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Title: **A Close Look at the Measurement of Shock Data—Lessons Learned**
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KEYWORDS

Pyroshock Testing, Structural Dynamic Testing, Structural Test Data Acquisition, Structural Test Data Analysis, Data Acquisition, Acceleration

ABSTRACT

Pyroshock testing and analysis is one of the most difficult regimens in the field of structural dynamics. The harsh and often-unpredictable environment has caused relatively poor behavior of the measurements systems used, often for reasons that were not well understood.

This paper reports on a study that was performed with the goal of better understanding of the problem areas and development of methods for improving results. Specific areas addressed include: 1) characterization of the broadband response and evaluation of its effects on standard measurement systems, 2) transducer mounting and cabling techniques, 3) the measurement of in-plane motion, and 4) the problem of justifying/normalizing the results obtained by different data acquisition systems.

INTRODUCTION

In early 1990 the authors embarked on a study of the procedures used to acquire and analyze the data from pyroshock events at Lockheed Missiles and Space Company (LMSC). The investigation was prompted by the unacceptable reliability of the data acquired by the methods in use at that time. At about the same time, the Proposed Military Handbook, Guidelines for Dynamic Data Acquisition and Analysis (Reference 1) was published, and it's section on pyroshock testing (Appendix A) added fuel to the concern about the procedures in use.

This investigation showed that errors induced by inappropriate (but commonly-used) procedures can amount to several hundred percent ... well beyond the level of making or breaking a vibration qualification specification. The objective of this paper is to discuss the most significant of these problems and to describe the approaches that Lockheed has developed to resolve them.

Shock testing/analysis is normally expected to provide reduced data with an accuracy of +10%. However, this criteria is confused because different measurement/analysis techniques will produce different results, all of which may be "locally accurate". Therefore, this paper will discuss potential sources of error and/or discrepancies that will produce errors/differences of 10% or greater. The final objective is to produce results that are not only "accurate" but accurate when referred to a technique/equipment independent standard.

Pyroshock testing is particularly demanding of transducers, transducer mounting, cabling, signal conditioning, and data acquisition. It is our experience that as many as 40% of the measurements in an initial installation produce, at best, questionable data. This performance is much worse than that found in other forms of structural-dynamic testing (shaker, acoustic) because the vibration environment is more violent and chaotic. The high frequency structural response and high acceleration levels can cause anomalous behavior in the instrumentation/measurement system if there are errors in installation or experiment/system design.

This harsh environment results in two major areas of concern. First, the dynamic range of the instrumentation/acquisition system must be sufficient to handle the full, broadband signal. Second, the transducer installation must be capable of withstanding the shock. Its adequacy must be proven before the test.

Once we are satisfied that our transducer and measurement systems are working correctly the next concern is whether we are measuring what we think we are. In the pyroshock frequency range, surface bending can produce errors of several hundred percent in the measurement of in-plane motion (parallel to the mounting surface) when conventional accelerometer-block-mounting methods are used. These errors will be discussed and techniques proposed that correctly measure the in-plane motion by canceling the effect of surface rotation.

Finally, the lack of standard data acquisition and analysis practices will result in differences of up to 100% in the results obtained by different systems. The paper will propose a method to "normalize" the data so that all machines will produce essentially the same outcome.

Hollowell, Smith and Hansen., “Measurement of Shock Data, Lessons Learned,” 1992.

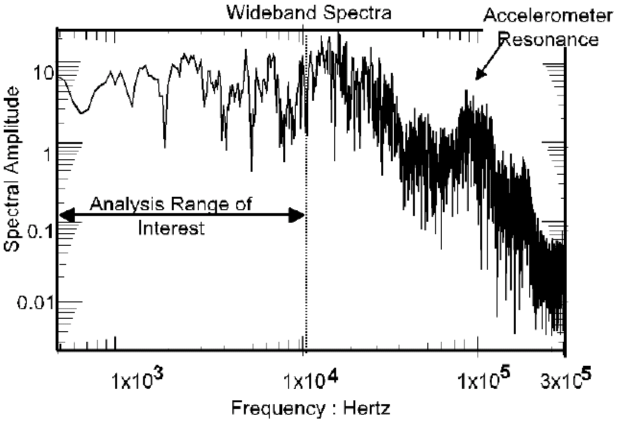

Figure 1 Broadband Pyro-shock Fourier Spectrum

THE PROBLEM

The integrity of data produced in pyroshock testing has been the subject of discussion for years. Investigators have examined the results from hundreds of tests (Reference 2) and concluded that a large proportion of the data is, at best, suspect and that, in general, the measurements are not as reliable as they should be.

The difficulties are all caused, either directly or indirectly, by the high-level, high-frequency, character of the excitation and structural response. Figure 1 shows the Fourier spectrum of a pyrotechnic test acquired with a broadband dataacquisition system. There are a number of notable features:

* Most of the energy in the signal is outside of the normal range of interest (0-10 Khz.).

* The high levels at high frequency are due to two factors:

  - The pyrotechnic event has significant energy at high frequency (good data) and
  - The transducer resonance will probably be excited (erroneous data). This will add to the signal that the system will have to handle.

The fact that high-frequency energy is generally disregarded because it is beyond the range of analytical interest does not mean that our instrumentation and data-acquisition systems do not have to handle it.

TRANSDUCER AND DATA ACQUISITION REQUIREMENTS

Figure 2 shows the raw, wide-band time history (spectrum shown in Figure 1) and the result after itis low-pass filtered in a way that is typical of shock analysis data-acquisition machines (i.e. as it would normally be seen). The peak magnitude difference is a factor of approximately 3. This means that the instrumentation system (transducer, signal conditioning, anti-alias filter, and data acquisition) must be selected/set such that the input signal (which is, in this case, three times what we see with our acquisition system) will not exceed the range of any device in the signal path. This, combined with uncertainty in the expected response, results in the necessity that the system must be scaled to acquiredata that is at least five, and preferably ten, times the expected-maximum response below 10 kHertz.

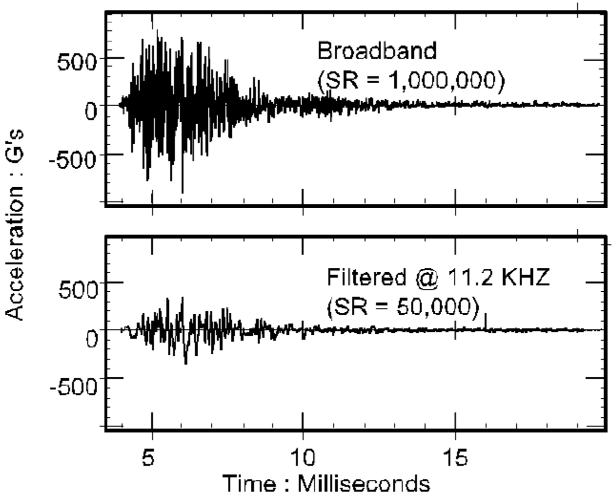

Figure 2 Wideband and low pass filtered time histories... SR is the sample rate in samples per second

Failure to provide this “headroom” can produce errors that are not only serious but that can be very hard to detect. Most systems use anti-alias filters that will smooth the discontinuities that are caused by saturation of the electronics upstream. The only evidence of the anomaly may be a small offset in the recorded data. It is impossible to back out or compensate for the error (or even tell how serious it is).

Recognition of this behavior has a critical effect on the selection of the transducers and other components of the measurement system. The required headroom means that the overall system must have a very high dynamic range to provide data resolution/accuracy of a small fraction of the expected response. Transducers, signal conditioning and data acquisition must be selected that will not be over scaled by the input but will accurately resolve the response at less than 1% of the expected value. A dynamic range of 60 dB is required and 75dB is recommended.

Hollowell, Smith and Hansen., “Measurement of Shock Data, Lessons Learned,” 1992.

The required dynamic range effectively eliminates analog tape recording systems from consideration and makes 12-bit digital data acquisition machines marginal. A digital system with 14 or more bits (and comparably-accurate signal conditioning) is recommended to properly acquire shock data.

TRANSDUCER ASSEMBLY/MOUNTING and VERIFICATION

The second issue is transducer-array assembly and mounting which involves testing philosophy as well as mechanics. A wide variety of accelerometer attachment techniques have been used with varying degrees of sucess. In some cases, both “bolt” and “glue” are used for high levels of acceleration. This study concentrates on attachment methods that are appropriate for relatively low acceleration levels, i.e. up to 5000 G’s.

LMSC has selected the “glue only” approach because, when the bond fails, the result will be obvious both in the data and by mechanical inspection.

Also a new procedure for glue mounting has been developed in response to problems shown in Figure 3. The five data sets were measured from nominally identical impacts produced with Lockheed’s pyroshock simulator (a modified Hopkinson’s bar) using an accelerometer mounted with the “filleted glue” method shown in Figure 4. As can be seen, the measured response is lower and has less highfrequency energy with successive impacts. However, there is no characteristic of the data that would lead the reviewer to suspect the data from a single set.

The problem is that the bond at the base of the accelerometer had failed but the fillet stopped the mounting from failing completely. This situation is similar to a bolt-and-bond attachment where the bond has failed.

This experience lead the LMSC laboratories to change their transducer mounting technique to use a minimum amount of glue and to eliminate glue fillets as shown in the left diagram of Figure 4. The result is that a poor bond causes an obvious failure, a consequence that we feel best serves the overall testing objective.

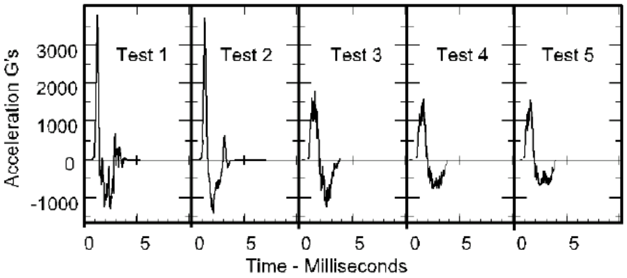

Figure 3 Accelerometer bond failing

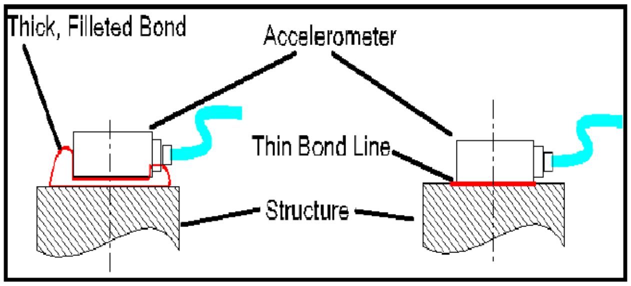

Figure 4 Filleted Glue Accelerometer Bond

A second installation problem area is in cabling, specifically in the connection at the transducer. At present, LMSC uses transducers that have screw-on connectors and we have had severe problems with reliability under testing conditions. The problem appears to be that there are momentary disconnections in the electrical path under shock loading. This, in turn, distorts the signal in a way that is evidenced by offsets in the measured acceleration. The normal method of testing the integrity of the signal path is to perform a tap test by hitting the specimen near the transducer. We have found that this is not a reliable test because it does not simulate the expected environment and may not cause the momentary disconnection.

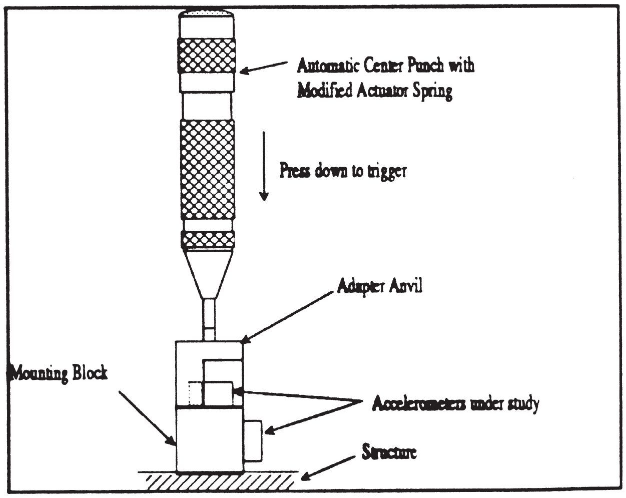

Figure 5. Installation Verification Tool.

Figure 5 shows an experimental device that is being used to excite the transducer mounting surface directly. It is made up a modified center punch and an anvil that is shaped so that it fits closely around the transducer. The center punch applies an impact (of up to 4000 g’s) to the transducer mounting block. The output of the transducer is recorded and examined. Mounting and electrical failures are normally obvious.

Hollowell, Smith and Hansen., “Measurement of Shock Data, Lessons Learned,” 1992.

This apparatus tests for both mechanical and electrical integrity at levels that are close to test excitations. In the first application of the installation/verification procedures using the device in figure 5 on a large spacecraft test, the initial installation success rate improved from 65% to 94%.

IN-PLANE MOTION MEASUREMENT

The issue of “in-plane” motion measurement was first addressed as part of Lockheed’s MIPSS (Mechanical Impact PyroShock Simulator) development activity. This issue was revisited in these studies when a series of simulated pyro-shock tests produced surprisingly high “in-plane” response. To analyze the cause-effect relationship of this phenomena, a series of experiments were performed, resulting in a clearer understanding of the motions involved and the development of new measurement approaches.

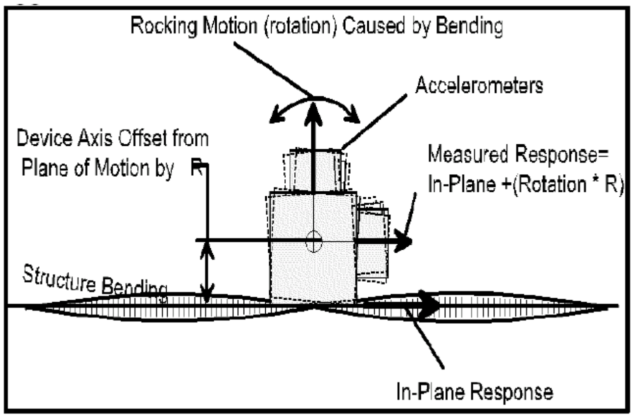

Figure 6 Structural bending influence on In-plane measurement

The problem occurs when conventional bi- or triaxial accelerometer mounting methods are used and there is significant bending of the mounting surface that results in rotation of the mounting block. Figure 6 shows how the indicated “in-plane” response will be corrupted by these motions. The response of the accelerometers will be the sum of the in-plane motion at the mounting surface and the rotation multiplied by the moment arm (R) from the surface to the accelerometer axis. The degree of corruption is dependant on the case at hand, but in the experiments performed, was often 150% or more ... the worst case observed was in excess of 400%. The degree of potential error increases with frequency and flexibility of the mounting structure.

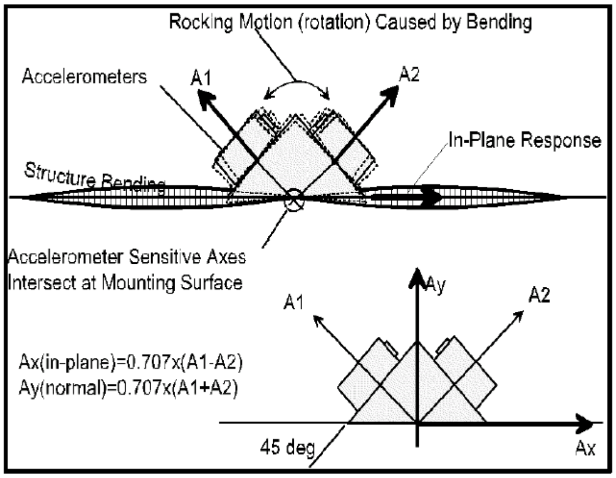

Figure 7 WEDGE accelerometer mount

To cancel the effects of rotation in the measurement of in-plane motion, the “WEDGE MOUNT” concept, shown in Figure 7, was devised. This configuration has the accelerometers arranged with their sensitive axes at 45 degrees to the mounting plane and positioned so that their axes intersect at the mounting surface. Equations 1 and 2 are used to calculate the normal and in-plane motions by vector summation of the accelerometer signals. As an extension of this concept, the axis-intersection point may be positioned to reference the bending cancellation to any desired plane.

(1) Wedge mount vector calculation of “In-plane” motion

$$Ax = 0.707 \times (A1 - A2)$$

(2) Wedge mount vector calculation of “Normal” motion

$$Ay = 0.707 \times (A1 + A2)$$

Figure 8 shows another mounting technique called the “EXTENDED CUBE”. This configuration is similar to a conventional multi-axis “cubic” arrangement for measuring “in-plane” motion, except that two “in-plane” accelerometers are mounted at different offsets from the block mounting surface. These responses are algebraically combined (Eq. 3 and 4) to compute the angular acceleration and translation at any plane parallel to the block mounting surface.

(3) Extrapolation of In-plane motion calculated from EXTENDED CUBE data

$$A_0 = \left[\frac{1}{1 - {}^{R1}\!/_{R2}}\right] \times \left[A1 - \left(\frac{R1}{R2} \times A1\right)\right]$$

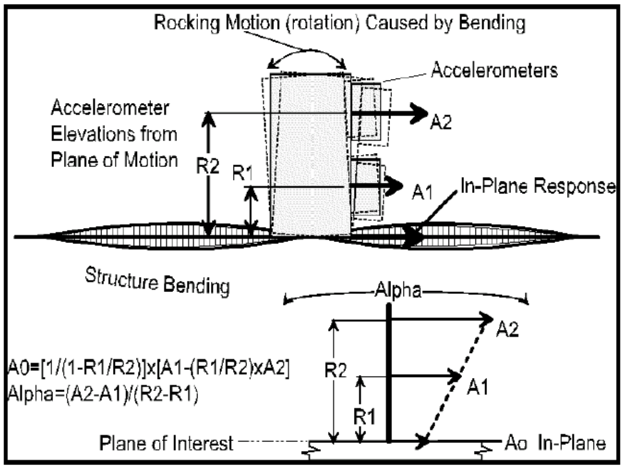

Figure 8 EXTENDED CUBE Mount

(4) Computation of rotational acceleration (alpha) with the EXTENDED CUBE

$$\alpha = \frac{A2 - A1}{R2 - R1}$$

A series of experiments (described more completely in Reference 3) were performed in developing these techniques. The layout of the most fundamental of these tests is shown in Figure 9. In this experiment, the accelerometers were mounted on an aluminum plate using the WEDGE MOUNT and EXTENDED CUBE configurations. A reference accelerometer attached to the edge of the plate was used to measure the “true” in-plane motion. Excitation was provided by striking the plate normal at its center with a steel ball.

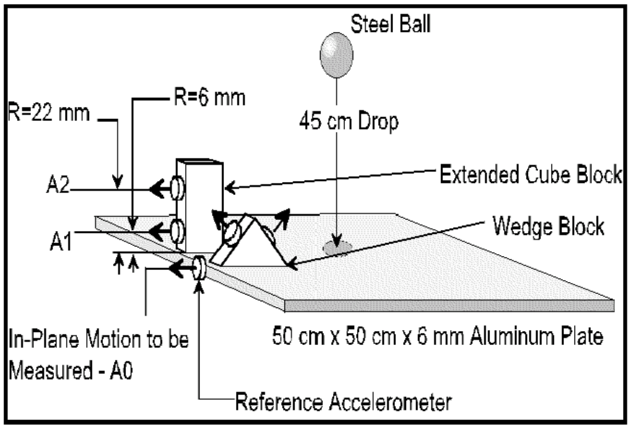

Figure 9 Rectangular plate experiment arrangement

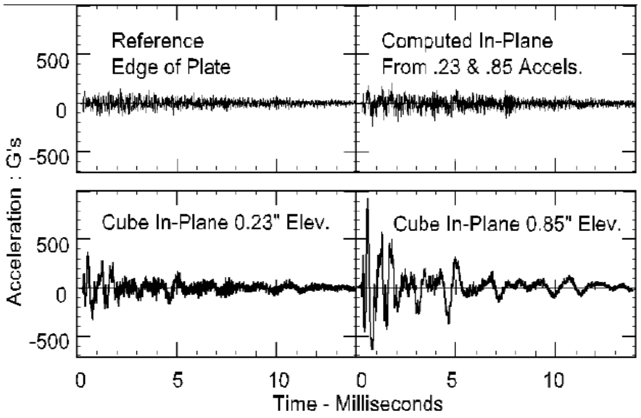

Figure 10 Experiment time histories..EXTENDED CUBE

The measured and computed in-plane motions from the “EXTENDED-CUBE” are shown in Figure 10. The upper-left frame shows the response of the reference (edge-mounted) accelerometer. The lower left frame is the response of the lower accelerometer (6mm from the surface) and the lower right shows the response at 21 mm from the surface. The upper right frame contains the result of the calculation of the in-plane motion from Equation 3. The following observations may be made:

- * The accelerometer at 6mm (emulates a conventional block mount) overestimates the peak-peak in-plane motion by 180%.
- * The accelerometer at 21mm overestimates the peak-peak in-plane motion by 480%.
- *The calculated in-plane response is very similar to the reference measurement.

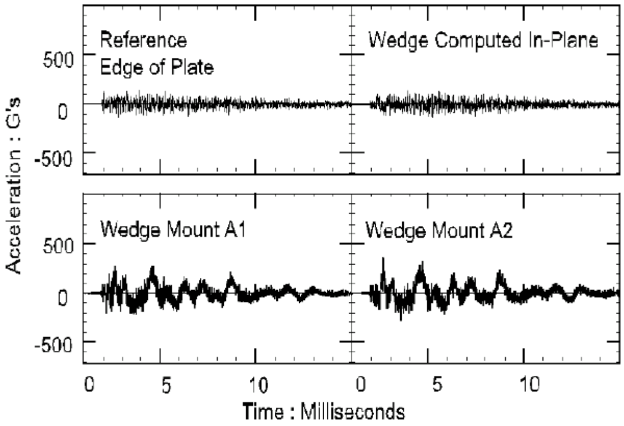

Figure 11 Experiment time histories...WEDGE MOUNT

Figure 11 shows the results from the WEDGEBLOCK mount. The upper left frame is again the reference response and the two lower frames are the individual measurements of the 45 degree accelerometers. The upper right frame contains the in-plane motion vector calculation (see Equation 1).

As can be seen, the vector summation of wedge mounted accelerometers produced peak-to-peak response measurements that agree within 4% of the edge-mounted reference accelerometer.

Several other experiments were performed using these accelerometer mounting techniques with both mechanical- and pyro-shock excitation (Reference 3). All of the experiments revealed similar results wherein conventional mounting methods overestimated the motion by 50% to over 400%.

The accelerometer mounting configuration termed “WEDGE MOUNT” appears to offer superior in-plane measurement capability. Where direct reference measurements are possible, this technique has proven to produce responses that more accurately describe the in-plane motion and reject rotational motion. As an added benefit, the WEDGE MOUNT geometry offers a lower moment of inertia and a larger footprint to bond to the structure thereby reducing mass influence on the measurement and providing improved mount integrity. The technique relies on accurate, simultaneous, data acquisition and does require mathematical computation.

DATA NORMALIZATION

The objective of the data acquisition system is to provide data reliably with required accuracy. There are several strategies that may be used to attain this goal, and they will give different, but equally valid, results.

The fact that pyrotechnic tests have such a wide bandwidth (typically over 250,000 Hertz) means that a very fast data acquisition system is required to record the full response. However, in the past, the engineer has only been interested in data to about 10,000 Hertz. This allows the use of lower-speed systems, if the signal is properly low-pass filtered.

The present study utilized two data acquisition systems that are representative of the extremes of the options:

* SYSTEM 1, High-speed acquisition/no antialias filtering. This data acquisition system samples at 1,000,000 samples/channel/second. Because of the absence of low-pass filtering (other than the inherent bandwidth limitations in the signal conditioning) the data must be examined to provide confidence that the data is not aliased. Examination of the pyrotechnic test Fourier spectrum in Figure 1 reveals that the response is at or below the system noise level at 400kHz. This is extrapolated to the conclusion that there is no significant energy above 900 kHz, and that the errors incurred due to aliasing below 10 kHz will be acceptable. (However, note that sampling at 500,000 samples/second would be marginal for this data set). We are not advocating systems without anti-aliasing filers, but recognizing the hardware capabilities and careful scrutiny of the data, data can be safely acquired under those conditions.

The data are processed (in either a real-time or post-processing mode) to produce response with the required bandwidth.

This approach is very straightforward from the acquisition standpoint but needs much more data storage and/or handling capability than the second approach. With hardware systems that are on the near horizon, this method will probably become the most cost effective, reliable and accurate. It will also allow the analysis of data to 100 kHz should it be required.

* SYSTEM 2, Medium-speed acquisition/high quality anti-alias filtering. This machine acquires 10kHz shock data by sampling at 50,000 samples/second. Aliasing signals are rejected by an 8-pole, Butterworth, low-pass filter at 11,200 Hz. Because of the hardware available when they were built, almost all of the systems presently in use employ variations of this approach.

Figure 2 shows the time history of the pyrotechnic response as it would appear if it were acquired by the two systems. Obviously the result is different because of the filtering that has been applied to the lower trace by System 2. If the signal were acquired by a third data acquisition system, similar differences would arise because different vendors/systems use different anti-alias filters and sample rates.

If these two time histories are analyzed with a conventional Shock Response Spectra approach the results in the 10kHz analysis are different by approximately 30%. Other sample-rate/anti-alias filter combinations will produce different results (all equally “correct”). Particularly unfortunate choices of anti-alias filters (Bessel) will produce differences of up to 100%.

To process the data on “equal” terms, a procedure has been developed (and described more fully in Reference 4) that normalizes the response by “removing” the effect of the filters used and then band-passing the result in a standard way.

Hollowell, Smith and Hansen, “Measurement of Shock Data, Lessons Learned,” 1992.

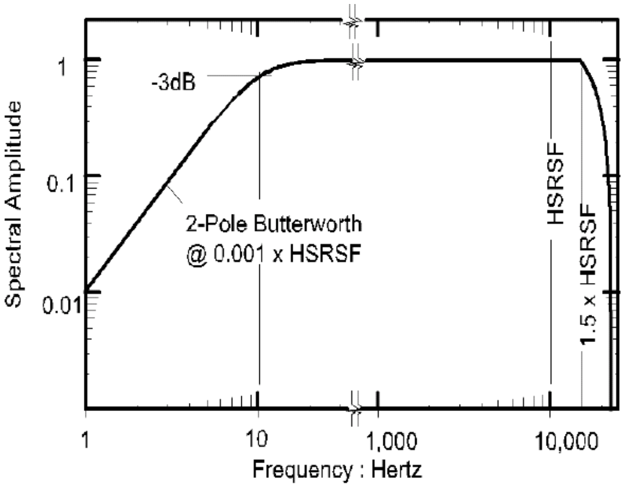

Figure 12 “Standard” data correction filter

The objective of the procedure is to adjust the acquired data so that the overall (hardware and analytical treatment) preconditioning has a “standard” characteristic. LMSC is using the following parameters:

* A high-pass with a 2-pole Butterworth filter (AC-coupling) at 0.001 times the Maximum Analysis Frequency (MAF).

* A “standard” low-pass filter with the following characteristics:

- Flat to MAF × 1.5
- Linear slope to zero at 2.25 × MAF.

This filter shape, for a MAF of 10 kHertz is shown in Figure 12.

The data normalization is performed by applying a two-stage correction in one combined process. The “Data Correction Function” is calculated by dividing the “Standard Data Correction Filter” by the transfer function of the hardware used (including accoupling, anti-alias filter, and other data distortions that can be expressed as a transfer function).

The Data Correction Function for:

- MAF = 10 kHz
- Anti-Alias Filter: 8-Pole Butterworth at 11.2 kHz
- AC-Coupling Filter: 1-Pole at 0.1 Hz

is shown in Figure 13.

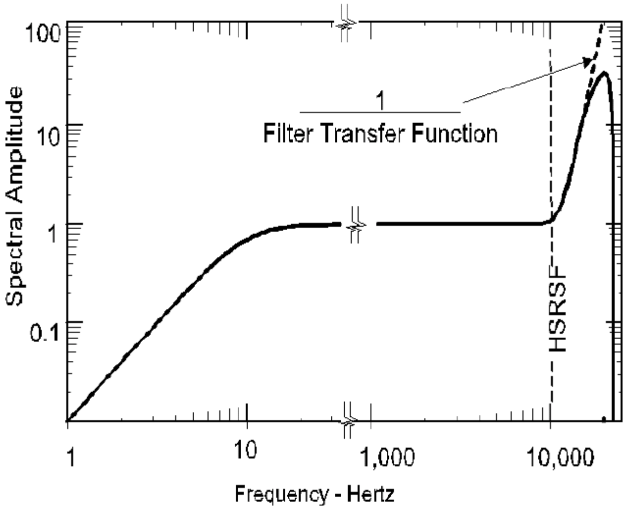

Figure 13 Data correction function

The correction function is applied by calculating the spectrum of the acquired data via Fourier transform, multiplying the result by the correction spectrum, and performing the inverse transform to obtain the “normalized” time history. The results of this procedure on a pyrotechnic data set are shown in Figure 14. It can be seen that the “normalized” result is significantly higher than the raw data acquired with system 2 but lower than the broadband response shown in figure 2.

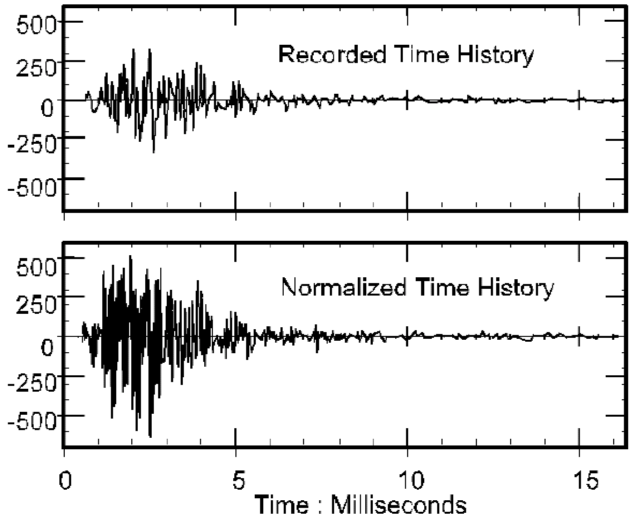

Figure 14 “Normalized” Pyrotechnic Data

Use of this normalization procedure will remove the inherent differences between data acquisition systems and produce results that should be independent of testing facility.

CONCLUSIONS

The objective of this study has been to develop methods that produce more reliable and reproducible data from pyrotechnic tests. The resulting recommendations include changes in transducer mounting geometry and methods, installation verification by excitation at expected levels, and the use of analysis techniques that will produce the same results regardless of the data acquisition equipment used.

These procedures are all in use at the Lockheed Missiles and Space Company and have shown to produce significantly improved results.

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