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Acquiring and Analyzing Pyrotechnic Test Data – The Right Way!

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Acquiring and analyzing data from pyrotechnic tests is one of the most difficult tasks in the vibration, sound and shock world. The nature of the motions produced by explosive events makes the measurement process very difficult, and as a result, it is very easy to produce data that look good but are still wrong.

One of the critical problems is that there are no universally accepted strategies that can be used for pyrotechnic data acquisition and analysis. There are several "standards," but none explicitly describes the processes or procedures required to produce useful, accurate, repeatable results.

Unfortunately, there have been several recent instances where critical data were improperly acquired and the conclusions drawn were completely, and expensively, wrong. In these tests, data acquisition errors produced results that satisfied the testing requirements and the tests were declared successful. Later investigations showed that, when the data were properly acquired and analyzed, the tests did not meet the desired objectives.

This article was primarily inspired by these testing experiences. Its objective is to describe and discuss procedures that have been proven to produce good pyrotechnic test results.

Why Test? Aircraft and spacecraft system components are subjected to a variety of high-frequency shock events. In the case of military aircraft, equipment is exposed to both enemy hits and explosive devices used to release under-wing stores. A spacecraft is exposed to a series of shock pulses from rocket motor ignition, staging events actuated by linear-shaped charges, and actuation of a pyrotechnic device used to deploy equipment such a solar arrays. Verifying via test that hardware components can withstand expected shock incidents is a prerequisite to successful operation.

At the low-amplitude end, small explosive devices are used on spacecraft and aircraft to release devices such as solar arrays and droppable stores. Pin pullers and pyro-driven valves produce accelerations of up to 1000 g, strong frequency components up to 50 kHz and can cause failures of equipment nearby.

High-amplitude events include direct excitation by explosives and impact/explosions of weaponry. These events cause accelerations of 10s of thousands of g with strong frequency content up to and above 1 MHz. Experiments are performed to characterize the actual events (flight/service environment) and to verify simulations (laboratory tests) of service behavior.

Why are Pyrotechnic Tests Difficult? The primary measurement problem is the high-frequency content of the motions produced. With a few notable exceptions, it is generally agreed that frequency content above 10 kHz does not cause mechanical damage. Energy at higher frequencies (which may be up 90% or more of the total) is not important to the damage potential assessment. However, this energy must be handled by the transducer, signal conditioning and data acquisition systems.

To analyze data to 10 kHz (using methods discussed below) we need a measurement bandwidth of about 20 kHz. This is termed the "frequency range of interest." Components above this frequency are called "out-of-band energy." At this point, we have two choices:

- Follow Shannon's theorem directly and acquire data with a sample rate that is more than two times that of the highest significant frequency component. For pyrotechnic testing, this means millions or tens of millions of samples per second. Although this can be done, it is inefficient and not as accurate as the second alternative.
- Acquire at a lower rate (40,000 to 200,000 samples/sec) after assuring that the signal is adequately protected against aliasing errors.

When the lower-sample-rate strategy is used, we must be assured of two things:

- High-frequency components are attenuated enough so that aliasing errors in the frequency range of interest are negligible.
- The analog input system is capable of handling the out-of-band energy.

Several features of the problem are illustrated in Figure 1. The data shown were taken in a low-level (pin-puller) pyrotechnic test using an acquisition system of 1 million samples/sec. It has a moderate amount of high-frequency energy. For this example, we will assume that the damage is caused by energy below 5 kHz. This allows a sample rate of 20,000 samples/sec.

To acquire accurate data below 5 kHz, the time history will have to be processed to insure that any energy, above the Nyquist frequency (sample rate/2) of 10 kHz, that would fold into the frequency range of interest (5 kHz.) will be insignificant. This process, called alias protection, is done with a low-pass filter. There are two basic strategies available to perform this function:

- A significant analog low-pass filter to attenuate the high-frequency energy. Eight-pole Butterworth and 8-pole/6-zero elliptical filters are appropriate commercially available options.
- A hybrid analog/digital "oversampling" system that uses a high sample rate combined with a relatively simple analog low-pass filter and a digital filtering operation.

Most modern systems built for structural dynamics testing use the second approach. In most cases, a sigma delta analog-to-digital converter is used. When properly implemented, this strategy provides a very-close-to-perfect low-pass filter/digitizing process.

Figure 1 shows that the magnitude of the filtered data that we see (black) is only 25% of the signal at the transducer (grey). The difference is the high-frequency components that we don't care about when assessing damage potential. However, it is essential that we recognize that the transducer and input amplifier (all of the components ahead of the filter) must be scaled to accept the broadband signal.

This means that our system needs to be scaled to accept signals much larger than what we see. If this is not the case, components upstream of the alias-protection filter will be saturated, and the data will be corrupted.

What do we do? We scale our system to handle a dynamic range that is much higher than expected. This is called headroom. For pyrotechnic testing, headroom of 10:1 is a minimum. To be really safe, 50:1 is a better choice.

If we scale our test to 50 times what we expect, we need a system with a high dynamic range. Fortunately, systems are available that have a dynamic range of more than 80 dB (10,000:1). So, if we use a headroom of 50, we can still see data that are 0.5% of what we expect (a really good day in pyro testing).

Is a System OK for Pyro Testing? We need to prove two things:

- That the data within the desired frequency range are adequately protected from aliasing.
- That out-of-band energy does not corrupt the data.

Both of these can be demonstrated with a sine sweep. Figure 2 shows the time history of a logarithmic sweep from 100 Hz to 2 MHz recorded with a DSPCon Piranha III™ data acquisition and analysis system that is sampling at 100,000 samples/sec. The horizontal axis has been converted from time to frequency by applying the known sweep parameters. It can be seen that:

- The signal magnitude is essentially constant to just under 50 kHz (sample rate/2).
- The signal is attenuated to very near zero above 55 kHz. Additional analysis confirms that the attenuation is >80 dB. This assures that after energy above 50 kHz is folded around the Nyquist point that the frequency range below 45 kHz is alias protected.

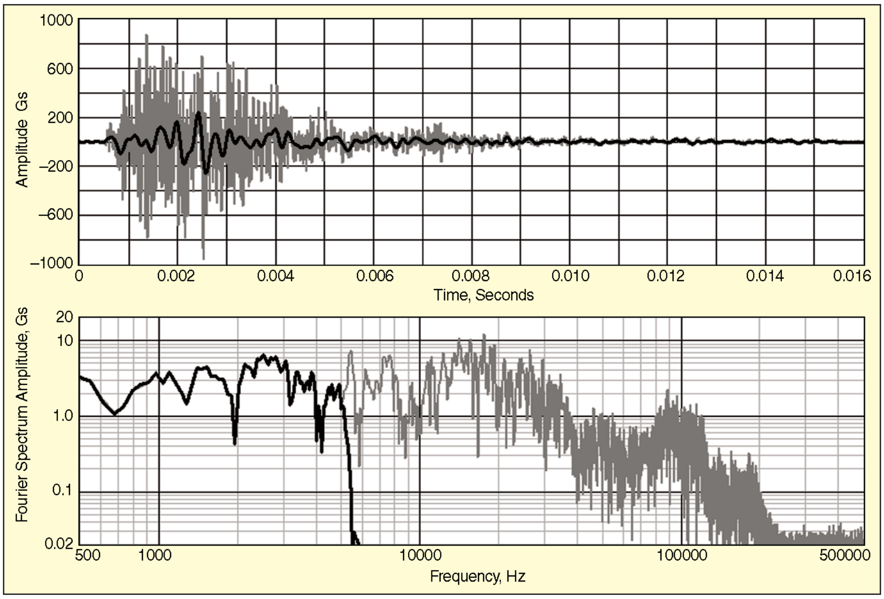

Figure 1. Effect of out-of-band energy – time history and Fourier spectra.

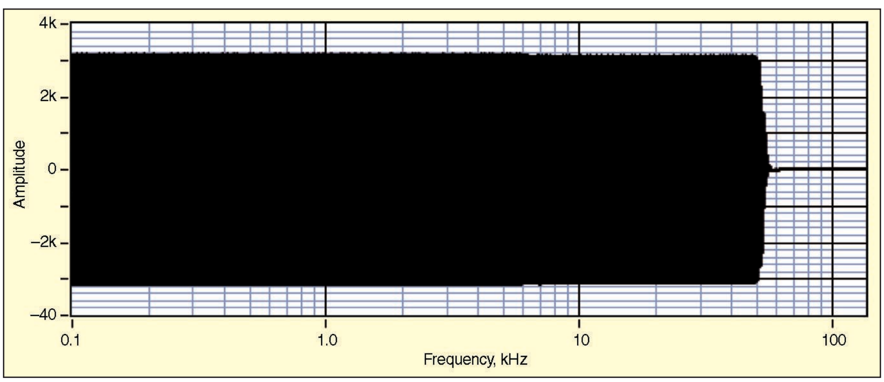

Figure 2. Sine sweep from 100 Hz to 2 MHz on DSPCon Piranha (S=100 Ksamples/sec).

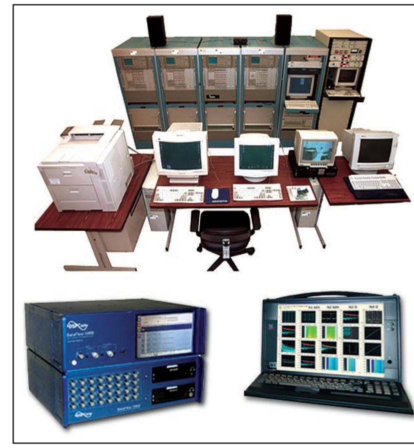

Figure 3. DSPCon Piranha III™, DataFlex-515 with MultiScope, and DataFlex-1000 (clockwise from top).

- The response above 55 kHz is essentially zero. Systems that do not adequately handle high slew rates will produce offsets when their capability is exceeded.

Many systems will fail this test set. Although deviations from constant magnitude (Item 1) can be analytically corrected, failure to satisfy the principles in either Item 2 or 3 properly is fatal for pyrotechnic testing.

How Are Data Analyzed? The damage potential of a pyrotechnic shock is normally characterized with a shock response spectrum (SRS) analysis. The calculation was originally conceived as a method of characterizing earthquake motions by Biot. The basic concept is that the calculation analyzes the motion of a set of spring/mass/damper systems that are driven by base motion.

Multiple algorithms that emulate this model in the digital domain have been developed over the years. One that is widely used was developed by David Smallwood at Sandia.[1] In this classic paper, the author developed a very accurate algorithm and provided all of the information required to implement it. It has been accepted by many investigators as one of the most accurate options and adopted as the approved processing technique in the ISO Standard for pyrotechnic data analysis (ISO 18431-4:2006).

To provide consistent results between laboratories it is essential that a consistent analysis procedure be used. The Smallwood algorithm is the obvious choice.

Before the time history is passed to the SRS processor, any low-frequency offsets must be removed. This operation, called preprocessing, is done in two steps:

1. A block of data just before the shock is averaged and the result is subtracted from the whole time history.
2. Then low-frequency signals and small in-shock offsets are removed by the application of a high-pass filter. The problem here is determining how much filtering is allowed and at what frequency. A filter that is "too strong" will hide unacceptable anomalies in the data. No standards have been established, but a four-pole filter set at 1/10 of the minimum SRS analysis frequency will remove reasonable errors.

Then low-pass filtering can be applied to attenuate the small amount of aliased data near the Nyquist frequency and to normalize the data.[2]

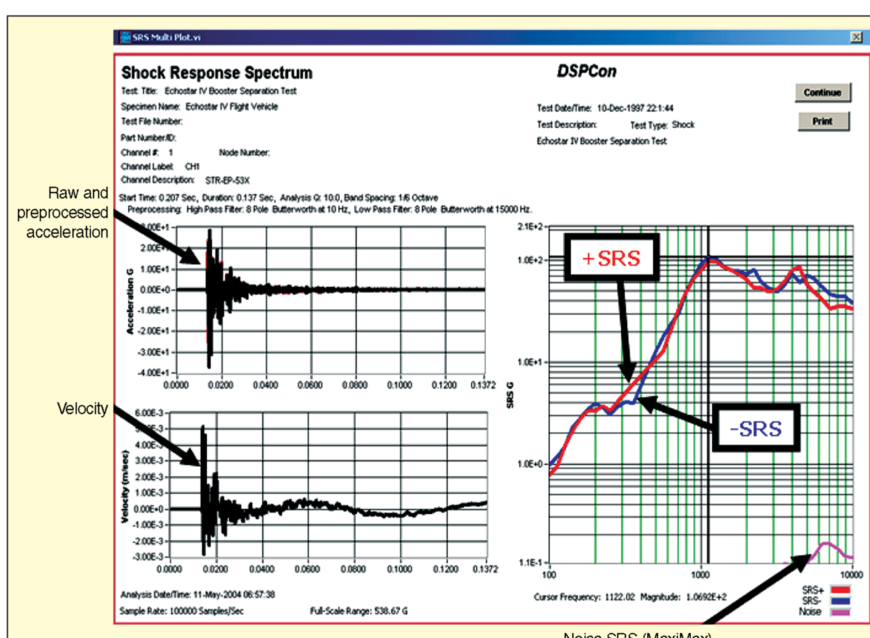

Figure 4. DSPCon SRS analyzer results display.

The DSPCon Solution. All of the considerations discussed here are provided by the DSPCon Piranha III, DataFlex-1000, and DataFlex-515 data acquisition/analysis systems (Figure 3). The Piranha III data acquisition hardware used in the tests discussed provides:

- Sigma-delta acquisition with sample rates of up to 256 K samples/sec. This provides signal bandwidths of up to 115 kHz
- From 16 to thousands of synchronously clocked channels
- Dynamic range – time domain: >90 dB; spectral domain: >105 dB
- Continuous acquisition for several hours at full data acquisition rate

Analysis software is available for a variety of applications. A few of the features of the DSPCon SRS processor, whose results are displayed in Figure 4, include:

- Smallwood SRS analysis algorithm
- Preprocessing to provide initial offset subtraction, high-pass filtering to remove small in-test offsets, and low-pass filtering to provide system normalization
- Calculation of velocity and positive and negative SRS to detect test-offset errors
- Calculation of the pre-shock "noise" SRS to demonstrate signal-to-noise ratio
- Interactive and multi-channel batch processing.

This combination of features makes the DSPCon systems particularly suited for pyrotechnic shock applications. For additional information on selecting the proper DSPCon data acquisition/analysis system for your pyrotechnic shock application, please contact DSPCon, Inc at www.dspcon.com or 908.722.5656.

1. Smallwood, David, "An Improved Recursive Formula for Calculating Shock Response Spectra," *51st Shock and Vibration Bulletin*, 1980.
2. Smith, Strether: "Why Shock Measurements Performed at Different Facilities Don't Agree," October 1995, 66th Shock and Vibration Symposium Proceedings, Biloxi, MS.