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A PROPOSED METHOD TO STANDARDIZE SHOCK RESPONSE SPECTRUM (SRS) ANALYSIS

(To Provide Agreement Between Tests Performed at Different Facilities)

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ABSTRACT

Discussions among practitioners of the shock-testing art and a series of round robins have shown that the results obtained from mechanical shock experiments performed in different laboratories vary widely. To emphasize the problem, it has been found that different generations of hardware/software systems from one of the major system vendors produce results that disagree by up to 30%.

A 1995 paper[1] described a study that examined some of the critical parameters that effect Shock Response Spectrum (SRS) results and reported on their use by some of the practicioners in the field. The paper showed that parameters such as anti-alias filter characteristics, ac-coupling strategies, and analysis algorithm/strategy can strongly effect the results and that they are not uniformly applied by system suppliers or users.

This paper discusses the problem further and presents an analytical procedure that may be applied to achieve agreement between the data sets acquired and analyzed by different laboratories.

THE PROBLEM

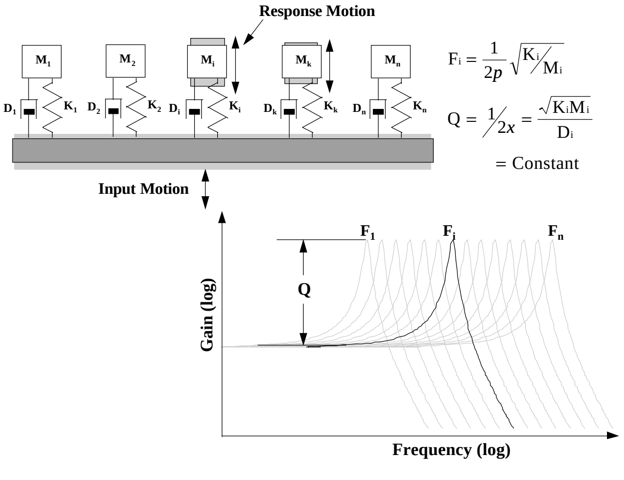

Figure 1 The SRS Model

There is growing concern that analyses of shock tests performed at different laboratories produce different results. This thesis is substantiated by round robins[2] that have produced results that can only be described as chaotic. Discussions with practitioners[3] reflect a general lack of confidence in the procedures in use.

The lack of repeatability/reproducibility arises from two, essentially-separable, sources: 1) differences associated with motion measurement techniques and practices and 2) differences in data acquisition and analysis strategies.

Problems of the first source are traceable to inadequate instrumentation, bad/inconsistent practice, or lack of understanding of the processes involved. Experiments where pyrotechnic devices provide the excitation are particularly susceptible to these errors. These are certainly prime contributors to errors in SRS results. Rectification of these problems must be a prime objective of all laboratories. However, this subject is not addressed here.

The second source of discrepancy is found in fundamental differences in methodologies used for data acquisition and analysis. Once the motions are correctly transduced and conditioned, different laboratories/vendors use different data acquisition and analysis techniques to perform the Shock Response Spectrum (SRS) analysis. Reference 1 reported on and assessed the effect of some of these differences. The results of a questionnaire presented in that study are found in the appendix.

For the most part, the techniques reported are allowed by the "recommended practices documents"[4,5]. However, their use does produce significant differences in analysis results from the same set of acquired data. ***A more stringent method/specification is required.***

BACKGROUND

It is impossible to perform a "true" SRS calculation in the real world. To appreciate this statement, we need to examine the basic concepts that underlie the SRS analysis procedure.

The basic "structural" model for the SRS calculation is shown in Figure 1. In essence, it is a set of "single-degree-of-freedom", mass-damper-spring oscillators that are excited by base motion. Each oscillator is characterized by:

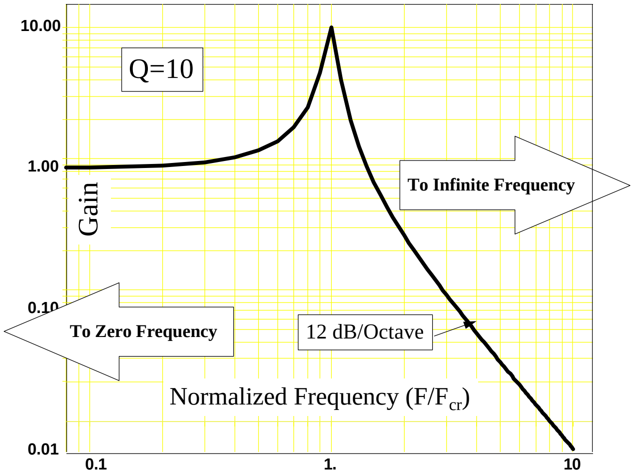

Figure 2 The SRS Oscillator Steady-State Response

- A natural (resonant) frequency. The oscillators are "designed" so that their resonant frequencies are logarithmically spaced at integer fractions of an octave. These are termed the analysis frequencies.

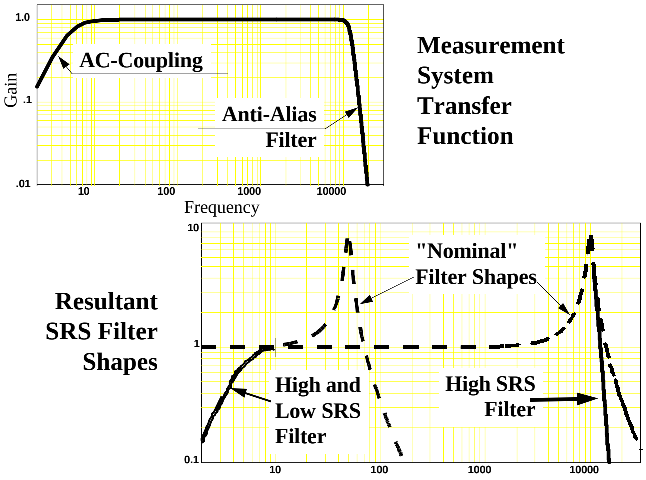

Figure 3 The Effect of Band Limiting on the SRS Filters

- A critical damping factor (ξ) or resonant gain (Q) (Q=1/2ξ). The same value is used for all of the oscillators (normally ξ = 5% or Q = 10).

When the base is moved (the input acceleration to the SRS model) each of the oscillators vibrates. The motion of each mass is "monitored" and its maximum and minimum excursions (in the form of absolute acceleration or displacement relative to the base) are found. These values are plotted as a function of the nominal frequency of the corresponding oscillator to make up the SRS.

The "steady-state" frequency-response characteristic for the absolute-acceleration model of one of the "ideal" resonators with a Q of 10 is shown in Figure 2. Note that there is significant response (>1%) from zero to frequencies up to 10 times the oscillator frequency. The gain at all frequencies less than the resonator center frequency is greater than one.

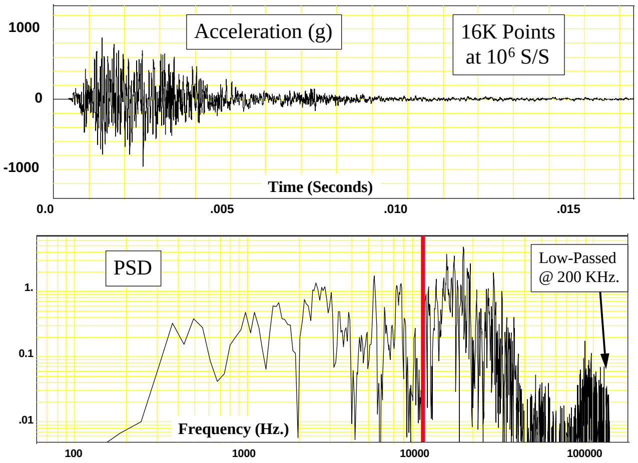

Figure 4 The Shock Time History and PSD

In "real" applications the ideal, continuous, single-degree-of-freedom model is violated in a variety of critical ways that compromise the results. Figure 3 shows one of the critical deviations from the ideal: the frequency-range limitations imposed by ac-coupling and anti-alias filtering which produce a band limiting of the signal. If this band limiting is not done consistently by the practitioners, the results that they obtain cannot agree.

Figure 4 shows the time history and power spectral density of the signal that was analyzed by the responders in the study described in Reference 1. It is a real data set that is well behaved, but not perfect.

Figure 5 shows the results of the analyses reported[a]. The SRS spectrum was calculated from .004% to 4% of the data acquisition sample rate. It may be seen that the results agree quite well for most of the frequency range but that there are significant differences at the high and low end of the frequency range.

Discrepancies seen in the results presented above can be primarily traced to strategies the investigators used to handle:

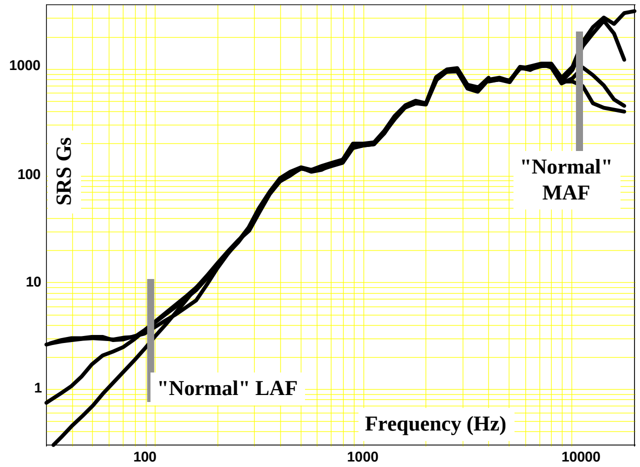

Figure 5 SRS Results from Reference 1

- implementation of the SRS mathematical model
- experimental data offsets and low-frequency errors
- restriction of the high-frequency content of the signal

The objective of this paper is to propose the definition of these three strategies that must be standardized to calculate a repeatable Shock Response Spectrum from data that is acquired by any of the hardware systems reported. The criteria used for selection of methods/strategies included (in order of importance):

- Repeatability from facility to facility. The SRS is the most common method for describing and characterizing shock test motions. The spread in results reported in Reference 1 represent the difference between over test (incorrect failure) and undertest (failures not detected).
- A good estimate of the real behavior. The SRS is a classical analysis technique and recommended procedures should not produce results that vary significantly from the "norm".
- A good match with as much of the previously-analyzed data (a perfect match is impossible) as possible.
- The capability to recognize good and bad data. There are a variety of instrumentation and measurement problems that can cause errors that are:
    - Significant from the standpoint of damage potential but that may not be obvious to the naked eye.
        - Momentary transducer or amplifier saturation.
    - Unimportant from the standpoint of damage potential that can be removed by appropriate manipulation.
        - Steady-state offsets and low-frequency signals caused by phenomena other than mechanical motion.

    The proposed method should provide a ready method of detecting errors of the first type and compensating for errors of the second.

- The ability to perform the analysis with hardware systems in use and on data already acquired. For the most part., the discrepancies discussed are due to the data acquisition capabilities/strategies of different hardware systems in use. The proposed method should not obsolete these systems or the data acquired by them. Re-analysis of acquired data to the suggested standard should be straightforward.

The three parameters/strategies to be discussed are:

1) **SRS Algorithm and Implementation:**
   Reference 1 reported that
    - Smallwood[6] was the most-commonly used method
    - Kelly and Richman[7] was used by one commercial vendor.
    - Two commercial vendors reported that they used "Proprietary" algorithms using methods that low-pass and decimate the input data for lower-frequency analysis. The study performed in Reference 1 showed that the results were virtually indistinguishable from those calculated by "conventional, full-bandwidth" techniques for all except the lowest part of the frequency range[b]. The approach has significant advantages from a computational standpoint (both speed and mathematical accuracy) but they do produce

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(a) The analysis shown is a composite of the SRS results reported by the vendors/users and calculated results reflecting the use of different anti-alias-filter strategies.

(b) In the lowest part of the frequency range the transient part of the response (high-frequency) may be greater than the steady-state (low-frequency) part. In this case, the low-pass/decimate process must produce different results from the classical approach.

different results than the classical methods that include all of the acquired data in the analysis.

Recommendation:

Until/unless the low-pass-filter/decimation approach is thoroughly investigated and accepted by the testing community, the most straightforward approach is to use the Smallwood algorithm. It is well documented, straightforward to implement, and already in use by many practitioners. Despite the fact that Reference 1 indicates that the use of other algorithms will probably not cause significant differences for most applications, the objective here is to achieve consistency.

2) AC-Coupling Strategy.

DC offset and low-frequency drift will directly impact all frequencies of the SRS but will be most evident at low frequency where the SRS is normally low. In addition to the DC offsets that all instrumentation and data acquisition systems exhibit, experience has shown that transducers used for shock measurements almost always display erroneous low-frequency components that can cause significant errors in the SRS calculation.

It is critical that the importance of accuracy of low-frequency SRS values be understood. One of the great faults of the SRS analysis/display is that it underemphasizes the importance of response in this region. The fact that SRS values are small at low frequency does not mean that they are less likely to indicate the potential for damage. If there are structural modes at low frequency, a 10-g SRS value at 10 Hz may be more likely to cause failure than a 1000-g measurement at 1000 Hz. Accurate and repeatable SRS determination at these frequencies is essential.

This consideration exposes one of the major practical problems in SRS characterization. Most of the measurement devices/systems that are used for shock measurement produce “false” low-frequency signals when they are excited by a shock pulse. There are a variety of suspect causes but a likely candidate is thermal excitation, precipitated by the mechanical input of the shock. The result is an oscillation whose magnitude is often on the order of .1 to 1% of the shock peak amplitude. The error is virtually impossible to see in the raw time history but causes significant inaccuracies in the SRS at low frequency. Reference 4 recommends detecting errors by integration of the acceleration time history and it defines a limit of acceptability of deviation in the integrated (velocity) time history. A “reasonable” offset removal and high-pass filtering of the data is allowed before performing the integration (and the SRS) but the method is not defined.

Inspection of the low-frequency end of Figure 5 shows the effect of the offset-removal and high-pass filtering strategies reported in Reference 1. It can be seen that, even for the “very-clean” signal used, the strategy employed has a very strong influence on the SRS results. Less “ideal” signals would have produced much larger discrepancies.

The objective of the low-frequency data rejection must be to:

- Remove “incidental” data acquisition errors.
- Provide a standard, repeatable, AC-coupling facility.
- Not corrupt the SRS measurement significantly.
- Not “hide” bad data..

Recommendation:

The following two-step process has been developed at Lockheed Martin Missile and Space (LMMS): It should be applied to the acquired data before it is passed to the SRS analysis.

- Subtract the mean of the first 100 points at the beginning of the buffer (“initial-offset removal”). This assures that the transient starts very close to zero and minimizes the initial “impact” at the beginning of the buffer.
- Analytically apply a high-pass filter to remove unwanted/erroneous low-frequency components. The adopted strategy is to use a digital emulation of an eight-pole, high-pass, Butterworth filter with a cutoff frequency of 2 Hz or .1 x the Lowest Analysis Frequency (LAF), whichever is higher.

3) Anti-Alias Filter Strategies

Real measurement systems are limited in reliable bandwidth and data acquisition speed and this compromises the high end of the analysis range. Normally, bandwidth is intentionally limited because:

- High-frequency data is normally inaccurate because of a variety of factors including transducer resonance, frequency-dependent sensitivity of signal conditioning systems and noise. Therefore, the data is often low-passed by a combination of mechanical- and electrical-filtering systems and analytical processing to reject the erroneous information.

- It is desirable to limit the sample rate to reduce the amount of data involved. This reduces:
    - the speed requirements of the data acquisition/
    - storage system.
    - the SRS calculation time by minimizing the amount of data to be processed.

Low data acquisition speed forces the investigators to limit the measured frequency response with low-pass filters to assure that the data is not aliased. Reference 1 reported a wide variety of hardware filters that caused the discrepancies in the results at high frequencies shown in Figure 6. As can be seen, there is a strong effect at frequencies near the top (Maximum Analysis Frequency (MAF) = 10 KHZ.) analysis band. This is because the different low-pass-filter strategies reject different amounts of high-frequency energy and cause different amounts of ringing.

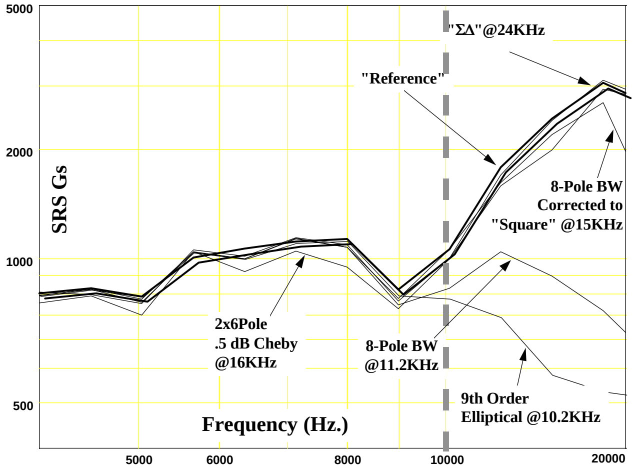

Figure 6 An Expanded View of the High Frequency Range

The objective here is to find a common ground that can be satisfied by most, if not all, of the hardware systems in use.

Some of the responders reported that they were using cutoff frequencies that were two or more times the Maximum Analysis Frequency. In this case, analytical low-pass filtering to a lower, "standard" cutoff frequency is straightforward.

Others reported that their systems use hardware anti-alias filters that have a cutoff that is not significantly higher than the MAF. An example is LMMS's use of 8-pole, Butterworth filters set at 11.2KHz to acquire data for SRS analysis to 10KHz. As seen in Figure 6, this filter produces a serious reduction in the calculated SRS at the MAF.

Smith and Hollowell[8] described a technique to modify this data so that it appears to have been acquired by a hardware system that has better characteristics. The technique "backs out" the transfer function of the real filter[a] and then applies a filter with ideal characteristics. Practical considerations, such as noise and discretization errors, limit the possible characteristics of the ideal filter, but the reference and several years of experience have shown that data acquired by this system can be reliably corrected to appear as if it were acquired with a square filter at 15 KHz (1.5 x MAF).

The use of a "square" filter has an immediate effect that causes concern: the sharp cutoff causes ringing in the signal that will lead to an increase in the SRS. However this appears to compensate for the rejection of high-frequency energy by the filter. Figure 6 shows the result of filtering the reference waveform with the 15KHz square filter on the SRS. The result at 10KHz (MAF) is essentially identical to the broadband (and the high-frequency-filter) results. This result has been confirmed with a variety of other waveforms.

Recommendation:

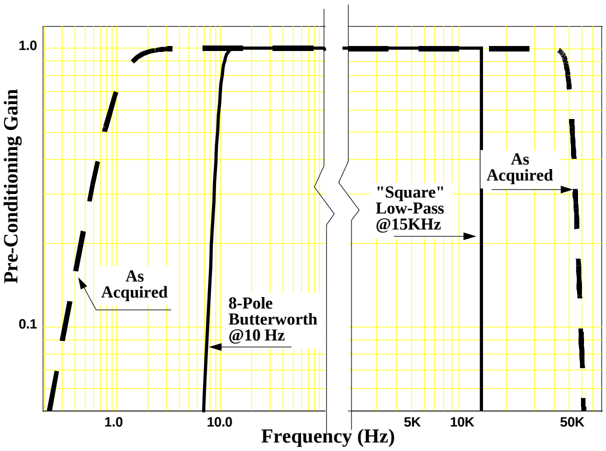

Figure 7 The Recommended Filter Preprocessing

> The data should be analytically low-pass filtered with a square, zero-phase filter at 1.5 x the Maximum Analysis Frequency before being passed to the SRS analysis. For data acquired with systems that do not have a cutoff frequency of at least 2 x MAF or have significant time delay skew in the frequency range of interest, the filter-correction method described in Reference 8 must be used.

(a) and any other characteristics that can be expressed as a transfer function such as transducer gain and phase shift.

Figure 7 shows the spectral view of the recommended filtering processing to be applied to the data that is passed to the SRS calculation.

Conclusions

Different data acquisition and analysis strategies can cause significant differences between the SRS results obtained at different facilities. The primary problems occur at the upper and lower ends of the analysis frequency range where discrepancies of 10 to 200% have been demonstrated. It should be noted that this is the result of assessing the effect on a single time history and hence is probably not a worst case.

This is obviously an unacceptable situation and a means of justifying and/or correcting the data to provide agreement is required.

A recommended method for analytically modifying the experimental data to make it appear to have been acquired and analyzed by a "standard" machine has been presented. The method has been in use a LMMS for three years and has proven to be robust and reliable. The "adjustment" system can be applied to the data acquired by any "appropriate" data acquisition system and the required tools are available in all of the popular signal analysis computer programs.

Other factors that are handled differently by the surveyed practitioners have not been discussed here. Among them are:

- The method of calculating the center frequency of the SRS analysis filters
- The method and strategy for interpolating the time-history data to determine the peak values.
- SRS analysis Q and octave spacing.
- Required data acquisition and instrumentation signal-to-noise ratio and resolution.

The effects discussed here only begin to explain the discrepancies found in the round robin studies. It would appear that, at least for the organizations that responded to the questionnaire, that large differences in results (100's of % over the full frequency range) cannot blamed on either analysis method or basic data acquisition technique. To resolve these problems, an intensive study of real laboratory practices must be undertaken.

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Appendix

SRS Data Acquisition and Analysis Procedures
Reported in Reference 1

	Vendor 1 (Old)	Vendor 1 (New)	Vendor 2	Vendor 3	Vendor 4	Homebuilt 1	Homebuilt 2
Dynamic Range(db)	68	90	86	72		80	56 (FM Tape)
Sample Rate	4.096x***MAF***	5.12x***MAF***	4.1 x AA-Filt	2.56xAA-Filt	20.48K max	5 x ***MAF***	100K
Hardware AC-Coupling	RC (1-pole) <1 Hz	Nulled DC +.2 Hz, 1 pole	1-Pole @ .07 Hz.	Nulled DC	2-pole HP	DC + Sig Cnd	DC + Sig Cond
Analysis Boundary/ Offset Handling	Subtract mean of buffer	Subtract mean of buffer	Pad With End Values	Subtract Mean and slope of Buffer	None	***SA***(100) + 8-pole BW HP at .1x***LAF***	***SA***(200)
AA Filter Type	2 x 6P Chby ±.5dB	Sigma Delta	3-P RC+Chby (80 dB Rej)	9th Ord Cauer +12th OrdDig	8-Pole BW	8P BW	6P/6Z Const Delay
AA Setting	1.6xMAF	24K	20KHz.	10.2K , 50K ,100K	.3125 x Sample Rate	11.2 KHz	15KHz.
Analysis LP and AA-Correction	None	None	None	Phase & Mag Correction		Corrected to square filter @1.5 ***MAF***	None
SRS Alg	Kelly & Richman	Kelly & Richman	Proprietary (octave filter & decimation)	Proprietary (octave filter & decimation)	Proprietary	Smallwood	Smallwood
Interpolation	Linear to >16 ***PPC***	Linear to >20 ***PPC***	Zero-Ins/LP Filter & Decimate 8<***PPC***<16	Upsample and Filter & Decimate ***PPC*** >10	2/4-Point Quadratic > 16 ***PPC***	Spectral Insertion to > 10 ***PPC***	None
1/N Frequency Calculation	Base 10	Base 10	Base 2 1K Ref.	Base 10	Base 2 Arb Ref.	Base 2 1 K Ref.	N/A

1. Smith, Strether and Melander, Roy, *“Why Shock Measurements Performed at Different Facilities Don't Agree”*, Proceedings of the 66th Shock and Vibration Symposium Proceedings, Biloxi MS, 1995
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