Spacecraft Vibration Testing: Benefits and Potential Issues

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Abstract

JPL has traditionally performed system level vibration testing of flight spacecraft. The benefits and potential issues of fully assembled flight spacecraft vibration testing are discussed herein. The following specific topics, which may be complementary to the special session on "Virtual Vibration Testing," are discussed: spacecraft workmanship, functional and structural integrity testing to uncover workmanship problems, force- and moment-limited vibration testing, potential issues with structural frequency identification using base shake test data, and several failures related to vibration shaker testing. The information provided in this paper is complementary to the special session on "Virtual Shaker Testing,' and attention is given to issues that virtual shaker testing may face.

1. Introduction

Spacecraft vibration testing involves the use of two types of vibration testing equipment: stinger- and base-drive shakers. Base-drive vibration tests are conducted with test articles mounted on a moving platform that is driven by an electro-dynamic shaker. The base-drive shakers are used to qualify flight hardware for launch dynamics environments. For base-drive shaker tests, three types of excitation are used in spacecraft vibration tests: sine, random, and transient. Stinger vibration tests, on the other hand, are conducted with the test article in either a free or a fixed position. Stinger vibration tests are commonly used for modal vibration testing where the objective of the test is to generate data for verifying a mathematical model, which assumes either fixed or free boundary conditions.

The primary objectives of a spacecraft dynamic test are to qualify it in a fully assembled flight configuration, to increase the probability of mission success by detecting possible workmanship problems and to validate that the system will survive the mission dynamics and loads environments. Spacecraft vibration tests also help verify assembly-level test requirements and spacecraft analytical models. In the past couple of years, the benefits of shaker vibration tests have been discussed including at the Spacecraft and Launch Vehicle workshop, 2014, where a special session was organized by this author to discuss this topic[1-3].

In this paper, the benefits of spacecraft dynamics testing are discussed briefly. The following specific topics are discussed: spacecraft workmanship, functional and structural integrity testing to uncover workmanship problems, force- and moment-limited vibration testing, potential issues with structural frequency identification using base shake test data, and several failures related to vibration shaker testing. The information provided in this paper is complementary to the special

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session on “Virtual Shaker Testing,’ and attention is given to issues that virtual shaker testing may face.

2. Shaker Test Benefits

There is a trend in the aerospace industry to rely more on structural analysis than on vibration testing to simulate the launch dynamics environments. The reasons provided generally are related to cost and schedule constraints and the potential risk of vibration testing a spacecraft close to its launch date. However, the essential role of testing and its importance are still widely recognized in the community at large. With recent gains in the efficiency of dynamics testing, flight hardware failures are avoided while maximizing performance and minimizing cost, and thus minimizing the impact of spacecraft launch schedule delays.

The primary reason for vibration testing of spacecraft is to verify the launch dynamics environments in the low/mid frequency mechanically transmitted launch vibration environment. A secondary reason for conducting dynamics tests is to identify workmanship defects, that left undetected, might cause operational or even mission failures in flight. One of the tests performed at the spacecraft level is the acoustics test, which provides significant excitation of low mass and large surface structures typically above ~100 Hz for most spacecraft modes[4]. Launch vehicle acoustic test spectra typically roll off quickly below 100 Hz and the reduced acoustic energy may not excite structures significantly. There is a misconception in the community that the acoustic test alone provides adequate workmanship (this will be discussed in more detail below), however, this physically is not supported as evidenced by the low acceleration responses of heavy components, which are not effectively excited by acoustic pressures. Additionally, structural excitation by mechanically induced vibration is inherently different from acoustic excitation. In general, if acoustics were really an adequate dynamics qualification test by itself, structures would be designed to acoustic loads, not to loads from coupled loads analyses.

Qualification by analysis or by static test is often not practical for frequencies above ~50 Hz and for non-primary structure. Launch vehicle and spacecraft coupled loads analyses typically cut off at 40 to 60 Hz and spacecraft models do not include secondary structure, non-structural hardware, or ancillary hardware[5]. Some of the ancillary hardware are: c*able harnesses, bellows, connectors, actuators, plumbing lines, wave guides, brackets, dampers, shades and shields, articulation/deployment mechanisms, shunt heaters, louvers, purge equipment, hinges and restraints, blankets/supports, etc.* These are usually responsive to low/mid frequencies. The only time these items have a chance of being excited is during a spacecraft vibration test.

Figure 1 shows an example of structural acceleration power spectral density (PSD) responses on the Aquarius instrument obtained from both a random vibration and acoustic test. The random vibration test was performed from 10 Hz to 200 Hz, whereas the acoustic test was performed from 25 Hz to 10,000 Hz. A sine test was not performed on this instrument. This figure illustrates not only the qualification of the instrument to launch dynamics environments, but also shows that the random vibration test provided good workmanship screening below 200 Hz, whereas the acoustic test did not. In fact, the acoustic responses are way below workmanship levels suggested in the NASA handbook[6] for components. A major design flaw in the instrument was identified during

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the random vibration test. Lack of a random vibration test would have potentially resulted in the loss of the mission during launch had the design flaws not been mitigated before launch.

Figures 2 and 3 show acceleration PSD responses obtained from two spacecraft that successfully completed random vibration and acoustic tests. The acoustic test was performed from 25 Hz to 10,000 Hz and the random vibration test was performed from 10 Hz to 250 (Figure 2) and 10 Hz to 400 Hz (Figure 3). The acceleration responses shown in Figure 3 are taken from the Mars Science laboratory (MSL) spacecraft acoustic test and the MSL Rover assembly vibration test. Again the random vibration test combined with acoustic test qualified the spacecraft to dynamics launch environments and covered a full workmanship screening test. A couple of minor workmanship issues were identified during these tests.

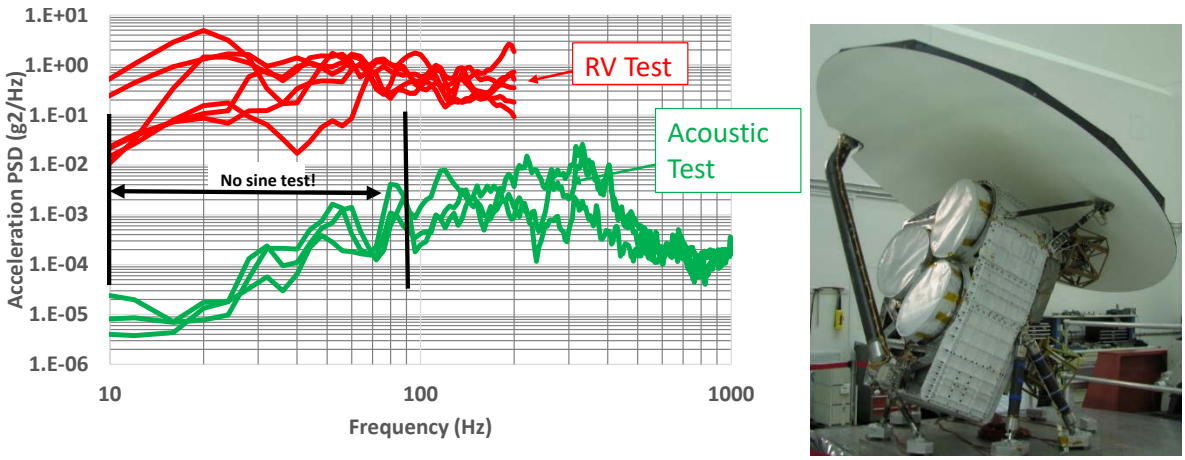

Figure 1. Acceleration responses from the Aquarius instrument that underwent random vibration and acoustic testing. The random vibration test that was performed from 10 Hz to 200 Hz provided a good workmanship screening test, whereas the acoustic test did not (no sine test was performed).

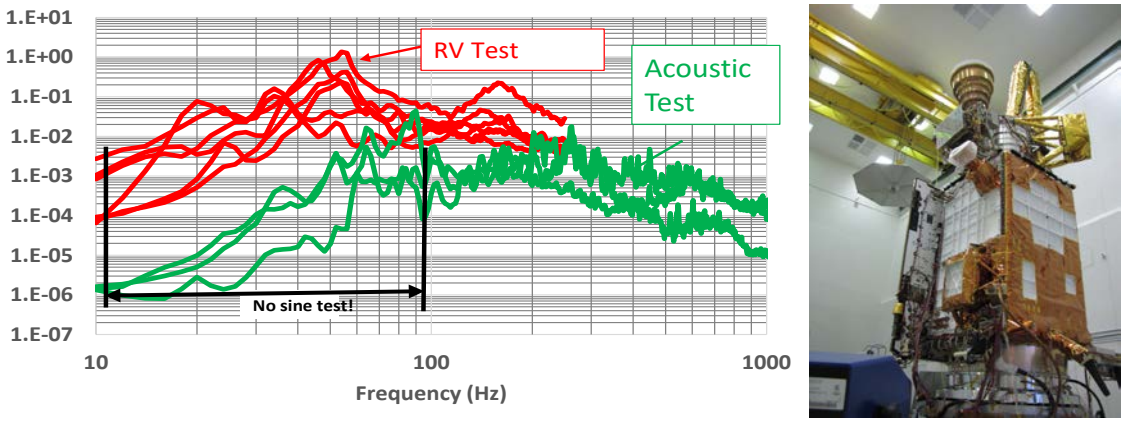

Figure 2. This figure shows another example of a spacecraft (SMAP) that successfully underwent random vibration and acoustic tests. Again the random vibration test combined with the acoustic test qualifies the spacecraft to the dynamics launch environments. Also, the random vibration test proved an adequate workmanship screening test. In these tests, a couple of minor workmanship issues were identified.

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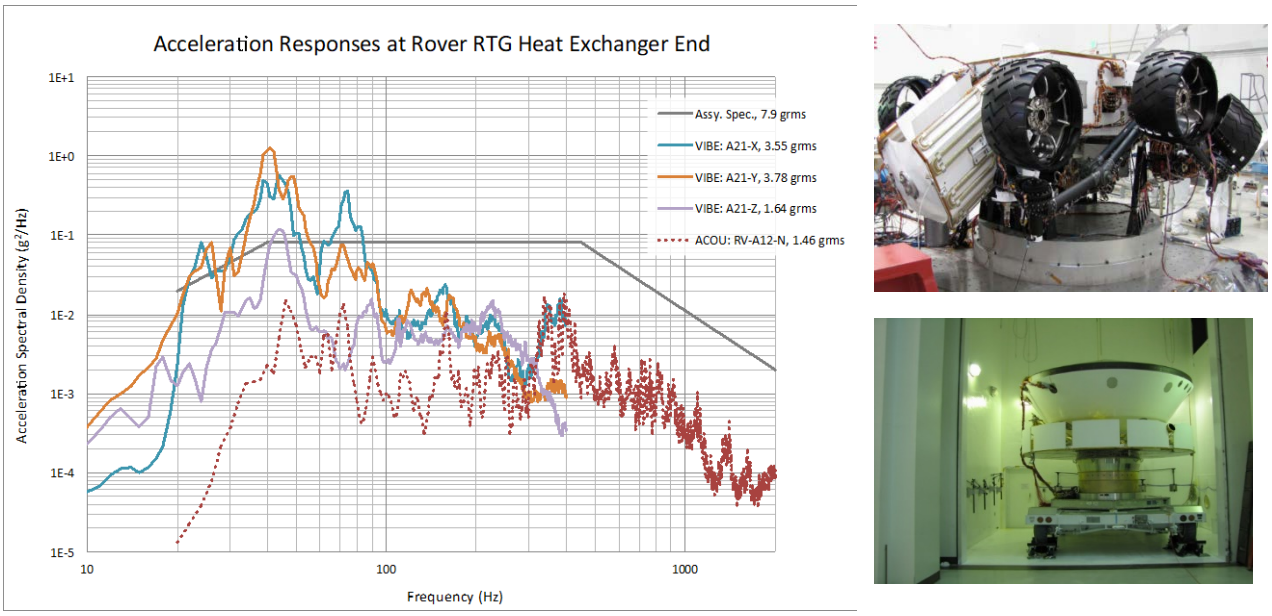

Figure 3. This is another example of a spacecraft (MSL) that successfully underwent random vibration and acoustic tests. Again the random vibration test combined with acoustic test qualifies the spacecraft to dynamics launch environments. The acoustic test does not provide adequate workmanship screening below ~300 Hz. During the RV test, several workmanship issues were identified, one related to a fastener that backed out of an encoder in a wheel actuator.

The flight system vibration test provides the only test verification of the mechanical integrity of flight subsystem interfaces. Structural loads tests are often performed only on non-flight primary structure. Also, the spacecraft vibration test signature survey may eliminate the requirement for a separate fixed-base modal test for some spacecraft, especially those with structural design heritage. However, a shaker modal test may not be an adequate substitute for a traditional modal test. This is discussed in the next section.

The bottom line for spacecraft vibration tests is that they provide a good workmanship screen and qualify the flight system for a significant mission environment. Analysis and other tests, such as static loads or acoustic test alone, are not a substitute. The vibration test may also be used to satisfy FE model verification requirements.

3. Shaker Test Issues

Base-drive vibration has sometimes been used to generate modal data. However, spacecraft modes of vibration on a shake table in general may be different and may not provide accurate modal information due to shaker boundary conditions[7]. Shaker tables do not replicate the interface impedance of a launch vehicle since the combined launch vehicle and spacecraft modes form coupled system modes. Also, spacecraft dynamic properties on a shaker table are not equivalent to those on a seismic mass, which is often used in modal survey tests. The modal test conductor needs to consider the dynamics of the shaker if this method is used for modal testing. Issues related to modal correlation using a shaker table were encountered recently at JPL a spacecraft (the image is shown in Figure 2) undergoing qualification random vibration tests. Figure 4 shows Observatory

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transmissibility plots obtained from a correlated FE model and the sine test data. The predicted primary mode is 22.6 Hz versus a measured mode of 22.7 Hz, which represents a 0.4% frequency difference. The computed transmissibility functions obtained from the vertical base shake random vibration test of the Observatory indicate the presence of modes at 14.8 Hz and 24.5 Hz that are not predicted by the test correlated model shown in Figure 4 (See Figure 5). The correlated FE analysis predicted these modes to be at 17.4 Hz and 32.7 Hz, respectively. The discrepancy between these primary frequencies is attributed to the dynamics of the shaker head not included in the FE analysis. The compliance of the shaker was included in the post-test FE analysis. The base rotational stiffness obtained from the shaker manufacturer ($K_{\theta x}$= $K_{\theta y}$= 94.7 E6 in-lbf/rad) was subsequently included in the model. This produced X-bending mode frequencies at 7.8 Hz & 26.0 Hz. The original spacecraft stiffness values were $K_{\theta x}$ = $K_{\theta y}$ = 1.0E13 in-lbf/rad. Although the X-bending mode frequencies for the flexible shaker do not exactly match the test frequencies, they do indicate that shaker compliance plays a significant role for those frequencies (See Figure 6).

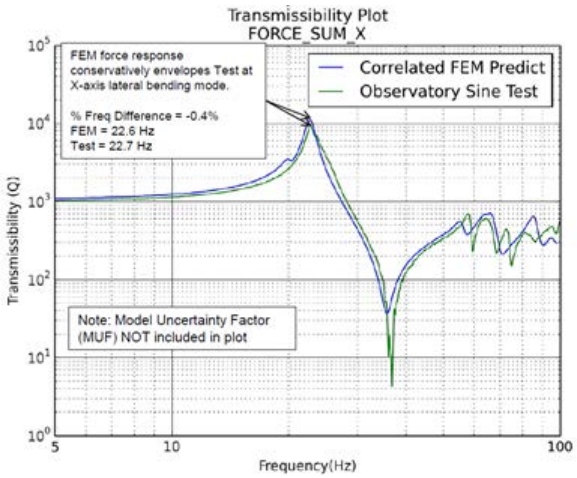

Figure 4. The transmissibility functions obtained from the Observatory FE prediction and sine test. The image of the Observatory is shown in Figure 2.

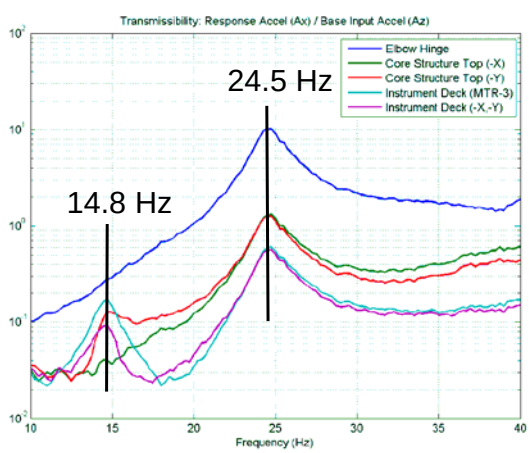

Figure 5. The transmissibility functions obtained from the Observatory FE prediction and sine test. The image of the Observatory is shown in Figure 2.

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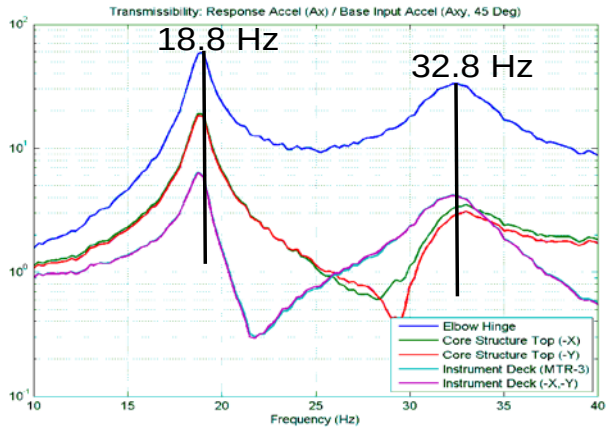

Mode	Frequency (Hz)	
	Rigid Shaker	Lateral Vibe Test
1st X-Bending	17.4	18.8
2nd X-Bending	32.7	32.8

Figure 6. The transmissibility functions after including the shaker compliance in the model.

The modal shaker test is one example that could potentially provide misleading information, unless shaker compliance is included in the FE model. Other issues with shaker tests are in general related to aged equipment and operator errors dealing with control systems. In the last couple of decades at JPL, there have been two major structural failures that occurred during dynamics testing. One such case is the High Energy Solar Spectroscopic Imager (HESSI) spacecraft that was subjected to a series of sine vibration tests (See Figure 7). A major over test occurred during the sine-burst structural qualification test and caused significant structural damage to the spacecraft. The failure was attributed to the stiction in the shaker slip plate during the shaker self-check test[8]. For this case, the failure was attributed to aging equipment and the fact that the open-loop vibration test control system had fewer safety features to limit the shaker from excessive excitation. An open-loop dynamics shaker test is in general a dangerous test.

The second major failure that occurred at JPL in the last several years was related to a reflector acoustic test for the Aquarius Instrument (An image of the Instrument is shown in Figure 1). Figure 8 shows the reflector suspended from the acoustic chamber. During a “trouble-shooting” phase of the test with the reflector inside the chamber, which was considered necessary because of anomalous data from previous runs, the operator accidentally sent extremely energetic pressure waves through controller system into the chamber that led to major structural damage to the reflector. Visual inspection of the reflector assembly indicated nine areas of damage around the periphery of the reflector. The root cause of the incident was the anomalous behavior of the acoustic test facility caused by deviation from the normal acoustic test procedure. Even though this test failure is not related to the main topic of this paper, it does highlight the potential for test related failures due to test operator errors.

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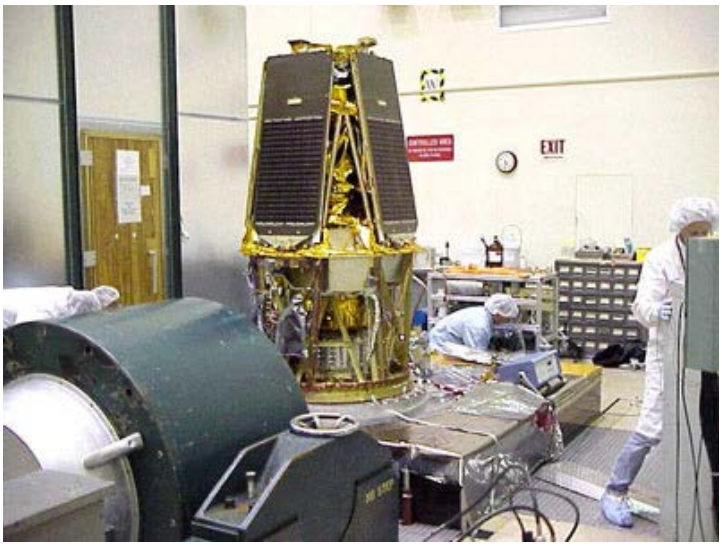

Figure7. HESSI Instrument is being prepared for dynamics test.

Figure 8. Aquarius reflector suspended in the acoustic chamber.

4. Force- and Moment-limited Vibration Testing

In the last couple of decades, JPL and other organizations have conducted many forced-limited vibration tests. Many examples of such tests can be found in the literature (See the monogramm[9]). A recent forced-limited random vibration test conducted at JPL is the spacecraft shown in Figure 2. The notched input for this test in the vertical direction is shown in Figure 9. The use of force gauges gives the test conductor the ability to measure reaction forces at the spacecraft to shaker interface and the over-turning moments of the spacecraft in real-time. Figure 9 shows power spectral densities (PSDs) obtained from a real-time moment-limited random vibration test of a mass mockup of the spacecraft shown in Figure 2. PSD overlays of dynamic M_x (left) and M_y (right) measurements limited to pre-specified values are shown in Figure 10. The near perfect overlays validate the proper design, configuration and performance of the hardware network used to limit to the overturning moments in real-time[10]. Figures 9 and 10 are examples of methods that

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can be used during vibration tests to insure that the test article undergoes qualification testing safely. These steps are necessary to remove excessive excitation of the hardware during shaker vibration tests.

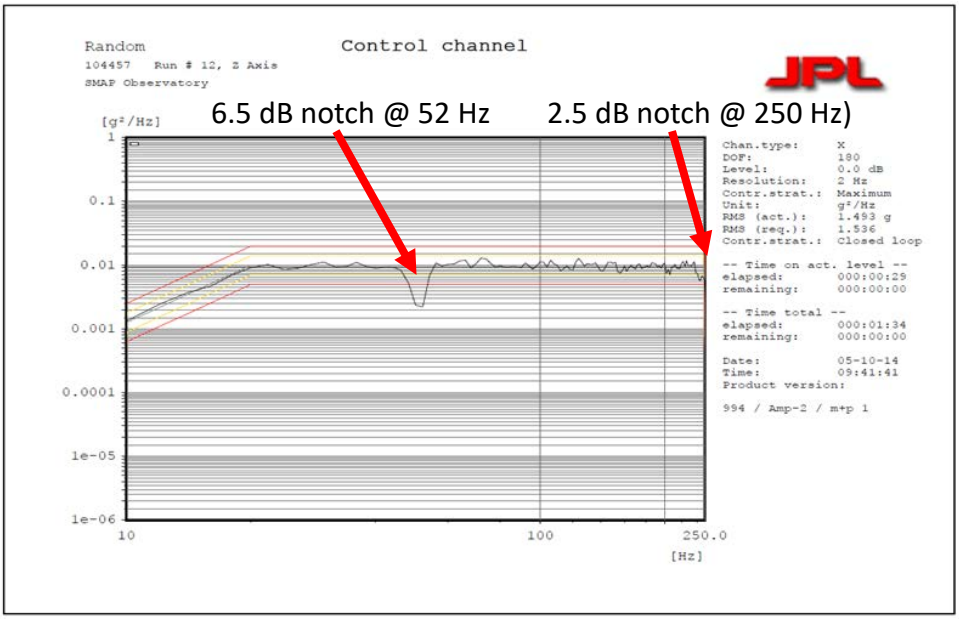

Figure 9. Force-limited random vibration input to the Observatory (an image of the Observatory shown In Figure 2) that resulted in two notches: 6.5 dB @ 52 Hz, and 2.5 dB @ 250 Hz.

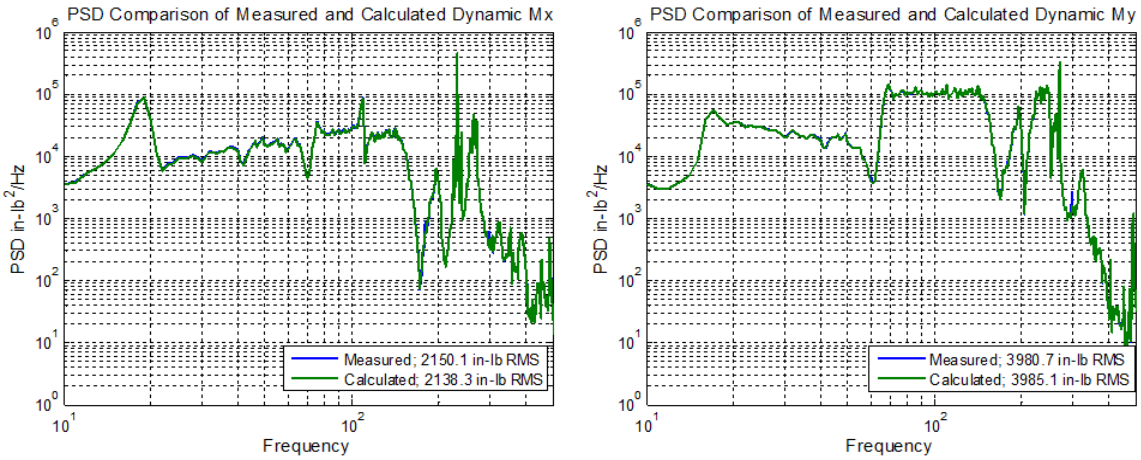

Figure 10. Real-time moment limiting capability applied during spacecraft random vibration test[10].

5. Summary

In this paper, the advantages of performing vibration tests (random vibration) are briefly discussed. Vibration testing of spacecraft is the only test that simulates the low/mid frequency mechanically transmitted launch vibration environment. Another reason for conducting vibration tests is to identify workmanship defects, which if not detected, might cause operational and/or other failures

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in flight. The acoustics test alone does not serve as a full workmanship screening test as it only excites low-mass and large surface structures above ~100 Hz for most spacecraft modes. Issues with shaker modal tests are discussed. Unless the dynamics of the shaker are included in the FE model, the modal information obtained from a shaker based test may provide misleading information. Several failures have occurred at JPL in the last couple of decades. These failures were attributed to aged equipment and/or test operator error. The test conductors should use force- and moment-limiting method to remove conservatism associated with shaker testing.

As part of the special session related to "Virtual Shaker Test," the following technical topics are provided for discussion and consideration by those involved with this method of testing:

- One-of-a-kind spacecraft with no heritage and flight data
- Spacecraft workmanship and qualification to launch dynamic loads
- Contact mechanisms
- Model fidelity of spacecraft components
- Structural damping and possible structural nonlinearity
- Structural modes (shapes and frequencies).

6. Acknowledgement

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