

SHAKER SHOCK PROGRAM JSYNTH USER MANUAL

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Introduction

The purpose of this manual is to explain the use of program jsynth. This program is used to synthesize and optimize a wavelet series to satisfy an SRS specification for a shaker shock test. This manual also gives a discussion of the background theory.

SRS Specifications

Most shock specifications in the aerospace industry are given in terms of a shock response spectrum.

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 fixed at 5%, or equivalently at $Q=10$. 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.

Now consider that an avionics component mounted on some vehicle must withstand a complex oscillating pulse which has been measured during a field test, for example. The data might also come from a flight in the case of a missile or aircraft.

The avionics component must be tested in a lab to withstand this base input time history. The measured time history may or may not be reproducible in a test lab, however.

The measured time history can be converted into an SRS specification. The SRS method provides an indirect method for satisfying the specification by allowing for the substitution of a base input time history which is different than the one measured in the field test. The important point is that the test lab time history must have an SRS that matches the SRS of the field data within prescribed tolerance bands. In addition, the SRS may contain a safety factor or statistical uncertainty margin.

Shaker Shock

Certain SRS specifications may be performed on a shaker table. Shaker shock tests have typically been limited to an upper frequency of 2000 Hz in the past. Shaker head and fixture natural frequencies may cause control problems at higher frequencies. Efforts are now underway to extend these tests up to 10,000 Hz, however.

Time History Synthesis

A time history must be synthesized to satisfy the SRS specification for a shaker shock test. A number of potential methods are discussed in References 1 and 2.

The synthesized time history must have zero net velocity and zero net displacement. Furthermore, the peak acceleration, velocity, and displacement values must each be within the shaker's limits.

The two most common methods are a damped sinusoid series and a wavelet series.

Note that the damped sinusoid series requires a compensation pulse to meet the zero net velocity and displacement requirements. The wavelet series, however, satisfies these requirements without compensation. The wavelet method is thus the preferred method in this report.

Control Computer

Most control computers have some capability to automatically synthesize time history pulses to satisfy an SRS. The goal of this report, however, is to provide a method for the user to apply his or her own synthesized time history. This approach allows greater testing flexibility. It also allows the possibility of extending the test capabilities beyond that of the control computer's canned algorithm.

Ideally, the user's synthesized time history can be loaded directly into the control computer software, regardless of the pulse type. Some control computers can accept an arbitrary pulse; others cannot.

As an alternative, some control computers allow the user to construct or manipulate a wavelet table. The software will then effectively generate the user's synthesized time history from the wavelet table.

Wavelet Equation

The equation for an individual wavelet is

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

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.

An equivalent acceleration formula for equation (1) is

$$W_m(t) = -\frac{A_m}{2} \cos\left[2\pi f_m\left(\frac{1}{N_m} + 1\right)(t - t_{dm})\right] + \frac{A_m}{2} \cos\left[2\pi f_m\left(\frac{1}{N_m} - 1\right)(t - t_{dm})\right],$$
$$\text{for } t_{dm} \leq t \leq \left[t_{dm} + \frac{N_m}{2f_m}\right] \quad (2)$$

Equation (2) reveals the “beat frequency” characteristic of the wavelet.

The wavelet formula is well established in the vibration test industry, as shown in References 1 and 2.

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

$$\ddot{x}(t) = \sum_{m=1}^n W_m(t) \quad (3)$$

The corresponding velocity and displacement are derived in Appendices A and B, respectively. These appendices also give proof that each amplitude metric has a net value of zero.

The following parameters are zero for each wavelet, as well as for a series of wavelets:

1. Initial velocity
2. Final velocity
3. Initial displacement
4. Final displacement.

Single Wavelet Example

A sample wavelet is shown on the next page.

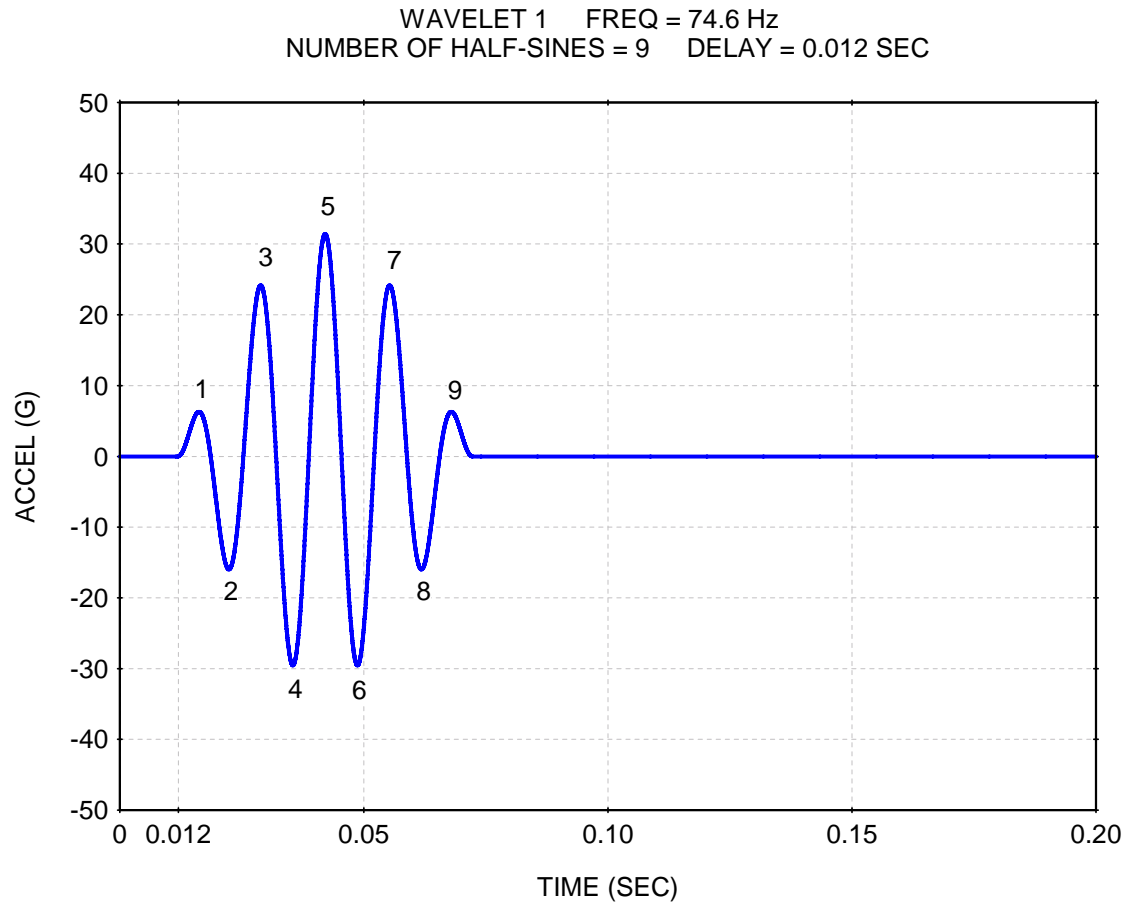


Figure 1.

A sample wavelet is shown in Figure 1.

Again, a given wavelet has a beat frequency effect, with two spectral lines over the defined frequency interval. The corresponding “spectral magnitude function” of the waveform in Figure 1 is shown in Figure 2.

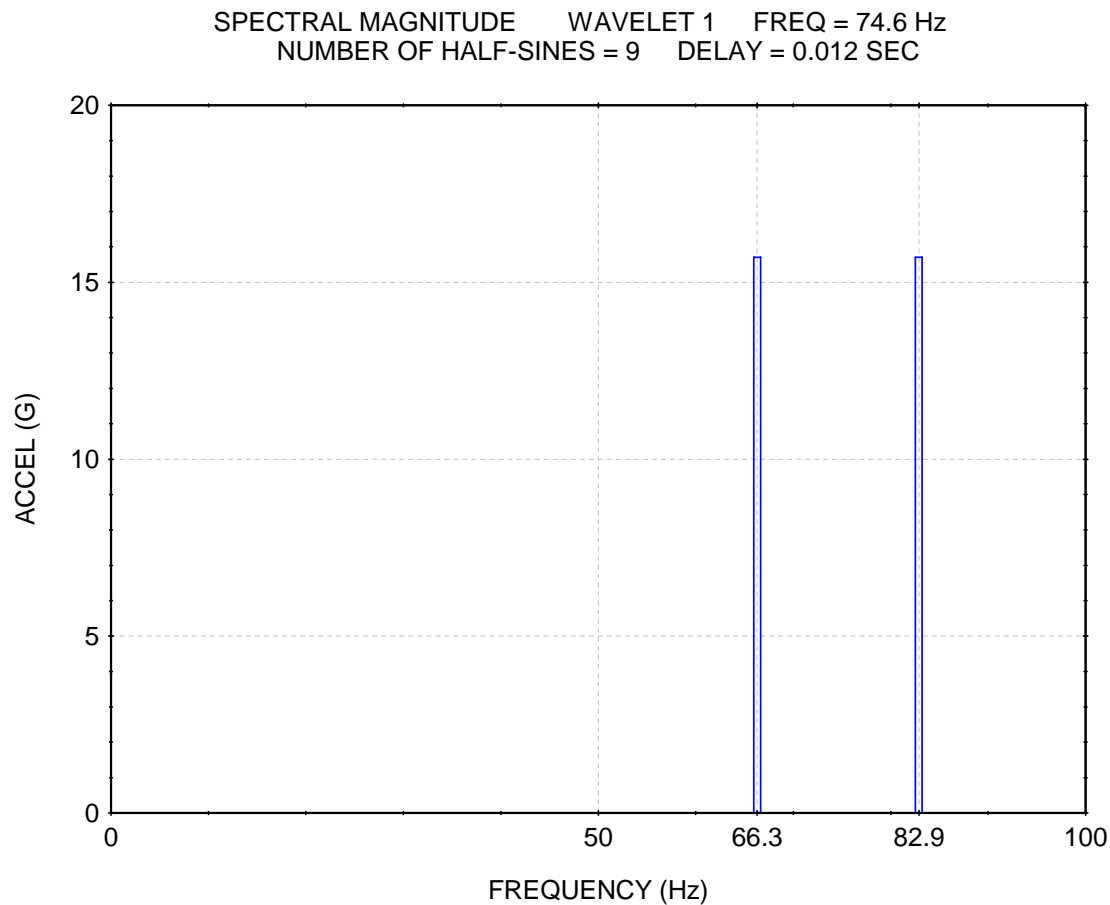


Figure 2.

The spectral magnitude function is somewhat analogous to a Fourier transform magnitude.

An actual Fourier transform of the data would be of limited value since the energy would be smeared over several frequencies due to “leakage” and other error sources. Note that the frequency increment of a Fourier transform is equal to the reciprocal of the signal duration. A Fourier transform is thus more suitable for data sets with longer durations.

Software Program

A software program called jsynth.cpp was written to synthesize a wavelet time series to satisfy an SRS specification.

The program runs in console mode. It is written in the C/C++ language. It is an interactive program that prompts the user for the needed input parameters.

The program actually generates up to 2000 candidate time histories, depending on the user's input.

Four parameters must be established for each wavelet:

1. Frequency
2. Amplitude
3. Delay
4. Number of Half-Sine Pulses

The frequencies are fixed by a combination of the input specification and the user's choice of the octave spacing.

The remaining parameters are generated by some amount of trial-and-error, using random number generation. There are certain constraints, however. For example, the number of half-sine pulses must be an odd integer.

The program attempts to arrange the individual components in a "reverse sine sweep" pattern. Low-frequency components may need to be scattered throughout the waveform, however.

The program then scales the amplitude of each wavelet to provide the best possible match to the SRS specification.

The steps described above are performed for each wavelet series.

The program then ranks each series in terms of the respective peak values of five metrics:

1. Acceleration
2. Velocity
3. Displacement
4. Total Error
5. Individual Spectral Error

The program then applies weighting factors to each of these parameters for each signal in order to obtain a weighted composite ranking.

The program then outputs two wavelet series. One is optimized for acceleration; the other for displacement. The effect of each of the five metrics is considered in each optimization, however. The program has some built-in safeguards in this respect.

A complete set of acceleration, velocity, and displacement time histories are given as output files for each of the two optimized series. An SRS of the acceleration is also given as an output file.

An example is shown in Appendix C.

References

1. D. Smallwood, Time History Synthesis for Shock Testing on Shakers, Shock and Vibration Information Center, Naval Research Laboratory, Washington, D. C., 1976.
2. D. Smallwood, Shock Testing on Shakers by Using Digital Control, Technology Monograph, Institute of Environmental Sciences, Mount Prospect, Illinois, 1986.
3. D. Smallwood, An Improved Recursive Formula for Calculating Shock Response Spectra, Presented at Shock and Vibration Symposium, San Diego, CA, 1980
4. R. Kelly and G. Richman, Principles and Techniques of Shock Data Analysis, SVM-5; The Shock and Vibration Information Center, United States Department of Defense, Washington D.C., 1969.

APPENDIX A

Wavelet Velocity

Again, the equation for an individual wavelet acceleration is

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

The velocity $V_m(t)$ at time t is

$$V_m(t) = \int_{t_{dm}}^t A_m \sin\left[\frac{2\pi f_m}{N_m}(\tau - t_{dm})\right] \sin[2\pi f_m(\tau - t_{dm})] d\tau, \quad \text{for } t_{dm} \leq t \leq \left[t_{dm} + \frac{N_m}{2f_m}\right] \quad (A-2)$$

Let

$$u = \tau - t_{dm}$$

$$du = d\tau$$

$$\alpha = \frac{2\pi f_m}{N_m}$$

$$\beta = 2\pi f_m$$

$$V_m(t) = A_m \int_{u_1}^{u_2} \sin[\alpha u] \sin[\beta u] du \quad (A-3)$$

$$V_m(t) = -\frac{1}{2} A_m \int_{u_1}^{u_2} \cos[(\alpha + \beta)u] du + \frac{1}{2} A_m \int_{u_1}^{u_2} \cos[(\alpha - \beta)u] du \quad (A-4)$$

$$V_m(t) = -\frac{A_m}{2(\alpha + \beta)} \sin[(\alpha + \beta)u] \Big|_{u_1}^{u_2} + \frac{A_m}{2(\alpha - \beta)} \sin[(\alpha - \beta)u] \Big|_{u_1}^{u_2} \quad (A-5)$$

$$V_m(t) = -\frac{A_m}{2(\alpha + \beta)} \sin[(\alpha + \beta)(\tau - t_{dm})] \Big|_{t_{dm}}^t + \frac{A_m}{2(\alpha - \beta)} \sin[(\alpha - \beta)(\tau - t_{dm})] \Big|_{t_{dm}}^t \quad (A-6)$$

The wavelet velocity equation is thus

$$V_m(t) = -\frac{A_m}{2(\alpha + \beta)} \sin[(\alpha + \beta)(t - t_{dm})] + \frac{A_m}{2(\alpha - \beta)} \sin[(\alpha - \beta)(t - t_{dm})],$$

$$\text{for } t_{dm} \leq t \leq \left[t_{dm} + \frac{N_m}{2f_m} \right] \quad (A-7)$$

The wavelet ends at $t = \left[t_{dm} + \frac{N_m}{2f_m} \right] = \left[t_{dm} + \frac{\pi}{\alpha} \right]$

The velocity at the end time is

$$\begin{aligned} V_m \left(t_{dm} + \frac{\pi}{\alpha} \right) = & -\frac{A_m}{2(\alpha + \beta)} \sin \left[(\alpha + \beta) \left(\left(t_{dm} + \frac{\pi}{\alpha} \right) - t_{dm} \right) \right] \\ & + \frac{A_m}{2(\alpha - \beta)} \sin \left[(\alpha - \beta) \left(\left(t_{dm} + \frac{\pi}{\alpha} \right) - t_{dm} \right) \right] \end{aligned} \quad (A-8)$$

$$V_m \left(t_{dm} + \frac{\pi}{\alpha} \right) = -\frac{A_m}{2(\alpha + \beta)} \sin \left[\left(1 + \frac{\beta}{\alpha} \right) \pi \right] + \frac{A_m}{2(\alpha - \beta)} \sin \left[\left(1 - \frac{\beta}{\alpha} \right) \pi \right] \quad (A-9)$$

Note that

$$\frac{\beta}{\alpha} = N_m, \text{ an odd integer } \geq 3$$

Thus

$$\sin \left[\left(1 + \frac{\beta}{\alpha} \right) \pi \right] = 0 \quad (A-10)$$

$$\sin \left[\left(1 - \frac{\beta}{\alpha} \right) \pi \right] = 0 \quad (A-11)$$

The net velocity is thus

$$V_m \left(t_{dm} + \frac{\pi}{\alpha} \right) = 0 \quad (A-12)$$

APPENDIX B

Wavelet Displacement

The wavelet displacement $D_m(t)$ for wavelet m is obtained by integrating the velocity.

$$D_m(t) = -\frac{A_m}{2(\alpha + \beta)} \int_{t_{dm}}^t \sin[(\alpha + \beta)(\tau - t_{dm})] d\tau$$

$$+ \frac{A_m}{2(\alpha - \beta)} \int_{t_{dm}}^t \sin[(\alpha - \beta)(\tau - t_{dm})] d\tau,$$

$$\text{for } t_{dm} \leq t \leq \left[t_{dm} + \frac{N_m}{2f_m} \right]$$

(B-1)

Again,

$$\alpha = \frac{2\pi f_m}{N_m}$$

$$\beta = 2\pi f_m$$

$$D_m(t) = +\frac{A_m}{2(\alpha + \beta)^2} \cos[(\alpha + \beta)(\tau - t_{dm})] \Big|_{t_{dm}}^t$$

$$- \frac{A_m}{2(\alpha - \beta)^2} \cos[(\alpha - \beta)(\tau - t_{dm})] \Big|_{t_{dm}}^t$$

(B-2)

The displacement equation is thus

$$D_m(t) = +\frac{A_m}{2(\alpha + \beta)^2} \{ \cos[(\alpha + \beta)(t - t_{dm})] - 1 \} - \frac{A_m}{2(\alpha - \beta)^2} \{ \cos[(\alpha - \beta)(t - t_{dm})] + 1 \},$$

$$\text{for } t_{dm} \leq t \leq \left[t_{dm} + \frac{N_m}{2f_m} \right]$$

(B-3)

The wavelet ends at $t = \left[t_{dm} + \frac{N_m}{2f_m} \right] = \left[t_{dm} + \frac{\pi}{\alpha} \right]$

The final displacement is thus

$$D_m\left(t_{dm} + \frac{\pi}{\alpha}\right) = +\frac{A_m}{2(\alpha + \beta)^2} \left\{ \cos\left[\left(1 + \frac{\beta}{\alpha}\right)\pi\right] - 1 \right\} - \frac{A_m}{2(\alpha - \beta)^2} \left\{ \cos\left[\left(1 - \frac{\beta}{\alpha}\right)\pi\right] + 1 \right\}$$

(B-4)

Note that

$$\frac{\beta}{\alpha} = N_m, \text{ an odd integer } \geq 3$$

Thus

$$\cos\left[\left(1 + \frac{\beta}{\alpha}\right)\pi\right] - 1 = 0$$

(B-5)

$$\cos\left[\left(1 - \frac{\beta}{\alpha}\right)\pi\right] - 1 = 0$$

(B-6)

The net displacement is thus

$$D_m\left(t_{dm} + \frac{\pi}{\alpha}\right) = 0$$

(B-7)

APPENDIX C

WAVELET EXAMPLE

Specification

A sample specification is shown in Table C-1.

Table C-1. SRS Q=10	
Natural Frequency (Hz)	Accel (G)
10	10
100	100
2000	100

Input File

The breakpoints are copied into a plain text ASCII file called srs.in. The format is free, but no header lines are allowed. The columns may either have a space or tab between them. The first column is Natural Frequency (Hz). The second is Accel (G).

File srs.in has three rows as shown below.

```
10.      10.
100.     100.
2000.    100.
```

Initial Execution and Data Input

The jsynth.exe program runs in DOS or console mode. It may also be executed using the Windows “My Computer” method. It is an interactive program that prompts the user for input parameters

Two screenshot images of the execution for the sample problem are given on the following pages. The colors are inverted for clarity.

```

C:\srs_syn>jsynth

jsynth.cpp, ver 4.1, April 13, 2006
by Tom Irvine
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This program synthesizes a time history using wavelets to satisfy
a shock response spectrum (SRS) specification.

The program also optimizes the time history to yield the lowest overall
error, acceleration, velocity, and displacement.

The optimization is performed via trial-and-error.

Select SRS algorithm:
1=Kelly-Richman 2=Smallwood
1

The input SRS specification file must have two columns:
    natural frequency(Hz) and SRS accel(G)
The format is free, but no header lines allowed.

Please enter the input filename.
srs.in
File: srs.in opened.

Enter octave spacing.
1= 1/3  2= 1/6  3= 1/12
3

Enter damping format for SRS.
1= damping ratio  2= Q
2

Enter SRS amplification factor Q (typically 10) 10

```

The SRS algorithm may be specified as either the Kelly-Richman formula from Reference 4 or the Smallwood formula from Reference 3. The difference between the formulas is insignificant as long as the sample rate is at least ten times the highest SRS frequency.

The octave spacing is the spacing between the spectral lines in the SRS.

The damping value is typically chosen as $Q=10$, which is equivalent to 5% damping.

```

Enter the number of trials.
2000

Enter units
1=English:  G,      in/sec,  in
2=metric:   G,      m/sec,   mm
3=metric:   m/sec^2, m/sec,   mm
1

Enter arbitrary integer (1 to 1000)
1

Recommend sample rate >=  2e+004 samples/sec

Enter sample rate
20000

Select condition
1=limit time history points  2=set duration
2

Enter duration (sec)
<Recommend 0.200 or greater>
0.3

dt=  5e-005 sec  dur= 0.3000 sec  sr=  2e+004 sample/sec  nt=6000

```

The number of trials for this example is 2000, which is also the maximum number allowed. This is the number of candidate wavelet series that will be generated. Iterations are performed within each series, as explained later.

The units are self-explanatory.

The arbitrary integer is simply a random number seed.

The sample rate is 20000 samples per second for this example, which is ten times higher than the maximum SRS frequency.

The duration is set to 0.3 seconds. It should be long enough to accommodate at least two cycles of the lowest SRS frequency, which is 10 Hz in this example. A longer duration will yield a more favorable waveform in terms of minimizing the amplitude metrics and reducing the error. On the other hand, the duration cannot be arbitrarily long because the waveform would cease to be a shock pulse.

The selected sample rate and duration yield a total number of time history points $nt = 6000$.

Intermediate Execution

Trial	Peak Accel (G)	Peak Vel (in/sec)	Peak Disp (in)	T.Error	I.Error	
0	34.30	63.630	1.649	173.71	5.28	9
1	36.65	52.076	0.505	157.63	3.46	9
2	48.99	67.718	0.736	532.87	4.98	11
3	36.93	38.857	0.751	137.25	2.40	9
4	26.47	46.404	0.367	139.80	3.65	9
5	43.70	49.242	0.733	140.97	4.37	10
6	35.56	45.358	0.598	97.97	1.99	18

The program prints the results of each trial to the screen. The first 7 of 2000 components is given in the screenshot above.

The peak amplitude metrics are given.

T.Error is the total error in dB for both the positive and negative spectral components.

I.Error is the maximum error in dB for any of the spectral components.

The number in the final column is the number of iterations per trial, as selected by the software.

Program Finish and Output Files

```
Optimum case for displacement = 1311

Peak Accel =      23.241 G
Peak Velox  =      33.343 in/sec
Peak Disp   =       0.294 inch
Max Error   =       2.086 dB

Acceleration file: accel_1311.out   - time(sec) & accel(G)
Velocity file:   velox_1311.out    - time(sec) & vel(in/sec)
Displacement file: disp_1311.out    - time(sec) & disp(inch)
SRS file:       srs_1311.out       - fn(Hz) pos(G) neg(G)
Wavelet Table:  wavelet_1311.out

Optimum case for acceleration = 1296

Peak Accel =      17.382 G
Peak Velox  =      37.704 in/sec
Peak Disp   =       0.443 inch
Max Error   =       1.343 dB

Acceleration file: accel_1296.out   - time(sec) & accel(G)
Velocity file:   velox_1296.out    - time(sec) & vel(in/sec)
Displacement file: disp_1296.out    - time(sec) & disp(inch)
SRS file:       srs_1296.out       - fn(Hz) pos(G) neg(G)
Wavelet Table:  wavelet_1296.out

Elapsed time (hr:min:sec)
= 0:13:6

Press any key to exit.
```

The program selects two of the waveforms to write as output text files.

Waveform 1311 is the optimal waveform for minimum displacement with some consideration also given to the other metrics.

Waveform 1296 is the optimal waveform for minimum acceleration with some consideration also given to the other metrics.

The program outputs five files for each of the two waveforms, as shown in the above image.

The acceleration, velocity and displacement for waveform 1296 are plotted in Figures C-1 through C-3, respectively. The corresponding SRS is plotted in Figure C-4.

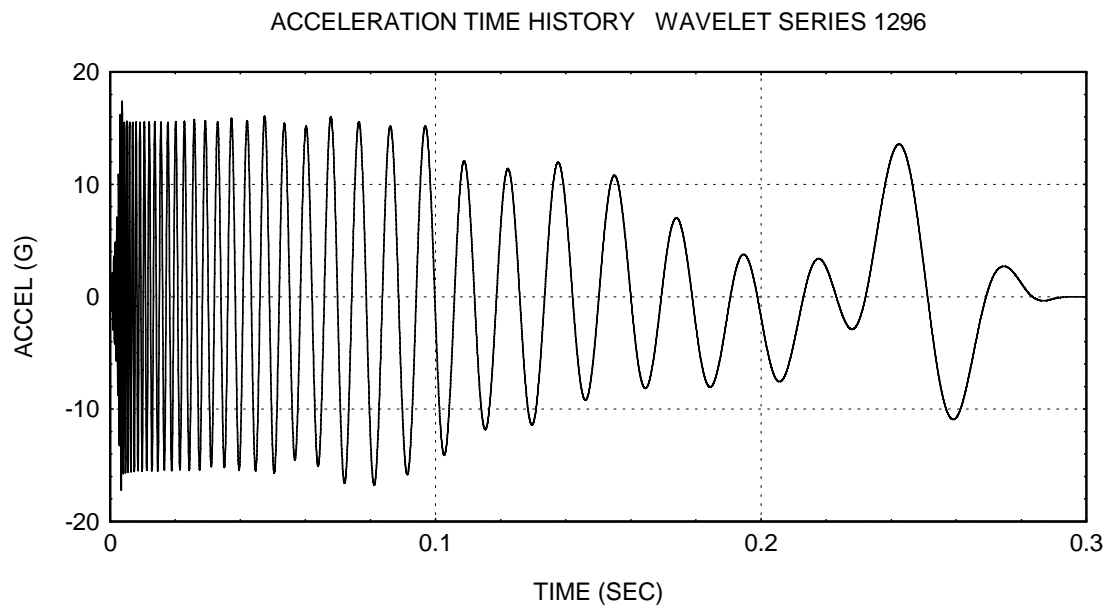


Figure C-1.

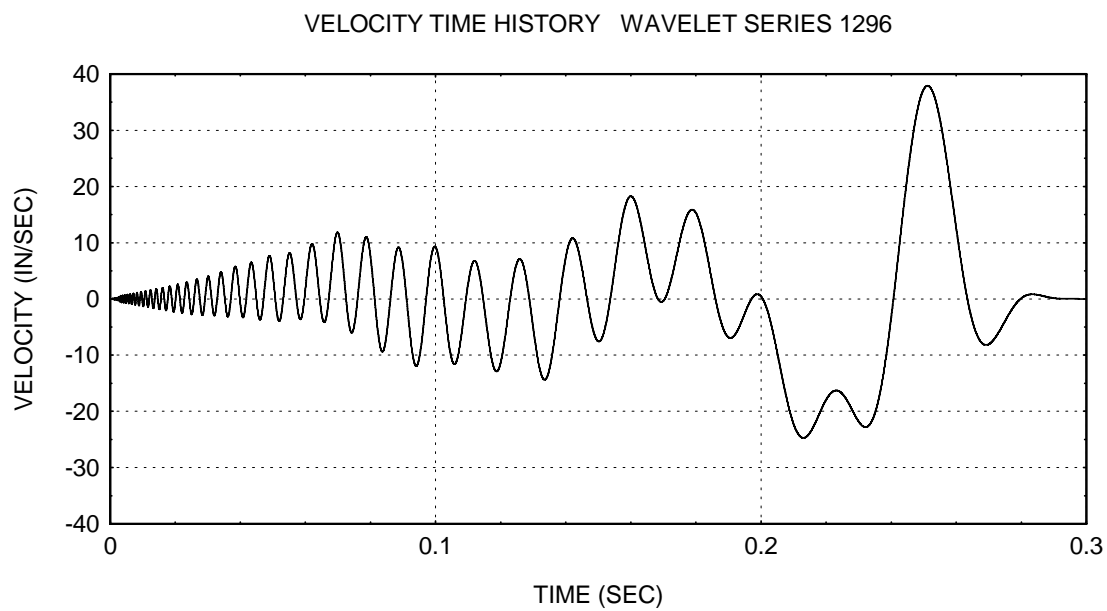


Figure C-2.

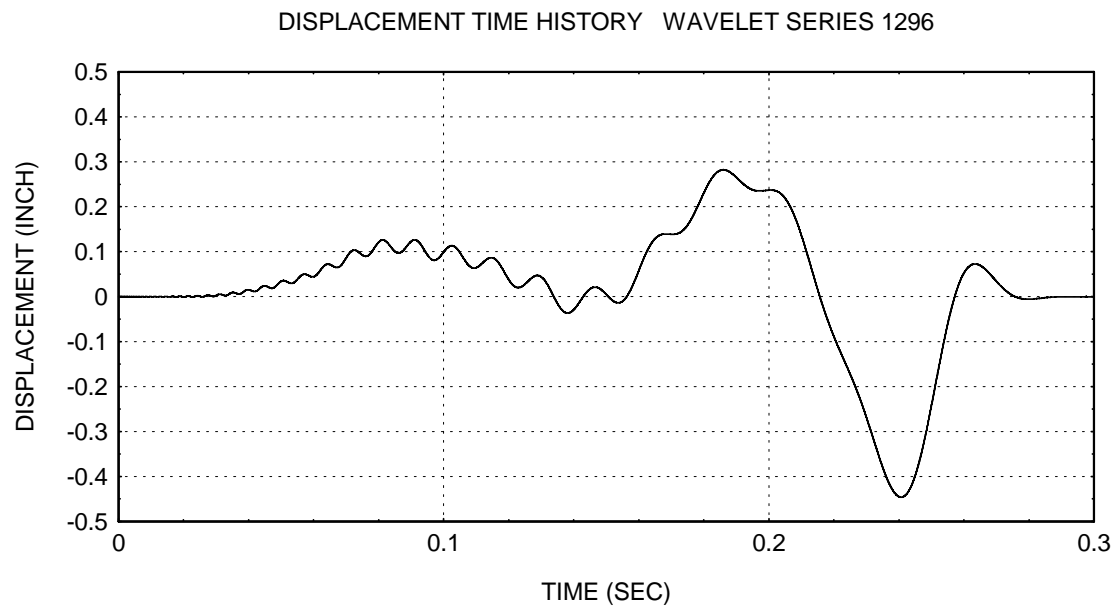


Figure C-3.

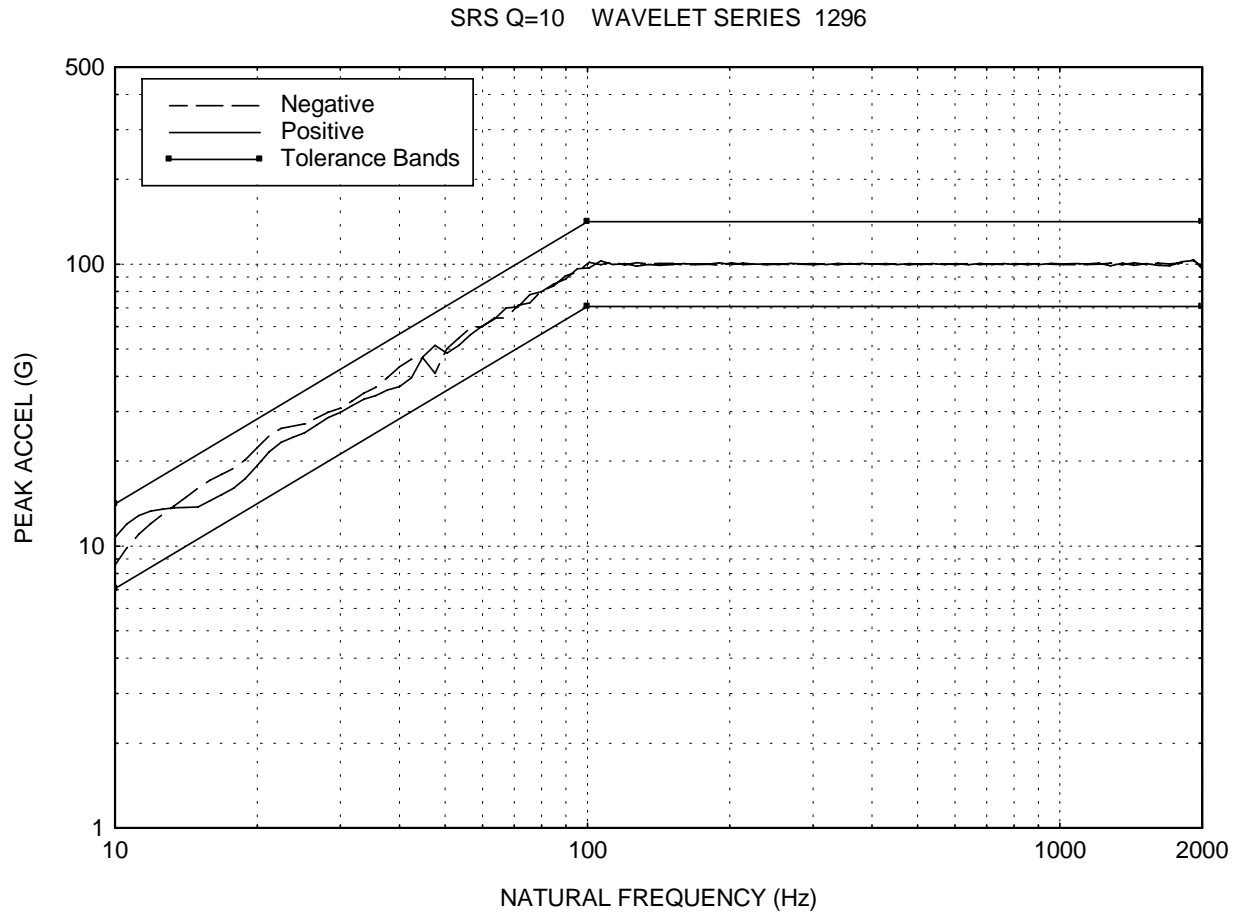


Figure C-4.

The positive and negative spectra are shown along with the ± 3 dB tolerance bands from the specification.

The corresponding wavelet table is shown on the next two pages. The wavelet table is in the Unholtz-Dickie format.

No.	Freq(Hz)	Polarity	NHS	Delay(msec)	Amp(G)
0	10	+	5	10.23	0.82
1	10.6	-	3	152.69	0.73
2	11.2	+	3	139.97	0.97
3	11.9	-	3	121.45	1.63
4	12.6	+	3	103.97	2.86
5	13.3	-	5	87.47	4.14
6	14.1	+	5	71.89	4.39
7	15	-	7	57.19	2.8
8	15.9	+	7	43.31	1.48
9	16.8	-	9	30.21	0.98
10	17.8	+	3	206.09	0.86
11	18.9	-	3	194.42	0.94
12	20	+	3	183.4	1.2
13	21.2	-	5	173.01	1.87
14	22.4	+	5	163.19	3.4
15	23.8	-	5	153.93	6.39
16	25.2	+	7	145.19	8.69
17	26.7	-	7	136.94	7.74
18	28.3	+	9	129.15	6.43
19	30	-	9	121.8	5.72
20	31.7	+	11	114.86	3.45
21	33.6	-	11	108.31	2.01
22	35.6	+	13	102.13	1.57
23	37.8	-	15	96.3	1.19
24	40	+	15	90.79	0.96
25	42.4	-	17	85.59	0.88
26	44.9	+	17	80.69	0.82
27	47.6	-	17	76.05	1.52
28	50.4	+	17	71.68	1.72
29	53.4	-	17	67.56	1.83
30	56.6	+	17	63.66	1.68
31	59.9	-	17	59.99	1.63
32	63.5	+	17	56.52	1.59
33	67.3	-	17	53.24	1.88
34	71.3	+	17	50.15	1.97
35	75.5	-	17	47.24	2.05
36	80	+	17	44.48	2.25
37	84.8	-	17	41.88	2.48
38	89.8	+	17	39.43	2.51
39	95.1	-	17	37.12	2.92
40	100.8	+	17	34.93	3.26
41	106.8	-	17	32.87	2.69
42	113.1	+	17	30.92	2.56
43	119.9	-	17	29.08	2.61
44	127	+	17	27.35	2.6
45	134.5	-	17	25.71	2.59

No.	Freq(Hz)	Polarity	NHS	Delay(msec)	Amp(G)
46	142.5	+	17	24.17	2.65
47	151	-	17	22.71	2.61
48	160	+	17	21.33	2.73
49	169.5	-	17	20.03	2.75
50	179.6	+	17	18.8	2.76
51	190.3	-	17	17.65	2.73
52	201.6	+	17	16.55	2.65
53	213.6	-	17	15.52	2.62
54	226.3	+	17	14.55	2.65
55	239.7	-	17	13.63	2.68
56	254	+	17	12.76	2.68
57	269.1	-	17	11.94	2.67
58	285.1	+	17	11.17	2.68
59	302	-	17	10.44	2.7
60	320	+	17	9.75	2.69
61	339	-	17	9.1	2.69
62	359.2	+	17	8.49	2.67
63	380.5	-	17	7.91	2.66
64	403.2	+	17	7.37	2.68
65	427.1	-	17	6.85	2.67
66	452.5	+	17	6.36	2.68
67	479.5	-	17	5.9	2.69
68	508	+	17	5.47	2.69
69	538.2	-	17	5.06	2.67
70	570.2	+	17	4.67	2.69
71	604.1	-	17	4.31	2.69
72	640	+	17	3.97	2.69
73	678.1	-	17	3.64	2.65
74	718.4	+	17	3.33	2.71
75	761.1	-	17	3.04	2.67
76	806.3	+	17	2.77	2.66
77	854.3	-	17	2.51	2.7
78	905.1	+	17	2.27	2.67
79	958.9	-	17	2.04	2.64
80	1015.9	+	17	1.82	2.73
81	1076.3	-	17	1.62	2.73
82	1140.4	+	17	1.43	2.7
83	1208.2	-	17	1.24	2.59
84	1280	+	17	1.07	2.77
85	1356.1	-	17	0.91	2.67
86	1436.8	+	17	0.76	2.69
87	1522.2	-	17	0.61	2.71
88	1612.7	+	17	0.47	2.69
89	1708.6	-	17	0.34	2.75
90	1810.2	+	17	0.22	2.52
91	1917.8	-	17	0.11	2.8
92	2000	+	17	0	5.67