TESTING OF A 20-METER SOLAR SAIL SYSTEM

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ABSTRACT

This paper describes the structural dynamic tests conducted in-vacuum on the Scalable Square Solar Sail (S[4]) System 20-meter test article developed by ATK Space Systems as part of a ground demonstrator system development program funded by NASA's In-Space Propulsion program[1-3]. These tests were conducted for the purpose of validating analytical models that would be required by a flight test program to predict in space performance[4]. Specific tests included modal vibration tests on the solar sail system in a 1 Torr vacuum environment using various excitation locations and techniques including magnetic excitation at the sail quadrant corners, piezoelectric stack actuation at the mast roots, spreader bar excitation at the mast tips, and bi-morph piezoelectric patch actuation on the sail cords. The excitation methods were evaluated for their suitability to in-vacuum ground testing and their traceability to the development of on-orbit flight test techniques. The solar sail masts were also tested in ambient atmospheric conditions and these results are also discussed.

INTRODUCTION

NASA Langley Research Center and ATK Space Systems performed structural dynamic tests on the S[4] 20-meter solar sail system in the 30-meter vacuum chamber (Space Power Facility) at the NASA Glenn Plum Brook facility in Sandusky, Ohio. A series of twelve tests, shown in Table 1, were aimed at determining the dynamics of the sail system once deployed and tensioned. Sail dynamics are influenced by the membrane geometry, mass distribution, three-point sail tensioning forces, distributed membrane stresses, sail seam characteristics, folding creases, gravity in the 1g environment (or solar pressure on orbit), etc. Therefore developing test plans and methods that take into account all these variables is extremely important[5-6]. Since the masts are the primary load bearing members, it is also important to measure their dynamics separately.

The sail dynamics measurements were made using vibrometry at 1 Torr vacuum conditions inside the Plum Brook vacuum chamber. System testing in vacuum was necessary because both the deploying and deployed dynamics of a sail could otherwise be greatly affected by the surrounding air mass. For the baseline test configuration, the sail spreader bars were horizontal, and then they were rotated 22.5 degrees from horizontal for another sequence of

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tests. The vibrometer scanner head is located inside an environmentally controlled canister that can operate in the vacuum conditions. Single Point Laser Vibrometry requires acquiring response measurements at retro-reflective target locations sequentially (one target at a time) and then post processing the results to determine system dynamic response behavior. Thus, it was important that the sail remain in a consistent configuration during the scanning period (which can be many hours for many target locations) to avoid data inconsistencies.

SAIL SYSTEM TEST CONFIGURATION

Figure 1 shows the 20-meter S^4 system in its deployed test configuration inside the Plum Brook vacuum chamber. The numbering of the sail quadrants and the mast coordinate reference frame is indicated. The test article was oriented parallel to the ground within the chamber, and off loaded during testing by an ATK-supplied, floor-mounted trolley system that supports each mast tip. For sail system dynamics tests in-vacuum, the mast tips were off loaded with a negator spring system designed by ATK that provides a low frequency suspension to minimize interference with sail system dynamics. Measurements for the dynamics tests were made at retro-reflective targets strategically positioned throughout the sail system, as can be seen in Figure 1. These targets allow for the laser signal to be properly returned to the scan head for accurate velocity measurements off the target surface.
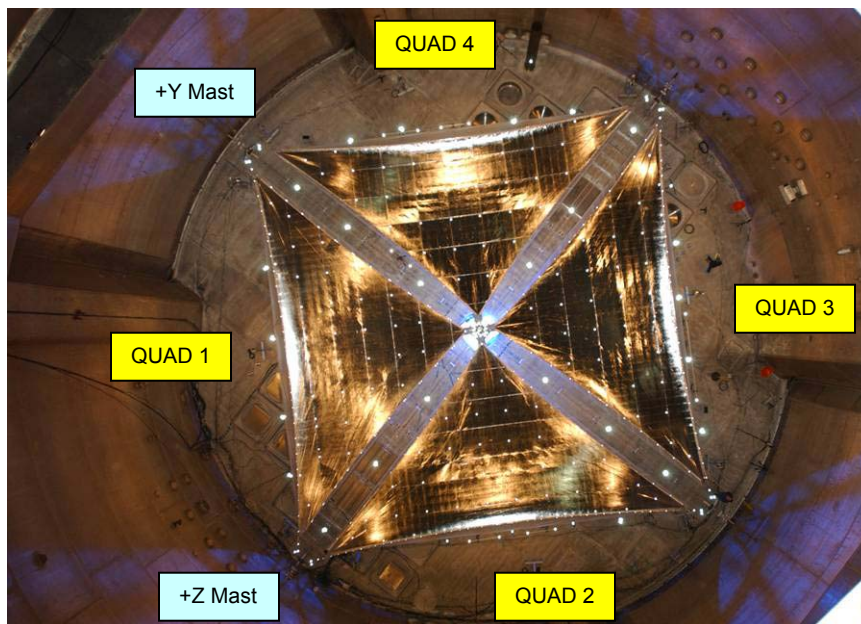
Figure 1. 20-meter Solar Sail inside Vacuum Chamber

Sail system dynamic testing was carried out with the solar sail assembly in the fully deployed orientation. The sail membranes are supported between the masts by a constant force suspension arrangement at the mast tip attachment of each sail quadrant. This arrangement yields predictable stresses within the sail membrane and masts and compensates for any thermally induced dimensional changes. The dynamics of the membrane/system were evaluated at a single nominal sail tension of ~2.5 lbs. halyard load (near mast tip), and at a baseline of zero degree spreader bar angle (sail rotation at mast tip) and then at an angle of 22.5 degrees from horizontal. Both of the moveable Attitude Control System (ACS) ballast masses were stowed inside the central assembly during dynamic testing.

The vibrometer test configuration consists of the vibrometer canister mounted on the chamber door ledge and oriented so the laser beam points up toward the center of the dome and crane structure above. Due to insurmountable limitations on the maximum length allowed for the vibrometer scan head cable (30-meters), the vibrometer cable is not long enough to allow for positioning the instrument directly overhead of the test article. Therefore, an active Scanning Mirror System (SMS) that can receive the laser beam from the vibrometer and redirect it toward the test article below for dynamic response measurement was mounted directly above the test article on a crane structure, about 20-meters from the vibrometer. This configuration is illustrated in Figures 2 and 3. The SMS system was composed of two mirrors mounted on galvanometer motors that are oriented orthogonal to one another to allow for two axis scanning with a range of +/- 20 degrees. The galvanometer motors have similar pointing accuracy specifications to those used in the vibrometer scanner system (Polytec PSV-400), which allows for precision target tracking from large distances. A specially developed target tracking algorithm enabled automatic centering of the laser beam on each retro-reflective target to be measured. Prior to this test, the vibrometer scanning system was validated to work at 85-meters range (although larger distances are possible), well beyond the required working distance of 60-meters for our configuration.
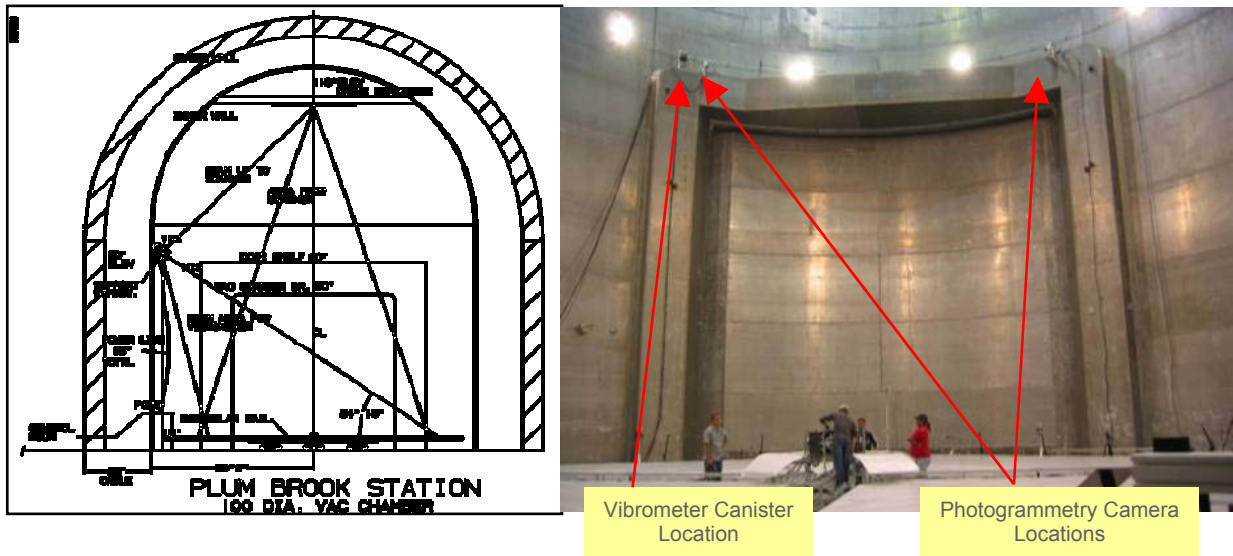

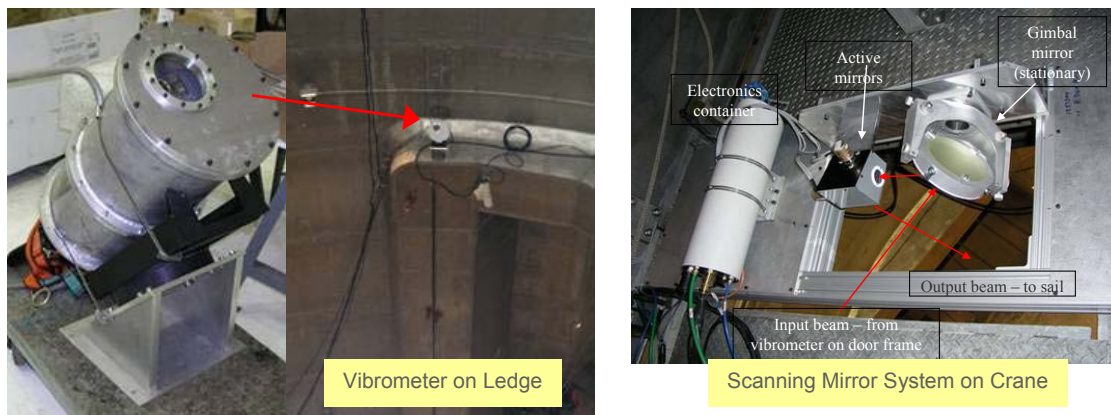Figure 2. Instrumentation inside Vacuum Chamber

Figure 3. Vibrometer and Scanning Mirror System inside Vacuum Chamber

The baseline excitation method for the tests consists of using electro-magnets mounted at each sail membrane quadrant corner[6-7]. A total of 12 magnets were precisely aligned at the corners of each sail (3 magnets per sail quadrant). In addition, magnets were positioned on the long cord at the center of the hypotenuse of each sail quadrant, as shown in Figure 4, to allow for capturing modes not possible to excite from the halyard corners. The halyard corner magnets (located near the mast tips) and the hypotenuse magnets were mounted on vertical translation stages with linear actuators for precise remote positioning of the magnets in-vacuum. The magnets need to be positioned within 5-mm of the sail to work properly, so small CMOS cameras were positioned next to each magnet and carefully aligned to validate that the proper gap size was achieved.

Figure 4. Magnetic Exciter System Configuration

To reduce sail motion during vacuum pump down the mast tips were secured with an electro-magnet, shown in Figure 5, which prevented vertical and lateral motion. During pump down, a constant voltage was supplied to the mast tip electro-magnets to prevent motion due to air currents. Once at vacuum the voltage to the electro-magnet was removed, allowing the spring to pull the magnet away from the test article. The mast tips were then free to move with the soft suspension system off-loader, shown in Figure 5.
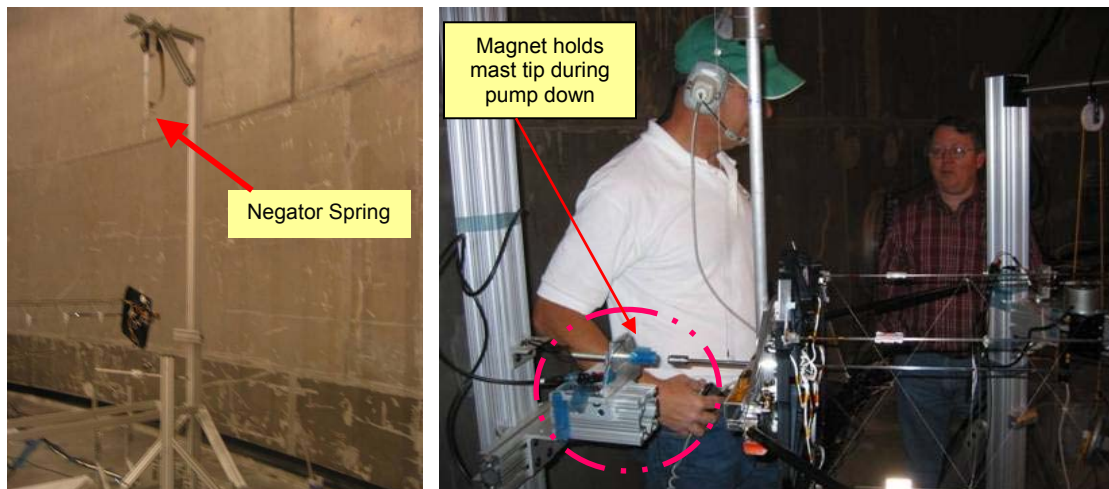
Figure 5. Mast Tip Off-loaded with Negator Spring and Fixed During Pump Down

SAIL SYSTEM TEST RESULTS AND DISCUSSION

Table 1 summarizes the twelve in-vacuum system dynamics tests completed on the sail in the zero degree spreader bar configuration. Most of the team's effort for this series of tests was focused on getting the best quality data possible on quadrant 4, as this quadrant was the most pristine sail membrane with few flaws and it had flight-like characteristics, such as rip stops, built into the membrane. Quadrant 3 was tested second with a reduced set of measurements since it was the next best quality quadrant with some differences from quadrant 4, such as the lack of rip-stops. Quadrants 2 and 1 were tested last with a reduced set of measurements, since these quadrants were of least interest for model correlation. Quadrant 2 had a major repair, while quadrant 1 had been used to develop and validate deployment methods and as a result had many wrinkles and small repairs. The quadrant tests were followed by a full sail system test in-vacuum, in which one halyard corner magnet on each quadrant is driven simultaneously and in-phase with a sine sweep excitation. This technique allows for adequate excitation of the entire sail system and allows for the identification of major system level vibration modes. To save test time, the full sail system test only measured 5 sail membrane locations per quadrant and two mast tip measurements per mast. Since the test article configuration did not change going from the quadrant tests to full sail system testing, the high spatial resolution quadrant test results could be compared with the lower spatial resolution system test results to make an assessment as to how the quadrants respond at each system level mode.

Table 1. Sail Dynamics Tests Completed In-Vacuum

System Tests with 0 Degree Spreader Bar (Sail Halyard Magnetic Excitation) – Vacuum			
#	Test Name	Meas. #	Explanation
1	Q4M1M2 - Mast Tips Fixed	11	Check-out techniques while mast tips are fixed with magnetic restraint
2	Q4M1 - Mast Tips Fixed	7	Check-out techniques while mast tips are fixed with magnetic restraint
3	Q4M1 - Test DC offset method – Tips Free	13	Check-out techniques with mast tips free to float on soft suspension system
4	Q4M1M2 – Test DC offset method – Tips Free	13	Check-out techniques with mast tips free to float on soft suspension system
5	Q4M1M2 – Sail Quad	44	1st baseline test on Quad 4 with M1 & M2 excitation out-of-phase
6	Q4M1 – Sail Quad	44	2nd baseline test on Quad 4 with M1 excitation
7	Q4M2 – Sail Quad	44	3rd baseline test on Quad 4 with M2 excitation
8	Q3M1M2 – Sail Quad	15	1st baseline test on Quad 3 with M1 & M2 excitation out-of-phase
9	Q3M1 – Sail Quad	15	2nd baseline test on Quad 3 with M1 excitation
10	Q1M1M2 – Sail Quad	15	Only baseline test on Quad 1 with M1 & M2 excitation out-of-phase
11	Q2M1M2 – Sail Quad	13	Only baseline test on Quad 2 with M1 & M2 excitation out-of-phase
12	Full Sail System – All Quads with M1	28	Only baseline test on Full Sail System with M1 excitation on each Quad in-phase

During the chamber pump down process, the sail sagged significantly (over 3 inches); it was discovered this sag was caused by moisture build up on the sail during chamber pump down, which added weight to the sail. The Plum Brook chamber produces a large moisture build-up (Fog) during pump down. The additional weight from the moisture on the sail caused the halyard negators to pay out the cord at the mast tips and the resulting sag at the center of the sail hypotenuse was sufficiently large that the linear actuators could not reposition the magnets close enough (within 5 mm) to the sail for proper excitation. Since the magnets were mounted above the sails for this test, the only impact was that the magnets on the hypotenuse were useless for excitation, which limited testing to using only halyard corner magnets for sail excitation. Ultimately, this did limit the mode shapes that were excited, as will be discussed later. All the tests used either one or both remaining halyard magnets for sail excitation. All in-vacuum sail system tests applied a sine sweep input signal to the exciter, with a bandwidth from 0 to 3 Hz. The sine sweep voltage signal was used as the reference for the Frequency Response Function (FRF) calculations, and the FRFs were computed using 4 averages.

Analysis of the test data began by reviewing the FRFs from each quadrant test, and identifying and listing all the resonant frequencies. Each of these modes where then categorized as to how well it was excited and identified in the FRFs. Modes with well-defined peaks in most FRFs were given a data quality rank of 1, or 1- for somewhat lower quality peaks. Modes with well-defined peaks, but perhaps closely coupled to other modes and/or in the residual of other modes as identified in the FRFs, were given a rank of 2 or perhaps 2- for modes of lower quality. Modes of potential interest that were in frequency ranges of high modal density and/or significantly buried in residuals of other modes were ranked a 3. Only modes with a rank of 2+ or better that also repeated well for every quadrant test (with only minor frequency differences) were considered to be successfully obtained and marked as useful for analytical model correlation. Only the data from the quadrant 4 tests were utilized for model correlation. The other quadrant tests were performed primarily to determine the differences between quadrants and their influence on system response behavior. Table 2 summarizes the dominant modes identified through this review process for the quadrant 4 tests.

Table 2. Sail Quadrant 4 Dynamics In-Vacuum Test Results

| ID #	Hz	Rating	Description	Notes
			SUMMARY of DOMINANT MODES	
1	0.391	1	Sail Vertical Motion / Heavily Damped Non-linear Mechanism Mode	Potentially related to negator springs in halyard and/or on mast tip
2	0.503	1	**Sail System 1st Mode "Pin Wheel Mode"** Sail Rocking / All Mast Tips Twist in-phase	Mast Dominant Mode, sail follows
3	0.625	1-	Sail Rocking / Y Tips OOP / Z Tips OOP	Mast Dominant Mode, sail follows
4	0.687	2+	**Sail Membrane 1st Breathing Mode** Long Cord 1st Bending / Centerline 1st Bending	Membrane Mode, 1st centerline
5	0.937	2+	Long Cord 1st Bending / Centerline 2nd Bending (1)	Membrane Mode, 2nd centerline
6	1.0	2+	Long Cord 1st Bending / Centerline 2nd Bending (2)	Membrane Mode, 2nd centerline
7	1.06	1	Asymmetric Sail Mode LT Side Short Cord & RT Side Long Cord OOP	Mast Dominant Mode, sail flex, Full system response
8	1.41	1-	Long Cord 1st Bending / Centerline 3rd Bending (1)	Membrane Mode, 3rd centerline
9	1.47	2+	Long Cord 1st Bending / Centerline 3rd Bending (2)	Membrane Mode, 3rd centerline
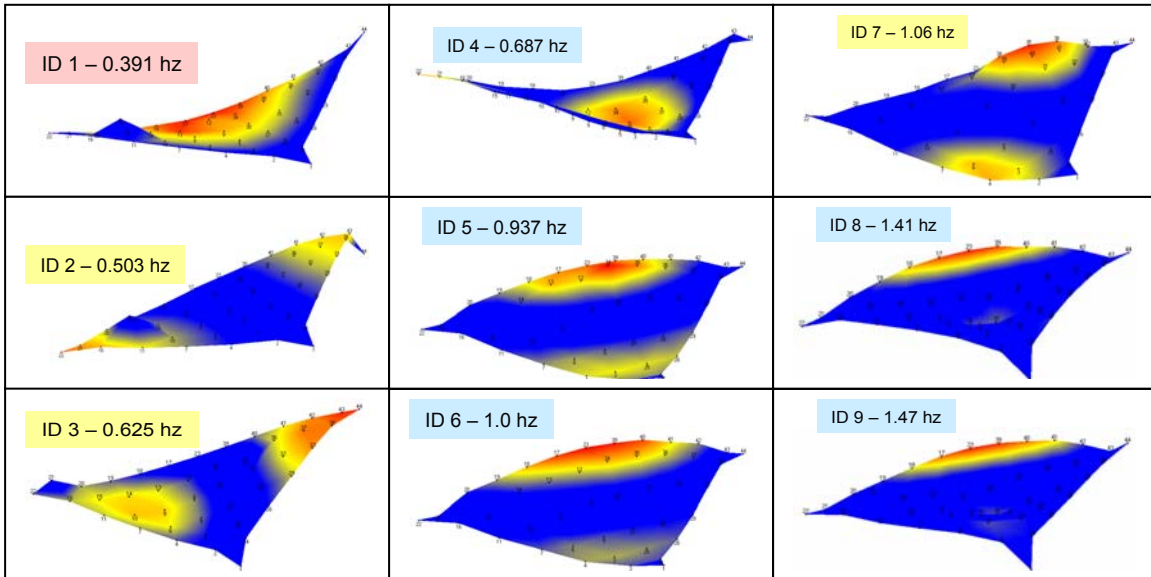
Figure 6. Summary of Dominant Operating Deflection Shape (ODS) Modes

Mode 1, as identified in Table 2 and Figure 6, was a dominant heavily damped mode with a damping factor of ~20%. This was significantly higher than all the other modes that have damping factors in the 2-3 percent range, which is more typical of a structural mode of vibration. The high damping indicates mode 1 was a non-structural mechanism mode, which may be caused by a non-linearity due to free-play or sliding friction. It is believed this non-linearity may have been introduced through the mechanism holding the system at the mast tips or through the sail membrane cord negator springs. The mast tip was supported by negator springs that are left unlocked during testing to allow for mast tip vertical motion, to minimize dynamic interference with the sail system. The sail membrane was also supported by negator springs at the mast tip halyards designed to allow for constant loading during thermal expansion, however this could also allow for cord sliding friction during dynamic excitation.

By comparing quadrant test results with system test results, it was found modes 2, 3 and 7 were primarily mast-dominated modes with the sail motion following the mast tips. Mode 2 was the first full system mode, where each sail membrane is rocking and pivoting about the quadrant centerline.

Modes 4-6 and 8-9 were sail membrane dominated modes. Mode 4 was a sail membrane 1st breathing mode, with the long cord in 1st bending and the quadrant centerline also in 1st bending. The other sail dominant modes were all in 1st bending along the long cord, but undergo various degrees of bending down the quadrant centerline starting with 2nd bending for modes 5-6 and then to 3rd bending for modes 8-9.

Modes 1-4 and 7-9 were easily identified in all the quadrant test data. Modes 5 and 6 were strong for most tests, but were not consistently excited for some. Figure 7 shows how modes 5 and 6 were well excited on quadrant 4 when using 1 halyard magnet exciter, but not for the other. It turns out that this mode was difficult to excite from the halyard corners, since these locations were near a node-line for the mode shape. The goal was to use the exciters at the quadrant hypotenuse for modes like these, but as mentioned previously the sail sag shifted the sail quadrant hypotenuse out of range for the exciter. This limited the testing to using only halyard magnets. Another limitation found was that no 2nd and 3rd order modes on the hypotenuse could be excited with the halyard magnets being at the node-line for these modes.
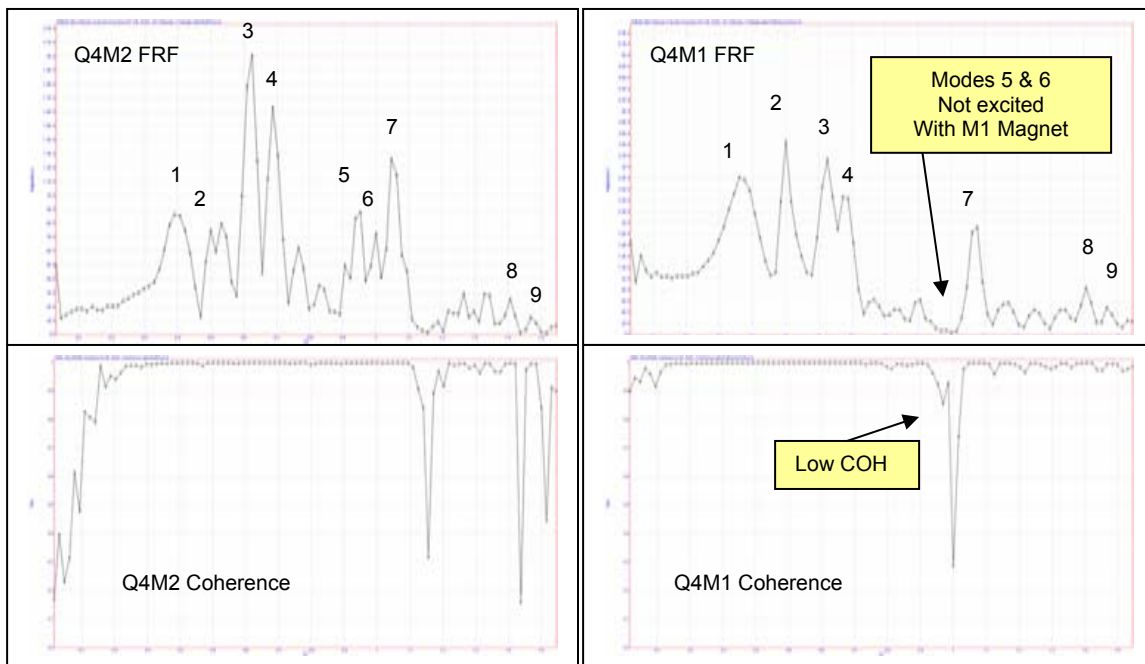

Figure 7. Response Measurement Comparison – M1 versus M2 Magnetic Exciter

The full sail system test (when all 4 quadrants were excited simultaneously) shows exceptionally strong mast participation for modes 2 and 7, as shown in Figure 8. These are system level mast dominated modes with the sail membrane following the mast as shown in the mode shapes. Mode 2, the 1st fundamental system mode of the solar sail, is a "Pin Wheel Mode" with all quadrants rocking in-phase. This mode was created by all mast tips twisting in-phase and the quadrants following the motion by rocking and pivoting about the quadrant centerline. Mode 7 is a mast-dominated mode with the sail membrane bending asymmetrically. In this asymmetric bending, the mast tips twist out-of-phase with one another at each quadrant halyard corner. Mode 3 at 0.625 Hz is another mast-dominated system mode. In this mode, the masts on quadrants 2 and 4 twist in-phase, causing the quadrants to rock by pivoting about their quadrant centerline. While the masts on quadrants 1 and 3 twist out-of-phase, causing these sail quadrants to rock about the centerline and also pitch forward-and-aft. The motion of mode 3 is best illustrated in Figure 9, where the darkest contour line (the mode shape node-line) represents the location about which the mode shape pivots. The labels in Figure 9 indicate which sail corners and mast tips are moving "up" or "down".
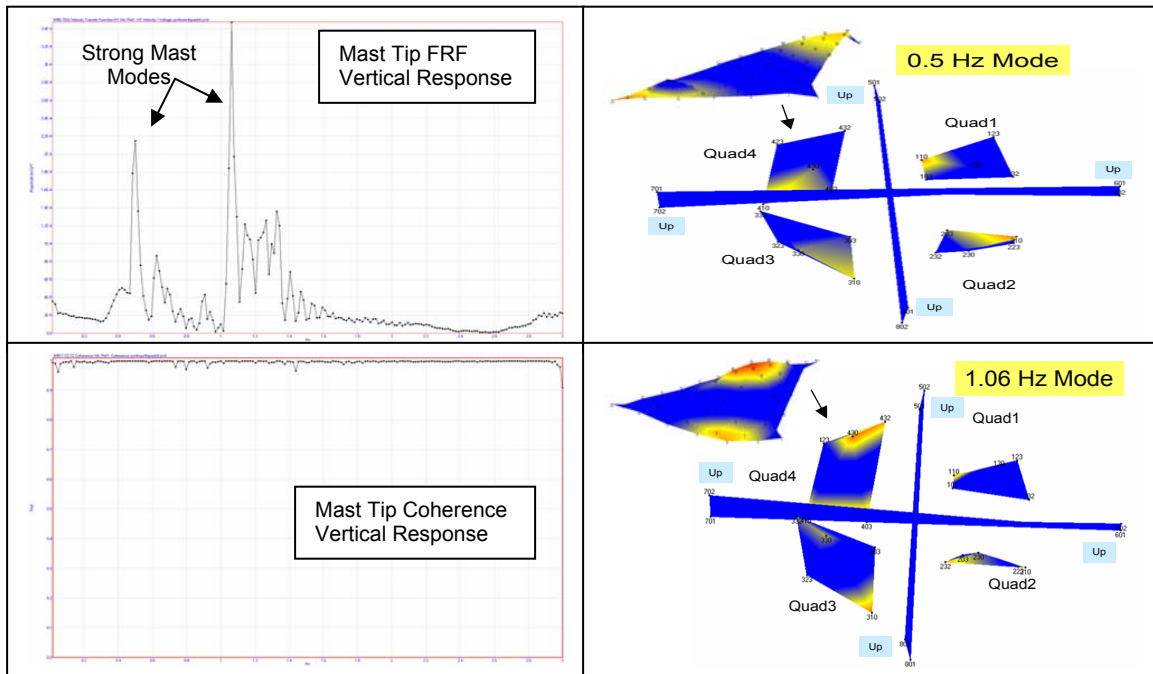
Figure 8. System Test Results showing the Mast Dominated Modes 2 and 7
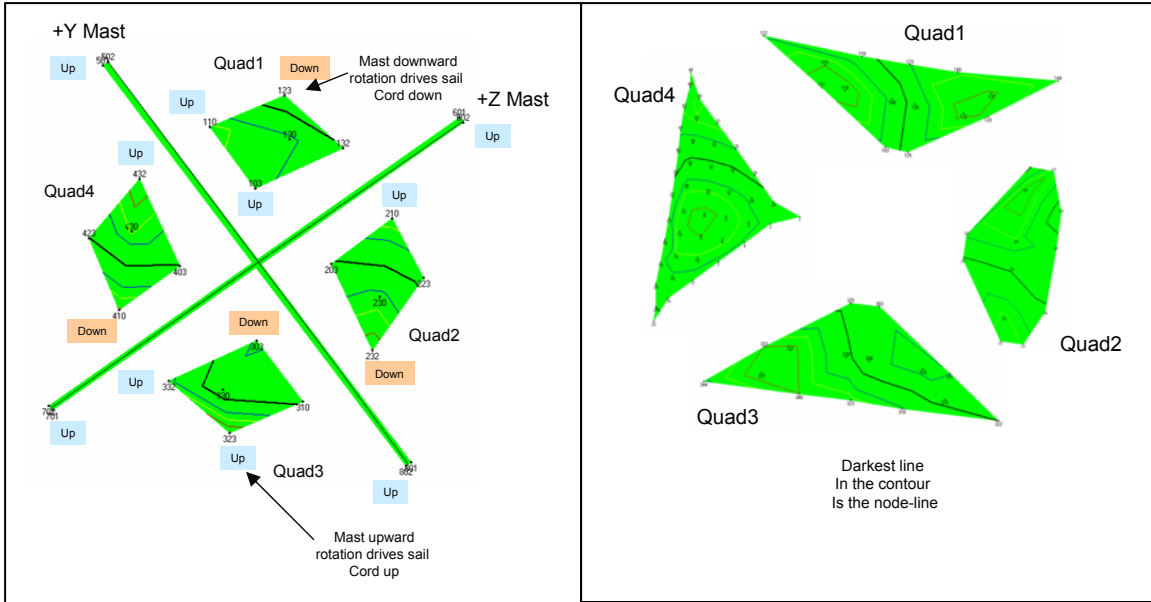
Figure 9. System and Quadrant Test Results showing the Mast Dominated Mode 3

MAST DYNAMICS TEST

The mast dynamics testing occurred immediately after the in-vacuum sail test. The chamber was vented so all the mast tests could be performed in ambient conditions. The sails were detached so mast only dynamics could be obtained. The mast dynamics tests were performed in ambient atmospheric conditions with the mast tips off loaded with a long cable system (without a negator spring), which was designed by ATK and included in the analytical models to allow for correlation with test data results. The baseline mast dynamics tests used piezo stack actuator excitation at the mast root. ATK Space Systems had pre-integrated piezo stack actuators at the root of each mast longeron, as shown in Figure 10, for the purpose of obtaining mast dynamics. This excitation configuration is a strong candidate for on-orbit flight-testing, and is considered the baseline test to which the Finite Element Model (FEM) analysis results are to be correlated. It was found that one actuator located on the upper longeron could provide enough excitation force to excite the mast fundamental modes in the longitudinal, lateral, and torsion directions. Therefore, all the masts were tested by driving just one upper longeron and the response was measured at the mast tip in the longitudinal direction at the two upper longerons and in the lateral direction at the lower longeron. These measurements were made with the laser vibrometer and required a mirror to redirect the beam to measure the lateral motion on the lower longeron, as seen in Figure 10. All mast tests applied a sine sweep input signal to the exciter with a bandwidth from 0 to 10 Hz. The FRFs were computed using the input voltage as reference and using 4 averages. By comparing the phase of the three responses at the mast tip from the FRF data, it was possible to determine if the mode was a dominant longitudinal bending mode, lateral bending mode, or torsion mode. Figure 11 shows the longitudinal and lateral response for the +Y axis mast tip. The FRFs and coherences were excellent from all the mast tests, with very well defined modal peaks and good coherence across the entire frequency spectrum. The consistency of the mast responses was excellent (see Table 3), with all 4 masts showing almost identical responses for all the fundamental modes. Thus, the piezo stack excitation at the mast root was very successful. This technique not only saved valuable testing time as no setup was required, but also has traceability toward flight-testing.
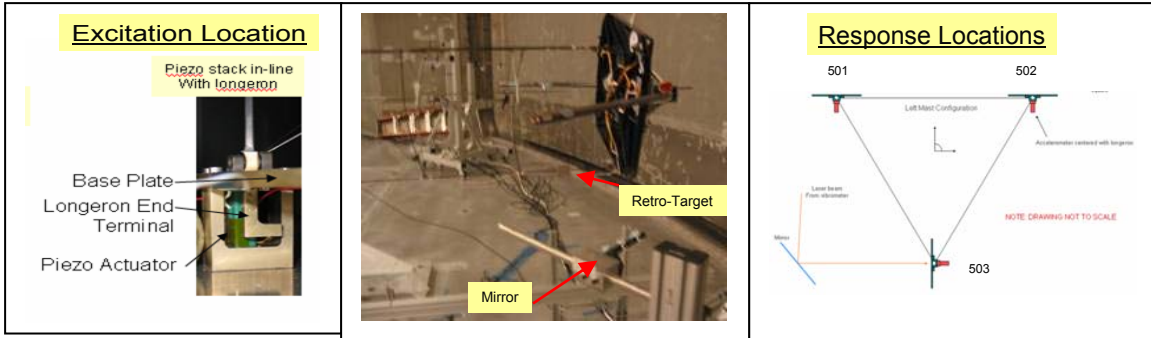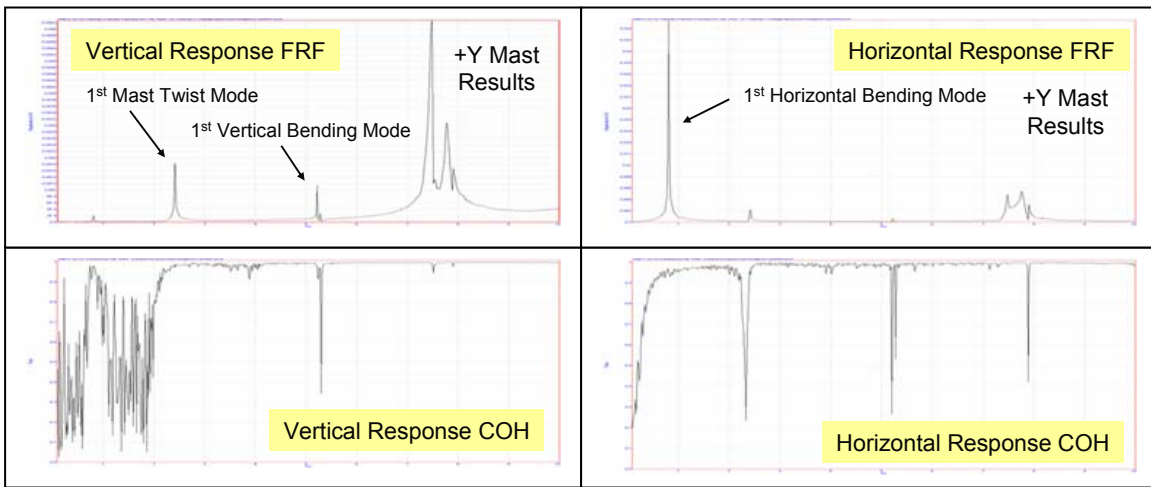
Figure 10. Mast Test Configuration in Ambient

Figure 11. Mast Test Vertical and Horizontal Response Measurements

Table 3. Mast Dynamics Test Summary

#	Mode Description	Frequency Comparison (Hz)			
		+Y Mast	-Z Mast	-Y Mast	+Z Mast
1	Mast Bending in Horizontal Plane	0.813	0.813	0.797	0.797
2	Mast Twist	2.41	2.39	2.41	2.39
3	Mast Bending in Vertical Plane (-Z Mast)	NA	5.14	NA	NA
4	Mast Bending in Vertical Plane	5.22	5.23	5.27	5.30
5	Mast Bending in Vertical Plane (some twist on –z mast)	7.47	7.50	7.55	7.50
6	Mast 2nd Bending (only mast tips measured)	7.75	7.84	7.75	7.84

SAIL IN-VACUUM EXCITATION METHOD VALIDATION TESTS

In addition to the baseline tests which used a magnetic exciter technique for obtaining modal dynamics results for model correlation, there was also interest in evaluating other excitation methods that could potentially be used in future on-orbit test programs. In particular, three techniques were evaluated on the 20-m system at Plum Brook that included the piezo stack actuators at the mast root, spreader bar excitation at the mast tip, and bi-morph excitation on the sail cords with Macro Fiber Composite (MFC) piezoelectric patch actuators[8].

The first tests evaluated how well the piezo stack actuators at the mast root could excite system modes in-vacuum on quadrant 3. The two masts supporting quadrant 3 were excited in-phase and the system response was measured at 5 sail locations and two mast tip locations on each mast. Then the test was repeated by driving the masts out-of-phase. The method for driving the masts in-phase was to drive the MFCs on the upper longerons of each mast with the same input sine sweep signal. The method for driving the masts out-of-phase was to drive one mast actuator at the lower longeron, while driving the other mast at the two upper longeron locations with the same input sine sweep signals. It was found that piezo stack excitation at the mast root could excite the fundamental system level modes that are "mast dominated" very well, while the local sail membrane modes were not well excited. There was good response on both the sail and masts for these "mast dominated" modes, and as seen in Figure 12 the FRFs and coherences were excellent across the entire frequency spectrum. The identified modes, shown in Figure 13, matched those identified with the baseline magnetic excitation techniques very well.
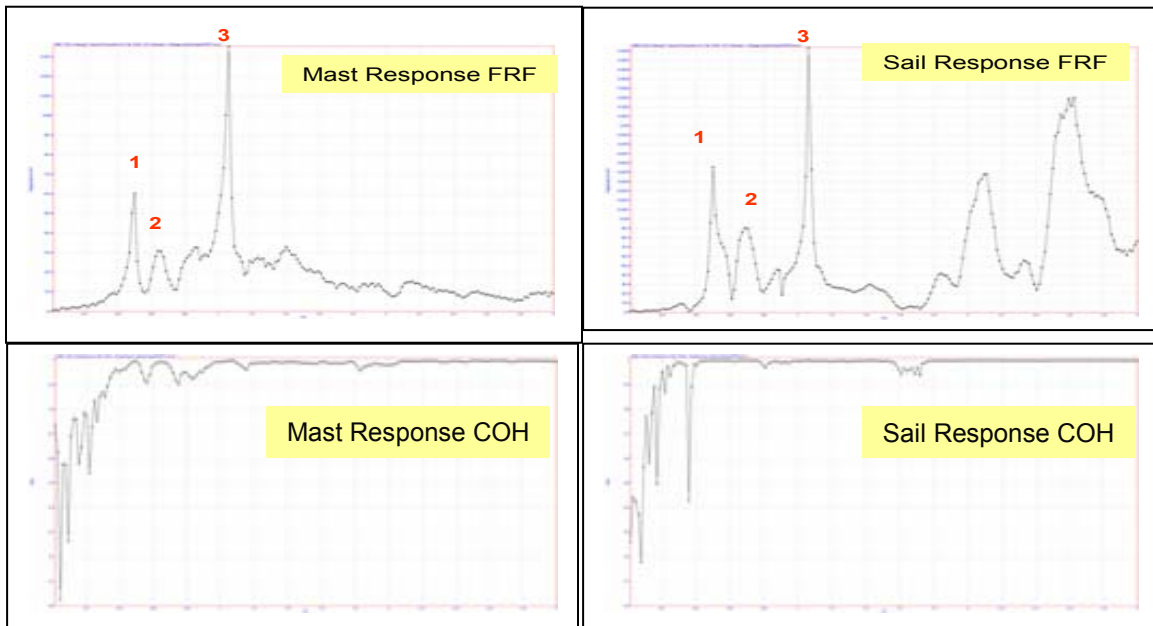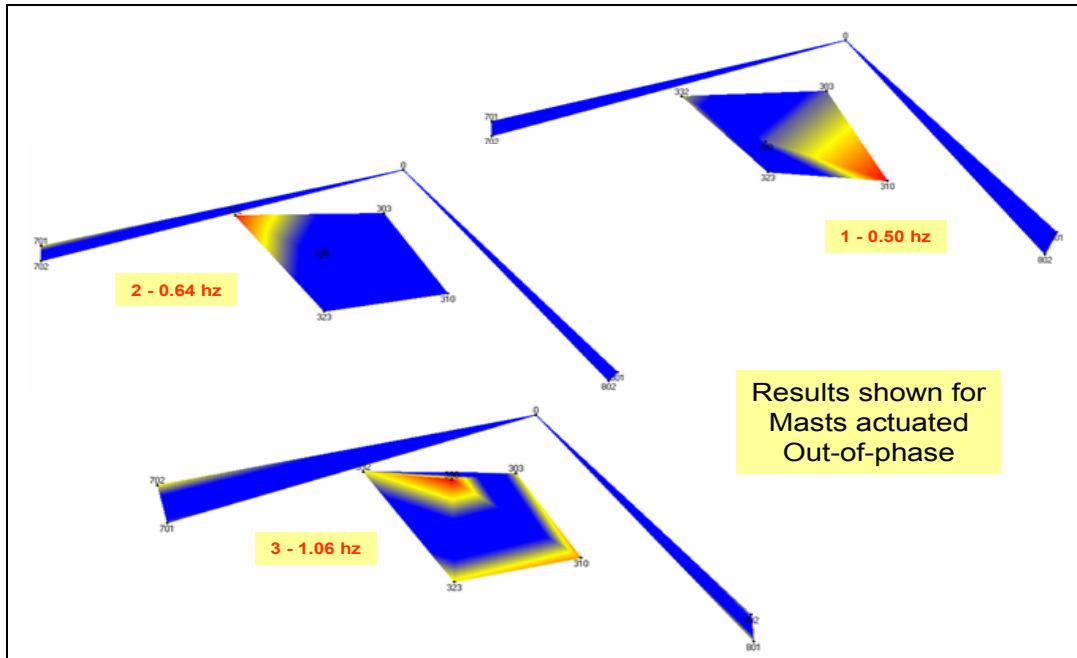

Figure 12. Sail Response In-Vacuum due to Piezo Stack Excitation at Mast Root

Figure 13. Sail ODS Modes due to Piezo Stack Excitation at Mast Root

Next the spreader bar (see Figure 14) excitation method was evaluated. This was done by driving one spreader bar for quadrant 3 with a sine sweep motion of various amplitudes. For these tests the spreader bar configuration was set at 22.5 degrees and required an eccentrically mounted mass to off-load the sail weight from the spreader bar. This eccentrically mounted mass interfered with the test objectives of evaluating how well the modal dynamics could be excited, as it caused a major swinging motion at the mast tip and interfered with the smooth sine sweep motion we were attempting to achieve. The tests did show that a significant motion of the system with spreader bar rotation is possible, but an improved setup would be required to properly evaluate system modal dynamics. However, it was felt that this technique would provide similar excitation capability to that found with the magnets and should be able to capture similar modes to those found with the magnetic exciters mounted at the halyard corners. Concerns about free-play and slop in the gears is still a concern and need further study.

Figure 14. Spreader Bar at Mast Tip

The third technique evaluated was using a bi-morph MFC patch actuator to provide out-of-plane excitation at various positions on the cord of quadrant 3. This technique was successfully demonstrated on a 10-m sail[6,9]. Figure 15 shows the new MFC design, which is

longer and narrower than the previous MFC design used in experiments documented in reference 9. The new MFC design was created to better fit the narrow cord on the sail. This new design was first validated to work during the 10-m sail quadrant dynamics tests documented in reference 6, and the MFC performed well in-vacuum with a cord loading of 2.5 lbs. The MFC technique has advantages over the other methods, in that it is the only one that allows for the actuators to be strategically positioned anywhere along the sail cord for exciting just about any mode desired. This is a very attractive capability, for as was demonstrated earlier the magnets at the halyards could not properly capture 2nd and 3rd order bending modes along the quadrant hypotenuse "long cord". This limitation would also apply to a fully functioning spreader bar exciter methodology. However, it was found during the 20-m system tests with the "new" MFC that the 6 lbs. cord load (due to gravity) severely restricted the MFC actuation performance, and that a redesigned actuator properly sized for this higher loading condition would be required to get good excitation. On a flight test program, studies should be conducted to optimize the MFC size for the loading conditions expected if this excitation method is used. Sail cord loading is significantly less (~0.5 lbs.) in a true on-orbit flight configuration that is free of gravity, so it is fairly simple to size the bi-morph MFC concept for this condition. So to summarize, the "new" MFC design has already been validated to work at 2.5 lbs. cord load on a 10-m sail, but not at 6 lbs. cord load on a 20-m sail. It should also be noted that the original MFC design (reference 9), which is shorter and wider with more piezo fibers than the new concept, did properly excite a 10-m sail with cord loadings at 1.5, 3, and 5 lbs. So perhaps this original MFC design would have been more appropriate for the 20-m sail which undergoes high cord loading due to gravity.
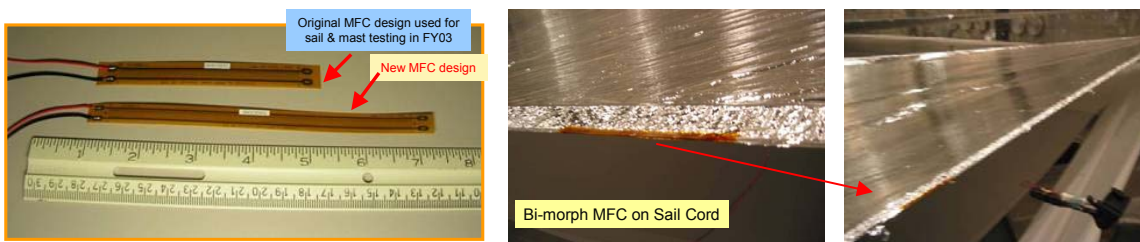
Figure 15. New MFC Piezo Patch Actuator used on Cord of 20-m Sail

SUMMARY AND CONCLUSIONS

The 20-meter solar sail dynamics test program performed at the Plum Brook vacuum chamber facility was successfully completed with all test requirements met on time and schedule. Most importantly, the fundamental sail system modes needed for model correlation activity were identified with high confidence. In addition, higher order sail membrane modes were identified through a combination of many tests on each quadrant. The mast fundamental modes, critical for model correlation, were also identified using an innovative excitation technique suitable for flight-testing. Also, various excitation techniques were evaluated for in-vacuum dynamic tests. These techniques were shown to have promise, and recommendations for further study are made for incorporation into future test programs.

ACKNOWLEDGMENTS

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