Coupled Facility/Payload Vibration Modeling Improvements

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Abstract

A major phase of aerospace hardware verification is vibration testing. The standard approach for such testing is to use a shaker to induce loads into the payload. In preparation for vibration testing at National Aeronautics and Space Administration/Goddard Space Flight Center an analysis is performed to assess the responses of the payload. A new method of modeling the test is presented that takes into account dynamic interactions between the facility and the payload. This dynamic interaction has affected testing in the past, but been ignored or adjusted for during testing. By modeling the combined dynamics of the facility and test article (payload) it is possible to improve the prediction of hardware responses. Many aerospace test facilities work in similar way to those at NASA/Goddard Space Flight Center. Lessons learned here should be applicable to other test facilities with similar setups.

Introduction

During spacecraft/component verification process sine vibration testing is typically performed on an electrodynamic shaker. These tests consists of lateral and vertical testing. A typical lateral and vertical test set up can be seen in Figure 1 and Figure 2, respectively. These test configurations can be used for sine burst, sine vibration and random tests.
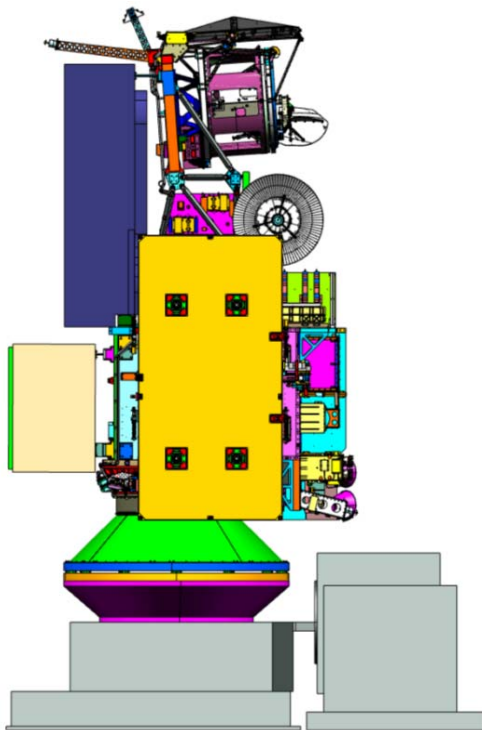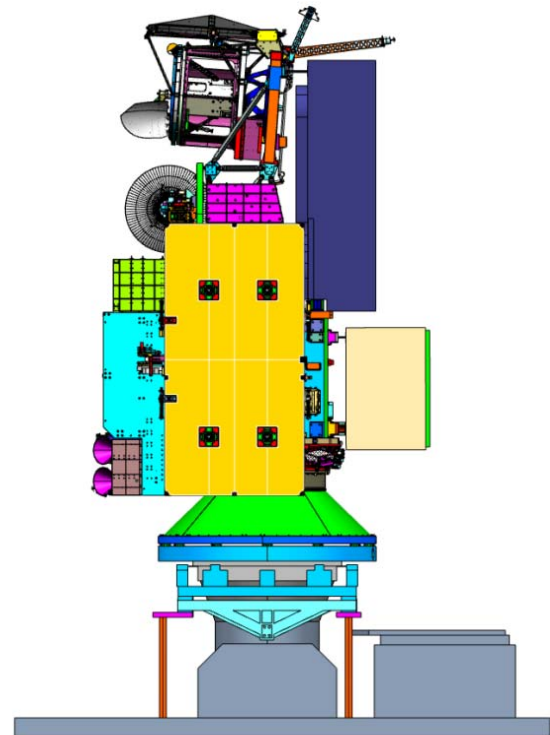

Figure 1 Lateral Test Configuration

Figure 2 Vertical Test Configuration

The lateral configuration uses a slip table with bearings that provide high stiffness in five degrees of freedom (DOF) that react many of the forces/moments from test article. The sixth DOF is used to impart dynamic forces into the test article. Due to the high dynamic stiffness of the slip table, modeling of slip table tests using NASTRAN has correlated well by using fixed base analysis in the past and no new approach is needed. Testing with very large masses [> 5000 Kg] may indeed need the following augmented modeling.

The vertical configuration has no slip table; instead the payload mounts to the shaker either to an unguided or guided head expander(GHE) affixed to the shaker armature. At GSFC, the shaker, GHE, slip table and payload are mounted to a seismic mass that in turn is spring mounted to the foundation of the facility (for both vertical and lateral testing). The GHE is present to react loads from the test that act to induce an overturning moment so as not to damage the shaker. The dynamic stiffness was not a primary design parameter in the original design implementation of the GSFC GHE, so much as the moment carrying capability. It is the dynamic stiffness of the combined shaker/payload that is the focus of this paper.

Vertical Facility Description

As was shown in Figure 2, the vertical testing balances the payload atop an Unholtz-Dickie T4000 shaker, which is bolted to a seismic mass spring mounted to the building foundation via huge coil springs. The ability of the shaker to react loads and provide high stiffness not in-line to the drive direction is limited. The shakers are essentially linear actuators using induction rings to move an armature that can apply 40,000 lbs. of load with a peak-to-peak armature displacement of 2 inches. The armature is suspended within an inductor coil by the use of blade flexures and some limited bearing support. As such, the armature deflects somewhat laterally and rotationally to the armature line of action (i.e. low dynamic stiffness). This deflection of the armature relative to the shaker body is the source of coupled dynamics that, if not modeled, generates dynamics responses that were not previously predicted, nor understood. The effect is more prevalent when the article mass and stiffness are greater than the head expander and armature (which is a large percentage of test done at GSFC.)

Past modeling

NASTRAN modeling of a payload response during dynamic tests has largely focused on the test payload dynamics and never included the coupled shaker/payload dynamics at GSFC. Typical payload test simulation uses a modeling technique that applies dynamic forces directly to a rigidly constrained payload (i.e. shaker assumed to be much stiffer than payload). A typical finite element model (FEM) and sinusoidal input can be seen in Figure 3 and Figure 4 .
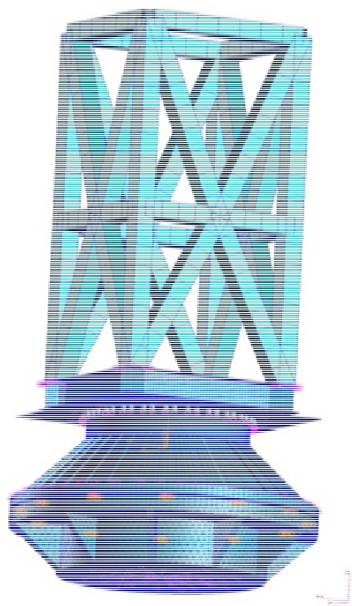
Figure 4 GPM SADDS Sine Spec

Figure 3 GPM Mass Simulator FEM

For the analysis, the shaker input point is held with a SPC boundary in 6 degrees of freedom (dof) and then the input dof is released and driven with the test input levels. For the test, the shaker imparts the input, and responses are recovered for critical locations with accelerometers. For many test payloads this approach generally was close enough to measured responses that no further model development was needed. However, as the payload grows in mass the facility dynamics interact with the payload dynamics such that the model predictions become less well correlated to test results. During past vertical (thrust) testing of spacecraft such as Lunar Reconnaissance Orbiter (LRO), Solar Dynamics Observatory (SDO) and others there have been issues with the pre-test analysis results matching the measured test responses. The differences in prediction versus response were generally accepted and response limiting was used to protect the payload. This presented somewhat of an uncertainty why there would be unexpected responses. Payload models were well correlated, from independent testing, and yet NASTRAN results varied when compared to test measurements. An example of this variability is shown next.

GPM SADDS testing

During the testing phase of the Global Precipitation Mission (GPM), the Solar Array Deployment and Drive Subsystem (SADDS) required a sine vibration test and sine burst as part of the verification plan. As part of the test preparations a pre-test analysis was performed to predict responses and establish limits to be used during testing. Lateral testing went as expected; There was no significant deviation from test
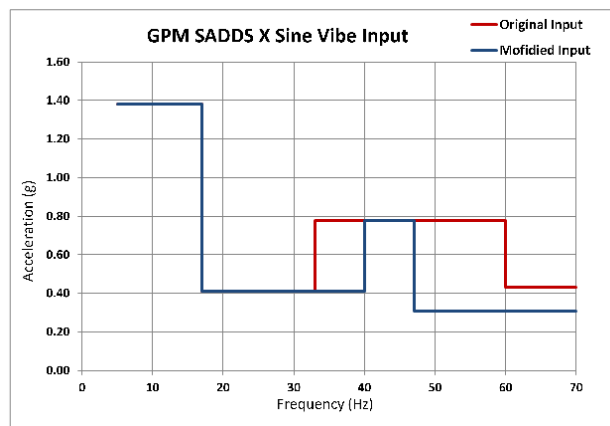
measurement to test prediction. During the vertical testing, responses from the payload had some differences when compared to the NASTRAN analysis. Responses on the SADDS between 35 to 60 Hz would have exceeded design limit loads had the test not been response limited at full level. Closer examination of the response data showed that both the SADDS subsystem and the interface to shaker had cross axis responses (recall that dynamic simulation only imparts one DOF of input), as shown in Figure 5 and Figure 6.
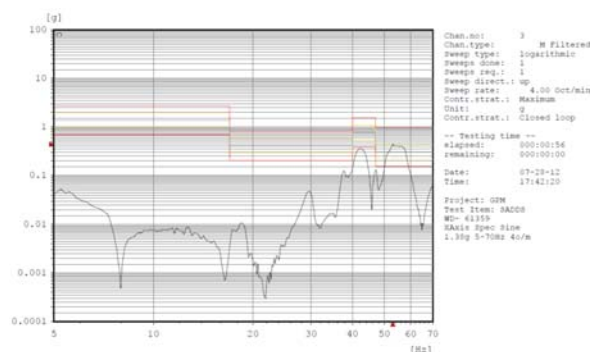

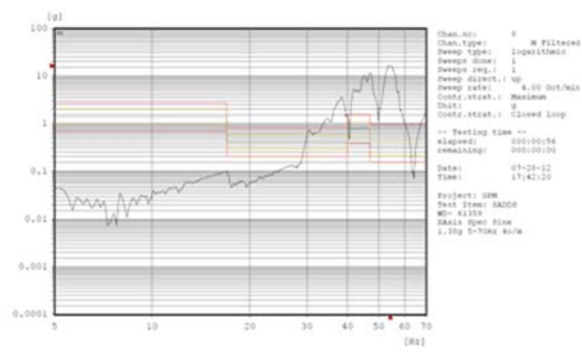**Figure 5 Cross Axis Shaker Interface Acceleration**

Figure 6 SADDS Response Acceleration of Concern

These responses are coupled system (payload and shaker) responses, that were not predicted since a model of the facility was not included (or in existence), nor had been considered as critical to the process. Thus an investigation was begun to find and generate an update to the modeling that would capture the behavior seen during SADDS testing for use in future tests performed on this shaker.

C-K Facility modeling

The NASA/GSFC shaker facility, as shown in **Error! Reference source not found.**, includes an Unholtz-Dickie(UD) T4000-2 shaker with a guided head expander (GHE), all mounted to a seismic mass approximately 250,000 lb. The seismic mass is spring mounted to the foundation of the facility with 24 very large coil springs (not shown in photo).
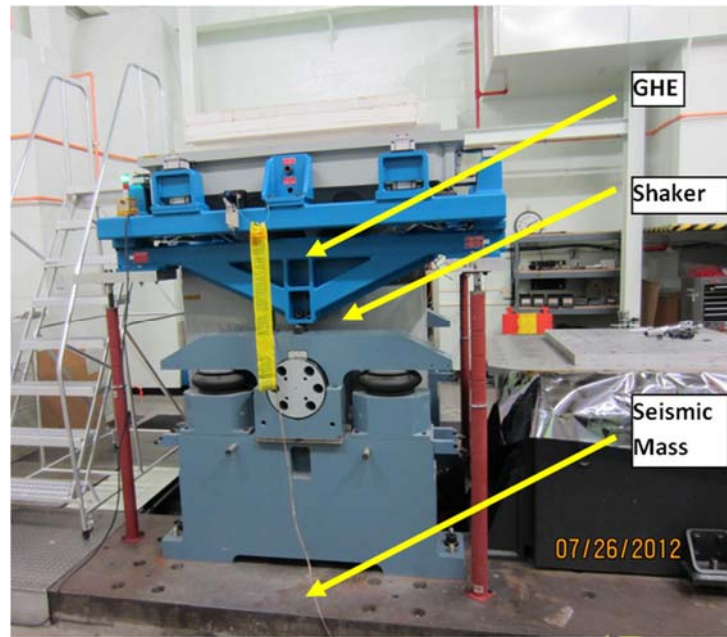
Figure 7 GSFC South Vibration Cell

The primary source of facility compliance occurs between the armature and shaker body, with a secondary effect being the sprung seismic mass modes. The GSFC setup makes use of a guided head expander, whose principal function is to limit the overturning moment seen on the armature of the shaker, and less so on providing additional dynamic stiffness. The GHE uses flexures to reduce the impact of overturning moment. There are two GHE that GSFC uses, a GSFC GHE and one borrowed from the Johns Hopkins Applied Physical Lap (JHU-APL). The JHU-APL GHE was used during the SADDS and GPM spacecraft testing, and is shown in Figure 8.
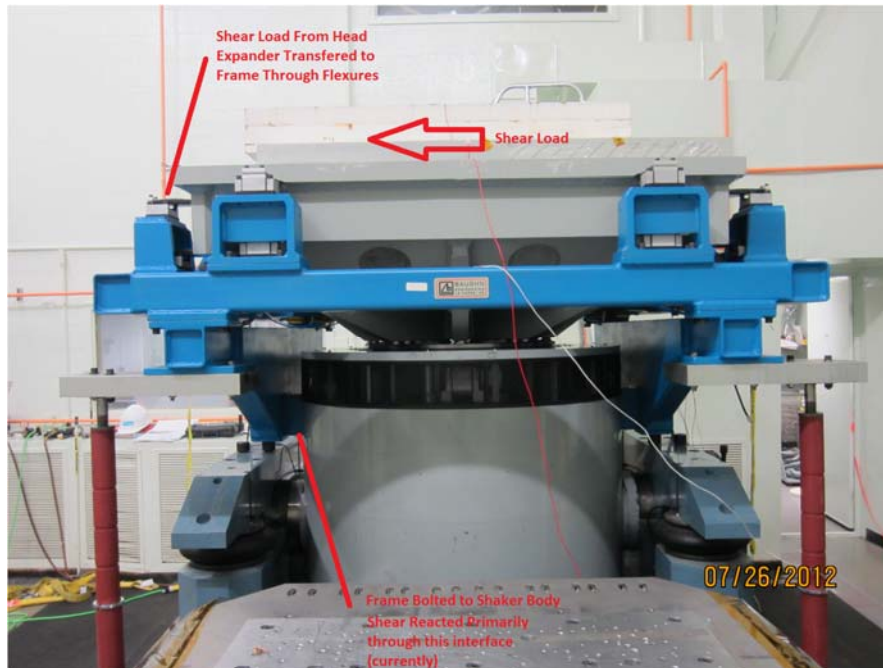
Figure 8 GSFC Vibration Facility, Close-Up of the GHE

The finite element model of the facility developed after the investigation is shown below in Figure 9. This includes a representation of the GHE, Shaker and Seismic mass. The shaker includes a rigid element spanning between the GHE and a CBUSH representing the overall stiffness of the shaker (provided by UD). There are two drive points for this model, where equal and opposite dynamic forces are applied which generates the axial acceleration. The acceleration at the payload interface is then scaled to the desired test input, as would be the case during the actual test. To validate this model a test of the GPM mass simulator with a flight like Payload Adapter Fitting (PAF) was conducted, and is discussed in the next section.
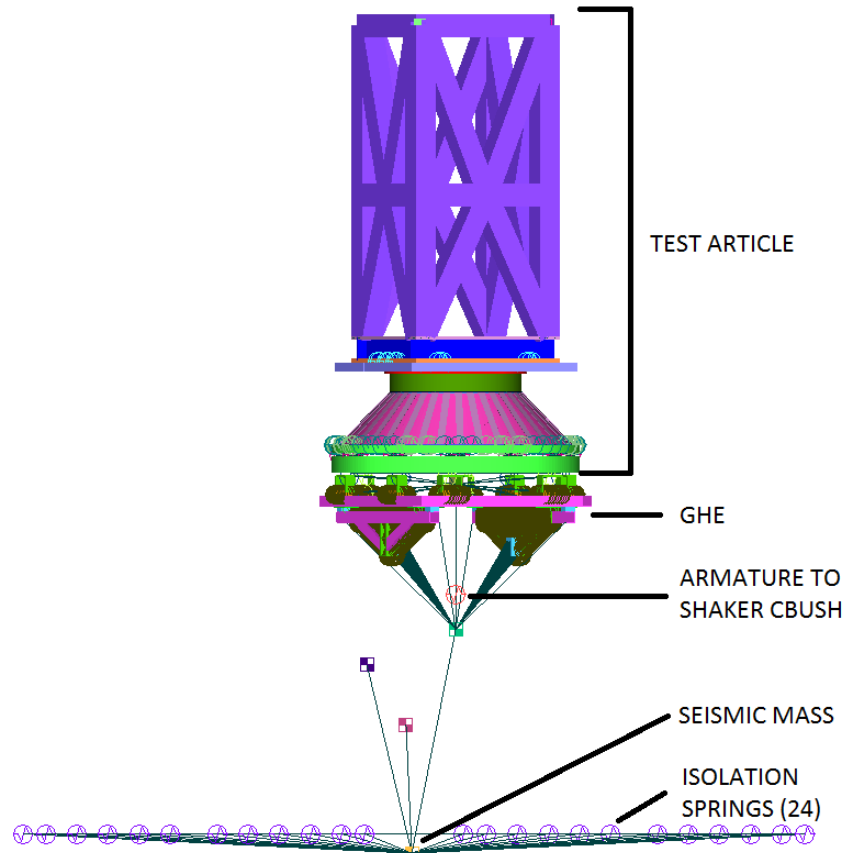
Figure 9 C-K Facility FEM

C-K Facility Model Validation

To validate the C-K facility model, a special test was designed to both excite and measure coupled facility/payload modal content. The test used a long duration (~17 min) low level flat random vibration (1.0-150Hz 0.00025g^2/Hz ->0.193grms) starting pre-resonant to the isolated seismic mass modes, to ascertain coupled modal behavior with fine frequency resolution. The test configuration included the facility (seismic mass, T4000 shaker, and GHE) and the payload (payload adapter fitting, clampband, and GPM mass simulator), shown in Figure 10. The payload was attached to the facility via 8 Kistler force gages, that monitored overall interface forces. Additionally several triaxial response accelerometers were mounted on both the facility side and payload side of the interface. The GPM mass simulator weighs 5036 kg with a c.g. height of 1.61 meters. The mass of the Armature/GHE and vibration plate was 2500kg. This test configuration was a good test case since there are only primary and secondary bending modes present due to PAF flexibility, thus has low error in predicting fixed base modal behavior. The lack of more complex dynamic content allowed for high confidence that the coupled behavior differences observed in test are due to the facility and not the payload.

Figure 10 GPM C-K Model Validation Test Configuration

The test configuration was simulated in Nastran using the C-K model, while recovering responses at the same locations as those being monitored in test. Figure 11, Figure 12, and Figure 13 are representative comparisons of the model prediction to the full level responses. Predictions using fixed base payload and using the coupled payload/facility are both shown. For in-axis responses there are only minor differences. For cross axis responses however, there are significant differences between fixed base and coupled facility/payload modes. The plots show that the C-K model is well correlated to this test. Only very minor tweaking was done post test, because the match was so good with the first attempt. Having such good correlation between test and analysis, this new model was used to perform the analysis work for the GPM Observatory, and subsequently the Magnetospheric Multiscale Mission Spacecrafts and James Webb Space Telescope instruments.
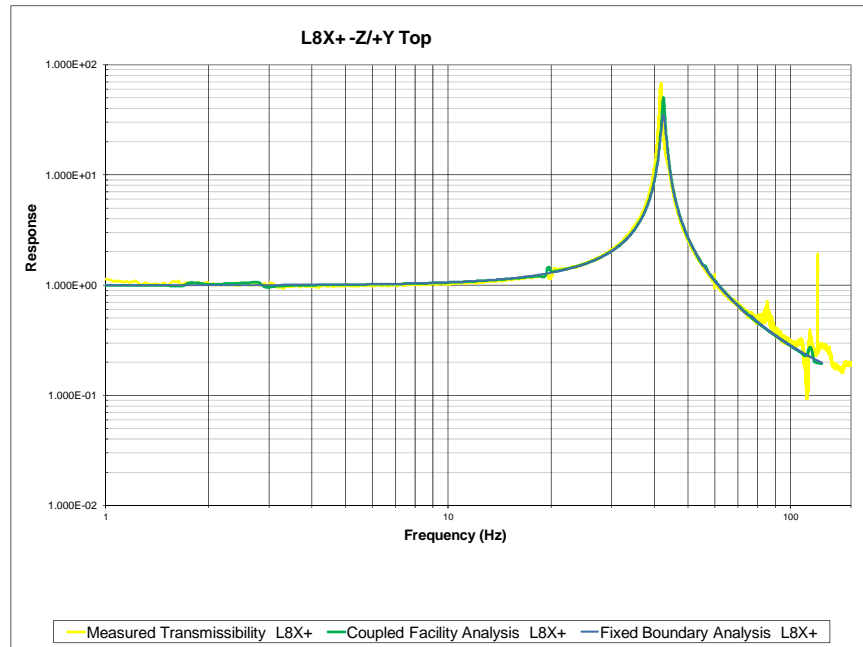
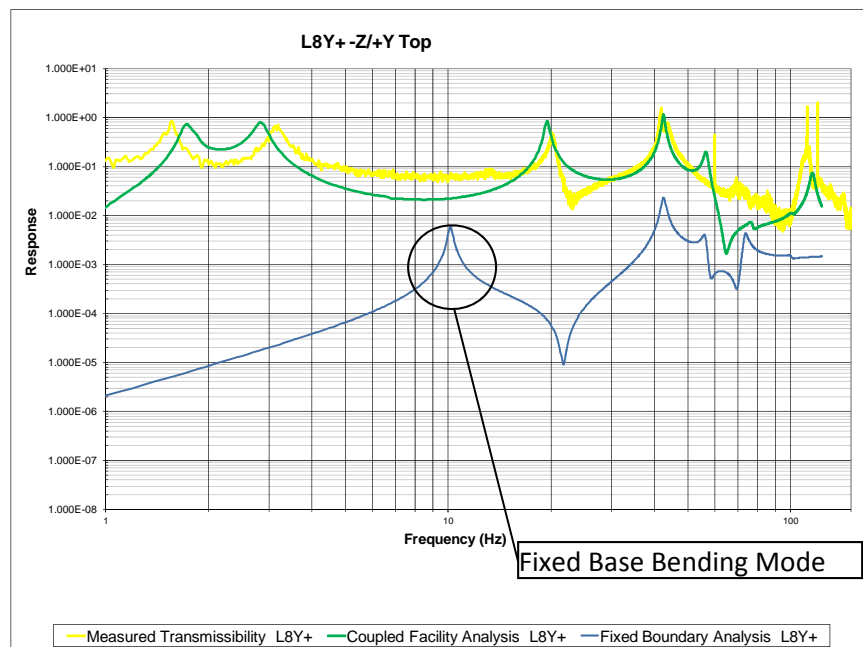**Figure 11 In-Axis Transmissibility Sample Model Predictions vs. Test Responses**

Figure 12 Cross-Axis 1 Transmissibility Model Predictions vs. Test Responses
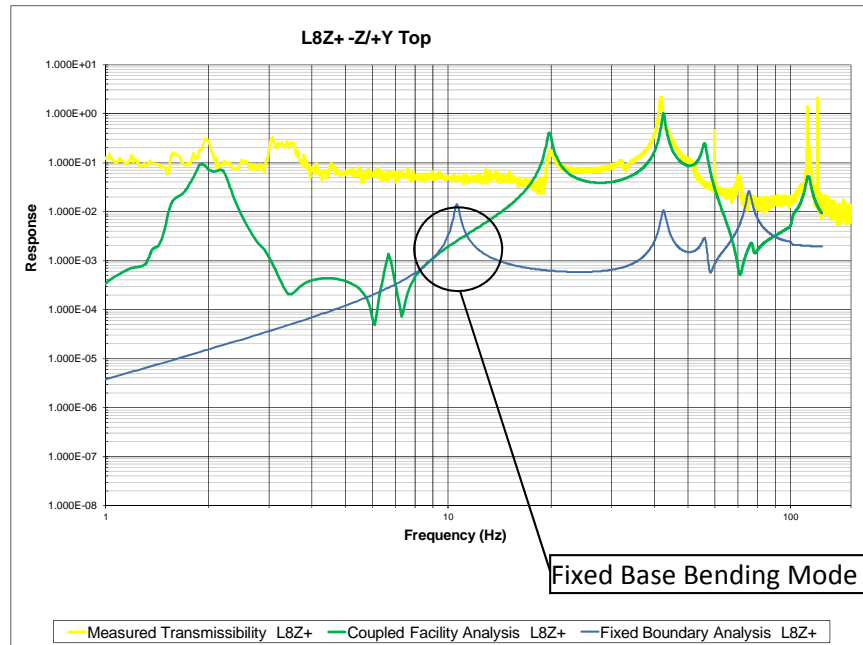
Figure 13 Cross-Axis 2 Transmissibility Model Predictions vs. Test Responses

One of the most important observations about the coupled facility/payload tests is that for large payloads, the previously assumed fixed base assumption is generally incorrect for low-stiffness vertical shakers. The bending modes measured during the lateral test are not present during the vertical testing since the boundary flexibility makes the coupled system behave somewhere between a fixed and a free boundary. This behavior explains why previous programs that had predicted high bending moments at the primary fixed base modes were never realized - the pure cantilevered mode shapes don't exist in the flexible axial shaker configuration. For payloads that have high coupling between thrust and bending modes (i.e. offset modal mass), measurements of acceleration and interface force/moments reveal that peak moments/acceleration at these off axis directions are much less than model predicts, sometimes as much as 10X less. Interestingly for well centered structures with low coupling between bending and axial, the fixed base model under predicts the measured interface moments.

Conclusions and Future work

Having developed this facility model for GPM it has been applied to other programs at GSFC, including MMS and pre-test work for JWST. MMS data showed that the coupled facility model was a much better representation of the peak interface moments than fixed base predicts. It is possible that there are components of this model that can be improved by future measurements; however, it is very effective as is. Having a tool that improves the NASTRAN responses and correlates better with test is an advantage that will be used in future NASA/GSFC testing. When a satellite or major subsystem is tested and the response is not as expected there can be significant delays and concerns to completing the testing in a timely fashion. Thus having the C-K facility model is now viewed as a standard approach to vertical shaker testing in our current facilities.