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TECHNIQUES FOR THE NORMALIZATION OF SHOCK DATA

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This paper describes a procedure developed at the Lockheed Missiles and Space Company to "normalize" the data acquired by different data acquisition systems so that the data sets measured by the machines are directly comparable and can comply with the requirements of the proposed handbook "Guidelines for Dynamic Data Acquisition and Analysis". The normalization process adjusts data acquired by any machine that is capable of acquiring shock data to appear as if it were acquired by a "standard" machine. Correction includes compensation for differences in data-acquisition speed, transducer characteristics, anti-alias filtering, and ac-coupling frequency.

INTRODUCTION

This paper is a product of a series of studies into the data acquisition and analysis techniques used at Lockheed Missiles and Space Company for pyroshock testing. The study was prompted by our review of the preliminary version of the of the proposed military handbook "Guidelines for Dynamic Data Acquisition and Analysis"[1]. The study revealed several shortcomings in standard practices and produced the acquisition/analysis procedures described in this paper and in overview form in Reference [2].

It has been recognized for some time that shock data acquired and analyzed by different machines and/or processors can produce different results [3]. Different data acquisition systems have been shown to produce Shock Response Spectra (SRS) results that differ by as much as 100%. Differences in the time history can be much greater.

The differences in measurements made at different facilities are reflected in testing requirements where "safety factors" are included to cover these (and other) uncertainties. Techniques described in this paper will reduce the inconsistencies, providing a more realistic data base to define the testing criteria.

Reference [1] describes the allowed sample rate and anti-alias (low-pass) filter characteristics that have been found to produce sufficiently accurate Shock Response Spectra (SRS) results. In essence the requirements are:

* Sample Rate = 10 times the Highest Shock Response Spectrum Frequency (HSRSF) [1].
* Highpass filter at .001 times HSRSF.
* Low Pass Filter at 1.5 times HSRSF.
* The system frequency response must be $\pm$5% over the analysis band.

The objective of the procedures described here is to provide data sets that satisfy the specification acquired from data acquisition machines whose hardware does not specifically meet these requirements. A wide range of anti-alias

1) HSRSF is defined in Reference 1 as the Highest Shock Response Spectrum Frequency in the analysis.

filters are allowed (including none, if the sample rate is adequate, and Bessel, which do not satisfy the flatness criterion). In addition lower sample rates are useable if adequate anti-alias filtering is provided. If these methods are used:

* Data from existing machines can be adjusted to meet the Handbook (or other) specifications.
* The shock data acquisition/analysis capabilities of new machines can be improved by permitting lower per-channel sample rates.

In this discussion, we will assume that the acquired data set is "error-free", i.e. that there are no mistakes in the experiment and the apparatus is operating within its nominal characteristics. The objective is to take the recorded data from a variety of machines and make the results (nominally) identical. To achieve this, a means of "normalizing" the acquired data is required.

In particular, we will discuss the following operations:

* Defining a "Standard" machine that band limits the data with well defined characteristics.
  - High-Pass filtering with a standard frequency and rolloff characteristic.
  - Low-pass filtering with a standard frequency and attenuation characteristic.

* Removing the effects of known, test-system-induced, biases such as:
  - Anti-alias filter characteristics.
  - Known faults in transducer behavior and transducer-mounting characteristics.

* Interpolating the time history data to provide adequate peak-determination capability when relatively-low sample rates are used.

DATA ACQUISITION SYSTEMS FOR SHOCK TESTING

Structural response to pyroshock excitation can have significant energy at frequencies far beyond the usual range of interest. For example, the spectral data shown in Figure 1 was acquired in a recent spacecraft test from an accelerometer near the excitation source. It may be seen that there is significant energy well beyond the range of analysis interest (normally 10 KHz). The response is due to two primary contributors:

* Significant "real" response in the 15-20 KHz. region.
* Accelerometer resonant response near 100 KHz.

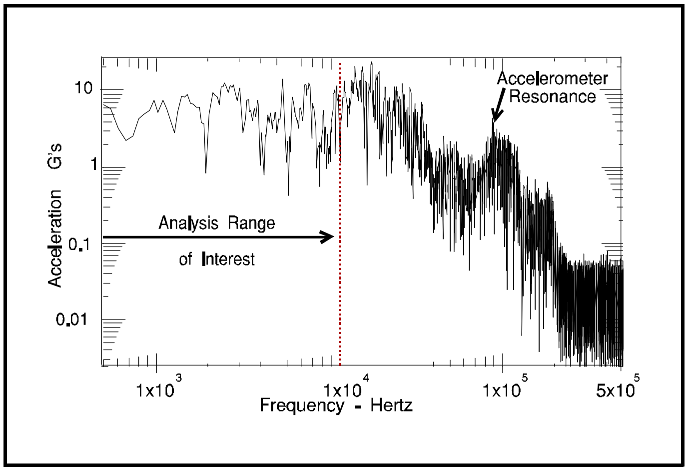

Figure 1 Broadband Pyroshock Spectrum

Most data acquisition systems do not have the capability of acquiring the full frequency content of the response signal because of inherent bandwidth limitations. Most shock-testing data acquisition systems in use today are restricted to ten to twenty KHz. This is generally considered to be a realistic restriction because it is adequate bandwidth to describe important structural motions. However, the technique used to restrict the bandwidth has a significant influence on the results.

For example, Lockheed performs Shock Response Spectrum (SRS) data acquisition and analysis operations using two fundamentally different types of general-purpose, computer-based, data acquisition and analysis systems. The two systems, and their SRS acquisition strategies are shown in Table I.

Table 1. Data Acquisition Machines for Shock Testing

System >	TOPCAT	ARDVARC
Type >	Transient A/D per Channel	Mult-Channel Multiplexed
Channels (in SRS mode) >	12	100
Sample Rate/Channel >	1,000,000	50,000
Anti-Alias Filters >	None	8-Pole Butterworth @ 11.2 KHz.
Analysis Frequency >	10,000 Hz	10,000 Hz.
Analysis Processor >	LMSC Shockana	LMSC Shockana

The "TOPCAT" system takes advantage of its very-high-speed "Transient Recorder" acquisition capability to acquire at a rate that assures aliasing protection by oversampling. System accuracy is approximately 0.1% of full scale to 25 KHz.

The "ARDVARC" system was built primarily to support acoustic testing. It is also used for large scale pyrotechnic tests (often run in conjunction with acoustic tests). Its significant features are very-high accuracy (.03% of full scale) and the ability to acquire and store data for over 5 minutes at an aggregate rate of 5 million samples per second.

The two machines represent extremes in the options available for shock data acquisition.

Because of their design, raw data from the two systems will provide different results for the same input. Figure 2 shows the time history of the pyroshock event as it would be recorded by the two systems [2].

It is obvious that the magnitude of the signal acquired with the broadband machine is about three times that of the "low-speed" system.

Other critical differences include:

* Recorded data bandwidth.
* Different distortion caused by anti-alias filters.
* Different sample rate/analysis frequency ratio.

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2) The "narrow-band" data was actually simulated by applying an analytically-generated, low-pass filter to the data acquired by the "wide-band" machine.

The objective of this paper is to describe analysis techniques that will produce (essentially) the same results from both, and other, machines.

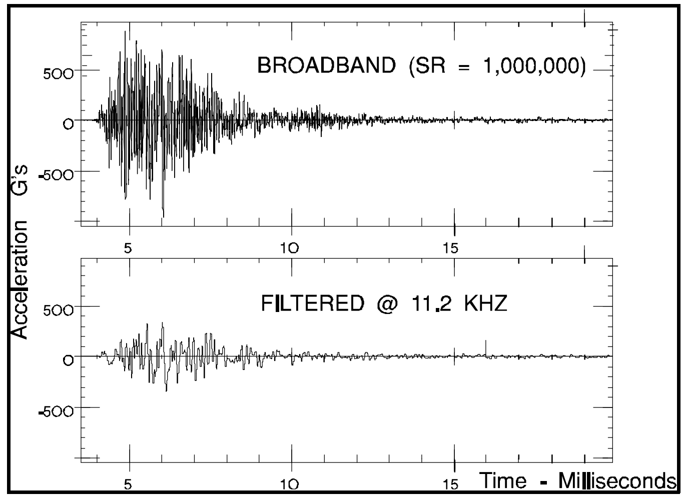

Figure 2 Wide and Restricted Bandwidth Time Histories

SHOCK RESPONSE SPECTRUM ANALYSIS

The calculated shock response spectrum at any frequency is dependent on at all frequencies. Figure 3 shows the "absolute acceleration model" transfer function that is used to calculate the response at each frequency. As can be seen[3]:

* At frequencies above the analysis frequency (frequency=1 in Figure 3), the response is attenuated at a rate of 12 DB/octave.
* For frequencies below the analysis frequency, the response is attenuated by, at most, a factor of "Q".

Therefore, if there is energy at frequencies that are not covered by the bandwidth of both systems, the results obtained by reducing the raw data must be different.

BROAD-BAND DATA ACQUISITION SYSTEMS

An apparently-attractive solution to the problem is to acquire the full signal bandwidth with a system like "TOPCAT" . This machine is typical of modern data acquisition systems that can acquire at rates higher than 1,000,000 samples/channel/second. Examination of Figure 1 will show that acquiring at this rate is fast enough to characterize the full bandwidth of the data at the recorder.

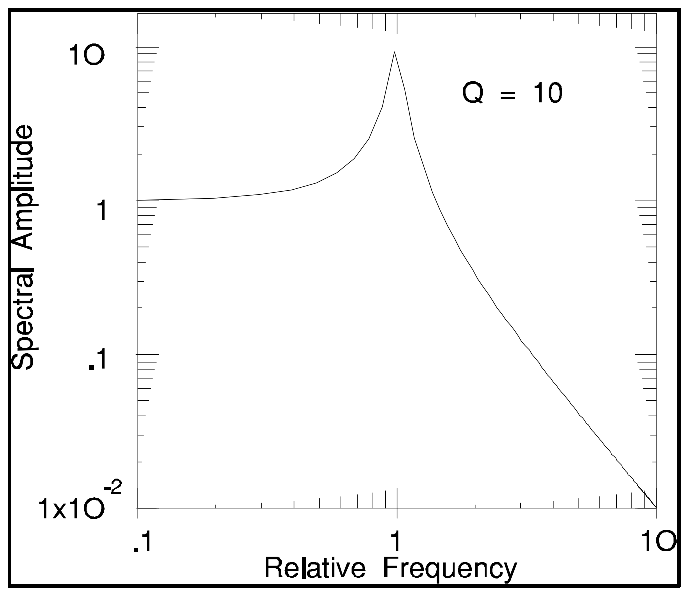

Figure 3 Absolute Acceleration Model

However, if this capability is used, high-frequency responses from phenomena other than the shock excitation will be included. These include transducer resonant response (normally above the frequency of meaningful structural response) and broad-band noise. They should be rejected from the SRS calculation.

At the low end, it is possible to design instrumentation/acquisition systems that are dc-coupled. However, there are also extraneous contributions to the signal that will pollute the results such as

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3) Examination also shows that 500,000 samples per second would have been marginal.

thermal excitation of the transducer (normally below the frequency of meaningful structural response) and rigid-body motions of the structure (normally not considered).

To reject these extraneous effects, a band-limiting strategy is required.

BAND LIMITING THE DATA
DEFINING the "STANDARD MACHINE"

The conclusion of the preceding sections is that some form of band limiting is necessary if consistent results are to be obtained from different facilities. Because this action will bias the data, the selected method must be consistent for all machines.

Because of the sensitivity of the analysis to frequency components below the analysis frequency, the most critical decision is the selection of a high-pass-filter configuration. Most transducer/signal conditioning/data acquisition systems use hardware that ac-couples the response at one Hertz or less. In spacecraft studies only SRS data above 50 Hertz is required and thus a significantly higher ac-coupling frequency can be applied without compromising the results. This additional filtering should be applied analytically to assure consistency.

A two-pole Butterworth filter with a cutoff frequency of 0.001 x the Highest Shock Response Spectrum Frequency (HSRSF)[4] has been chosen for ac-coupling.

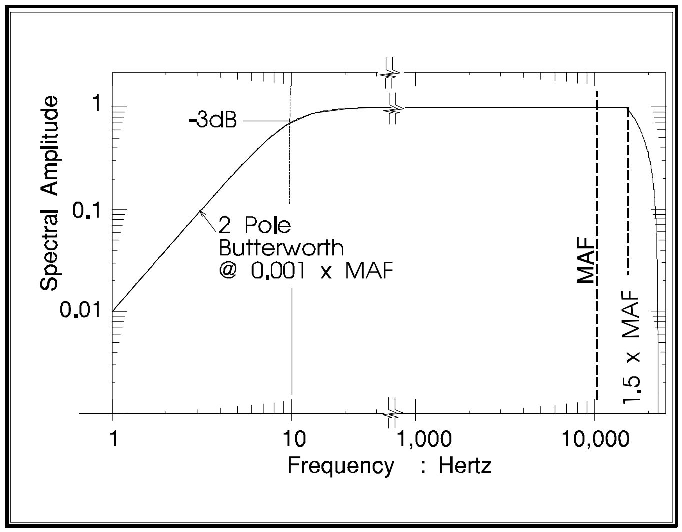

Figure 4 "Standard Machine" Transfer Function

Because of the rapid attenuation of the SRS filter characteristic, the upper cutoff characteristic is less critical and will only effect the SRS results at higher frequencies. However, differences in allowed bandwidth can produce SRS analysis differences of the order of 40%. The authors propose that a maximum frequency "standard" be adopted that is within the bandwidth capability of any data acquisition system that might be used to perform the required task. The data would be low-pass filtered using a standard characteristic at that frequency.
Lockheed uses the filter shape shown in Figure 4. The cutoff frequency is set a 1.5 times the Maximum Analysis Frequency. The filter attenuates linearly (in the linear/linear amplitude/frequency view) to zero at 2.25 times the HSRSF.

This band limiting strategy defines the characteristics of the "standard machine". It complies with the specifications in Reference 1.

4) 10 Hertz for a Maximum Analysis Frequency of 10 KHz.

The objective of the following sections is to describe how to correct the data acquired by any (appropriately-capable) machine so that it complies with the standard.

CORRECTING FOR KNOWN DATA-ACQUISITION BIASES

There are several errors that are induced by the data measurement and acquisition process that can be analytically compensated. For many systems, the most important correction is for the anti-alias filter transfer function. However, non-idealities in the transducer and mounting block characteristics can also be compensated if they are known and can be expressed as a transfer function.

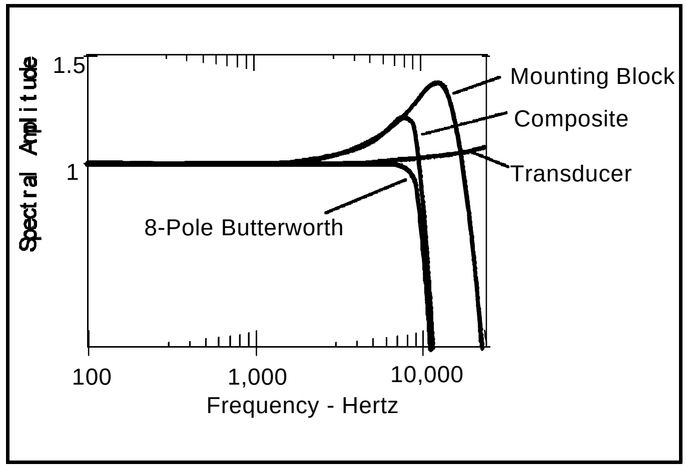

Figure 5 Measurement System Transfer Functions

As an example, Figure 5 shows the transfer functions of a typical anti-alias filter, a non-ideal accelerometer, and a phenolic accelerometer mounting block. These are multiplied together to obtain the "composite" transfer function".

For most systems, the nominal transfer function of the anti-alias filter will normally be sufficiently accurate. Mounting block behavior and transducer response will have to be experimentally determined.

SRS DATA PREPROCESSING

To "normalize" the data before the SRS analysis, the following operations are performed.

1. Generate the "Normalization Transfer Function" by dividing the "Standard Machine" transfer function (Figure 4) by the composite transfer function (Figure 5). The result is shown in Figure 6.
2. For each channel, select a block of samples enclosing the data of interest.
3. Calculate the signal spectrum (via FFT).
4. Multiply the signal spectrum by the correction spectrum.
5. Calculate the resultant time history (via inverse FFT).

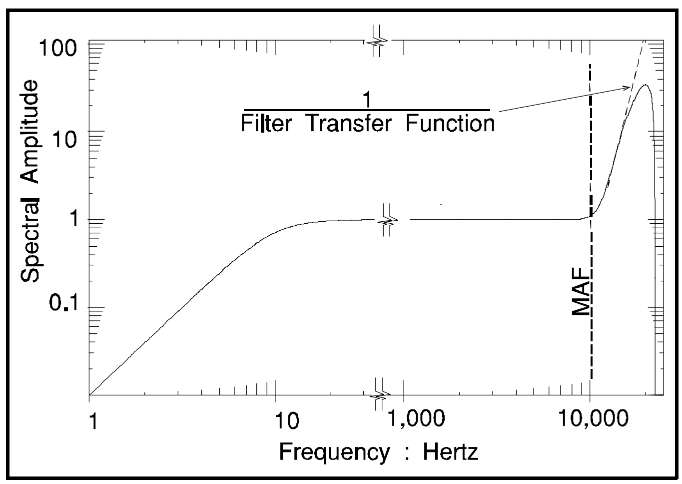

Figure 6 Normalization Transfer Function

The result, for the raw ("Filtered @ 11.2KHZ") data set in Figure 2, is shown in Figure 7.

After this processing, the data sets acquired by either (or any) machine are nominally identical.

The characteristics of the band-limiting function used have been selected based on engineering judgement. Obviously, there are other options.

COMPENSATING FOR LOW SAMPLE RATES IN SRS ANALYSIS

The techniques discussed above produce data sets whose frequency content is independent of the data acquisition machine. Because of the nature of the Shock Response Spectrum calculation other factors must be considered.

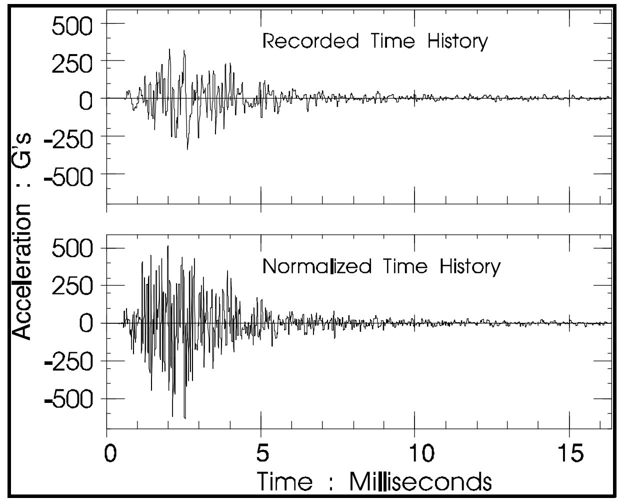

Figure 7 Corrected/Normalized Time History

The SRS calculation includes an operation that requires an accurate determination of the peak time-history value. If the peak detection is to be made by direct inspection, ten or more points per cycle are required to assure analysis accurate to 10%. If fewer points are available (a sample rate of less than 100,000 samples per second in the examples presented) then a method of interpolating the data is required.

Several options are available. The curve-fitting algorithm [4] has been used for SRS analysis and shown to guarantee maximum peak-detection errors of less than 10% at fewer than four points per cycle.

Lockheed's present processor uses the method shown in Figure 8. It calculates interpolated time domain values by performing a zero-fill in the spectral domain. The procedure is carried out when there are fewer than 32 points per cycle of the analysis frequency for data points that are "suspected" of being within one time interval of a positive or negative peak[5].

The procedure is:

1. Select a block of eight points around the "suspect" value.
2. Window the block with a linear-taper window that does not modify the four central points.
3. Do an eight-point FFT to calculate four spectral values.
4. Zero-fill to produce a 16-point spectrum.
5. Inverse FFT to produce a 32-point time history.
6. Search the center points for the extrema.

This process has been shown to provide maximum errors of less than 3% at four points per cycle.

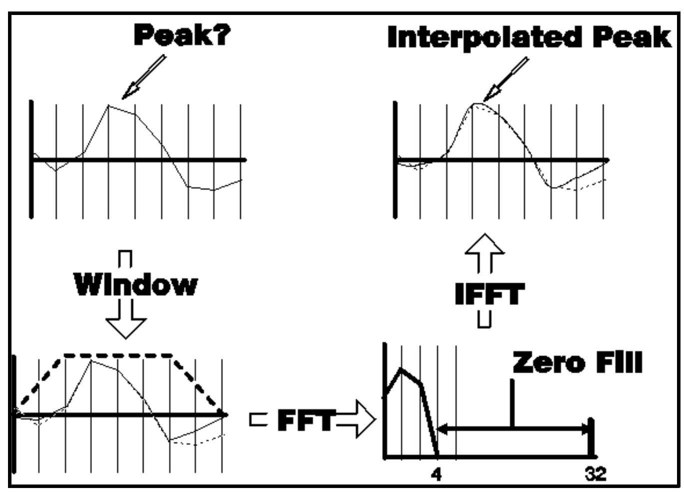

Figure 8 Time History Interpolation/Peak Detection

5) The analysis is time consuming so it's use is restricted to suspect points.

THE EFFECT OF CORRECTIONS ON THE SHOCK RESPONSE SPECTRUM

Because of the inherent band-limiting function of the SRS analysis, the effect of normalization on SRS is not as pronounced as in the time domain results. However, the influence of anti-alias filter and other biases can produce differences of as much as 100% with the largest errors appearing at high frequencies.
Figure 9 shows the SRS results for several data sets that are derived from the pyroshock data presented in Figures 1, 2, and 7. It may be seen that up to the Maximum Analysis Frequency of 10KHz:

* The results for the "broadband" data are virtually identical to the "standard filter" (i.e. Normalized) values.
* The results for the 11.2KHz Butterworth filter ("raw, as acquired") are about 20% low at the HSRSF but agree well below 9KHz.
* Data for an eight-pole, 11.2KHz Bessel filter emulation are also shown. As may be seen, the differences with this filter are greater than 10% to less than 6KHz. These results could have been corrected using the same normalization procedure as was used for the Butterworth data.

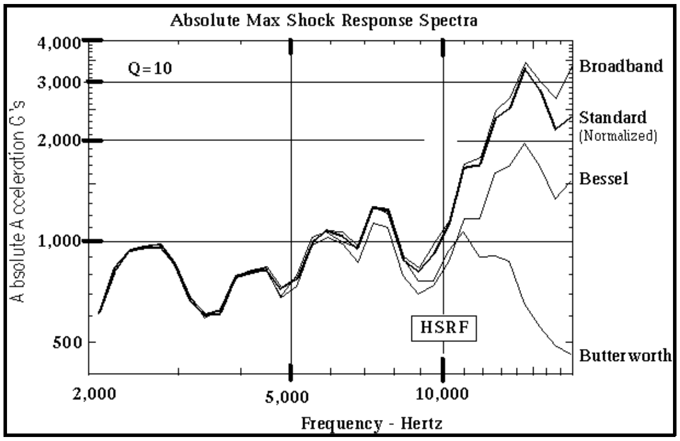

Figure 9 SRS results from different filter operations

It should be noted that SRS results are very sensitive to the characteristics of the input time history and that this study only considers a single (but conservative) example. Differences with other inputs may be greater or less than those demonstrated.

However, the normalization procedure should make the SRS results for any particular data set acquired by any machine essentially identical.

CONCLUSIONS

The techniques described here allow the adjustment of data acquired from a variety of data acquisition machines so that they will all produce the same results. This procedure requires the definition of a "standard" band-limiting function that is applied to all data. In addition, critical characteristics of the measurement and data acquisition system used that effect the data are compensated.

These procedures have been implemented in Lockheed's SHOCKANA II Shock Spectrum Analysis processor.

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