16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 17

Registration Code: S-G1459897163

A PRACTICAL METHOD FOR MODIFYING AN HISTORICAL MEASURED TIME HISTORY TO SATISFY SRS SPECIFICATIONS

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Abstract

A launch vehicle mounted on a pad at Vandenberg Air Force Base (AFB), California must be able to withstand a potential earthquake per the shock response spectrum (SRS) in the National Aeronautics and Space Administration NASA-HDBK-7005 [1], due to the nearby San Andreas Fault. Nuclear, power substation, and telecommunication equipment in active seismic zones must likewise survive spectra given in the Institute of Electrical and Electronics Engineers IEEE Std 693-2005 [2] and other standards. Launch vehicles and equipment are idealized as single-degree-of-freedom (SDOF) systems as a first approximation, but are in reality multi-degree-of-freedom (MDOF) systems. The response of an MDOF system to an SRS base excitation can be approximately calculated via the square-root-of-the-sum-of-the-squares (SRSS), National Research Laboratory (NRL) or some other modal combination method. But a time domain direct or modal transient analysis is desired in certain cases, which requires synthesizing a non-unique time history to meet the SRS. Time history synthesis is also needed for testing equipment on a shaker table, although this would be more typical in the nuclear industry than aerospace for seismic events. A common concern, however, is that the synthesized time history may be vastly different than the true source event, which could affect the response in terms of linearity, MDOF behavior, temporal moment energy, etc. This paper demonstrates a method for modifying a representative historical measured time history to satisfy a specified SRS to mitigate this concern. The measured data is decomposed into a series of wavelets as an intermediate step. The wavelets can then be scaled so that the synthesized time history meets the SRS specification. The focus of this paper is on seismic shock, but the method may be adaptable to other types of shock events such as pyrotechnic shock. The results of the method can be used for both transient analysis and shaker table testing.

Keywords: seismic, shock, synthesized time history

1. Introduction

An example of a launch vehicle in an active seismic zone is given in Figure 1. An example of equipment undergoing shaker table testing is given in Figure 2. The base input to these structures is specified as an SRS. The SRS models the responses of individual single-degree-of-freedom systems to a common base input. The natural frequency of each system is an independent variable. The damping value is usually held constant. The SRS calculation retains the peak response of each system as a function of natural frequency. The resulting SRS is plotted in terms of peak acceleration (G) versus natural frequency (Hz). A synthesized time history is need to meet the SRS specification. The following steps use trial-and-error-random number generation with some built-in convergence for the synthesis process. The method is implemented as a function in the Vibrationdata Matlab GUI package, which may be downloaded per the link in Reference [3].

The first step is to decompose the reference time history into a series of wavelets using the method in Reference [4]. An acceleration wavelet has zero net velocity and zero net displacement. A series of wavelets also has these properties. Wavelets are very amenable to shaker table shock testing, and are also convenient for analysis. The examples in the paper use a series of 250 wavelets to model a reference time history. Note that these wavelets are non-orthogonal and differ from the wavelets used in image processing.

Figure 1. Launch Vehicle Liftoff from Vandenberg AFB.

The vehicle as mounted on the pad is a tall cantilever beam. Its ability to withstand seismic events must be verified via analysis per Reference [1].

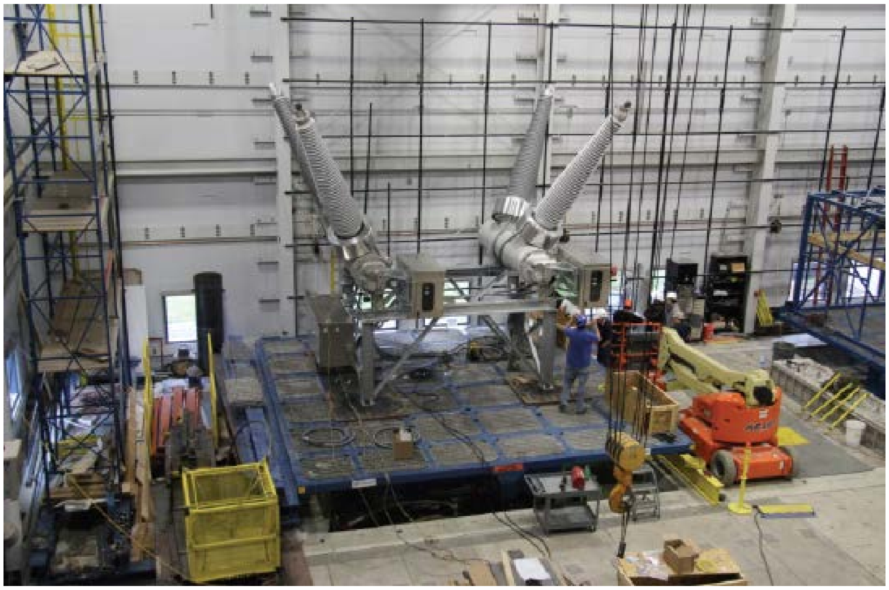

Figure 2. Electric Power Substation Bushings are Readied for Testing on a Shaker Table

Power transmission and telecommunication equipment must remain operational after an earthquake for public safety. Testing and analysis is required per Reference [2] and other standards.

2. Literature Review

The El Centro time history data is commonly used in earthquake engineering as a transient input [5]. Furthermore, wavelets have been used in shaker shock testing for many years [6]. Note that shock wavelets may be nonorthogonal; in contrast to Haar, Daubechies, and other orthogonal sets. There is no direct method to decompose a time history into a series of shock wavelets as a result of this nonorthogonality, rather trial-and-error methods are used. But NASA has used this approach to model the splashdown shock of a space shuttle solid rocket booster [4]. Again, this NASA research is a precursory basis for this seismic paper.

Commercial shaker control computer vendors have proprietary algorithms for synthesizing SRS time histories which resemble plausible earthquake events, but none appears to be based on actual measured data. The author is thus unaware of any published methods which have attempted to manipulate the El Centro data, or any other historical seismic record, for the purpose of satisfying an SRS specification consisting of a simple ramp and plateau.

3. Wavelet Decomposition & Scaling

A sample wavelet is shown in Figure 3. The wavelets formulas are given in equations (1) and (2). The basis for the wavelet decomposition is the El Centro 1940 North-South seismogram [7], as shown in Figure 4. The magnitude of this earthquake was 7.1 per the USGS [8]. It was the first earthquake for which useful "strong motion data" was measured for engineering purposes. Note that the North-South component was horizontal with respect to the ground.

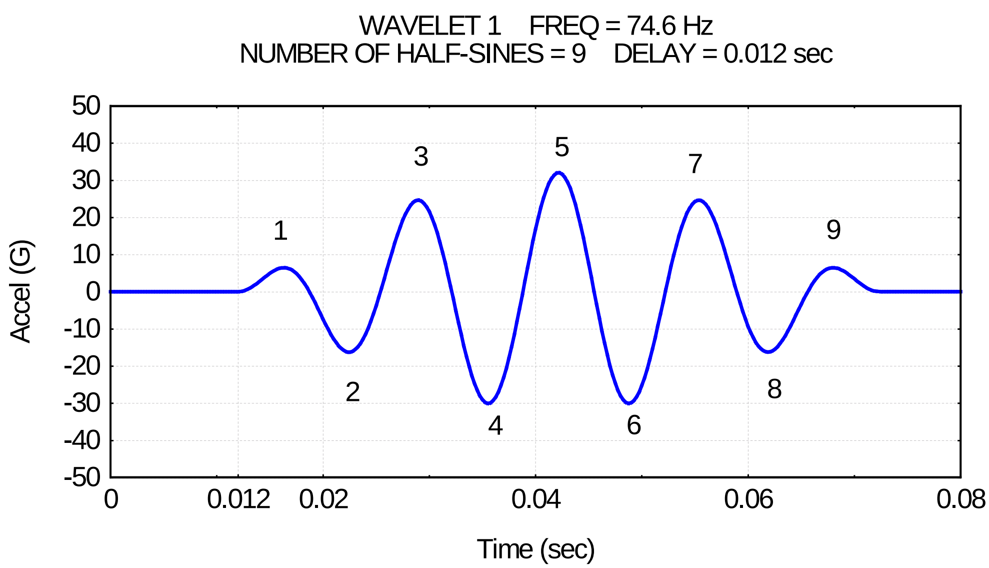

Figure 3. Sample Wavelet

A time histories can be modeled with a series of wavelets, each with its own frequency, amplitude, number of half-sine pulses, and delay.

$$W_m(t) = \begin{cases} 0, \quad \text{for } t < t_{dm} \\ A_m \sin\left[\frac{2\pi f_m}{N_m}(t - t_{dm})\right]\sin[2\pi f_m(t - t_{dm})], \quad \text{for } t_{dm} \le t \le \left[t_{dm} + \frac{N_m}{2f_m}\right] \\ 0, \quad \text{for } t > \left[t_{dm} + \frac{N_m}{2f_m}\right] \end{cases} \tag{1}$$

where

$W_m(t)$	=	acceleration of wavelet m at time t
A_m	=	wavelet acceleration amplitude
f_m	=	wavelet frequency
N_m	=	number of half-sines
t_{dm}	=	wavelet time delay

Note that N_m must be an odd integer greater than or equal to 3. This is required so that the net velocity and net displacement will each be zero.

The total acceleration at time t for a set of n wavelets is

$$\ddot{x}(t) = \sum_{m=1}^{n} W_m(t) \tag{2}$$

The second step is to randomly vary the wavelet amplitudes so that the modified wavelet series will have an SRS that matches the specification as closely as possible. The number of iterations may be 80000 or so. The modified time history will thus have some distortion relative to the reference, but this is needed to shape the time history so that its SRS meets the specification. The second step yields an SRS that has some peaks and dips relative to the specification. This is a consequence of trying to adapt a measured time history to a smoothed SRS.

The third step is to add wavelets so that the resulting SRS meets the specification within, say, + 3 dB tolerance limits. This step also adds some distortion. The amount of distortion depends largely on how much the SRS specification differs from that of the reference data. These steps are demonstrated in the following examples.

4. NASA Example

The fundamental mode of a launch vehicle mounted on a pad at Vandenberg AFB might have 1% damping, with an equivalent amplification factor Q=50. The NASA SRS specification [1] along with that of the El Centro time history are shown in Figure 4. The acceleration time history decomposition and modification are shown in Figure 5. The corresponding velocity and displacement are shown in Figures 6 and 7, respectively. The SRS of the modified time history are compared in Figure 8.

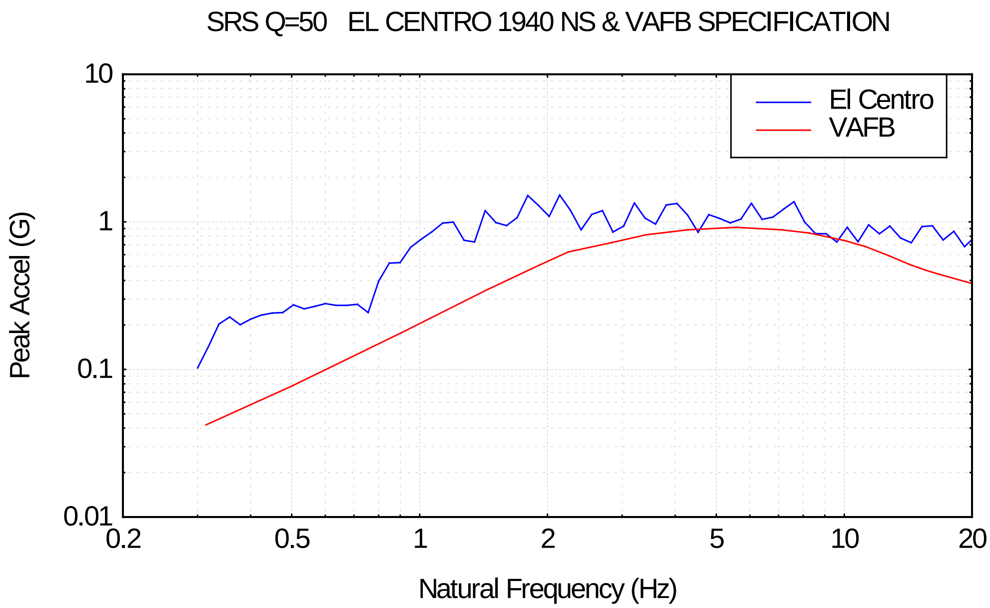

Figure 4. NASA Example Shock Response Spectra Comparison

The comparison shows that a direct application of the El Centro time history would be overly conservative across most of the natural frequencies.

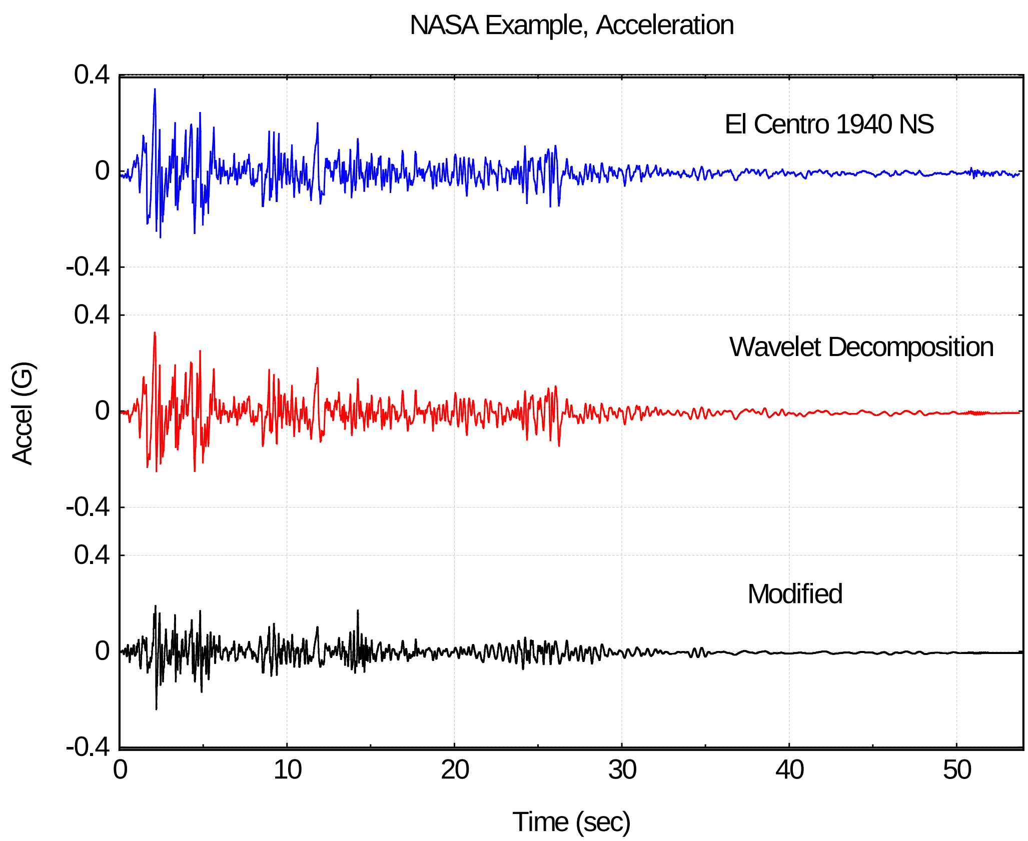

Figure 5. NASA Example, Time History Evolution

The top time history is the measured El Centro NS data. The middle time history is the wavelet series model. The bottom time history is somewhat attenuated and has additional wavelets to improve the SRS match.

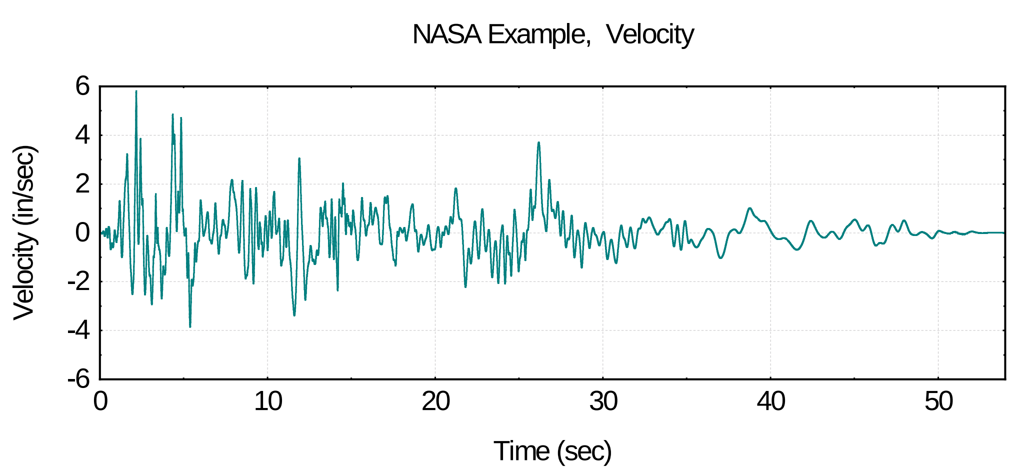

Figure 6. NASA Example, Corresponding Velocity for Modified Acceleration

The velocity time history is well behaved with a net value of zero.

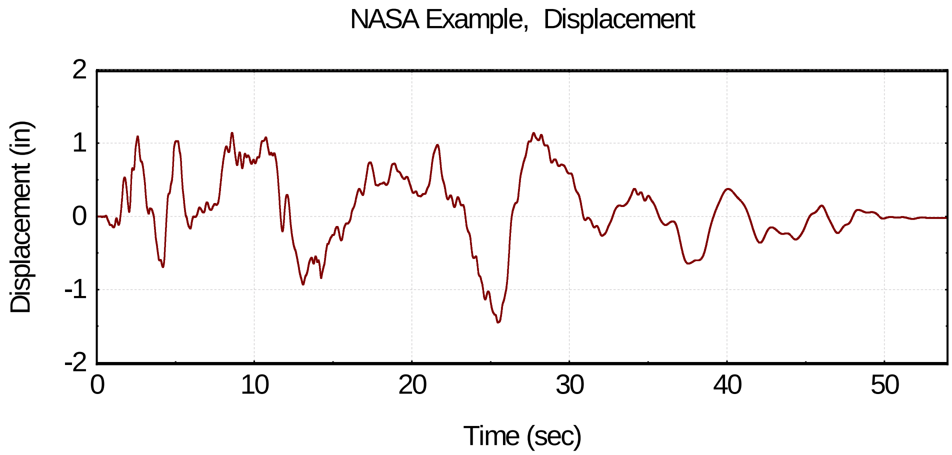

Figure 7. NASA Example, Corresponding Displacement for Modified Acceleration

The displacement time history has a net value of zero. This is essential for shaker table testing. It is also desirable for analysis. Stress analysis depends on the strain from relative displacement. But stable absolute displacement time histories are needed for numerical precision in the relative displacement calculation

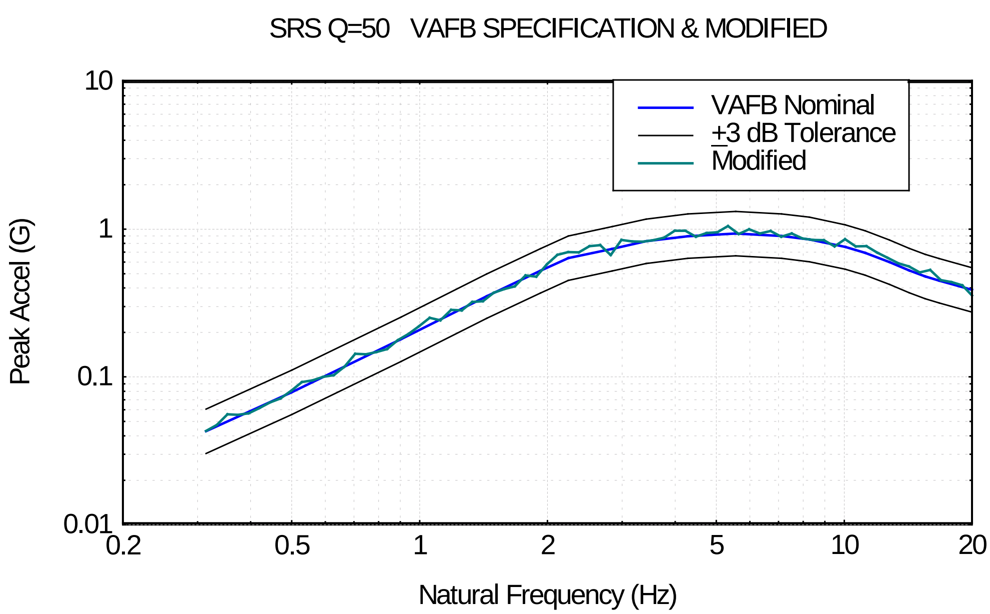

Figure 8. NASA Example, SRS Comparison

The Modified time history's SRS is well within the tolerance bands. It can thus be used for testing and analysis for launch vehicles and ground support equipment at a Vandenberg launch site.

5. Alternate Synthesis Method

This section shows another approach for satisfying the Vandenberg SRS specification where an arbitrary time history is allowable. The time history and its resulting SRS are shown in Figures 9 and 10, respectively. The alternate time history consists of wavelets that approximately follow a reverse sine sweep pattern. This is accomplished by trial-and-error staggering of the delay times, such that lower frequency wavelets have longer delays.

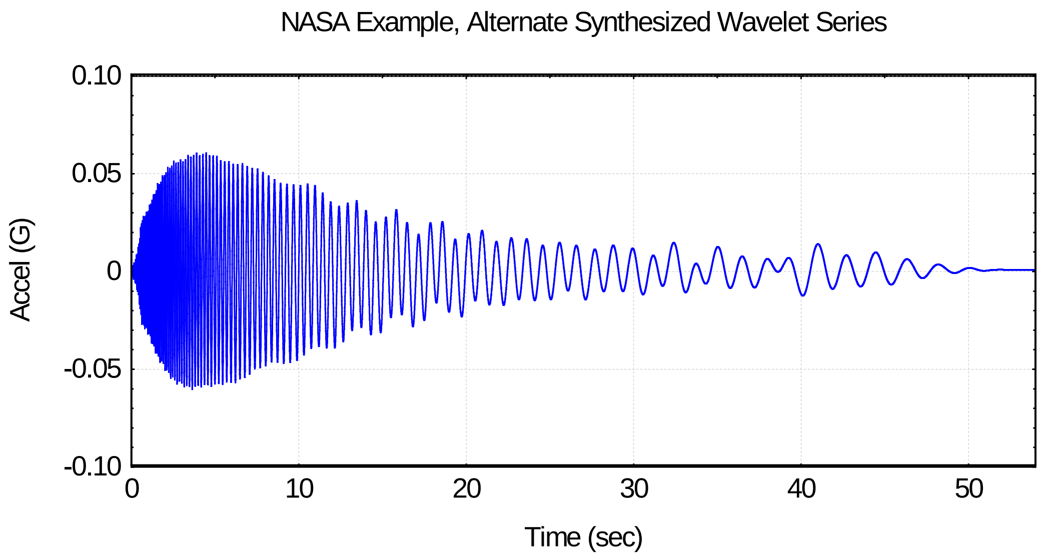

Figure 9. NASA Example, Alternate Time History

The alternate signal is very efficient, with a peak acceleration of one-quarter that of the modified signal in Figure 4. But the altérnate synthesis does not resemble an actual seismic event.

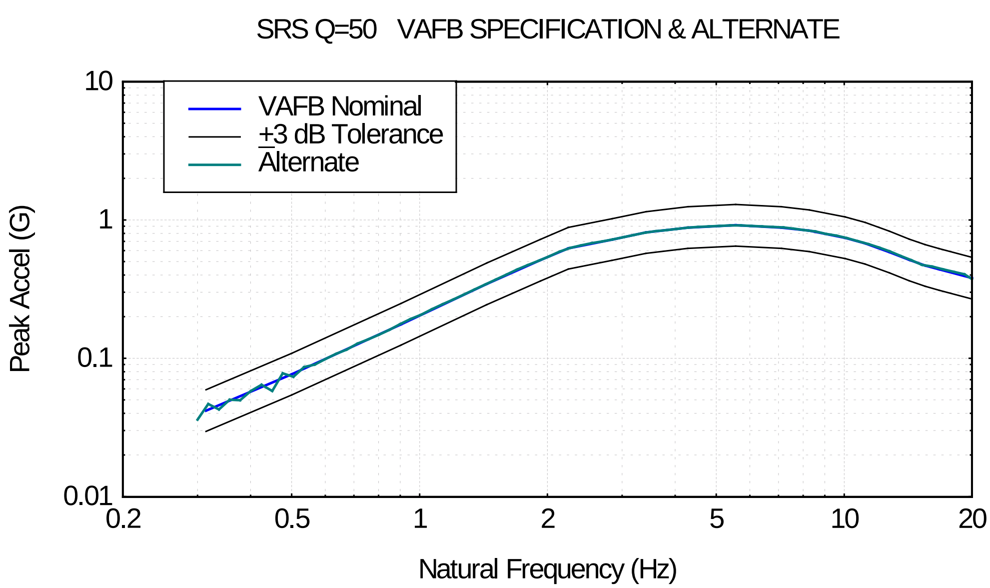

Figure 10. NASA Example, SRS Comparison with Alternate Synthesis

The agreement is excellent.

The modified El Centro and the alternate input time histories can be compared in terms of temporal moments [9] as shown in Table 1. Again, both inputs satisfy the Vandenberg specification. But the alternate synthesis has less energy and thus may cause an "under test."

Table 1 - Temporal Moments

Parameter	El Centro Synthesis	Alternate Synthesis
Energy E (G^2 sec)	0.042	0.019
Root energy amplitude Ae	0.072	0.048
Central time T (sec)	9.45	9.69
RMS duration D (sec)	8.07	8.14
Central skewness St (sec)	8.61	10.25
Normalized skewness S	1.07	1.26
Central kurtosis Kt (sec)	11.3	13.5
Normalized kurtosis K	1.40	1.66

6. IEEE Example

The IEEE Std 693-2005 SRS specification [1] along with that of the El Centro time history are shown in Figure 11. The acceleration time history decomposition and modification are shown in Figure 12. The corresponding velocity and displacement are shown in Figures 13 and 14, respectively. The SRS of the modified time history is compared to the specification Figure15.

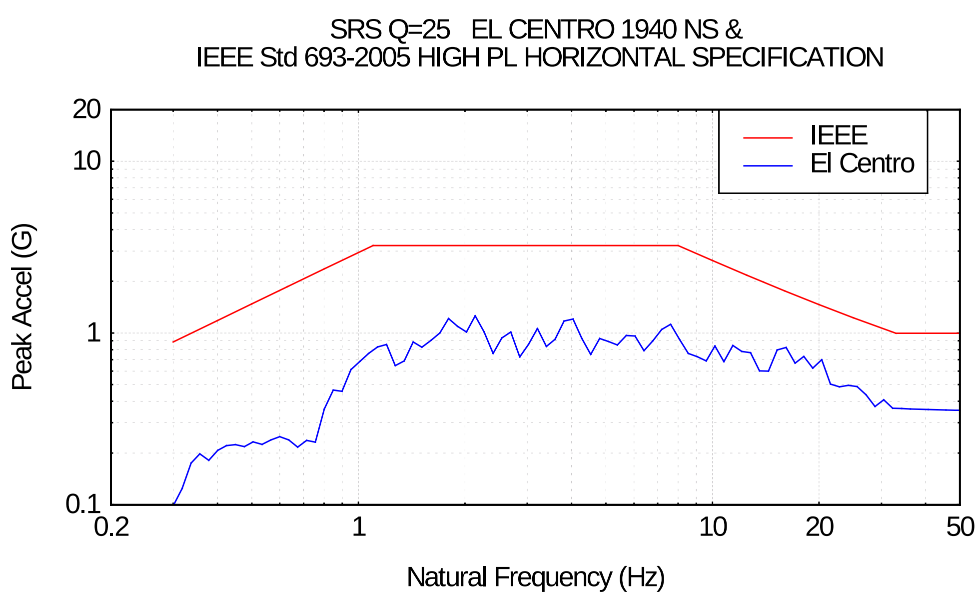

Figure 11. IEEE Example, Shock Response Spectra Comparison

The El Centro time history must be amplified in order to meet the specification.

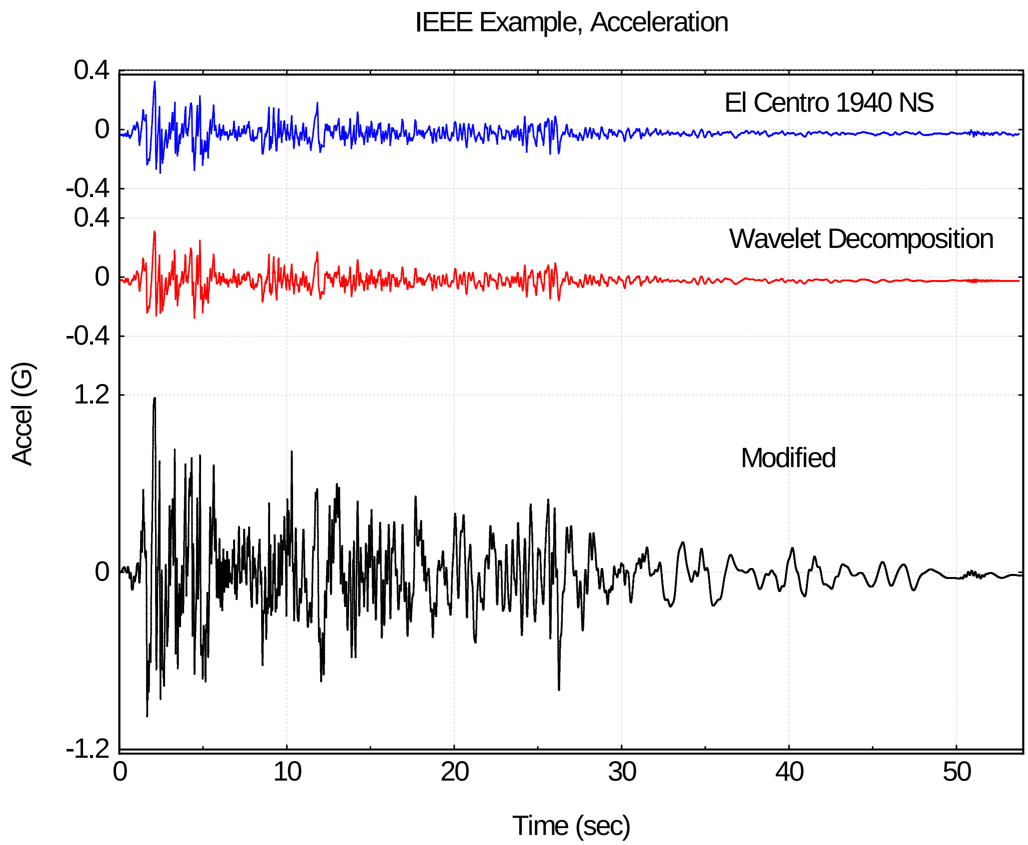

Figure 12. IEEE Example, Time History Evolution

The top time history is the measured El Centro NS data. The middle time history is the wavelet series model. The bottom time history is amplified and has additional wavelets to improve the SRS match.

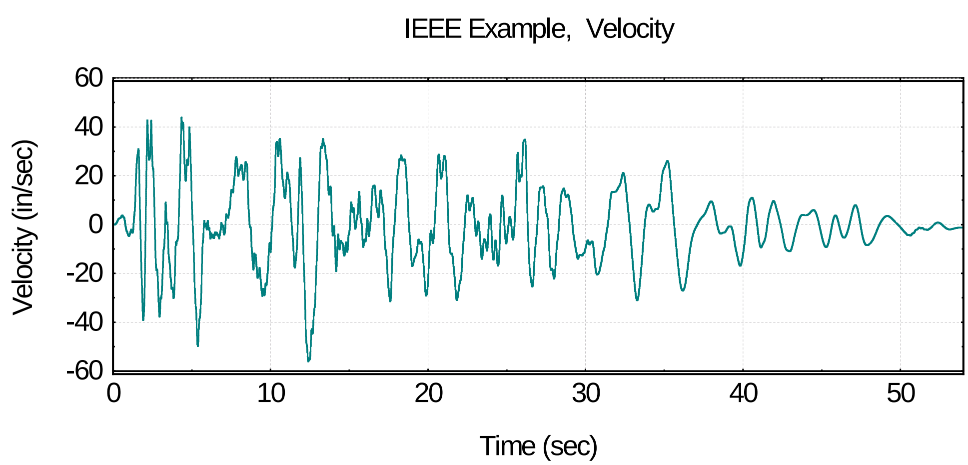

Figure 13. IEEE Example, Corresponding Velocity for Modified Acceleration

The absolute peak velocity is 56 inch/sec (1.4 m/sec) which is very harsh.

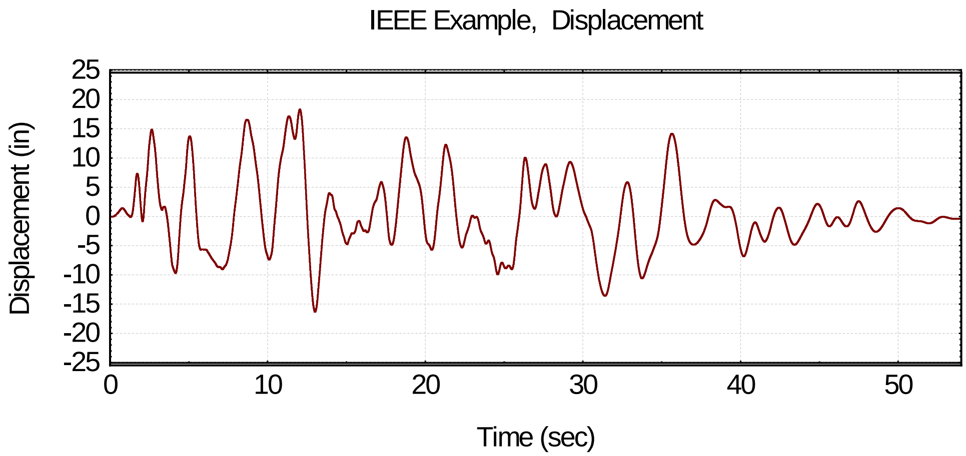

Figure 14. IEEE Example, Corresponding Displacement for Modified Acceleration

The peak displacement is 18.5 inch (0.47 m). This is mostly due to the starting SRS coordinate at (0.30 Hz, 0.89 G) and the initial ramp. There are only a few shaker tables in the world that could achieve the displacement in Figure 14, such as the Hyogo Earthquake Engineering Research Center, Japan. The IEEE standard acknowledges that "Test laboratories may not be able to attain these acceleration levels, especially at low frequencies." It thus allows for testing at lower levels. But the synthesized waveform could still be used for analysis or scaled-down for a lower level test.

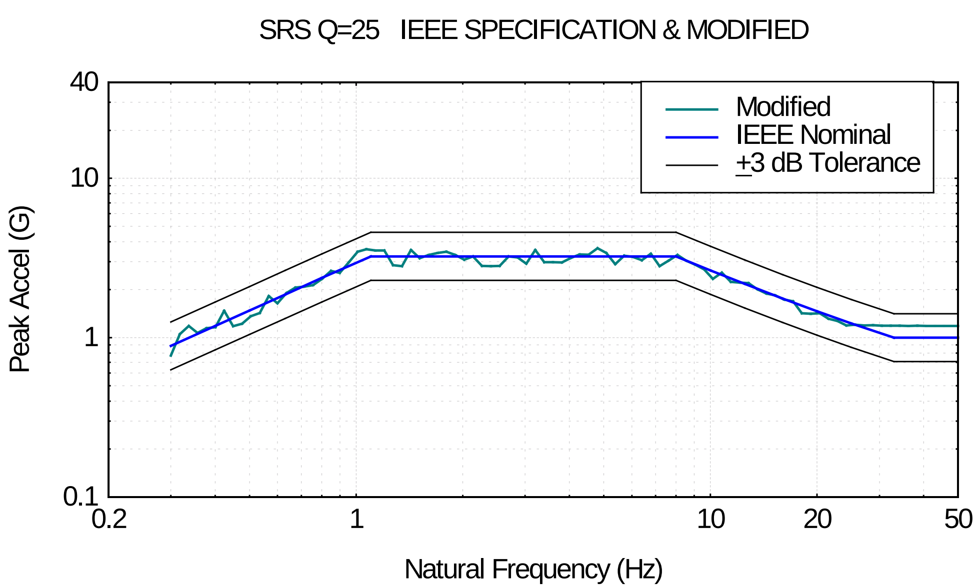

Figure 15. IEEE Example, SRS Comparison

The Modified time history's SRS is within the tolerance bands. It converges to the peak input acceleration as the frequency approaches 50 Hz.

7. Conclusions

The method in this paper appears useful for satisfying SRS specification with time histories that resemble measured seismograms. The method has already been successfully used by one American company for analyzing the seismic shock response of missiles mounted in underground silos near active seismic zones. Further development of the method is needed for other requirements, including the Bellcore/Telcordia specifications. In addition, other historical strong motion accelograms may be used as references, aside from the El Centro earthquake.

8. Acknowledgements

I am grateful to Dr. Curtis E. Larsen from NASA for his ongoing support of my research, and to Siamak Ghofranian from Boeing who prompted me to develop this methodology.

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