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Random and Quasi-static Vibration Testing of a Flight System: Logistics, Challenges, and Results.

Eric Stasiunas, David Gurule, Troy Skousen
Sandia National Laboratories*
Albuquerque, NM

Abstract

Before a Flight System can be considered for launch, it must first survive environmental testing that simulates the launch environment. This testing can be performed in the laboratory with quasi-static and random vibration environments using electro-dynamic shakers with closed-loop control. The proto-flight testing of a Flight System, subjected to both environments in this manner, is presented in this paper. The logistics of the test setup, the applied response limits, and the challenges encountered during testing will be discussed, as well as test results.

Overview

Environmental tests were performed on a Flight System in order to meet two main objectives: 1) verify the strength of the system using proto-flight quasi-static loads, and 2) verify system survival when subjected to proto-flight random vibration environment. These objectives were met by performing two standard types of vibration tests—quasi-static loading and random vibration. In addition, a low-level excitation test, known as a signature vibration test, was performed both before and after the major vibration tests to provide structural response comparisons for health monitoring.

The vibration environments were achieved by attaching the Flight System to an electro-dynamic shaker table—capable of 40,000 lbs force—and applying proto-flight level loads and acceleration environments to the structure in both horizontal and vertical directions. Vibration test control was provided by three tri-axial accelerometers, one located at each foot of the Flight System. Tri-axial force transducers were located at each foot as well. The force at each of these locations due to the vibration input were summed and measured in the same axial directions, and were used to apply force limiting for the random vibration tests. Accelerometers located on the Flight System were used to measure the system response as well as provide additional response limiting at select locations.

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The Flight System

The Flight System under test consisted of an assembly of numerous components including a baffle, mirrors, gimbal rings, and azimuth yokes. Also included in the assembly were electronic component boxes, providing system operation support, that had previously undergone qualification testing individually. The total system measured approximately 4 feet long by 4 feet wide by 4 feet tall and weighed approximately 500 lbf. For the vibration testing, the system was configured for stowed flight and was supported by three legs.

Proto-flight Test Environments

The quasi-static test environment was applied to the Flight System to verify the strength of the assembled system. This environment consisted of a sine burst input with five full-level cycles and five ramp cycles, up and down. The frequency of the input was 11 Hz, which was in the rigid-body frequency range of the Flight System. Proto-flight acceleration load levels were 9.35g for the horizontal direction and 7.7g for the vertical direction. A normalized plot of the sine burst waveform is shown in Figure 1.

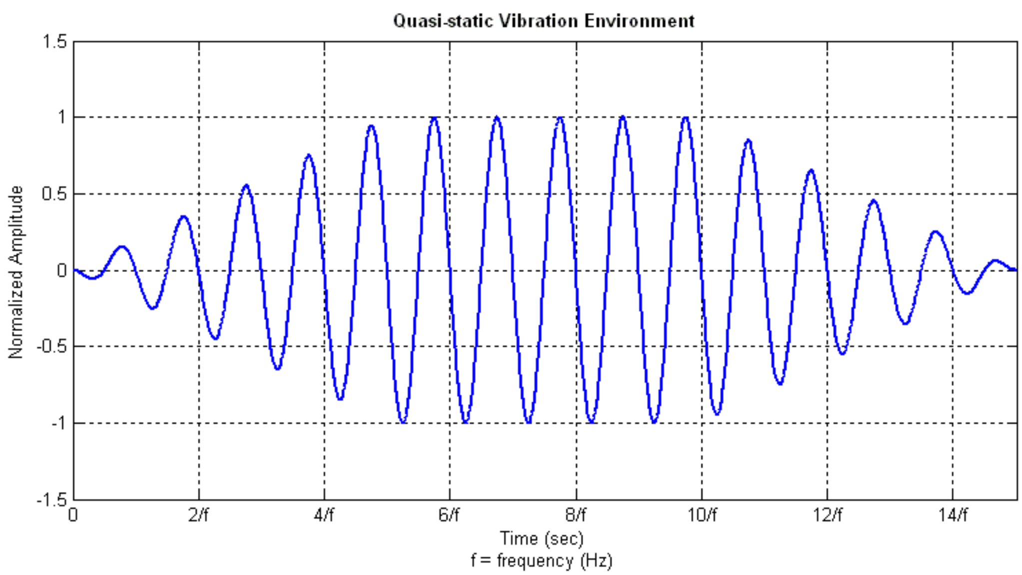

Figure 1: Flight System Quasi-static Input Profile (Normalized)

The random vibration environment was applied to the Flight System to verify system survival during launch. This environment consisted of a horizontal acceleration level of 4.8 gRMS and a vertical acceleration level of 4.9 gRMS, as plotted in Figure 2, for the duration of one minute. In addition, summed input forces for each axis (total x-direction force, total y-direction force, and total z-direction force) were used to apply force limiting to the profiles shown in Figure 3. These force limits were used in all random vibration tests except for the x-axis, proto-flight random vibration environment, where a modified x-force limit was used—at 320 Hz, a force limit of 35 lbs^2/Hz was used out to 2000 Hz. This will be discussed in further detail in the results section.

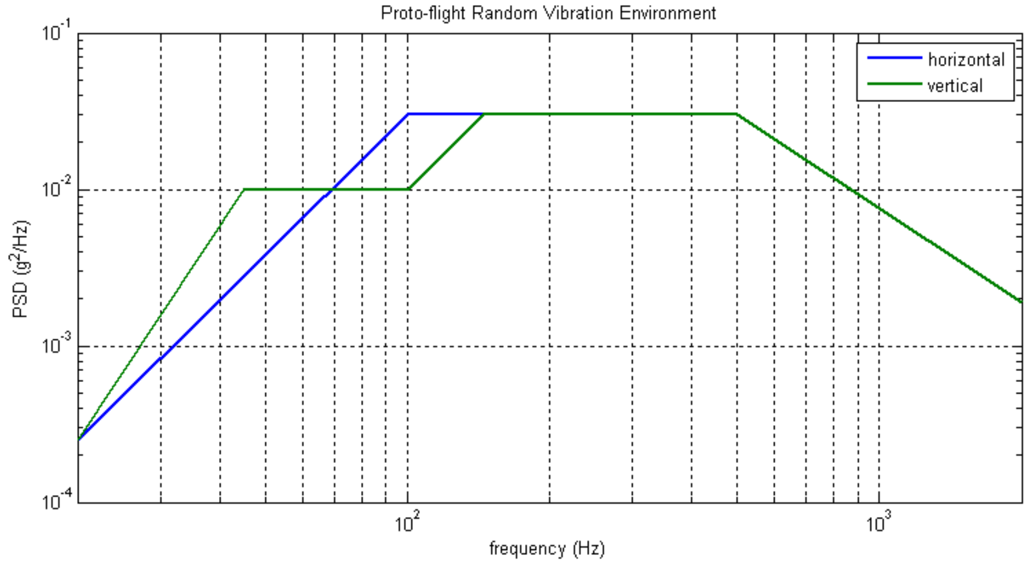

Figure 2: Flight System Proto-flight Random Requirement

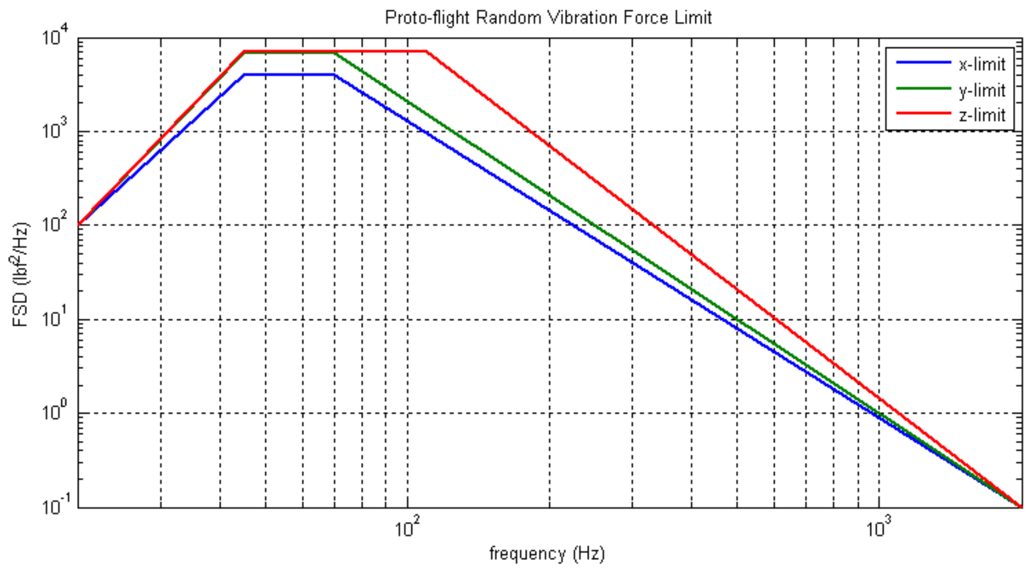

Figure 3: Flight System Force Limit Profile

A low-level random vibration test, referred to as a signature vibration test, was performed before and after the full-level quasi-static and proto-flight vibration tests. This vibration environment was the proto-flight random test profile shown in Figure 2, at -15dB with response acceleration and force limits set at the 0dB level. The acceleration values for the signature vibration test were 0.871 gRMS for the horizontal direction and 0.854 gRMS for the vertical direction. Comparison of the signature vibration test results served as a health monitor of the Flight System. Large changes in the structural response may indicate structural changes or damage that may have occurred during full level testing.

Vibration Test Setup

Vibration test control was provided by three tri-axial accelerometers placed at the feet of the Flight System; force limiting was provided by three tri-axial force transducers at the same location. A single, instrumented foot of the Flight System is shown in Figure 4. A control accelerometer (sensitivity of 10mV/g) can be seen in the figure (black cable) and is located on the slip table adaptor plate. All accelerometer cables were connected to 12-channel gather boxes located next to the slip table, and routed to the control system in the control room with RS232 cables. A tri-axial force transducer, installed with a pre-load of 26,000-lbf, is shown (green cables), and was located between the foot adaptor plate and the slip table adaptor plate. An additional response accelerometer was placed on the foot itself (not shown). The white material in between the force transducers and the surrounding adaptor plates is dental cement. If the cement were to crack or fall off during a test, it may be an indication of excess movement of the foot assembly.

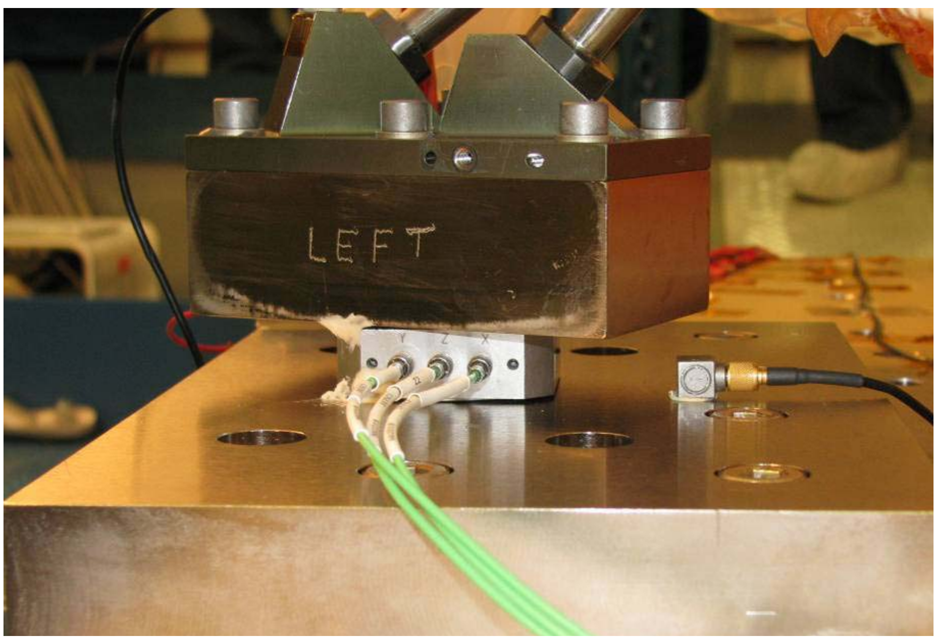

Figure 4: Left Foot Control Transducers (X-Axis Configuration)

The summation of the in-axis input forces was performed with a National Instruments (NI) system. Nine charge amplifiers were located on the shaker platform, one for each individual force measurement. Output voltages from these amplifiers were routed into the control room with a gather box and RS232 cable. Once in the control room, each RS232 output was split into two BNC cables—one was connected into the data acquisition system to measure the individual force, the other was connected into the NI input. The NI would sum these forces and output them as a voltage with a sensitivity of 1 mV/lbf. The three voltages equivalent to the summed x-direction, y-direction, and z-direction forces were then connected to the control system and used to provide force limiting.

For both horizontal axes (x- and y-direction), the Flight System was tested on the shaker slip-table with a 90-degree rotation between axes. The vertical axis (z-direction) required the use of a 1000-lbf expander head, attached to the head of the vertically-rotated shaker. It was discovered during dry run testing that that the vertical quasi-static test required the shaker trunnions be locked out and the supporting airbags deflated. While these airbags provided a nice isolation system for the random vibration input, with the quasi-static environment input they resulted in a noisy response signals. This noise was due to the resonance of the test system (shaker armature, expander head, and Flight System weight with airbag stiffness) being very close to the input 11 Hz. The locked-out configuration results in stiffer supports, and very clean test response. Again, this was done for the vertical quasi-static test environment only.

Control System Configuration

For the quasi-static test environment, only one control channel was allowed by the control system. With the input frequency at such a low value (11 Hz), the entire system was expected to behave as a rigid body. Therefore, the tri-axial accelerometer at the base of the left foot of the Flight System was arbitrarily chosen as the control location. A sampling frequency of 2560 Hz was used to obtain a frequency bandwidth of 1000 Hz, with a frame length of 1.6 seconds. Testing began at -15dB of full level, and was increased by 3dB for each additional input. As the level increased, the resulting peak amplifier drive voltage and control acceleration measurements were used to calculate the expected value for the next higher test level. As these estimated values agreed with the measured values, the test was confidently increased to full-level.

For the proto-flight random test environment, an average control scheme was used with the three tri-axial accelerometers located on the Flight System foot adaptor plates. A sampling frequency of 5120 Hz was used to obtain a frequency bandwidth of 2000 Hz with a resolution of 5 Hz. Testing began at -15dB of full level, and was increased by 3dB after equalization at each level. In addition, the control DOF value was set to 240 in order to achieve the tight test tolerances (abort limits) of ±1.5dB below 500 Hz, and ±3.0dB above 500 Hz. The signature random vibration test used the same control scheme as the proto-flight test; the sampling frequency and frequency bandwidth were the same, but because more refined PSDs and FRFs were desired for heath monitoring comparisons, the frequency resolution was increased to 1.25 Hz (1600 spectral lines).

Quasi-static Test Results

The full-level, quasi-static time histories of the control accelerometers for the three test axes are shown in Figure 5. As seen in the data, the input/control waveform was smooth and the resulting peak acceleration values ranged from -0.9% to +2.5% of the specified input values. These test results satisfied the desired environment specifications.

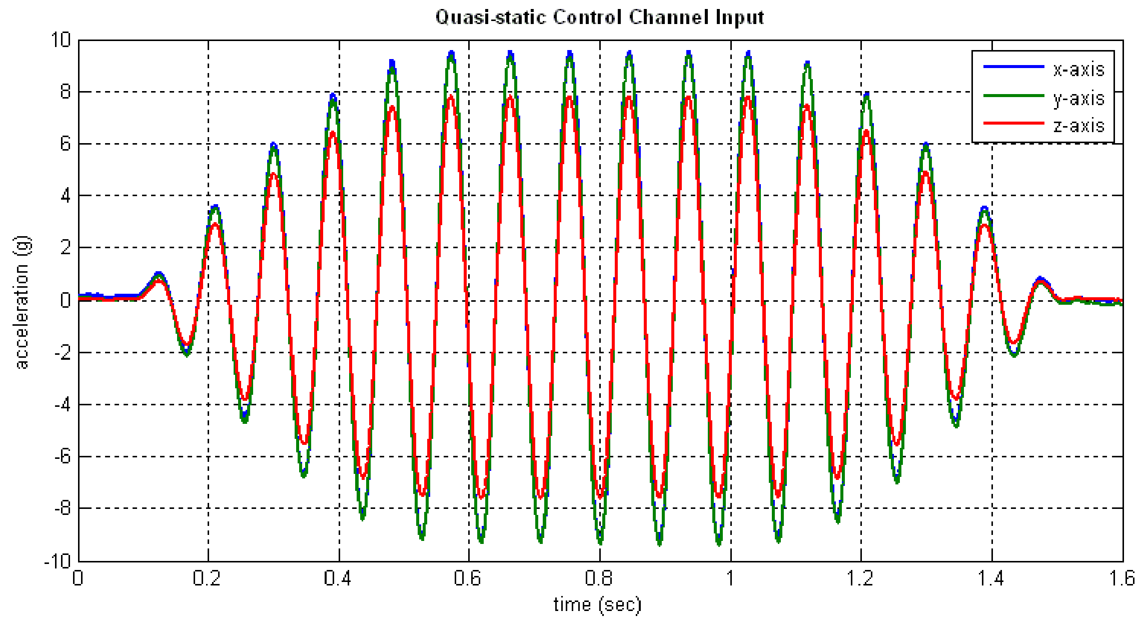

Figure 5: Quasi-static Control/Input Time Histories (x, y, z-axes)

During the quasi-static testing for both horizontal test configurations (x-axis and y-axis), it was noted that the in-axis summed force values very closely estimated with $F=ma$ up to the -6dB test level. Any test level above -6dB however, resulted in a much lower measured summed force than the estimated value, as much as 40% at full level, as shown in Figure 6 for the x-axis. In the figure, the blue data represents the calculated value using the control acceleration from Figure 5 with the Flight System weight, and the green data represents the measured, summed forces from the NI computer. The data has been normalized to the maximum calculated force. At the time, it was hypothesized that this lower summed-force discrepancy was due to the Flight System no longer acting as a rigid-body mass at higher input acceleration levels at 11 Hz.

In addition, the high input acceleration level test data indicated smooth DC, or low frequency, offsets that occurred at higher test levels in some of the individual force measurements for the horizontal test axes. Several causes of these offsets were investigated. Initially, individual Flight System foot acceleration responses were compared and were nearly identical. Next, the Kistler charge amplifiers were examined. If an over-range had occurred, an error light would have remained lit on the amplifier following the test event; they were not. The time constant setting of the amplifier, which acts as a high pass filter, was analyzed as well. With the short time constant setting, the filter frequency was set to less than 1 Hz, much lower than the 11 Hz input. The individual gages themselves were rated for forces up to 4500 lbs horizontally, and 9000 lbs vertically; none of the horizontal directions saw more than 1600 lbs individually at full level. The test unit itself could have caused some unloading of the gage preload. If this did occur, there was not enough movement of the test unit setup to crack or displace the glue on the feet as described in the test setup

This full-level, quasi-static x-axis and y-axis data was further analyzed by Hunter, et al. and the results were published in a memo [1]. The analysis showed that the Flight System was indeed moving as a rigid body—the low peak force measurements occurred because something slipped (i.e. components, joints) internally in the Flight System, not the feet. When this slip occurs, the entire structure readjusts the dynamic and static load path, resulting in the offsets seen in the force data during the high level acceleration input. This slipping does not imply that damage occurred to the system, only that something in the system slipped a small amount as the system adjusted to the peak load.

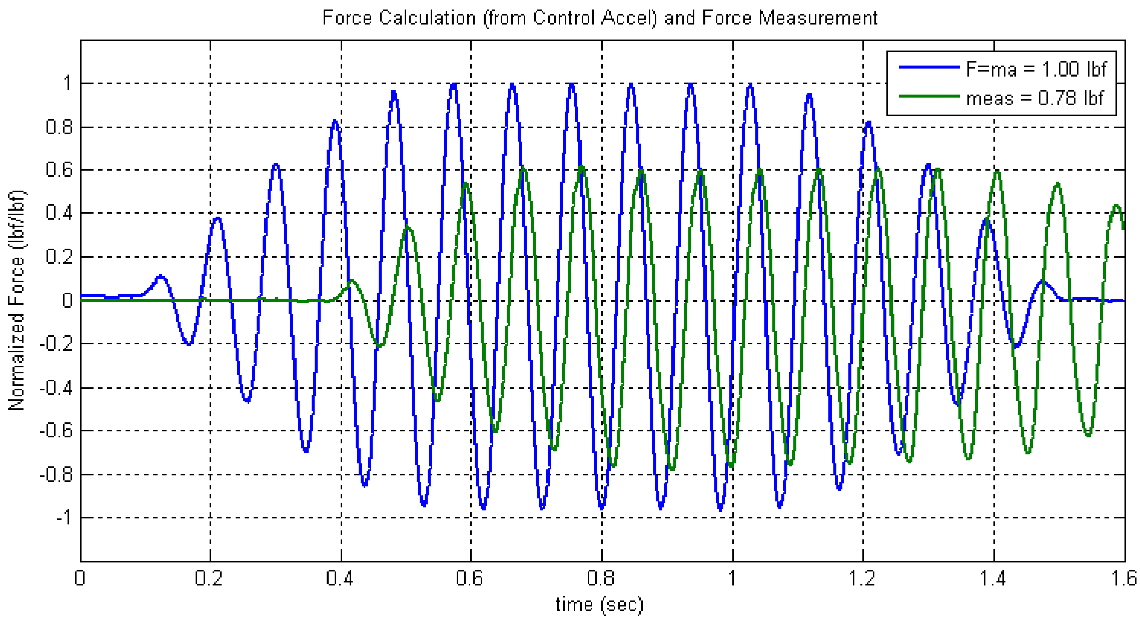

Figure 6: Quasi-static Normalized Force Measurements (x-axis)

In addition, an analysis of the summed Flight System foot acceleration as a function of the summed force further confirmed that the non-linearity (due to slipping) of the test unit occurred at levels over 2000 lbs. To determine how this non-linearity affected the summed-force limiting during the random vibration environment, a post-test analysis was performed on the proto-flight, full-level data. From the PSD data, the x-axis and y-axis summed-force RMS value were calculated. Using a 3σ value (99.7%), the calculated, expected peak force was much less than the 2000 lbs where the non-linearity occurs. Therefore, no significant force limit errors were expected to occur during the random vibration test for the horizontal axes test configuration.

In contrast to the horizontal test directions, the z-axis summed force values for the vertical, quasi-static input were very closely estimated with *F=ma* up to the full test level. The measured summed force and the estimated value only differed by about 1%, indicating that the test unit did not slip internally in this excitation direction. In addition, the individual z-axis force measurements did not exhibit gradual offsets.

One other obvious detail in the quasi-static data for all axes that must be discussed was the time delay that occurs between the actual acceleration input (blue) and the measured summed force data (green) as shown in Figure 6. For the x-axis quasi-static test, this delay was approximately 0.3 seconds; for the y-axis test, this delay was 0.6 seconds. This delay occurred because the individual force signals must be measured, summed, then outputted by the NI system, all before being measured by the control system, whereas the acceleration data is instantaneously measured by the control system. The delay *could* have caused a problem for the control system during the random vibration test, since these channels are used for active limiting. The frame length for one random data PSD measurement was 0.2 seconds; therefore, the control input could be up three frames behind the actual force measurement.

Judging by the random vibration results however, the control system seemed to work properly in all but one case (x-axis proto-flight, as will be discussed). Even though the frame length for one random data PSD measurement was 0.2 seconds, the control system uses numerous data frames per control loop, allowing for the force signals to "catch up" with the control algorithm. This delay is worth noting, and should not be allowed to be too long. Future testing that requires *both* individual and summed force measurements may want to use a more instantaneous summation system if possible.

Random Vibration Test Results

Random vibration testing began on the Flight System in the x-axis, and was initially performed up to -6dB of the proto-flight random environment, as a verification of the limiting channels. The resulting control plot for this test environment is shown in Figure 7. The control spectrum is shown in black, averaged from the individual in-axis control accelerometers in blue, green, and red. Specified test tolerances of ±1.5 dB (<500 Hz), and ±3.0 dB (>500 Hz) are shown in orange. Several notches in the control spectrum are observed in the data at: 50Hz, 180 Hz, 700 Hz to 800 Hz, and above 1000 Hz. This test was initially considered to be a success, as these notches were thought to be caused by limiting of the summed force measurements.

The summed force limit spectra are shown in Figure 8, with required force limits for all three axes shown as dashed lines, and the measured force data shown as the solid lines with corresponding colors. If the -6 dB test was properly controlled, the measured data should be below or overlap the limit lines if limiting occurred. Comparing the notch frequencies in the control spectrum to force limit spectrum, it is clear that the notches at 50Hz and 180 Hz are due to x-axis force limiting, and the notches above 1000 Hz are due to force limiting in all the axes. However, it was not clear as to why the broadband notch from 700 Hz to 800 Hz occurred, as the measured x-axis force is lower than the limit line at these frequencies.

An inspection of all acceleration response limit channels showed no limiting in the 700 Hz to 800 Hz frequency band either. Even more puzzling was the fact that the drive spectrum was shown to decrease in magnitude in this frequency band during the test. Decreasing the drive would be correct course of action by the control system if response limiting were occurring on one of the limit channels. However, none of the data from these channels were close to their respective limits at these frequencies. If the measured x-axis force was still below the limit, as it was shown to be, and the drive should have stopped decreasing and maybe even increased a small amount.

Finally, the control system error plot and limit channel plot from this test were examined. The error plot displayed a large broadband error in the 700 Hz to 800 Hz frequency range. The limit channel plot displayed that the control system was indeed limiting the x-axis summed force, even though the measured spectra was shown to be below the limit, hence the large error in this frequency range.

Data was then examined from the signature random environment performed prior to the -6dB proto-flight test. Response limits are engaged during the signature random test, but they are scaled up to the 0dB level, while the input is at -15dB proto-flight. This scenario resulted in an almost unconstrained test, with almost no response limiting, due to the relatively high limits. A sharp (low-damped) resonance of the slip table was observed at 730 Hz in the drive spectrum of this test, as shown in Figure 9. This resonance was speculated as being the most likely source of the error in the control.

It appeared that the control system was in conflict between the slip table resonance at 730 Hz and the limiting that was occurring over the 700 Hz to 800 Hz frequency range. The delay due to the force limiting software may have also had some effect in this control problem, but it was unclear how much. Because the Flight System was actual flight hardware, a path forward was required that would result in proper control over these conflicting frequencies.

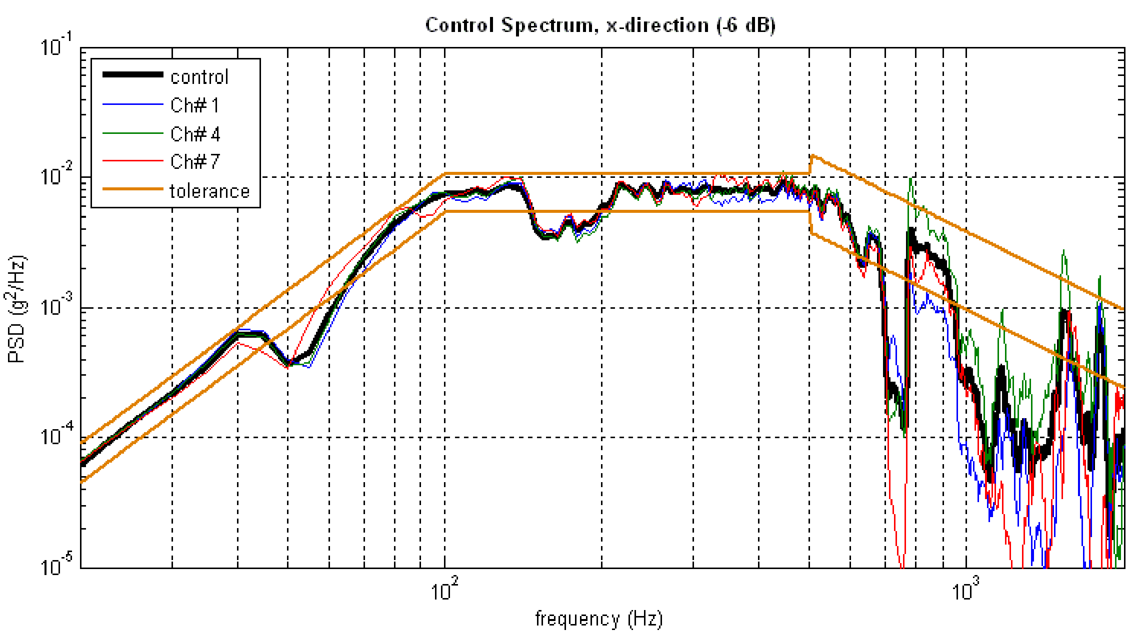

Figure 7: Control Spectrum for Proto-flight Random, -6dB (X-Axis)

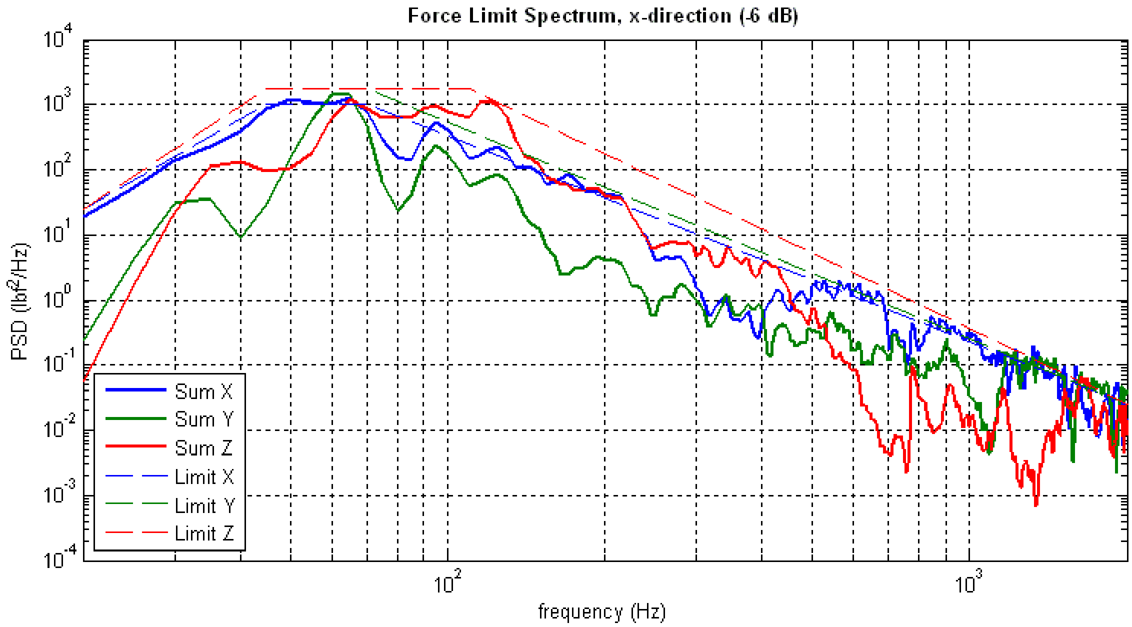

Figure 8: Force Limit Spectrum for Proto-flight Random, -6dB (x-axis)

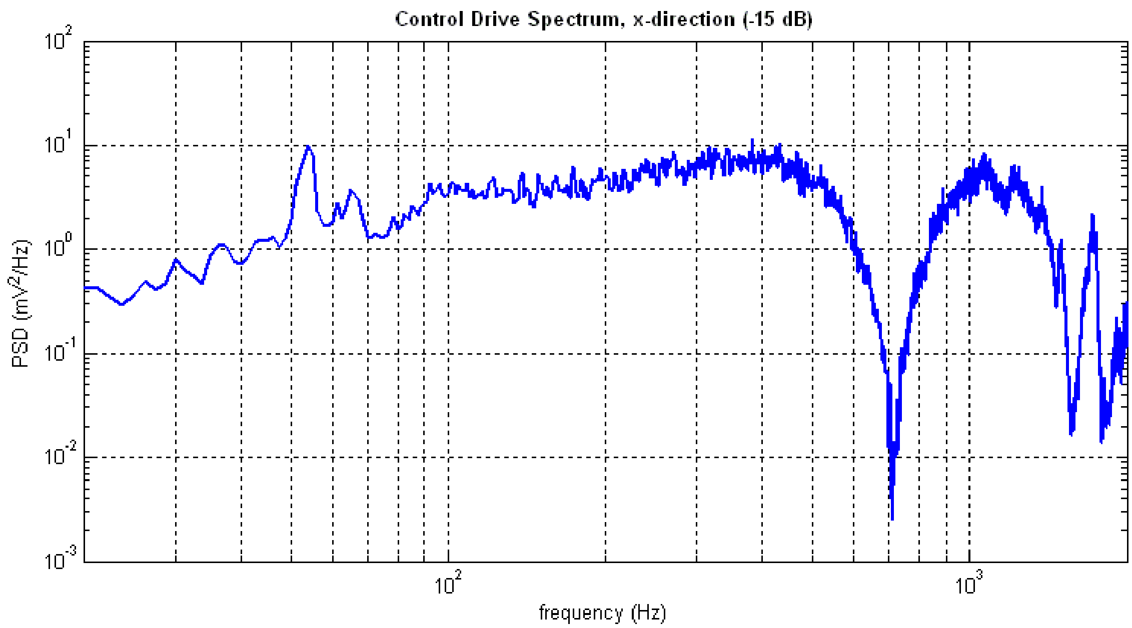

Figure 9: Drive for Signature Random x-axis Test

Several testing options were discussed with the vibration SMEs and even the control system vendor. One option included beginning the test at -15dB with limits deactivated, allow the system to equalize, then apply limits at a higher test level. Unfortunately, this could be dangerous to the test item, as control instabilities could occur when the limits are turned on. Another option was increase the frequency resolution. This was actually done at -15dB, but did not help the test control. The final solution agreed upon was to increase the x-axis force limit to 35 lbf^2/Hz from 320 Hz to 2000 Hz.

With the modified x-axis force limits entered in the control system, the test began at -15dB. The problematic notch at 700 Hz to 800 Hz was initially observed in the control spectrum. However, as the test time increased, the notch ceased dropping in magnitude, increased, then eventually disappeared as it aligned with the reference profile in the tolerance band. With the increased force limit, the control system handled the system resonance properly, taking approximately a minute and a half to do so. Once it was clear that all control and limiting was performing correctly, the test was stepped up from -15dB to full-level in steps of 3dB and was performed for one minute.

The full-level, proto-flight random control spectrum for the x-axis is shown in Figure 10, and the corresponding force limit spectrum with the modified x-axis limit is shown in Figure 11. As seen in the control spectrum, the notches in the control occur at the same frequencies as with the -6dB test level results shown in Figure 7, except for the now non-existent notch from 700 Hz to 800 Hz. The overall measured acceleration level was 4.59 gRMS, which was within 6% of specification, even with the allowed notching.

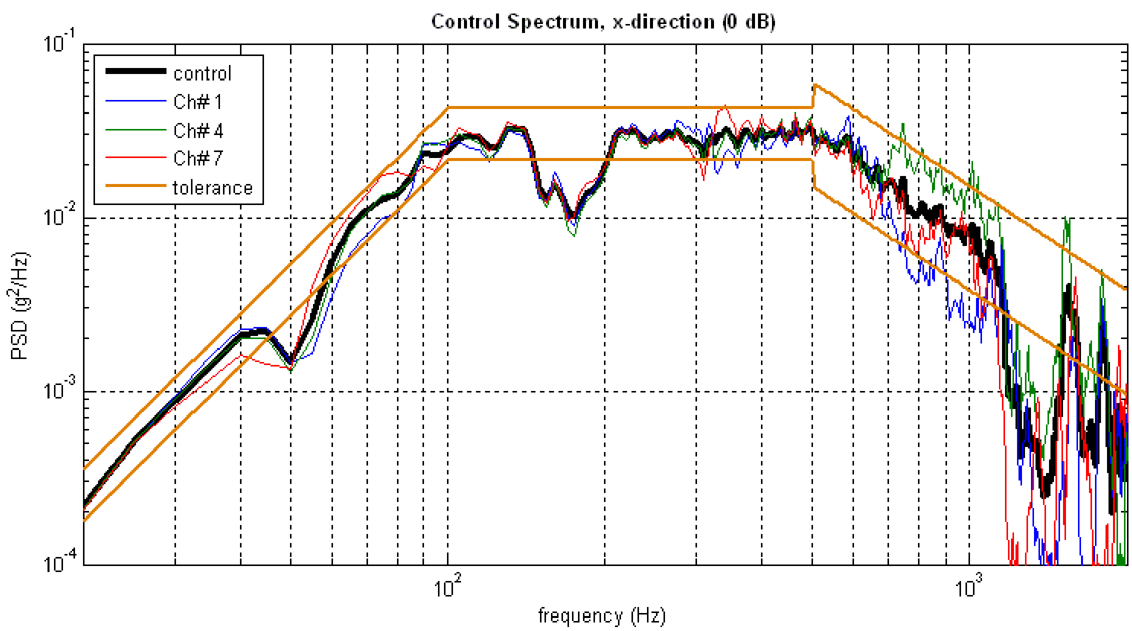

Figure 10: Control Spectrum for Proto-flight Random, 0dB (x-axis)

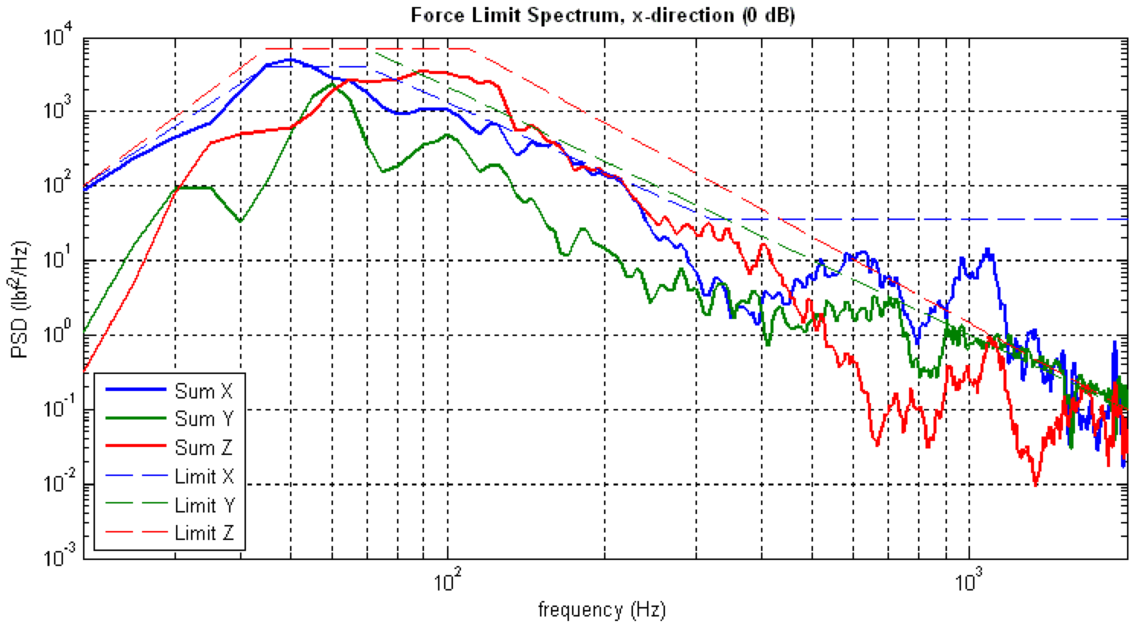

Figure 11: Force Limit Spectrum for Proto-flight Random, 0dB (x-axis)

Proto-flight testing for the y-axis began at -15 dB and was stepped up to -9 dB. Initially, the control system did appear to decrease the drive in the 700 Hz to 800 Hz frequency range, possibly due to the table resonance and force limiting conflict as experienced in the x-axis test. However, about 20 seconds into the -9dB test level, the control system increased the drive and correctly force limited in both the x and y-directions. Correct control was also verified with the real-time error plot, which had values within the specified tolerance. At this point, the environment was increased in steps of 3dB to full level for one minute. The resulting control data for the y-axis test environment is shown in Figure 12, and the summed force limit spectra are shown in Figure 13. The data displays proper force limiting, and it can easily be seen that y-axis force limit dominated the control spectrum. Overall, the measured input acceleration level for the y-axis, proto-flight random environment was 4.23 gRMS, within -13% of specification.

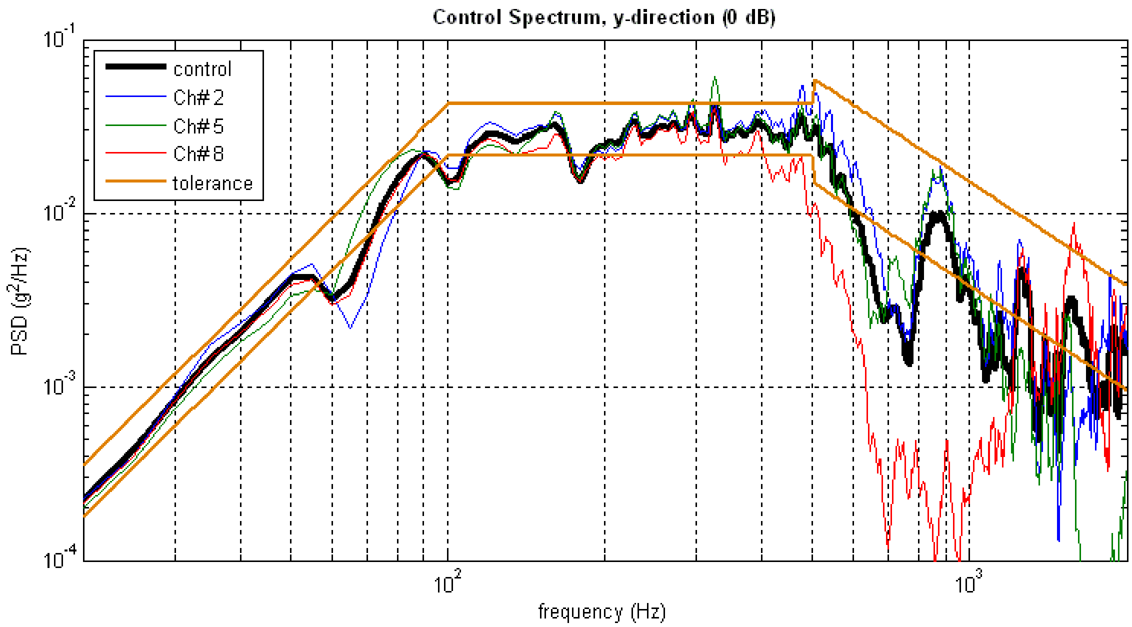

Figure 12: Control Spectrum for Proto-flight Random, 0dB (y-axis)

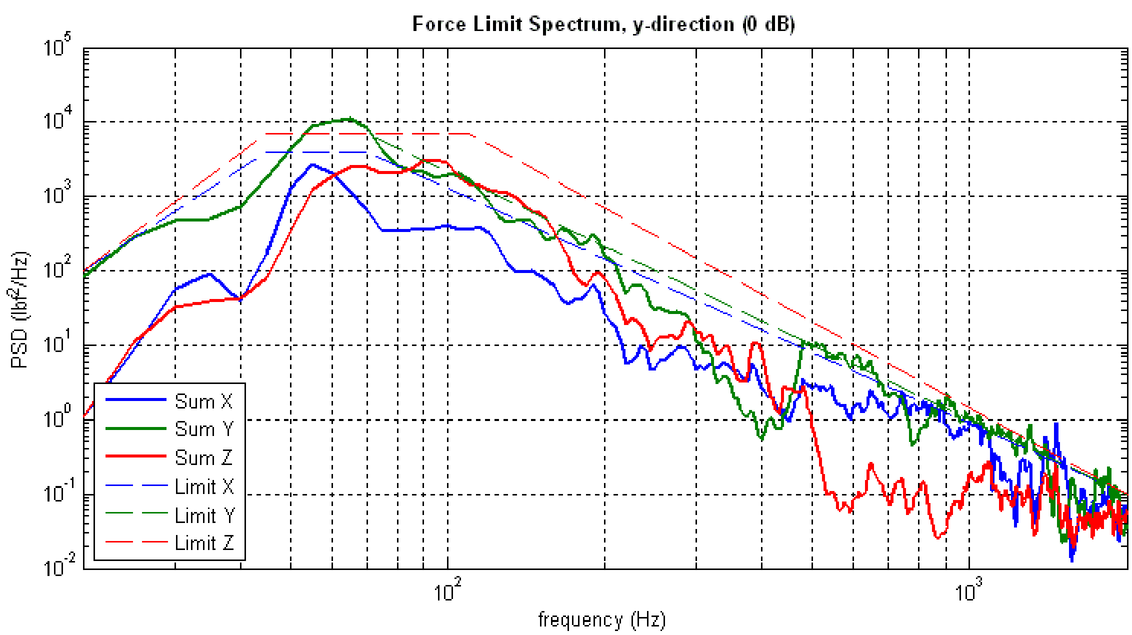

Figure 13: Force Limit Spectrum for Proto-flight Random, 0dB (y-axis)

Proto-flight testing for the z-axis began at -15 dB and was increased in steps of 3dB to full level for one minute. During this time, correct control was verified with the real-time error plot, which had values within the specified tolerance except at low frequencies of 20 Hz to 30 Hz near the end of the test. The resulting control data for the z-axis test environment is shown in Figure 14, and the summed force limit spectra are shown in Figure 15. Using the limit channel plot, data from a single limit accelerometer was discovered to have a large DC offset. This offset resulted in large magnitude, low frequency content, which was greater than the corresponding response limit. The control system decreased the drive at these frequencies to no avail; the DC offset remained. Therefore, the control spectrum in Figure 14 displays out of tolerance values at these low frequencies. This faulty accelerometer only affected two to four spectral lines out of 400, making little difference in the overall gRMS value of the input. Overall, the measured input acceleration level for the z-axis, proto-flight random environment was 3.9 gRMS, within -18% of specification.

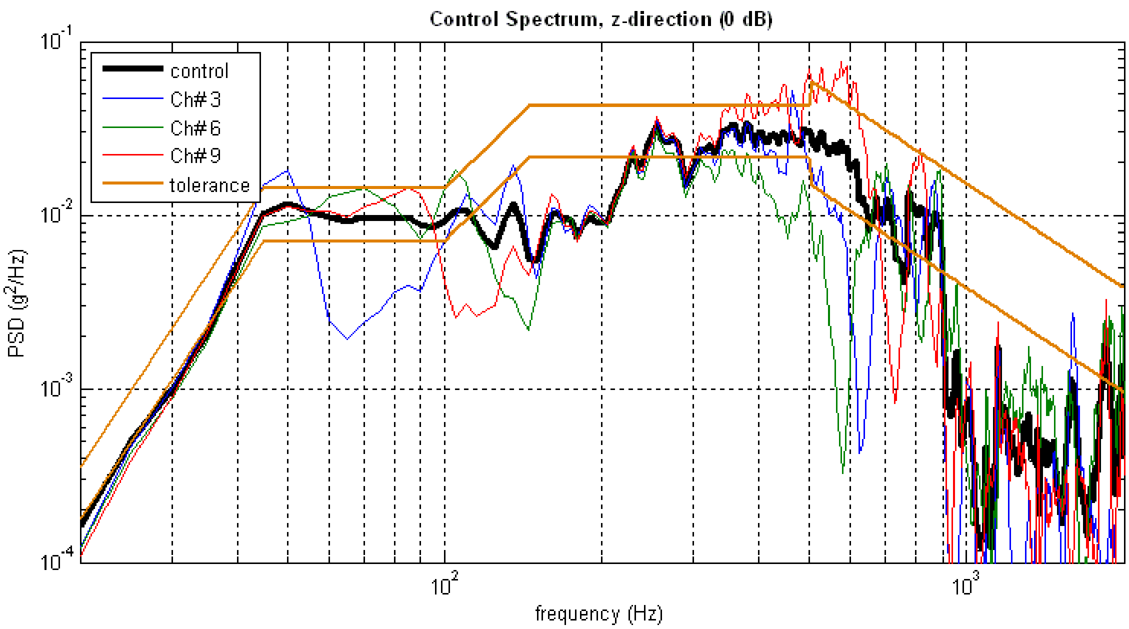

Figure 14: Control Spectrum for Proto-flight Random, 0dB (z-axis)

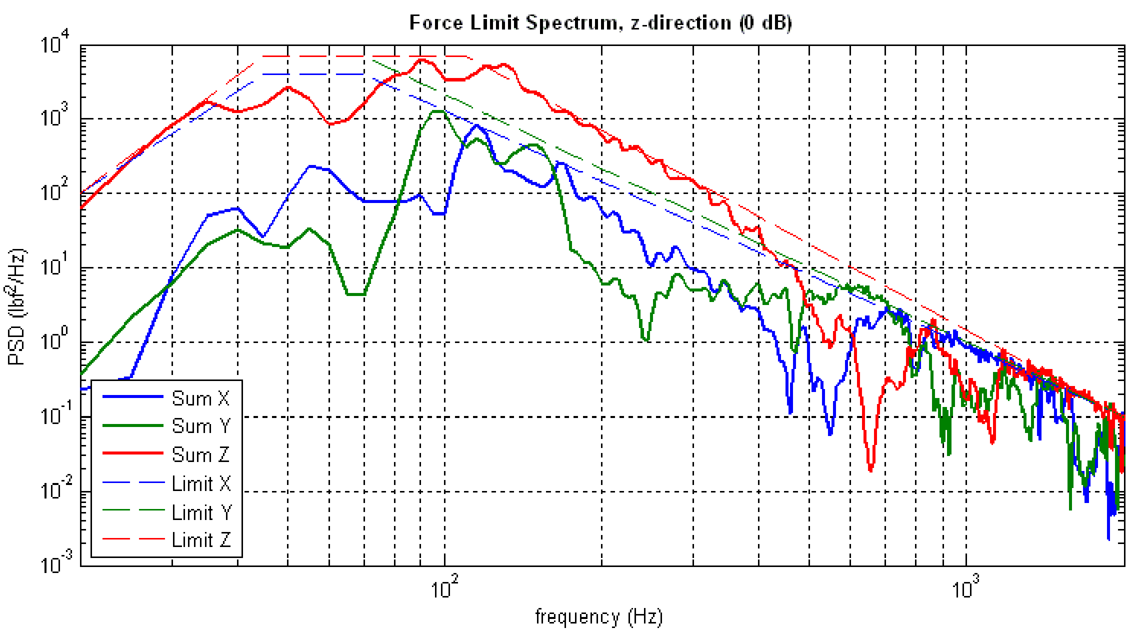

Figure 15: Force Limit Spectrum for Proto-flight Random, 0dB (z-axis)

Signature Random Vibration Test Results

For the signature random results, only the z-axis data will be plotted, as the PSD responses differed most between environments in this direction. As for the x-direction data, the response PSDs were similar at most frequencies except for two locations. At these frequencies, the initial signature random data exhibited much higher magnitudes than the data from the subsequent signature tests. This was considered as being due to settling of the joints and components of the Flight System, resulting in lower responses (higher damping values). This settling was expected as part of the design—not due to damaged components. Signature results for the y-axis data was similar over the entire test frequency range, indicating that the no major shifting (or possible damage) occurred during the major test environments.

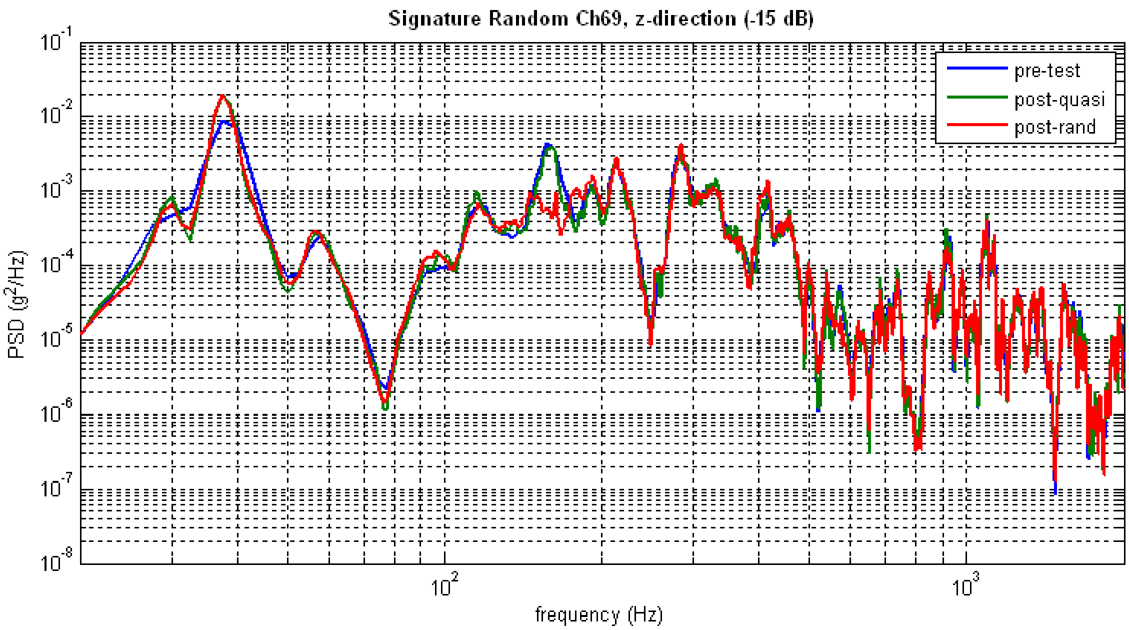

Figure 16: Signature Random Response Comparison PSDs (Z-Axis)

Signature results for the z-axis test are shown in Figure 16, with each color representing a different signature test run. The initial signature test run is shown in blue, the signature run performed between the full-level quasi-static and proto-flight random tests is shown in green, and the signature run performed after full-level proto-flight is shown in red. As seen in the data, the overall shape of the PSDs for all three tests is similar over the entire test frequency range except for a large difference at approximately 160 Hz. Not only does the magnitude of the mode differ, but the shape and perhaps frequency has changed as well. This change was most evident in responses around certain electronic box component locations. The belief was that component flex cables may have shifted, and/or the other components settled to a much more severe extent than had been evident in the x-direction signature random tests, resulting in this difference.

Concern was expressed that the response level at 160 Hz might continue to lower over time, suggesting that something had broken and would accumulate additional damage.

To alleviate that concern, PSDs were calculated for four consecutive 15 second chunks of time during the full level proto-flight, one minute environment. The PSDs indicated that the response more than likely stabilized during the full level excitation. Further analysis and results for all other channels are documented in the memo by Stasiunas [7]. Following this analysis, it was agreed that no further testing would be performed on the Flight System, as not much more information regarding the difference at 160 Hz would be gained. After the testing as described here was completed, the Flight System was ultimately subjected to an Integrated System Test (IST), where no sign of damage or structural malfunction was detected.

Test Conclusions

All quasi-static and random vibration test environments, as required by the Flight System launch environment specifications, were achieved successfully using an electro-dynamic shaker with closed-loop control. During testing, several challenges were encountered including: discrepancies in the horizontal summed forces measurements at full level, incorrect force limiting for the x-axis proto-flight random test, and significantly differing PSDs from the health-monitoring, signature random test.

Quasi-static testing in the horizontal axis resulted in correct input acceleration, but much lower-than-expected values and DC offsets for the in-axis summed force measurements above -6dB proto-flight. An analysis of the data found that these discrepancies were due to an internal component of the Flight System slipping a small amount at these higher acceleration levels, effectively creating a non-linear system at input levels above 2000 lbf. RMS calculations indicated this did not affect the force limiting during the horizontal proto-flight random test environment. The vertical test configuration did not exhibit this discrepancy in the summed force measurement.

Proto-flight random vibration testing of the x-axis configuration at -6dB revealed a broadband notch in the control spectrum at 700 Hz that was not due to either force limiting or acceleration response limiting, as the PSD were below their respective limit values. It was speculated that a sharp resonance of the slip table at 730 Hz may have been causing a conflict with the control software. In response, the x-axis force limit value was increased at this frequency range and above, and the test performed at full level without further problems. The y-axis initially displayed the same issue, but performed properly at -9dB and above. The z-axis test limited much more overall than the horizontal configurations, but did not have the same resonance issue due to the new shaker configuration.

Signature random environment data comparisons showed lower PSD magnitudes and frequency shifts following the x-axis and z-axis proto-flight random tests. For both tests, it was believed that settling of joints and preload changes in the Flight System components caused this change. An analysis of the z-axis data was performed to verify that this change leveled out during the full-level test. Post-test system check data exists that indicate preload change did occur, further verifying this assumption.

Despite these challenges, the Flight System was successfully exposed to these required test environments, and was considered certified for launch. As a final note, an Integrated System Test was performed on the Flight System following all vibration testing, and no sign of damage or structural malfunction was detected.

References

[1] Hunter, Norman, et al., *Force Gage Readings During X Axis Full Level Quasi-static and Random Tests*, Ares Corporation, March 2009.

[2] Stasiunas, Eric, *PSD Analysis of Flight System Z-direction versus Time*, Sandia National Laboratories, November 2008.