

REPRINT

Title: Why Shock Measurements Performed at Different Facilities Don't Agree

Author: Roy Melander, Strether Smith

Source: Proceedings, Shock & Vibration Symposium October 1995

This paper was presented at the 1995 Shock and Vibration Symposium.

INTRODUCTION

The round robins that have been performed and discussions among practitioners of the shock-testing art demonstrate that the results obtained from mechanical shock experiments performed in different laboratories vary widely. In addition, it has been found that different generations of hardware/software systems from one of the major system vendors produce results that disagree by 30%. The obvious question is: WHY?

The paper describes a study that examines some of the critical parameters that effect Shock Response Spectrum (SRS) results and reports on how they are used by the practitioners in the field. Parameters that effect the analysis include anti-alias filter characteristics, ac-coupling strategies, analysis frequencies, sample rate, and analysis algorithm/strategy. The paper reports the effects of the parameters as used in several commercial and homebuilt systems.

The Problem

There is a growing concern that shock tests performed at different laboratories produce different results. This thesis is substantiated by round robins[1] that have produced results that can only be described as chaotic. Discussions with practitioners[2] reflect a general lack of confidence in the procedures in use.

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

Problems of the first form 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 probably the prime contributors to errors and lack of reproducibility in SRS results and rectification of these problems must be a prime objective of all laboratories. However, they are not be addressed here.

The second form of discrepancy is found in fundamental differences in methodologies used for data acquisition and analysis. Once the motions are correctly transduced and

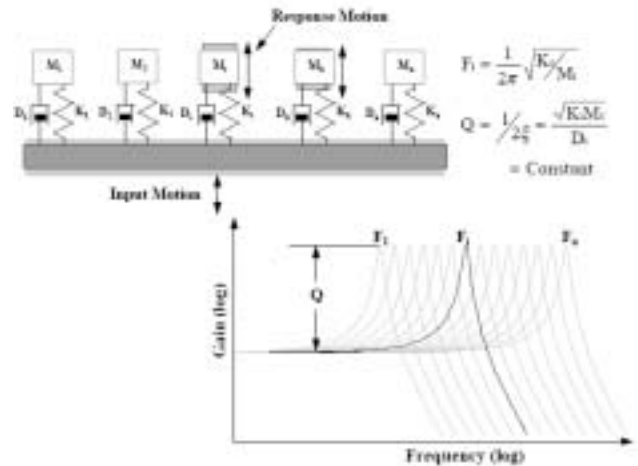


Figure 1 The SRS Model

conditioned, different laboratories/vendors use different data acquisition and analysis techniques to perform the Shock Response Spectrum (SRS) analysis.

The objective of this paper is to isolate some of the parameters that produce the disagreements. As will be discussed, it is impossible to perform a "true" SRS calculation in the real world. Different hardware systems have different capabilities and their builders/appliers have employed a variety of, often-clever, techniques to bypass or correct for their inability to perform a perfect calculation.

Different techniques produce different results and discrepancies as large as 30% between systems in general use can be demonstrated. For the most part, the techniques in use are allowed by the "recommended practices documents"[3][4]. A more stringent specification is required.

Discussion

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

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

Melander and Smith, "Why Shock Measurements Performed at Different Facilities Don't Agree," 1995.

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

When the base is moved (the accelerometer input) each of the oscillators vibrates. The motion of each mass is "monitored" and its maximum and minimum excursions (normally 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 natural frequency. The gain at all frequencies less than the resonator natural frequency is greater than one.

In "real" applications the ideal, continuous, single-degree-of-freedom, model is violated in a variety of crucial ways that may compromise the results. Figure 3 shows one of the critical deviations from the ideal model: the frequency-range limitations imposed by ac-coupling and anti-alias filtering. Different investigators have used different techniques in an attempt to minimize the consequences of these shortcomings. They produce different results.

The Study

The approach used to identify differences was to send a questionnaire and an ASCII file of a "representative" pyroshock time history to several laboratories and SRS acquisition/analysis system manufacturers. The list of recipients was short but was designed to include the important system vendors and a few laboratories that the

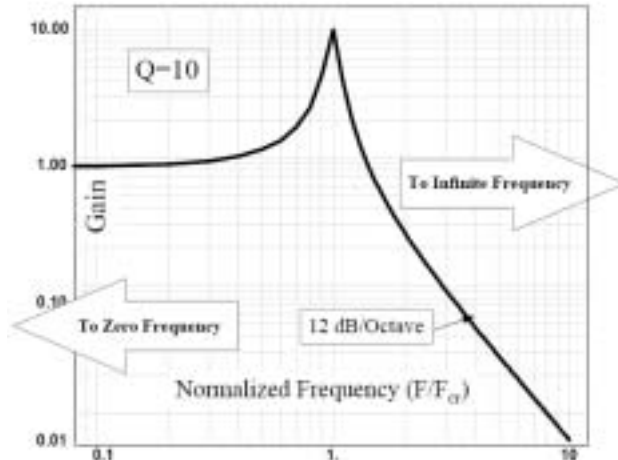


Figure 2 The "Ideal" SRS Oscillator

authors knew used "home-made" systems. About half of the recipients responded.

A selected subset of the questionnaire responses is shown in the following table. Examination shows a variety of practices and very little commonality. The question is: which parameters effect the results significantly? The time history, and its power spectral density^a are shown in Figure 4. It is a real data set that is well behaved, but not perfect^b. The objective was to find out

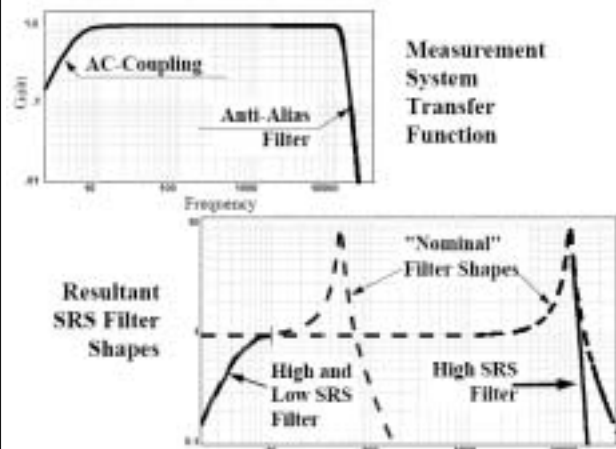


Figure 3 "Real System" SRS Filters

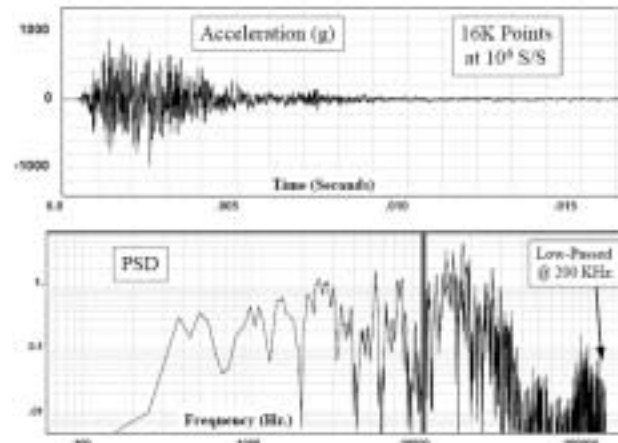


Figure 4 The Distributed Data Set

(a) The PSD is shown as an indicator of the spectral-energy content of the signal.

(b) The data set was acquired in a pyrotechnic test at 1 million samples/second with no filter. It was then analytically low-passed with an eight-pole Butterworth filter at 200 kHz. Note the accelerometer resonance at about 90 kHz.

Melander and Smith, "Why Shock Measurements Performed at Different Facilities Don't Agree," 1995.

	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	4.096 x MAF	5.12 x MAF	4.1 x AA-Filt	2.56 x AA-Filt	20.48K max	5 x MAF	100K
Hardware AC-Coupling	RC (1-pole) <1 Hz	Nullled DC +.2 Hz, 1 pole	1-Pole @ .07 Hz.	Nullled DC	2-pole HP	DC + Sig Cond	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 .1 x LAF	SA(200)
AA Filter Type	2 x 6P Chby ±5dB	Sigma Delta	3-P RC+Chby (80 dB Rej)	9th Ord Cauer+12 th OrdDig	8-Pole BW	8P BW	6P/6Z Const Delay
AA Setting	1.6 x MAF	24K	20KHz	10.2K, 50K,100K	.3125 x Sample Rate	11.2 kHz	15 kHz.
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

SA(n) = Subtract the Average of the first n points PPC = Points Per Cycle at the Maximum Analysis Frequency
 MAF = Maximum Analysis Frequency LAF = Lowest Analysis Frequency

whether the analytical algorithms used in the systems in use produced results with significant differences. The responders were asked to apply the analytical tools that they would normally use. These tools included preprocessing such as interpolation to improve the data density to enhance peak detection and filtering the data to remove low-frequency offsets and unwanted high-frequency data. Figure 5 shows the results of the SRS analyses of the time history as calculated by the responders. The SRS spectrum was calculated from .004% to 4% of the data acquisition sample rate. It may be seen that the results from different responders agree quite well for most of the frequency range but that there are significant differences at the low end.

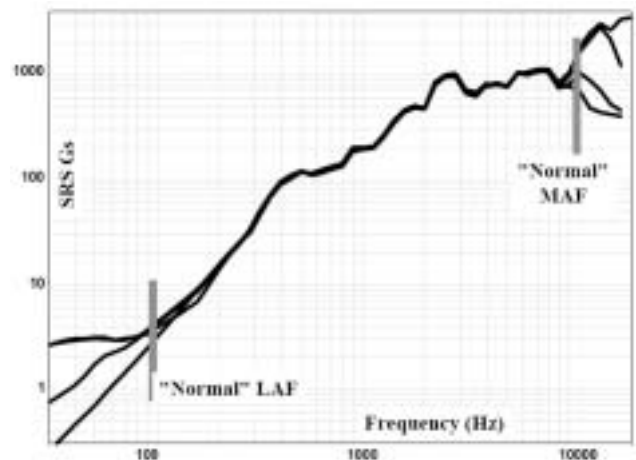


Figure 5 Analysis of SRS Data File

Melander and Smith, "Why Shock Measurements Performed at Different Facilities Don't Agree," 1995.

Parameters covered by this "experiment" include:

- SRS Algorithm and Implementation
Several algorithms are in use:
 - Kelly and Richman[5] is used by one commercial vendor
 - Smallwood[6] is the most commonly used "public-domain" algorithm.
 - "Proprietary" algorithms were used by several vendors/practitioners.
 - Two commercial vendors use a proprietary algorithm combined with low-pass filtering and decimation at each octave. This is in contrast to all other implementations that used all of the acquired/provided data for the analysis of all frequency bands. The effect of this strategy is twofold: The effect of high-frequency energy is reduced which should lower the calculated SRS. This is "compensated" to some extent by the fact that the low-pass filtering causes ringing in the signal that is passed to the calculation which will increase the SRS estimate. The fact that the SRS results agree so well for this data set indicates that the two effects do compensate.

This approach ignores the fact that the SRS response is made up of "transient" and "steadystate" terms. For most of the SRS analysis frequency range, the "steady-state" part of the response dominates. However, at the low-frequency end of the spectrum in cases where there is relatively-little "real" energy, the transient portion of the response may be dominant. In this case, the results should be significantly different.

This approach has significant advantages when viewed from a computing and aesthetic standpoint. First, less mathematical accuracy is required in the filter calculation and the process is faster because fewer points are manipulated. Second, the resulting filter shapes are more consistent throughout the analysis range.

However, the results must be somewhat different from those produced by "conventional" analysis methods.

All of the responders reported that they use the "absolute acceleration" form of the calculation almost exclusively.

These results indicate that the basic SRS algorithms in use provide essentially the same results for most of the frequency range (for this particular time history). Discrepancies at low frequency are primarily due to differences in

ACcoupling strategies.

- Different AC-Coupling Strategies. DC offset and low-frequency drift will directly impact all frequencies of the SRS but will be most obvious 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.

For most applications^a the effect of these errors should be minimized before the SRS calculation is performed. However, choice of a "removal" technique is not straightforward. Four fundamentally different strategies were reported.

- Subtract the mean of the complete buffer (average offset rejection).
- Subtract the mean of the first n (10 < n < 100) points of the buffer (initial offset rejection).
- Subtract the mean of the first n (10 < n < 100) points followed by high-pass filtering. Several high-pass filtering strategies have been used including:
 - 1 or 2 poles at 1 Hz.
 - 2 to 8 poles at 10 Hz.
 - 2 to 8 poles at 10% of the lowest analysis frequency.

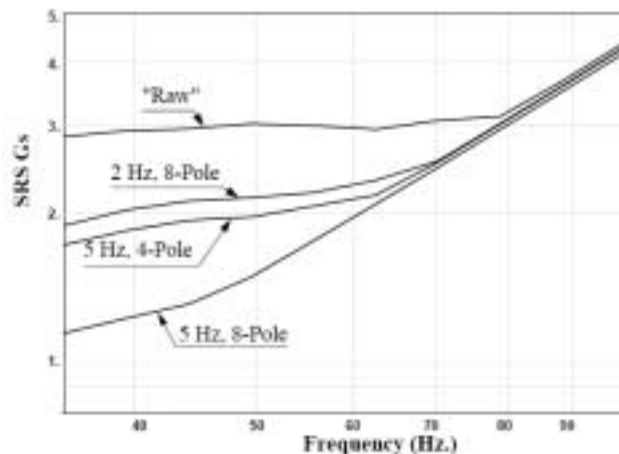


Figure 6 The Effect of AC-Coupling Strategies

- (a) The fact that the SRS is small at low frequencies is not an indication that the damage potential is small. Relative accuracy in this range is often just as important as the large values found at higher frequencies.

Melander and Smith, "Why Shock Measurements Performed at Different Facilities Don't Agree," 1995.

- Subtract the mean of the first n ($10 < n < 100$) points (initial offset rejection) followed by subtraction of a best-fit straight line (trend removal). This results in rejection of constant velocity components.

As an example of the sensitivity of the analysis to AC-coupling strategy, Figure 6 shows the effect of a variety of analytically-applied high-pass filters on the low-frequency portion of the SRS for the reference waveform. The interaction between the filters and the low-frequency part of the signal are complex and specific conclusions drawn from the figure must be considered to be unique to the time history used. Other time histories will produce different results.

Analytical Simulation of Anti-Alias Filter Effects

The results discussed above are those that would be produced if the data acquisition system is capable of acquiring data at frequencies that are significantly higher (100x) than the maximum analysis frequency. However, most practitioners must (or want to) use systems that are somewhat lesscapable and this compromises the high end of the analysis range. Bandwidth limiting is used because:

- High-frequency data measurement is normally inaccurate because of a variety of factors including transducer resonance. Therefore, the data are often low-passed by a combination of mechanical and electrical-filtering systems and analytical processing.
- 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 reducing 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. Filter types and cutoff frequencies found in the responses included:

- 2 x 6-pole (~12-pole equivalent), .5dB ripple, Chebychev filters set at $1.6 \times$ MAF.
- 9th order elliptical at $2 \times$ MAF.
- 6-pole/6-zero Constant Delay set at $1.5 \times$ MAF.
- 8-pole Butterworth at 11.2 KHz (raw and analytically corrected to appear to be a square filter at $1.5 \times$ MAF).
- 12th order Cauer at 10.2 KHZ
- 12th order Cauer at 50 KHZ.
- SD^a at 24 KHz.

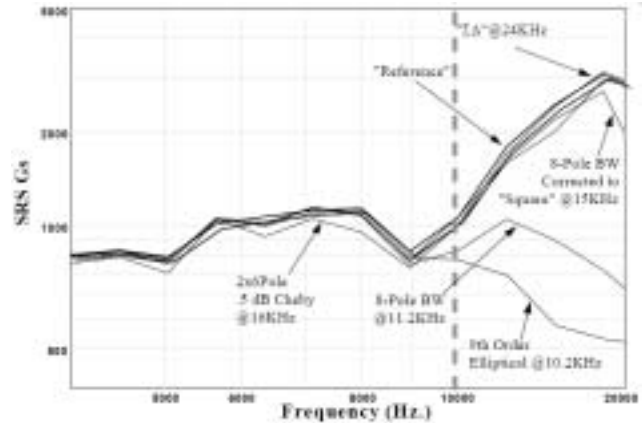


Figure 7 The Effect of Various Anti-Alias Filters

To evaluate this problem, an analytical study was undertaken to emulate the reported filtering and sampling strategies used. The results are found in Figure 7 for bands near the maximum analysis frequency (10kHz.). The curves include:

- Data acquired at 100 times the MAF ("Reference").
- A variety of filtering strategies including some of those listed above.

As can be seen, there is a strong effect on the top (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. This is most strongly felt at bands near the cutoff.

In particular, note the differences between curves labeled "2x6-Pole Cheby" and "ΣΔ @ 24 KHz." which represent the results produced by old and new generations of system from one of the major commercial vendors. Differences on the order of 20% are evident. Again, the results are unique to this particular time history and different inputs will produce better or worse agreement.

Conclusions

This study shows that 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 30 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.

(a) "ΣΔ" hardware filters produce a "very-nearly-square" low-pass amplitude cutoff with constant time delay (linear phase).

Melander and Smith, "Why Shock Measurements Performed at Different Facilities Don't Agree," 1995.

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 correcting the experimental data to make it appear to have been acquired and analyzed by a "standard" machine is under development. Some of the concepts involved have been previously discussed[7] and they will be developed/enhanced in the form of a "suggested practice". The challenge is to develop a technique that will produce realistic, transportable, results that can be used by all (or, at least most) of the hardware systems in use.

The effects discussed here do not 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 (hundreds of %) in results cannot be blamed on either analysis method or basic data acquisition technique. To resolve these problems, an intensive study of real laboratory practices must be undertaken.

References

1. Chalmers, Richard H., "The NTS Pyroshock Round Robin", Proceedings of the IES Conference, Chicago Ill, Spring 1994.
2. Discussions with Chuck Wright of TRW produced a significant number of the questions that are discussed here. His help as a sounding board is gratefully acknowledged.
3. Himmelblau, Harry, Piersol, Allan G. Et al "Handbook of Dynamic Data Acquisition and Analysis". IES-RP-DTE012.1, Institute of Environmental Sciences
4. Bateman, Vesta, "Recommended Practices for Pyroshock", Proceedings of the Institute of Environmental Sciences, 1995
5. Kelly, R.D. and Richman, G., "Principals and Techniques of Shock Analysis", SVM-5, Sec. 6.7, Shock and Vibration Information Center. 1969.
6. Smallwood, David: "An Improved Recursive Formula for Calculating Shock Response Spectra" 51st Shock and Vibration Bulletin, 1980.
7. Smith, Strether and Hollowell, Bill, "Techniques for the Normalization of Shock Data", 62nd Shock and Vibration Symposium Proceedings, Springfield VA. 1991