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Spacecraft vibration testing: Benefits and potential issues

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Abstract. Jet Propulsion Laboratory has traditionally performed system level vibration testing of flight spacecraft. There have been many discussions in the aerospace community for more than a decade about spacecraft vibration testing benefits or lack thereof. The benefits and potential issues of fully assembled flight spacecraft vibration testing are discussed herein. The following specific topics are discussed: spacecraft screening test to uncover workmanship problems for launch dynamics environments, force- and moment-limited vibration testing, potential issues with structural frequency identification using base shake test data, and failures related to vibration shaker testing and ways to prevent them.

Keywords: random vibration and sine test; acoustic; shaker vibration; virtual shaker; force limited RV test

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 to a moving platform that is driven by an electro-dynamic shaker. For base-drive shaker tests, three types of excitation are used in spacecraft vibration tests: sine, random, and transient. The base-drive shakers are used to qualify flight hardware to launch dynamics environments and workmanship screening before it is transported to the launch site. Stinger vibration tests, on the other hand, are conducted with the test article in either a free-free or a fixed-interface configuration. Stinger vibration tests are commonly used for modal testing where the objective of the test is to generate data for verifying and potentially updating a mathematical model. Fixed-interface testing is the most commonly employed technique for spacecraft. Shaker testing to recover modes and modes shapes have also been used by other organizations. The pitfalls of shaker dynamics coupling with the spacecraft are discussed in this paper.

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 issues 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

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discussed within the aerospace community including at the Spacecraft and Launch Vehicle Dynamic Environments workshop, 2014, where a special session was organized by this author to discuss this topic (Gordon and Kern 2015, Kolaini 2015).

In this paper, the benefits of spacecraft dynamics testing are reviewed. The following specific topics are discussed: spacecraft workmanship, functional and structural integrity testing to uncover workmanship problems (a few examples are provided of flight projects where issues were uncovered during vibration testing), force- and moment-limited vibration testing benefits, potential issues with structural frequency identification using base-shake test data, and several failures related to vibration shaker and acoustic testing. The information provided in this paper is complementary to the "Virtual Shaker Testing" session extensively discussed at the recent ECSSMET conference held November 2016 in Toulouse, France (Remedia 2016, Steffen 2016). 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 generally provided 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 minimizing the impact of spacecraft launch schedule delays.

The primary reason for system vibration testing is to verify spacecraft to mechanically transmitted launch dynamics environments in the low- to mid-frequency range. A secondary reason for conducting system dynamics tests is to identify workmanship defects, which if left undetected, might cause operational or even mission failures in flight. The shaker tests may also unravel unexpected structural nonlinear behavior of the spacecraft, which such behavior is in general not included in the FE analysis. Another spacecraft level dynamics test performed by most organizations is the acoustics test, which provides significant excitation of low mass and large surface structures typically above ~100 Hz for most spacecraft modes (NASA-STD-7001A 2001). 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 screening (this will be discussed in more detail below), however, this is physically 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 test by itself, structures would be designed to acoustic loads, not to loads generated from coupled loads analyses.

Qualification by analysis or by static test, which is considered by some organizations, 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 50 to 60 Hz and spacecraft models often do not include all secondary structure, non-structural hardware, or ancillary hardware (NASA-HDBK-7008). Some of the spacecraft 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 many of these items have a chance of being significantly excited is during a spacecraft vibration test.

To explore the differences in mechanically and acoustically induced structural vibration, in the context of workmanship screening of the hardware, a few examples are considered of spacecraft that have recently completed both vibration and acoustic testing. Figure 1 shows an example of structural acceleration power spectral density (PSD) responses on the large Aquarius Instrument obtained from both random vibration and acoustic tests. 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 adequate workmanship screening below 200 Hz, whereas the acoustic test did not. In fact, the acoustic responses are significantly below component level workmanship recommended in the NASA handbook (NASA-HDBK-7005, 2001). A major design flaw in the Instrument was identified during the random vibration test. Such a flaw was not discovered during the Instrument acoustic test. Lack of a random vibration test would have potentially resulted in the loss of the mission had the design flaw not been mitigated before launch.

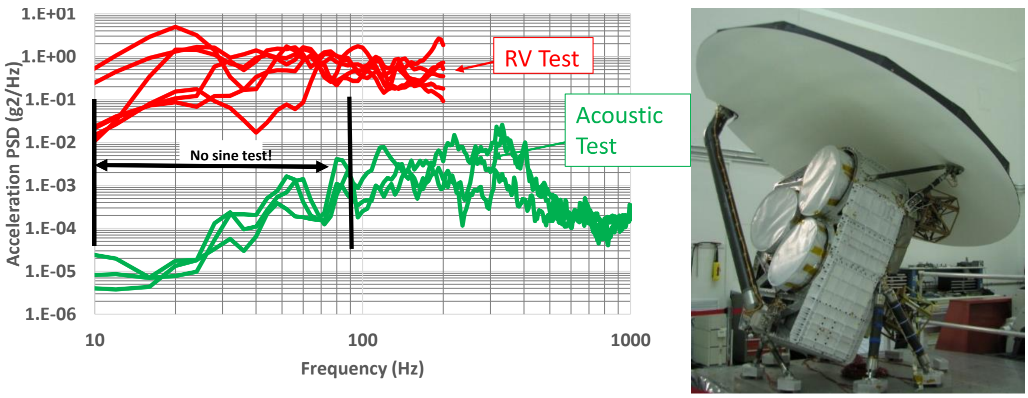


Fig. 1 Acceleration responses of a component measured at its interfaces on the Aquarius Instrument that completed random vibration and acoustic testing are shown in this figure

Two more spacecraft test examples are shown in Figs. 2 and 3. These figures indicate 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, whereas the random vibration test was performed from 10 Hz to 250 Hz (Fig. 2) and 10 Hz to 400 Hz (Fig. 3). Acceleration responses of one of the Soil Moisture Active Passive (SMAP) Observatory components measured at its interfaces obtained from system level random vibration and acoustic testing are shown in Fig. 2. The random vibration test combined with the acoustic test qualified the Observatory to its dynamics launch environments. This figure indicates that random vibration test provided adequate workmanship screening for this component, whereas the acoustic test did not. A sine test was not performed on the Observatory. A couple of minor workmanship issues were identified during Observatory random vibration tests. The acceleration responses shown in Figure

3 are taken from the Mars Science laboratory (MSL) fully assembled spacecraft acoustic test and the MSL Rover assembly vibration test. The random vibration test combined with the acoustic test qualified the spacecraft to dynamics launch environments and adequately covered a full workmanship screening test. This figure also indicates that the spacecraft acoustic test did not provide adequate workmanship screening below ~300 Hz for this component. A couple of minor workmanship issues were identified during the rover random vibration tests. Additional JPL spacecraft where random vibration tests helped reveal workmanship issues include: *Cassini*, where one of its radioisotope thermoelectric generators (RTG) experienced significant degradation in its electric power; *Deep Space I*, where the spacecraft experienced several workmanship problems such as the hydrazine tank premature valve release, Langmuir Probe falling off and a few screws backing out, etc.; *MER I*, where improper fastener torque values on tank attachment brackets would have resulted in reduced tank frequencies, therefore, invalidating the CLA analysis; and *CloudSat*, where the cloud profiling radar waveguide failed due to the adhesive bonding, which would have resulted in the loss of science data. These are just a few more examples that demonstrate the effectiveness of the system vibration test in uncovering workmanship related issues, which in some cases could have caused mission failures or loss of science data. The flight system vibration test provides the only test verification of the mechanical integrity of flight subsystem interfaces and is probably the most important dynamics test that readies the spacecraft for launch. Structural loads tests often are performed only on non-flight primary structure. Also, the spacecraft vibration test signature survey may eliminate the requirement for a separate fixed-based modal test for some spacecraft, especially those with structural design heritage. However, a shaker modal test may not be a substitute for a traditional modal test.

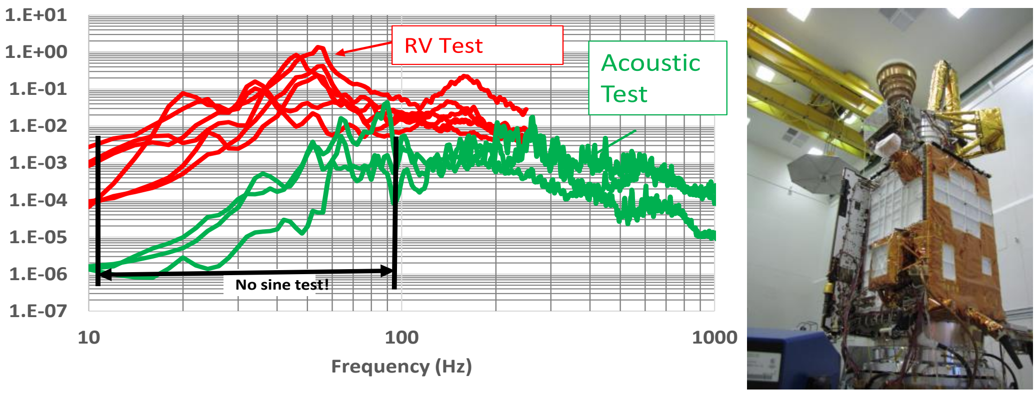


Fig. 2 Acceleration responses of a component measured at its interfaces on the SMAP Observatory that completed random vibration and acoustic testing are shown in this figure

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

3. Shaker test related issues

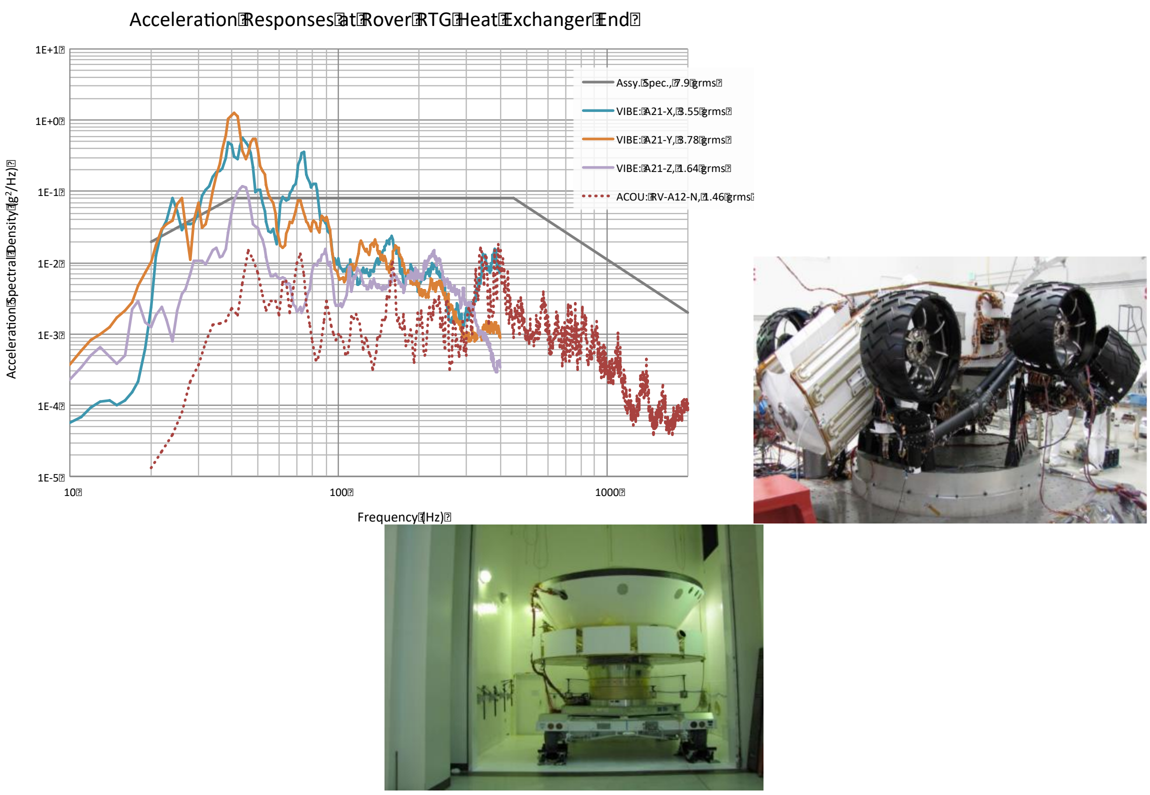


Fig. 3 A third example of a spacecraft (MSL) that successfully completed random vibration and acoustic testing. Acceleration responses from a component on the Rover are shown in this figure

A base-drive vibration test is sometimes used for model correlation purposes. However, one has to be careful when doing this test. Spacecraft modes on a shake table can be different from those obtained from a fixed-based modal test (Tsuha *et al*. 2015). The spacecraft modal test conductor needs to consider the dynamics of the shaker, in particular the bending stiffness of the shaker armature as discussed in the following section, if a base-drive shaker will be utilized for model correlation purposes. Issues related to model correlation using a shaker table were encountered recently at JPL when the SMAP observatory (the image is shown in Fig. 2) underwent random vibration qualification tests.

Measured transmissibilities obtained from the SMAP vertical-axis base shake random vibration test shown in Figure 4, indicate the presence of X-bending modes at 14.8 Hz and 24.5 Hz. The correlated FE random vibration analysis, however, predicted those modes to be at 17.4 Hz and 32.7 Hz, respectively. The discrepancy between these primary frequencies was determined to be attributed to the compliance of the shaker that was not included in the FE analysis. The SMAP Observatory random vibration test objectives were to qualify the hardware for launch dynamics environments and use it as a workmanship screening test. The model correlation was not part of the test objectives. Therefore, observations made in this paper related to SMAP model correlation are to highlight the importance of the shaker dynamics if shaker test is used for this purpose.

The compliance of the shaker was included in the post-test FE analysis. The base shaker rotational stiffness obtained from the shaker manufacturer ($K_{\theta x}$= $K_{\theta y}$= 94.7 E6 in-lbf/rad) was

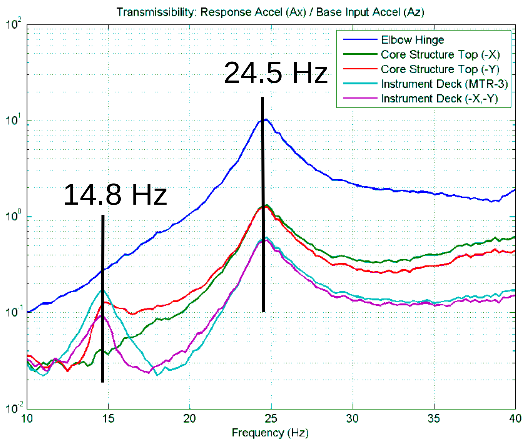
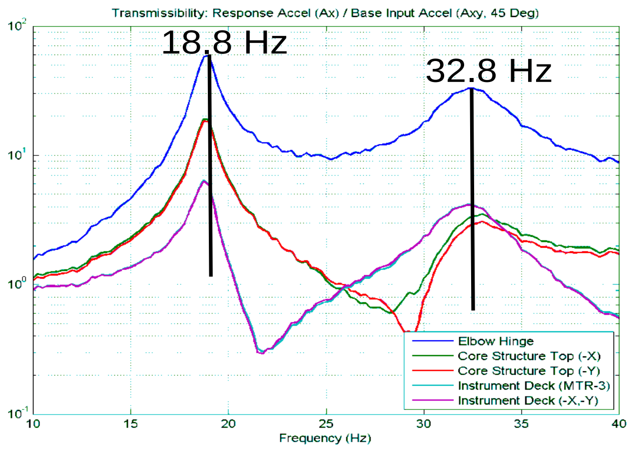


Fig. 4 Transmissibilities obtained from the SMAP Observatory vertical axis RV test indicating the presence of x-bending modes at 14.8 Hz and 24.5 Hz

subsequently included in the FE model (previously, they were set at $K_{\theta x} = K_{\theta y} = 1.0E13$ in-lbf/rad). This produced X-bending mode frequencies at 7.8 Hz & 26.0 Hz. Although the X-bending mode frequencies (7.8 Hz & 26.0 Hz) with the flexible shaker included in the FEM did not exactly match the test frequencies (14.8 Hz & 24.5 Hz), they do indicate that shaker compliance plays a significant role for these frequencies.

Fig. 5 shows the transmissibilites for the lateral axis RV test. It indicates the presence of x-bending mode frequencies at 18.8 Hz and 32.8 Hz. These frequencies agree well with those predicted by the test correlated FEM. The Table shown in Figure 6 compares the frequencies from the lateral axis RV test to those predicted by the test correlated FEM. It shows good agreement between test and analysis, and it also provided confirmation that the shaker compliance was the source of the erroneous frequencies that were obtained from the vertical axis RV test.



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

Fig. 5 Transmissibilities from the lateral axis RV test indicate x-bending mode frequencies that agree with those predicted by the FE model

A shaker based modal test has the potential to provide misleading information unless shaker compliance is included and verified in the FE model. The shaker armchair bending stiffness, spacecraft/shaker interface flexibility both in lateral and axial directions, and potential cross-coupling must be considered in the FE model. Other issues with shaker tests in general are related to aging equipment and operator errors while interfacing with vibration control systems. In the last couple of decades at JPL, there have been two major structural failures that occurred during dynamics testing. The first is the High Energy Solar Spectroscopic Imager (HESSI) spacecraft that was subjected to a series of sine vibration tests (See Fig. 6). 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 stiction in the shaker slip plate during the shaker self-check test (Terry Scharton 2002). Factors contributing to the failure included aging equipment and conducting a vibration test in open-loop control, which provides fewer safety features to limit excessive shaker excitation. In general, an open-loop dynamics test on a shaker can be a dangerous test.

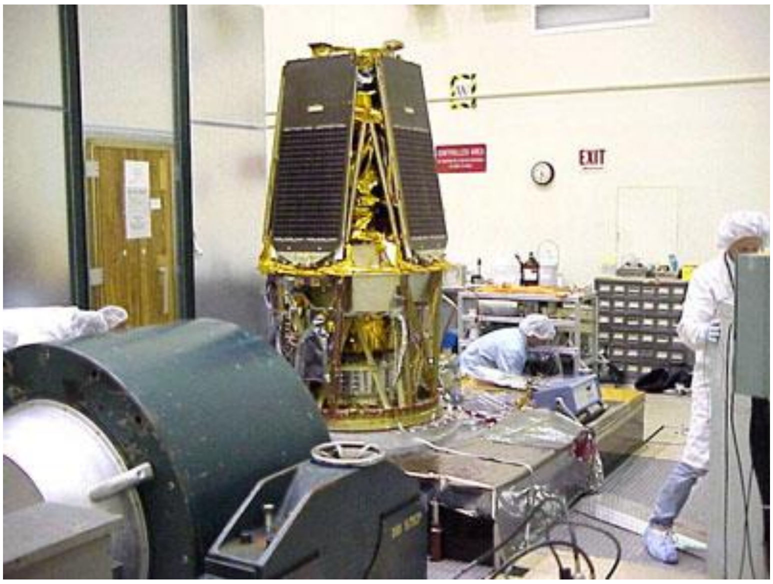


Fig. 6 HESSI Instrument test configuration on vibration shaker

It is important to highlight risks associated with operational errors that have resulted in flight hardware failures in the past during vibration and acoustic tests. A major failure that occurred at JPL due to operational error involved a reflector acoustic test for the Aquarius Instrument. An image of the reflector on the Instrument is shown in Fig. 1 and the reflector suspended from the acoustic chamber is shown in Fig. 7. During a “trouble-shooting” phase of the test to resolve anomalous data from previous test runs and with the reflector still inside the chamber, the operator accidentally sent extremely energetic pressure waves through the controller system. This led to excessive structural excitation that resulted in major 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 reverberant chamber 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.

Fig. 7 Aquarius Reflector suspended in the acoustic chamber

4. Force- and moment-limited vibration testing

Over the last couple of decades, JPL and other organizations have conducted many force-limited vibration tests. Many examples of such tests can be found in the literature (Scharton 1977). The SMAP spacecraft shown in Fig. 2 is an example of a recent force-limited random vibration test conducted at JPL. The notched test input in the vertical direction is shown in Fig. 8. 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. Fig. 9 shows power spectral densities (PSDs) obtained from a real-time moment-limited random vibration test of a mass mockup of the SMAP spacecraft. PSD overlays of dynamic M_x (left) and M_y (right) measurements limited to pre-specified values are shown in Fig. 9. 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 (Van Dyke and Landry 2015). Figs. 8 and 9 are examples of methods that can be used during vibration tests to ensure that the test article undergoes qualification testing safely without compromising input acceleration requirements. These approaches are often necessary to remove excessive excitation of the hardware during shaker vibration tests.

The application of the force limited vibration test in general does not pose any challenges since JPL conducts spacecraft modal test by placing it on a seismic pit. However, if shakers are used for model correlation, it is recommended that the load cells compliance to be included in the finite element model.

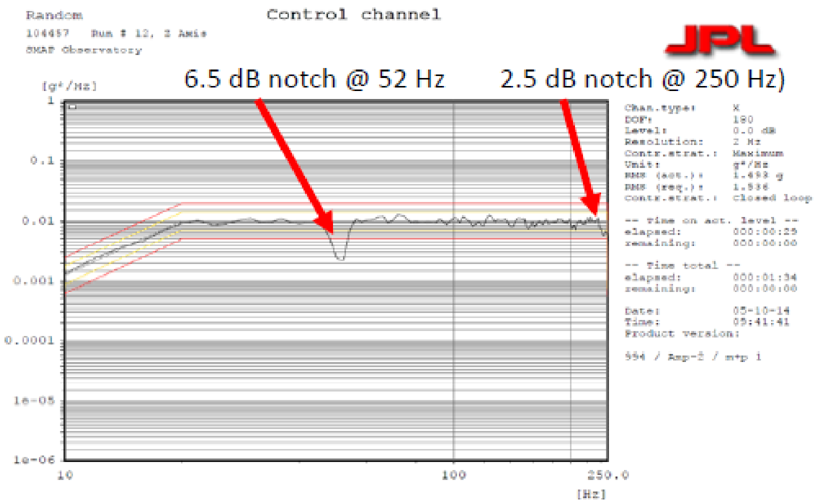


Fig. 8 Force-limited random vibration input to the SMAP Observatory that resulted in two notches: 6.5 dB @ 52 Hz and 2.5 dB @ 250 Hz

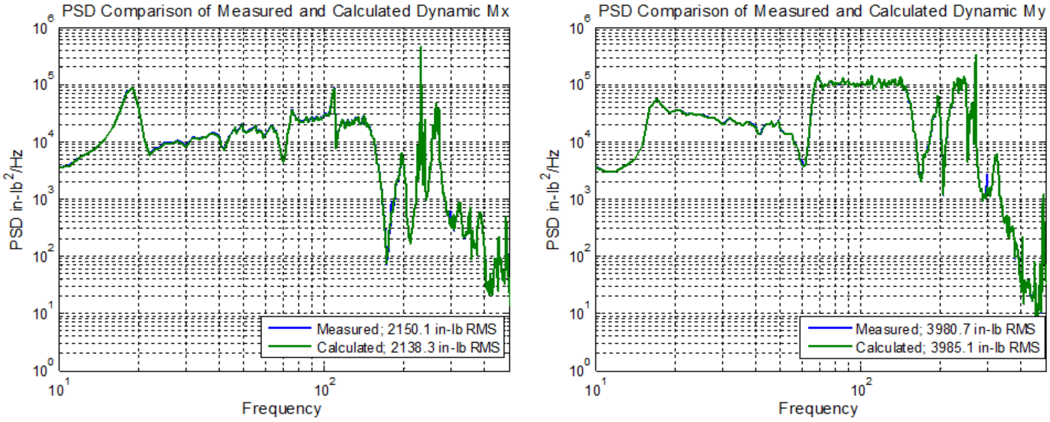


Fig. 9 Real-time moment limiting capability applied during spacecraft random vibration test (Van Dyke and Landry 2014)

5. Virtual shaker testing

Several authors discussed “Virtual Shaker Test” methods at the special session held at the ECSSMET 2016. The advantages of such methods were discussed at this conference (for example see M. Remedia, W. Steffen). It is important to emphasize that virtual shaker testing should not be interpreted by the community as a means to eliminate actual shaker testing of spacecraft that the authors of this paper promote. However, the method can be used as way of preparing for testing and ensuring that the FEM accounts for the compliance of the shaker to provide adequate modal testing information for model validation purposes. Attempts by organizations to replace spacecraft vibration testing with “virtual testing” is discouraged as it does not provide some of the advantages that shaker testing offers as discussed in this paper.

6. Conclusions

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 of spacecraft is to identify workmanship defects, which if not detected might cause operational and/or other failures 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 were also discussed. Unless the dynamics of the shaker and shaker head expander and/or slip table compliance with spacecraft interfaces are included in the FE model, the modal information obtained from a shaker-based test may provide misleading information. A couple of failures have occurred at JPL in the last couple of decades. These failures were attributed to aging equipment and/or test operator errors. Test conductors need to have adequate knowledge of the shaker equipment, the control system and its built-in safety features, and an understanding of how test articles behave under shaker excitation. It is recommended that test conductors use force- and moment-limiting methods to remove conservatism associated with shaker testing. Standard safety features combined with implementation of force- and moment-limiting methods will help ensure that a spacecraft shaker test will achieve its intended qualification and workmanship screening test objectives and limit the risk of a failure occurring a few months before delivery to the launch site.

The authors recognize the advantage of “Virtual Shaker Test” method. It is important to emphasize that virtual shaker testing should not be interpreted by the community as a means to eliminate actual shaker testing of spacecraft.

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