A NEW LARGE VIBRATION TEST FACILITY CONCEPT for the JAMES WEBB SPACE TELESCOPE

Brian Ross and Eric Johnson
NASA Goddard Space Flight Center

Joel Hoksbergen and Doug Lund
Team Corporation

ABSTRACT

The James Webb Space Telescope consists of three main components, the Integrated Science Instrument Module (ISIM) Element, the Optical Telescope Element (OTE), and the Spacecraft Element. The ISIM and OTE are being assembled at the National Aeronautics and Space Administration's Goddard Spaceflight Center (GSFC). The combined **OT**E and **IS**IM Elements, called OTIS, will undergo sine vibration testing before leaving Goddard. OTIS is the largest payload ever tested at Goddard and the existing GSFC vibration facilities are incapable of performing a sine vibration test of the OTIS payload. As a result, a new large vibration test facility is being designed. The new facility will consist of a vertical system with a guided head expander and a horizontal system with a hydrostatic slip table. The project is currently in the final design phase with installation to begin in early 2015 and the facility is expected to be operational by late 2015. This paper will describe the unique requirements for a new large vibration test facility and present the selected final design concepts.

INTRODUCTION

When completed, NASA's James Webb Space Telescope (JWST) will be the most powerful space telescope ever built and will allow scientists to look farther into galaxies and planetary systems by collecting infrared measurements with the telescope's four instruments. The telescope will utilize a deployable 6.5-meter diameter segmented, adjustable primary mirror. The OTE and ISIM Elements of the observatory are kept at cryogenic temperature to improve the infrared performance. The main components of the telescope are shown in Figure 1. The OTE and ISIM Elements will be assembled at the GSFC. The combined payload, called OTIS, will be subjected to sine vibration and acoustic testing at the GSFC before being transported to Houston, TX for cryo-vacuum testing. Figure 2 shows the stowed test configuration of OTIS with the defined V coordinate system used by the project. The origin of the V coordinate system is at the base of OTIS at the centroid of the mounting interface points.

LIMITATIONS OF EXISTING VIBRATION FACILITY

The main requirement behind this activity is the need to subject the OTIS payload to a sine vibration test using the test specifications in Table 1. Initial review of the OTIS payload size and mass characteristics revealed that the existing GSFC vibration facilities would be insufficient to conduct the required test. Being the largest space flight payload ever tested at the GSFC, OTIS does not fit through the doors into the test cells where the existing shakers are located. Also, by the time a head expander and/or test fixturing mass is added to the OTIS mass, the existing shakers would not have enough force capability to achieve the acceleration levels of the sine vibration test specification. Therefore, it was decided that a new vibration test system would have to be purchased and installed in the GSFC integration and test complex. Team Corporation of Burlington, WA was selected to design, fabricate, and install the new vibration test system. The project is currently in the final design phase with the final Critical Design Review (CDR) scheduled for October 2014. The installation and acceptance testing of the facility is scheduled to be complete by the Fall of 2015.

CRITICAL REQUIREMENTS

A requirements document was developed that included requirements for technical capabilities, installation, and post installation performance verification. There were three areas where the requirements had a significant impact on the shaker system design; the physical size of the OTIS payload, the predicted shaker interface moment reaction loads, and the cross-axis input limit.

Test Item Physical Size

The OTIS payload is very large and has a significantly offset center of gravity (CG). The mass of the payload is 3940 kg and it has an enveloping volume of 4.1 m x 4.5 m x 8.33 m. Its mounting interface footprint is 2.40 m x 2.57 m. The OTIS CG position is -0.22 m in V1, +0.03 m in V2, and +3.00 m in V3. In addition to the OTIS payload mass, a requirement was given to include a mass of 2810 kg for the fixture used to attach OTIS to the vibration test system. It was also specified to assume this fixture provides a rigid connection of OTIS to the vibration test system interface but raises the OTIS CG 0.46 m above the interface plane.

Shaker Interface Moment Reaction Loads

Analysis of the Finite Element Model (FEM) of the OTIS payload predicted that when the OTIS payload is subjected to the required sine vibration acceleration profiles that very high moment reaction loads are generated at the payload mounting interface. In particular, when testing the vertical, V3, axis, the moment about the V2 axis at the payload mounting interface is predicted to be 1.47×10^5 N-m. This is significantly higher than the moment carrying capacity of commonly available guided head expanders.

Cross-Axis Input Limitation

The JWST project also needed to keep cross-axis input from the shaker system to minimal levels. Cross-axis input is unwanted acceleration in the two axes that are not being driven and is usually caused by dynamic response of the shaker system. The project levied two separate requirements for cross-axis input. The first is that with nothing attached to the vibration system the cross-axis input, measured at the vibration test system mounting interface surface, should be less than 10% of the in-axis acceleration level across the entire OTIS test frequency band of 5 to 100 Hz. This will be verified by testing. The second requirement is that with OTIS attached to the vibration test system the cross-axis input, measured at the vibration test system to fixture interface, shall be less than 40% of the in-axis acceleration level across the entire OTIS test frequency band of 5 to 100 Hz. This will be verified by analysis using the NASA provided FEM of the OTIS payload.

DUAL FACILITY CONCEPT

Due to the size of the JWST OTIS payload and the single axis requirements for the system, it was decided that the test facility would be split into separate horizontal and vertical test systems. In addition, it was desired that the design limit the impact upon the existing facility and provide a reaction mass and isolation system for each sub-system. These requirements lead to a design consisting of two standalone vibration test systems. The vibration facility under development consists of a horizontal slip table to test in the V1 and V2 axes and a vertical guided head expander to test in the V3 axis. Both systems are designed with the specific goal of reducing the cross-axis motion that often results during a vibration test. The working surface of each system is 3.3 m x 3.3 m and is capable of mounting the OTIS and a supporting fixture, for a total estimated payload of 6,750 kg.

Horizontal Vibration Test System

The horizontal system is an expansion of Team Corporation's standard T-Film slip table technology with the slip table assembly mounting to a large air isolated reaction base. This base is designed to have a high rotary inertia for properly reacting overturning moments and minimizing the cross-axis motion. The design is capable of reacting the moments listed in Table 1 with a sizeable factor of safety. The slip table is driven by a single Data Physics Model 5022 shaker with an air isolated trunnion mount, 76 mm total armature stroke, and 220 kN force capacity. The design is shown in **Error! Reference source not found.** and 4, with **Error! Reference source not found.** including the OTIS payload on the system.

Hydrostatic bearings guide the slip table and transfer over turning moment loads into the reaction base. The bearing configuration is comprised of a set of yaw bearings to guide the table in the axial direction and an array of sixty-five T-Film bearings to provide the roll and pitch restraint. The key benefit of T-Film bearings is that the moment loads are transferred to the reaction base through compression and tension loads in the bearing elements. This provides a much stiffer load path over journal bearing designs that react the loads through bending of the bearing elements [1].

A sub-requirement for the horizontal system was to accommodate future testing of smaller payloads with a footprint of 1.9 m x 1.9 m. On this large of a slip plate, it important to know this requirement in the early design stage because it becomes critical in how the bearings are arranged underneath the slip plate. Best performance is attained by minimizing the bending of the slip plate and properly supporting it with bearing elements. The horizontal system was developed for both the OTIS payload and this smaller future payload.

With the given bearing arrangement, the slip table design is capable of resisting the over turning moments listed in Table 2. This table lists the capacity for the OTIS payload, the smaller 1.9 m payload, and the system requirements and assumes reacting moments in one axis only. It is possible to simultaneously resist any combination of roll and pitch moments that satisfy the following equation:

$$M_{Total} = \frac{M_{Pitch}}{1.47e6} + \frac{M_{Roll}}{1.2e6} < 1.0 \qquad (1)$$

This equation applies because the T-Film bearings react both pitch and roll, while the yaw moment is reacted only by the yaw bearings. Using the required moment capacities from Table 2, the horizontal system has a factor of safety of 3.5 for the simultaneous load case.

Vertical Vibration Test System

The design of the vertical vibration test system is also an expansion of an existing Team Corporation design. In 2006 Team developed, and patented, a guided head expander system for Orbital Sciences that effectively reduced the lateral cross-axis motion on the DAWN spacecraft from 250% down to 14% during vertical vibration testing [2]. This system was for a 1.5 m diameter head expander and much smaller payload, however, the JWST system is built around the same fundamental concepts as this earlier system. The key to this design is to bring the required reaction mass for resisting cross axis motion very close to the head expander, rather than using support structures to transfer the loads from the head expander down the reaction mass. The advantage is that the dynamics of any support structure are eliminated providing better vibration control and drastically reduced cross-axis motion. This is accomplished by supporting and isolating large inertial masses on a structure very close to the head expander. The head expander moment loads are then transferred into the inertial masses through Team's pad bearing technology. These bearings use oil-film technology to provide a short, stiff load path to the masses and also include self-alignment characteristics. The vertical system for the JWST is shown in **Error! Reference source not found.** and **Error! Reference source not found.** with the OTIS payload attached.

The inertial mass is designed to have a large rotary inertia in the appropriate axes, with a total of two masses arranged orthogonally to accommodate both axes. Each mass uses three pad bearings to constrain a total of 3-degrees-of-freedom (DOF) each. The masses are independent, and both react the yaw motion, so overall the system constrains 5-DOF, leaving the vertical translation DOF to be controlled by the shakers.

The geometry and load capacity of the pad bearings on each inertial mass defines the moment capacity of the system. Assuming only one axis is loaded with a moment at a time; the moment capacity of this system is listed in Table 3 along with the design requirements. If the required moments are all applied simultaneously the system has a factor of safety of 1.84 on the pad bearing with the highest resulting load. This situation is the worst case. The moment loads listed can be applied in different combinations, resulting in larger factors of safety.

Dual Data Physics Model 5022 shakers were chosen to drive the head expander. These are the same shaker model as the one used in the horizontal system, with the exception that the shakers are rigid mount trunnion style, mounted to a common air isolated mass. The dual shakers are controlled by Data Physics multi-axis Matrix SignalStar vibration controller and will be operated using Multi-Input-Multi-Output (MIMO) Sine Vibration control software.

PRELIMINARY DESIGN RESULTS

Both systems were developed in detail as Finite Element Models (FEM) and the designs are in the final stages of review and approval by the JWST project. Each FEM includes a Craig-Bampton reduced model of the OTIS payload, such that the modeled dynamic characteristics of the OTIS are accounted for in the design. The cross-axis motion results for both systems are given in **Error! Reference source not found.** through **Error! Reference source not found.**. These plots list the cross-axis motion while exciting the V2 horizontal axis, as this is the axis with the most excitation, and the V3 vertical axis.

Considering the horizontal system, the FEM results predict that the cross-axis motion will remain below 20% for the ratio of the lateral motion relative to the primary axial motion and below 30% for the ratio of vertical to primary motion. In the vertical cross-axis motion plot, the response reaches above 30% at 2 Hz. This is the system's isolator natural frequency, and is outside of the test bandwidth. These results are for the test driving the V2 axis, which has the highest excitation of the two horizontal axes.

The vertical system FEM predicts that the cross-axis motion will remain below 40% for both lateral directions relative to the primary vertical axis. This result is shown in **Error! Reference source not found.**. In this plot, the FEM was excited with 1g acceleration in the V3 (Z) direction and the V1 (X) and V2 (Y) response at the corners of the head expander plotted over the full bandwidth. The dashed line represents 40%. The highest cross-axis response occurs at the vibration modes of the OTIS payload, however they all remain below 40%, satisfying the system requirement.

CONCLUSIONS

The JWST OTIS payload will be the largest space flight payload tested at the GSFC to date. As part of its verification testing program it must be subjected to a sine vibration test. Due to the size of the OTIS payload and the vibration test requirements, two new systems are in the final design stages, a dedicated horizontal system and a dedicated vertical system. The resulting systems will be capable of extremely high overturning moment capacity and minimal cross-axis motion. Both designs are nearing completion and will soon move into the manufacturing stage, with installation and commissioning to occur during the summer of 2015. Subsequent papers will follow to detail the final design and performance characteristics of both systems.

REFERENCES

1. Team Corporation. (2014, September 13). Technical Analysis of Team T-Film Slip Table. Retrieved from http://teamcorporation.com/images/technical_documents/app_notes/Application-Notes-White-Papers/T-Film-Slip-Table-Analysis.pdf
2. Lund, D. and Crawford, R. "Novel Guided Head Expander Design Uses Close Coupled Inertial Masses and Hydrostatic Bearings to Minimize Cross-Axis Motion". Proceedings of the 24th Space Simulation Conference, November 2006. Annapolis, MD.

Table 1: Vibration Test Specifications

Axis	Frequency (Hz)	Test Level (zero to peak)
V1	5-50	1.00 g
	50-80	1.25 g
	80-100	1.00 g
V2	5-50	1.00 g
	50-60	1.50 g
	60-80	1.00 g
	80-100	1.50 g
V3	5-20	1.50 g
	20-40	0.75 g
	40-60	1.25 g
	60-100	1.00 g

Table 2: Horizontal System Moment Capacity

	OTIS Payload	Small Payload	Requirement
Pitch	1.47e6 N-m	1.1e6 N-m	395,000 N-m
Roll	1.20e6 N-m	1.1e6 N-m	20,000 N-m
Yaw	214,000 N-m	214,000 N-m	56,000 N-m

Table 3: Vertical System Moment Capacity

	OTIS Payload	Requirement
Pitch	328,000 N-m	147,000 N-m
Roll	328,000 N-m	45,000 N-m
Yaw	358,000 N-m	34,000 N-m

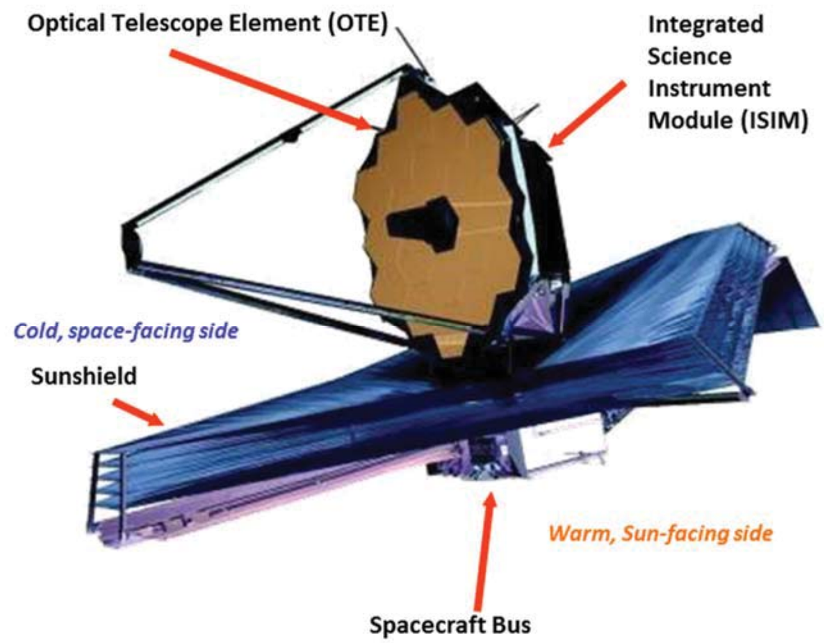

Figure 1: James Webb Space Telescope

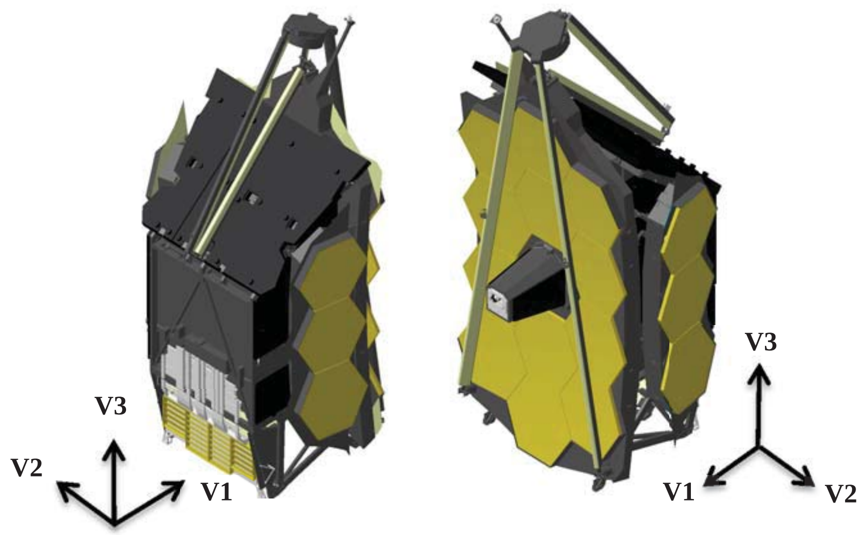

Figure 2: JWST OTIS Sub-Assembly

Figure 3: Horizontal Slip Table

Figure 4: Horizontal System with OTIS Payload

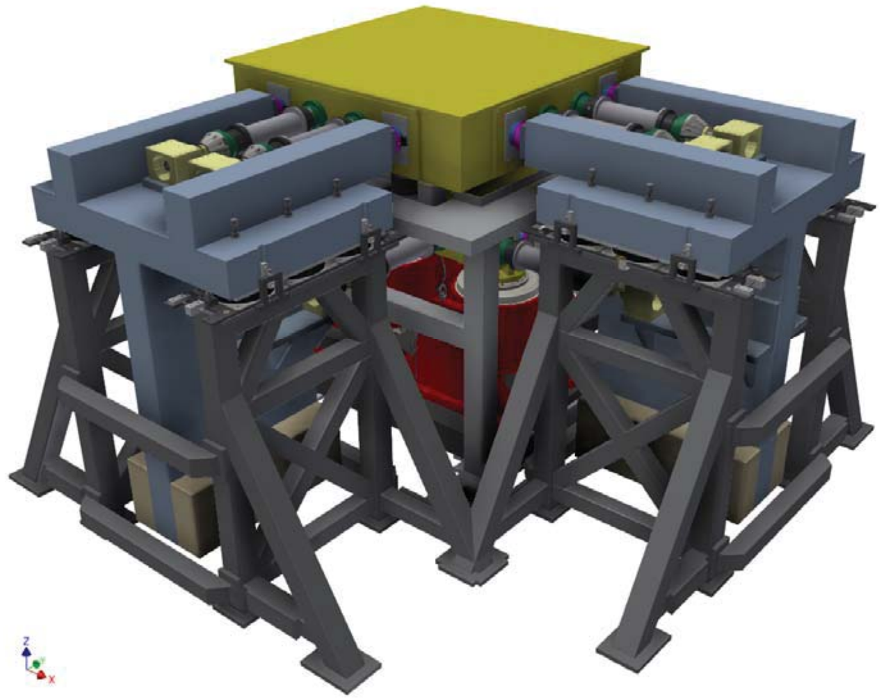

Figure 5: Vertical Guided Head Expander Design

Figure 6: Vertical System with OTIS Payload Attached

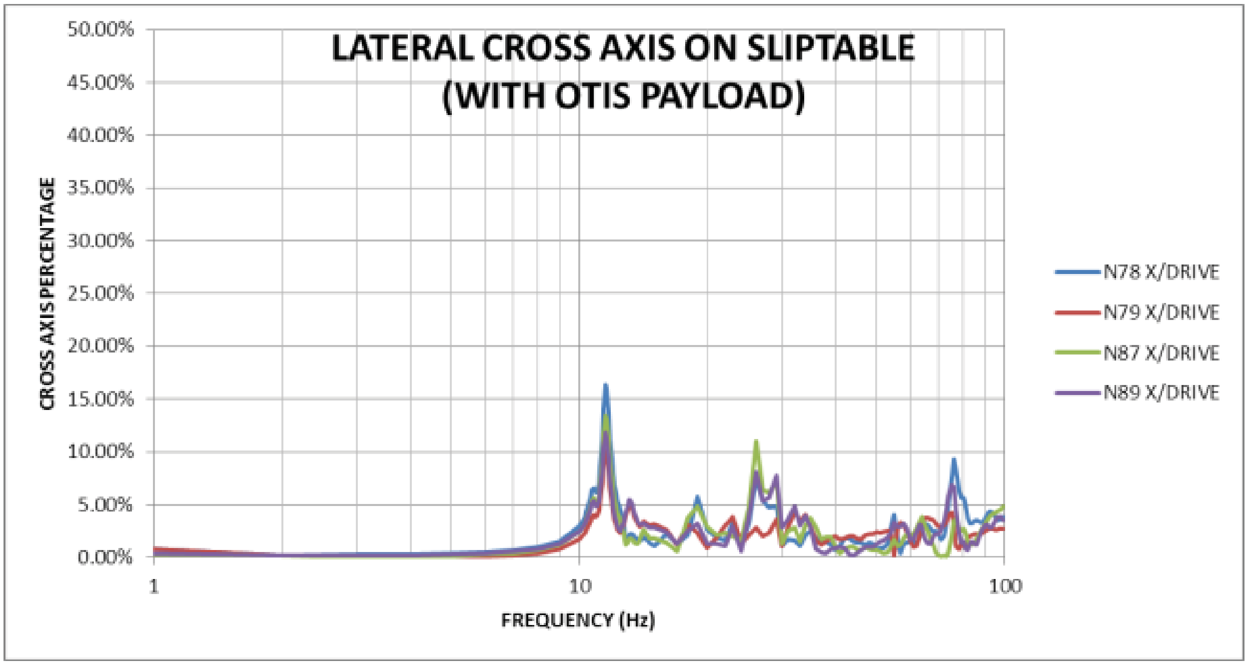

Figure 7: Horizontal V2 Excitation, V1/V2 Cross-Axis Motion

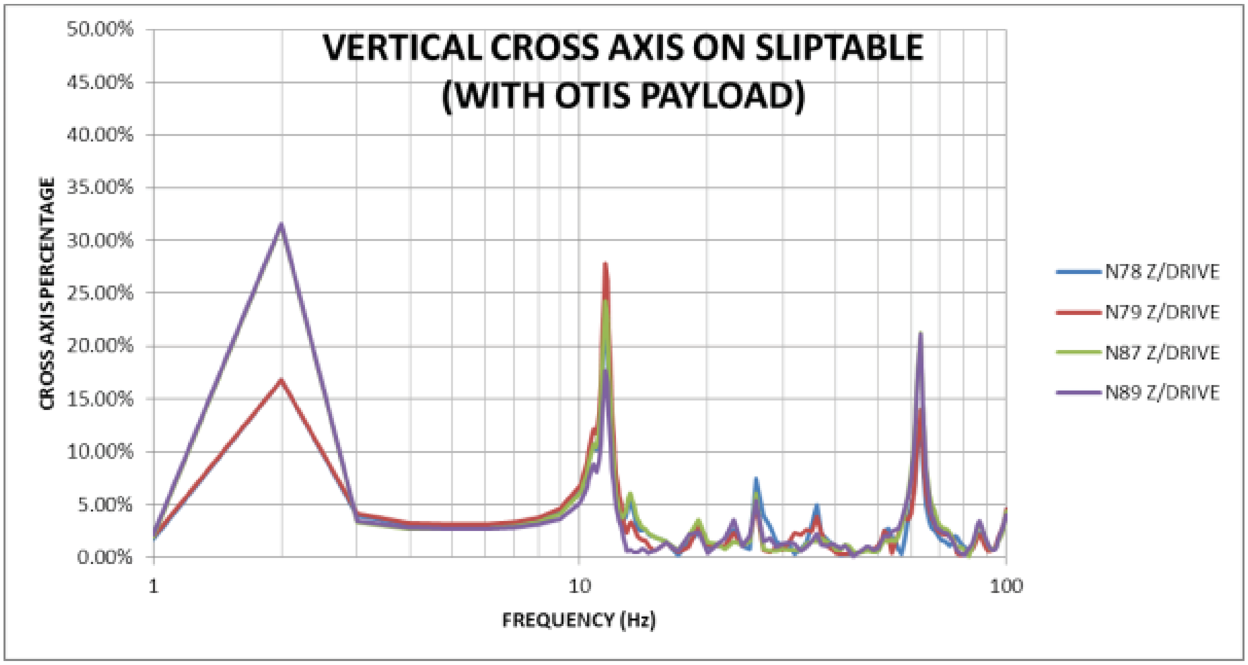

Figure 8: Horizontal V2 Excitation, V3/V2 Cross-Axis Motion

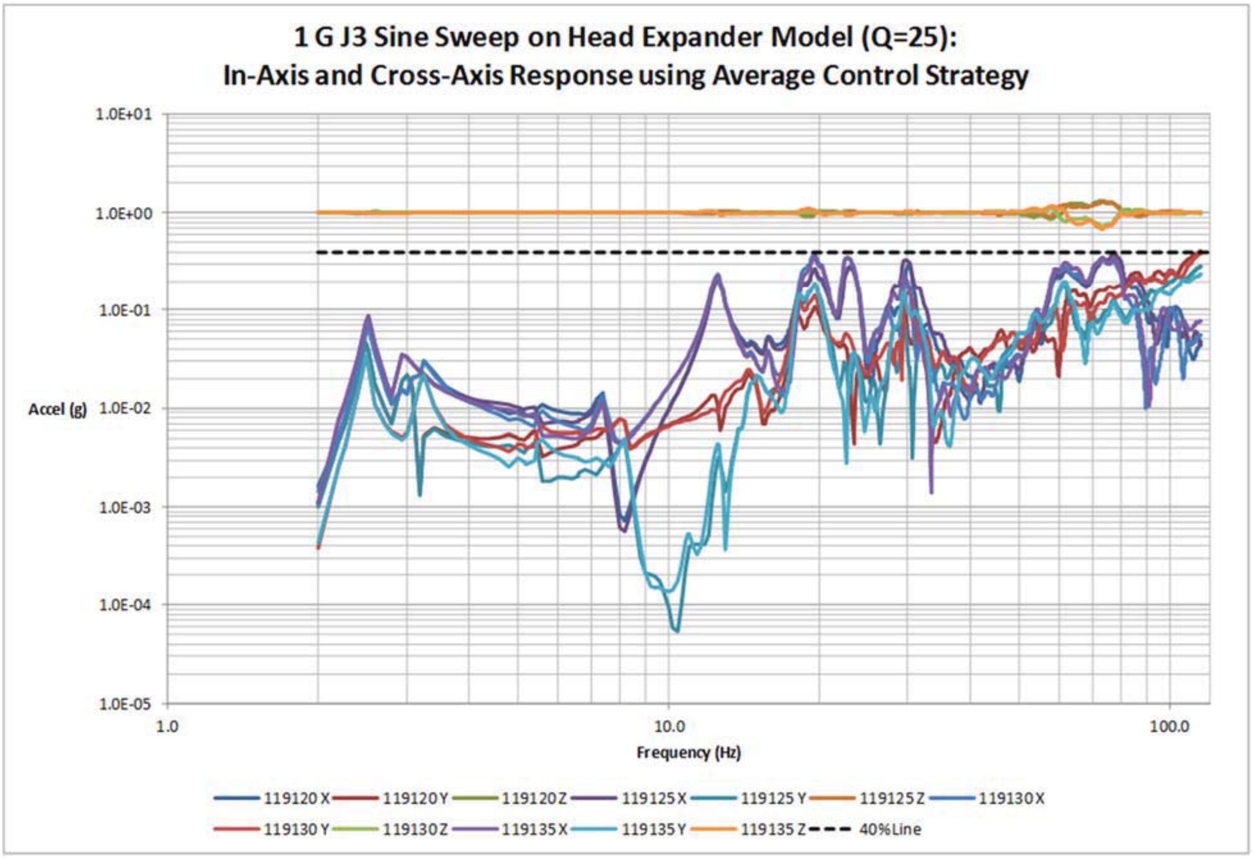

Figure 9: Vertical V3 Excitation, Horizontal Cross-Axis Motion