SHAKER TABLE SEISMIC TESTING OF EQUIPMENT USING HISTORICAL STRONG MOTION DATA SCALED TO SATISFY A SHOCK RESPONSE SPECTRUM

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The purpose of this paper is to apply the author's aerospace shock testing experience to earthquake engineering. The resulting method can be used either for shaker table testing or for finite element modal transient analysis.

Introduction

Consider the following type of equipment:

1. Telecommunication
2. Medical life-support
3. Network servers
4. Nuclear power plant control consoles

Now consider that this equipment is to be installed in buildings in an active seismic zone. The equipment must be designed and tested accordingly to withstand the dynamic loads.

Specification Format

A typical specification format for the loading is the shock response spectrum (SRS). The testing is performed on a shaker table. A control computer applies a drive signal to the shaker table to meet the 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 given time history has a unique SRS. On the other hand, a given SRS may be satisfied by a variety of base inputs within prescribed tolerance bands. A typical specification is given in Figure 1.

The specification could be satisfied by a sine sweep or by a random signal, if the waveform parameters are properly chosen in each case. But neither of these signals would likely represent an earthquake in the time domain.

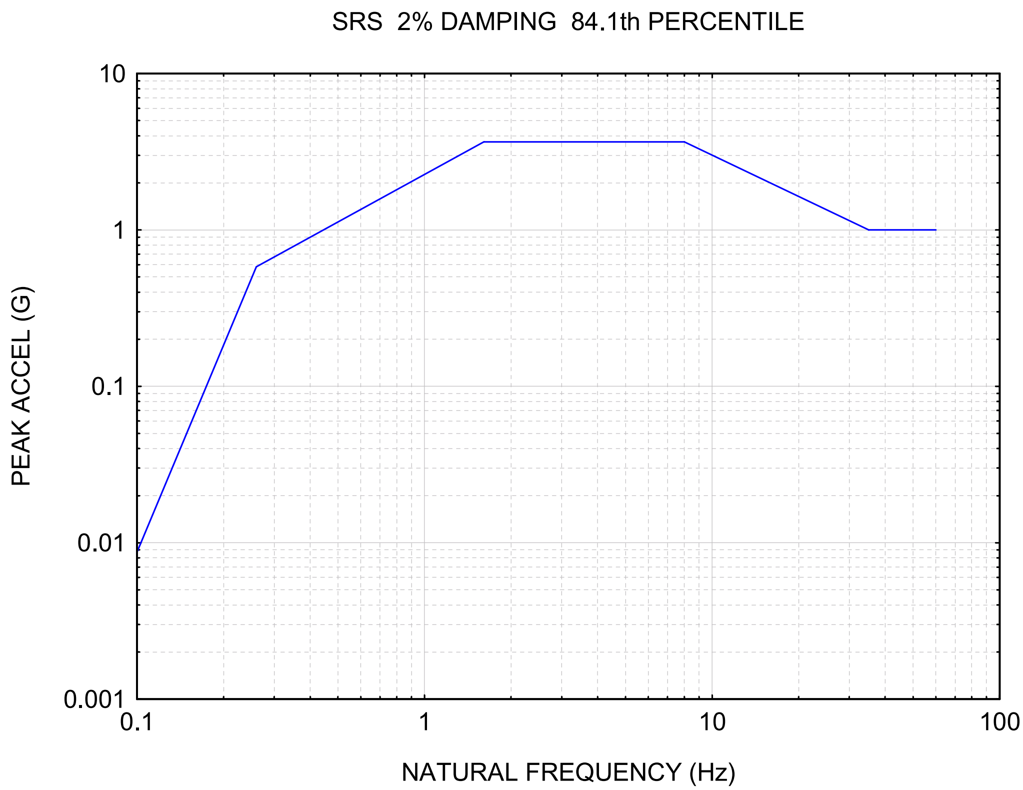

Figure 1.

Table 1. SRS, 2% Damping, 84.1th Percentile	
re Natural Frequency (Hz)	Peak Accel (G)
0.10	0.0087
0.26	0.58
1.61	3.66
8.00	3.66
35.00	1
60.00	1

There are a number concerns regarding linearity, fatigue, duration, and multi-degree-of-freedom behavior. These and other concerns can be addressed by using a drive signal which both satisfies the SRS and which "resembles" a potential strong motion time history.

The sample specification in Figure 1 is taken from Reference 2. It is a "smoothed spectrum" which has five straight-line segments as plotted in log-log format. It has similar characteristics as the Bellcore specification family.

The initial constant displacement ramp is challenging from a synthesis perspective.

Wavelet Approach

A constraint for any base input time history for shaker testing is that the net displacement and the net velocity must each be zero. Each wavelet satisfies these constraints, as does a series of wavelet.

The wavelet method tends to be the preferred method for shaker table testing in the aerospace industry. A wavelet series is relatively stable for the control computer's drive algorithm. A mathematical description of wavelets is given in Appendix A.

Time History Replication

Reference 1 showed that a given time history can be modeled as a wavelet series. This is done via trial-and-error curve-fitting. The resulting series is an approximate model which is not unique.

The given time history could be measured from field data for example. It could then be used as a base input signal for a shaker table test via its corresponding wavelet series.

Note that the SRS from both the measured data and the wavelet synthesis should have very good agreement.

The resulting SRS from each data set would likely have a series of jagged peaks and dips, unlike the smooth spectrum in Figure 1.

Specification Fulfillment Goals

Recall the specification in Figure 1. The time histories from which the specification was derived are unknown. The amount of safety margin is likewise unknown. The smooth segments in Figure 1 were likely drawn to envelope the measured data in some simplified manner, adding conservatism.

The primary goal is to meet the SRS specification for a given piece of equipment via a shaker table test.

A secondary goal for this example is to synthesize a corresponding time history which "resembles" an actual earthquake accelogram.

Specification Fulfillment Plan

The measured 1940 El Centro North-South time history from Reference 3 will be used as a basis. This time history will be modeled with a series of wavelets.

The wavelet parameters will then be manipulated so that the corresponding time history satisfies the SRS specification in Figure 1. The specification is interpolated to one-twelfth octave format for the calculation.

The resulting time history will thus meet the SRS but will still retain many of the characteristics of the measured strong motion data. The resulting time history can then be used as the base input for a shaker table test of the equipment. The shaker's control computer must be able to accept and to implement the resulting time history, which is typically entered into the computer as an ASCII file.

Again, the resulting time history will be a modified version of the measured El Centro data.

The time history could also be applied as the base excitation function for a finite element modal transient analysis.

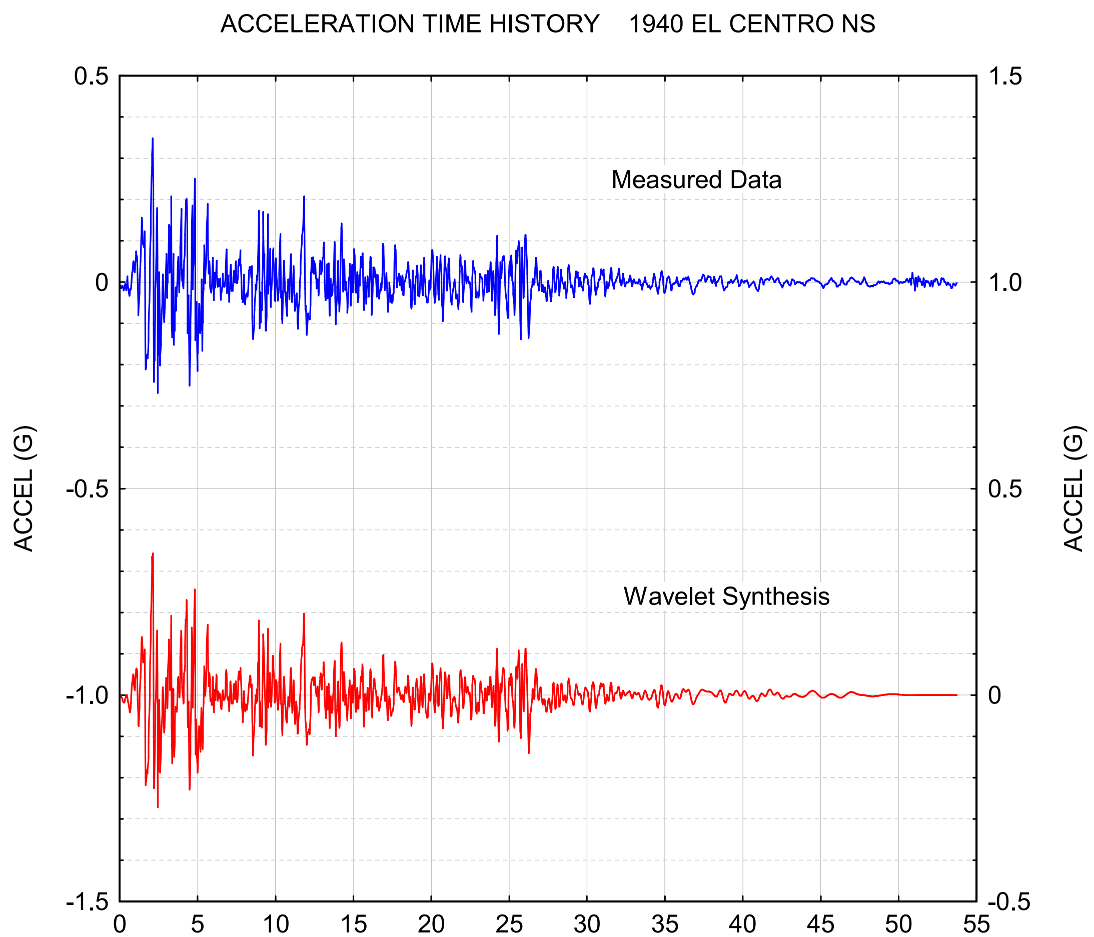

Figure 2.

The synthesized waveform consists of 150 wavelets. The agreement between the two waveforms is very good, although no error metric is calculated.

Filenames:

Measured Data:	elcentro_NS.dat
Synthesis:	el_NS_syn.dat
Wavelet Table:	el_NS_wavelet_table.out

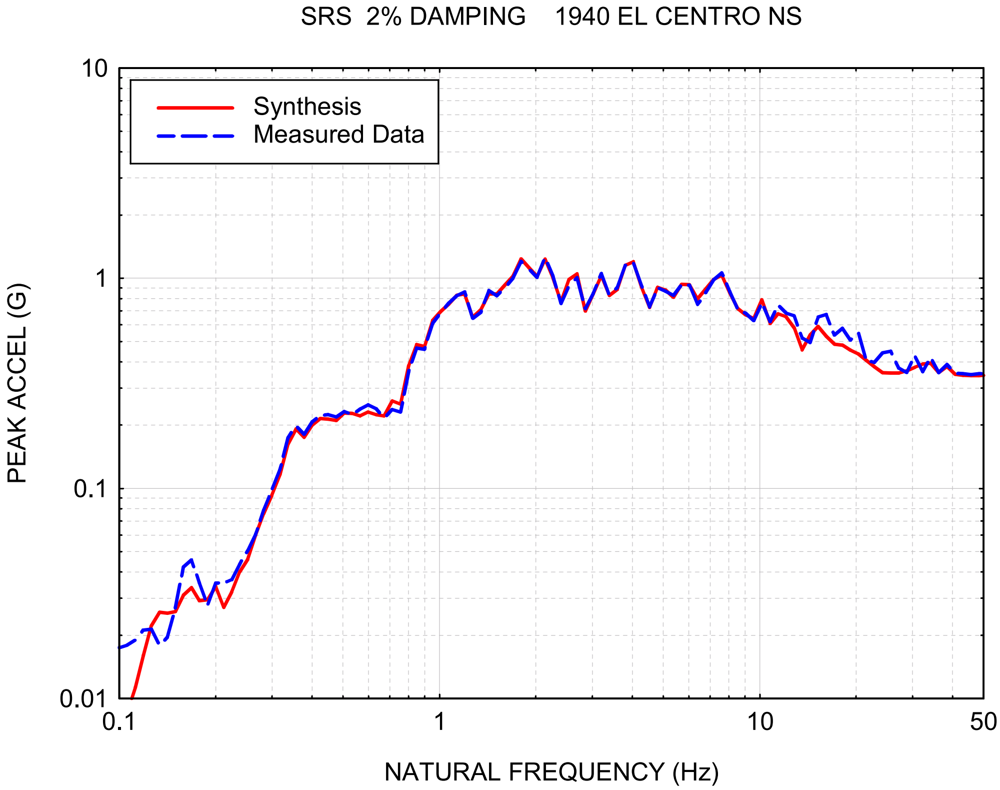

Figure 3.

The agreement is very good.

Each SRS curve was calculated using the Smallwood algorithm. The format is one-twelfth octave.

Filenames:

Synthesis SRS	syn.srs
Measured Data SRS	el_centro_ns.sav

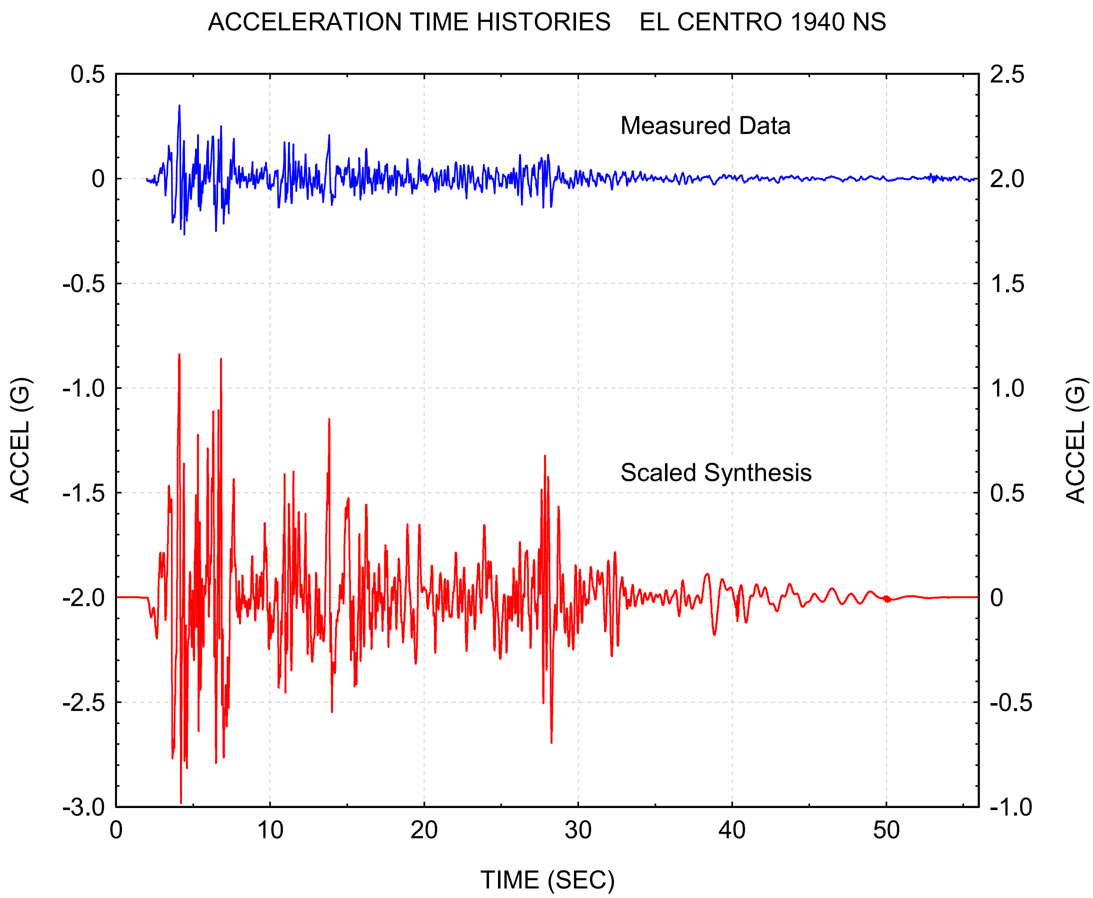

Figure 4. Acceleration Time History Comparison

The amplitudes of the original 150 wavelets were scaled so that the resulting SRS would meet the specification as closely as possible. Additional wavelets were intermittently added to series and scaled as well.

The final scaled synthesize history consists of 228 wavelets. Thus 78 wavelets were added to the original 150. It still has "reasonable" resemblance to the measured El Centro NS data.

Also note that each time history has been shifter by two seconds to the right, but this is a minor point. This was done to allow for possible pre-pulse additions for the synthesize signal, although none occurred.

The SRS comparison between the scaled synthesized data and the specification is shown in Figure 7.

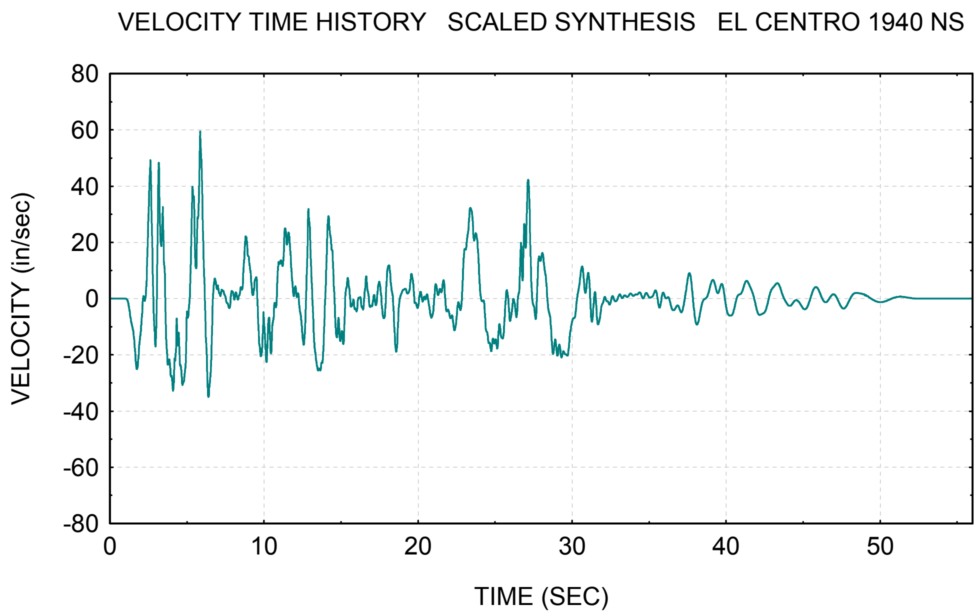

Figure 5.

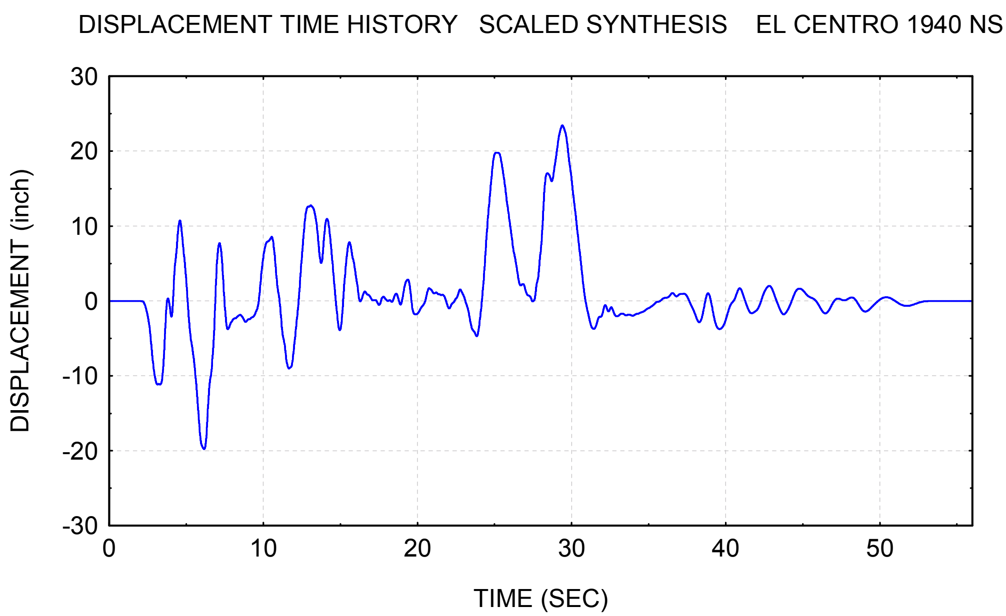

Figure 6.

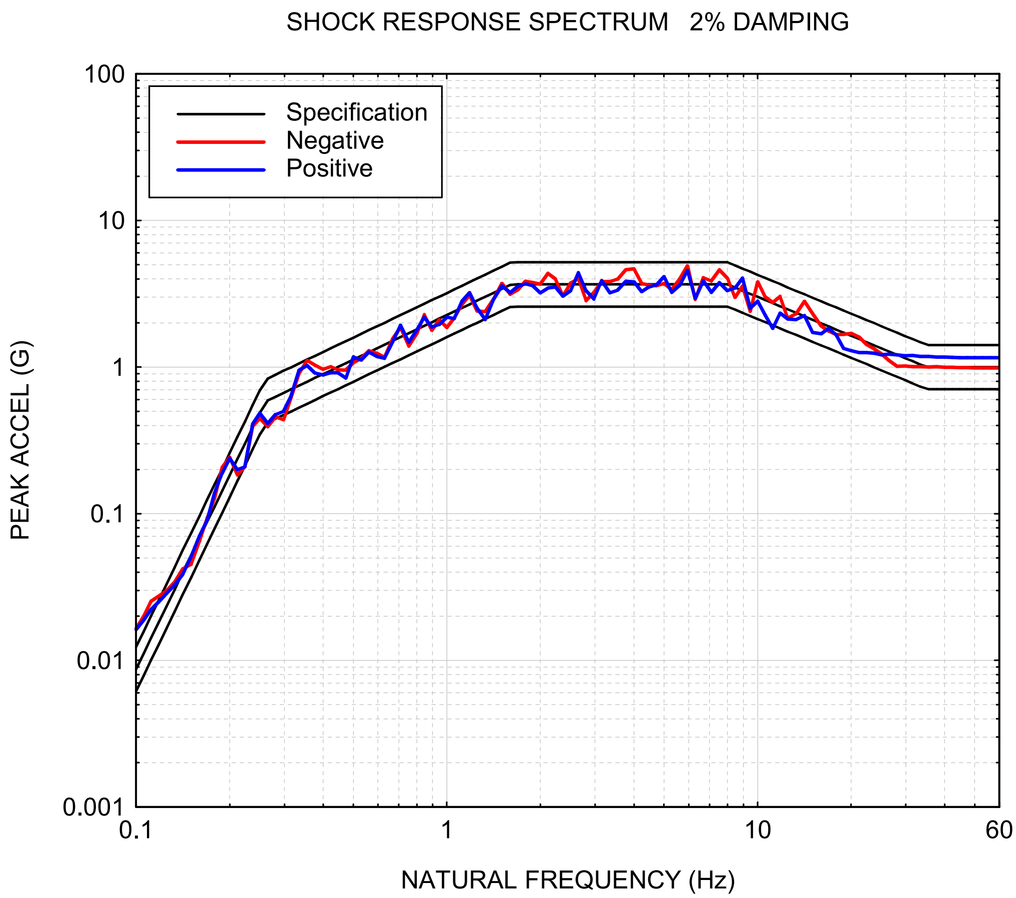

Figure 7.

The Positive and Negative curves are calculated from The SRS comparison is shown in Figure 7.

the scale synthesized acceleration time history. The agreement is good, although the initial displacement ramp is challenging.

Tolerance bands of ± 3 dB are added to the specification.

The files are

Acceleration	accel_40.txt
Velocity	velocity_40.txt
Displacement	displacement_40.txt
Wavelet Table	wavelet_40.txt

Computer Codes

The Matlab scripts are.

Purpose	Script Name
Waveform Reconstruction	wavelet_reconstruct.m
Waveform Modification to Meet SRS	wavelet_scale_SRS_add.m werror2.m wqsrs.m

Future Work

Additional specification should be considered, including the Bellcore specifications.

Additional historical strong motion accelerograms should also be considered.

A standard library of scaled time histories could then be established with all the permutation.

The synthesis process may be more appropriate for the velocity rather than the time history given that geophones are often used for source measurements. The resulting acceleration could then be obtained by closed-formed differentiation.

The scale synthesis process is very time-intensive. The process that generated the scale acceleration time history required about 14 hours. The convergence efficiency needs improvement. Meeting the initial 12 dB/octave constant displacement slope of the specification was very difficult.

It may also be possible to meet all of the goals while still optimizing the pulse for minimum displacement, which could be a concern for the shaker table displacement limits.

References

1. R.C. Ferebee, T. Irvine, et al., An Alternative Method of Specifying Shock Test Criteria, NASA/TM-2008-215253, 2008.

2. C. Harris, Shock and Vibration Handbook, Fourth Edition; W.J. Hall, Chapter 24, Vibrationdata of Structures Induced by Ground Motion, McGraw-Hill, New York, 1996.

3. Pacific Earthquake Engineering Research Center http://peer.berkeley.edu/research/motions/

4. D. Smallwood, An Improved Recursive Formula for Calculating Shock Response Spectra, Sandia National Laboratories, New Mexico.

APPENDIX A

Wavelet Equation

The equation for an individual wavelet is

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

(A-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

$$\ddot{x}(t) = \sum_{m=1}^{n} W_m(t) \qquad \text{(A-2)}$$

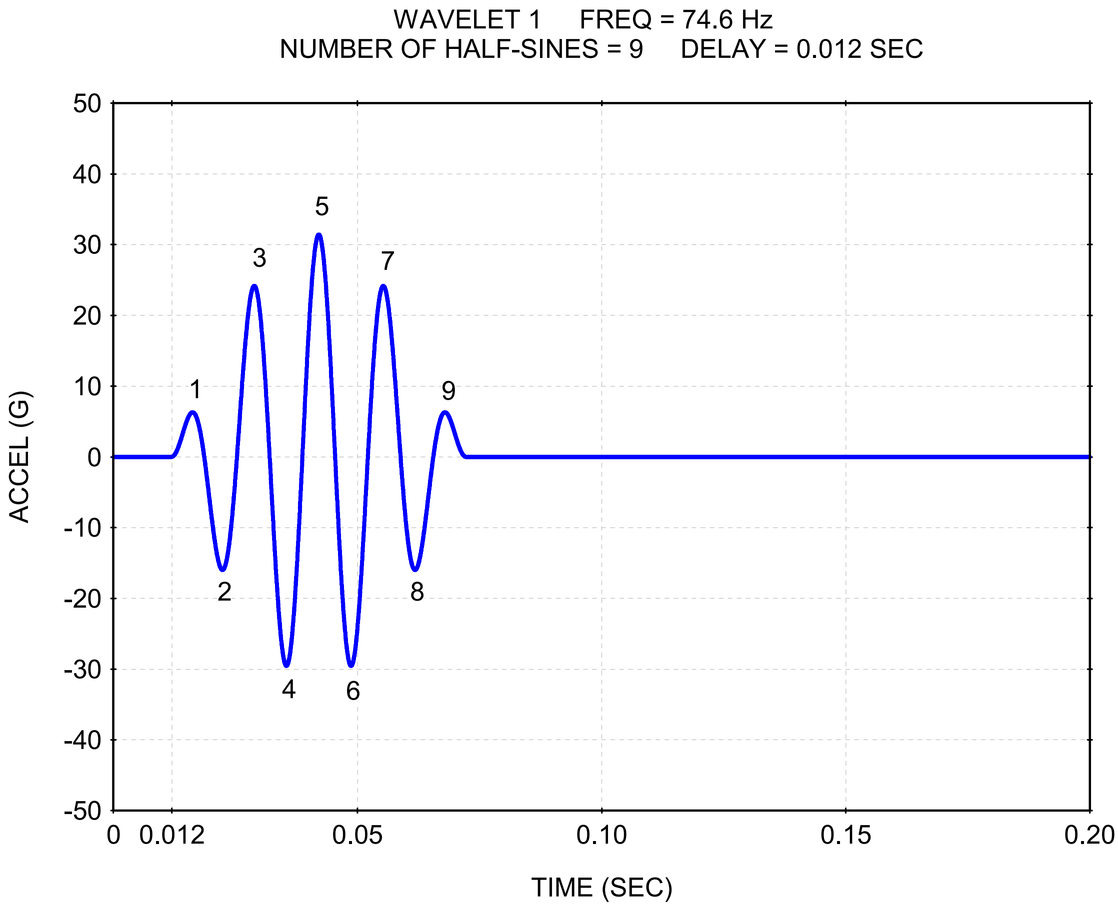

Figure A-2.

A sample, individual wavelet is shown in Figure A-2. This wavelet was a component of a previous analysis for an aerospace project.