Spacecraft Vibration Testing: Benefits and Potential Issues

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Introduction

- JPL has performed system level base shake testing on flight spacecraft for the past couple of decades.
- The advantages of fully assembled flight spacecraft vibration testing are presented with attention given to the following specific topics may be complementary to the special session on "Virtual Shaker Testing":
  - Spacecraft workmanship, functional and structural integrity test to uncover workmanship problems when exposed to the mission dynamics and loads environments
  - Force and moment limited vibration testing
  - Potential issues with structural frequency identification using base shake test data
- A discussion on how the "Virtual Shaker Testing" concept will address some of the challenges outlined in this presentation is suggested

Spacecraft Vibration Tests

Benefits of Shaker Testing

- Shaker vibration is the only test that simulates the low/mid frequency mechanically transmitted launch vibration environment.
  - Acoustics provides significant excitation of low mass/large surface structures
  - Heavy components are not excited by acoustics.
  - Acoustics provides poor excitation at low frequencies as acoustic test spectra typically roll off quickly below 100 Hz
  - Vibration and acoustics excite spacecraft structures differently!
  - If acoustics were really an adequate dynamics qualification test by itself, structures would be designed to the acoustic loads not to the coupled loads analysis.

Benefits of Shaker Testing

- Qualification by analysis or by static test is often not practical for frequencies above ~50 Hz and for non-primary structure:
  - L/V-S/C coupled loads analyses typically cut off at 50 to 60 Hz
  - S/C models usually do not include secondary structure, non-structural hardware, or ancillary hardware, such as:

    cable 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 types of hardware are usually responsive to low/mid frequency excitation.
  - These items are typically tested only at the S/C level

Benefits of Shaker Testing

- The flight system vibration test traditionally 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.)
- The spacecraft vibration signature survey may eliminate the requirement for a separate fixed base modal test for some spacecraft, especially those with structural design heritage.
  - However, there may be deficiencies with using this approach, which ~~in shaker modal test~~ is discussed in the subsequent charts
- **Bottom line:** Spacecraft vibration tests provide a workmanship screen and qualifies the flight system for a significant mission environment. Analysis and other tests, such as static loads or acoustics are not a substitute. The vibration test may also be used to satisfy FE model verification requirements.

Random Vibration Workmanship Testing

- Workmanship related issues often uncovered by random/sine vibration tests
- Random vibration testing is an effective workmanship screen for non structural hardware that is typically tested only at the system level, such as:

  Cable 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.
- Random vibration testing is a good simulation of the flight vibration environment and alleviates the over-test inherent in sine vibration tests.
  - Reduces resonance buildup. Sine vibration is swept relatively slowly across resonance frequencies allowing full build up of each resonance. Random vibration induces excitation of all frequencies at once, with randomly varying amplitudes
  - Random vibration reduces the number of peak response cycles when compared with an equivalent sine sweep test.
  - Excites modes simultaneously thus simulates flight environment well since dominant flight events are often broadband.

JPL Spacecraft Anomalies Revealed during Random Vibration Testing (a few examples)

- **Cassini:** experienced an RTG electrical short to spacecraft mount in system RV test. Significant degradation in spacecraft electrical power could have resulted. Spacecraft mount was redesigned and retested.
- **Deep Space 1:** experienced several workmanship problems during system random vibration test - a hydrazine liquid service valve opened prematurely, the Spherical Langmuir Probe fell off the bottom of the Remote Sensing Unit, one screw in the Star Reference Unit backed out part way and two others fell out, and fasteners loosened in the Star Tracker bracket leaving chatter marks on the shear panel. Any one of these problems may have seriously degraded the mission.
- **MER 1:** vibration test revealed improper torque of bolts on tank attachment brackets, which would have reduced tank frequencies and may have invalidated coupled loads analysis results.
- **CloudSat:** Cloud Profiling Radar waveguide failure due to apparent poor workmanship of adhesive bonding. Possible loss of science data averted.
- **MSL Rover:** experienced several motor encoder screws that backed out of at least one of the rover actuators. The actuators are used throughout Rover and the issue was unlikely to have otherwise been found before launch, which could have been a serious threat to the mission.
- **Aquarius:** Instrument level RV revealed serious design issues with mono-ball bipods/Instrument interfaces

Force and Moment Limited SC Vibration Tests

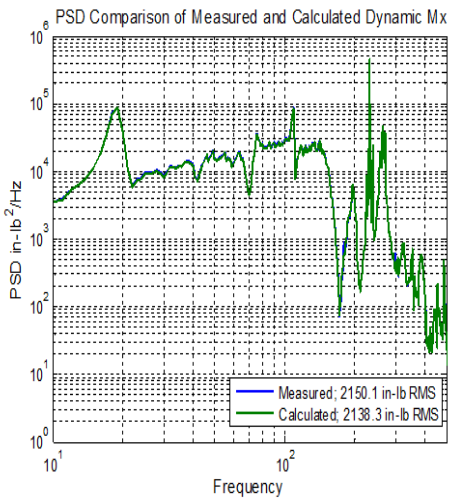
JPL SC Force Limited RV Tests (1)

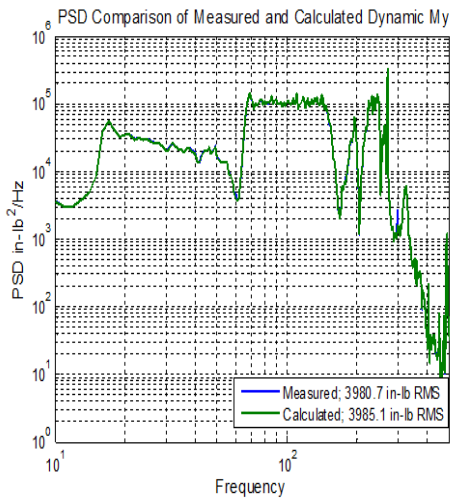
- Cassini spacecraft vertical force limited random vibration test at JPL, November 1996:
  - A single channel - the total vertical force - was used for notching. (Previous spacecraft sine vibration tests - Galileo, TOPEX - typically required hundred-plus response limiting channels for notching).
  - The test was successfully completed in two and a half days.
- Deep Space 1 spacecraft two axis force limited random vibration test at JPL, November 1997.
- QuikSCAT spacecraft two axis force limited random vibration test at Ball, October 1998.
- ACRIMSAT spacecraft three axis force limited random vibration test at Orbital Sciences, August 1999.
- GALEX spacecraft three axis force limited random vibration test at Orbital Sciences, January 2002.
- Mars Exploration Rover spacecraft three axis force limited random vibration test at JPL, October 2002.
- Deep Impact spacecraft three axis force limited random vibration test at Ball Aerospace, September 2004.

JPL SC Force Limited RV Tests (2)

- CloudSat spacecraft three axis force limited random vibration test at Ball Aerospace, November 2004.
- Dawn spacecraft three axis force limited random vibration test at Orbital Sciences, Nov./Dec. 2006.
- Orbiting Carbon Observatory three axis force limited random vibration test at Orbital Sciences, May 2008.
- Wide-field Infrared Survey Explorer three axis force limited random vibration test at Ball Aerospace, February 2009.
- Mars Science Laboratory Descent Stage system three axis force limited random vibration test at JPL, June 2010.
- Aquarius/SAC-D Observatory three axis force limited random vibration test at INPE/LIT, Brazil, September 2010.
- Mars Science Laboratory Rover system three axis force limited random vibration test at JPL, February, 2011.
- NuSTAR Observatory three axis force limited random vibration test at Orbital Sciences Corporation, September 2011.
- RapidScat, OCO-2, JASON, 2011-2014
- SMAP, 2014
- **No handling accidents or inadvertent over tests occurred in any of the above tests.**

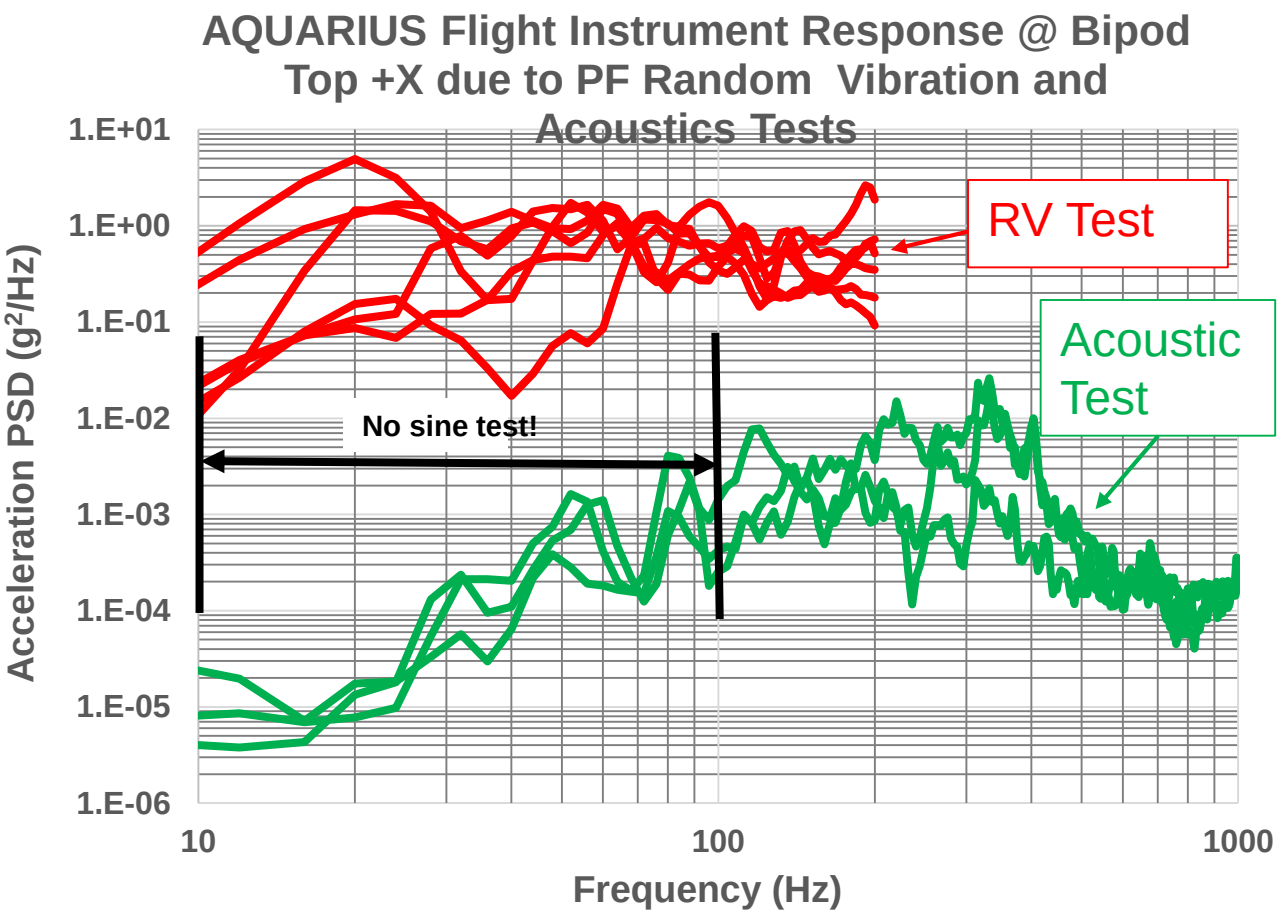
Moment Limiting Example

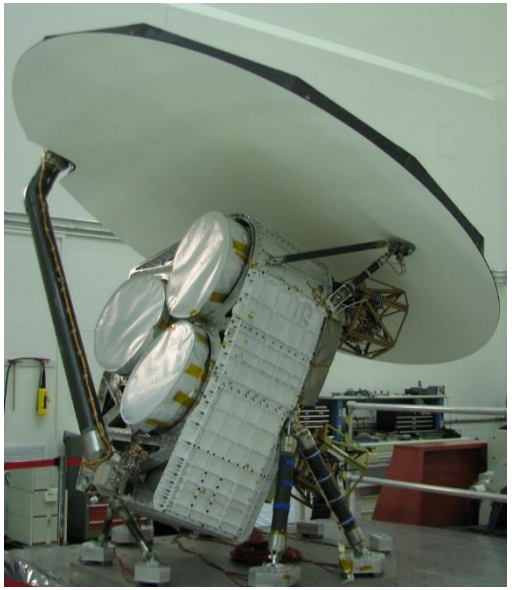




- PSD overlays of dynamic M_x (left) and M_y (right) measurements limited to pre-specified values.
- The near perfect overlays validate the proper design, configuration and performance of the hardware network used to limit to the over-turning moments in real-time.

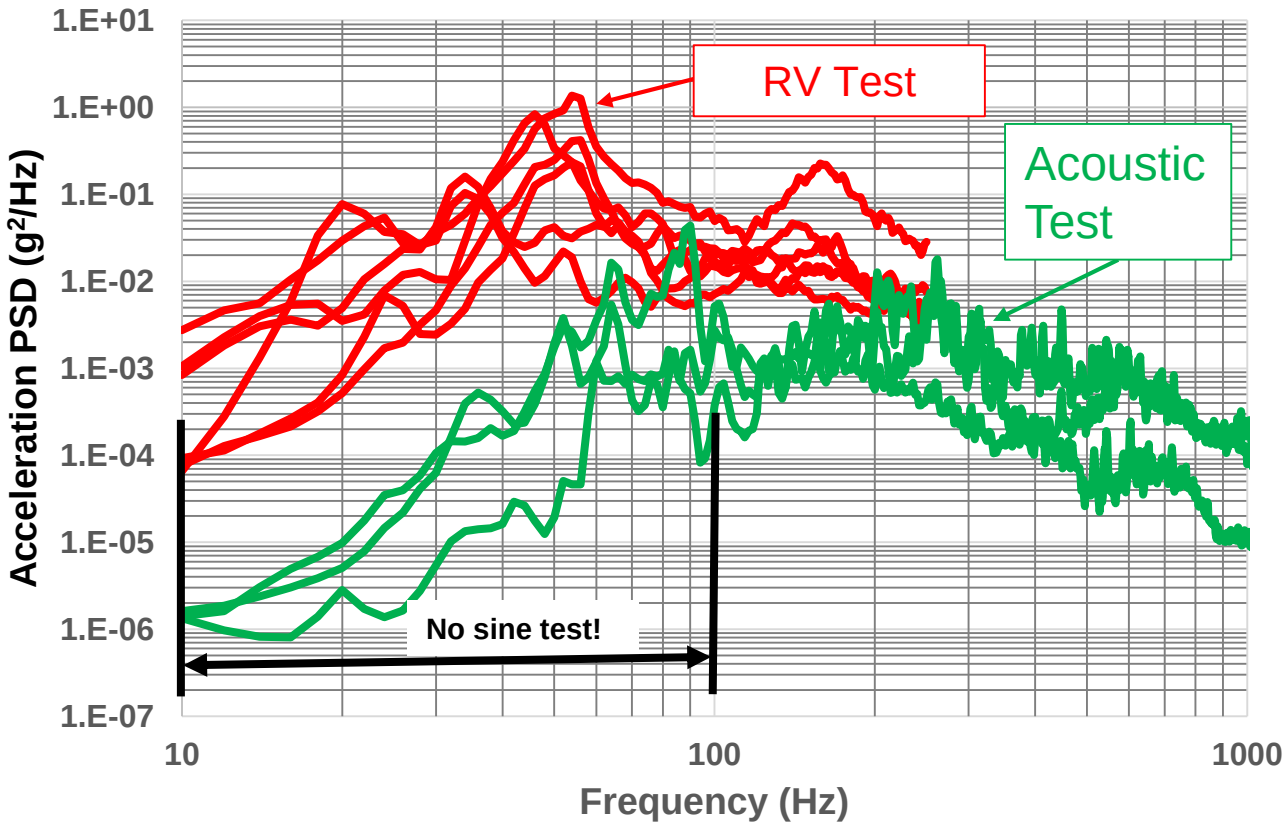
Instrument RV Shaker Tests





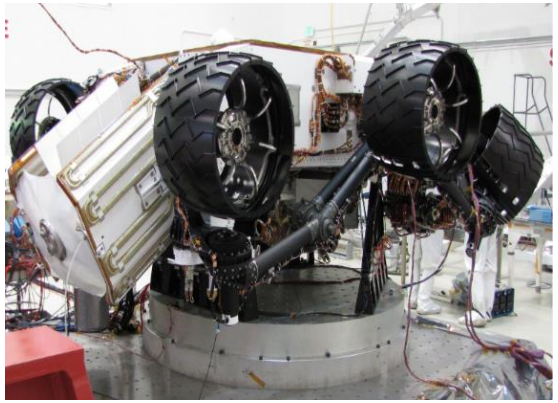
RV from 10 Hz to 200 Hz provided qualification and workmanship verification, whereas acoustics did not (no sine test was performed); major design flaws were discovered during RV testing!

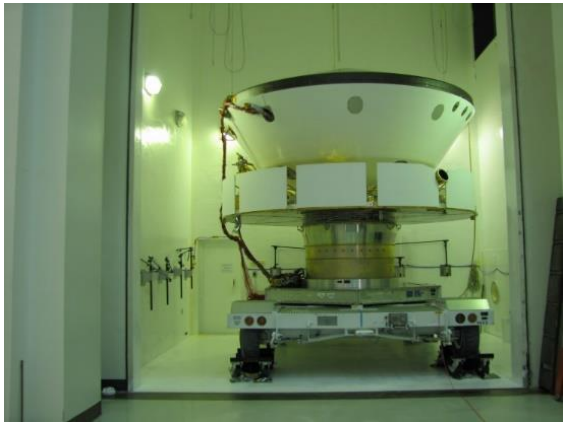
Spacecraft RV Shaker Test

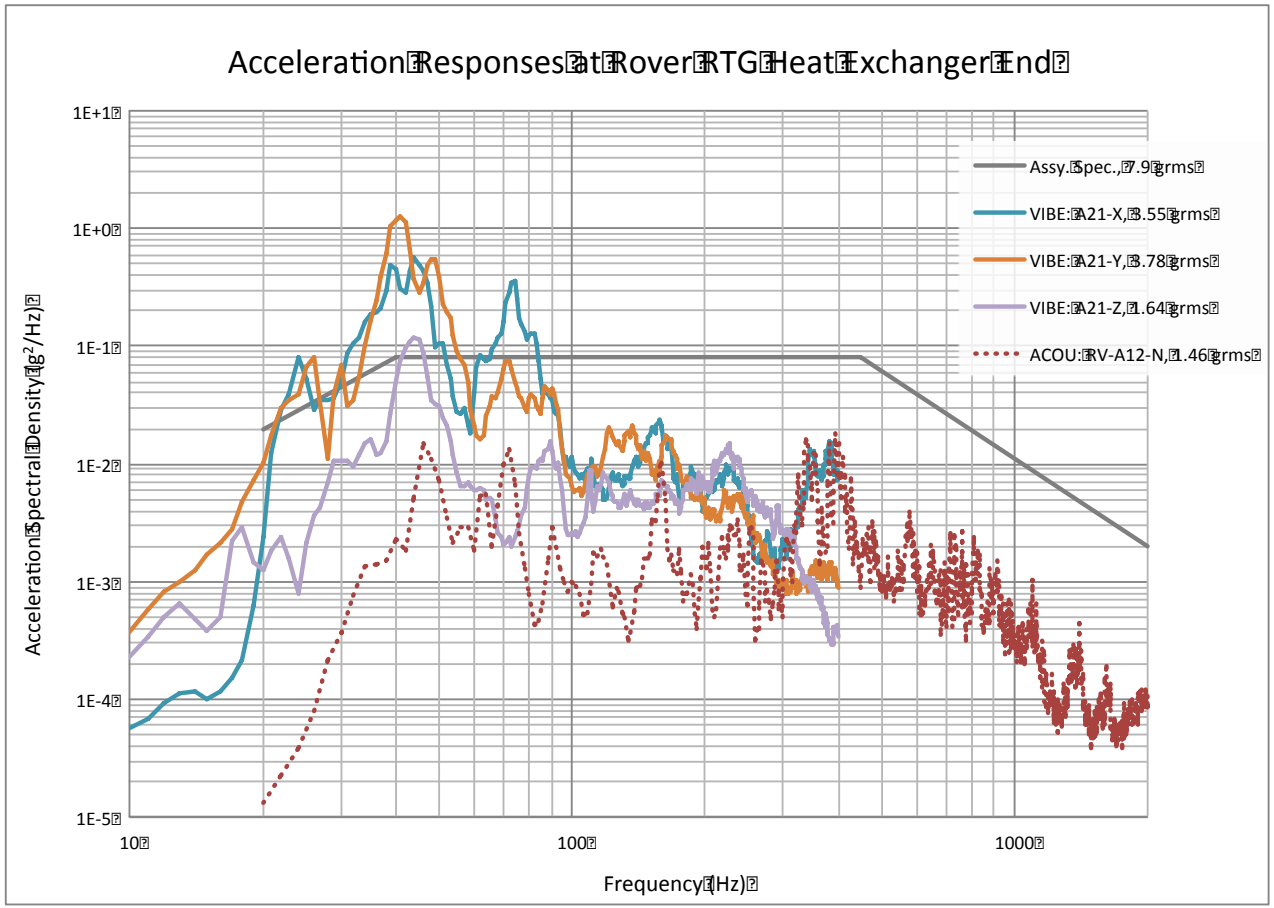


RV from 10 Hz to 200 Hz provided qualification and workmanship screening verification whereas acoustic did not (no sine test was performed)

MSL Rover RV vs Acoustic Test





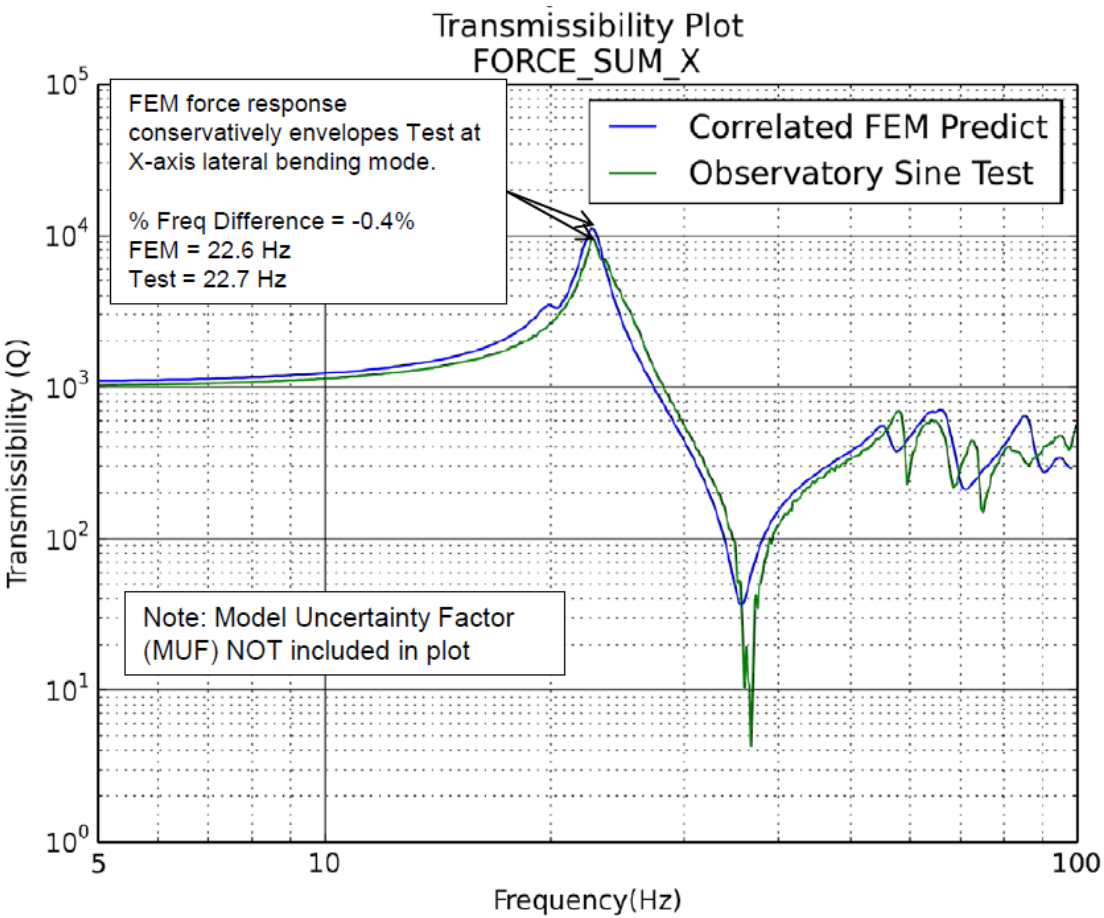


Random Vibration Test from 10 Hz to 200 Hz provided qualification and workmanship screening whereas acoustic test did not (sine was not performed)

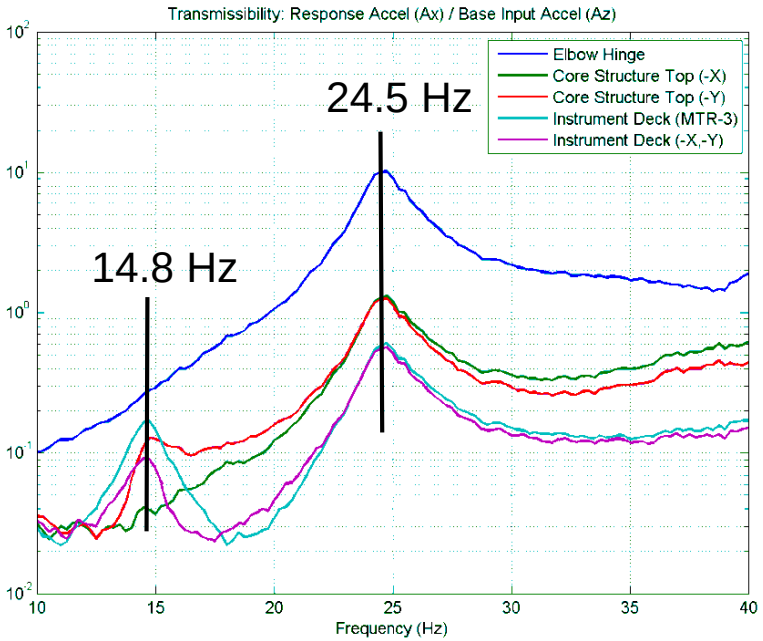
Modal Shaker Test

Introduction

- Model correlation and updating using base driven vibration test data is often used in practice.
- However, if one is not careful, there can be some pitfalls with this approach.
- Outlined herein is one such instance from the SMAP program.



Random Vibration Vertical Axis Test



- Transmissibilities indicate presence of modes at 14.8 Hz and 24.5 Hz that were not predicted by the sine test correlated model.
  - Analysis predicted these modes to be at 17.4 Hz and 32.7 Hz.
- If the test frequencies are correct, then there are major flaws with the test correlated model.

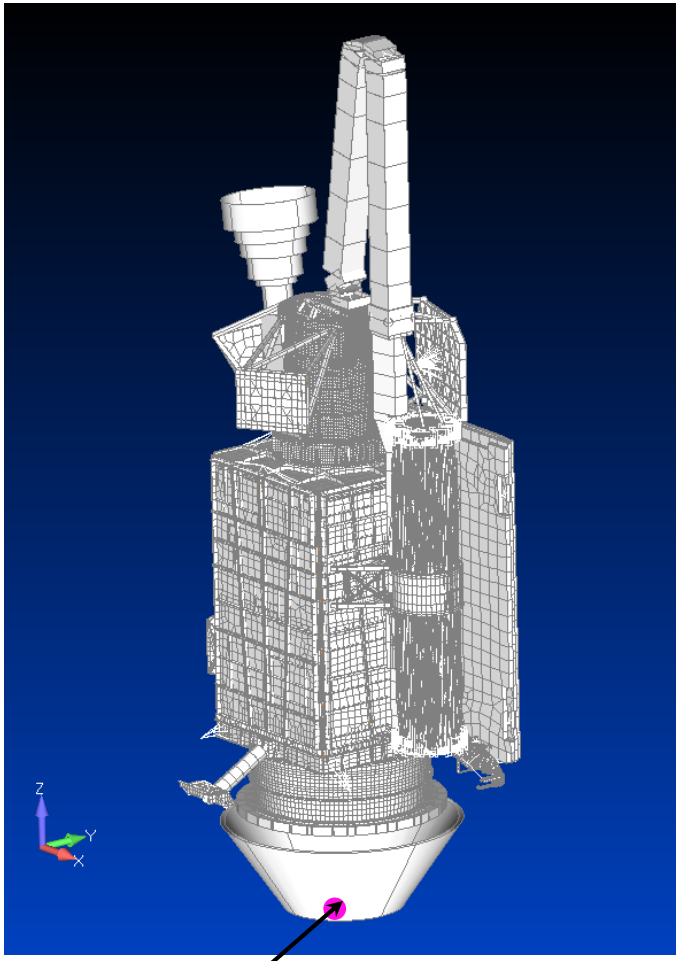
Introduce Shaker Compliance into Model

X-Bending Mode Frequencies

Mode	Frequency (Hz)		
	Rigid Shaker	Flexible Shaker	Axial Vibe Test
1st X-Bending	17.4	7.8	14.8
2nd X-Bending	32.7	26.0	24.5

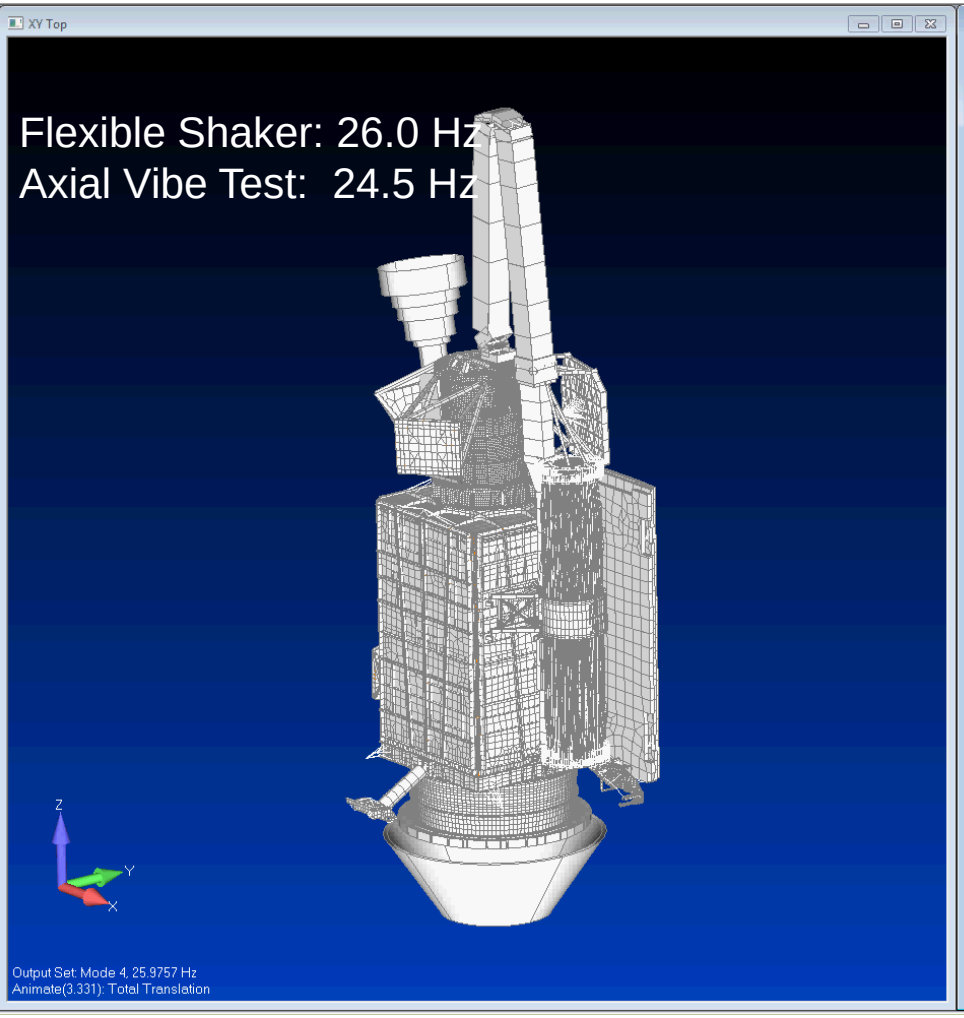
- Changing base rotational stiffness to vendor supplied value of
  - $K_{\theta x} = K_{\theta y} = 94.7$ E6 in-lbf/rad

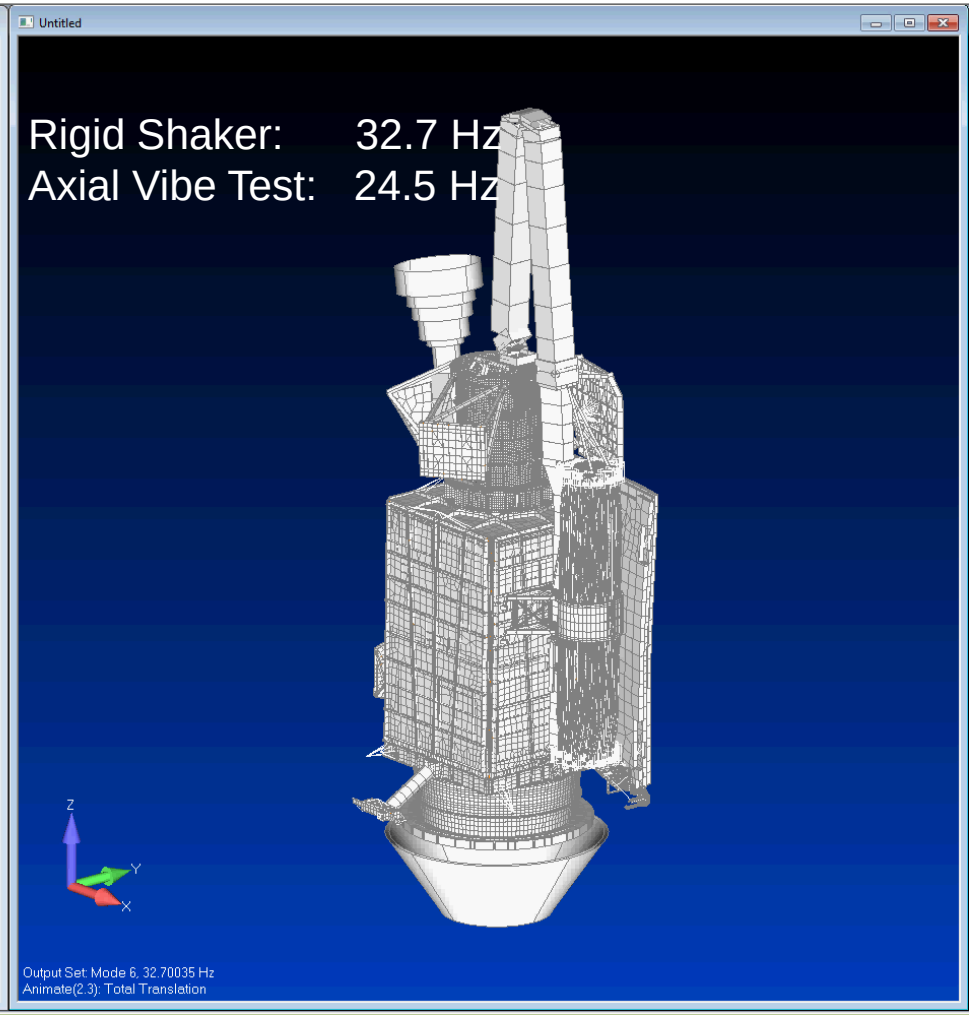
  produced x-bending mode frequencies at 7.8 Hz & 26.0 Hz
- Original stiffness values were
  - $K_{\theta x} = K_{\theta y} = 1.0$E13 in-lbf/rad
- Although the x-bending mode frequencies for the flexible shaker do not exactly match the test frequencies, they do indicate that shaker compliance plays a significant role for those frequencies.



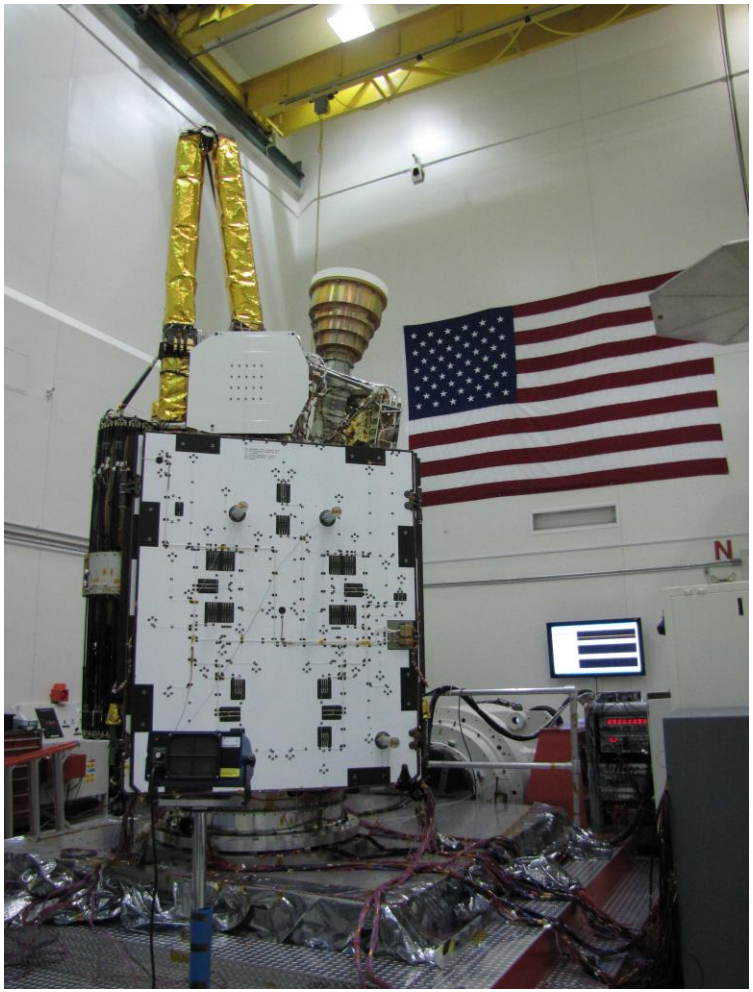
Changed rotational spring stiffness from 1.0E13 to 94.7E6 in-lbf/rad

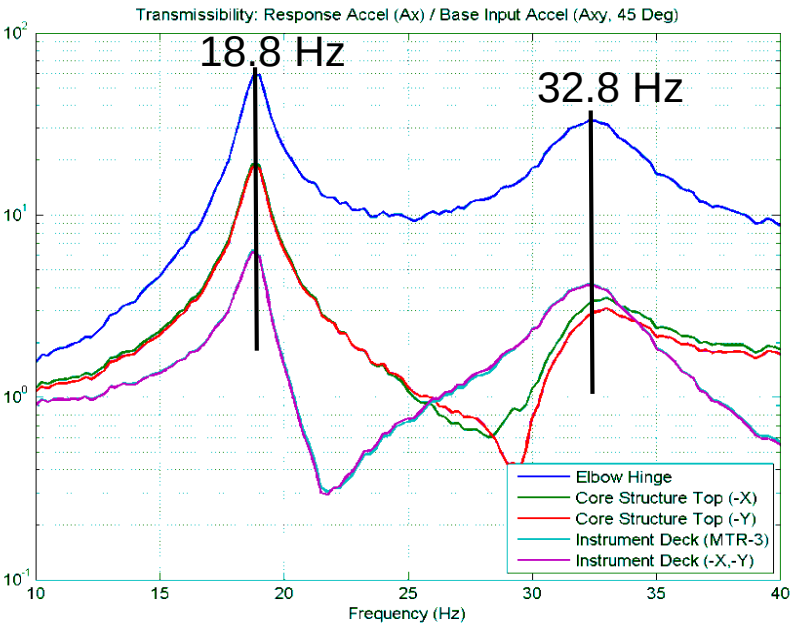
2nd X-Bending Modes: Flexible vs. Rigid Shaker





Random Vibe Lateral Axis Test





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

- Frequencies from lateral axis test agree well with those predicted by analysis
- Results validate test correlated model

Frequencies may be contaminated by shaker compliance. Model correlation may require the shaker to be included in the model

HESSI Instrument Dynamics Test Failure

- High Energy Solar Spectroscopic Imager (HESSI) spacecraft was subjected to a series of sine vibration tests in early 2000.
- 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

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.

Aquarius Reflector Acoustic Chamber

- Aquarius reflector suspended from the acoustic chamber.
- During a “trouble-shooting” phase of the test with the reflector inside the chamber, the operator accidentally sent extremely energetic pressure waves through controller system into the chamber that led to major structural damage to 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

Topics to Discuss in This Session

- The following technical topics need to be addressed in this session pertaining to “Virtual Shaker Testing”
  - One-of-a-kind spacecraft (no heritage and flight data)
  - Spacecraft workmanship and qualification to launch dynamic loads
  - Structural damping and contact mechanisms
  - Model fidelity of spacecraft components
  - Structural damping and possible structural nonlinearity
  - Structural modes (shapes and frequencies)