FIDELITY, INDEPENDENCE, AND STATIONARITY PERFORMANCE OF THE ANCO TRIPODAL INDEPENDENT TRIAXIAL SEISMIC SHAKE TABLE

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1. Introduction

The tripodal independent triaxial seismic shake table design was developed by ANCO in 1980 in order to provide high performance, compact, seismic shake tables capable of testing equipment according to IEEE-344 standards [4].

A schematic of a typical ANCO table is shown in Figure 1. Three linear actuators, joining a tripod, are inclined at a 35.26° angle (to the horizontal), equi-spaced at 120° about the vertical axis. Hence, these actuators are each perpendicular to each other (orthogonal, although not in the traditional two horizontal and one vertical directions). Consequently, these actuators can control all three translational degrees of freedom and produce any desired independent motion of the table (typically specified as X, Y and Z motions in the two horizontal and one vertical directions). Three torque tubes are used to constrain pitch, roll, and yaw of the table. Hence the design produces a totally controlled and determined dynamic system.

Since the three actuators are orthogonal to each other but rotated with respect to the standard X, Y and Z axes used to define test motions, it is necessary to counter rotate the actuator drive signals so that the resulting motion of the table closely matches the desired motions. This can be accomplished either by using an analog mixing circuit, or by digital preprocessing. In practice either technique works well, and the table user is generally concerned only with desired X, Y and Z motions which are generally specified in terms of required test response spectrum (RRS), and achieved X, Y and Z motions and their corresponding achieved test response spectra (TRS).

Note that ANCO has used these techniques successfully for 13 years, with three installed tripodal triaxial tables (the R-5 and R-6 at ANCO's own laboratory, and the R-7 that ANCO delivered in 1991, to Southern California Edison's commercial dedication laboratory).

In order to demonstrate the satisfactory performance of a tripodal triaxial table, a variety of tests were performed on the R-7 table, and are reported herein.

2. Fidelity, Independence, and Stationarity.

A seismic shake table should be judged on its ability to provide multi-axial test motion that has Fidelity, Independence, and Stationarity. Fidelity means that the achieved motion (TRS) closely matches the desired motion (RRS). While this closeness is most often measured through a direct comparison of the desired and achieved response spectra, one can also consider similarity of time histories and Fourier Transforms (or Power Spectral Density). One important aspect of fidelity is that the spectra not be matched simply by having a high ZPA (Zero Period Acceleration). In practice it is possible (3) to match a spectra with a high acceleration spike, but have insufficient energy at all frequencies to adequately excite all the modes of vibration in a realistic manner. This condition can be avoided by 1) making sure that the peak spectral acceleration is somewhat higher than the ZPA, 2) that the Fourier Transform of the signal shows the desired energy spread at all frequencies (not just high frequencies), and 3) that the signal is stationary (as discussed below).

The fidelity tests presented herein check to see 1) if the motion desired is achieved and 2) if when motion is not required (e.g., when motion is asked for in two axis, but not the third) then indeed little motion occurs.

Independence between motions in different directions is required to avoid creating vector motion at an off angle only, thereby producing no motion in a direction perpendicular to this motion. For example, if the same motion (100% dependence) occurred in both horizontal directions, then the result would be a vector motion at 45 degrees between the X and Y axis, and no motion in any other direction of the X-Y plane. If the test object had a mode of vibration with principal axis at or near to a vector perpendicular to the 45° vector (e.g., a 135° vector), then this mode would be severely under tested. Hence the different signals in the different directions of the table must be sufficiently independent. The commonly used measure of independence is the Coherence function between the axis motions [3]. If the coherence is below 0.5 in the frequency range of interest, then the signals are sufficiently independent.

Stationarity of the table motion is required to assure that all modes are sufficiently excited at all times. In essence, this means that energy is contained at all frequencies at all times. (For example, a sine sweep is not stationary, and the modes are excited one at a time, which is not realistic or acceptable). There are tests that can be performed on a signal to show an adequate degree of stationarity [3,4], and as shown below.

In this study, three spectrum compatible time histories were created using the program SIMQKE [2]. The nature of the SIMQKE process assures stationarity because the time history is developed from a segment of stationary random noise. Only gross distortion of the SIMQKE signal could disturb this, and this does not generally occur on seismic shake tables.

3. Fidelity - Matching of RRS by TRS

In order to demonstrate table fidelity seven separate test cases were performed, as shown in Figure 2. In Case "123" the table was commanded to move, independently, in all three axis. In Cases 12, 13, and 23, only two axis motion was commanded. The missing axis was commanded to not move. In Cases 1, 2, and 3, only one axis was commanded to move, the other two being commanded to not move.

In all cases, the command signals (different for each of the three axis) were independent time histories created by the program SIMQKE, and matching the SQURTS [1] standard spectrum, as shown in Figure 3. As can be seen, the maximum deviation of the response spectra of these artificially generated numerical time histories is about ±15%, a measure of the capabilities of the SIMQKE program. Note that, for the purposes of this experiment, we sought to match the spectra in a best fit sense, with both over and under fits (i.e., + and - 15%). In typical IEEE-344 testing one would seek to overlap the RRS (or 110% of the RRS, as appropriate) everywhere.

In Figure 4, we present the result of Case 123 in which all three axis were commanded to respond. As can be seen, in the region from about 2 to 15 Hz, the maximum over test is about 50%. The ZPA are as great as 80% higher than desired. In our experience these results are typical of seismic shake tables. The ZPA is often higher than desired due to the fact that it can be elevated by even a single shock due to table or test object rattle. Figures 5 and 6 present the acceleration time histories and Fourier Transforms of the table motion.

In Figures 7, 8, and 9 we present the results of Cases 12, 13, and 23, in which one axis was commanded not to move. As can be seen, the commanded axes continue to fit the RRS as well as in the triaxial case (123). In the direction that "no motion" was commanded, the response is much less. Below 10 Hz, the response is from 3-10 times smaller than in the driven directions. Above 10 Hz, again mechanism clearance produces a higher than desired ZPA and that approaches the driven axis ZPA values.

Because of the ZPA elevation phenomena, the motion in the "no motion" direction appears, in a logarithmic response spectra, to be significant. In actuality, this is not the case. Figures 10, 11, and 12 present the time histories and Figures 13, 14, and 15 present the Fourier Transforms of all axis. These more clearly show how small the motion in the "no motion" direction is, compared to the directions in which motion was commanded.

In Figures 16-24, similar data and similar conclusions apply for Cases 1, 2, and 3.

Based on our experience, this demonstrated ability of the R-7 to match spectra and reject motion on unwanted axes is equal to the performance of other seismic tables. In the next section we also show that the table is able to maintain the required independence between orthogonal XYZ axes, while maintaining the fidelity levels indicated above.

Note that these TRS are the first attempt to fit the RRS. They are sufficiently close for most seismic qualification testing. An improvement in the fit can be achieved through an iterative process called equalization. This process, which will be fully discussed and demonstrated in a forthcoming companion paper, involves, briefly, the modification of the table drive signals according to the error found between the desired table motion and the measured table motion. The error is computed in the frequency domain, an inverse transfer function correction applied, and the correction is transformed back into the time domain and added to the drive histories. Using these iterations, a factor of 2-3 reduction in the TRS to RRS error has been achieved.

4. Independence - Incoherence of cross axis signals

Figure 25 indicates the coherence between each of three pairs of commanded signals in Case 123. As can be seen, except for a few isolated spikes reaching 0.7, the coherence is less than 0.5, the generally accepted value for independence in seismic shake table testing. The 0.5 value was derived from performing coherence studies on actual earthquake time histories (3). Figure 25 does have a few isolated spikes over 0.5 coherence. However, note that the coherence function shown in Figure 25 is computed with a band width of 0.39 Hz.

The criteria "0.5 coherence or less" is meant to be applied to a coherence function computed at a band width of approximately 0.78 Hz (3). Thus the isolated peaks at 0.7 would be averaged with the smaller coherences around the peak, resulting in a coherence everywhere less than 0.5, satisfying the criteria.

Note that independence of two measured table motions can also be shown by evaluation of their correlation coefficient (3, 4). The criterion for correlation coefficient is that it be less than 0.3. Either the coherence criterion (less than 0.5) or the correlation criterion (less than 0.3) assure sufficient independence, and are essentially equivalent. It is important to understand that satisfaction of either of these criteria satisfies the IEEE-344 requirement and neither test is considered superior to the other.

Figure 26 presents similar data for Case 12. Note that, as the "no motion" direction motion is small, and generally parasitic from the two axes commanded to move, the coherence with respect to the "no motion" axis can be larger than 0.5. This is not significant, as the "no motion" axis motion is not large enough to significantly effect the test. Of importance, the coherence between the two directions in which motion was requested is less than 0.5, as desired. The data for Cases 13 and 23 are presented in Figures 27 and 28, and support similar conclusions.

5. Stationarity - Uniform presence of energy

Figure 29 shows the Power Spectral Density (PSD) of the direction 1 axis of table motion for 4 consecutive time segments of 4 seconds each (using a band width of 0.98 Hz.). In order for a table motion to be considered stationary (as stationary as real earthquakes are, as defined by reference 3), the following computation must be made and the indicated criteria met.

Let GMAX(f) be the maximum value, at each frequency point, of any of the 4 PSDs.

Let GMIN(f) be the minimum value, at each frequency point, of any of the 4 PSDs.

Let GAVE(f) be the average value, at each frequency point, of the 4 PSDs.

Let GMAX be the average value of GMAX(f) over the frequency range of interest. Similarly define GMIN and GAVE.

Let RMAX = GMAX/GAVE

Let RMIN = GMIN/GAVE

Then the table motion is stationary if

RMAX $<$ 2.80 and RMIN $>$ 0.17

In essence what this says is that the PSD does not vary too much as you proceed through the earthquake. The numbers 2.80 and 0.17 were derived from performing such computations on actual measured earthquake time histories (3).

Figure 30 is the output of a spreadsheet program to compute the RMAX and RMIN values from the PSD shown in Figure 29. As can be seen RMAX (at 1.61) is well under 2.80, and RMIN (at 0.42) is well over 0.17. Hence the measured table motion is stationary. Similar results were obtained for directions 2 and 3 table motion.

6. Conclusions

As is the case for all shake tables, the R-7 table has some cross axis coupling, evidenced by the low level motion measured in directions that were requested to not move. This motion, when represented by a response spectra, is well below the RRS at frequencies below 20 Hz and only approaches the RRS at frequencies between 20 and 30 Hz. Hence, in most practical situations, cross axis coupling will not effect test results. The coherence of motions in different directions is suitably low to achieve the needs of IEEE-344 testing. Finally, as discussed above, the measured table motions are suitably stationary.

Consequently, the ANCO tripodal design produce table motions suitable for IEEE-344 testing.

References

1. SQURTS (Seismic Qualification Reporting & Testing Standardization). A consortium of several electric utilities performing seismic tests jointly and coordinated by Ken Huffman of the EPRI NDE center in Charlotte. Spectrum kindly provided by John Richards of Duke Power.

2. SIMQKE - Gasparini, D. and Vanmarcke, E.H., "Simulated Earthquake Motions Compatible with Prescribed Response Spectra," M.I.T. Department of Engineering Research Report R76-4, Order No. 527, January 1976.

3. Kana, D. and Pomerening, D., "Suitability of Synthesized Waveforms for Seismic Qualification of Equipment," Dept. of Engr. Mech., Southwest Research Institute, San Antonio, Texas, ASME Paper 83-PVP-22., 1983.

4. IEEE-344-1987 (and earlier versions), "IEEE Recommended Practice for Seismic Qualification of Class IE Equipment for Nuclear Power Generating Stations".

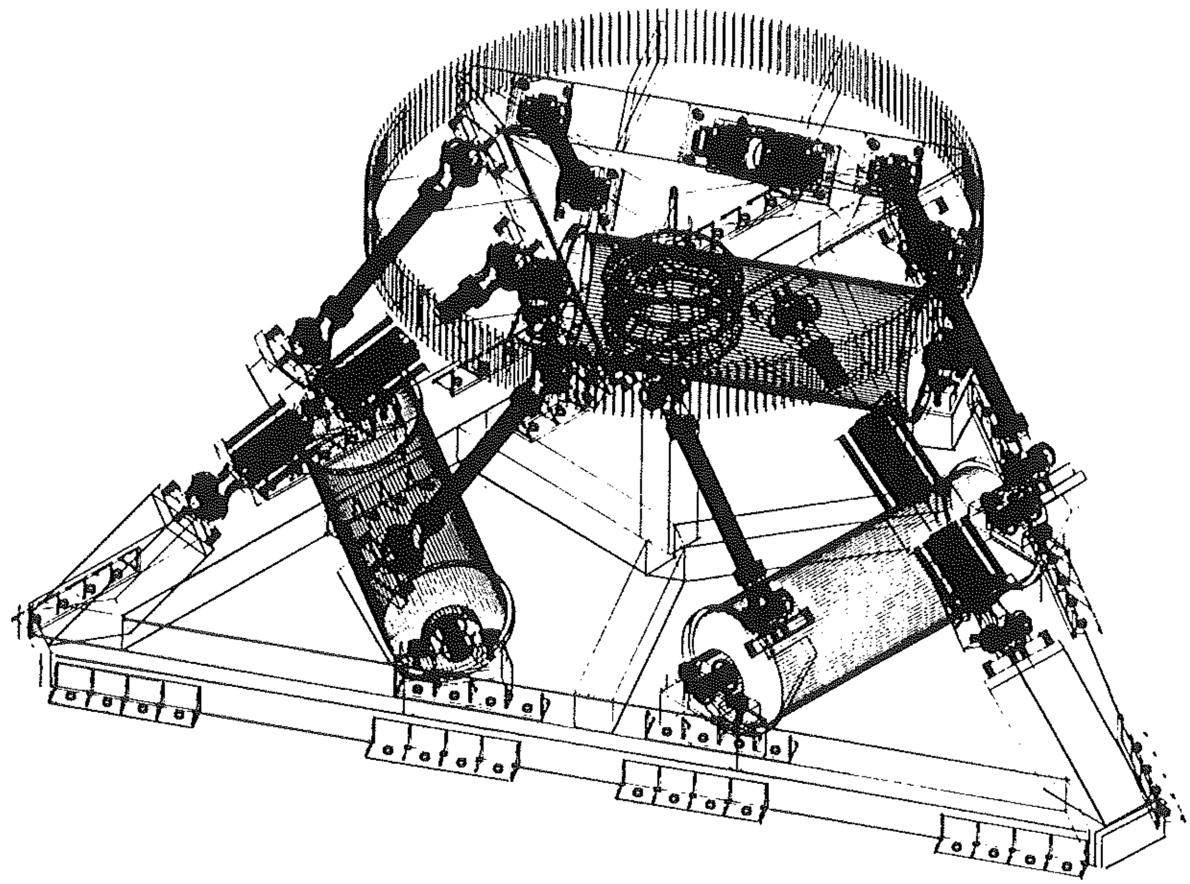

Figure 1. Typical and Tripodal Triaxial Table

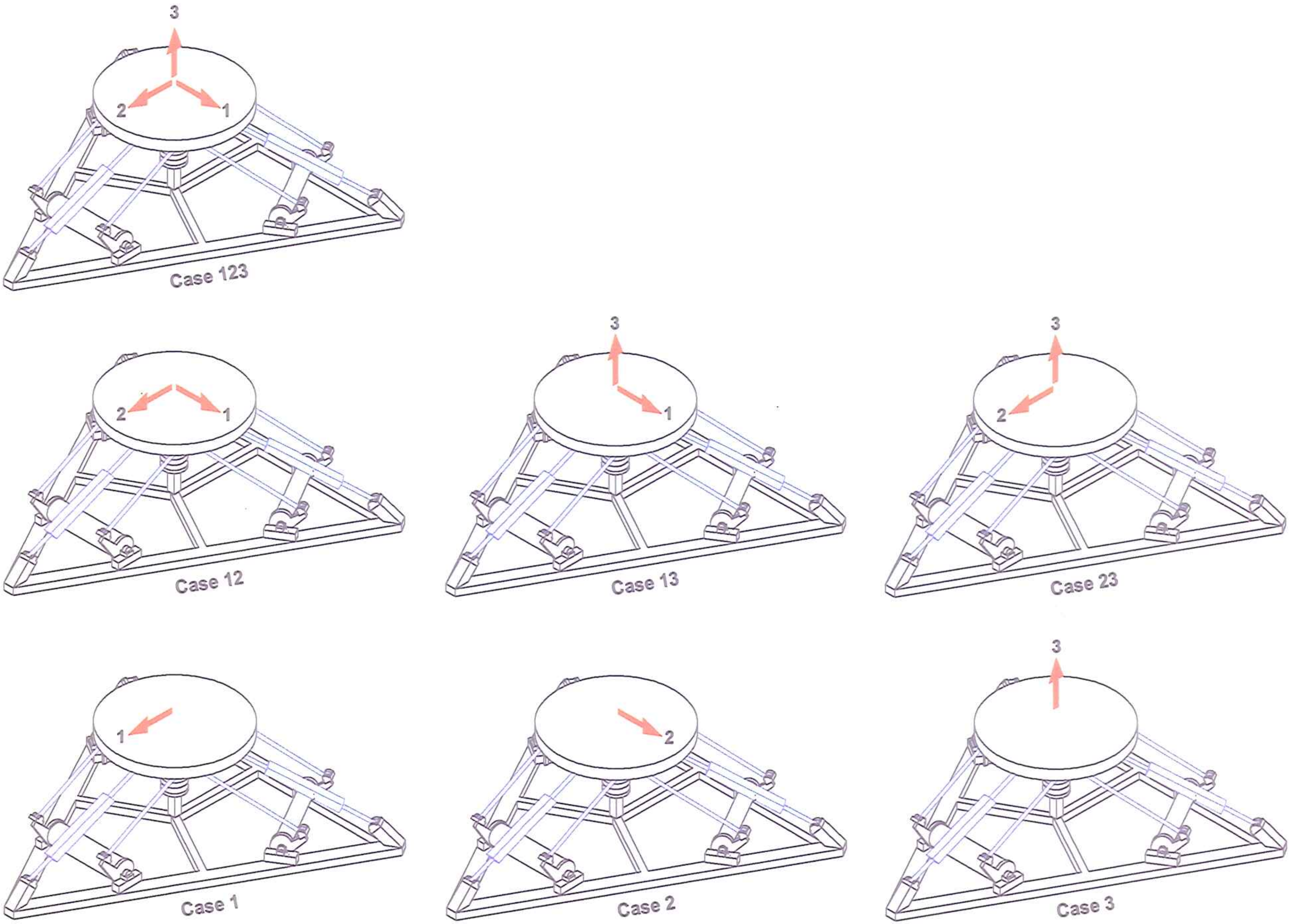

Figure 2. Table Fidelity Performance Cases

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SQURTS RRS vs. Artificial Time History
Spectral Match (5% Damping)

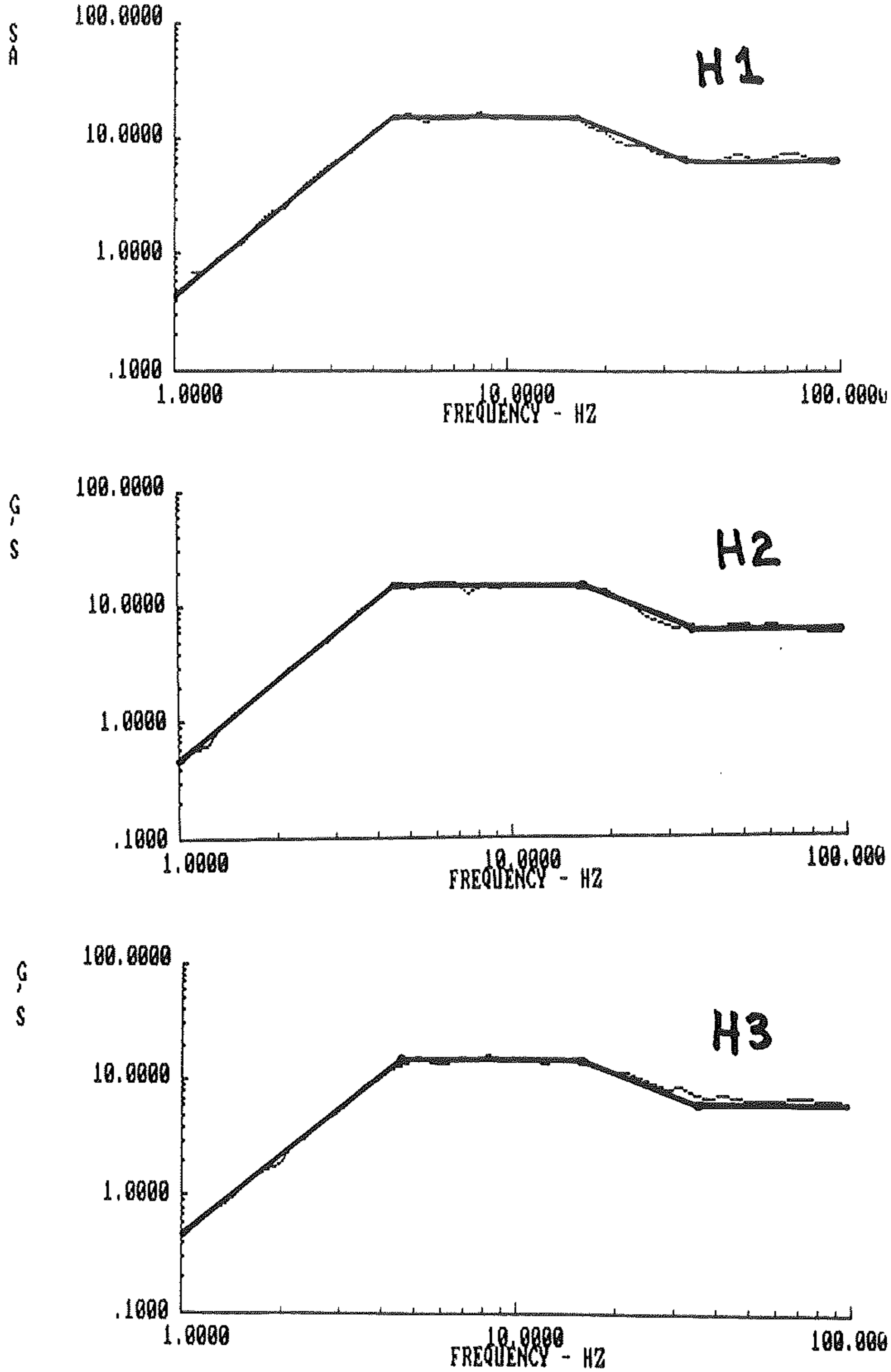

Figure 3. SIMQKE Match to SQURTS Spectrum

SQURTS RRS vs. Achieved Table TRS (5% Damping)

ANCO

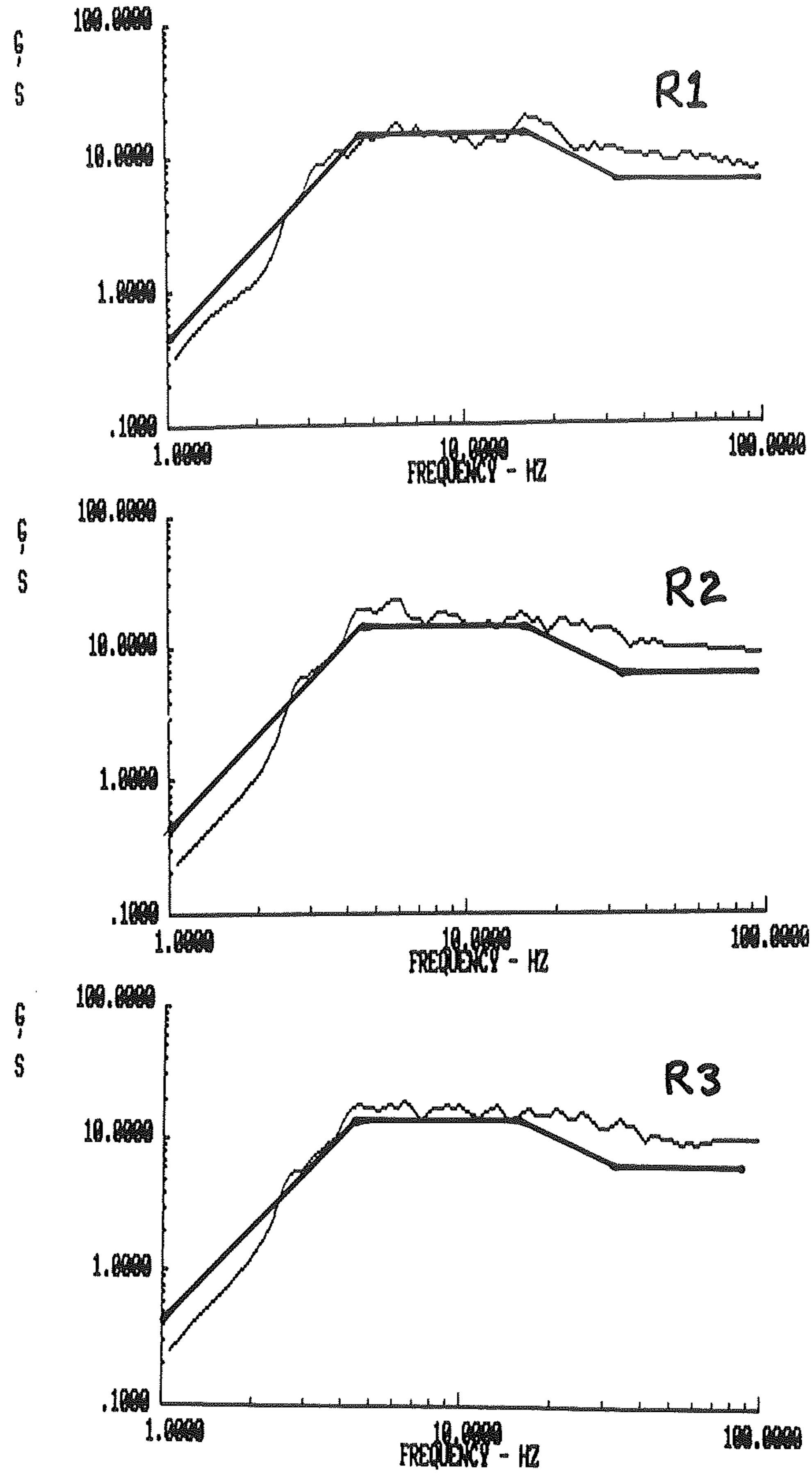

Figure 4. Case 123 Response Spectra

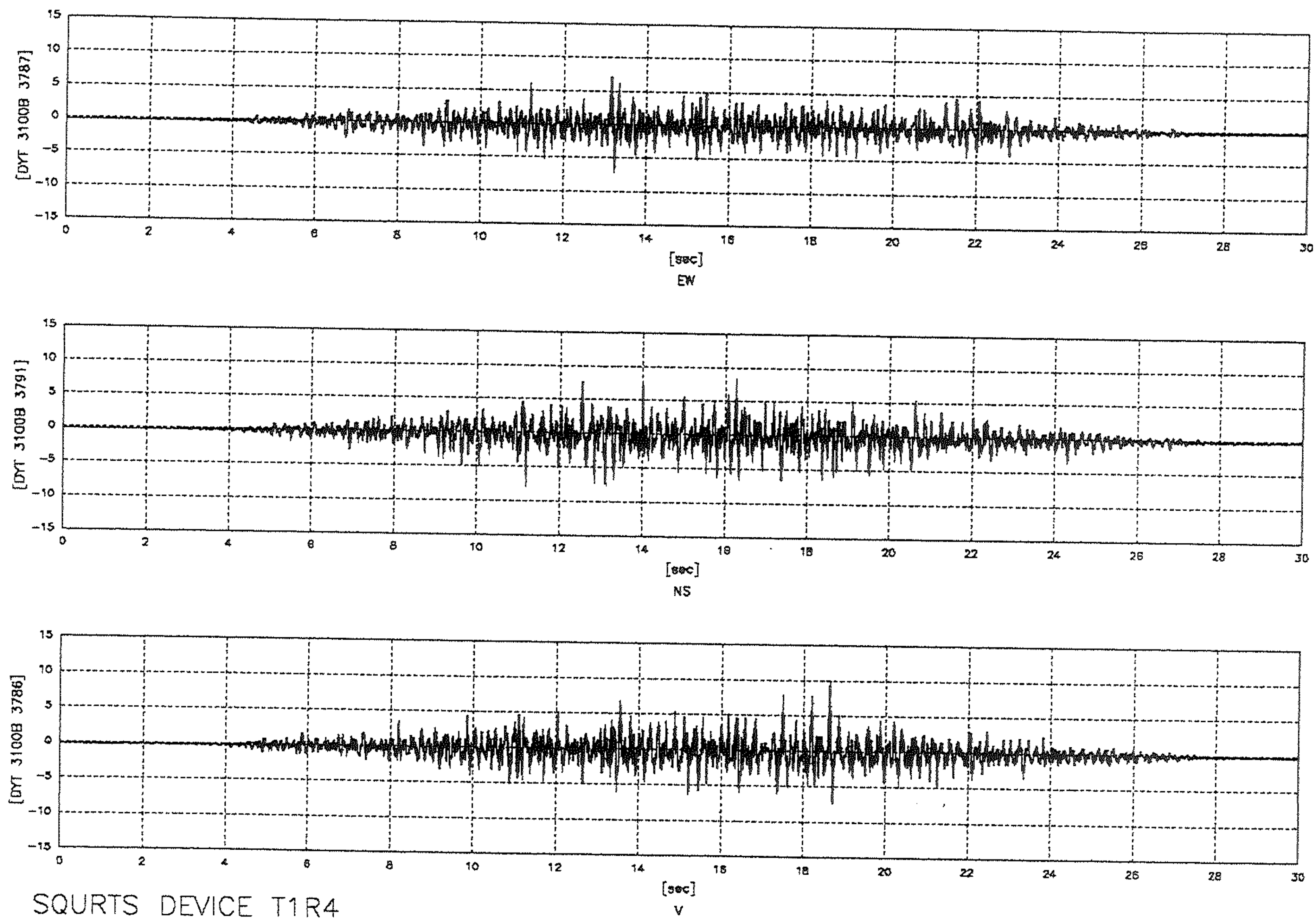

Figure 5. Case 123 Time Histories

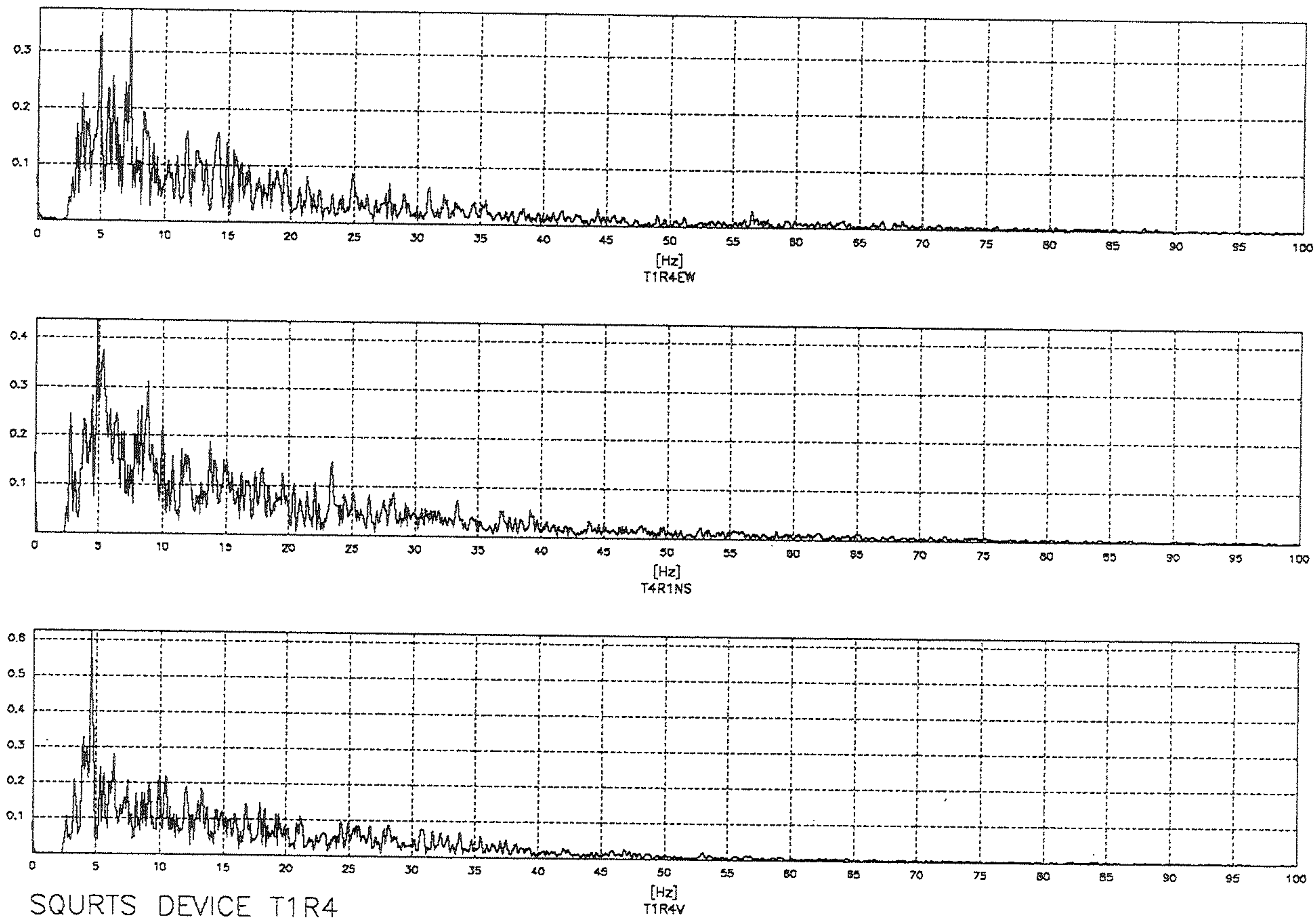

Figure 6. Case 123 Fourier Transforms

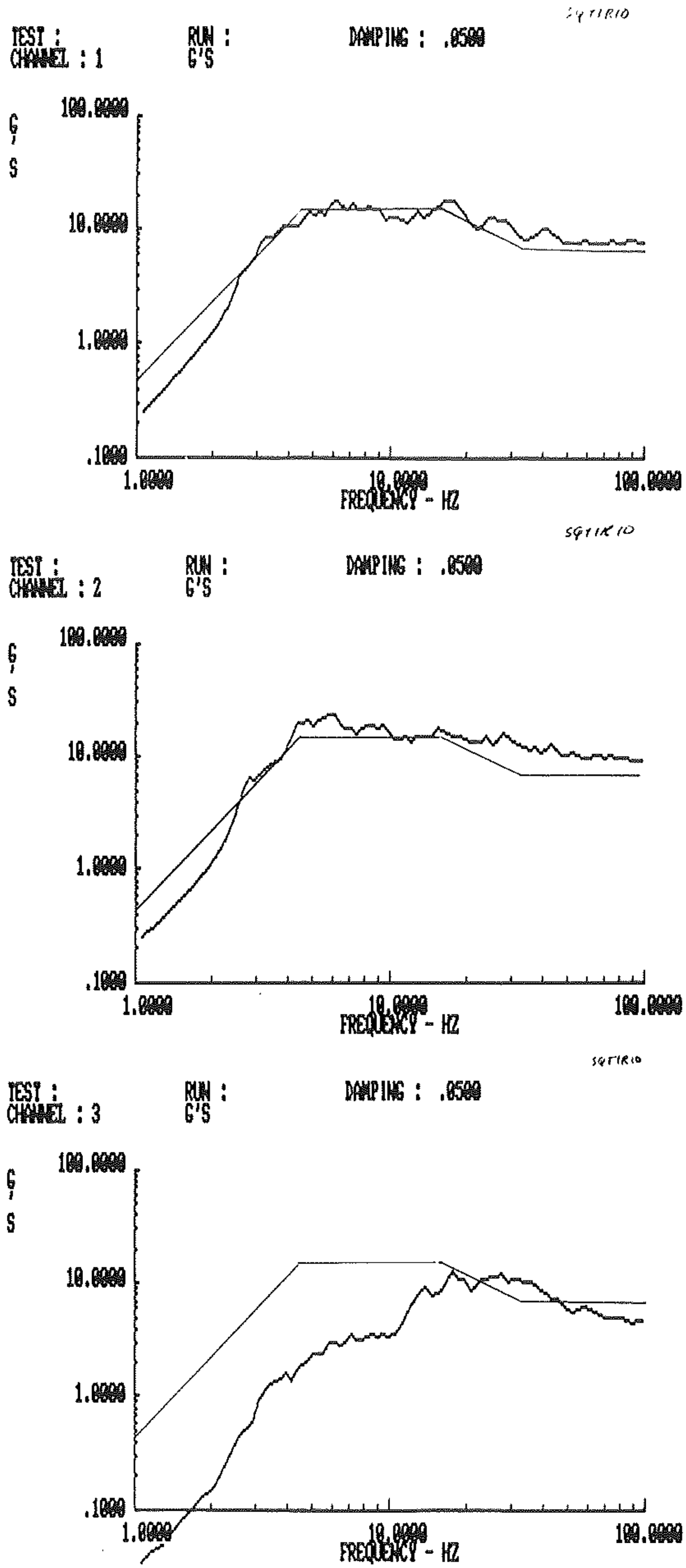

Figure 7. Case 12 Response Spectra

Case 13

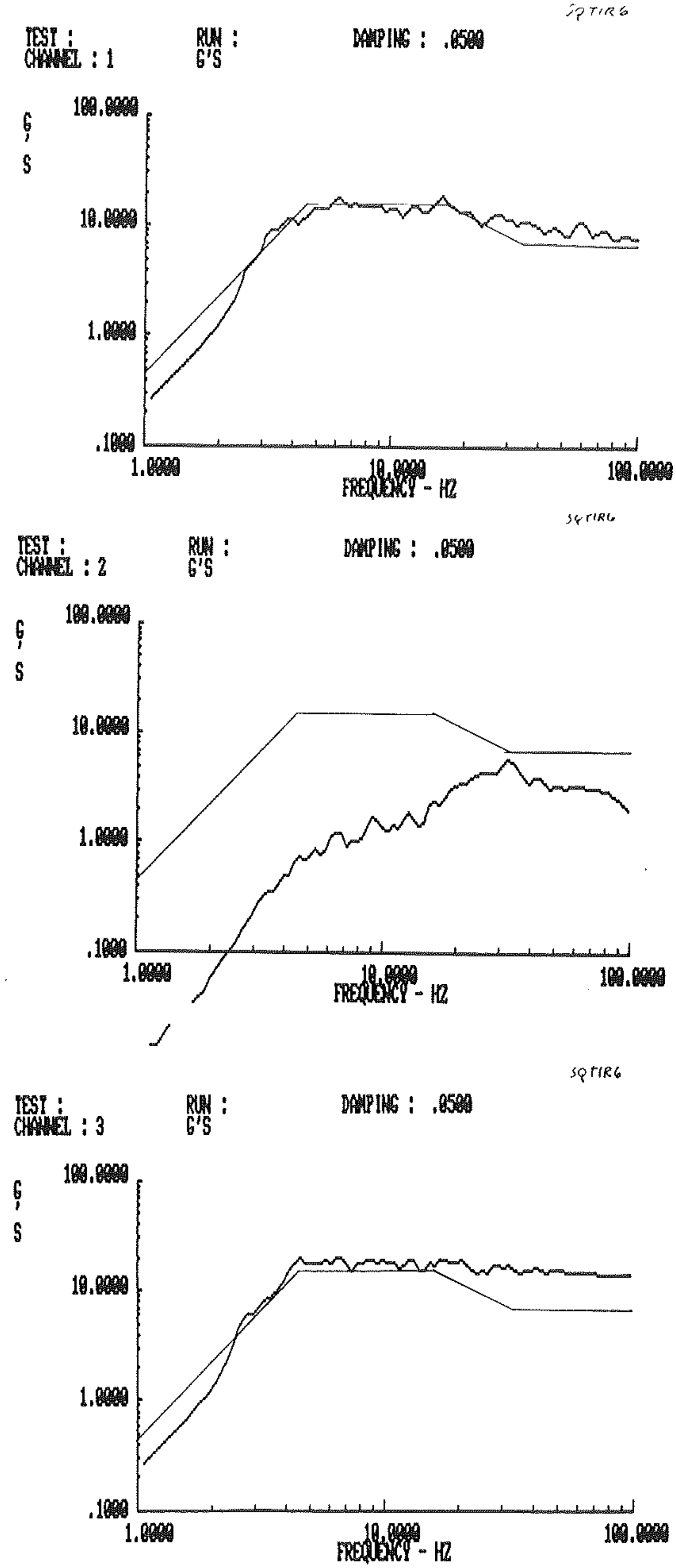

Figure 8. Case 13 Response Spectra

CASE 23

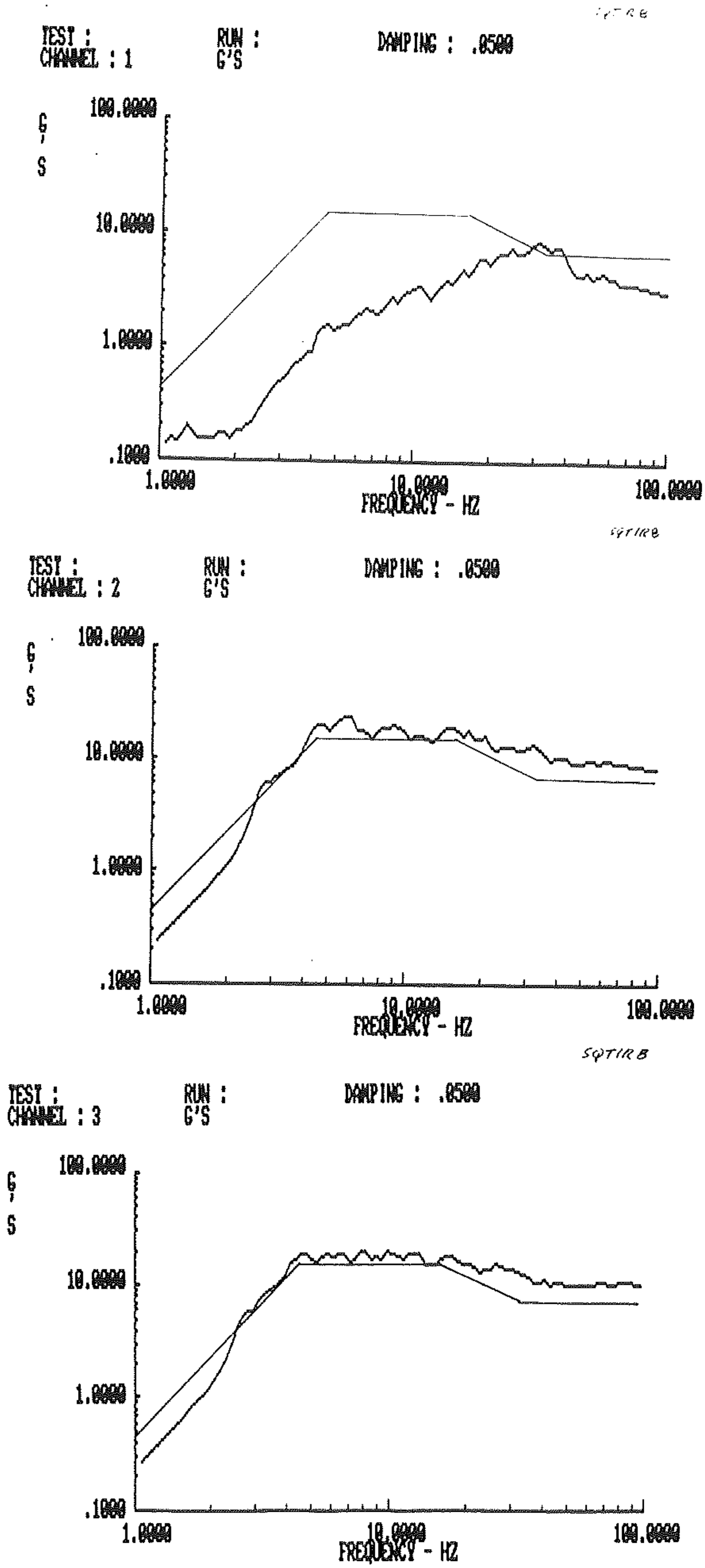

Figure 9. Case 23 Response Spectra

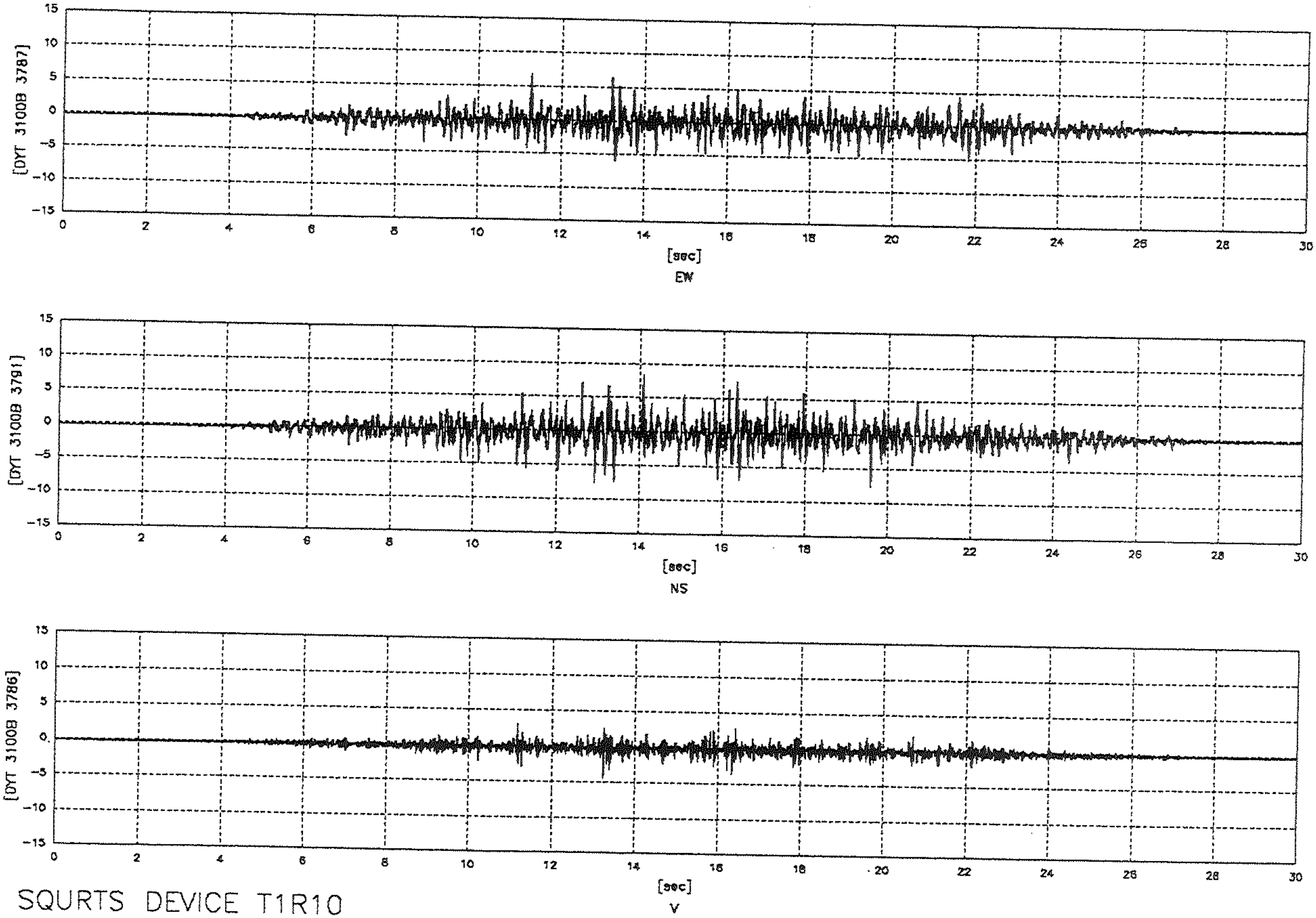

Figure 10. Case 12 Time Histories

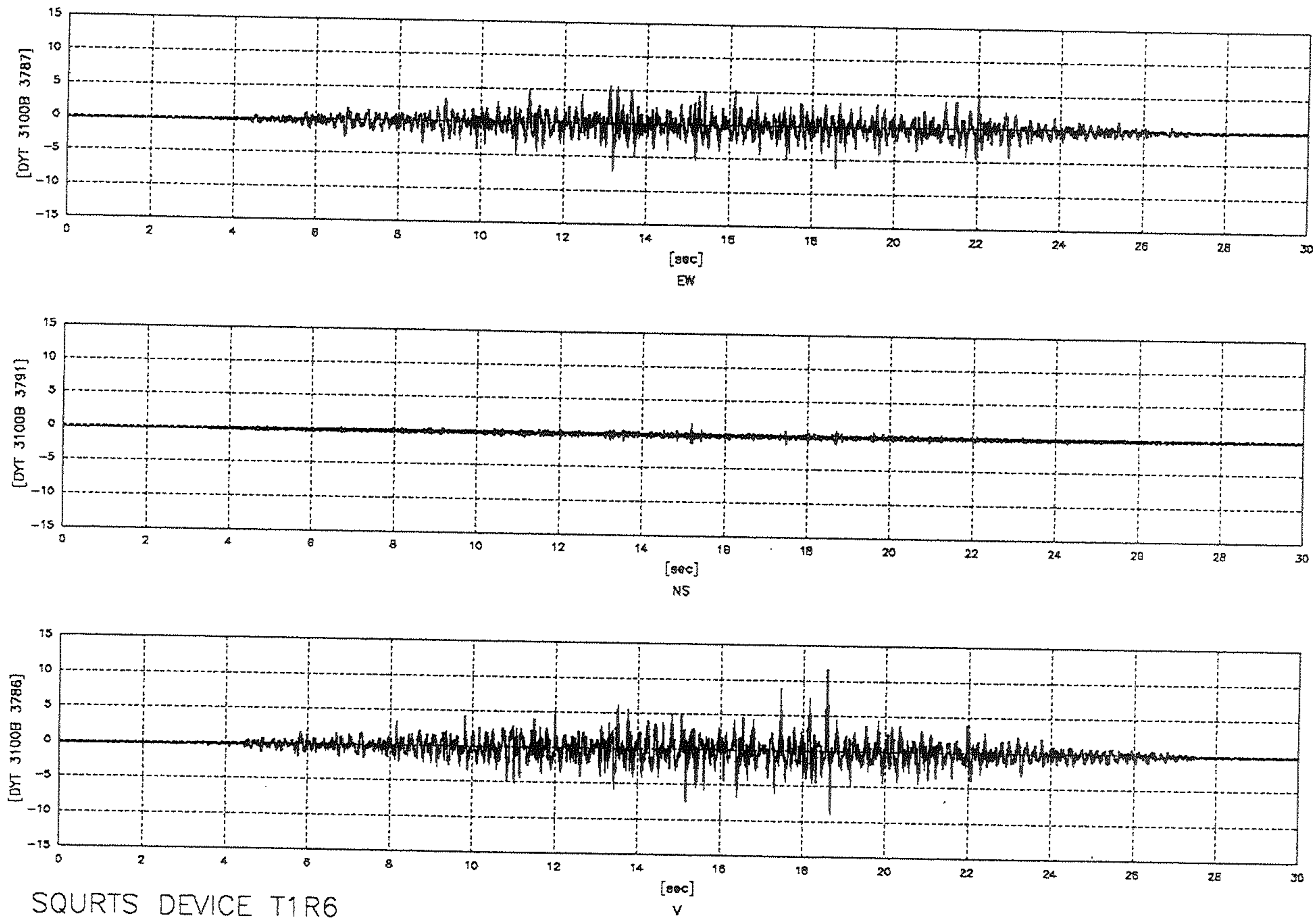

Figure 11. Case 13 Time Histories

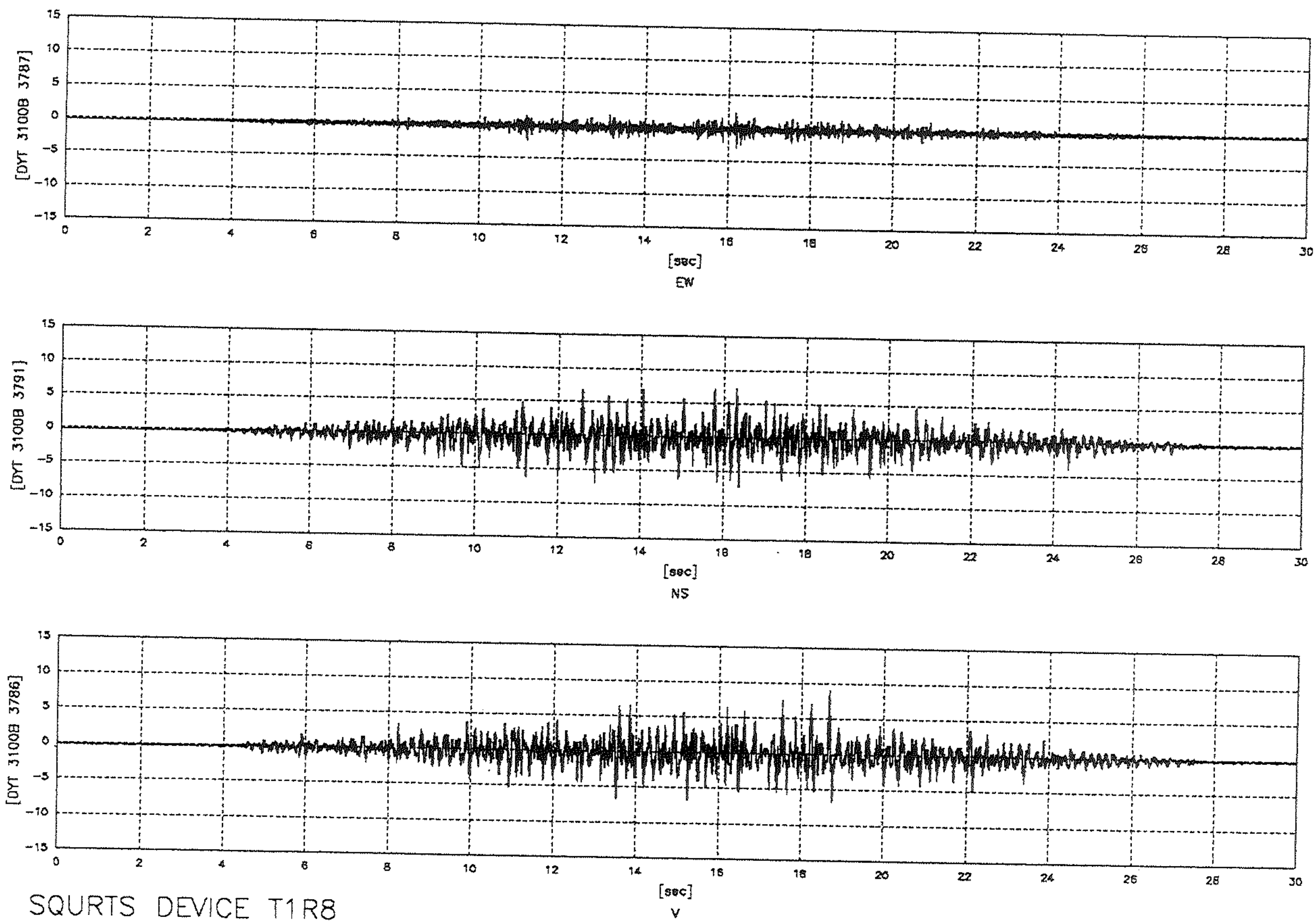

Figure 12. Case 23 Time Histories

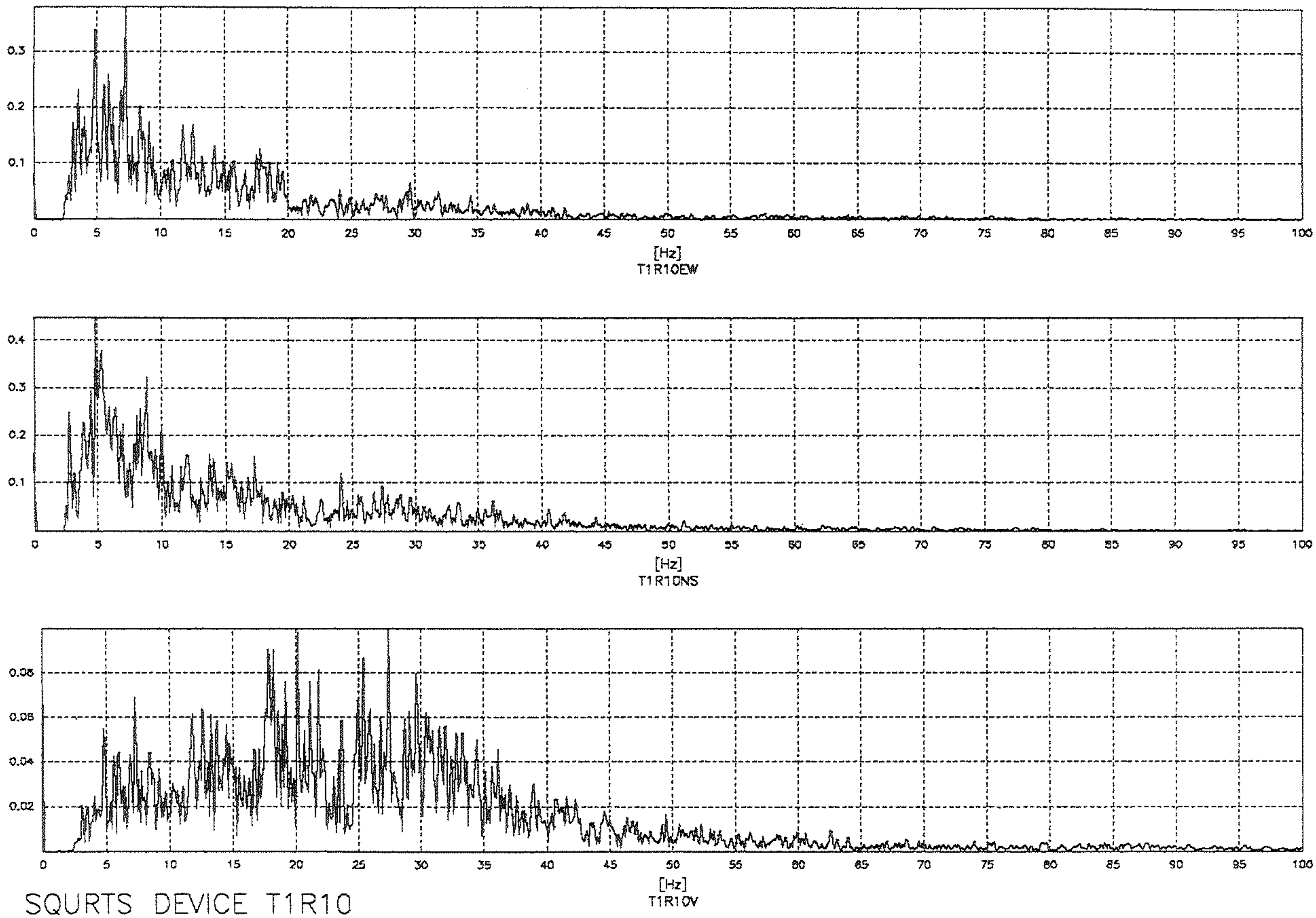

Figure 13. Case 12 Fourier Transforms

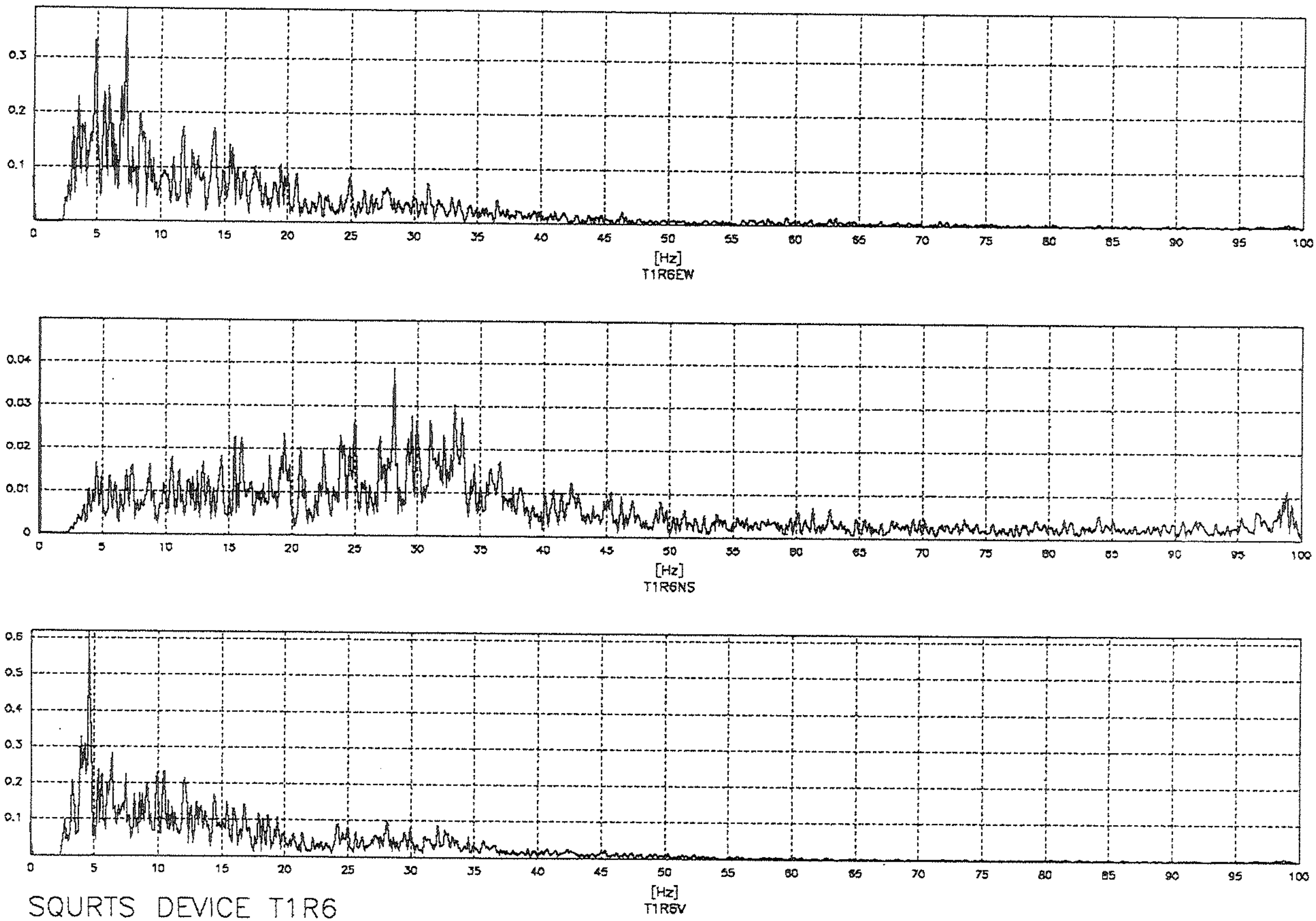

Figure 14. Case 13 Fourier Transforms

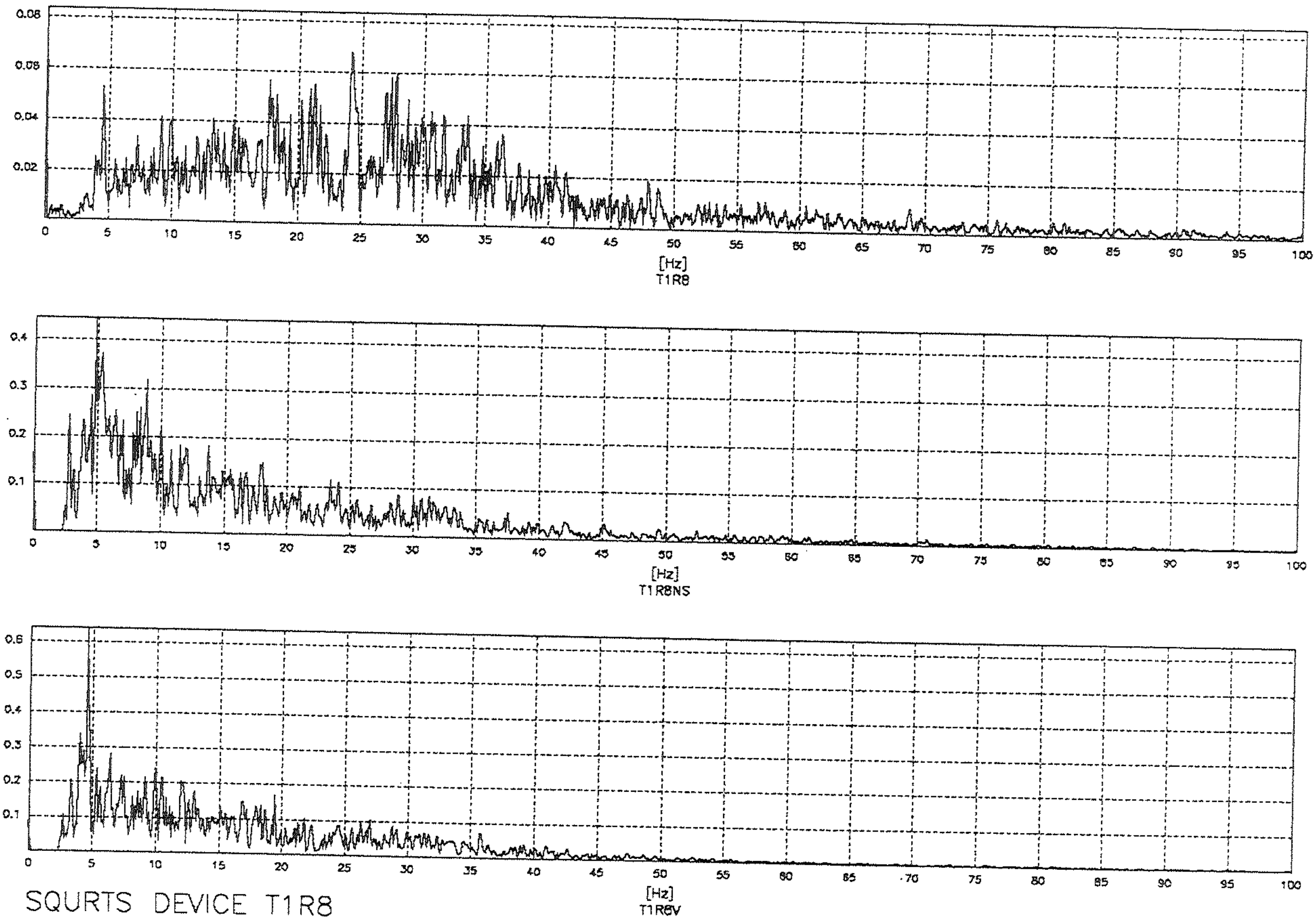

Figure 15. Case 23 Fourier Transforms

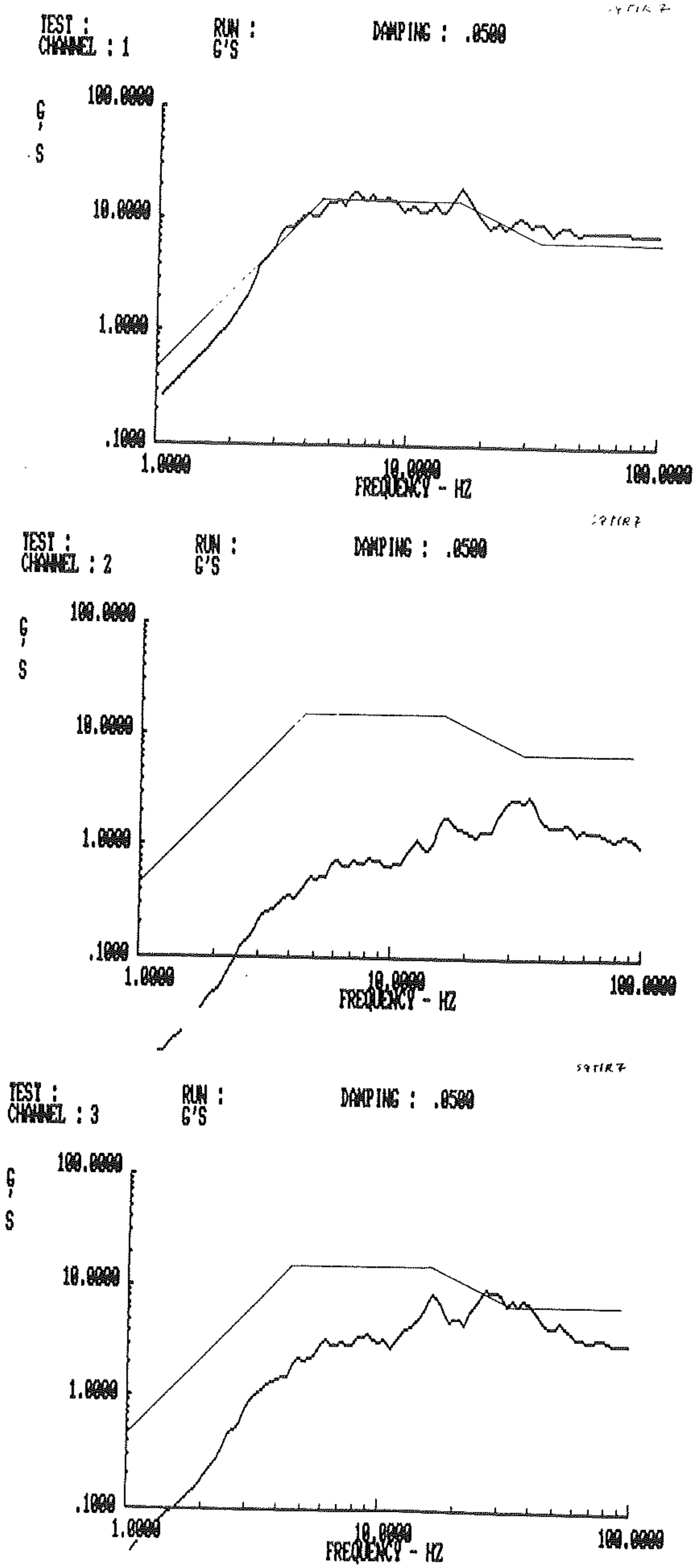

Figure 16. Case 1 Response Spectra

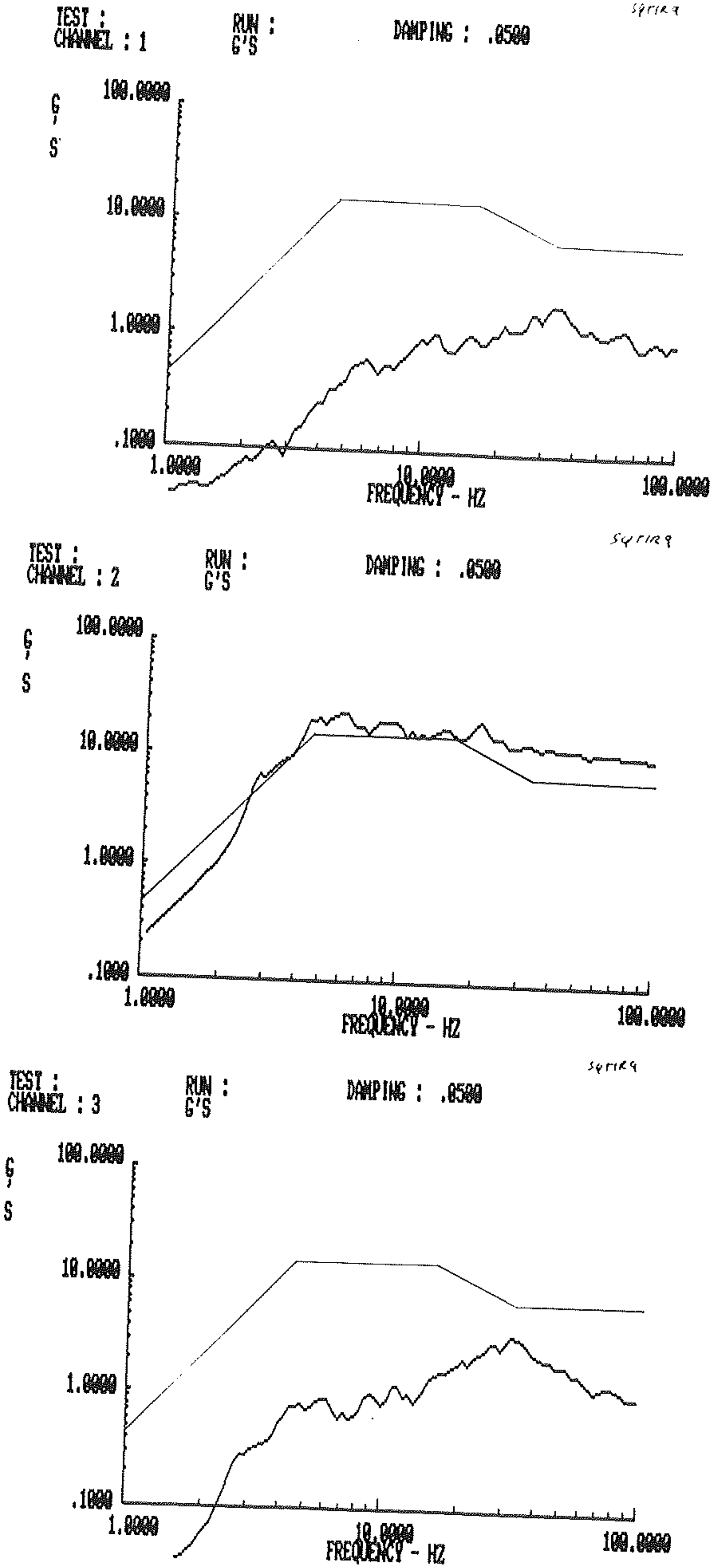

Figure 17. Case 2 Response Spectra

CASE 3

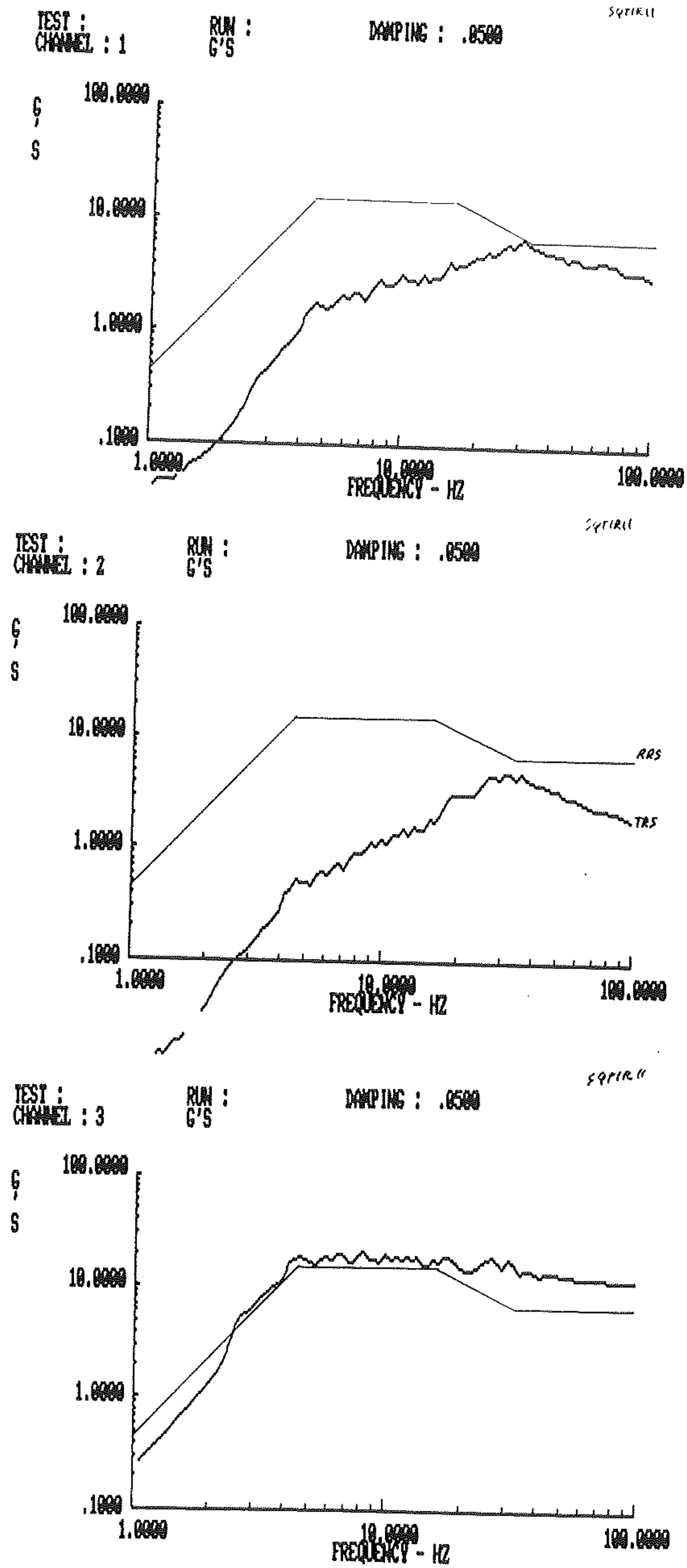

Figure 18. Case 3 Response Spectra

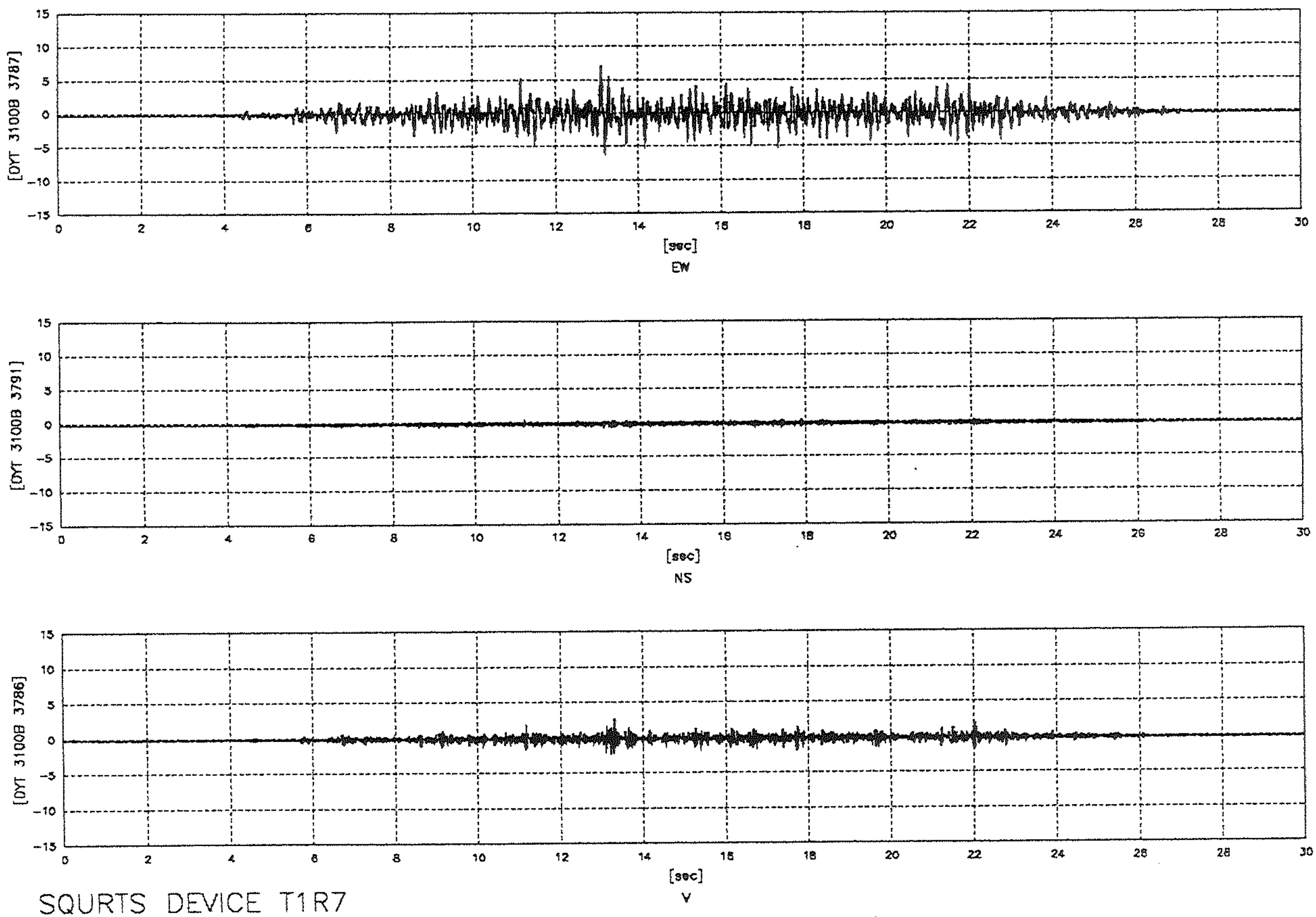

Figure 19. Case 1 Time Histories

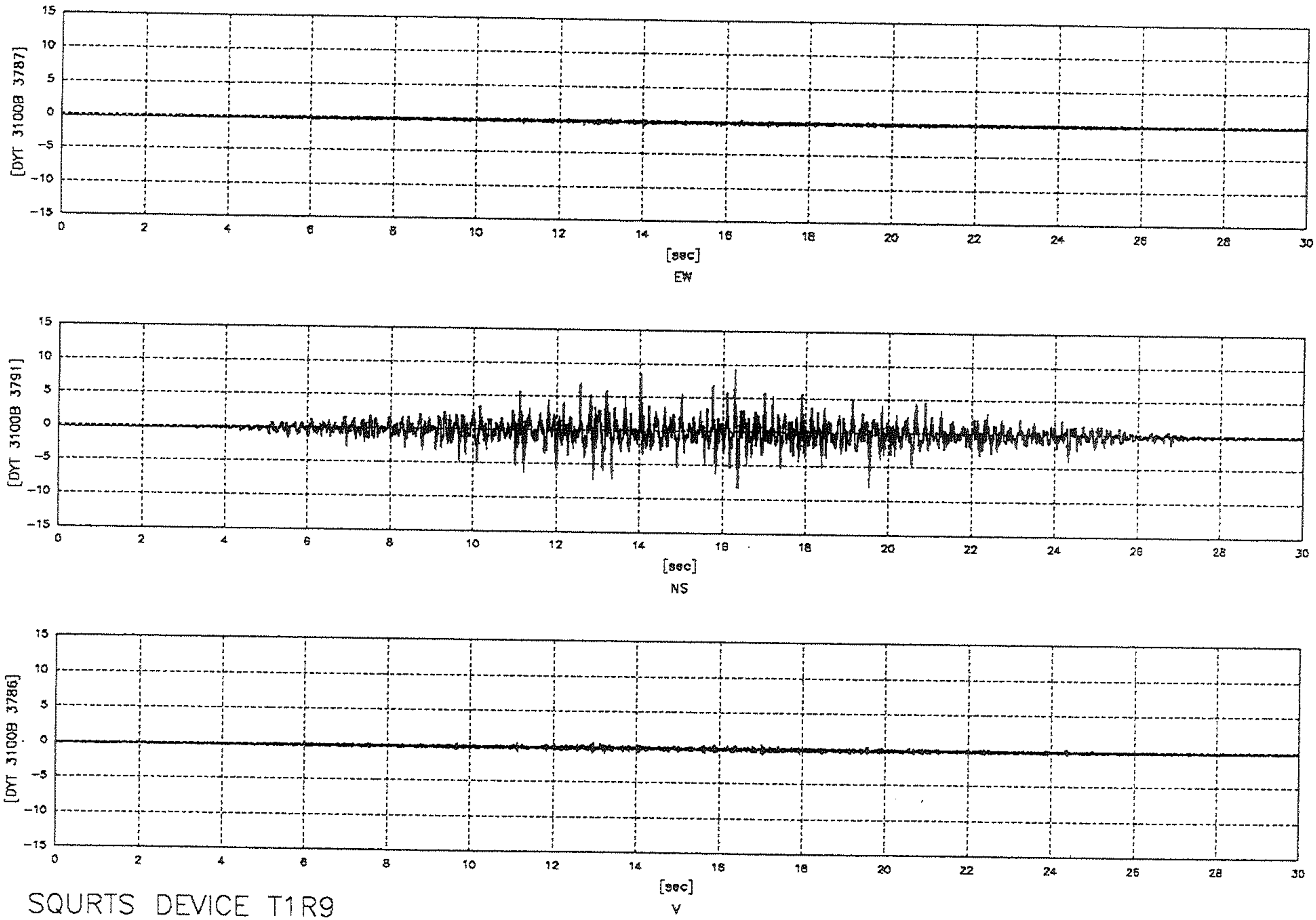

Figure 20. Case 2 Time Histories

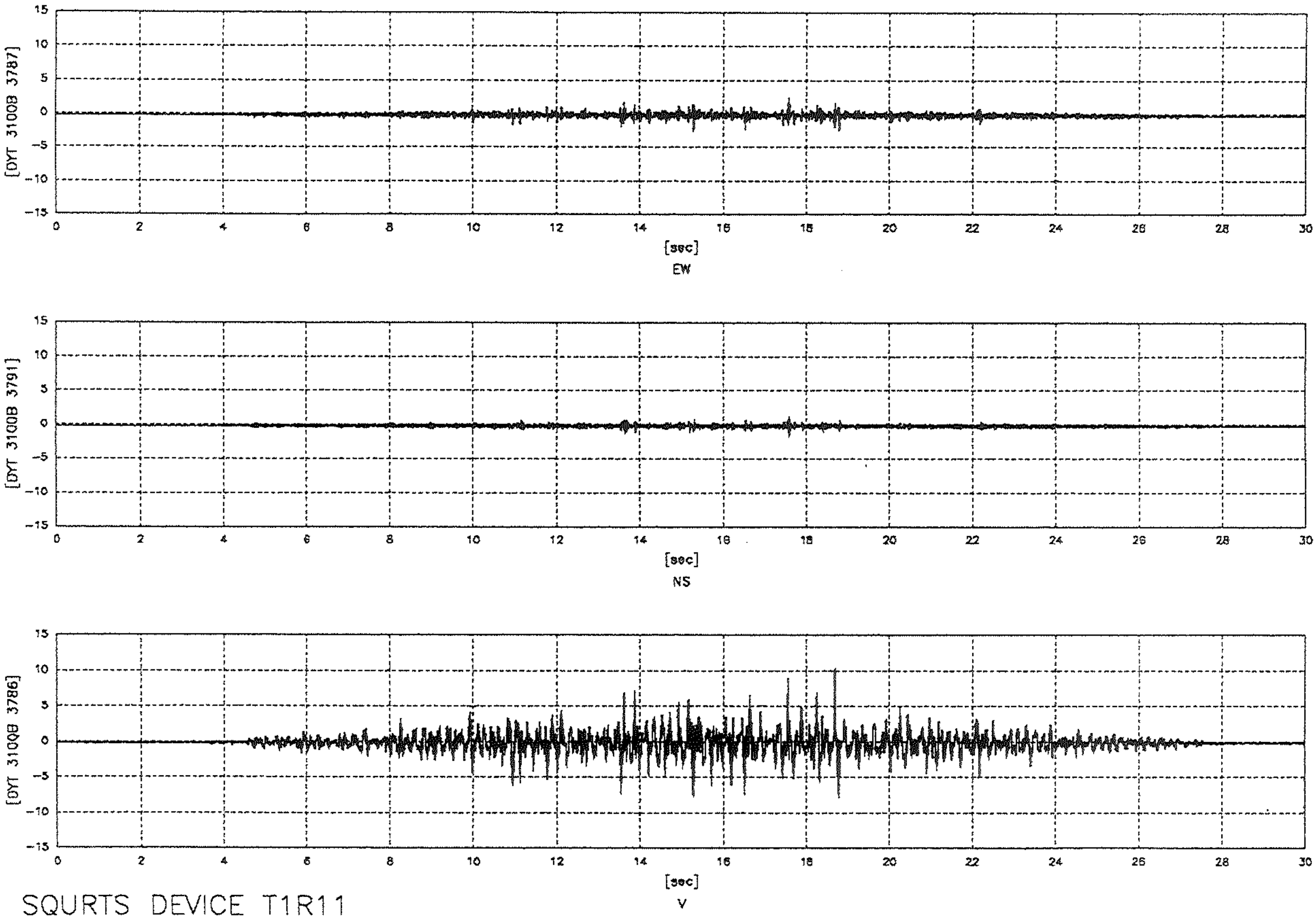

Figure 21. Case 3 Time Histories

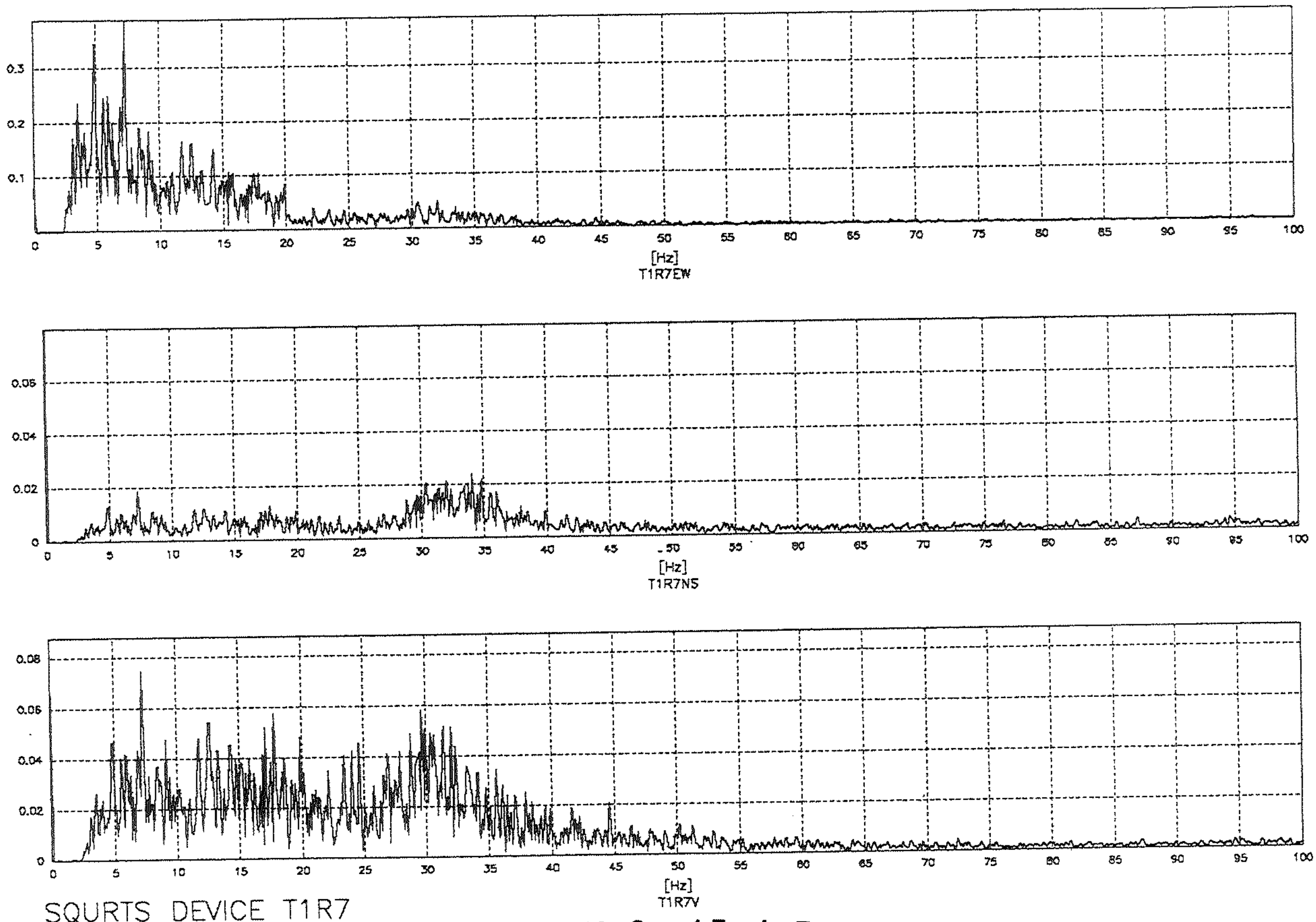

Figure 22. Case 1 Fourier Transforms

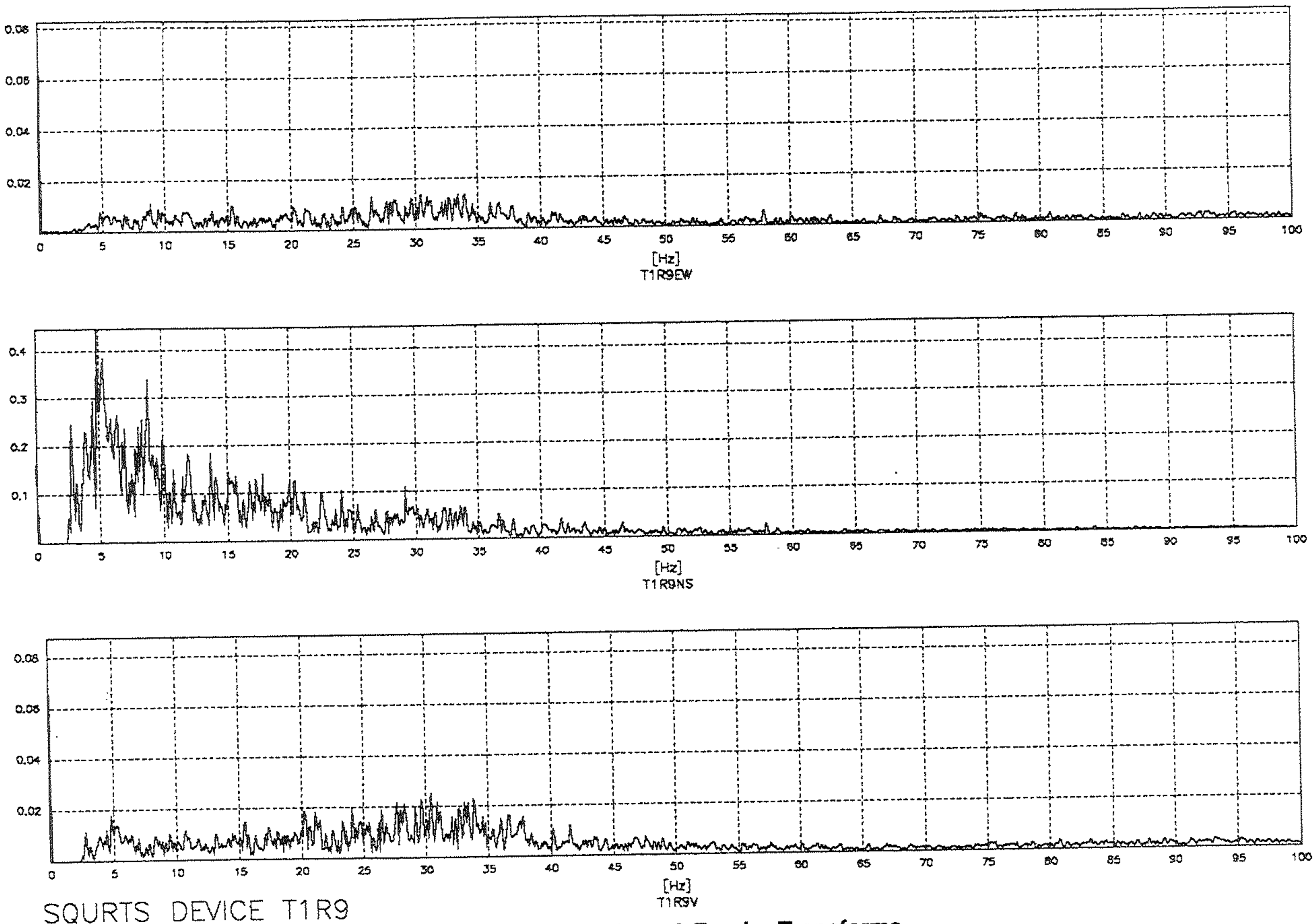

Figure 23. Case 2 Fourier Transforms

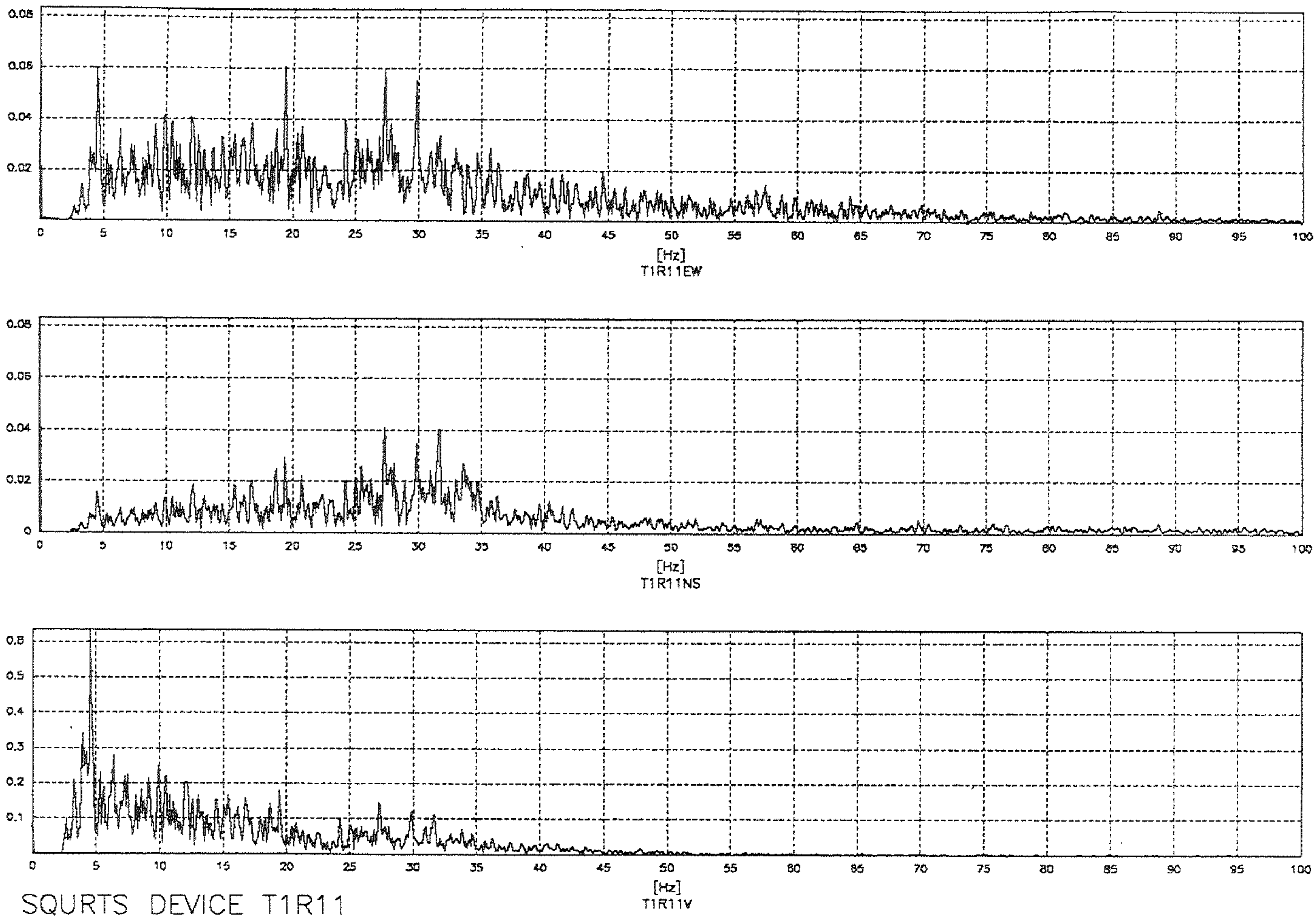

Figure 24. Case 3 Fourier Transforms

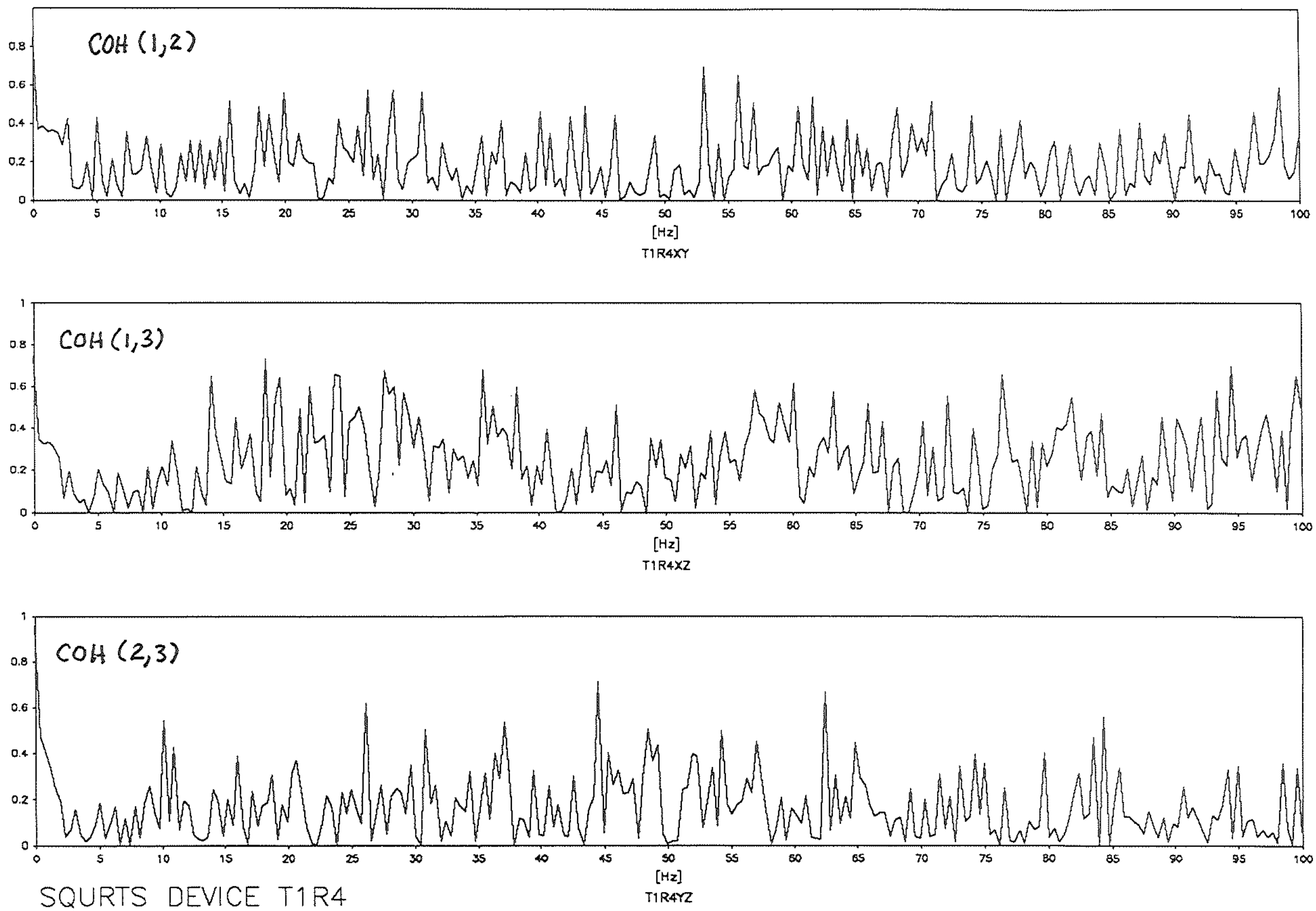

Figure 25. Coherence for Case 123

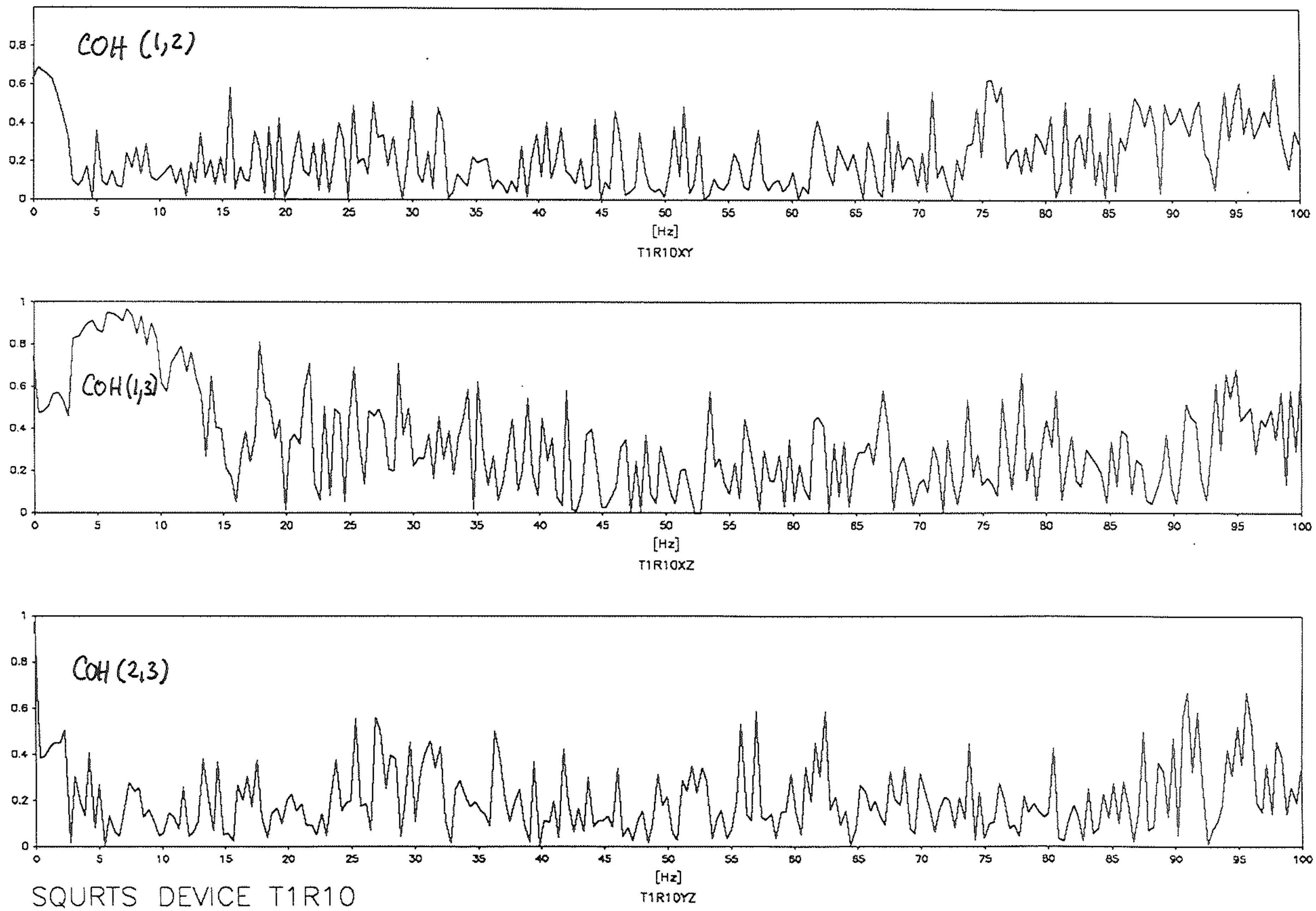

Figure 26. Coherence for Case 12

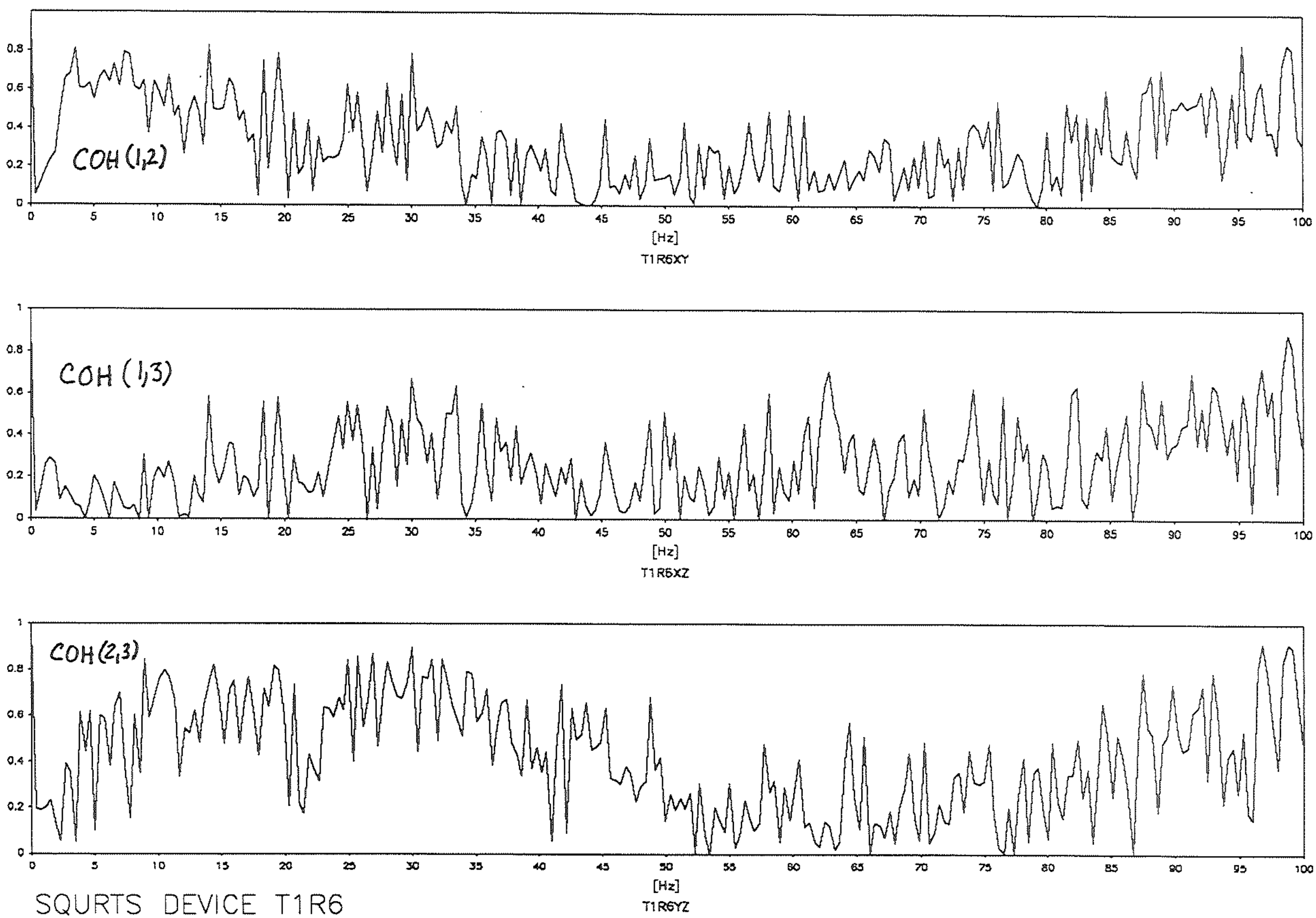

Figure 27. Coherence for Case 13

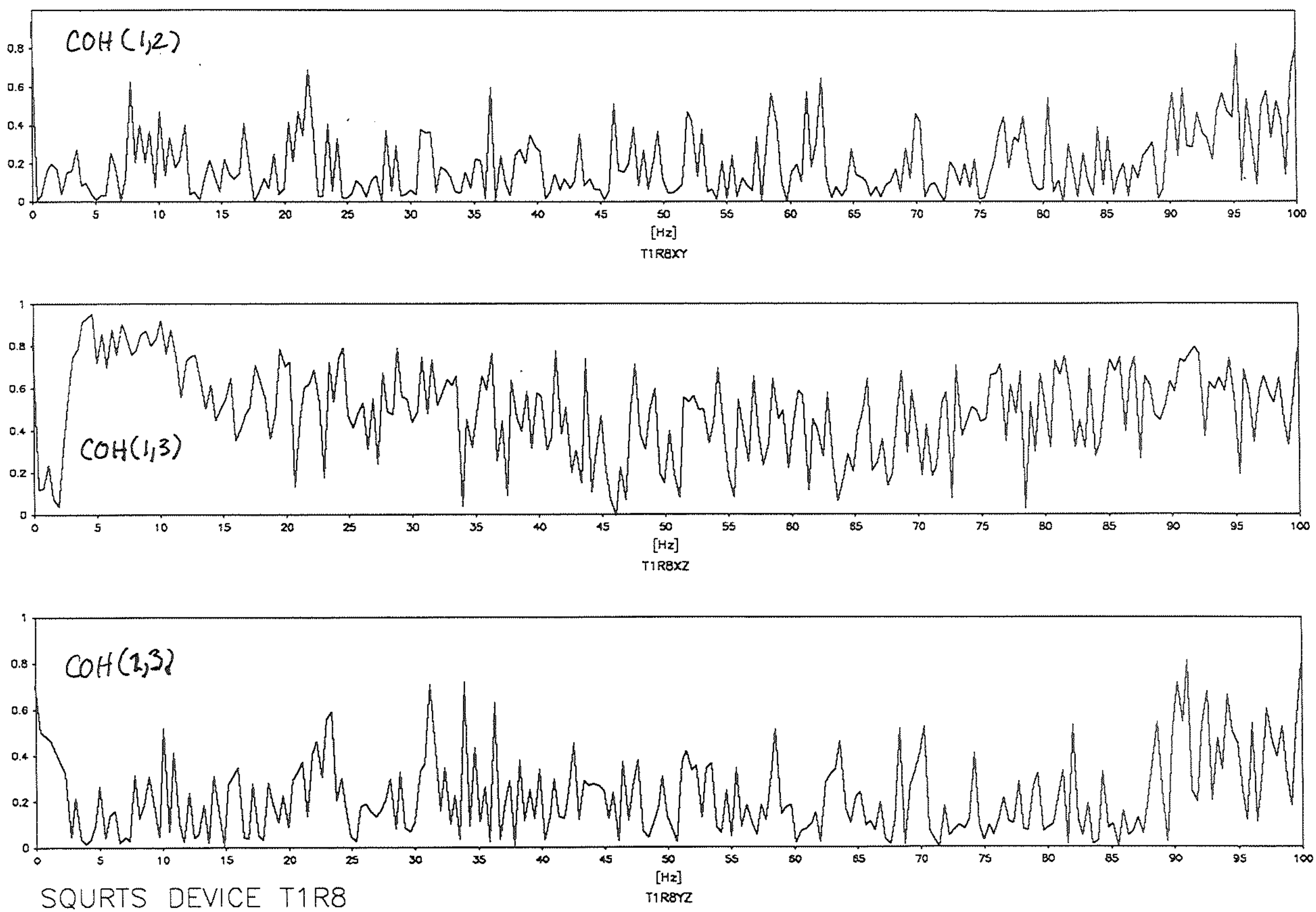

Figure 28. Coherence for Case 23

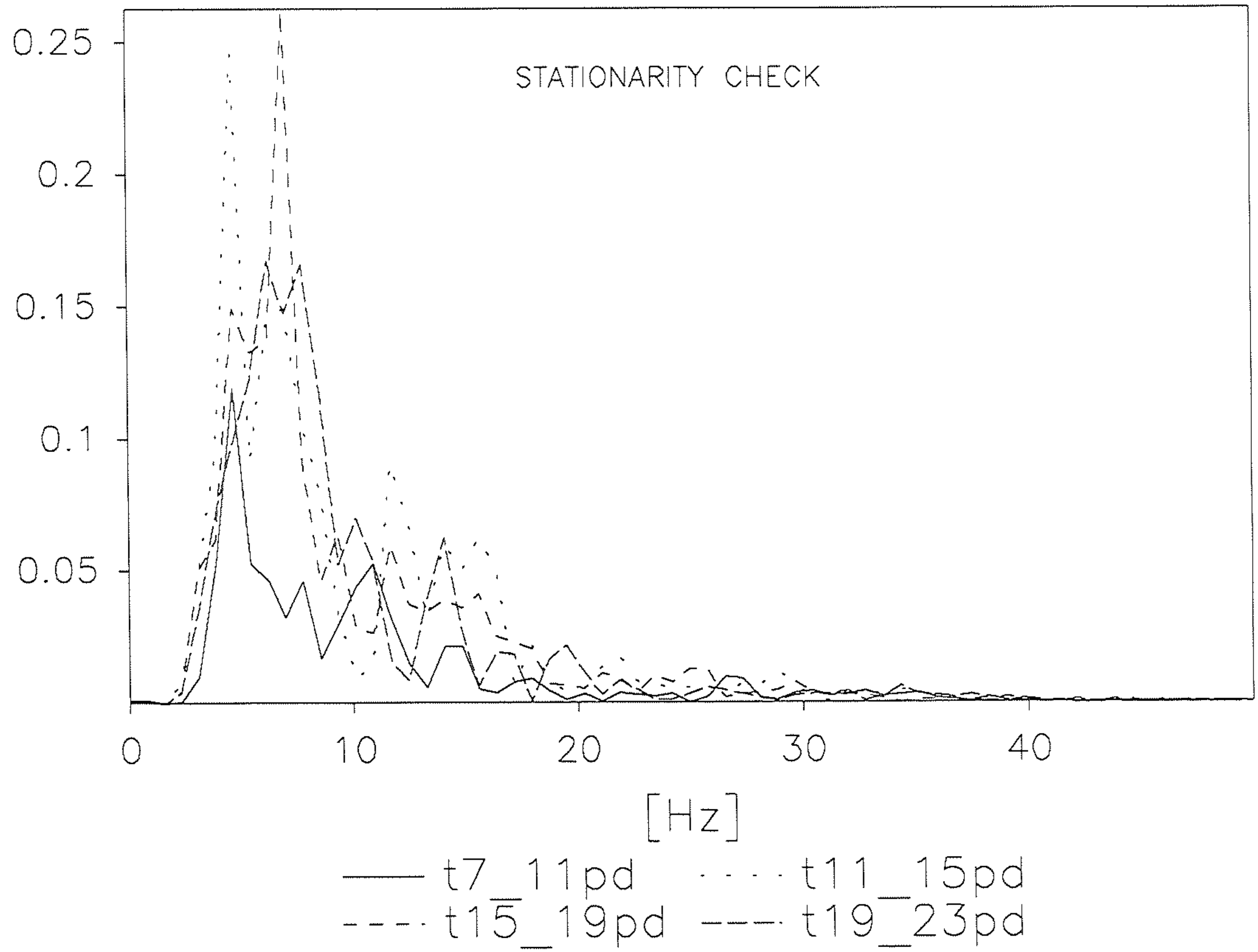

Figure 29. Direction 1, Time Segment PSD

		STATIONARY CHECK				
19-23SEC	7-11SEC	15-19SEC	11-15SEC	G-MAX	G-MIN	G-AVG
0.001366	0.001337	0.001303	0.001351	0.001366	0.001303	0.001339
0.001304	0.001359	0.001256	0.001448	0.001448	0.001256	0.001342
0.00003	0.000002	0.00002	0.000037	0.000037	0.000002	2.23E-05
0.004363	0.000816	0.004637	0.007855	0.007855	0.000816	0.004418
0.034861	0.010132	0.050564	0.049519	0.050564	0.010132	0.036269
0.071948	0.053079	0.062485	0.094684	0.094684	0.053079	0.070549
0.098981	0.119522	0.149734	0.24679	0.24679	0.098981	0.153757
0.123294	0.052743	0.1331	0.092227	0.1331	0.052743	0.100341
0.167544	0.046858	0.138296	0.146824	0.167544	0.046858	0.124881
0.147863	0.032633	0.26271	0.149924	0.26271	0.032633	0.148283
0.166225	0.046508	0.09292	0.106182	0.166225	0.046508	0.102959
0.117481	0.017161	0.046319	0.08058	0.117481	0.017161	0.065385
0.052398	0.030163	0.064368	0.033739	0.064368	0.030163	0.045167
0.070184	0.044593	0.028447	0.009517	0.070184	0.009517	0.038185
0.053677	0.053071	0.026487	0.015651	0.053677	0.015651	0.037222
0.016318	0.03204	0.060021	0.091584	0.091584	0.016318	0.049991
0.008727	0.015036	0.037646	0.068209	0.068209	0.008727	0.032405
0.039629	0.005987	0.035264	0.032167	0.039629	0.005987	0.028262
0.063004	0.021547	0.039248	0.060708	0.063004	0.021547	0.046127
0.026979	0.021551	0.036275	0.050423	0.050423	0.021551	0.033807
0.006824	0.005339	0.041436	0.063136	0.063136	0.005339	0.029184
0.019761	0.004086	0.025265	0.05098	0.05098	0.004086	0.025023
0.018541	0.008003	0.023809	0.00722	0.023809	0.00722	0.014393
0.00087	0.009397	0.020638	0.022252	0.022252	0.00087	0.013289
0.017169	0.004952	0.007791	0.00882	0.017169	0.004952	0.009683
0.022083	0.001643	0.007129	0.004412	0.022083	0.001643	0.008817
0.012224	0.003671	0.005796	0.005661	0.012224	0.003671	0.006838
0.003472	0.000977	0.011309	0.013939	0.013939	0.000977	0.007424
0.008906	0.004192	0.010199	0.018146	0.018146	0.004192	0.010361
0.005591	0.003631	0.004385	0.008282	0.008282	0.003631	0.005472
0.001356	0.002972	0.010593	0.007843	0.010593	0.001356	0.005691
0.001377	0.003664	0.008055	0.005358	0.008055	0.001377	0.004614
0.003861	0.000394	0.013131	0.006594	0.013131	0.000394	0.005995
0.006451	0.002456	0.013051	0.006473	0.013051	0.002456	0.007108
0.005008	0.010201	0.002371	0.004972	0.010201	0.002371	0.005638
0.003913	0.009486	0.003785	0.00743	0.009486	0.003785	0.006154
0.002561	0.002647	0.004477	0.00674	0.00674	0.002561	0.004106
0.001179	0.001388	0.005109	0.012863	0.012863	0.001179	0.005135
0.00303	0.003984	0.008365	0.007653	0.008365	0.00303	0.005758
0.003707	0.004916	0.004561	0.002243	0.004916	0.002243	0.003857
0.003949	0.003228	0.00268	0.001253	0.003949	0.001253	0.002778
0.004833	0.003764	0.003603	0.00373	0.004833	0.003603	0.003983
0.001176	0.004643	0.003322	0.004813	0.004813	0.001176	0.003489
0.002963	0.002864	0.002197	0.003376	0.003376	0.002197	0.00285
0.006921	0.003312	0.000391	0.005089	0.006921	0.000391	0.003928
0.003835	0.004289	0.001339	0.005201	0.005201	0.001339	0.003666

Figure 30. Spreadsheet Computation of Stationarity Criteria

0.002982	0.002213	0.001594	0.001986	0.002982	0.001594	0.002194
0.002377	0.001429	0.001418	0.002151	0.002377	0.001418	0.001844
0.00354	0.000861	0.001366	0.002641	0.00354	0.000861	0.002102
0.00239	0.000984	0.002199	0.001497	0.00239	0.000984	0.001768
0.001295	0.000531	0.00248	0.001034	0.00248	0.000531	0.001335
0.001933	0.000965	0.002137	0.000883	0.002137	0.000883	0.00148
0.000881	0.000768	0.001586	0.002155	0.002155	0.000768	0.001348
0.00071	0.000818	0.001235	0.001291	0.001291	0.00071	0.001014
0.001644	0.000294	0.000613	0.001291	0.001644	0.000294	0.000961
0.000901	0.000302	0.000131	0.000525	0.000901	0.000131	0.000465
0.000973	0.000458	0.001525	0.000946	0.001525	0.000458	0.000976
0.000935	0.000242	0.00184	0.000328	0.00184	0.000242	0.000836
0.000667	0.000056	0.000397	0.000097	0.000667	0.000056	0.000304
0.000743	0.000156	0.000281	0.001525	0.001525	0.000156	0.000676
0.000718	0.000159	0.000194	0.001361	0.001361	0.000159	0.000608
0.000752	0.000204	0.000157	0.000402	0.000752	0.000157	0.000379
0.000525	0.000698	0.000213	0.000171	0.000698	0.000171	0.000402
0.000264	0.000891	0.000627	0.000442	0.000891	0.000264	0.000556
0.000407	0.00032	0.000551	0.000339	0.000551	0.00032	0.000404
			AVG.	0.033248	0.008744	0.020701
	STATIONARITY		R-MAX	1.606065	OK	
	STATIONARITY		R-MIN	0.422404	OK	

Figure 30 (concluded)