STANDARDIZATION OF SHOCK MACHINES USING SRS ANALYSIS

By George Henderson

A procedure exists for standardizing shock machines. This procedure is related directly to procedures already in use in many environmental test laboratories.

INTRODUCTION

This paper describes the theory and a special application of a method of analysis of acceleration shock transients known as shock response spectrum, or SRS. This method is widely used in environmental shock testing areas to standardize or specify acceleration shock pulses. It is proposed to use the SRS method as a means of comparing shock machines with the goal of standardizing their performance.

The need to standardize shock machines becomes apparent when different results occur when testing the same product on different shock machines using nominal pulse specifications. The three point nominal specification, amplitude and pulse duration at the base, does not truly specify a shock pulse. This is because any number of pulses can pass through three points even though each may have significantly different frequency components as the base nominal specifications.

These differences have been most apparent when using the nominal shock pulse shapes as required in several test standards such as ASTM-D-3332,[1] and the pass-fail military shock testing using nominal pulse shapes under MIL-STD 810,[2] and IEC Publication 68-2-27.[3] For this reason, the latter two specifications have been changed to use an SRS method as the preferred method. Certain edited figures and descriptions used in this paper were taken from Figure 3.

BACKGROUND

Shock machines are used to test the mechanical integrity of products. For various reasons, generally relating to economics, the method of testing involves the use of input shock pulses having nominal waveshapes of variable severity. The waveshapes used are termed half sine, trapezoid, and terminal peak (or sawtooth). Each shock pulse shape has one or more technical reasons for being used in a specific test. These reasons center on the need to input energy of specific amplitude, velocity change, and spectral content.

Until recently, most test standards specified pulse shapes by the minimal nominal criteria only. These criteria being general shape, acceleration peak amplitude, and time duration. By these criteria, it was intended that frequency content and velocity change of the nominal shock pulse would be controlled and meet the needs of specific types of tests.

In 1983, the D version of MIL-STD-810 was published changing the requirement from nominal pulse shapes to tailored pulse shapes to better match the real environmental shock hazard to which the product will be

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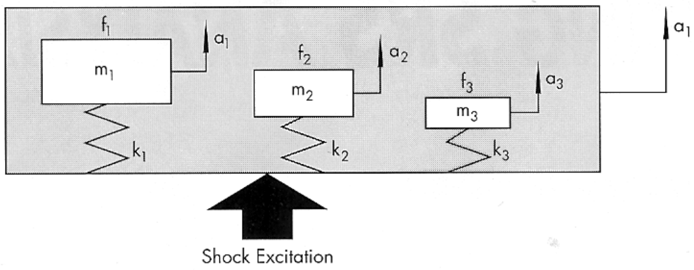
Figure 1.



Three element SDOF model with base excitation, af. Each SDOF will resonate at a different frequency fx, depending on kx and mx values. Each SDOF will exhibit a different time history of acceleration, ax.

subjected. As expected, the change resulted in a tighter specification such that better test reproducibility was obtained.

The specifications of tailored shock pulses under MIL-STD- 810D are controlled by the SRS method. When the SRS plots of two tests are identical then the products are certain to have been subjected to the same shock excitation. The SRS method results in an exacting specification for a shock pulse that goes far beyond the minimal peak amplitude and time duration criteria previously used.

BASIC SRS THEORY

The SRS is presented as a spectral plot of the peak acceleration response amplitudes of an infinite number of single degree of freedom (SDOF) spring mass systems to a given excitation. Figure 1 shows a model of a three SDOF spring mass system. When an acceleration excitation shock, af, is input to the base of the system, each mass will resonate at a specific frequency, f1, f2, and f3 equal to:

$$f = \frac{1}{2}\left[\frac{k}{m}\right]^{1/2}$$

where M is the mass, and k is the force deflection constant of the spring of an SDOF model. In this illustration, we assume each mass and k is different, and hence, each SDOF resonates at a different frequency.

If an arbitrary shock pulse, as seen in Figure 2a, is applied to our multiple SDOF model in Figure 1, then each SDOF may respond in a manner similar to the three acceleration versus time plots, a(t)x, shown in Figure 2b, 2c, and 2d.

The SDOF with the lowest resonant frequency responds with a long period sine oscillation, as shown in Figure 2a. The SDOF system with a mid-resonant frequency responds with a shorter period sine oscillation and a higher amplitude, as seen in 2b. The third SDOF system with a high resonant frequency responds as in 2c.

The reason for these three types of responses relates to the time duration of the input pulse and the resonant frequency of the SDOF models.

If the input pulse duration D is not long enough for the SDOF mass to reach full amplitude during one or more cycles of its resonant frequency, then a low amplitude response similar to that in 2b will occur.

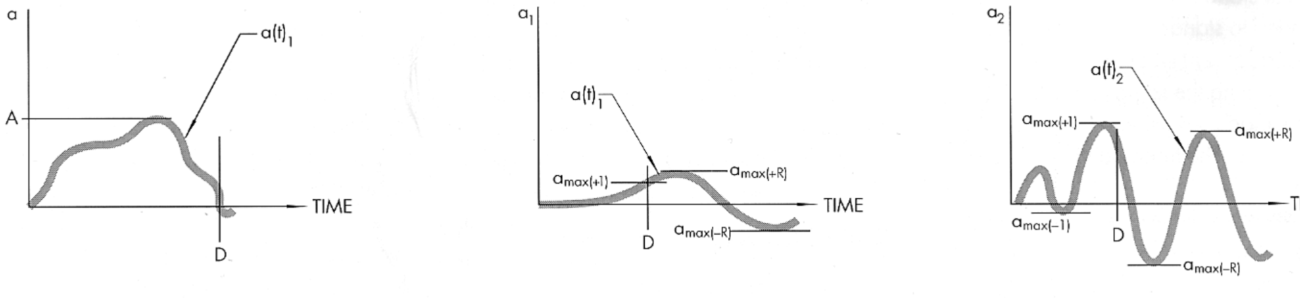
As the frequency of the SDOF increases, its period shortens until it nears equality with the input pulse duration. At this point, acceleration amplitude of the undamped SDOF mass increases and reaches a maximum of 1.8 times the input pulse, as seen in 2c.

At higher SDOF resonant frequencies, response starts early during the input excitation pulse duration, as seen in 2d. In 2d, the SDOF mass is so small that it responds quickly, riding on the input pulse while oscillating at its own frequency. In this case, a composite response plot will occur. At the highest frequencies, the acceleration amplitude of this SDOF will approach and equal the amplitude of the input pulse.

If we now plot the maximum amplitude peak responses for an infinite number of SDOF spring masses tuned to different frequencies, the spectra curves as seen in Figure 2e will result.

It is important to understand the relationship between what is known as the initial and residual shock spectrums. If an SRS plot is ob-

Figure 2.



SDOF BASE EXCITATION

RESPONSES OF THREEE SDOF ELEMENTS ☛

tained from the response signal that coincides in time with the duration of the principal excitation pulse, it is known as an initial, or I spectrum.

Likewise, if an SRS plot is obtained from the portion of the response signal that coincides in time to the response to the noise or ripple signal after the termination of the initial excitation pulse, it is known as a residual, or R spectrum.

In addition, the response may be unidirectional, i.e., a positive going excitation pulse will produce a positive going response, and visa versa. Therefore, there are several variations in types of SRS plots based on the characteristics of the excitation pulse and the desired analysis.

The positive initial shock spectrum, +I, in Figure 2e, is the plot of the maximum response occurring during the input pulse duration, D, in the same direction as the excitation pulse. This is known as the positive initial amax (+I) SRS.

The positive residual shock spectrum, +R, in Figure 2e is the plot of the response occurring after the excitation duration. This is the positive residual amax (+R) SRS.

The negative initial shock spectrum, –I, in Figure 2e, is the plot of the maximum response during the excitation pulse in the opposite direction to the exciting pulse. This is the negative initial amax (–I) SRS.

The negative residual shock spectrum, -R, in Figure 2e, is the plot of the same maximum response after the excitation pulse. This is the negative residual amax (–R) SRS.

All four types of SRS are shown plotted in Figure 2e with the contribution of the resonance frequencies of the three SDOF systems, f1, f2, and f3 also noted.

Since the damping in our first example is assumed to be zero, the response of each SDOF after termination of the input pulse duration is a steady sine type oscillation. Thus, the positive and negative residual spectra are images in the frequency axis of each other.

The amax (+R) and (–R) SRS's are equal in amplitude but different in sign, and for simplicity, for positive direction in input shocks, only the positive residual is shown in presenting spectra if the residual spectra is desired.

Also, in our example and for our shock machines of concern, the negative initial spectrum is less than the positive initial spectrum for the positive excitation pulse and is therefore of less importance for analysis. The envelope that includes both the positive initial and residual spectra shows the maximum response acceleration of the masses whenever in time it occurs. This is termed the "maximax" response or overall shock spectrum. Because the envelope defines all important spectral information, the maximax is the most used form of response spectrum.

Although the maximax is the most universally used method of presenting SRS, to show the concept clearly, the following illustrations of nominal shape SRS plots show the initial (+i) and residual (+R) spectra plotted separately.

A key point to remember is that normalized (generalized) SRS plots for pulses of differing amplitude and time parameters, but with the same pulse shape, will be identical. For this reason, SRS plots are sometimes plotted with the horizontal frequency scale normalized to the basic shock pulse frequency (f*D) and the amplitude scale normalized to shock pulse amplitude (amax/A).

Once normalized, pulses with differing parameters may be compared. Normalized spectra will be valid for any shocks of the same pulse shape. For example, a half-sine 490 M/s^2 (50 g) 11 msec pulse as well as half-sine 9800 M/s^2 (1000 g) 0.5 msec pulse will have identical normalized SRS plots. Although when normalized spectra for two different pulses may appear to be the same, damage potential must still be determined in the un- normalized case.

Three normalized SRS plots for perfect nominal pulse shapes are seen further in Figures 4, 5, and 6. The plots shown are the +I and +R responses of undamped half-sine, trapezoidal and final peak terminal shock pulses. Only pulses with perfect geometry will produce these SRS plots.

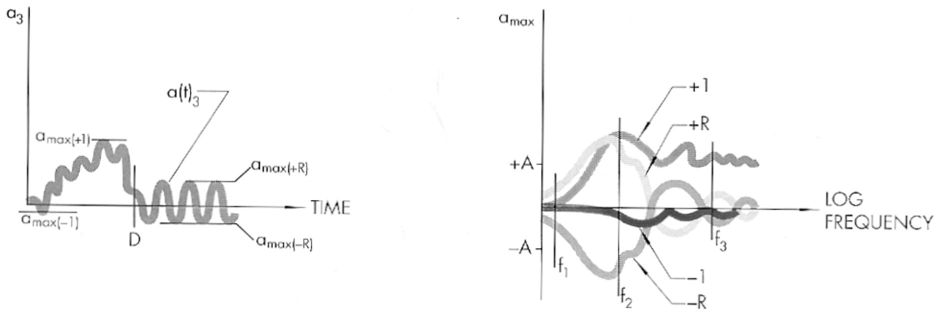
Many shock machines, not being perfect, have noise or ripple caused by table resonances or programmer performance that causes pulses which are not nominal.

These deviations will affect the SRS plot. In fact, residual shock machine noise due to table resonance is a major factor in SRS plot difference.

Affect of Damping on the SDOF Model

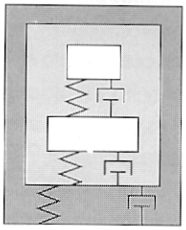
Real world spring mass systems have some degree of damping. Figure 3 shows a model of SDOF's with dampers added. Dampers work like shock absorbers. They are velocity dependent devices; the faster the motion, the more resistance of the damper.

In general, damping of the SDOF model will have the affect of lowering response at intermediate frequencies during the input pulse duration (primary response) and at intermediate and higher frequencies after the



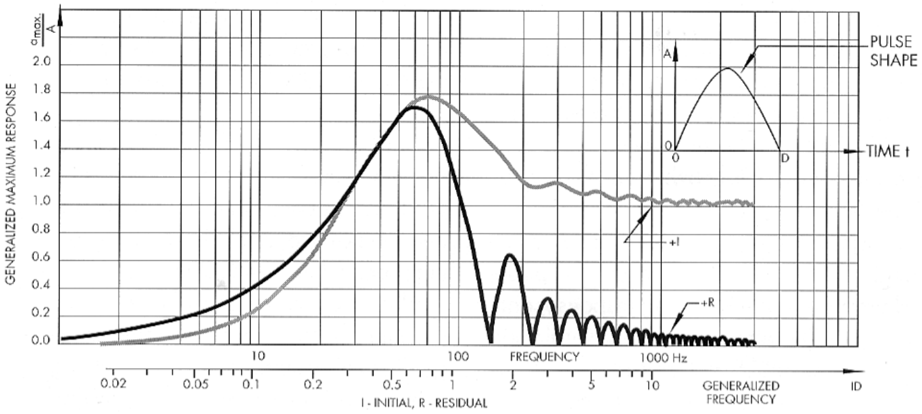
SRS OF CONTRIBUTION OF SDOF

Figure 3.



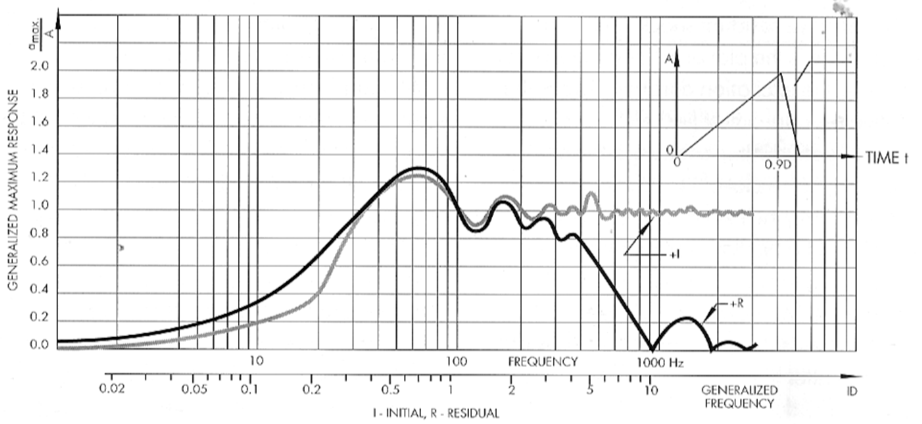
MULTI DEGREE OF FREEDOM MODEL WITH DAMPING

Figure 4.



Normalized SRS of nominal halfsine shock pulse, D=11ms, showing Positive Initial and Positive Residual SRS plots.

Figure 5.



Normalized SRS of nominal terminal peak shock pulse, D=11ms, showing Positive Initial and Positive Residual SRS plots.

input pulse duration (residual response). This is related to the velocity of the spring mass system.

Damping will decrease both the amplitude and the decay time during which any oscillatory content dies out, thereby appreciably attenuating the response of any SDOF system. When shocked by a long duration step input signal, the damped SDOF model will exhibit an amplitude response that quickly reaches a maximum, generally within a few cycles, and then decays to zero exponentially with time.

The damage potential of a shock is generally, lower for damped than for undamped spring masses, particularly from multi-degree of freedom systems.

Shock machine table resonance, or ripple that occurs coincident with and after the initial shock pulse, is an important type of distortion in the nominal pulse shape. This distortion can have a major affect on the SRS signature, and hence, on the product being tested.

The probability of product damage is increased if the table resonance frequency spectrum overlaps the fragility frequency spectrum of the product and therefore merits special consideration. Spring mass systems where ratios of actual to critical damping are small (<.1, Q=5) are very sensitive to ripple on the shock pulse. As an example, if the 49 m/s^2 (5 g) 460 Hz ripple in Figure 7 is coincident with the initial half sign 490 m/s^2 (50 g) 11 ms shock pulse, then the composite pulse shown results. The ratio of actual to critical damping here was 0.5, Q=10. Note the composite SRS magnitude.

In our example, if the amplitude of the ripple is just 10% of the excitation, and assuming a damping ratio of 0.1 (Q=5), then the SRS plot shown in Figure 7 will result. Note the high +R and +I response maximax envelope reaches a peak of nearly 2X the nominal shock amplitude input level. This level of residual input can damage products when undamped spring masses resonating at this frequency have a fragility of 10 g's or less.

If one now considers a shock machine producing a noisy trapezoidal shock pulse, (example 98 m/s^2 (10 g) average amplitude) producing a response of 980 m/s^2 (100 g) (product damping of .05, Q=10) with frequency content to several KHz's, then the damage potential of a shock machine with table ripple signature becomes quite evident.

It should be emphasized that accurate shock testing requires a judgement of the importance of analyzing the response oscillations that remain after the termination of the principal shock excitation. The judgement should be based on possible fatigue failure modes of the product being tested, especially due to high frequency vibration.

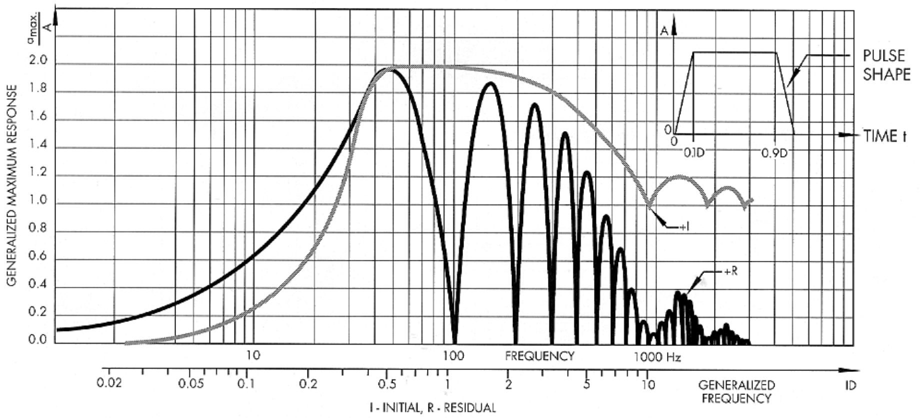
As an example, MIL-STD-810D requires SRS analysis of the input excitation pulse out to a point where the residual response amplitude falls to 1/3rd of the initial amplitude. This is done to insure that the product is tested in a manner that simulates the real shock environment pulse in a real worst case scenario.

Discussion of Nominal Pulse Shape SRS

It can be seen that the initial spectra for the three types of pulses seen in Figures 4, 5, and 6 are nearly the same for low frequencies up to fD=0.2, and the residual spectra are nearly proportional to the velocity change (area) of the pulse.

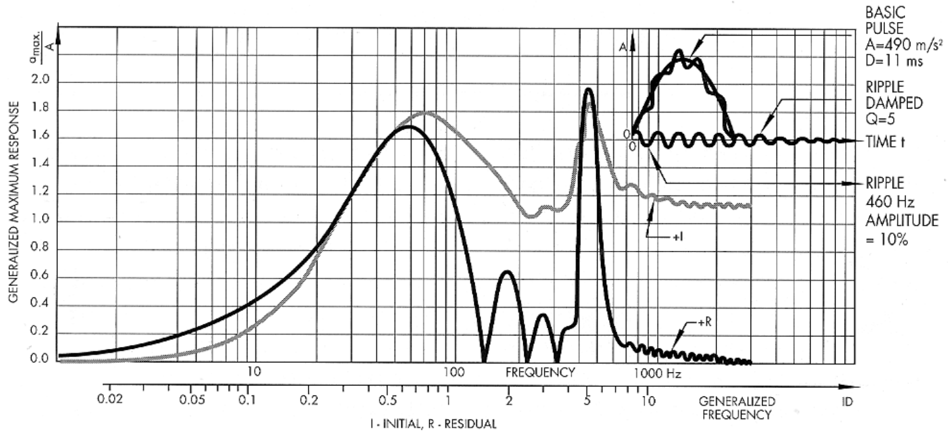
The trapezoidal pulse shape has the highest velocity change for a given peak acceleration and duration of the three nominal pulses shown, and this is the reason it is used as one parameter of the damage boundary curve developed using ASTM D-3336 [1].

Figure 6.



Normalized SRS of nominal trapezoidal shock pulse, D-11ms, showing Positive Initial and Positive Residual SRS plots.

Figure 7.



Normalized SRS of nominal half-sine shock pulse, D=11ms, of 490 m/s^2 (50 g) with superimposed ripple of 49 m/s^2 (5 g). Both Positive Initial and Positive Residual SRS plots are shown.

The initial spectra of the three nominal pulses show differences in amplitude at intermediate frequencies (0.2<fD<10). These differences depend on the rise time of the pulse.

The trapezoidal pulse shows the highest response for a given peak acceleration value due to the very short rise time and flat peak. The long duration of constant acceleration allow the low frequency oscillations of relatively large spring masses as well as all smaller elements to reach peak values during the principal duration.

Response Gain Related to Damping

The damped spring mass system has a narrow band width, and in terms of response, it acts just like a narrow band electronic filter where the band width is a function of the damping ratio. At low damping ratios, the gain of the SDOF may be high. For example, for a damping ratio of 0.05%, the Q or gain of the spring mass system will be 10%. However, for a damping ratio of 0.5%, the Q will be only 1X.

The damping ratio is defined as the relation between the functional damping to the critical damping of the SDOF model. Critical damping is the damping that would cause the SDOF to respond to a step input with the minimal overshoot and decay time.

For the narrow band damped SDOF model (damping ratio 0>d>0.5%), high amplitude response is only reached after several cycles of a coherent excitation signal tuned to the resonant frequency of the SDOF. This is because filters such as the narrow band SDOF have a time constant that requires the application of a coherent excitation for some period of time before the filter reaches full amplitude. Of course, if the excitation is noncoherent (having many frequency and phase components), then the response will not reach as high an amplitude as it does in the coherent input signal case.

Another example of the gain of a damped SDOF model is in the case in which a coherent single frequency sine oscillation excitation is applied.

In this case, and assuming a damping ratio of .05 yielding a gain (or Q) of 10X, the resulting SRS plot would peak at a value ten times the amplitude of the excitation at a point equal to the frequency of the excitation.

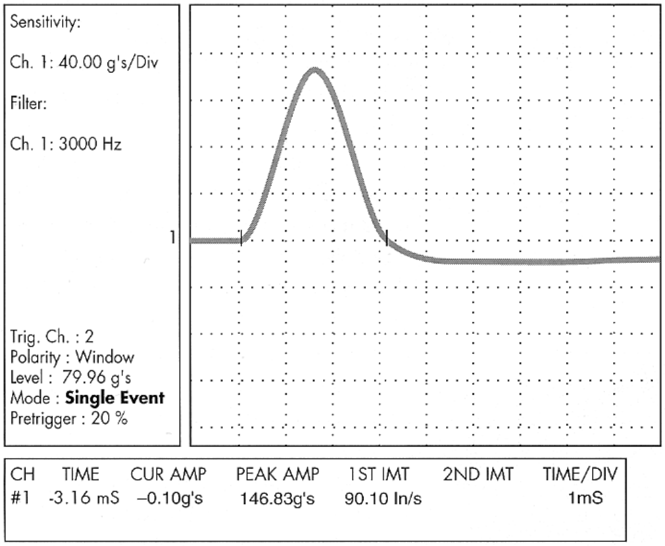
As previously stated, the long duration of the trapezoidal pulse allows low frequency SDOF oscillations time to build up, while at the same time the fast rise time excites higher frequency SDOF response. This is one reason that square wave programmers on shock machines can excite undesirable intermediate through high frequency machine table resonances with high amplitudes. It is not surprising to see an unfiltered trapezoidal pulse from a shock machine with a nominal amplitude of 50 m/s^2 (10 g's) primary excitation produce table resonances with frequencies up to 10 to 20 KHz and amplitudes of 500 m/s^2 (50 g's) or higher.

Any shock machine is comprised of various components designed to support, attach, and input a shock into a product to be tested. It is a mechanical system comprised of a number of multi-degree of freedom spring mass systems.

Those who have used shock machines know that nominal shock pulses produce complex spectral content waveforms on the table. In fact, filtering is often needed to measure the basic low frequency amplitude and time duration values of trapezoidal pulses. It should be kept in mind that the product tested is subjected to unfiltered excitation. The response excitation may include many high frequency and amplitude components which will be lost in filtering.

One problem with fragility assessment us-

Figure 8.



Sensitivity:

Ch. 1: 40.00 g's/Div

Filter:

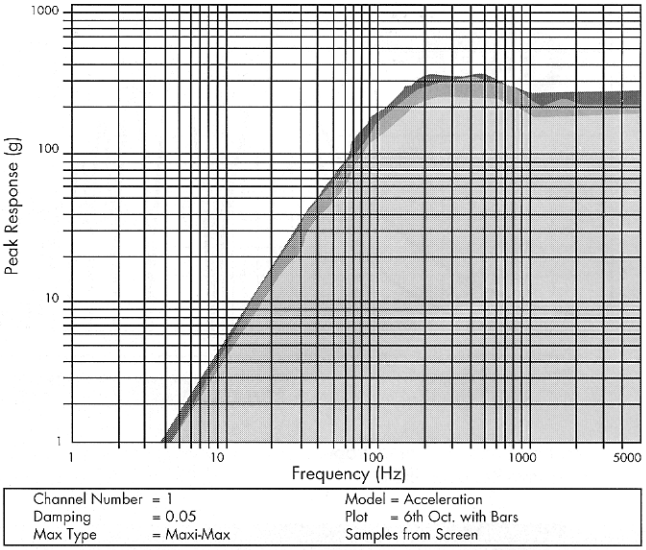
Ch. 1: 3000 Hz

Trig. Ch. : 2
Polarity : Window
Level : 79.96 g's
Mode : **Single Event**
Pretrigger : 20 %

CH	TIME	CUR AMP	PEAK AMP	1ST IMT	2ND IMT	TIME/DIV
#1	-3.16 mS	–0.10g's	146.83g's	90.10 In/s		1mS

Time domain plot of clean waveform from shock machine table.

Figure 9.



Channel Number = 1
Damping = 0.05
Max Type = Maxi-Max
Model = Acceleration
Plot = 6th Oct. with Bars
Samples from Screen

SRS plot from data in Figure 8. Typical tolerance bars are superimposed to show +0.5 and -3 dB arbitrary tolerance limits as an example of the method of standardizing a shock machine. This would be a passing test.

ing half-sine and trapezoidal pulses with residual spectra is that damage may be incorrectly attributed to the clean filtered waveshape, rather than to the resonances of the residual spectrum of the shock machine. The "noise," "ripple," or "response," is usually filtered out of the waveforms presented on storage scopes.

PROPOSED METHOD OF STANDARDIZATION

The proposed method of shock machine standardization differs little from the requirements of MIL-STD-810D, except in the sequence of execution. A five step procedure is suggested:

Step 1. Review the standard SRS profiles for perfect nominal pulse shapes shown in Figures 3, 4, and 5. Using the normalized plots, determine the frequency vs. spectrum amplitude points that describe the pulse shape that the shock machine is to produce.

Step 2. Determine an allowable variation limit from the standard SRS profile that can be tolerated, considering the desirability to limit high frequency resonance. One method of doing this is to establish tolerance bars of min and max response that can be plotted on the computed SRS, similar to those used with PSD analysis. Such tolerance limits can be expressed in +/-dB from the un-normalized nominal shape. If justified, an allowance for exceeding the tolerance limits over a narrow frequency ranges should be allowed as in the procedure described in MIL-STD-810D.

Step 3. Since the table load of a shock machine may affect table resonance and pulse shape to some degree, load the shock machine with either the item to be tested, or a reasonable surrogate. Place the response recording accelerometers at the attachment points, or on the product at the points of attachment, in order to monitor the input excitation to the product. Several channels of data recording may be required since it may be desired to record the principal table input signal as well as several attachment point responses.

Step 4. Set the shock machine for the prescribed nominal excitation and record the resulting response data. Using a maximax SRS algorithm, analyze the time vs. amplitude data out to a point where the residual signal falls to 1/3rd of the initial shock amplitude. Plot the tolerance limits from Step 2 on the resulting SRS plot to determine if deviations of the machine exceed the specific limits.

Step 5. Perform the above on data from the other locations on the subject shock machine. If all locations fall within the predefined tolerance limits, the machine can be considered to be accurate for the nominal shock pulse being tested. Programmable shock machines would be required to perform the analysis for the full range of pulse shapes to be used in practice.

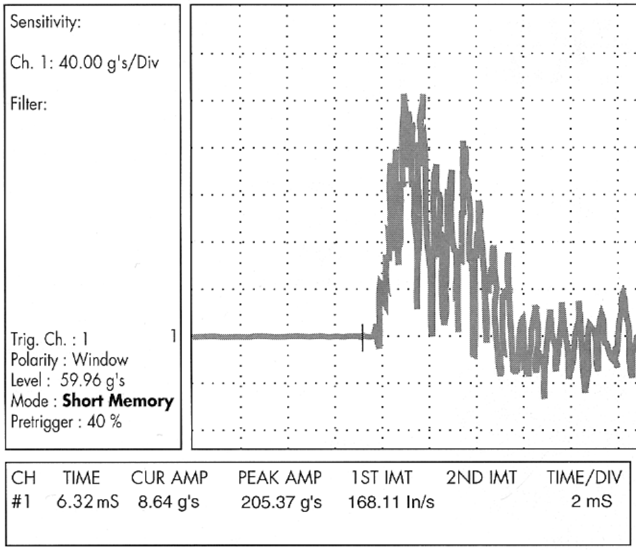
Perform the above on secondary shock machines used to test the same product and compare the results. If both machines produce the same SRS profile, even though the time domain signal profile deviates slightly from the nominal standard shape, it may be assumed that both machines produce the same test excitation. If one machine produces an SRS plot that deviates greatly from another, then deficiencies in the latter machine may be addressed and the problem solved.

This last step may also be performed on the same shock machine at some later time to track "machine health." Mechanical changes in the machine that affect pulse shape will show up quickly on the SRS plot.

DISCUSSION

The concept of loading the shock machine table with the product or surrogate to be tested has validity for accurate comparison of

Figure 10.



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Sensitivity:

Ch. 1: 40.00 g's/Div

Filter:

Trig. Ch. : 1
Polarity : Window
Level : 59.96 g's
Mode : Short Memory
Pretrigger : 40 %

CH   TIME      CUR AMP   PEAK AMP     1ST IMT       2ND IMT   TIME/DIV
#1   6.32 mS   8.64 g's  205.37 g's   168.11 In/s             2 mS
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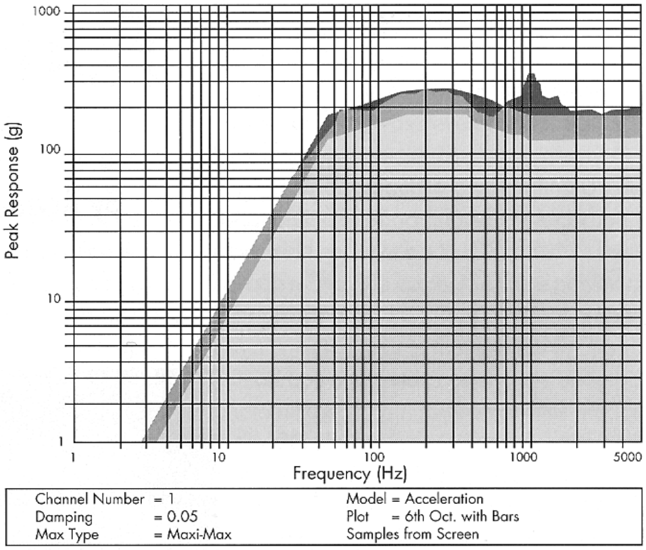
Time domain plot of noisy waveform from shock machine table.

Figure 11.



```
Channel Number = 1              Model = Acceleration
Damping        = 0.05           Plot   = 6th Oct. with Bars
Max Type       = Maxi-Max       Samples from Screen
```

SRS plot from data in Figure 10. Typical tolerance bars are superimposed to show +0.5 and -3 dB arbitrary tolerance limits as an example of the method of standardizing a shock machine. This would be a failing test.

two machines under the same test conditions. However, the unloaded case deserves consideration also. In this case, free unloaded table response may or may not affect the product to be tested due to the loading (and damping) that the tested product provides. But it can be argued that it is valid to "profile" the unloaded shock machine as a starting point. This is because it will be easier to identify design problems in the unloaded case.

Profiling is done by taking several excitation signal recordings from various points on the table, corresponding to locations where products may be located. The resulting SRS plots can be averaged as a function of amplitude versus frequency to establish an overall unloaded excitation specification for the machine.

In this case, a tolerance bar set up can be applied to the average SRS which would predict the unloaded performance at any given location on the table.

Figure 8 shows a clean nominal type shock pulse with a duration of 3.16 ms and an amplitude of 146 g's taken at one location on a shock machine.

Figure 9 shows the SRS plot for the data from Figure 8. The tolerance bars are based on a nominal 3 ms 166 g clean half sine pulse. The top tolerance line is equal to a 7 point profile of the nominal. The lower tolerance line is –3 dB below the nominal line. This would represent a good or passing SRS test of the shock machine.

Figure 10 shows a table shock signal with severe residual response that masks the nominal pulse shape.

Figure 11 shows the SRS plot from the data from Figure 10. Again, the tolerance limits are based on the nominal pulse shape intended. Note that in this example, the upper tolerance bar is exceeded starting at a frequency of 1000 Hz and continuing up to 1000 Hz. In fact, the peak of the SRS occurs at 1700 Hz with an amplitude of 300 g's peak.

If the product being tested has a fragility frequency within this band, it is very probable that damage may occur. This would lead to a false damage boundary point based on the residual spectrum and not that of the principal pulse.

CONCLUSION

A procedure exists for standardizing shock machines. This procedure is related directly to procedures already in use in many environmental test laboratories to comply with the requirements of MIL-STD-810D, and hence equipment and technology is readily transferable to the standardization concept. A concept of tolerance bar limitations from un-normalized nominal pulse shape SRS plots is proposed.

Once an allowable profile for machine performance is established, then shock machines yielding the same SRS results can be expected to produce the same product test results.

Examples in this paper were recorded and analyzed using a computer aided test (CAT) system with application software. ■

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