Testing of a 10-meter Solar Sail Quadrant

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Abstract

The purpose of this paper is to address the technical challenges and requirements of modal testing a solar sail system (Fig. 1). Specific objectives of this work are to investigate the effectiveness (i.e. accuracy, precision, repeatability, etc.) of laser vibrometer measurements obtained on solar sail components (i.e. sail membrane quadrant and masts) actuated with various excitation methods in vacuum conditions. Results from this work will be used to determine the appropriate test technique for testing large scale full quadrant flight-like solar sail system hardware in vacuum conditions.

This paper will focus on the dynamic tests conducted in-vacuum on a 10-meter solar sail quadrant development by AEC-ABLE as part of a ground demonstrator system development program funded by NASA's In-Space Propulsion program. One triangular shaped quadrant of a solar sail membrane (Fig. 2) was modal tested in a 1 Torr vacuum environment using various excitation techniques including, shaker excitation through the masts, magnetic excitation (Ref. 3), and surface-bonded piezoelectric patch actuators (Ref. 4 & 5). The excitation methods are evaluated for their applicability to in-vacuum ground testing and their traceability to the development of on-orbit flight test techniques. The solar sail masts (Fig. 3) were also tested in ambient atmospheric conditions and vacuum using various excitation techniques and these methods will also be assessed for their ground test capabilities and traceability to on-orbit flight testing.

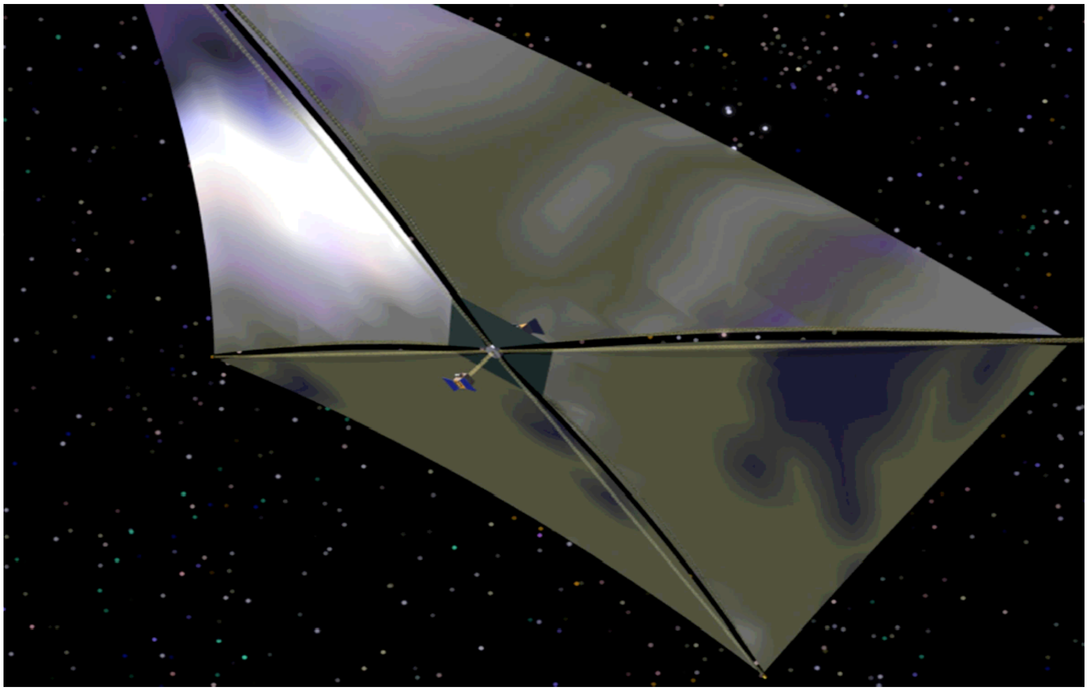

Figure 1: Solar Sail System with Mast and Sail Quadrants

Figure 2: 10-Meter Solar Sail Quadrant

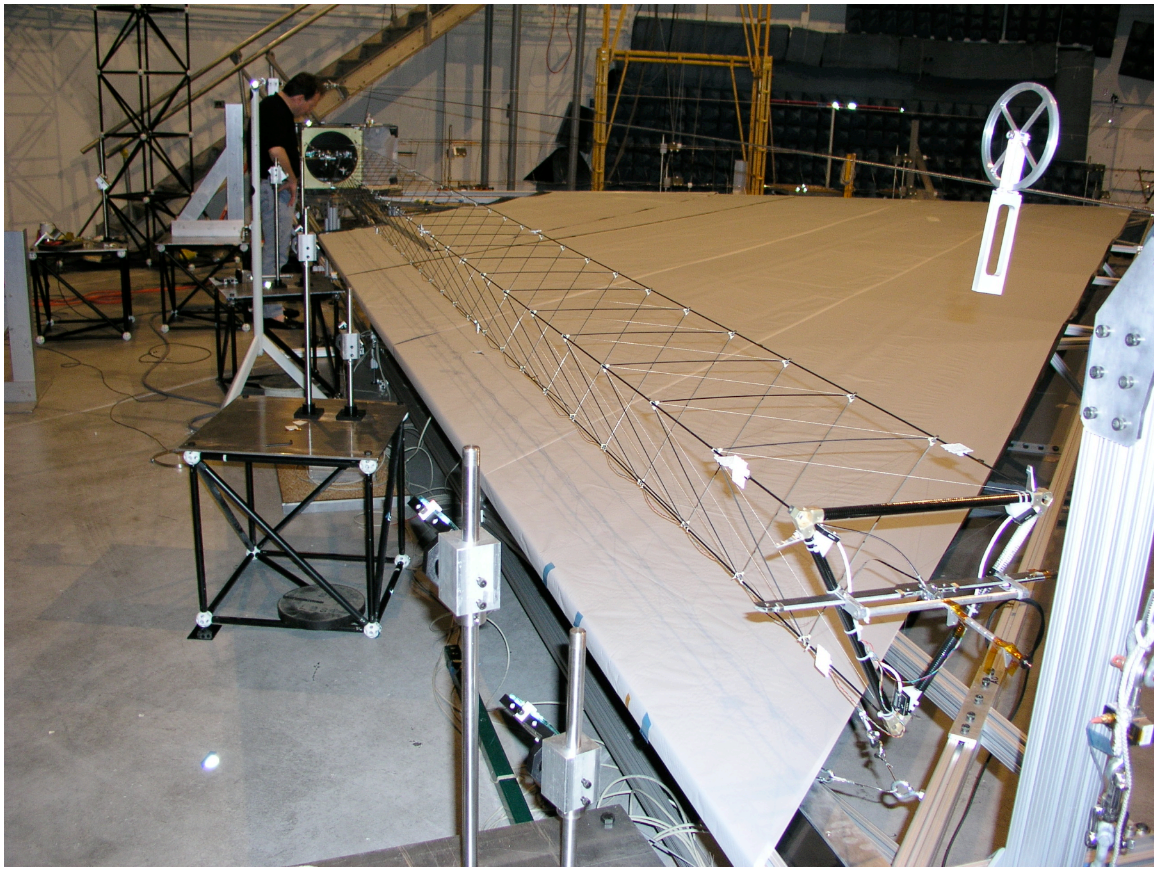

Figure 3: 10-Meter Solar Sail Quadrant Mast

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5. Gaspar, J. L., Pappa, R. S., “Membrane Vibration Tests Using Surface-Bonded Piezoelectric Patch Actuation,” Proc. of the 21st International Modal Analysis Conference, Kissimmee, Florida, February 3-6, 2003.

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The NASA In-Space Propulsion (ISP) program has been sponsoring system design, development and hardware demonstration activities of solar sail technology for the past 2 years. Test and analysis efforts to validate a moderate-scale (10-m) ¼-symmetry ground demonstration sail system have been completed. Results of component- and system-level tests using different excitation methods to determine modal structural dynamic response characteristics are discussed in this paper.

I. Introduction

Large-scale gossamer technologies such as solar sailing have yet to be demonstrated successfully in space (Figure 1). Over the past decade many small disparate activities in solar sail technology development have been pursued [Ref. 1]. As a result, materials technology, fabrication experience, and applicable analytics have been advanced to a point that projections for system performance have begun to have real credibility [Ref. 2-3]. Under a 30-month NASA ISP program, ATK Space Systems, in concert with other activities also under the purview of the ISP program office, has developed a ¼-symmetry ground demonstration sail system [Ref. 4]. The ISP Ground System Demonstrator development and validation effort is led by ATK Space Systems, with assistance by SRS Technologies for sail membrane assembly, NASA Langley Research Center (LaRC) for sail shape and dynamics test measurements and analytical model correlation, and NASA Marshall Space Flight Center's (MSFC) Space Environmental Effects Laboratory for materials characterization and life evaluation. This paper will describe the sail system tests completed at LaRC to demonstrate in-vacuum sail dynamics measurement necessary for model validation; corresponding analytical efforts are described in another paper [Ref. 5].

II. Solar Sail System Test Program Overview

System testing in vacuum is necessary because both the deploying and deployed dynamics of a sail could otherwise be greatly affected by the surrounding air mass. In order to validate deployment characteristics as well as sail shape and system dynamics, a series of tests were completed utilizing the 16-m vacuum chamber at LaRC. The objectives for the tests were to validate deployment, measure deployed shape of the (horizontal) sail billowed under gravity loading, and to measure sail system dynamics for analytical model validation. The ATK/LaRC test team planned an extensive series of tests to capture the data needed to support these objectives, as well as to meet goals for developing test methods applicable to larger scale testing and to in-flight investigation [Ref. 4]. Over a period of months leading up to the Quadrant Assembly Testing, the LaRC test team developed and validated dynamic test methods and conducted other test readiness preparations using (Engineering Development Unit) EDU hardware (sails and mast) prior to formal testing [Ref. 6]. The focus of this paper will be on the modal dynamics testing completed on the sail quadrant in-vacuum.

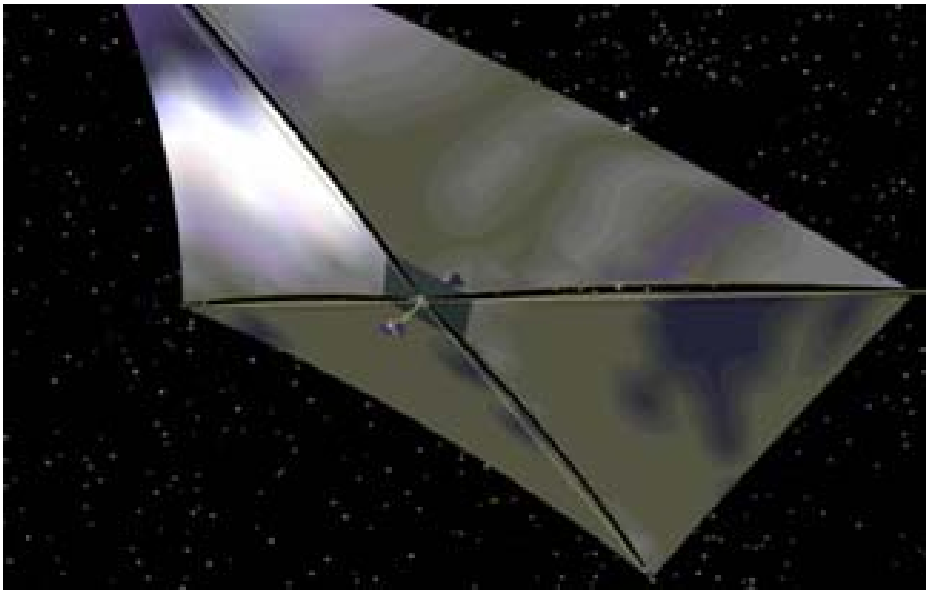


Figure 1. Solar Sail Concept with Masts and Sail Quadrants

III. Test Article Description

The test article, shown in Figure 2, was a single quadrant of a 10 meter solar sail system and consists of a central hub structure, two self supporting masts, and a solar sail membrane. The scalloped triangle shaped sail membrane was made from 3-micron thick aluminized CP1 material and features a shear compliance border with cords running along the edges. The cords connect to the sail area by means of a shear compliant border that is designed to reduce wrinkling of the membrane. The triangular membrane connects to the hub at the interior corner by a tack-line, and connects to the boom tips via halyards. The load on the membrane was measured by a load cell on the tack line with the tension applied at the halyard lines. Measurements were made at 31 retro-reflective targets evenly distributed across the sail membrane.

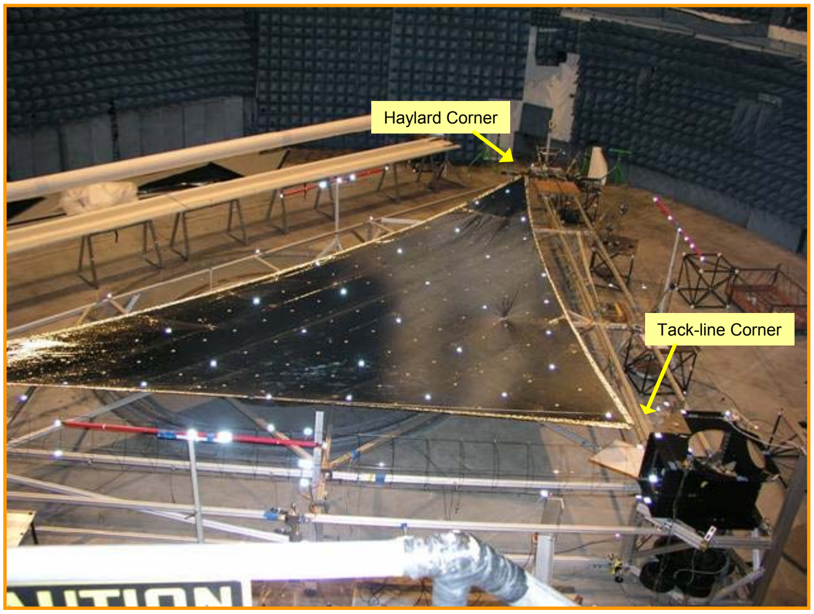


Figure 2. 10-m S^4 Quadrant Test Article inside Langley's 16-m Vacuum Chamber

IV. Sail Dynamics Tests

A. Sail Vibration Measurement Method

A Polytec PSV-300-H scanning laser vibrometer system was used to measure vibration modes of the test article (Figure 3). To provide accurate measurements, 31 retro-reflective dots were adhered to the sail membrane in a grid pattern at even spacing to allow for increased reflection of the laser beam to the vibrometer. To protect the delicate laser scan head from the vacuum environment, a pressurized canister was fabricated to place the scanner inside. The canister has a window port from which the scanner can view the test article. Forced air flow was used to cool the inside of the canister, and a temperature sensor inside the canister fed a switch that automatically shuts the scan head down at 100 degree F. The Polytec software was used to view frequency response functions (FRFs) and operating deflection mode shapes (ODS) for real time preliminary assessment of test progress.

A cable suspension system was designed to properly lift, position, and restrain the canister. The suspension system hoisted the canister to the required 45 foot height, and also supported and restrained the associated power lines, air tubes, and sensor wires. A single ¼ inch diameter multi-strand steel aircraft cable was used to hoist the canister, and support its weight. Six 3/16 inch steel multi-strand aircraft cables were used to restrain the remaining five degrees of freedom consisting of translations and rotations about the suspension cable attachment point, especially the canister side motion. An additional line restrains power cables, sensor wires, and airflow tubes. All multi-strand cables were attached to the chamber wall and tightened with winches. One lateral degree of freedom had stiff springs in series with the cables to allow for predictable cable loads as dimensional variations in the chamber due to thermal, or other effects, act upon the suspension system setup.

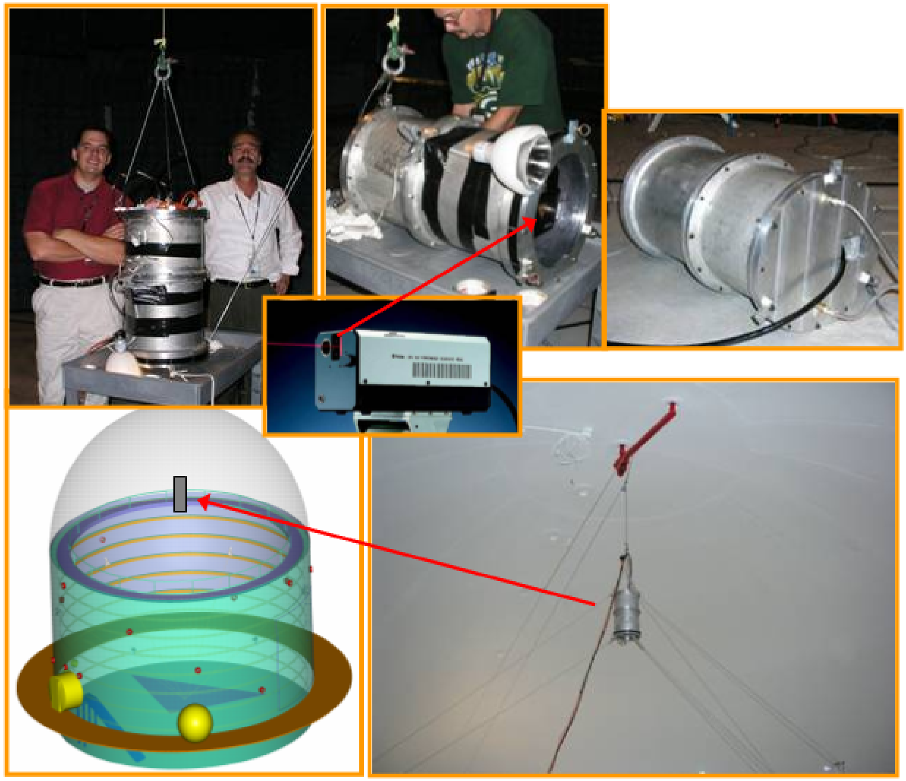


Figure 3. Laser Vibrometer Suspended Above Test Article

B. Sail Test Description

All sail test vibration measurements were made under vacuum conditions with a pressure of ~1 Torr in LaRC's 16-meter vacuum chamber. Tests were performed with the membrane at a ~2.5 lbs. tack-line tension level. All in-vacuum sail system tests applied a sine sweep input signal to the exciter, with a bandwidth from 0 to 4-5 Hz depending on the test (small bandwidth differences between tests). For most tests the sine sweep voltage signal from the signal generator was used as the reference for the FRF calculations, while for the shaker test a force sensor was used as the reference. The FRFs are computed using 4 to 5 averages, as the number of averages varied slightly among the tests. To actuate the piezoelectric patches, the signal is amplified by 200 volts-per-volt with a Trek amplifier (Model PZD700) to produce a maximum input voltage of 1400 volts peak-to-peak (±700 volts).

C. Shaker Excitation

Sail system modal excitation was first attempted by driving the test article with an electromagnet shaker attached near the mast root with a stinger. The excitation was a slow sine sweep with the input forcing function being measured with a PCB force sensor. Results from dual in-phase mast excitation produced poorly excited sail modal response. The mode shapes showed local motion at halyard corners, indicative of poor energy transfer through the much stiffer mast to the sail membrane.

D. Magnetic Excitation (Baseline)

The baseline test for membrane dynamics consisted of exciting each of the three sail membrane corners with electro-magnets as shown in Figure 4. The magnetic excitation method is a non-contacting technique where an electro-magnet is used to provide out-of-plane motion to the sail via moving a small strip of metal fixed to the sail corner grommets [Ref. 6,7]. The magnets were driven with a slow sine sweep with each magnet actuated in-phase or out-of-phase to one another to capture the lowest order modes important for finite element correlation. All sail membrane dynamics tests were perform in ~1 Torr vacuum.

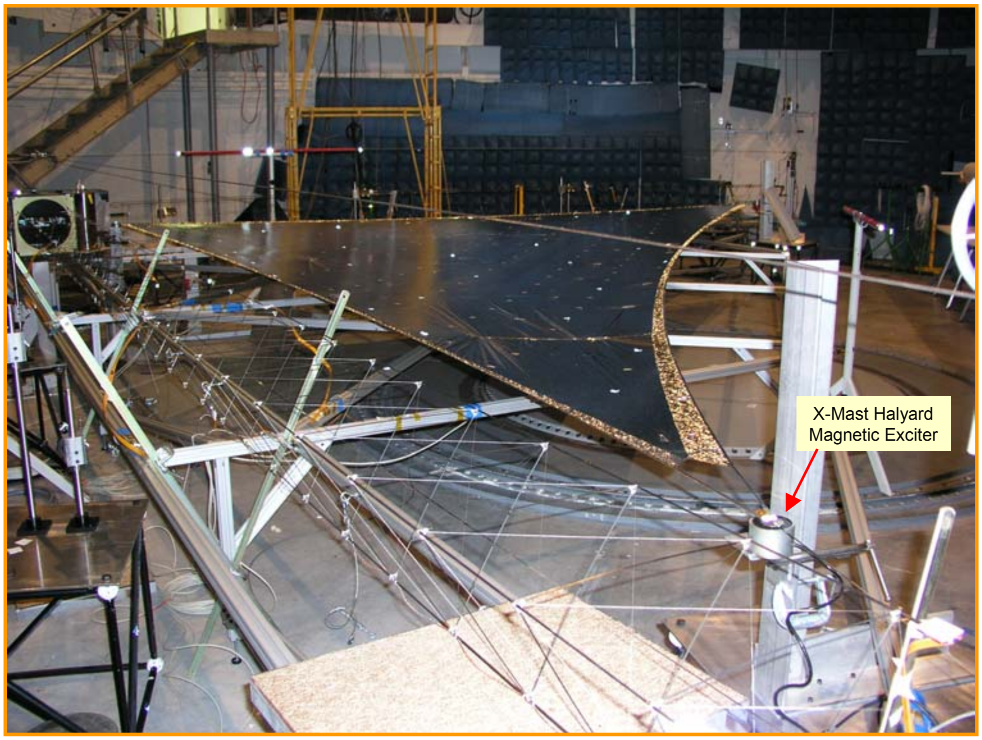
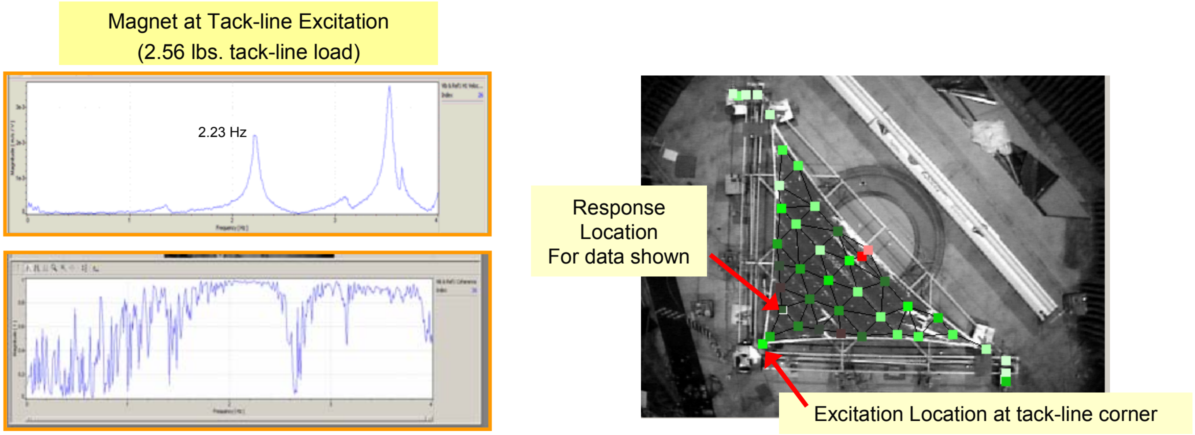


Figure 4. Magnetic Excitation Setup at Each Corner

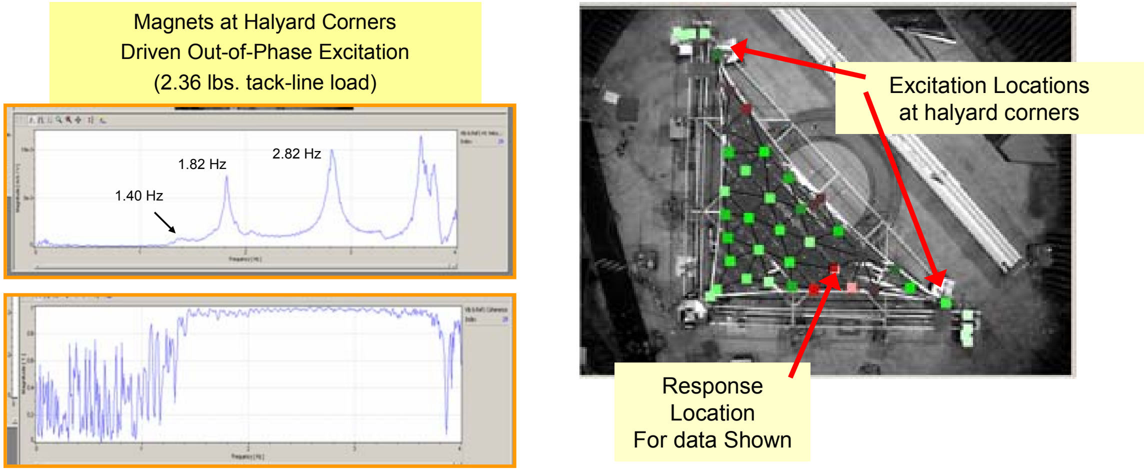
The first four sail membrane modes were properly identified via in-vacuum modal tests with very clean Frequency Response Functions (FRFs) and high coherences (COH) at resonance, as shown in Figures 5 and 6. Figure 7 shows that the mode shapes are smooth and symmetric. Modes 1, 2, and 4, were all obtained with the two magnets at the halyard corners (shown in Figure 6) driven out-of-phase with one another with a slow sine sweep, while mode 3 was obtained in a separate test with only the magnet at the tack-line active (shown in Figure 5) during the sine sweep.


Magnet at Tack-line Excitation
(2.56 lbs. tack-line load)

Response
Location
For data shown

Excitation Location at tack-line corner

Figure 5. Sail FRF and Coherence from Tack-line Magnet Excitation


Magnets at Halyard Corners
Driven Out-of-Phase Excitation
(2.36 lbs. tack-line load)

Excitation Locations
at halyard corners

Response
Location
For data Shown

Figure 6. Sail FRF and Coherence from Halyard Corner Magnet Excitation

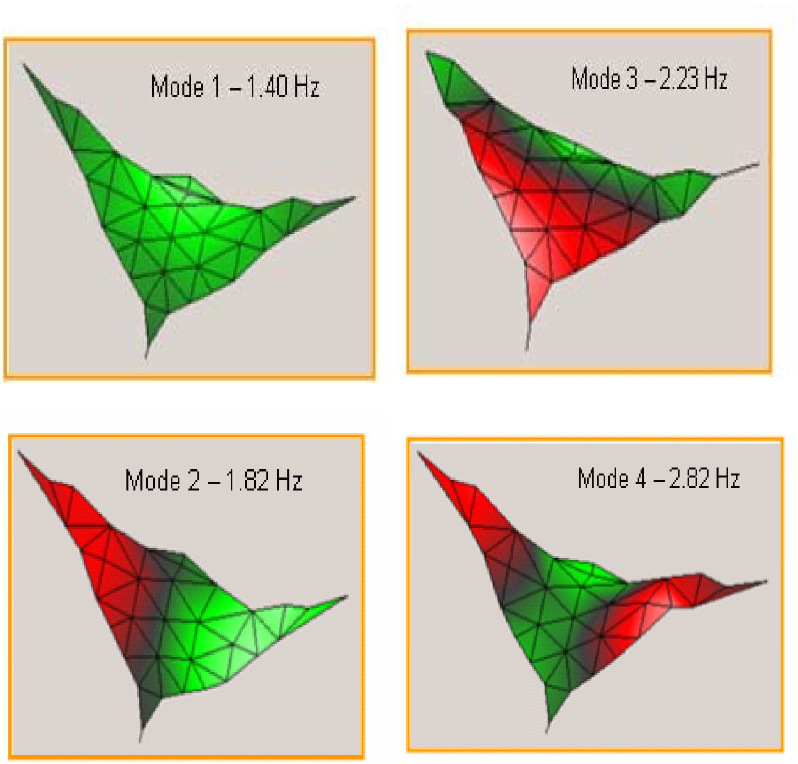


Figure 7. Sail Mode Shapes from Magnet Excitation

E. MFC Piezo Excitation

A third excitation method used ceramic fiber based piezoelectric patches (Figure 8) applied to the cords around the edge of the sail. The ceramic based patches were invented at LaRC and are denoted MFC's (Macro Fiber Composites) [Ref. 8]. Similar actuators have been demonstrated to work on smaller scale membranes in previous experiments [Ref. 6,9]. Figure 8 shows the new MFC design, which is longer and narrower than the previous MFC design used in experiments documented in References 6 and 9. The new MFC design was created to better fit the narrow cord on the sail. A bimorph MFC configuration was utilized, in which two MFCs were bonded to each other and driven out-of-phase to provide an out-of-plane motion. Unlike the non-contacting magnetic exciter, the MFCs were surface-bonded to the top of the cord region of the sail with 51 micron thick 3M 501FL double-backed adhesive transfer tape. Strain gage wires are soldered to the MFC leads and sealed to prevent arcing in-vacuum. For all tests performed, the actuator wires were carefully secured to minimize their effect on the sail membrane vibrations.

The surface-bonded bimorph MFC configuration excitation method provides a small out-of-plane disturbance on the membrane due to the bending caused by the shear force created at the interface between the two MFCs when driven out-of-phase with high voltage. This bending can be seen as a small bulge on the surface of the membrane at the actuator location. The out-of-plane disturbance is capable of exciting the vibration modes of the structure when the actuator is strategically positioned on the membrane. Piezoelectric patches are most effective when placed at strain anti-nodes, i.e. the strain in the direction of the actuator is high. This is different from a traditional shaker modal test, where the shaker is most effective at displacement anti-nodes. Many actuator locations were tested to determine how best to excite various modes of the membrane. Figures 9-10 show a single MFC bi-morph actuator positioned on the cord near the sail central hub was able to excite the first three sail membrane modes very well.

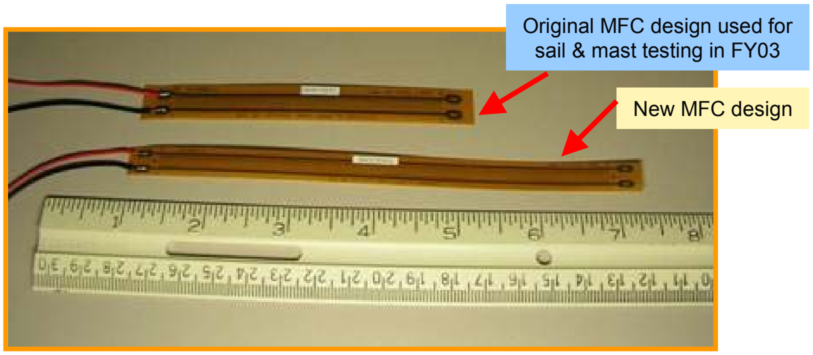


Figure 8. New Bi-Morph MFC Design

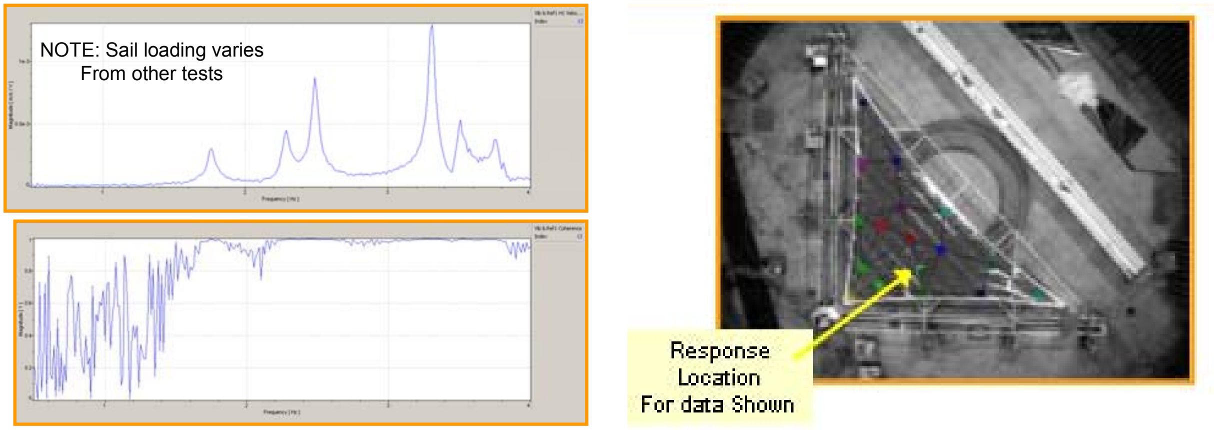


Figure 9. Sail Response due to MFC Excitation

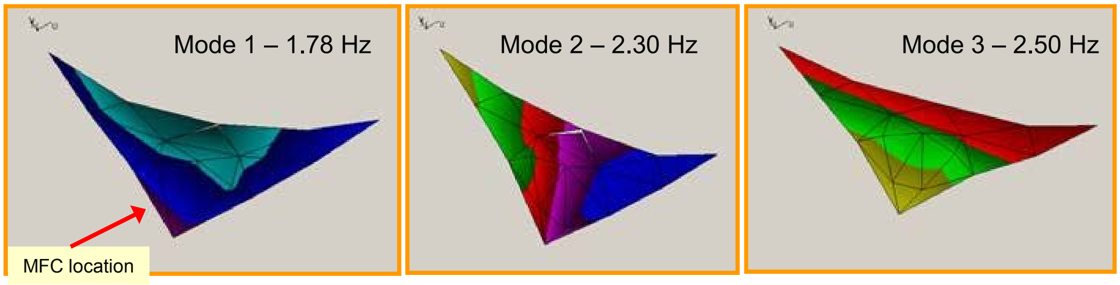


Figure 10. Sail ODS Shapes due to MFC Excitation

V. Mast Dynamics Tests

In addition to the complete sail system, the masts subsystem was also tested using two different excitation techniques.

A. Shaker Excitation (Baseline)

The first component test was a dynamic test of the masts in ambient atmospheric conditions, where the sail was detached but the rest of the system remained. Both mast tips are free, allowing the masts to droop under gravity load. Each mast was excited near the root with an electro-dynamic shaker mounted to capture lateral and torsion modes and then reconfigured to capture the vertical modes as shown in Figure 11. The excitation was provided in the form of a sine sweep from 3.5-8.5 Hz, with 5 averages to compute the FRFs. Mast tip responses were measured with laser vibrometry at retro-reflective targets measuring vertical motion at the two upper longerons, and one retro-reflective target measuring lateral motion at the lower longeron. The laser beam was redirected with a mirror in order to measure the lateral motion.

The vertical, lateral, and torsion modes were properly identified for each mast. The FRFs and coherence are excellent, as shown in Figure 12. However, it should be noted that the X-mast frequencies are consistently lower than the Y-mast results (Table 1), which is attributed to the two loose diagonal wires at the root on the X-mast as illustrated in Figure 13. Gravity loading of the mast tends to off-load these diagonals, in this case the X-mast was off-loaded more so than the Y-mast.

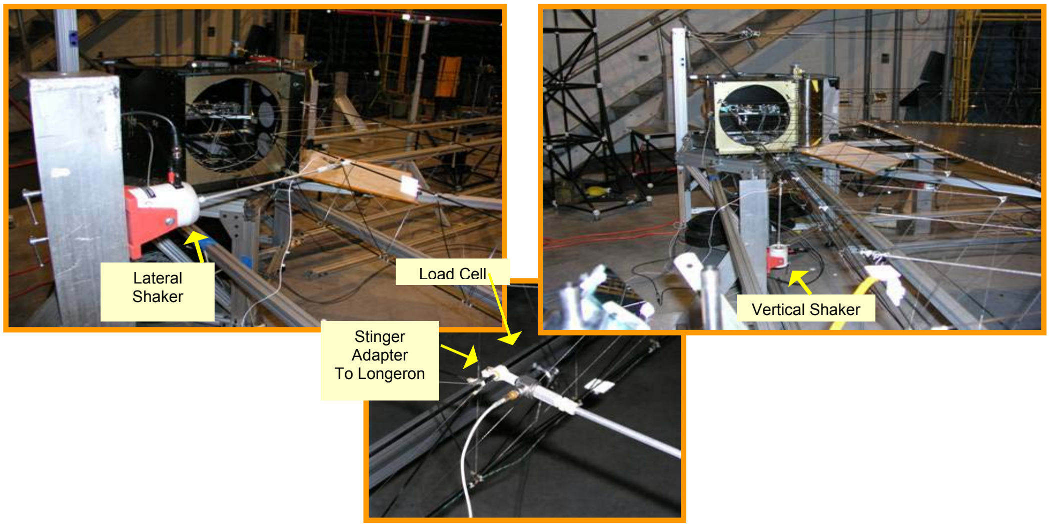


Figure 11. Mast Excitation with Shaker

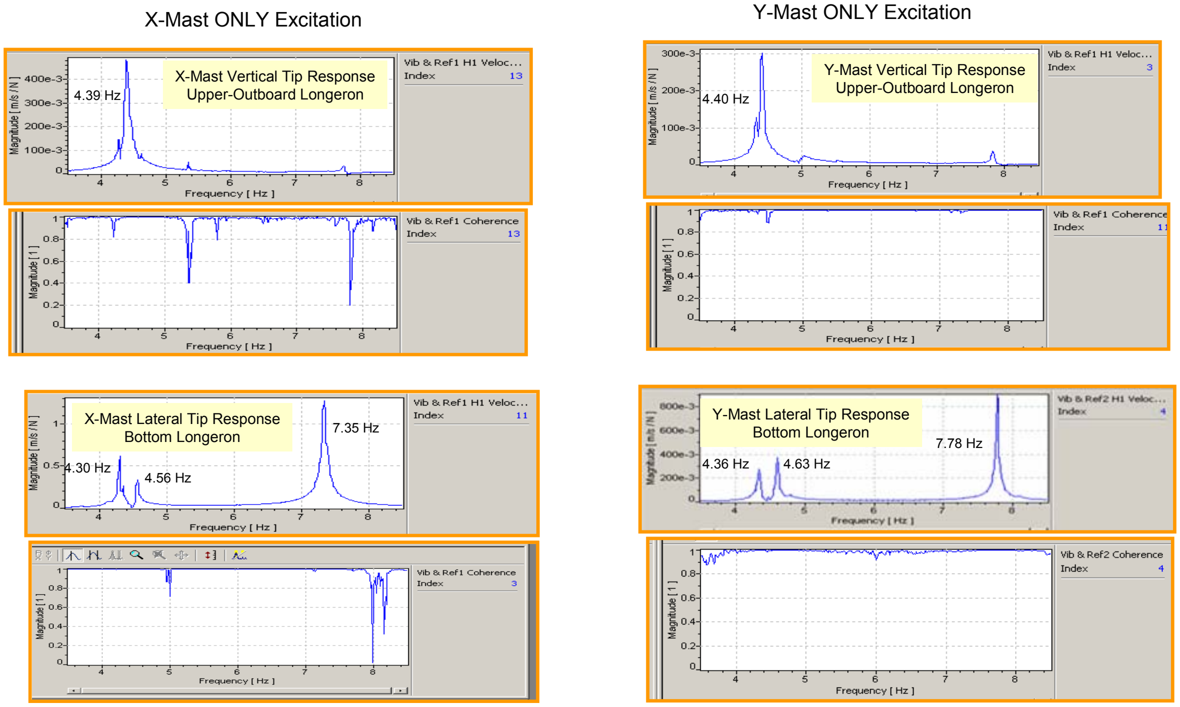


Figure 12. Response of X and Y Masts in Vertical and Lateral Directions

Table 1. Response of X and Y Masts in Vertical and Lateral Directions

Mode #	Frequency		Operating Deflection Shape (ODS) Description
	X-Mast (Hz)	Y-Mast (Hz)	
1	4.30	4.36	1st Lateral Bending – X & Y Mast In-Phase
2	4.39	4.40	1st Vertical Bending – Relative phasing between masts not identified
3	4.56	4.63	1st Lateral Bending – X & Y Mast Out-of-Phase
4	7.35	7.78	1st Torsion – Relative phasing between masts not identified

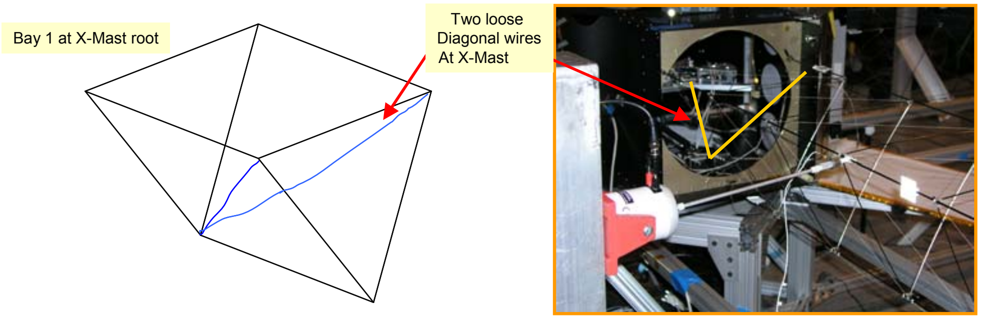


Figure 13. Two Loose Diagonal Wires at X-Mast Root

B. MFC Piezo Excitation – Ambient

The other actuation method used ceramic fiber based piezoelectric MFC patches bonded to the long narrow longerons near the mast root, as shown in Figure 14. The excitation was provided in the form of a sine sweep from 3.5-8.5 Hz, with 5 averages to compute the FRFs. To excite vertical mast response, the two MFCs on the upper longerons were driven in-phase with one another to induce vertical bending vibration near the mast root. Then to excite lateral mast response, the two MFCs on the upper longerons were driven out-of-phase with one another to induce lateral bending vibration near the mast root. This directional control of mast vibration is achieved due to the fact the MFCs are mounted diagonally on the longerons, such that they produce a component of excitation both in the vertical and lateral directions. When driven in-phase the net mast response in the lateral direction is diminished (the two MFCs react against one another), while the vertical component is enhanced (the two MFCs work together to induce vertical motion). While driven out-of-phase, the MFC excitation enhances the lateral component and diminishes the vertical. In both cases this MFC concept was able to produce visible motion at the mast tips in either the vertical or lateral directions.

The results from the MFC actuator test were very encouraging. It was observed that the MFCs could effectively identify the first two mast modes including torsion. The two upper longeron MFCs were driven in-phase with a sine sweep signal to excite vertical modes, and then the MFCs were driven out-of-phase to excite the lateral modes. The MFCs reacted against a very stiff longeron and only required a small surface area for bonding. The results shown in Figure 15 indicate that the modes were very well excited with good coherence at resonance.

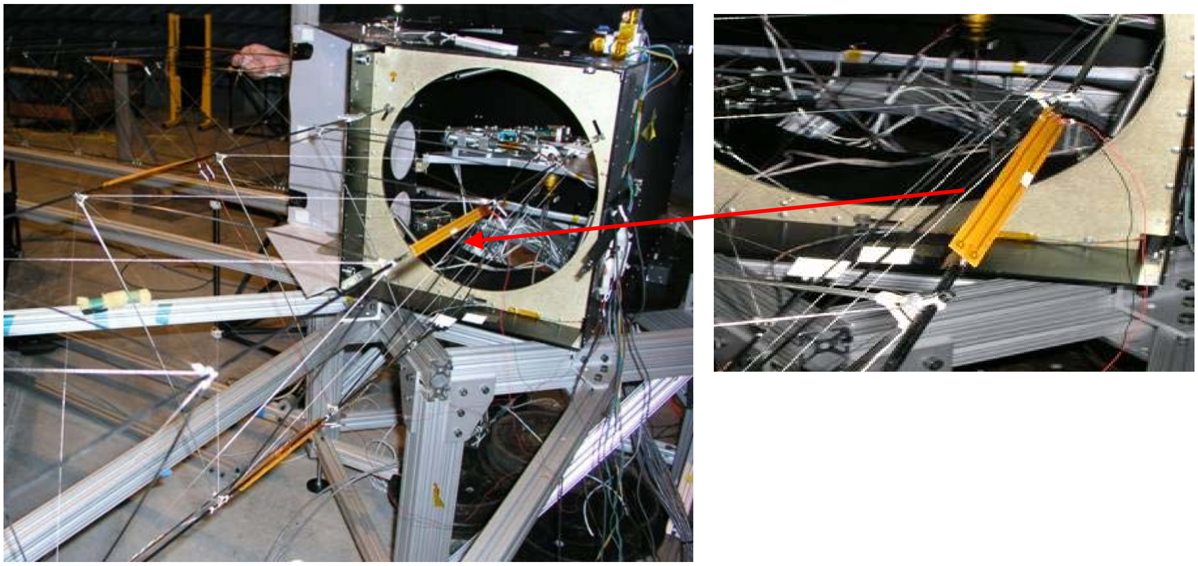
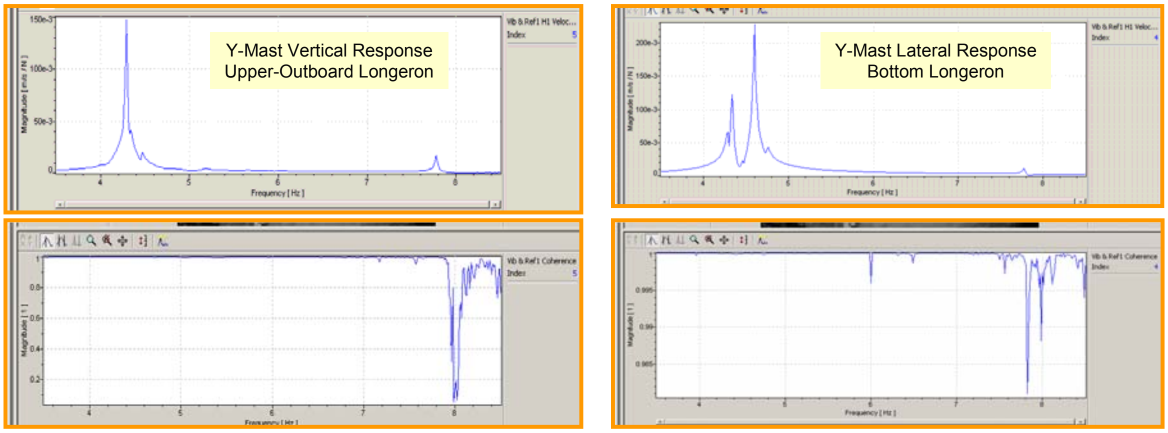


Figure 14. MFCs Near Mast Root used to excite Mast Modes

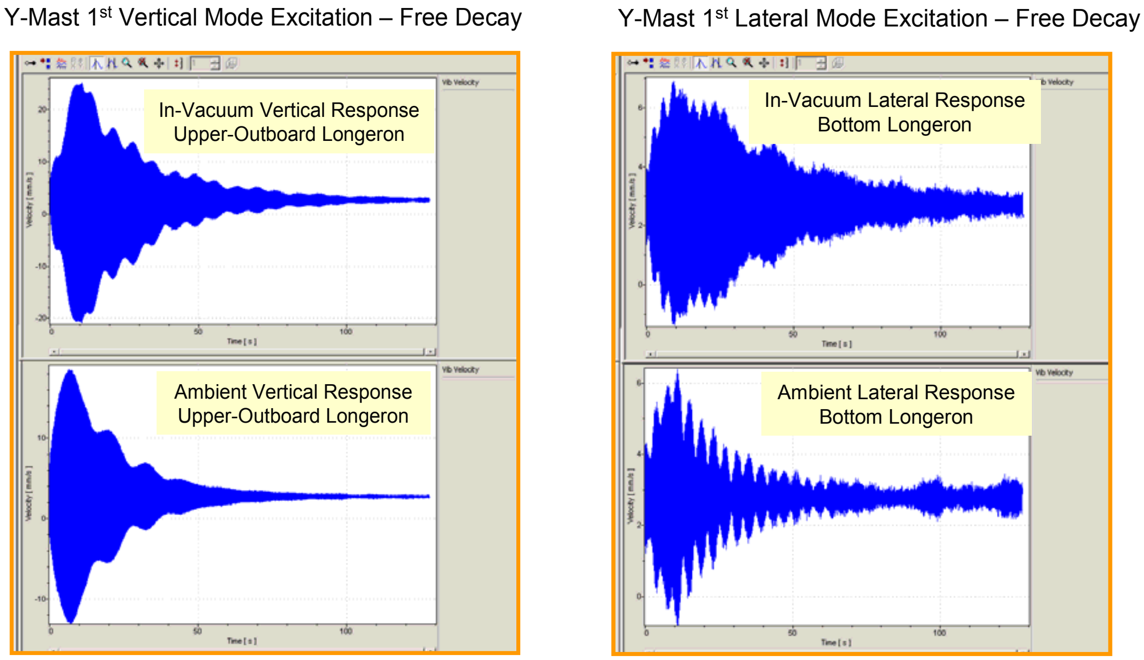

Upper piezo's driven in-phase

Upper piezo's driven out-of-phase

Figure 15. Response due to MFCs near Mast Root

C. MFC Piezo Excitation – Vacuum

In-vacuum mast dynamic free decay tests were completed to determine the influence of air on structural dynamic damping. For this test, the masts were striped of all accelerometer wires and attachments. The mast was then excited identically in ambient and then vacuum for comparison of results. In each case, the 1st vertical mast mode was excited at its resonance for a duration of 10 seconds, then allowed to free decay. Then, the 1st lateral mode was excited in a similar manner to determine lateral response behavior in air and vacuum conditions. The mast where shown to have reduced damping in-vacuum for both vertical and lateral responses, as shown in Figure 16.



Y-Mast 1st Vertical Mode Excitation – Free Decay

Y-Mast 1st Lateral Mode Excitation – Free Decay

Figure 16. Comparison of Mast Response in-air and in-vacuum

VI. Conclusions

The ATK Solar Sail has been tested to determine its in-vacuum system dynamic response for correlation with analytical simulations to aid in future design efforts for potential flight missions. The Sail has been shown to respond in a predictable manner, and test results have been found to be reliable and useful for model correlation efforts. Test techniques have been refined, and potential on-orbit methods identified for further investigation for a flight validation mission.

Acknowledgements

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