FalconSAT-3 Structural Engineering Model #2 Test Report
Appendix: Key Data and Interpretation

CONTENTS

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1. Introduction

This report contains observations made and conclusions drawn by myself, Tom Sarafin. I was not present during testing so can report only on my interpretation of the data, along with the following additional information:

- Test photos showing test configurations and accelerometer locations
- Analysis I had done with the CDR-pedigree finite-element models, FS3FM-2LS and FS3FM-2L (with and without the Shock Ring), in September 2003. These models matched the flight design as of the CDR and, as such, did not accurately represent the SEM-2. My understanding is that the SEM-2 was approximately 10 lb lighter than the flight design, with the difference mostly in the MPACS simulators.

Section 2. summarizes the key conclusions and recommendations. Sections 3 – 6 give observations and conclusions for each axis and configuration tested

2. Summary of Conclusions and Recommendations

2.1 Overall Structural Integrity

The SEM-2 appeared to withstand all test environments without damage.

2.2 Shock Ring Performance

When at room temperature, the Shock Ring reduced the fundamental rocking frequency from 91 Hz to 33 Hz and created a fundamental axial (bouncing) frequency of 92 Hz. The visco-elastic material (VEM) in the Shock Ring adds damping by dissipating heat; as it works in shear, it heats up. When it does so, its stiffness drops. Sine sweeps conducted immediately after qualification random vibration testing showed the fundamental rocking and axial frequencies dropped to 30 Hz and 86 Hz, respectively.

I believe the Shock Ring was designed to provide a 30-Hz fundamental rocking mode at room temperature. The actual frequency was 33 Hz, not because of a design deficiency in the Shock Ring but because the SEM-2 weighed approximately 10 lb less than intended, with most of the missing mass at the top.

With the Shock Ring, the top panel of the SEM-2 responded to acceptance-level lateral random vibration with 8.8 g-rms acceleration, or about 4 g-rms associated only with the fundamental rocking mode. In the qual run (6 dB above acceptance), the top-panel acceleration associated only with the rocking mode was about 6.5 g-rms. The 3-sigma level for acceptance and qualification were about 12 g and 18.5 g for the rocking mode. As a point of comparison, the qualification-level quasi-static load is 15 g when the Shock Ring is present and 21.3 g when it is not. Note that, because acceleration builds linearly from the shaker to the top panel, the center of gravity saw considerably less acceleration than 18.5 g on a 3-sigma basis. Without actually doing the analysis, I believe the 3-sigma response in random vibration did not load up the base of the structure (or the Shock Ring) as highly as did the sine-burst test. Thus, there was (and is) no need to notch the test environment with the Shock Ring present.

Without the Shock Ring, the response of the top panel during random vibration at levels 3 dB below acceptance was 10.8 g-rms, with 8.5 g-rms associated only with the rocking mode. Acceptance levels were not run, but, if the structure stays linear, response at such levels should be 41% greater as a result of the 3-dB increase. This makes the predicted response of just the rocking mode 12.0 g-rms at the top panel for acceptance, as compared with 4 g-rms when the shock ring was used. The 3-sigma response without the Shock Ring would be approximately 36 g for acceptance and 72 g for qual. **Thus, the Shock Ring appears to have reduced stresses in the base plate and adapter ring by about 75%.**

In the Z (axial) direction, the Shock ring reduced the response at center of the top panel by about 50%, from 59 g-rms (projected) to 30 g-rms at qual levels. However, many lateral accelerations were not significantly reduced by the presence of the Shock Ring. This is not surprising because the Shock Ring was not designed to provide lateral isolation.

2.3 Boom Response

With the Shock Ring present, the tip of the boom simulator experienced a lateral acceleration of 33 g-rms at acceptance levels, nearly all of which was associated with the boom's rocking mode (Fig. 7). This is nearly 100 g at 3-sigma. In the qualification test—predicted at this point to cause twice the peak acceleration for the boom—an unexplained anomaly occurred. Something in the structure became nonlinear (my guess is shifting of the bolted joint between the boom and the base plate), and response of the boom's rocking mode was severely blunted, with actually a lower acceleration than was measured during the acceptance test. Although the structure appeared to suffer no permanent damage, such behavior is not good because it presents an unquantifiable risk. A common result of joint shifting is loss of preload in the bolts and possible fatigue failure.

As I pointed out last fall, as a result of vibration analysis, I recommend the boom be designed to have a rocking frequency of about 50 to 70 Hz. In the test, this mode had a frequency of about 140 Hz. Reducing the natural frequency will greatly reduce the boom's loads.

Axial (Z) response of the boom was not measured in the test.

2.4 Module Stack Response

In the lateral direction, with Shock Ring, data from the acceptance-level random vibration test is meaningful or valid (Fig. 6), whereas for the qual test it is not. Something went wrong either with the instrument or the data processing. At acceptance, the stack top saw 26.9 g-rms, with most of the energy between 200 and 500 Hz.

In the axial (Z) direction, all data was contaminated by what appears to be high-frequency response of a plate-bending mode in the simulator near 240 Hz. In assessing or testing module capability, I recommend ignoring the 240-Hz peak in the response PSD (Fig. 29).

2.5 MPACS Response

In both lateral and axial directions, the data was contaminated by what appears to be high-frequency response of multiple bending modes in the thin side wall for the MPACS simulator. In assessing or testing the capability of the actual MPACS, I recommend ignoring the peaks in the response PSDs above about 400 Hz (Figs. 9 and 30). Response PSDs for the center of the top panel (Figs. 5 and 28) are probably much more representative of the high-frequency inputs to the MPACS. Bottom line: The vibration environments for the MPACS should be much less severe than are indicated by Figs. 9 and 30.

2.6 Sine-burst Anomalies and Shaker Stroke Limitations

Three anomalies occurred during sine-burst testing. First, in the lateral test with Shock Ring, the low (33-Hz) fundamental frequency of the SEM-2 required low-frequency input to avoid significant dynamic gain in the response. The shaker did not have enough stroke to obtain the specified 15 g at low frequency. The test was done to 13 g at 17 Hz. The dynamic response, however, was high enough that this was a sufficient test (the overturning moment in the Shock Ring was at least as high as would have been achieved by a quasi-static 15 g). To aide planning for future tests, I generated Table 1, which gives the allowable acceleration vs. frequency that should be counted on for the Kirtland shaker.

Table 1. Maximum Acceleration Capability of the Kirtland Shaker in Sine-burst Tests.

Stroke (maximum full-range displacement) of shaker: 1.00 inch
Max displacement of shaker from zero = half the stroke: 0.50 inch
f = forcing frequency in cycles per second
w = forcing frequency in radians per second = 2*pi*f

a-max = maximum acceleration = max displacement * w^2
a-allow = 80% of a-max (to account for the shaker not being centered at start)
(a-allow is the assumed max acceleration that you can count on the shaker providing)

f (Hz)	w (rad/s)	a-max (in/s^2)	a-allow (in/s^2)	a-max (g)	a-allow (g)
6	37.7	711	568	1.8	1.5
7	44.0	967	774	2.5	2.0
8	50.3	1263	1011	3.3	2.6
9	56.5	1599	1279	4.1	3.3
10	62.8	1974	1579	5.1	4.1
11	69.1	2388	1911	6.2	4.9
12	75.4	2842	2274	7.4	5.9
13	81.7	3336	2669	8.6	6.9
14	88.0	3869	3095	10.0	8.0
15	94.2	4441	3553	11.5	9.2
16	100.5	5053	4043	13.1	10.5
17	106.8	5705	4564	14.8	11.8
18	113.1	6396	5116	16.6	13.3
19	119.4	7126	5701	18.5	14.8
20	125.7	7896	6317	20.4	16.4
21	131.9	8705	6964	22.5	18.0
22	138.2	9554	7643	24.7	19.8
23	144.5	10442	8354	27.0	21.6
24	150.8	11370	9096	29.4	23.6
25	157.1	12337	9870	32.0	25.6
26	163.4	13344	10675	34.6	27.6
27	169.6	14390	11512	37.3	29.8
28	175.9	15476	12380	40.1	32.1
29	182.2	16601	13281	43.0	34.4
30	188.5	17765	14212	46.0	36.8

The second anomaly occurred in the Z-axis test without Shock Ring. For presently unknown reason, the shaker suddenly stopped half-way through the test, causing a high dynamic response in the SEM-2 (Fig. 23). The structure was not damaged, but someone needs to get to the root of this problem, determine its cause, and correct it so it won't happen again. The test was run to 21.3 g at 25 Hz, which is well within the capability of the shaker, as shown in Table 1, unless the shaker did not start in a relatively centered position. This problem has occurred several times in previous tests (one coming to mind is the FS2 engineering model test). Depending on the configuration and the nature of the event, such an occurrence may cause damage to future FalconSAT hardware.

The third anomaly also occurred in the Z-axis test without Shock Ring. Following the above sudden stop, the frequency was raised to 35 Hz. The test was successful, but distortion in the input wave form cause cross-axis excitation of the harmonic 105-Hz lateral rocking mode. Again, nothing was damaged, but the test lab should be more careful in the future about ensuring the input is a true sinusoid.

2.7 Recommendations for Future Tests

- Come prepared with predicted mode shapes and responses to random vibration to aid in real-time data interpretation. If you wait until after the test to find problems, nothing can be done about them. Some problems may relate to whether the test article has been properly assembled or adequately tested; others may mean that important data are not obtained. Identifying suspicious-looking data during test allows you to call it to the attention of the test technician, who usually can fix the problem and get you good data.
- Be more meticulous about assessing pass/fail criteria associated with sine-sweep data. As noted herein, several tests did not pass the criteria (more than 5% change in natural frequency and 20% drop in peak).
- When testing with the Shock Ring, or any other device containing visco-elastic materials (VEMs), allow the VEM to cool down before running the final sine sweep. Otherwise, as occurred here, the pre- and post-test sine sweeps will not compare well because the stiffness of the VEM changes with temperature. The sine-sweep data is the best tool for assessing structural health following testing.
- Take care in placing accelerometers to dodge locations affected by unimportant, local shell modes.
- Make sure accelerations of large-mass items such as the boom simulator are measured in the axis of excitation. In this test, not enough channels of instrumentation were available to accommodate all the data requested. In future such cases, plan to reorient accelerometers as needed between tested axes. If there will be no access to accelerometers between tested axes, initially install a tri-axial accelerometer, label the wires and route them through an access hole, and then repatch wires between tests.
- Take better care in taking, retaining, and documenting field notes. My understanding is that actual locations of accelerometers were measured from reference surfaces, but such measurements were not available to me to support data interpretation. Also, during test it is easy to determine actual frequencies for response peaks. Afterwards, the data is available digitally, but it takes much more time to get that data. I did not have such time available, so I simply read the frequencies off the plots by eye, which is not very accurate. Field notes should be documented in the form of an appendix to the report as soon as possible after the test so that key information is not lost.

- Request the test-lab personnel at Kirtland to investigate the cause of the sudden stop of the shaker during sine-burst testing. This anomaly has occurred repeatedly in FalconSAT testing and needs to be corrected. Otherwise, flight hardware may be damaged.
- Request test-lab personnel to test the shaker's sinusoidal input for sine-burst testing to make sure it is a true sinusoidal function. Other input functions can excite harmonic modes.
- In case the above problem is not corrected, avoid running the sine-burst test at frequencies that are 1/3 that of any known resonant frequencies in the test article. The third harmonic is particularly sensitive to distortion in the input.
- When planning sine-burst tests, recognize shaker limitations regarding peak acceleration versus frequency.

3. Y Axis, With Shock Ring

Key natural frequencies (only as accurate as can be read from the plots):

- Fundamental (overall rocking): 33 Hz
- Stack rocking, with outer structure rocking opposite: 235 Hz
- Boom rocking: 140 Hz

Figures 1 – 3 show these modes in data from the initial sine sweep.

3.1 Sine-burst Test

The sine-burst test was planned for 15-g peak acceleration at a frequency of 1/3 that of the fundamental frequency to ensure there would be little dynamic amplification. Because the fundamental frequency was about 33 Hz, the intended test frequency was 11 Hz. The shaker at Kirtland does not have enough stroke (range of motion) to reach 15 g at 11 Hz. The test was run at 17 Hz, reaching a peak acceleration of 13 g.

On the surface, it would appear the sine-burst test did not sufficiently load the Shock Ring. (The objective of this test was to verify the strength of the Shock Ring to qualification loads, building confidence in the preliminary design until the flight design is qualified to the same loads in the upcoming FS3 Qualification Model (QM) test. The sine-burst test done in the configuration without the Shock Ring tested the rest of the SEM-2 structure, and the same test on the QM will qualify the FS3 structure.) However, because the test frequency of 17 Hz was nearer the fundamental frequency than intended, the SEM-2 experienced considerably greater acceleration than the input acceleration, as a dynamic response. As Fig. 4 shows, the top panel saw a peak acceleration of about 20 g.

Assuming acceleration varied linearly over the distance between the Shock Ring and the top panel, from the 13-g input to the 20-g peak response, the SEM-2 center of gravity experienced at least 16 g, which exceeds the target level of 15 g. In addition, the rigid-body rotational acceleration caused even greater moment on the Shock Ring. Thus, the test met its objectives and demonstrated margin in the strength of the Shock Ring.

3.2 Random Vibration Test

The full qualification levels (16.3 g-rms) were sustained. Table 2 gives the measured response accelerations (g-rms) for both acceptance and qualification levels.

Table 2. Response Levels (g-rms) for Random Vibration Testing in the Y Axis, with Shock Ring.

Location & Direction	Acceptance Level (8.17 g-rms input)	Qualification Level (Accep +6 dB)
Top center Y	8.8 (Fig. 5)	11.7
Stack top Y	26.9 (Fig. 6)	(bad data—see text)
Boom tip Y	33.0 (Fig. 7)	24.6 (Fig. 8)
MPACS Y	78.8* (Fig. 9)	114*
Antenna bracket (unknown orientation)	36.1	37.9
*The RMS accelerations for the MPACS simulators are not an accurate representation of the environment that the actual MPACS will experience during test or flight. See Sec. 2.5.		

The following data are considered bad or suspect for random vibration testing in this configuration:

- Ch. 6, Y panel Y axis for both acceptance and qualification levels (suspected saturation or other problem)
- Stack top Y for qualification levels (suspected saturation or other problem; Fig. 10). Data from the acceptance-level test appear valid (Fig. 6).
- MPACS Y—Measured RMS response acceleration is, I believe, artificially high as a result of several high-frequency modes in the MPACS simulator (Fig. 6). (See discussion of MPACS data in Sec. 2.5.)

An unexplained anomaly relates to the boom simulator. The response of the boom in the acceptance-level test has a pronounced peak at about 140 Hz (Fig. 7), with an RMS acceleration of 33.0 g. At qual levels, though, the peak flattened (Fig. 8), with 24.6 g-rms total response. At 6 dB up from acceptance, this response would have been 66 g-rms if the structure had remained linear. The cross-axis response (Boom Tip X) shows similar results, so I don't think the problem is with the data. One possible explanation is that the bolted joint between the boom and the base plate shifted under the higher loads. This anomaly should have been investigated during the test.

3.3 Comparison of Pre- and Post-test Sine-sweep Data (success criteria):

Between the initial sine sweep and the final one, after the qual-level random vibration, the fundamental frequency dropped from 33 Hz to 30 Hz. This drop apparently was because the shear stiffness of the visco-elastic material (VEM) in the Shock Ring drops with temperature. Two minutes of qualification-level random vibration worked the VEM and caused it to heat up. Unfortunately, this frequency shift prevents us from conclusively judging whether the structure suffered any damage during testing. The success criteria—no frequency shifts greater than 5% for key modes and no drop in the associated peaks greater than 20%--are clearly not satisfied, not only for the fundamental mode but also the boom-rocking mode and the stack-rocking mode. (See Figures 11 to 13.) It is unknown whether the shifts in higher-frequency peaks are the result of the nonlinearity in the Shock Ring or degradation of the structure. In the future, a second post-test sine sweep should be conducted after the VEM has cooled.

4. Y Axis, No Shock Ring

Key natural frequencies (only as accurate as can be read from the plots):

- Fundamental (overall rocking): 91 Hz
- Stack rocking, with outer structure rocking opposite: 250 Hz
- Boom rocking: 145 Hz

Figure 14 shows these modes in data from the initial sine sweep, as measured at the top panel.

4.1 Sine-burst Test

This test was done to 21.3 g at 25 Hz. The top panel had a peak response of about 24 g. No anomalies noted.

4.2 Random Vibration Test

This configuration was tested, as planned, to levels 3 dB below acceptance. Table 3 gives the measured response accelerations (g-rms).

Table 3. Response Levels (g-rms) for Random Vibration Testing in the Y Axis, No Shock Ring.

Location & Direction	Max Tested Level (5.8 g-rms input)
Top center Y	10.8 (Fig. 15)
Stack top Y	27.3 (Fig. 16)
Boom tip Y	28.8 (Fig. 17)

The following data are considered bad or suspect for random vibration testing in this configuration:

- Ch. 6, Y panel Y axis
- MPAC Y—Measured RMS response acceleration is, I believe, artificially high as a result of several high-frequency modes in the MPACS simulator.

4.3 Comparison of Pre- and Post-test Sine-sweep Data (success criteria):

No anomalies noted.

5. Z Axis, No Shock Ring

Key natural frequencies (only as accurate as can be read from the plots):

- Fundamental (top panel bending): 170 Hz
- Fundamental rocking: 110 Hz
- Local mode on stack top: 235 Hz
- Boom axial (suspected): 310 Hz
- Boom axial (suspected: boom up, everything else down): 410 Hz

Figures 18 - 21 show these modes in data from the initial sine sweep. I believe the 235-Hz mode is a local plate mode on the top equipment simulator in the stack and thus is not meaningful for the actual equipment modules. This conclusion is based on the following:

- The 235-Hz mode shows strongly only in the acceleration measured at the stack top (Fig. 21).
- Analysis with the CDR-pedigree finite-element model, FS3FM-2L, predicts no axial mode for the stack below 400 Hz.
- The accelerometer was placed in the center of the mass simulator's 0.157-inch-thick machined plate (Fig. 22). In the future, accelerometers should be mounted in locations that would not influence or respond much in local modes that are not important.

Axial (Z) response of the boom simulator was not measured. Thus, the conclusion that the 235-Hz mode is local plate bending may be incorrect. The suspected boom modes noted above are based on analysis with the FS3FM-2L model and comparison of sine-sweep data at different locations (Figs. 18 – 21). In future such tests, accelerometers should be used in the axis of excitation for all high-mass items.

5.1 Sine-burst Test

The 21.3-g sine-burst test was first attempted at 25 Hz. Upon achieving the peak acceleration, the shaker suddenly stopped, causing high transient loads in the SEM-2. The 170-Hz axial mode of the top panel responded with a peak acceleration measured at about 40 g (Fig. 23). The 235-Hz local mode in the top module simulator saw a peak of 68 g. These accelerations were not as high as those achieved during qual-level random vibration in the Z axis with the Shock Ring (Sec. 6.). It is unknown how much acceleration the boom experienced during this test.

Although nothing was apparently damaged, it is imperative that the test lab investigate and correct the cause of this anomaly. Depending on how the shaker stops next time (at what point in the sine trace and how abruptly), damage could be done to qualification or flight hardware. Shaker stroke limit should not have been encroached in this test. As discussed in Sec. 2.6, at 25 Hz the shaker should have been able to achieve 32-g acceleration if it had been properly centered.

The test was repeated at 35 Hz, successfully reaching 21.3 g. This test excited the overall rocking mode at about 105 Hz, which is a harmonic to the input (three times the input frequency). If the shaker moved with purely sinusoidal motion, the 105-Hz mode should not have been excited. I enlisted the aid of Pete Abbott, a dynamics expert, and he believes the excitation is the result of distortion in the input wave form. Figure 24 shows the Y-axis response measured at the top panel superimposed onto the input acceleration, as measured on the adapter plate. As can be seen, the input is not a true sinusoid.

In the future, before the test the test lab should check the input to make it more closely sinusoidal. The lateral response was not insignificant, peaking at 18 g. Such distortion could cause hardware damage in future tests. A second recommendation is to avoid sine-burst tests at a frequency of 1/3 that of one of the test article's natural frequencies. Pete told me that the 3rd harmonic is most sensitive to distortion.

5.2 Random Vibration Test

This configuration was tested, as planned, to levels 3 dB below acceptance. Table 4 gives the measured response accelerations (g-rms).

Table 4. Response Levels (g-rms) for Random Vibration Testing in the Z Axis, No Shock Ring.

Location & Direction	Max Tested Level (5.6 g-rms input)
Top center Z	20.9
Stack top Z	80.2

The following data are considered bad or suspect for random vibration testing in this configuration:

- Ch. 6, Y panel Y axis
- Stack top Z—The data is good except the large peak at 235 Hz, which provides most of the RMS acceleration, is the result of a local plate mode on the simulator, which has no meaning for the flight modules.
- MPAC Z—Measured RMS response acceleration is, I believe, artificially high as a result of several high-frequency modes in the MPACS simulator.

5.3 Comparison of Pre- and Post-test Sine-sweep Data (success criteria):

No anomalies noted.

6. Z Axis, with Shock Ring

Key natural frequencies (only as accurate as can be read from the plots):

- Fundamental (overall axial): 92 Hz
- Top panel bending: 185 Hz
- Local mode on stack top: 250 Hz

- Boom axial (suspected): 380 Hz
- Boom axial (suspected: boom up, everything else down): 450 Hz

Figures 25 - 27 show these modes in data from the initial sine sweep.

Axial (Z) response of the boom simulator was not measured.

6.1 Sine-burst Test

The 21.3-g sine-burst test was successfully conducted at 25 Hz. There was again a small amount of distortion in the input wave form, but there was little response of the SEM-2's modes.

6.2 Random Vibration Test

The full qualification levels (16.3 g-rms) were sustained. Table 5 gives the measured response accelerations (g-rms) for both acceptance-minus-3dB and qualification levels. Acceptance levels were not run.

Table 5. Response Levels (g-rms) for Random Vibration Testing in the Z Axis, with Shock Ring.

Location & Direction	3 dB below Accep (5.8 g-rms input)	Qualification Level (Accep +6 dB)
Top center Z	7.8	29.9 (Fig. 28)
Stack top Z	10.1*	37.9* (Fig. 29)
MPACS Z	23.0*	76.3* (Fig. 30)

*The RMS accelerations for the stack top and the MPACS simulator are not an accurate representation of the environment that the actual equipment will experience during test or flight. See below text, Sec. 2.4, and Sec. 2.5.

Worth noting is the high cross-axis response at 820 Hz. Figure 31 shows the response PSD for Y-axis acceleration measured at the center of the top panel. The high peak at 820 Hz appears also in the X axis and at several other locations. I do not know what mode this is, but the response acceleration is quite high at that frequency. Nearly all of the 10.3 g-rms response for "top center Y" was associated with this unknown mode. Any PSD's generated for separately testing FS3 equipment should include this peak.

The following data are considered bad or suspect for random vibration testing in this configuration:

- Ch. 6, Y panel Y axis
- Stack top Z—The data is good except the large peak at 240 Hz, which provides much of the RMS acceleration, is probably the result of a local plate mode on the simulator, which has no meaning for the flight modules.
- MPAC Z—Measured RMS response acceleration is, I believe, artificially high as a result of several high-frequency modes in the MPACS simulator.

6.3 Comparison of Pre- and Post-test Sine-sweep Data (success criteria):

The fundamental axial frequency dropped from 92 Hz to 86 Hz. This drop is most likely the result of the VEM in the Shock Ring heating up and becoming less stiff during the qual-level random vibration test. Otherwise, there were no significant shifts or drops in the key peaks.

Data for "Stack top X" in the final sine sweep looks bad (no good).

7. Supporting Data Plots and Photos

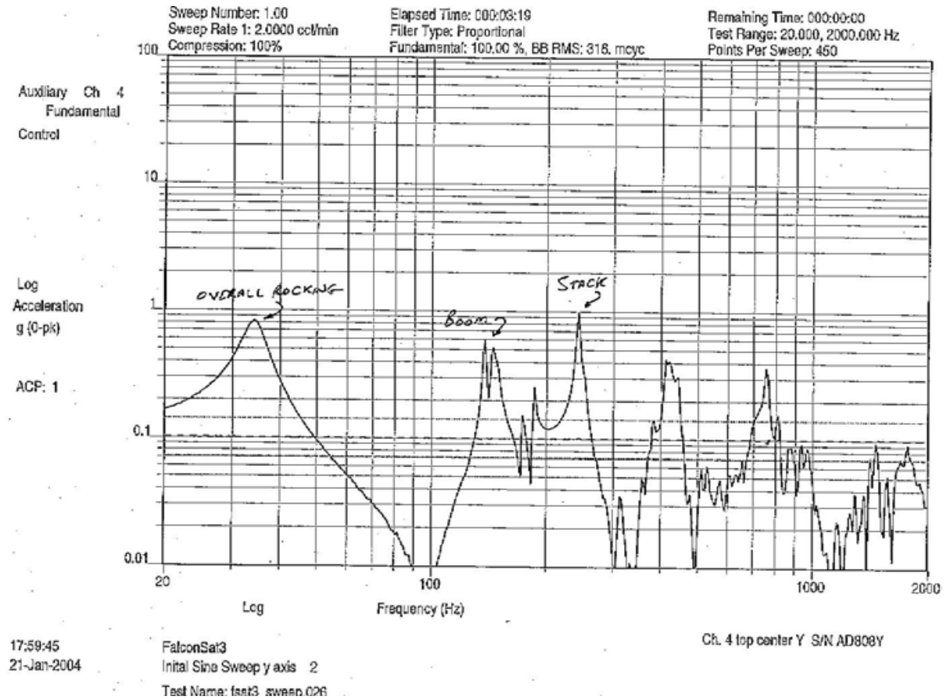

Fig. 1. Y Axis, with Shock Ring, Initial Sine Sweep—Top Center Y Response.

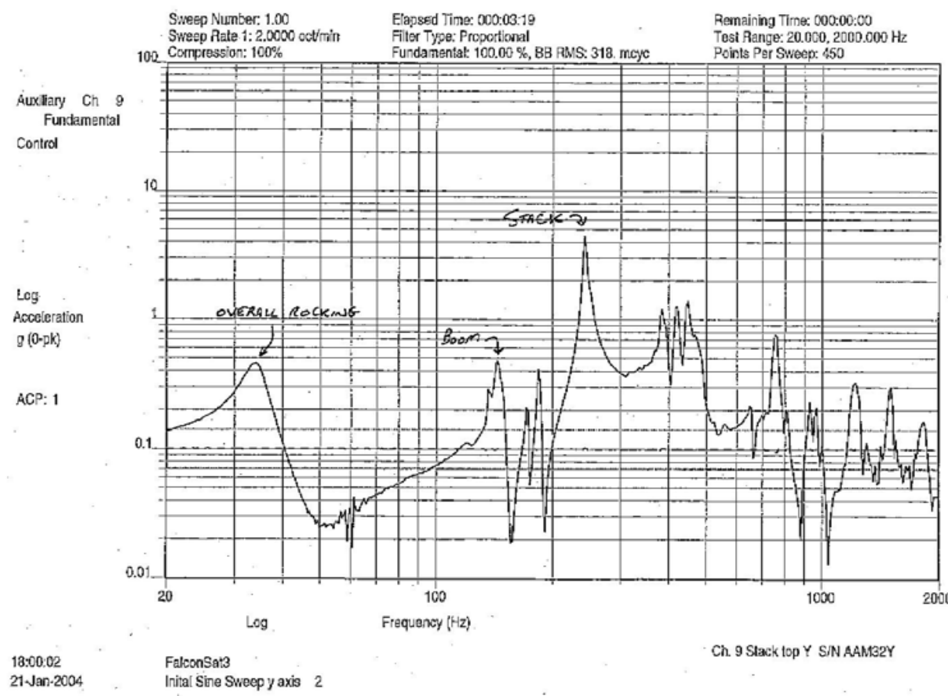

Fig. 2. Y Axis, with Shock Ring, Initial Sine Sweep —Stack Top Y Response.

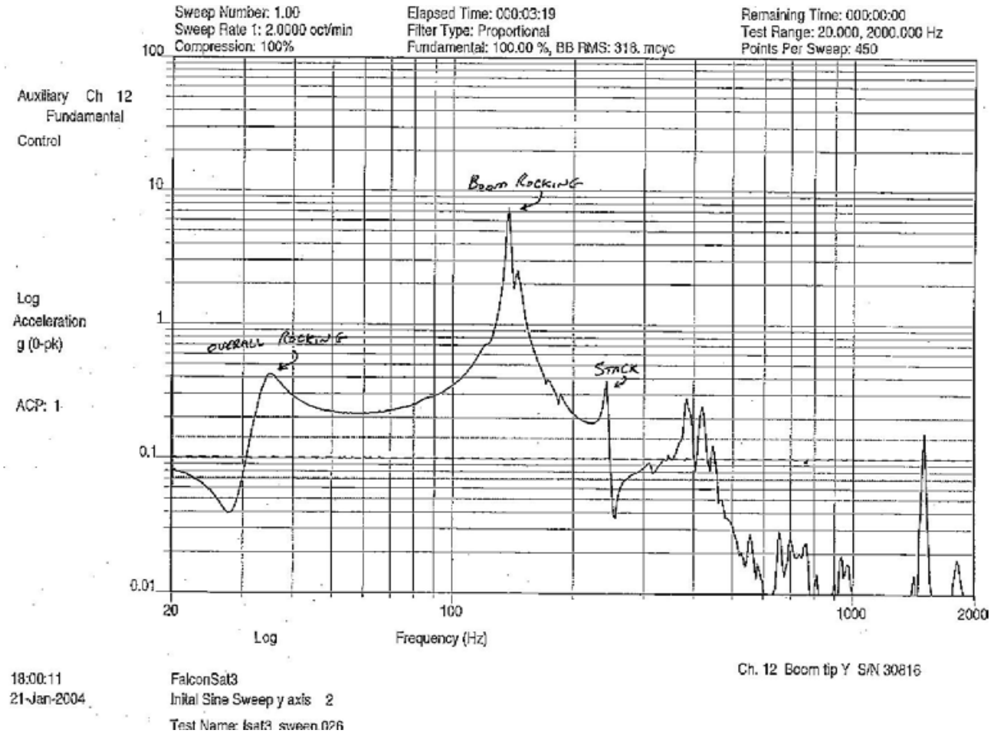

Fig. 3. **Y Axis, with Shock Ring, Initial Sine Sweep —Boom Tip Y Response.**

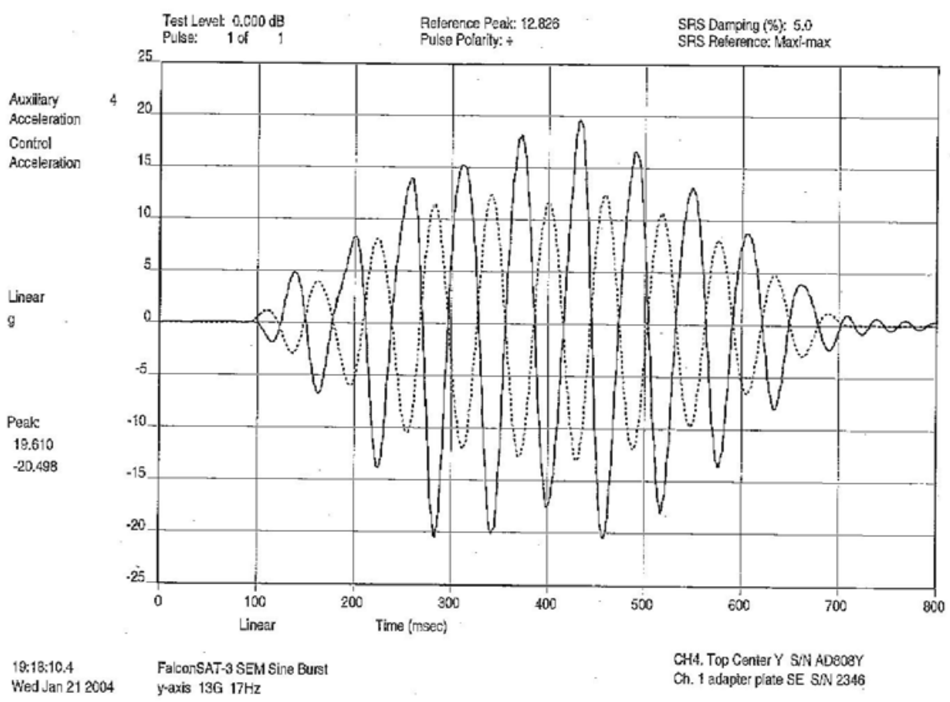

Fig. 4. **Y Axis, with Shock Ring, Sine-burst Test—Top Panel Y Response.** For 13-g input at 17 Hz, the top of the SEM-2 responded with a peak acceleration of about 20 g's. Note that the response and input plots are 180 degrees out of phase. This is not what actually happened. The accelerometers were either mounted or wired to read opposite in sign from each other.

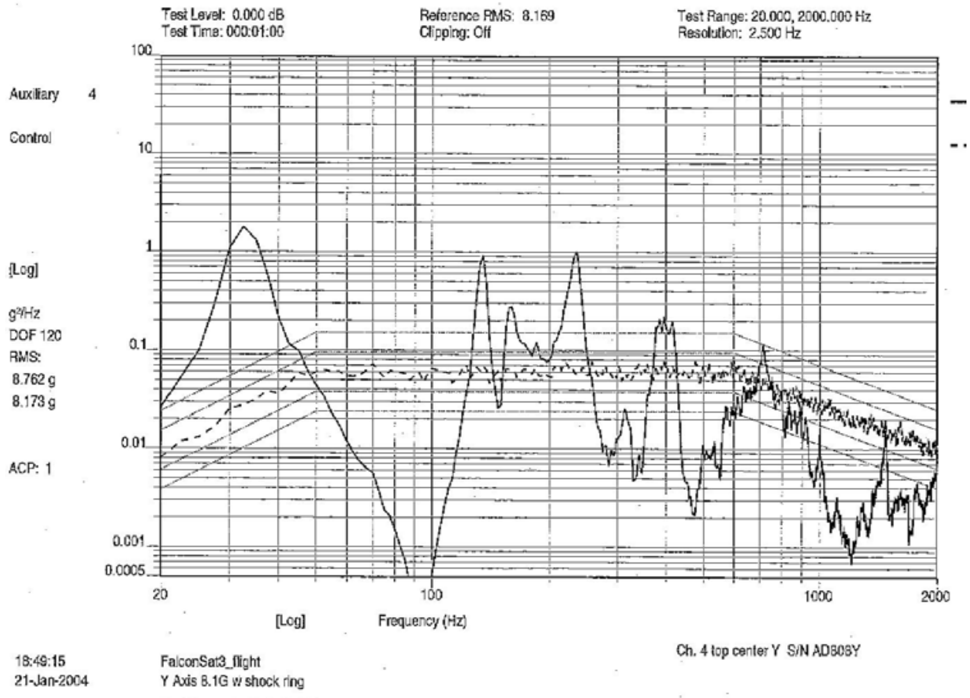

Fig. 5. Y Axis, with Shock Ring, Acceptance-level Random Vibration—Top Center Y Response. 8.8 g-rms.

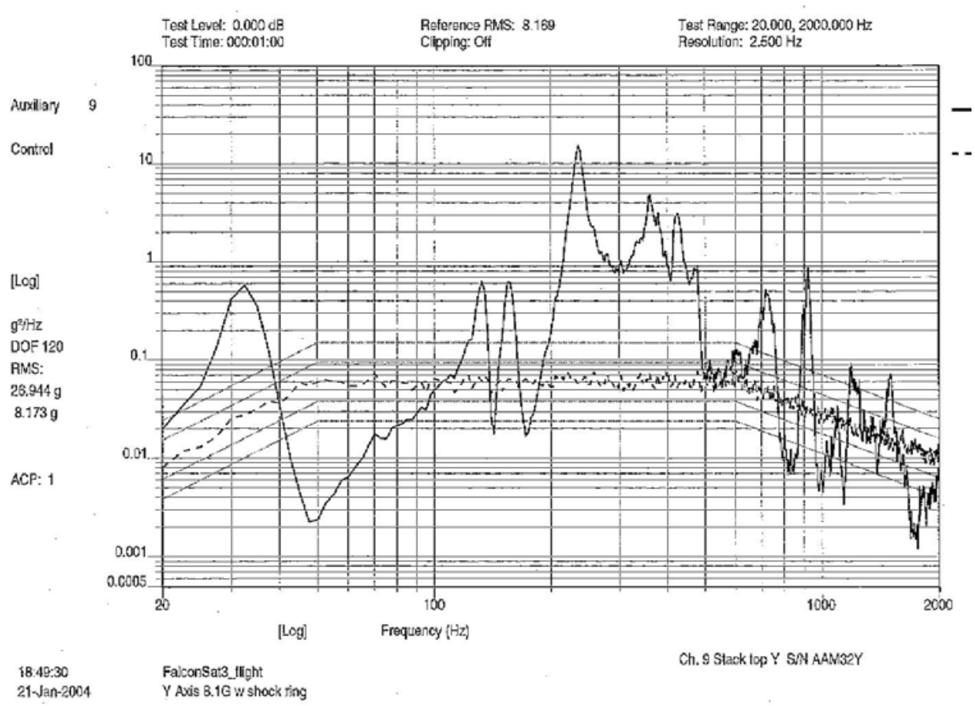

Fig. 6. Y Axis, with Shock Ring, Acceptance-level Random Vibration—Stack Top Y Response. 26.9 g-rms.

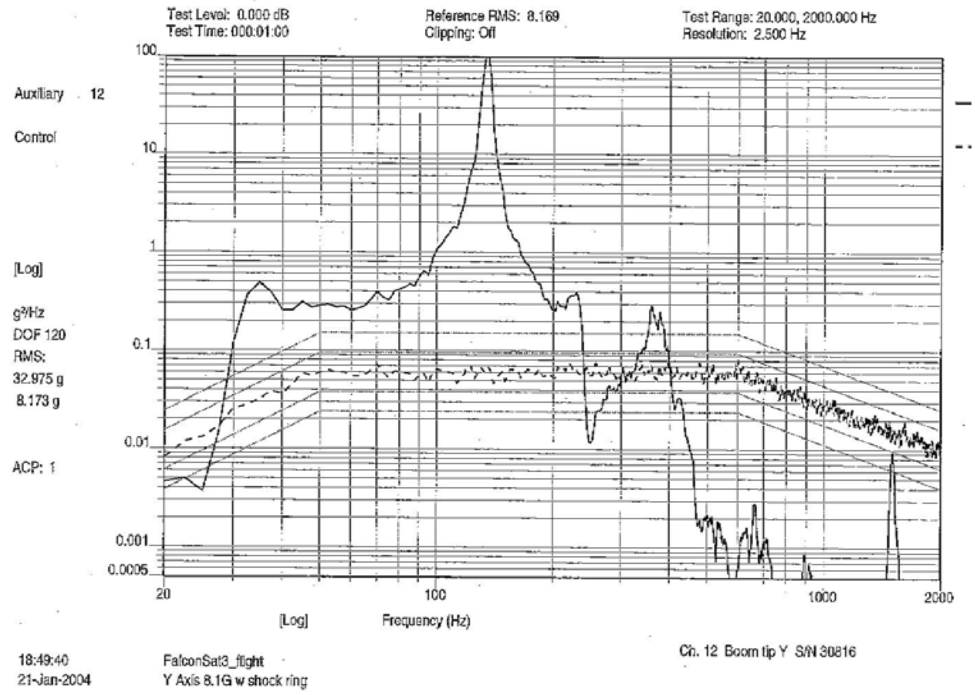

Fig. 7. **Y Axis, with Shock Ring, Acceptance-level Random Vibration—Boom Tip Y Response.** 33.0 g-rms.

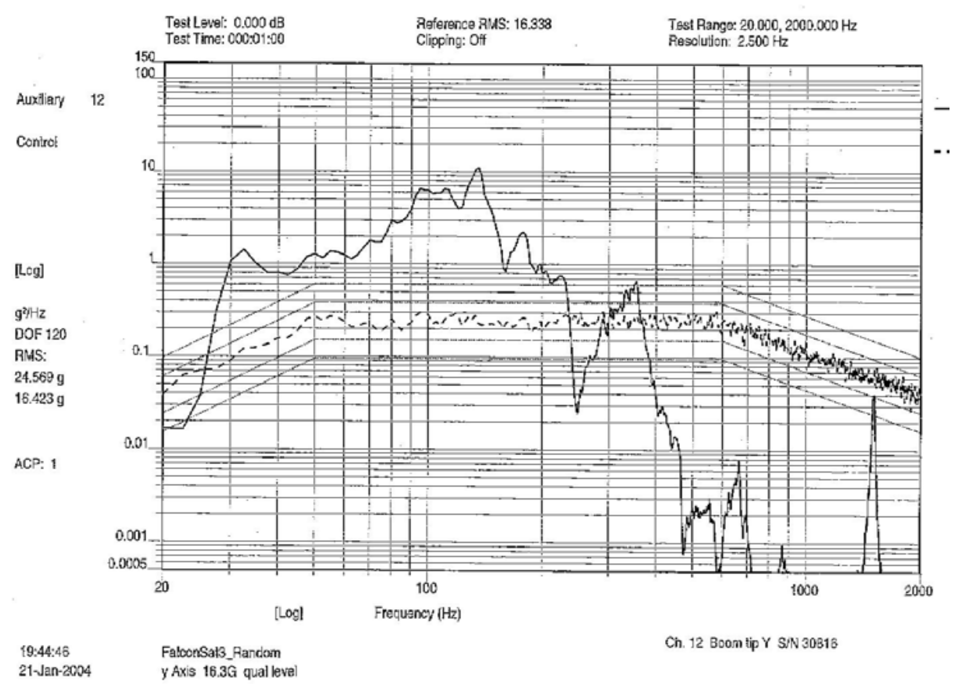

Fig. 8. **Y Axis, with Shock Ring, Qual-level Random Vibration—Boom Tip Y Response.** 24.6 g-rms. If the structure had stayed linear, this plot would have the same shape as Fig. 7, with a total response level of twice 33.0, or 66.0 g-rms. Something apparently changed in the structure. The change was not identified in test and was not apparent in post-test inspections.

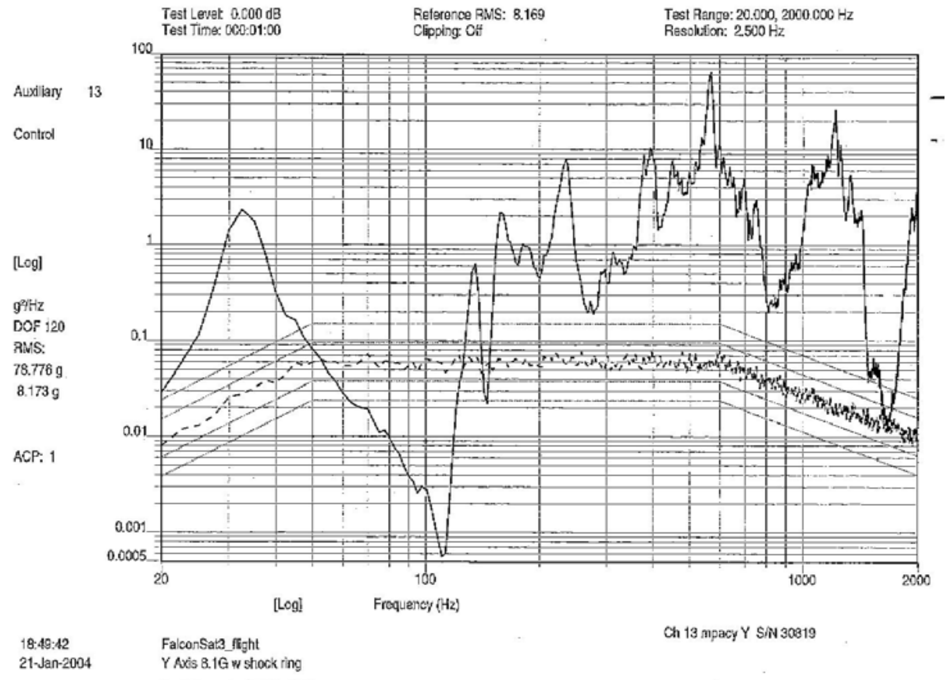

Fig. 9. **Y Axis, with Shock Ring, Acceptance-level Random Vibration—MPACS Y Response.** 78.8 g-rms. Most of the energy here is high frequency and is, I suspect, the response of local modes in the MPACS simulator. The accelerometer was mounted on a thin, sheet-metal side of the simulator.

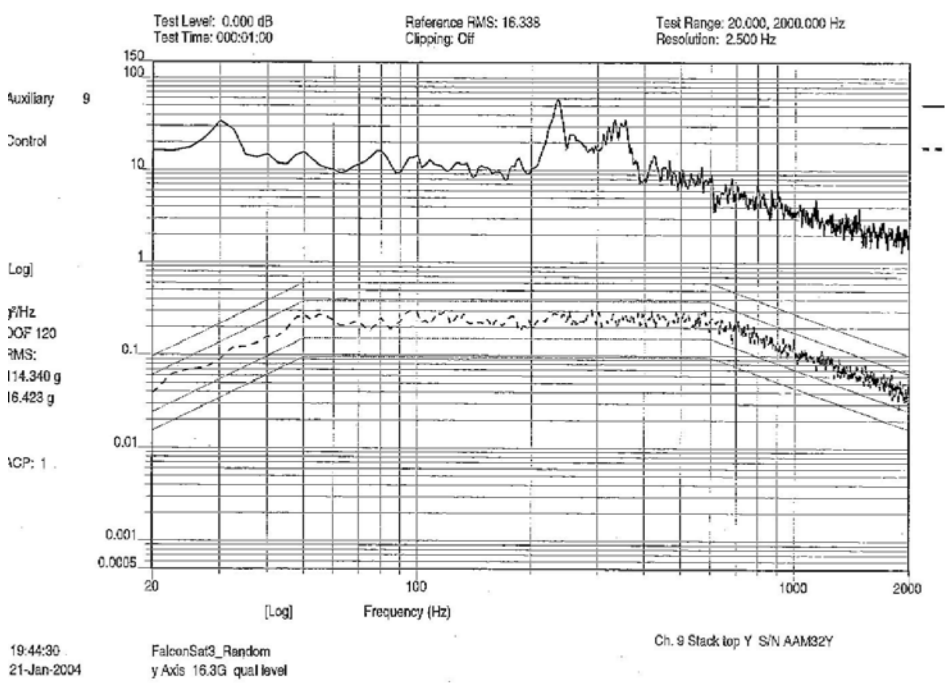

Fig. 10. **Y Axis, with Shock Ring, Qual-level Random Vibration—Stack Top Y Response.** This is bad data. The plot should have the same characteristics as for the acceptance-level test, shown in Fig. 6.

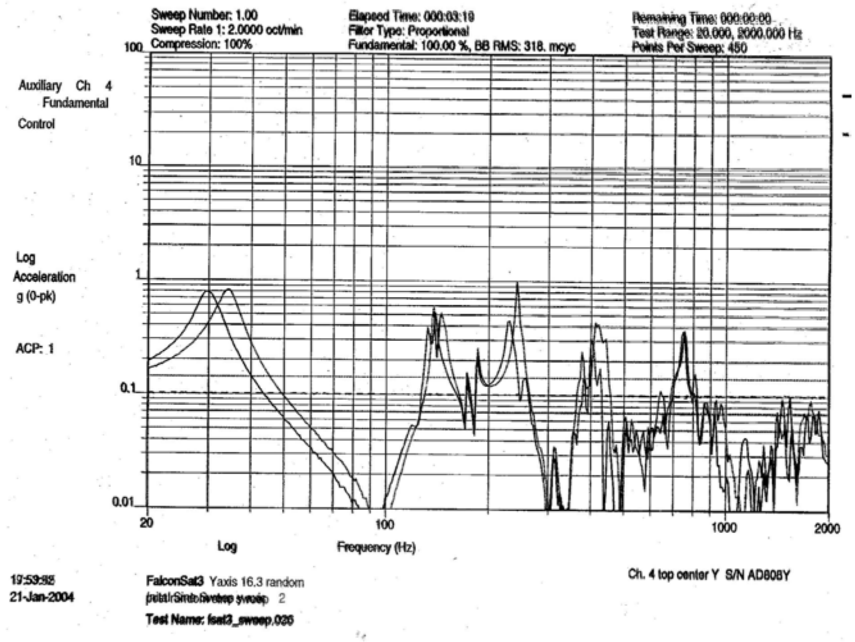

Fig. 11. **Y Axis, with Shock Ring, Pre- and Post-test Sine Sweeps—Top Center Y Response.** The drop in fundamental frequency from 33 Hz to 30 Hz is attributed to the shear stiffness of the visco-elastic material (VEM) in the Shock Ring dropping with temperature.

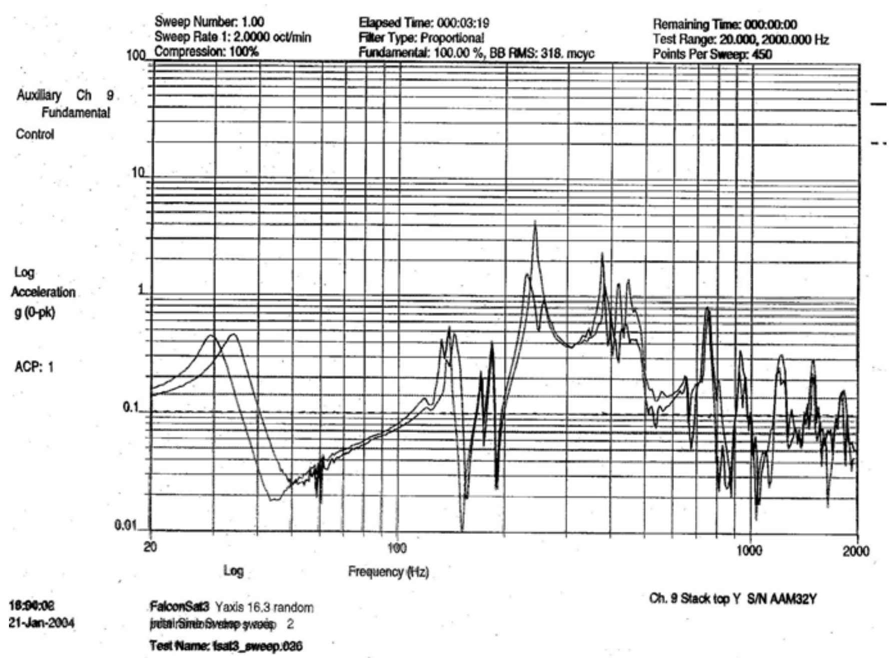

Fig. 12. **Y Axis, with Shock Ring, Pre- and Post-test Sine Sweeps—Stack Top Y Response.** The frequency of the stack-rocking mode dropped from about 235 Hz to about 225 Hz, and the peak dropped from 4.3 g to 1.5 g. The frequency shift is within the 5% criterion, but the peak reduction does not satisfy the 20% criterion. It is unknown how much this mode was affected by the change in the fundamental rocking frequency resulting from heating of the Shock Ring VEM.

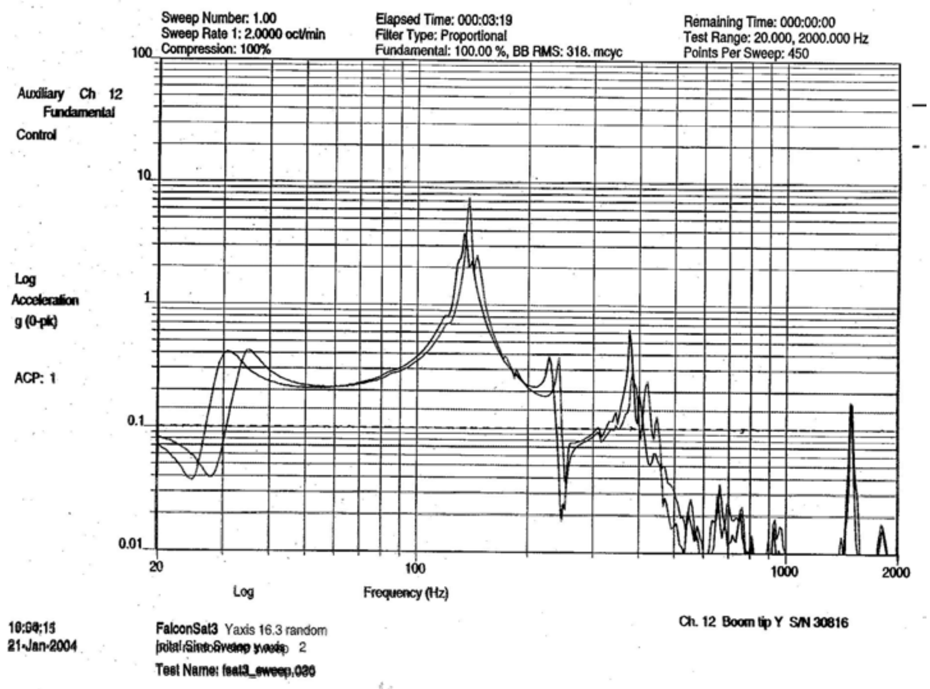

Fig. 13. Y Axis, with Shock Ring, Pre- and Post-test Sine Sweeps—Boom Tip Y Response. The 140-Hz boom mode shows a drop in peak from 7.5 g to 3.8 g, or 50%.

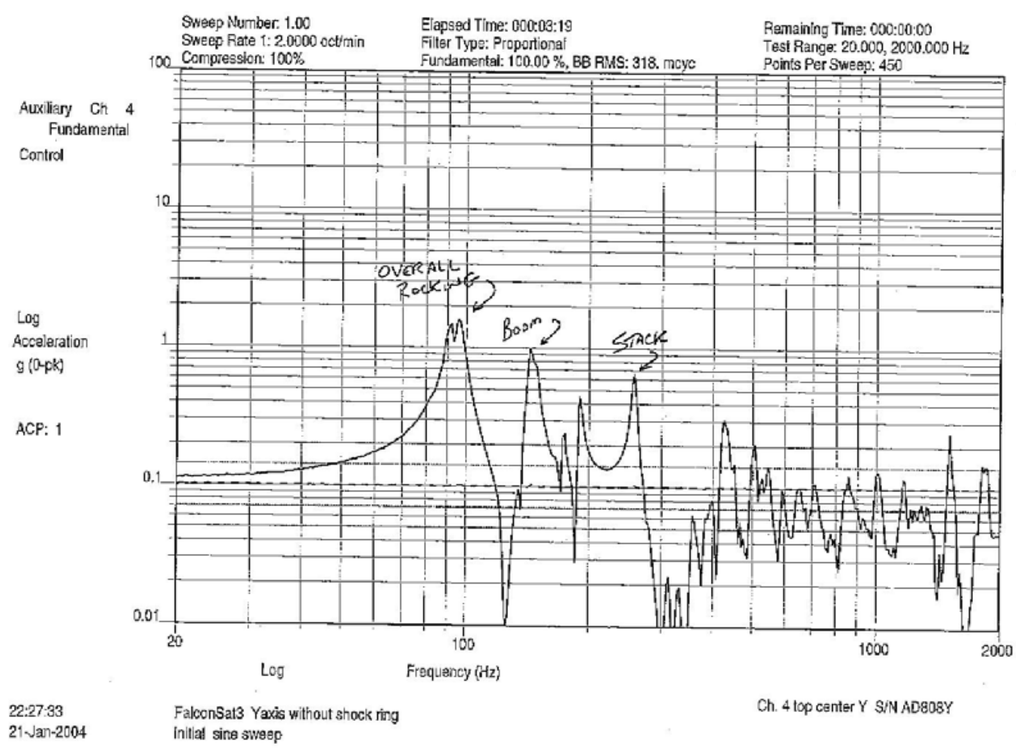

Fig. 14. Y Axis, No Shock Ring, Initial Sine Sweep—Top Center Y Response.

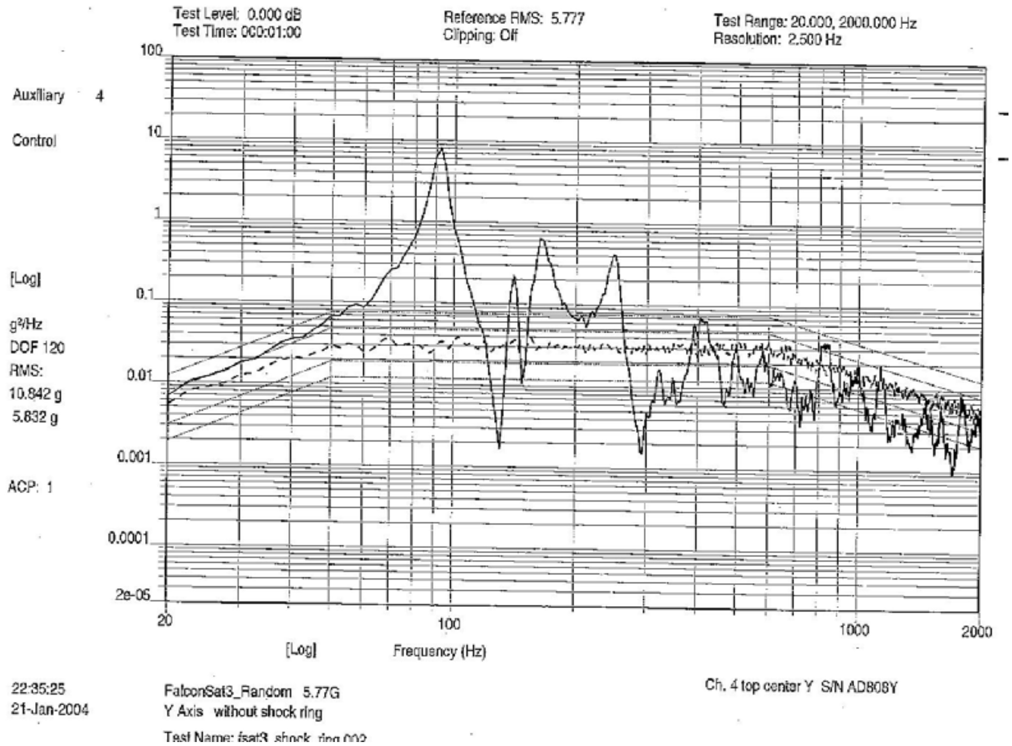

Fig. 15. **Y Axis, No Shock Ring, -3dB Random Vibration—Top Center Y Response.** This test was done to 3 dB below acceptance.

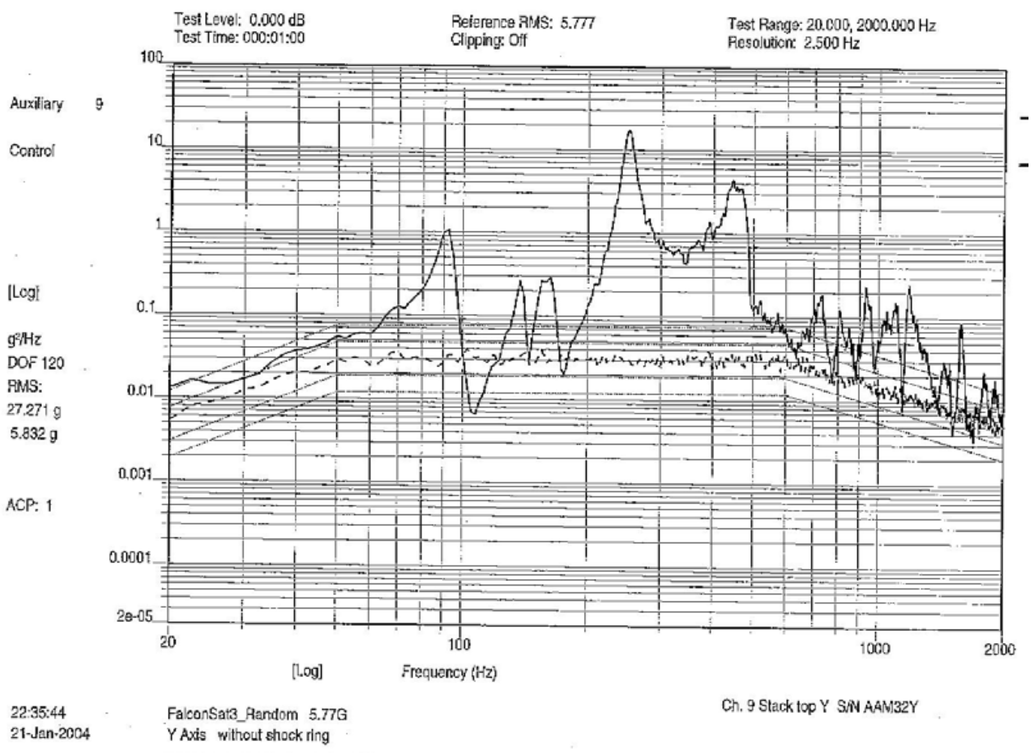

Fig. 16. **Y Axis, No Shock Ring, -3dB Random Vibration—Stack Top Y Response.** This test was done to 3 dB below acceptance.

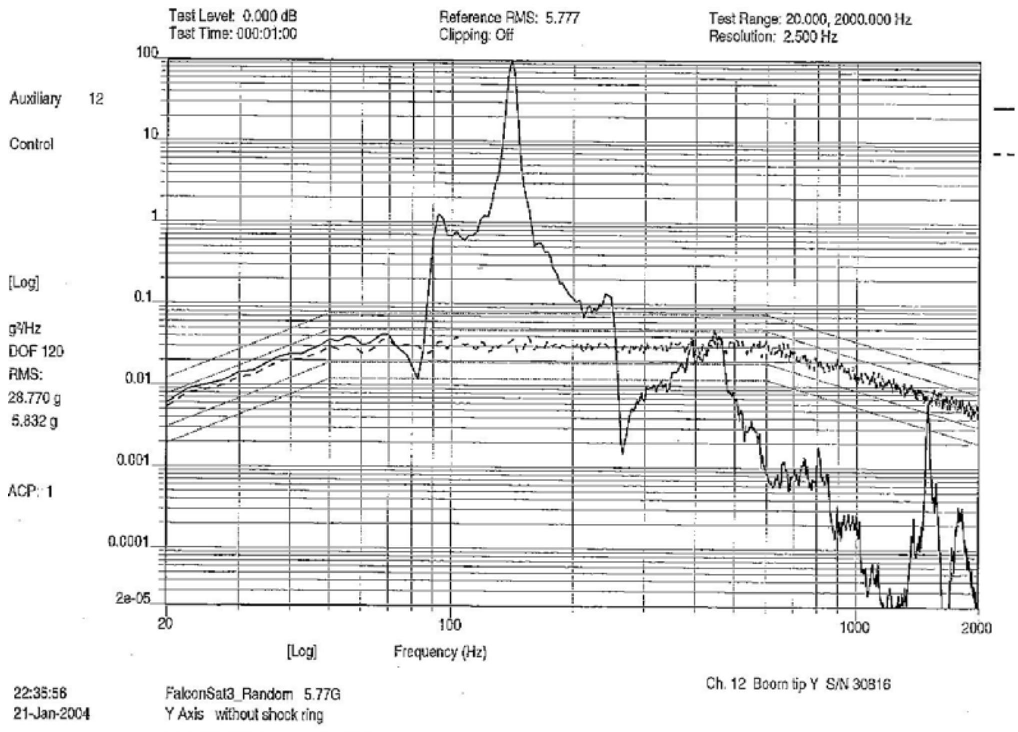

Fig. 17. Y Axis, No Shock Ring, -3dB Random Vibration—Boom Tip Y Response. This test was done to 3 dB below acceptance.

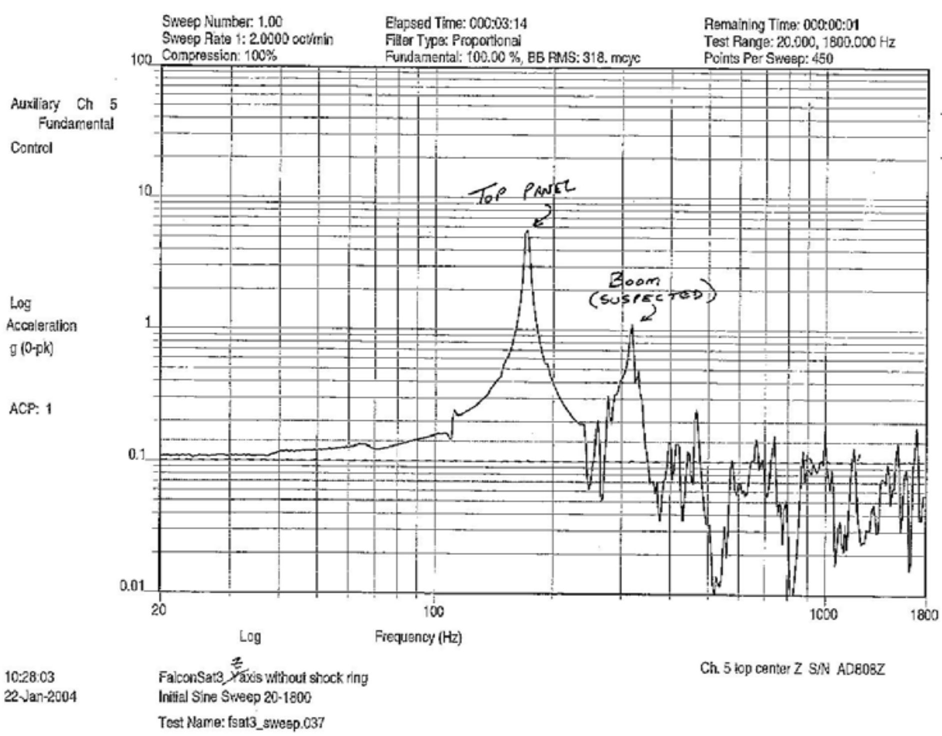

Fig. 18. Z Axis, No Shock Ring, Initial Sine Sweep—Top Panel Z Response. The big peak at 170 Hz is a bending mode of the top panel.

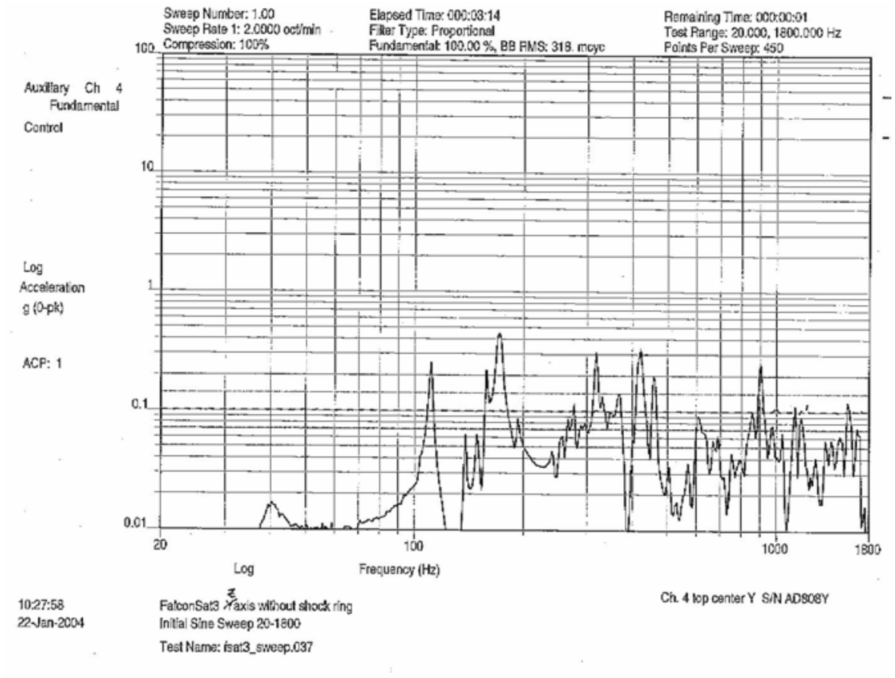

Fig. 19. **Z Axis, No Shock Ring, Initial Sine Sweep—Top Panel Y Response.** The peak at 110 Hz appears to be the fundamental rocking mode, which is excited by axial motion because of the small offset in center of gravity.

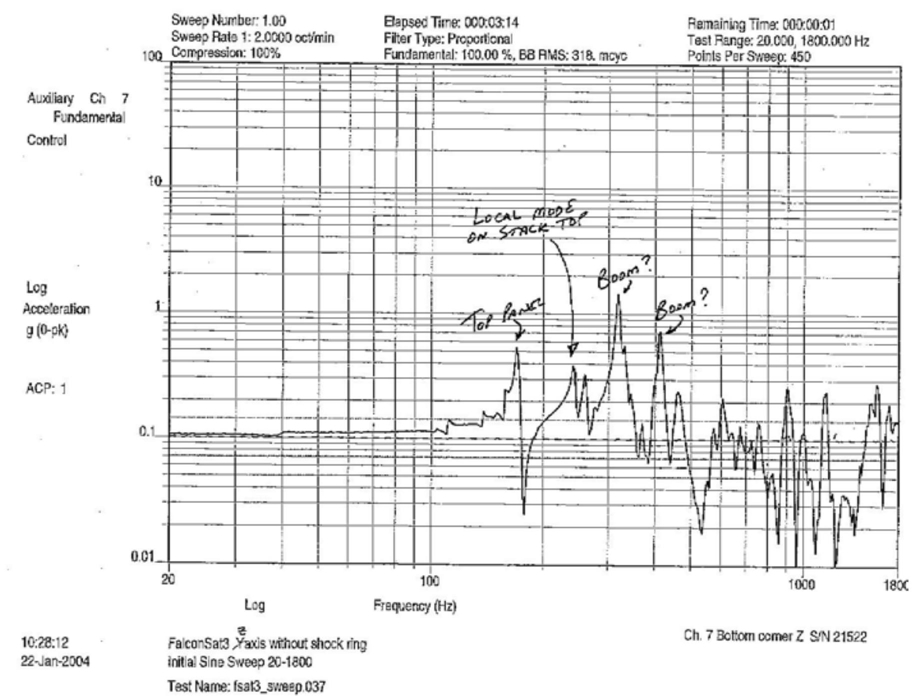

Fig. 20. **Z Axis, No Shock Ring, Initial Sine Sweep—Bottom Corner Z Response.** The response peaks at 310 Hz and 410 Hz indicate that a fair amount of mass is moving in those modes. I believe they both are axial modes involving a lot of boom motion.

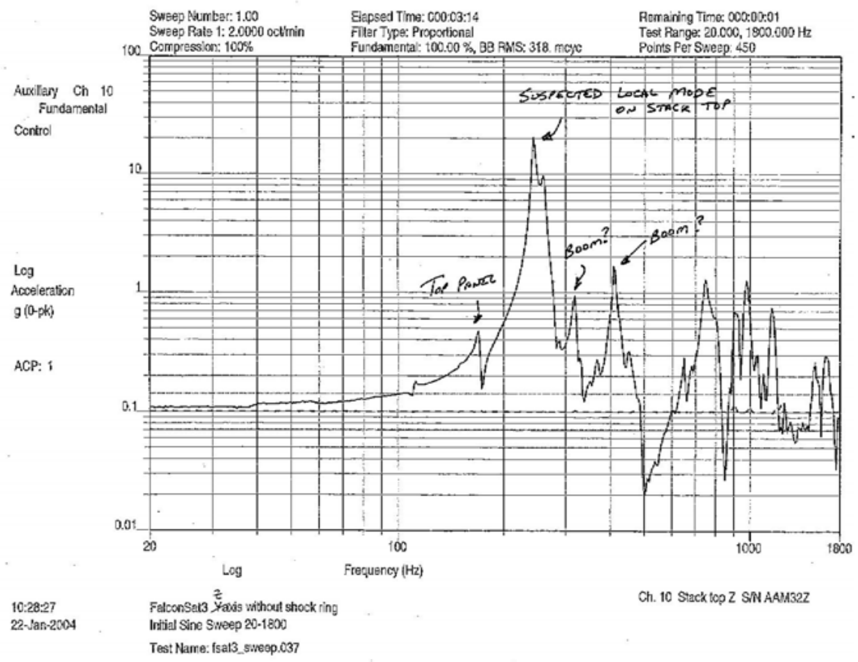

Fig. 21. Z Axis, No Shock Ring, Initial Sine Sweep—Stack Top Z Response. The large peak at 235 Hz is most likely a local plate-bending mode in the module simulator. The second peak at about 260 Hz may be associated with local plate modes in the lower simulators. The mode for the top plate would have been lower because of the added mass of the accelerometer and its mounting block. (See Fig. 22.)

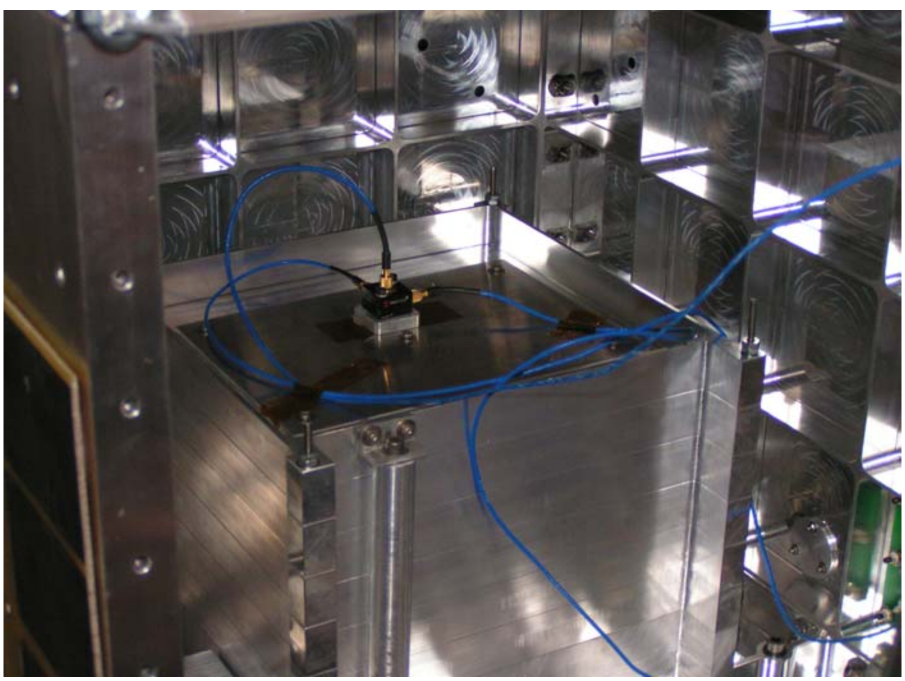

Fig. 22. Location of "Stack Top" Accelerometer. The accelerometer was placed in the center of the thin machined plate on the top module simulator. The 235-Hz response mode is most likely the fundamental bending mode of this plate, reduced in frequency by the mass of the accelerometer and its mounting block.

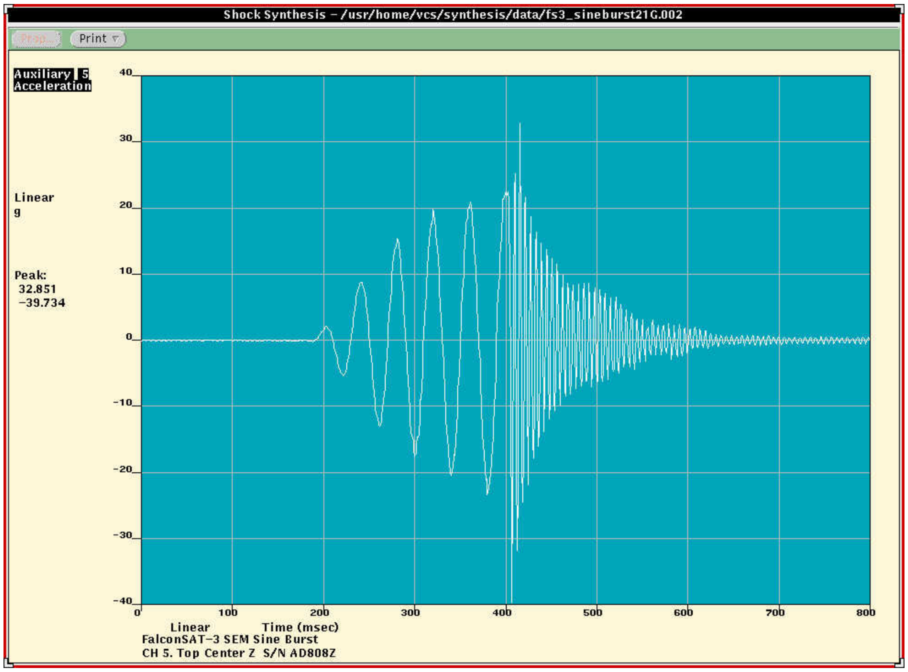

Fig. 23. **Z Axis, No Shock Ring, Sine-burst Anomaly—Top Center Z Response.** When the shaker abruptly stopped, the acceleration at the top center spiked at –40g. From counting the peaks after the sudden stop, it appears this plot is showing response of the 170-Hz panel-bending mode.

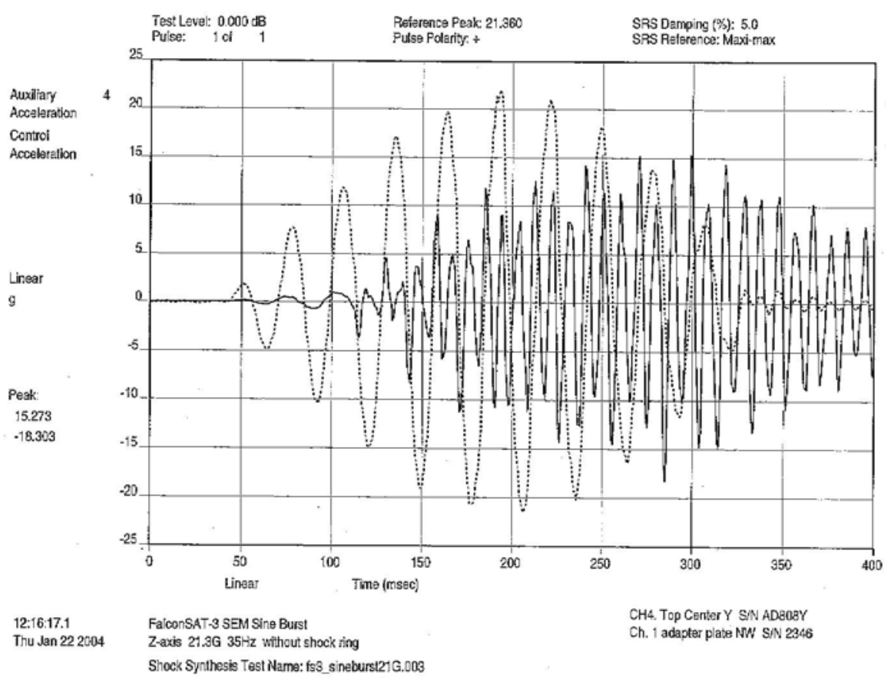

Fig. 24. **Z Axis, No Shock Ring, Sine-burst Test #2—Top Center Y Response.** This plot shows off-axis response of the top panel in the 35-Hz sine-burst test. The off-axis response is associated with the fundamental rocking mode, which is about 105 Hz, or three times the input. See text (Sec. 5.1) for discussion.

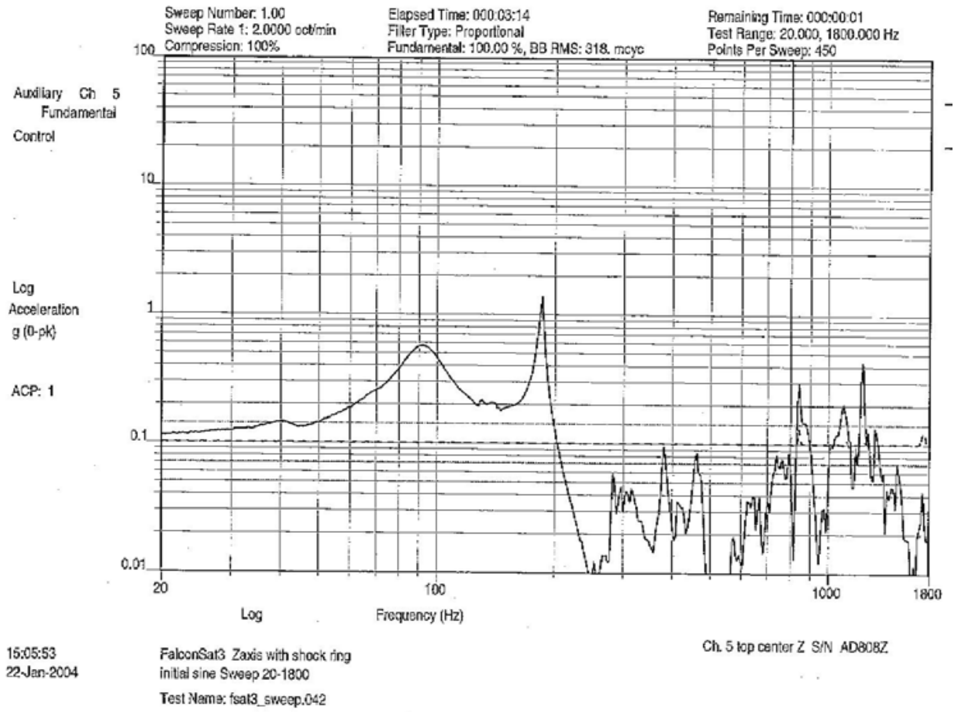

Fig. 25. **Z Axis, with Shock Ring, Initial Sine Sweep—Top Center Z Response.** The peak at 92 Hz is the fundamental axial mode (SEM-2 bouncing on top of the Shock Ring). The 185-Hz peak is the bending mode for the top panel.

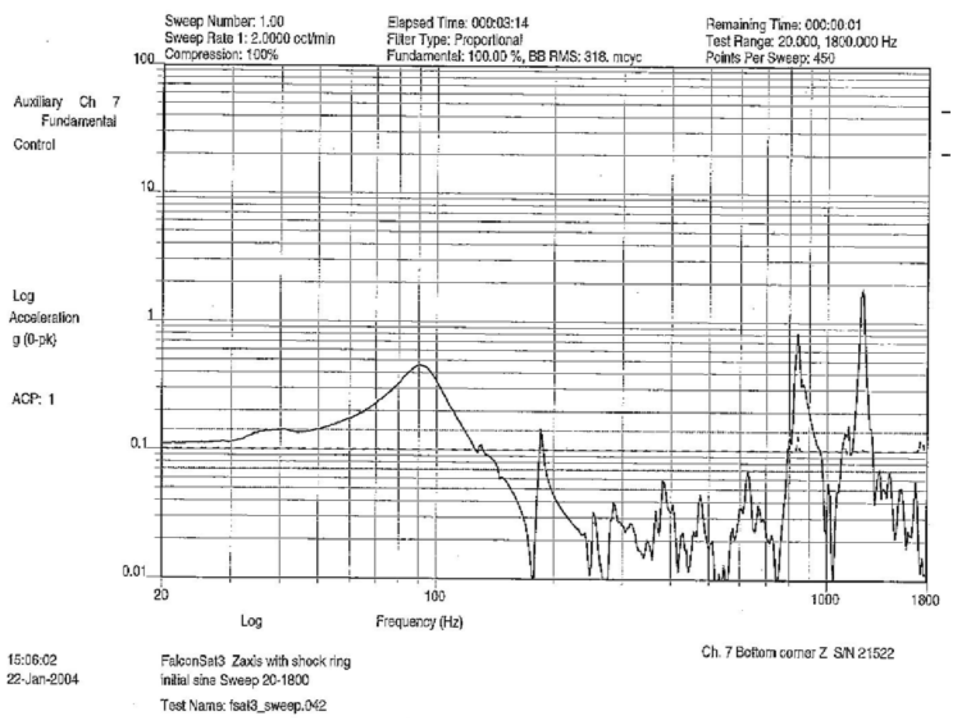

Fig. 26. **Z Axis, with Shock Ring, Initial Sine Sweep—Bottom Corner Z Response.**

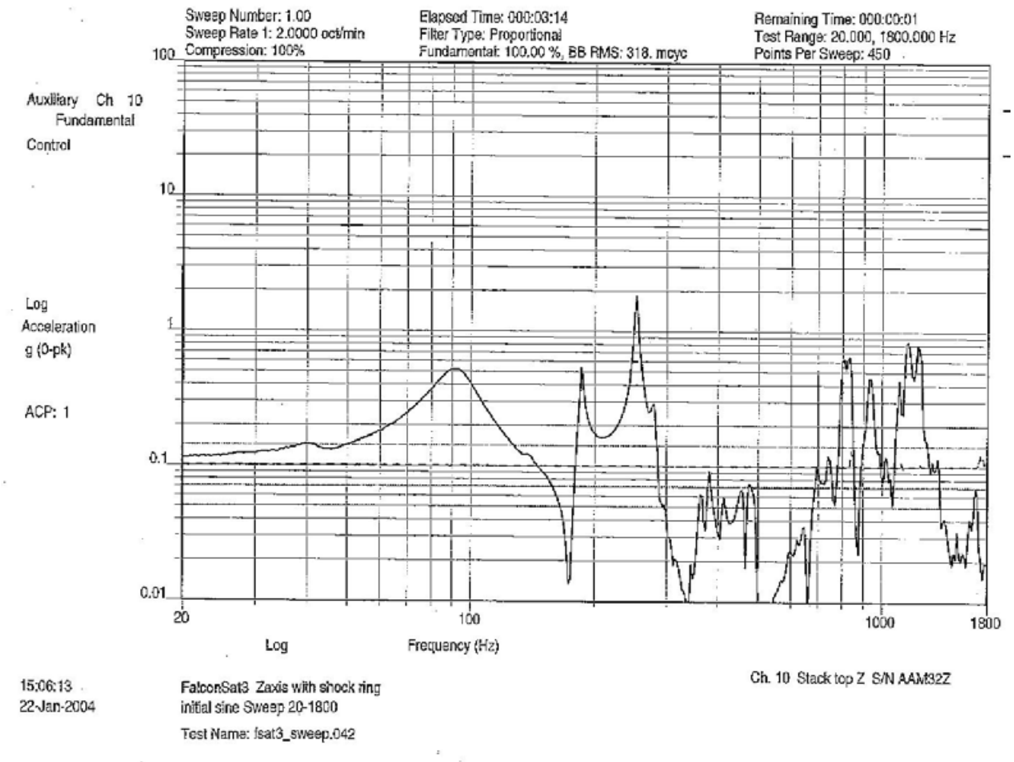

Fig. 27. Z Axis, with Shock Ring, Initial Sine Sweep—Stack Top Z Response.

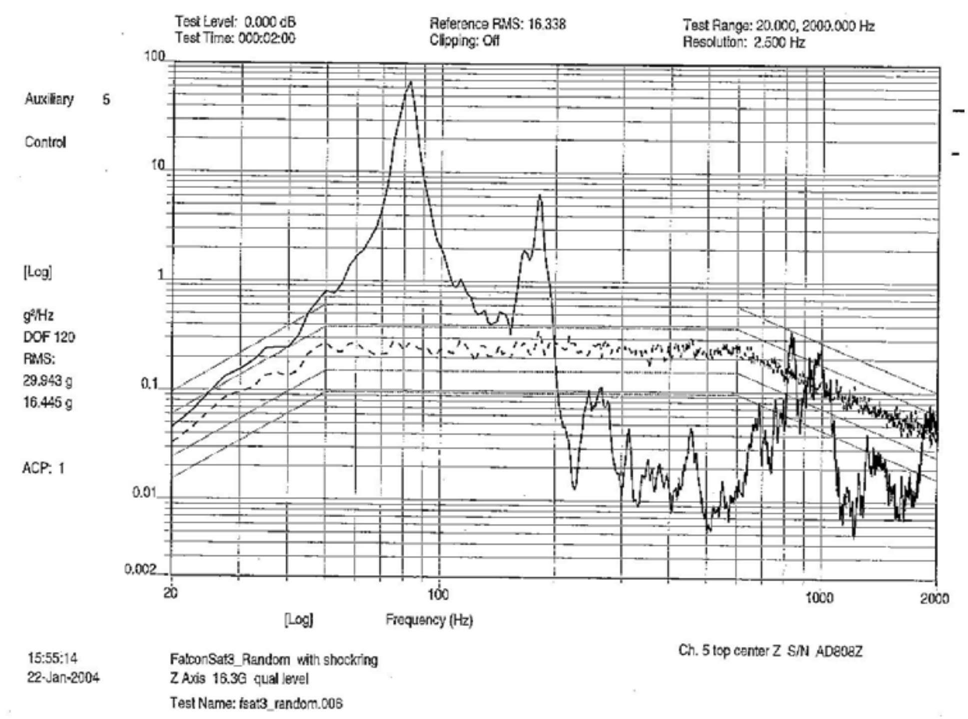

Fig. 28. Z Axis, with Shock Ring, Qual-level Random Vibration—Top Center Z Response.

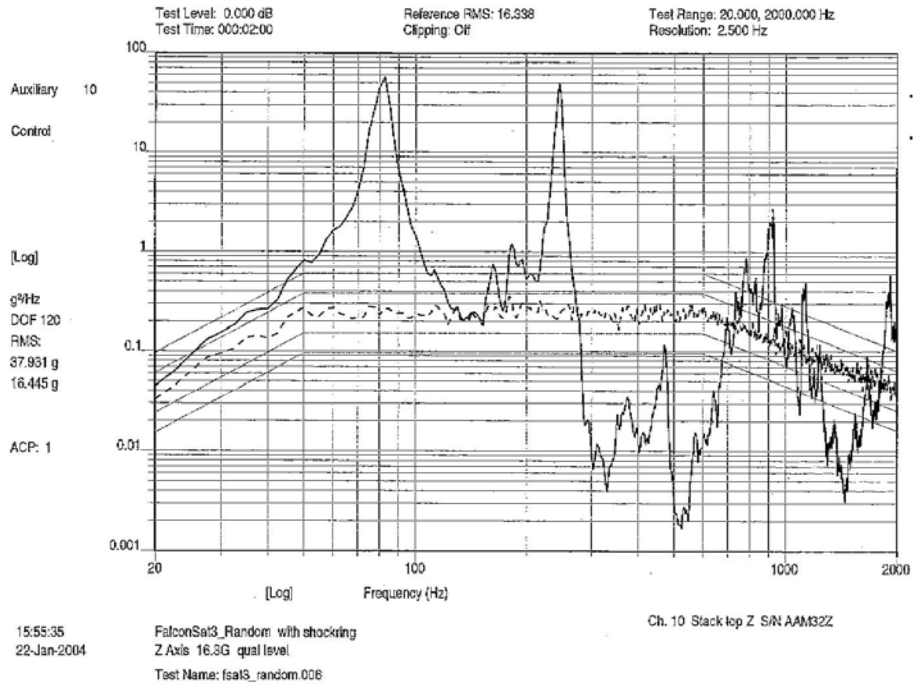

Fig. 29. **Z Axis, with Shock Ring, Qual-level Random Vibration—Stack Top Z Response.** 37.9 g-rms.

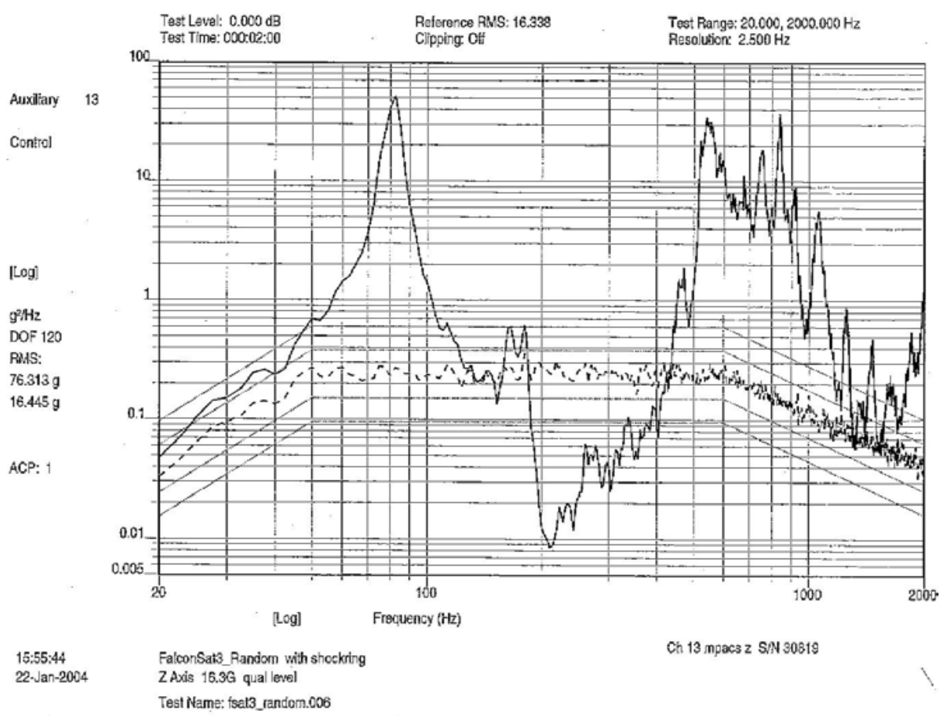

Fig. 30. **Z Axis, with Shock Ring, Qual-level Random Vibration—MPAC Z Response.** The high-frequency (500 – 1000 Hz) peaks are most likely local bending modes of the MPACS simulator's side walls.

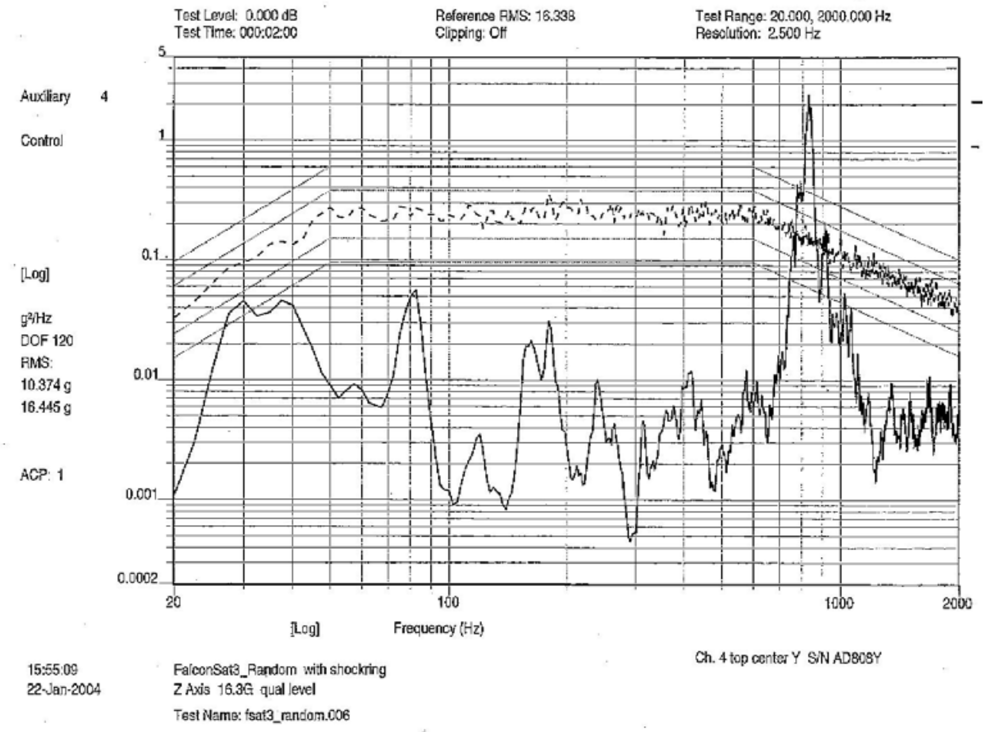

Fig. 31. Z Axis, with Shock Ring, Qual-level Random Vibration—Top Center Y Response. The high peak at 820 Hz appears in data at other locations. It indicates high cross-axis response of some unknown mode.