnitude, high frequency data resonances renders the historical data useless. The historical gun fire data reviewed by the author (and shown in the next section) suffers from both under-sampling (incorrect time-domain amplitude) and aliasing. The question that has to be answered is: Does this poor quality historical data still give an accurate enough picture of the shock environment which the weapon system components are subjected to, so it can still be used as a specification for simulation development and qualification of future accessories? [1, 2]

PREVIOUS DATA: GUNFIRE, NEAR-FIELD PYROSHOCK TEST PARAMETERS AND DATA

Previous PR accelerometer data, as shown in Figure 1, was not captured in a manner consistent with the recommended practices in “Handbook for Dynamic Data Acquisition and Analysis” and “Pyroshock Testing Techniques“ [1, 2]. It was sampled at 25 KHz using a traditional non oversampling ADC , (***<u>Not</u>*** a Sigma -Delta data acquisition system architecture) with a Signal Conditioner bandwidth of 20 KHz, 4-pole Butterworth low-pass and antialiasing (AA) filter (~80 dB/decade =24 dB/octave). This combination of hardware would give correct amplitude (5% accuracy) for measuring signals where the bandwidth of interest is no more than 2.5 KHz if it had an effective analog antialiasing (AA) filter. The recommended practice is to sample at least ten times higher than the desired bandwidth of the measurement in order to achieve 5% or less amplitude error.

The signal conditioner’s AA filter specification means that the filter attenuation is only 80 dB down in a decade (200,000 Hz) and is really inadequate as an AA filter. Since the Nyquist frequency for these data is 12.5 KHz, there is no aliasing protection at all between 12.5 KHz and the 20 KHz cutoff frequency of the AA filter. All of the frequency content between 12.5 KHz and the 20 KHz cutoff frequency will fold back, without attenuation, between 12.5 KHz down to 5 KHz. The recommended practice for pyroshock data is an anti-aliasing filter that has a 60 dB/octave rolloff, and the cutoff frequency should be placed at least one octave below the Nyquist frequency [1, 2]. The PR accelerometers used to acquire this test data have a resonance that is at about 60 KHz and has 10 times the magnitude of the signal of interest. Consequently, the PR accelerometers’ resonance will alias into the data bandwidth of interest. Mild aliasing may be detected by a Fourier transform of the data. However, severe aliasing may be detected by an examination of the data parameters. This gunfire acceleration time-history in Figure 1 looks plausible. However the velocity time-history in Figure 2 is clearly wrong for gunfire data taken with a stand holding the rifle stationary! The velocity should oscillate about zero according

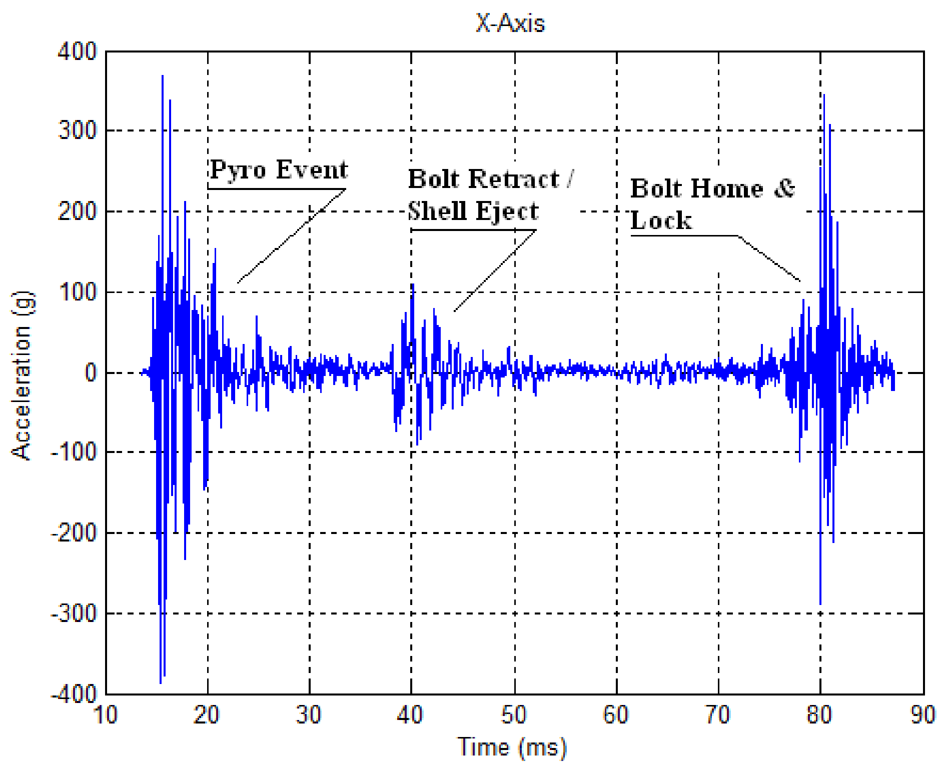

Figure 1: Historical Longitudinal Gunfire Shock.

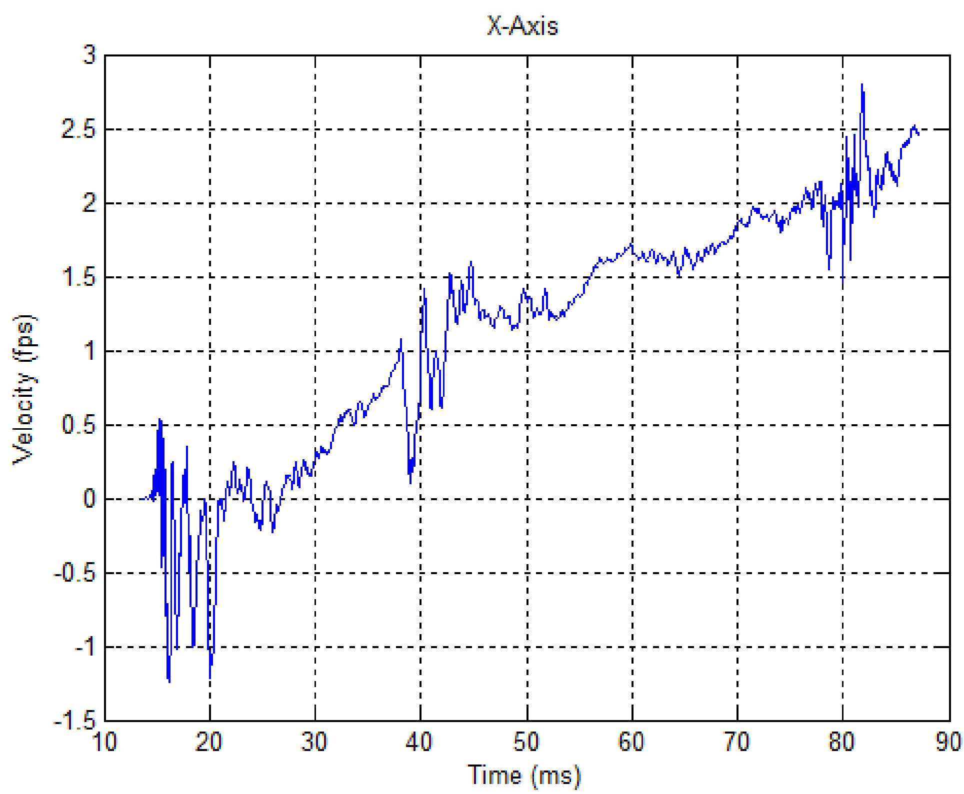

Figure 2: Velocity for Longitudinal Gunfire Shock (Integral of Acceleration in Figure 1).

to the test configuration. With the recent advances in data analysis and our knowledge of the data acquisition system (DAS), the velocity data exhibit the now well known evidence of aliasing [3]. The integral of the acceleration time history is the best single indicator of the quality of the data and should be routinely used as an accelerometer data quality screen [1, 2].

Finally, Figure 3 shows the shock response spectrum (SRS) for the data in Figure 1 that is calculated over a wider range (10 Hz to 100,000 Hz) than conventionally shown (100 Hz to 10,000 Hz). The SRS is plausible: it has the correct low frequency slope for pyroshock that is, in this case, about 9 dB/octave or +1.5 decades in amplitude for one decade of frequency and the SRS magnitude and settles out to a constant value by 30,000 Hz. However, the absence of the accelerometer resonance at 60 KHz clearly indicates that the data are aliased because the attenuation of the analog AA filter is not sufficient to prevent the resonance appearance in the SRS.

Aliasing cannot be detected by an SRS, so if the acceleration time history and the SRS are all that is examined, then the data appears plausible. However, the examination of the DAS specifications, data parameters, and the velocity time history reveal that these data are severely flawed and should be discarded.

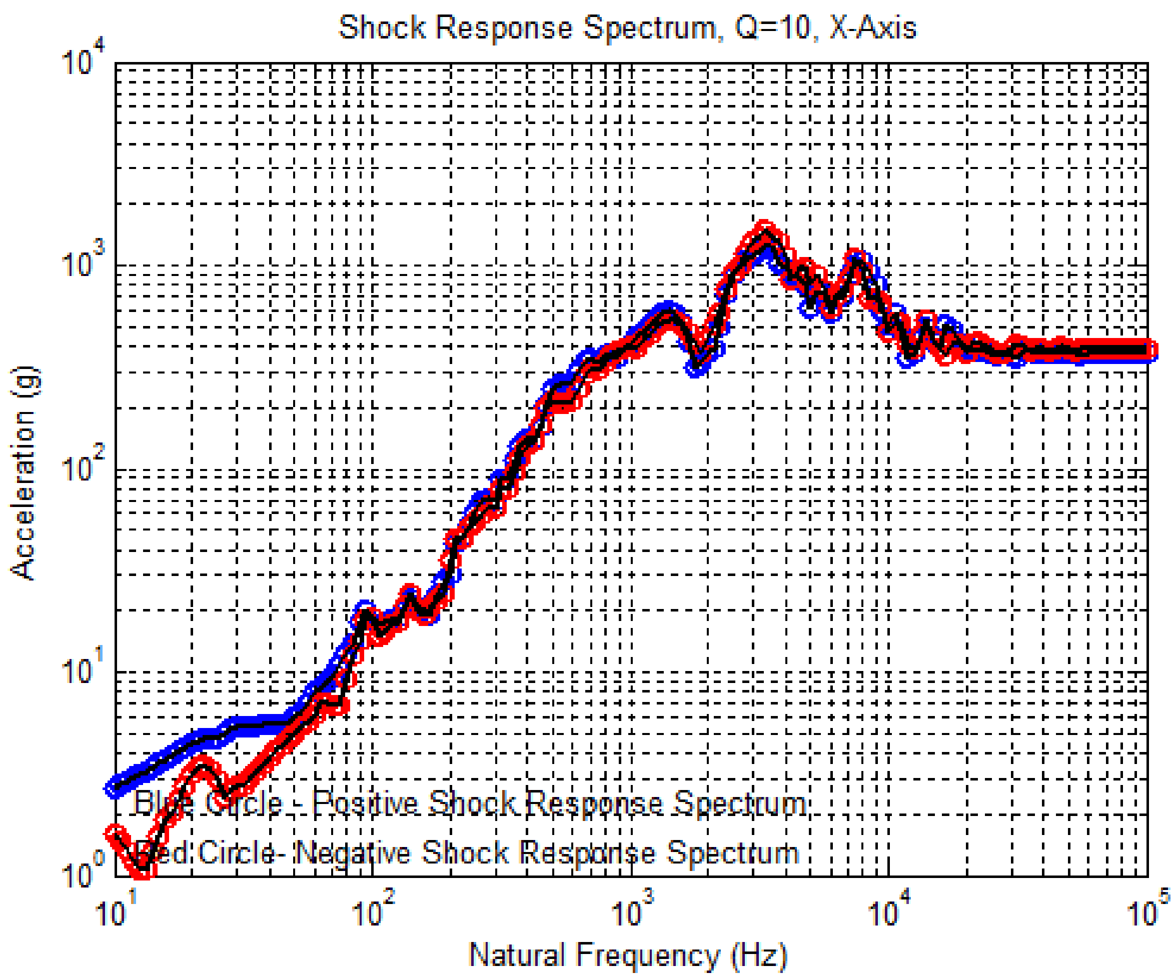

Figure 3: Shock Response Spectra for Longitudinal Gunfire Shock in Figure 1.

DATA ACQUISITION SYSTEM AND TRANSDUCER CHARACTERISTICS

In order to accurately quantify the test article shock environment, it is necessary to configure a DAS which has sufficient performance to faithfully capture the broadband signals normally attributed to pyroshock events. The system must not be affected by the high frequency resonances associated with the chosen Meggitt (Endevco) 7270A–60,000 g, PR accelerometer (nominal resonance is 750 kHz). The effective sampling rate (SR) used for this testing was 2.5 MHz which yields 400 ns internal sample timing accuracy and is sufficient to digitize a 1MHz signal. The digitizing resolution is 16 Bits, and the broad band amplifier is specified to 0.1 dB flatness @ 1.0 MHz. The converter system is a high speed Sigma-Delta clocked at 20MHz.

These combined DAS specifications are sufficient to accurately digitize not only the main frequencies of interest, but also the resonances of the chosen transducer, without fear of perturbation or contamination of the lower frequencies which is common in lower cost amplifiers which are slew rate limited (say 40 KHz -3dB of bandwidth). Slew Rate is generally specified in V/s or V/µs and is also referred to as the full power bandwidth. An ideal amplifier has unlimited gain and infinite power, so it would never be slew rate limited. Slew rate limiting is also tied to specifications known by the terms linearity and harmonic distortion, they are interrelated.

One must be very careful in reading signal conditioner specifications. It is very common in the industry to specify the -3dB (half power) point of an amplifier at a specific gain, rather than state the flatness specification which applies to all input ranges (gains). An inexpensive signal conditioning card will specify the broadband response of the amplifier without the AA filter, and usually at unity (1) gain and -3dB.

For example, a commercially available signal conditioner has specifications of 3.1 V/µs (RTO – Referred To Output), and 1.5 V/µs RTI (Referred To Input). This is only a gain of 2 from input to output). The second number is important because is the fastest rise time the input signal can have without distortion. With that type of slew rate specification, it would be easy to assume the amplifier could handle a 1 MHz low-level signal quite well (1MHz = 1 µs), and it probably would at unity gain. However the amplifier is specified to be “less than -3db at 100kHz” for all gains 1-1000, with the caveat: “Bandwidth is reduced in proportion to gain above 1000” This means that as long as the gain is less than 1000, there will be 100 KHz of useable bandwidth. But the filter stage for AA filtering further reduces to the bandwidth to just 10 KHz. The input buffer amp must have sufficient bandwidth to present the broadband signal to the AA filter. With a gain of 1000, 1.0mV on the input will turn into 1.0 V at the output of the amp stage. However when gain at high frequencies is required, such as a transducer in resonance, the input waveform will be corrupted by slew rate limiting.

The Sigma-Delta DAS used has auto-tracking, Nyquist, digital finite impulse response (FIR), AA filtering. The system is unique in that it utilizes an M-Derived analog AA filter at 20 MHz, (-90dB) [4] which is far above any frequencies of interest and is the only frequency requiring analog AA filtering. The above specifications are achieved with sigma delta architecture. The effective AA filter rolloff for sigma-delta architecture is greater than 120 dB/octave [5]. This rolloff slope has been historically documented for over two decades as necessary to prevent aliasing [6].

MEASURED DATA AND DATA ANALYSES

Examples of the triaxial acceleration time histories are shown in Figure 4, and their corresponding velocity time histories (integral of the data in Figure 4) are in Figure 5. The velocity time histories show the correct velocity that is indicative of the test configuration: zero velocity change. The discrete Fourier transforms of these data are in Figure 6 that shows the correct reproduction accelerometer resonances indicating the high quality of these data. Time history data digitally filtered at 10 KHz and 100 KHz are in Figure 7. A slew rate limited amplifier will not present the waveforms in Figure 7c to the digitizing system.

These data have three distinct events shocks as shown in Figure 4. Consequently, little of what is in the literature is useful for analyzing these data since these references deal with a sequence of very similar (single) shocks. The shocks exhibited by the data in Figure 4 are classified as multiple shocks [7] for a single phenomenon or as "complex shocks" in MIL-STD-810G Method 516.7 and the analysis of "complex shocks" are left to the discretion of the data analyst. The analysis presented below validates the pyroshock and shock data present in the gunfire and should also be used to compare the simulated weapon fire and live fire measurements [7]. The events have been separated and analyzed with SRS. The results are shown in Figures 8-10 that clearly show the high-frequency content in all three shocks and must be replicated to qualify future accessories. These data have passed the pyroshock validation criteria [8].

In Figure 7c, using a 100 µS time slice, we can clearly see the resonance of the PR transducer. The Red and Green traces have been digitally filtered to 10 KHz and 100 KHz, respectively, to emphasize the magnitude differential seen by the input amplifier. In a slew rate limited system the red and green traces would have much larger excursions as the slower waveform is actually modulated by the higher frequency.

Ultimately, three round burst data must also be evaluated. Time history accelerations, velocity time histories, Fourier transforms and SRS for three round burst data are shown in Figures 11-14 and indicate valid data [8]. Figure 15 shows the data broadband and filtered at 100 KHz and 10 KHz.

A RECOMMENDED DATA ACQUISITION SYSTEM EVALUATION

Without using expensive and exotic testing gear, you can characterize your data system to validate its efficacy to handle these types of signals, and it is recommended. A data acquisition system needs to be evaluated by the user that its performance is as required. Additionally, verify AA and slew rate capability for high frequency, large amplitude data such as pyroshock. A poor man's summing junction can be used, and needs only a few resistors and two signal generators. The key to the test is to have a low frequency sine wave (in band energy) say 20.12 KHz @ 500mV and a high frequency sine wave which represents broadband energy, say 901.1 KHz @ 5V. (Choose odd numbers, this helps when evaluating digitized results.) You need to first measure the low frequency signal and verify that you are digitizing a clean (not distorted) Sine wave (use spectrum analysis to look for spurious energy). Next feed in the broadband signal, if you are sampling at a rate of less than 2.0 MHz and your AA filters are working properly, you should see no signal. If you measure a DC offset, your AA filter is overloading. If you see something other than a flat line signal near zero, you should look at the spectrum of this signal. Your AA filter probably does not have sufficient roll off for the chosen sample rate.

Assuming you measured a flat line at zero volts above, sum the two signals via ten kilo ohm resistors and feed them into the input. If your system has sufficient analog bandwidth prior to the AA filter, you should measure a nice clean sine wave of 20.12 KHz @ 500mV. Verify purity by viewing a spectrum of the signal. If the time domain waveform is distorted you are probably slew rate limited. Lower the applied broadband frequency until your low frequency sine wave is clean. If the broadband frequency is below 400 kHz, to get a clean low frequency signal, your system is inadequate for use with Meggitt (Endevco) 7270A– 20kG, 60kG and 200kG accelerometers as their resonance signature will corrupt your data.

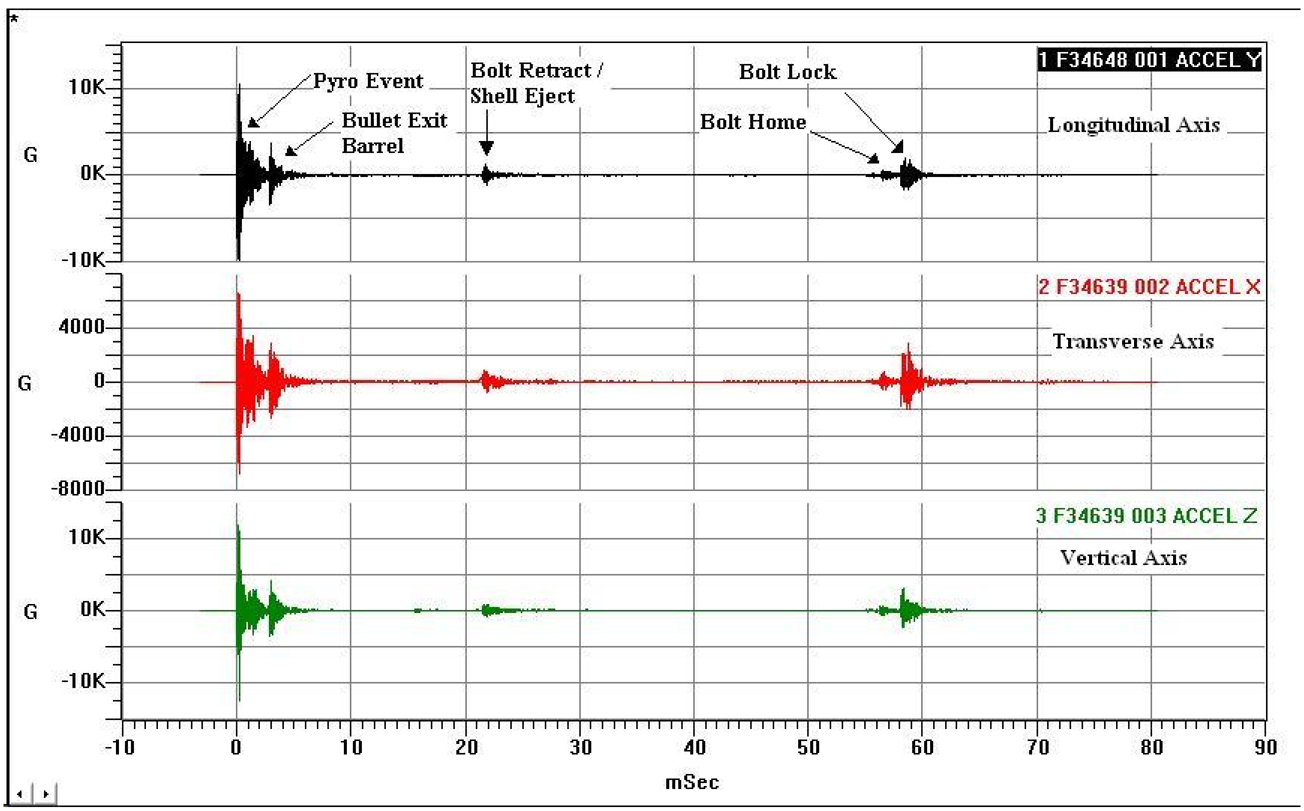

Figure 4: Broadband Data capture Single Fire Event X, Y, Z axis: Note G Levels ~10kG.

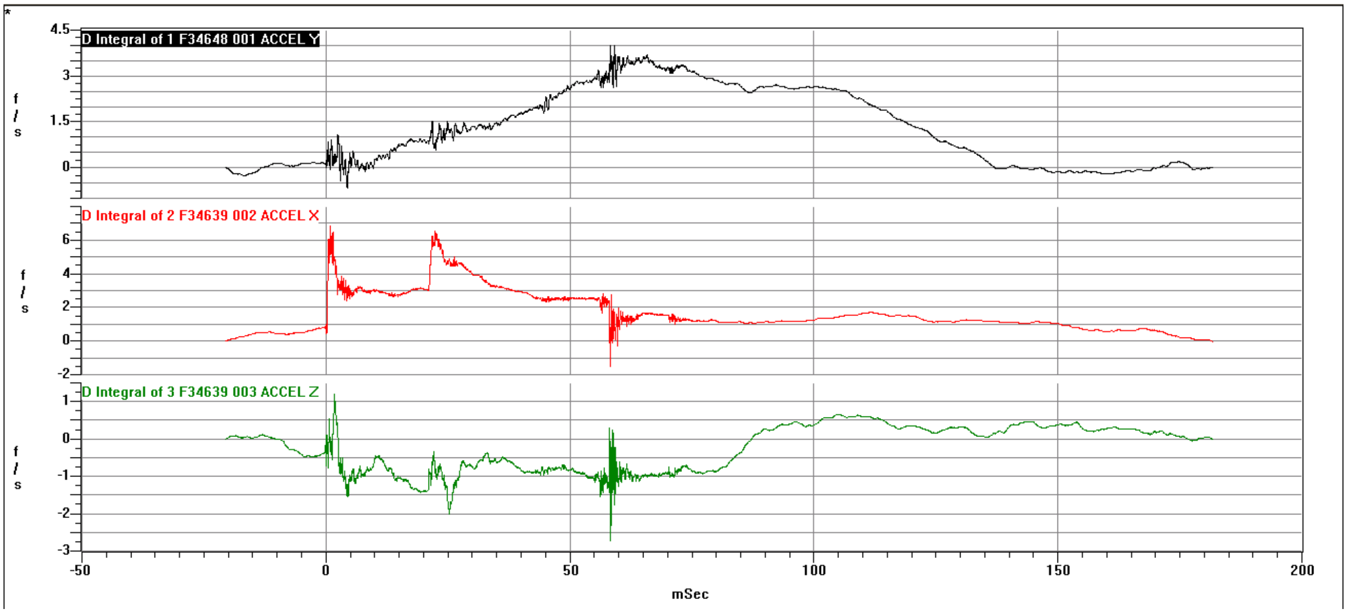

Figure 5: Velocity Time Histories (Integral of Acceleration Data in Figure 4).

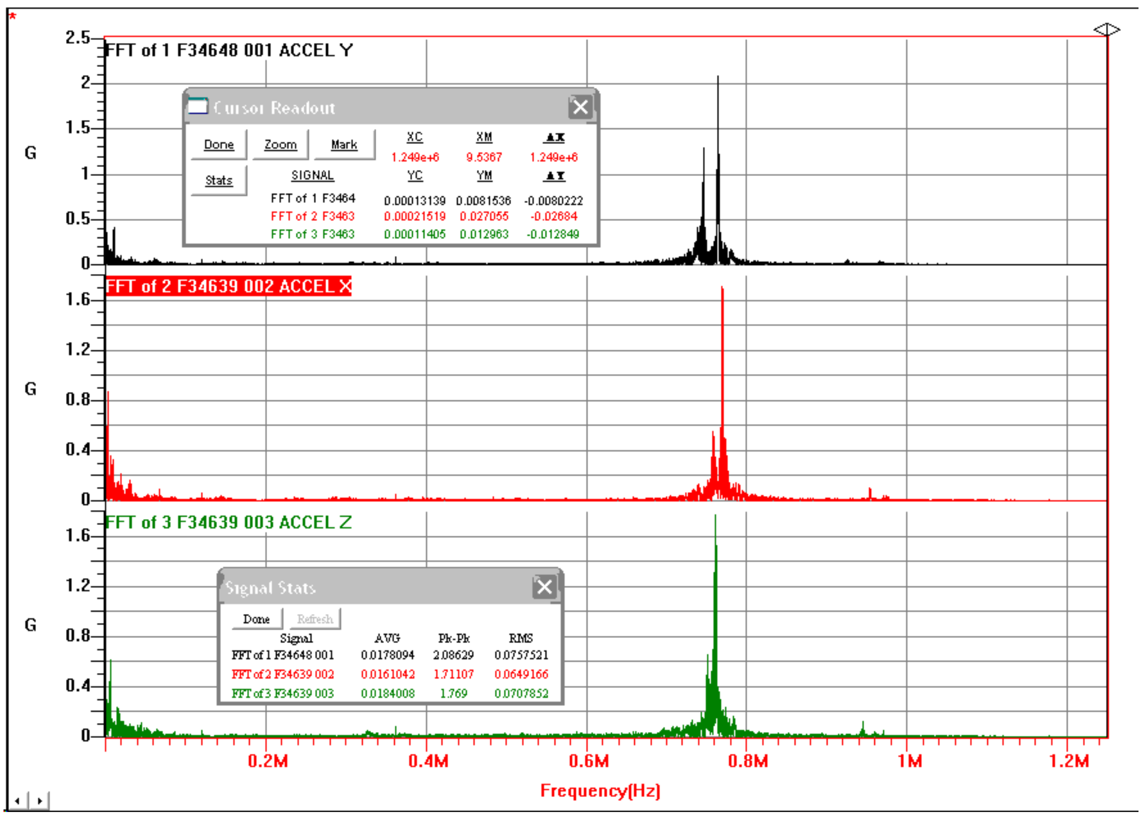

Figure 6: Discrete Fourier Transforms for Triaxial Data in Figure 3 Depicting the Significant Transducer Resonance at ~750 KHz in all 3 axes.

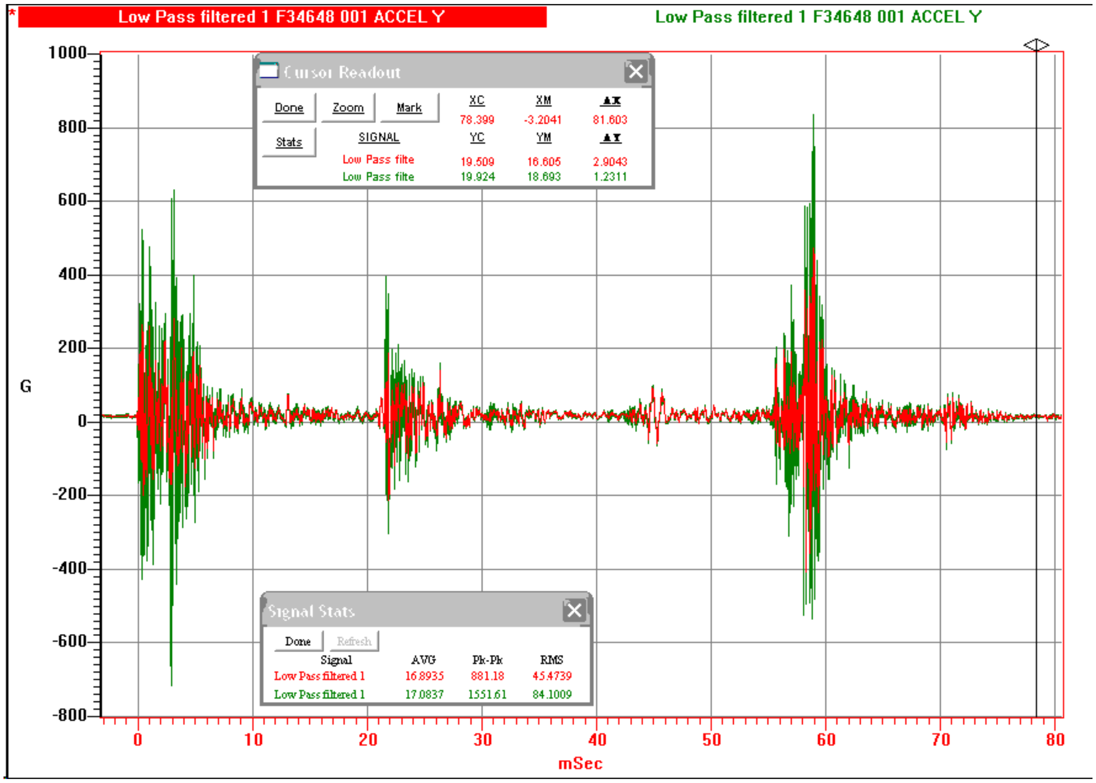

Figure 7a: Y-Axis Live Fire Event (from Figure 4) Filtered to 10 KHz (Red) and 100 KHz (Green).

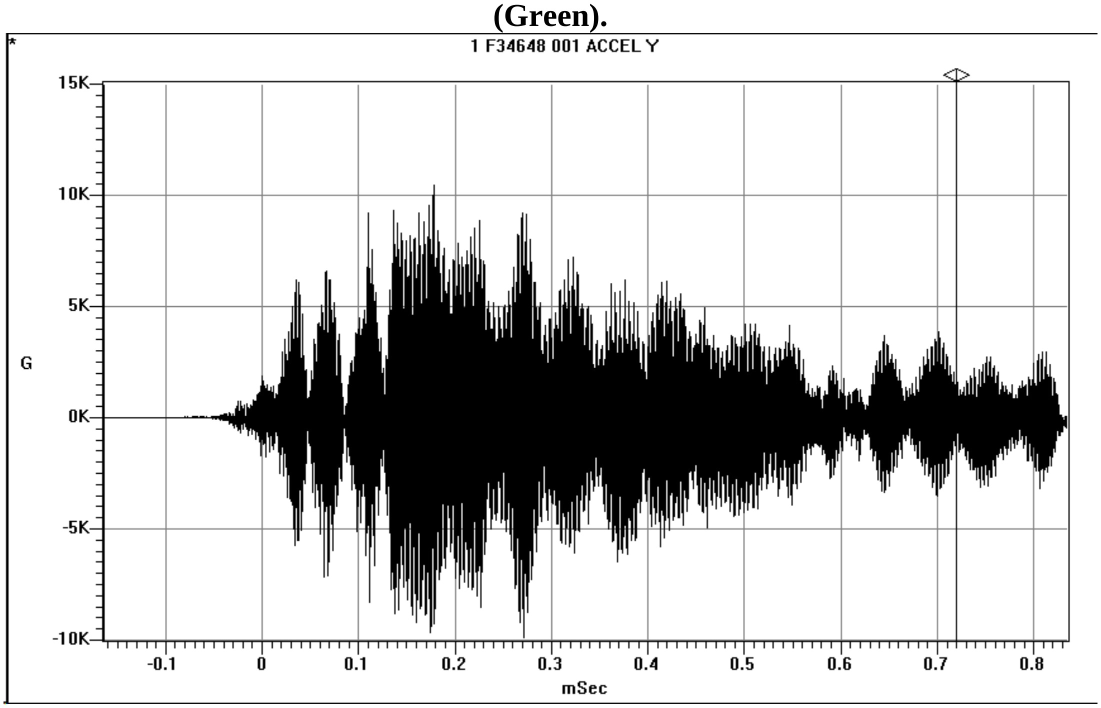

Figure 7b: A zoom of the time history of just the Y axis Pyroshock (first impulse) event showing ~20,000 g Peak-to-Peak content.

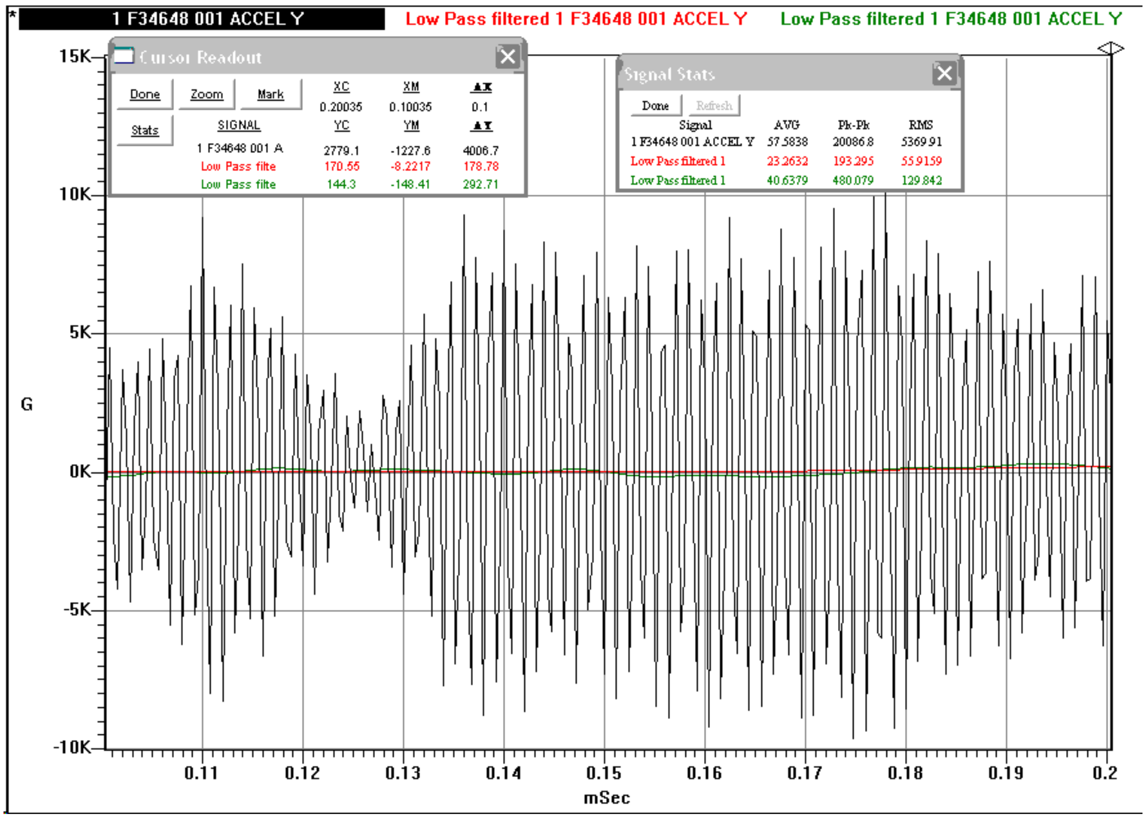

Figure 7c: A closer zoom showing broadband content. A slew rate limited amplifier will not present this waveform to the digitizing system.

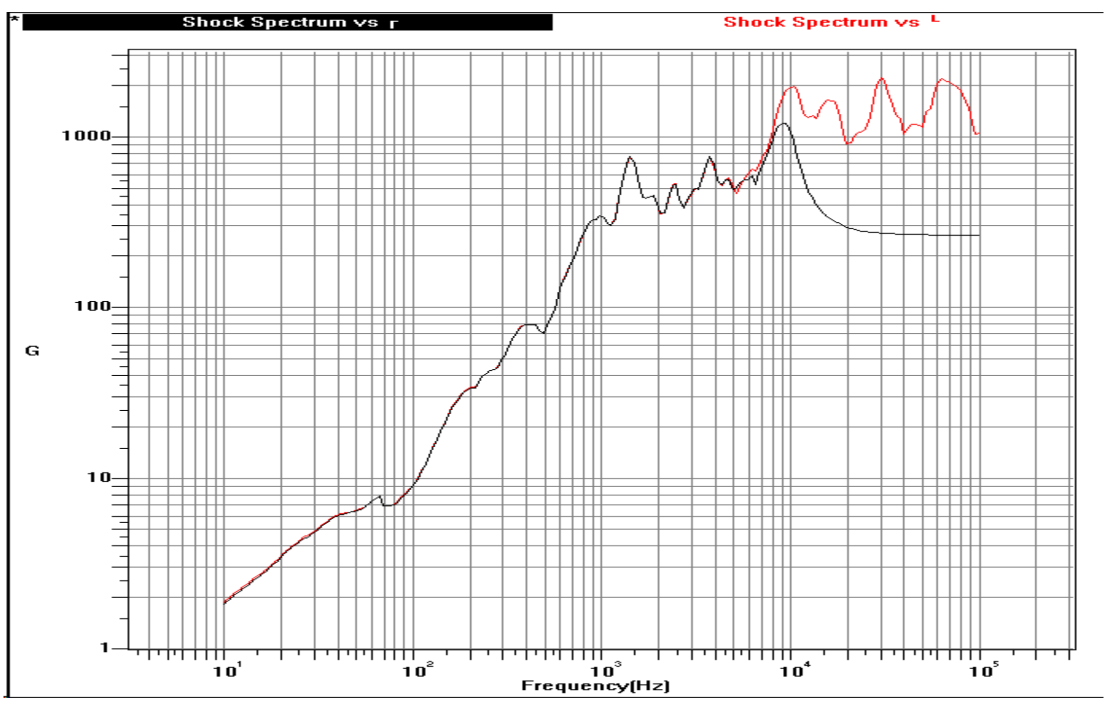

Figure 8: Y axis, SRS of Pyro-Segment, Digitally Filtered to 10 KHz (Black) and 100 KHz (Red) with Q=10.

(Note the significant energy content above 10 KHz.)

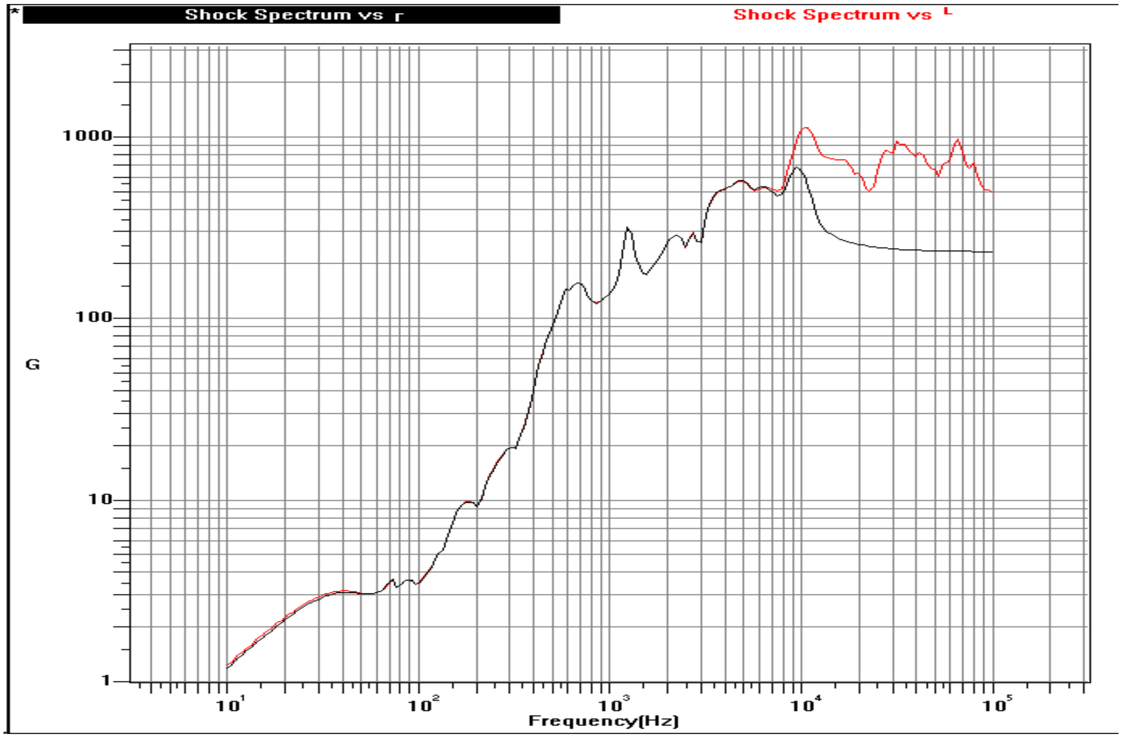

Figure 9: Y axis, SRS of Retract / Eject pulse-Segment, Digitally Filtered to 10 KHz (Black) and 100 KHz (Red) with Q=10.
(Note the significant energy content above 10 KHz.)

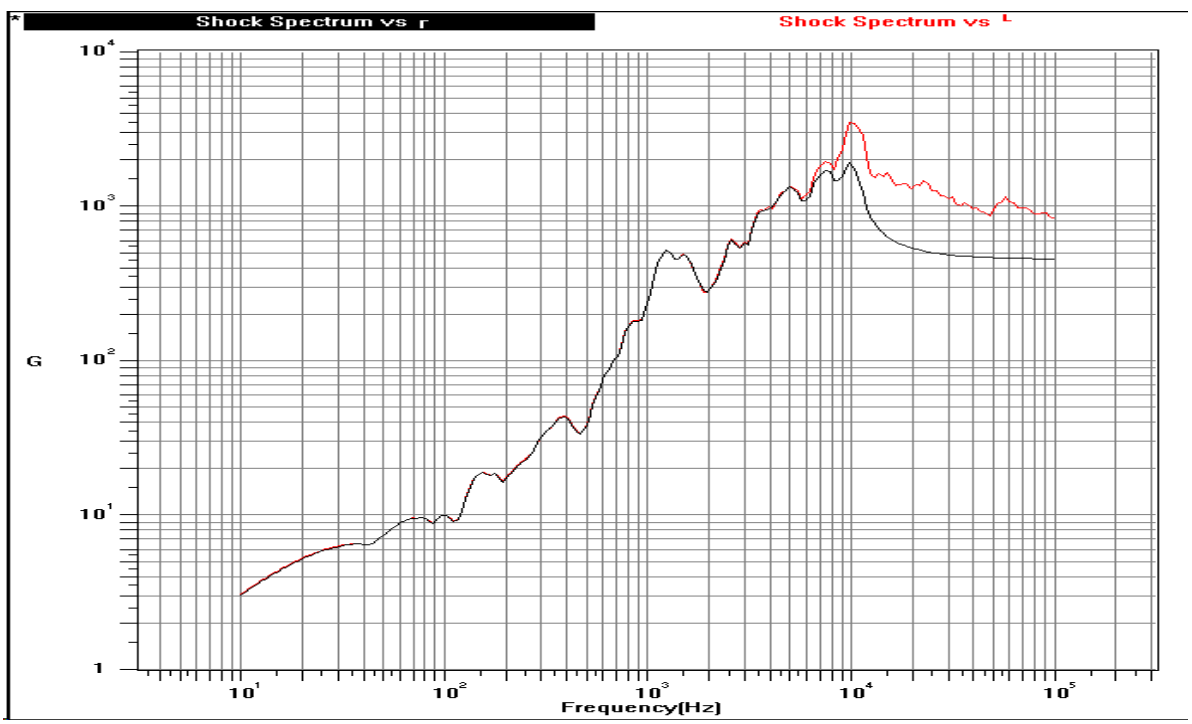

Figure 10: Y axis, SRS of Bolt Home/Lock Pulse-Segment, Digitally Filtered to 10 KHz (Black) and 100 KHz (Red) with Q=10.

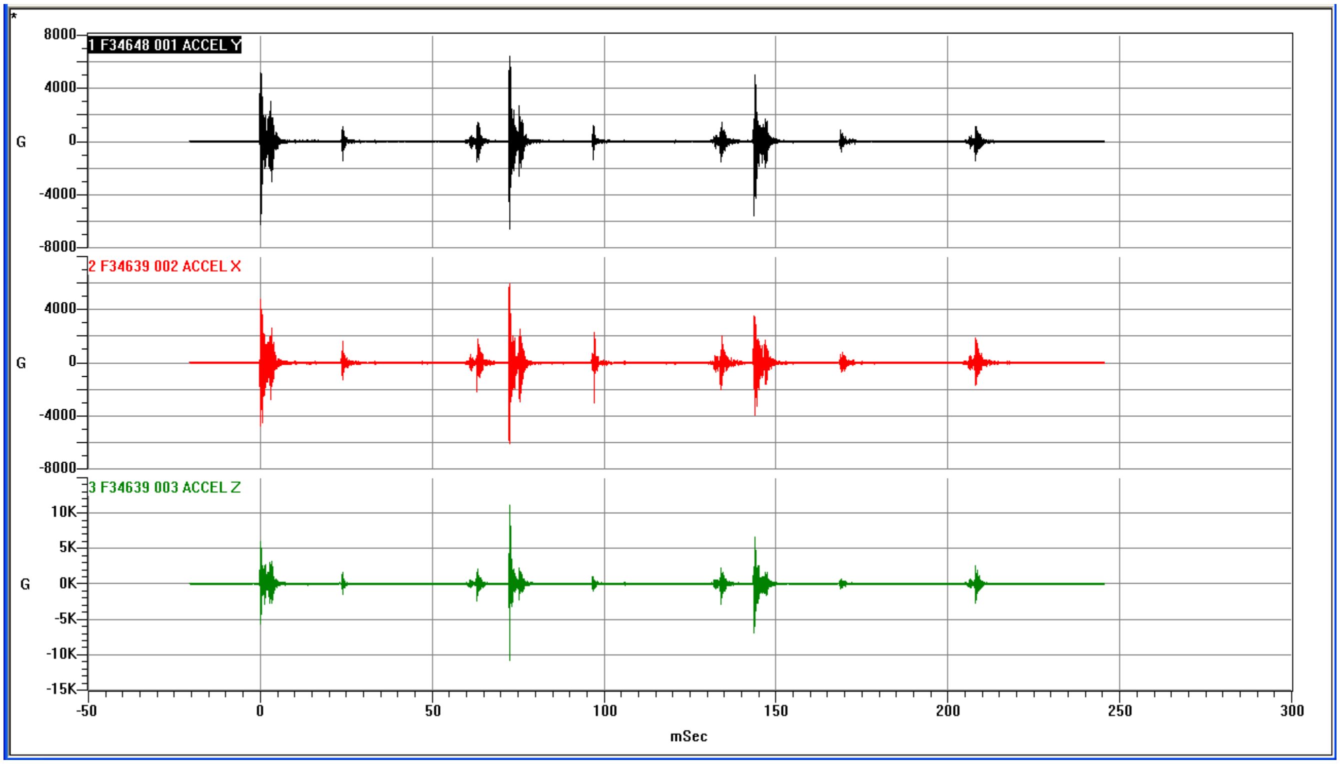

Figure 11: Triaxial Acceleration Time History for three round burst in all three axes. The signature is identical to single shot data.

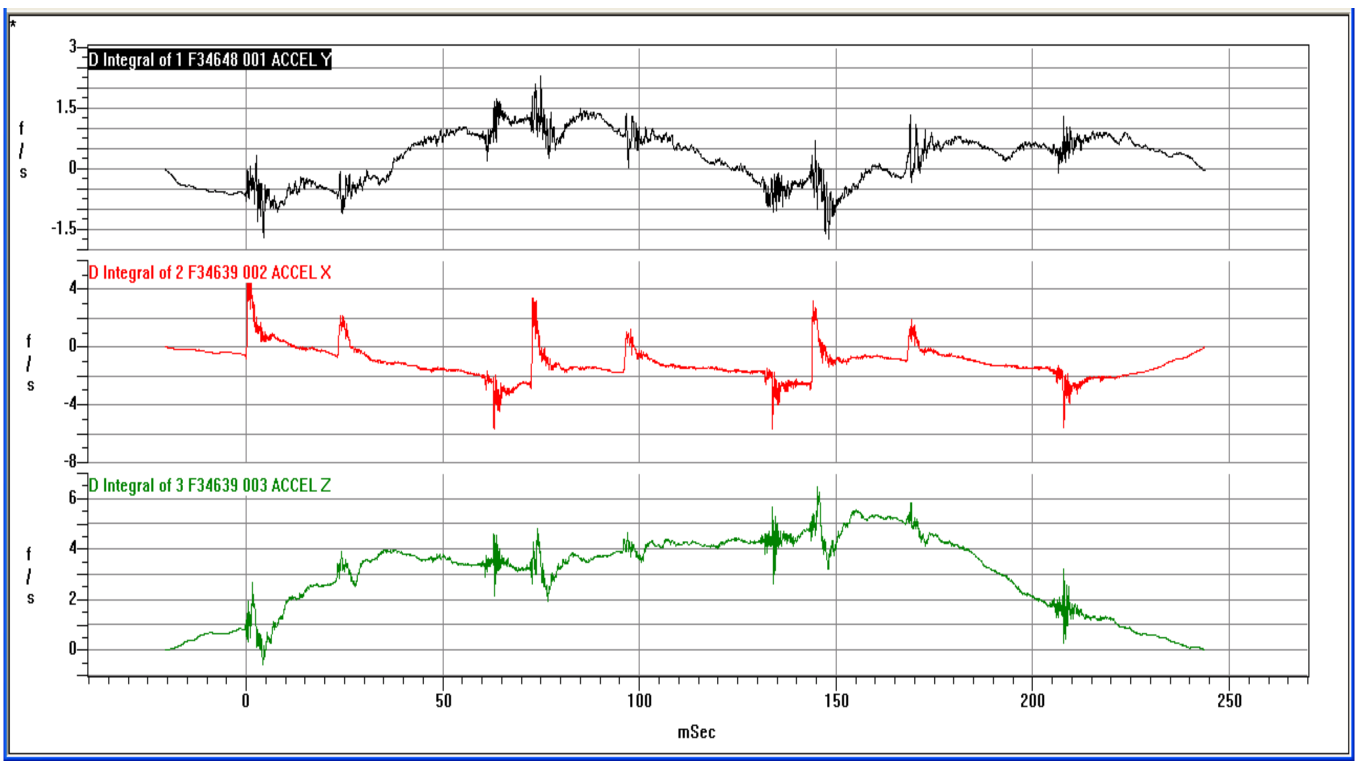

Figure 12: Triaxial Velocity Time Histories for three round burst in all three axes. (Integrals of the data in Figure 11)

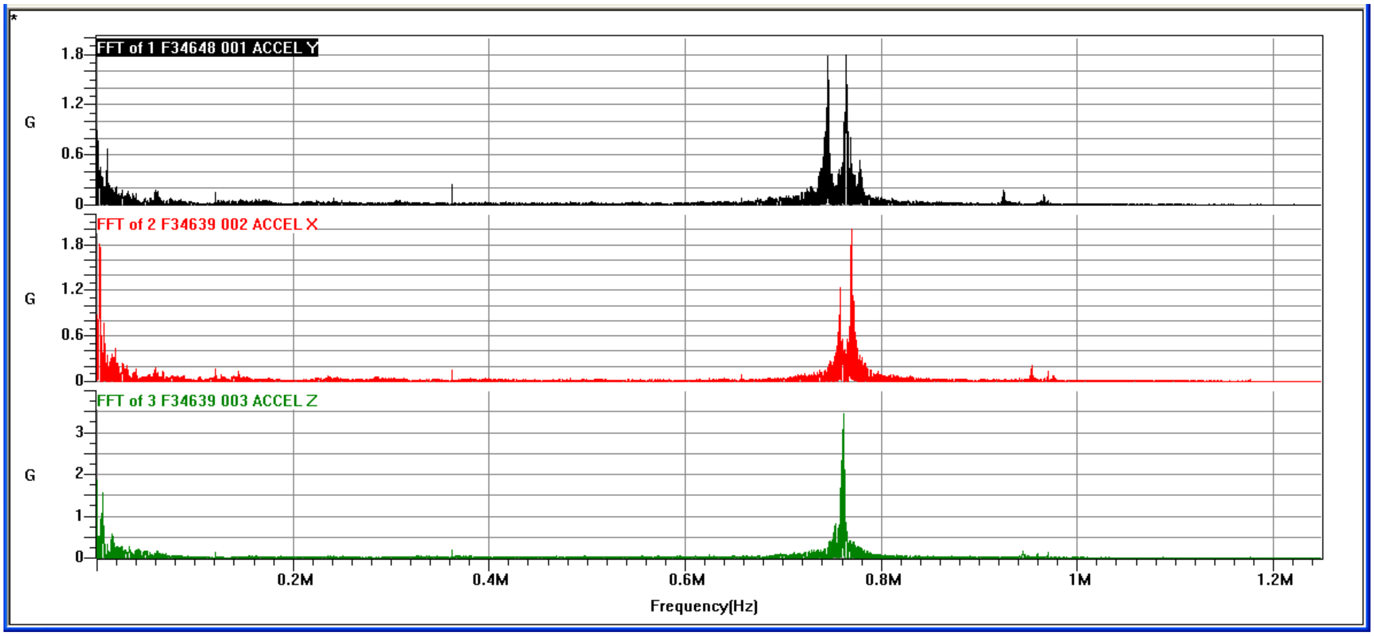

Figure 13: Three Round Composite FFT for Triaxial Acceleration (Black - Longitudinal, Red – Transverse, Green – Vertical)

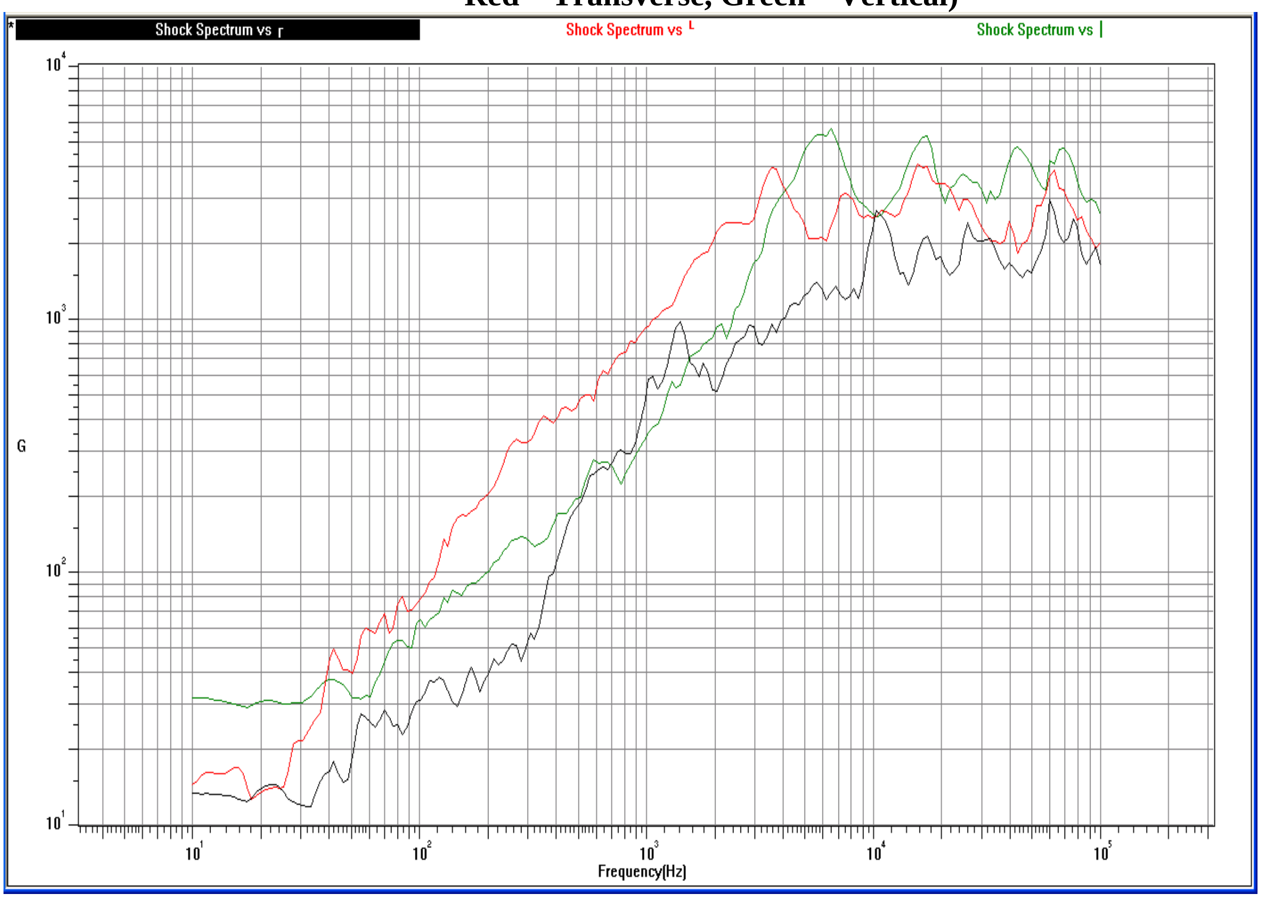

Figure 14: Three Round Composite SRS for Acceleration Time History in Figure 11 (Black - Longitudinal, Red – Transverse, Green – Vertical with Q=10).

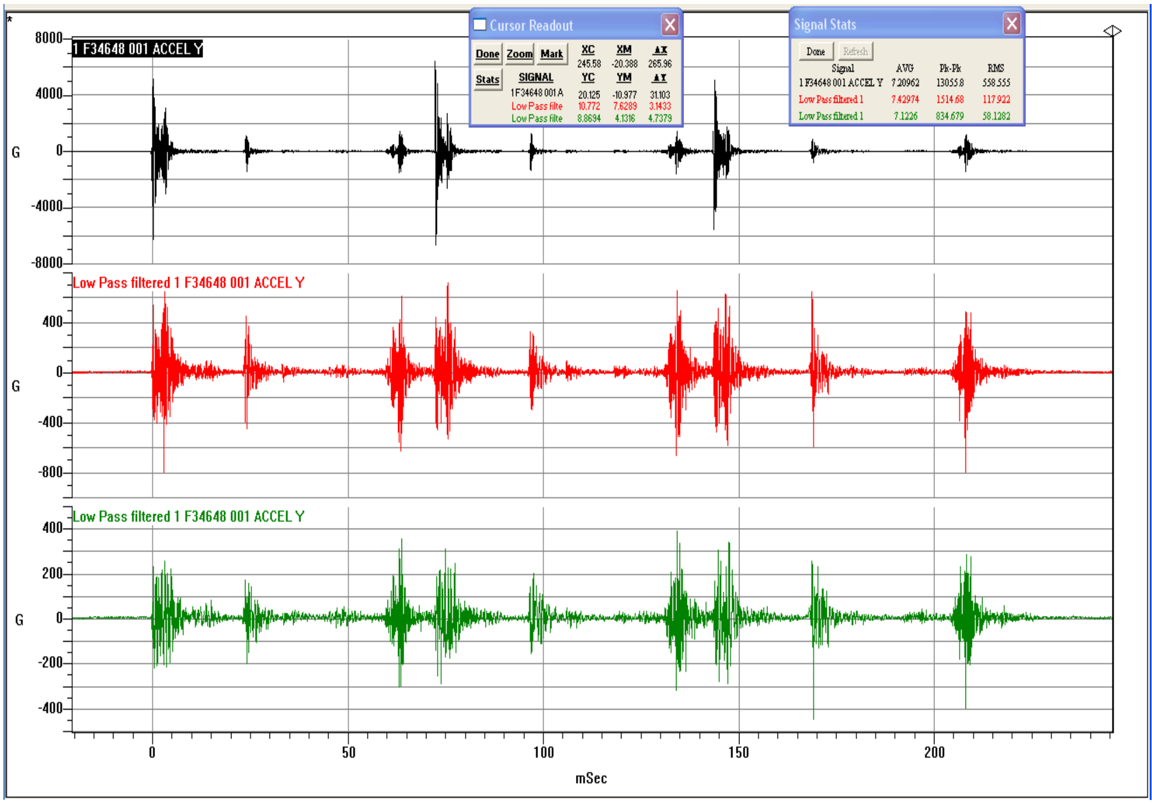

Figure 15: Three Time History plots show the longitudinal axis only. (Black = Broadband, Red = 100 KHz, Green = 10 KHz)

CONCLUSIONS

The pyrotechnic shock is the most severe event in the gunfire environment and requires a higher frequency DAS than mechanical shock. Given another opportunity to run this test, I would run at 5.0 MHz instead of 2.5 MHz to provide better time resolution (200ns) for identification of the discrete events contained in live fire. For the data from this live fire test series, both single shot and three round burst, the dominant frequency content in both the discrete Fourier transform and the SRS is at and above 10 KHz (ignoring transducer resonance). It is clear that data beyond 10 KHz must be used to qualify components and accessories for the pyrotechnic environment. Since data should never be filtered at less than 1.5 times the desired bandwidth, these data should always be recorded with a wide band data system. The system bandwidth of 1 MHz allowed the correct measurement of the accelerometer resonance at 750,000 Hz without digital aliasing or analog corruption (slew rate limited) and is the recommended bandwidth of these data. Removal of unwanted broadband data as a post processing function is far more desirable than being unsure that potentially important frequency content was missed. While gunfire data is repeatable, explosive testing on one-of-a-kind test articles should never be left to chance. It is always better to have too much, than not enough!

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