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Structural Dynamics Experimental Activities in Ultralightweight and Inflatable Space Structures

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Structural dynamics will play a major role in the design and eventual in-space deployment and performance of future ultralightweight and inflatable space structures (gossamer spacecraft). To date, there are no standardized test methods for validating the structural dynamic behavior of this class of structures. Many factors combine to make such tests unusually difficult, including facility size limitations, gravity and air effects, low natural frequencies, nonlinearities, and the need for nontraditional structural measurement approaches, which generally must be noncontacting, optical methods. Original structural dynamics experimental activities with gossamer structures conducted at three NASA centers (NASA Langley Research Center, NASA Marshall Space Flight Center, and NASA Goddard Space Flight Center) are summarized. Nine aspects of the work are covered: 1) inflated, rigidized tubes, 2) active control experiments, 3) photogrammetry, 4) laser vibrometry, 5) modal tests of inflatable structures, 6) in-vacuum modal tests, 7) tensioned membranes, 8) deployment tests, and 9) flight experiment support. The test articles are individual components or prototypes of future gossamer space structures, such as inflatable antennas and solar concentrators, solar sails, membrane sunshields, and lightweight solar arrays.

Introduction

NASA is focusing renewed attention on the topic of large, ultralightweight space structures, also known as gossamer spacecraft.[1,2] New materials and new structural concepts, including inflatables, offer the possibility of creating space structures that are orders of magnitude larger and/or lighter than existing ones.[3] This technology can enable many new classes of missions within the next 5–30 years, such as space observatories with collectors 30 m or larger in size with submillimeter surface accuracy, solar sails 100 m or larger in size with areal densities of less than 5 g/m^2, orbital transfer vehicles with large inflatable concentrators for solar thermal propulsion, next-generation space telescopes with large membrane sunshields for passive cooling, space solar power collectors and transmitters that are hundreds or even thousands of meters in size, and inflatable habitats for the International Space Station or for future lunar and planetary exploration.

A predominant design factor for future ultralightweight space structures is their dynamic response to self-generated and environmental loads. Therefore, structural dynamics and vibration control technologies will play a major role in the development and performance of these systems. Analysis methods for predicting the structural dynamic response of gossamer spacecraft are mostly unproven.[4,5] Ground and flight tests of prototype hardware are required as soon as possible to validate the accuracy and sufficiency of analytical methods for this new class of structure.

Initial experimental work along these lines has been accomplished recently at NASA Langley Research Center (LaRC), NASA Marshall Space Flight Center (MSFC), and NASA Goddard Space Flight Center (GSFC). Because of the uniqueness of the structures being tested, experiments conducted to date generally have required as much effort in developing the test methods as in acquiring test results. Test procedures used for traditional aerospace structures are often not applicable. Therefore, the results presented in this paper are pathfinder accomplishments, to be undoubtedly followed by improved experimental methods and facilities in the months and years ahead.

This paper discusses nine examples of structural dynamics experimental activities with gossamer-related structures. Each NASA center contributed three examples. Topics from LaRC are inflated, rigidized tubes; active control experiments; and photogrammetry. Topics from MSFC are laser vibrometry, modal tests of inflatable structures, and in-vacuum modal tests. Topics from GSFC are tensioned membranes, deployment tests, and flight experiment support. There is considerable synergism and overlap between these nine topics, and related efforts in several areas occurred at more than one location.

Structural Dynamics Experimental Activities

Inflated, Rigidized Tubes (LaRC)

LaRC, in cooperation with the Jet Propulsion Laboratory (JPL) and the Department of Defense, is developing a database of measured structural characteristics of inflated, rigidized tubes suitable for space application. These tubes can serve as primary load-bearing members for many gossamer concepts, such as large space solar power satellites.[6] LaRC conducted static load tests on each tube to measure its axial stiffness, bending stiffness, and buckling resistance.[7] Most test articles for the program have a length-to-diameter ratio L/D of approximately 10, with diameters of approximately 10.16, 12.70, or 15.24 cm. Two long tubes with an L/D of 100 (15.24-cm diam) were also tested for comparison with short tubes of similar construction.

To supplement the static test results, vibration tests were conducted on some of the tubes. Figure 1a shows a set of eight 10.16-cm-diam inflated, rigidized, composite tubes that were tested in a cantilevered configuration as shown. Figures 1b–1d show the

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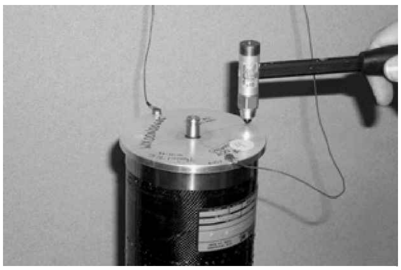
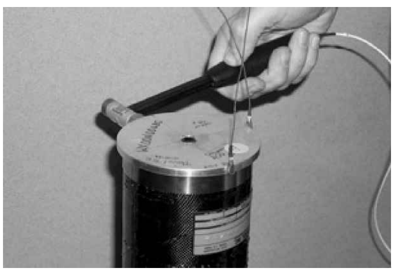
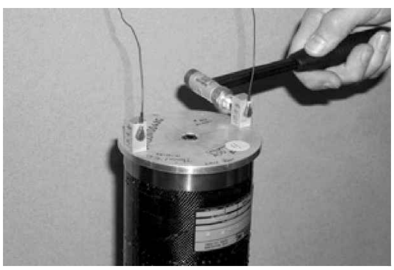
a) Test articles and aluminum calibration specimen



b) Axial test

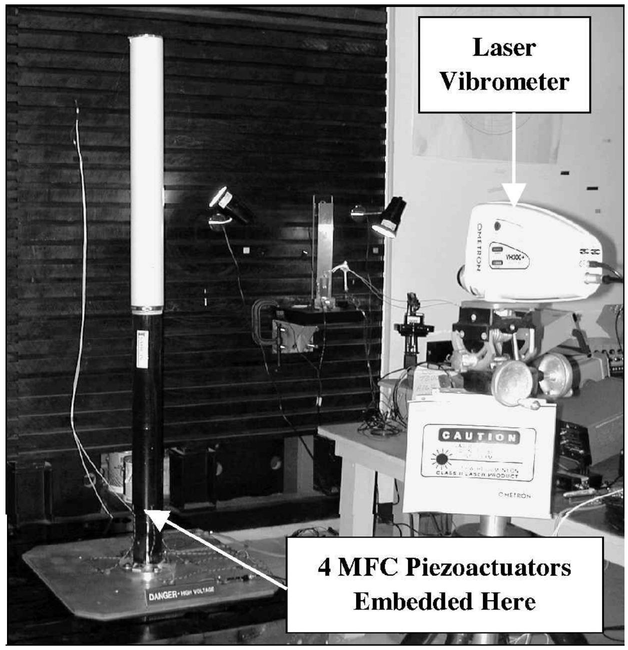


c) Bending test

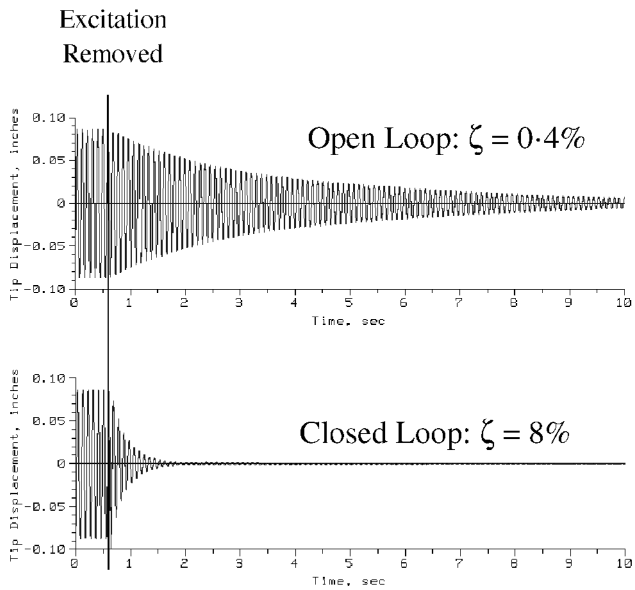


d) Torsional test

Fig. 1 Vibration tests of cantilevered inflated, rigidized tubes at LaRC.



a) Test configuration



b) Open-loop vs closed-loop free decay desponse

Fig. 2 Active vibration control experiment at LaRC.

approaches used for exciting and measuring axial, bending, and torsional vibration with tip impact excitation and two miniature accelerometers. The main objective of the tests was to calculate the effective Young's modulus E and shear modulus G of each tube from the experimental natural frequencies. To validate the testing and data analysis procedures, several aluminum "calibration specimens" (with known E and G) were also tested. Figure 1a also shows one of the calibration specimens. In each test, data were acquired with varying amounts of added tip mass ranging from 10 to 500 g. Figure 1b shows an example of an added mass. Acquiring data sets with varying tip mass provided a consistency check of the calculated structural properties under several inertial loading conditions, increasing confidence in the identified structural parameters of the tubes.

This test program measured structural parameters for many leading types of tube materials and concepts. The effects of rigidization technique, manufacturing procedure, and the method of packaging for launch were examined, all of which can significantly affect structural performance. The resulting database provides validated structural parameters for gossamer spacecraft designers.

Active Control Experiments (LaRC)

Figure 2 shows a proof-of-conceptactive vibration control experiment conducted at LaRC. The objective was to demonstrate that the damping of the first bending mode of the structure could be increased to at least 5% of critical damping using embedded piezoactuators. The test article is a 0.914-m, 10.16-cm-diam, inflated, rigidized composite tube (the lower, dark-colored tube in Fig. 2a) with embedded actuators. Before inflation and curing, the tube was flattened and then z folded like an accordion as tubes of this type can be folded for launch. A 0.914-m piece of white plastic pipe was attached to the top of the composite tube as a dummy mass, lowering the bending frequency to the desired value of 10 Hz to simulate the fundamental vibration frequency of a proposed mission.

Four 5.72 × 8.57 cm piezoelectric patch actuators are embedded in the wall of the composite tube near its base at 90-deg intervals around the circumference. These piezoactuators were developed at LaRC and are called macrofiber composite (MFC) actuators.[8] They use the d_{33} direction of the piezoelectric material to achieve a response that is about twice as high as the response in the more commonly used d_{31} direction (500 vs 250 microstrain/kV · mm). Additional features of the MFC actuator are its high maximum free strain level (∼2000 microstrain peak-to-peak), directional strain capability, and high flexibility and durability.

For active vibration control, the experiment used a basic analog feedback circuit with gain adjustment. The feedback signal is the fore–aft vibration velocity of the tube measured with a laser vibrometer. Only the front and rear piezoactuators are used, and they are wired out-of-phase electrically to work together in bending. Figure 2b shows the open-loop vs closed-loop free-decay vibration response of the tip of the beam. Without control (open loop), the natural damping of the first bending mode is 0.4%, corresponding to a free-decay vibration period greater than 10 s. With control (closed loop), the damping increases to 8%, a factor of 20 increase, corresponding to a free-decay vibration period of only 1 s. The use of digital controllers enables even higher damping levels to be obtained.

Supplementary studies examined the effectiveness of piezoactuators for static shape adjustment of gossamer structures. These actuators can be used to remove unwanted shape distortions of a structure before it rigidizes in space. Other supporting work included better definition of actuator performance in a simulated space environment. Although piezoelectric patch actuators have performed with good success in several previous aeronautics applications (e.g., to twist helicopter blades or reduce buffet loads in aircraft tails[9]), the harsh space environment poses new design and implementation challenges for their use.

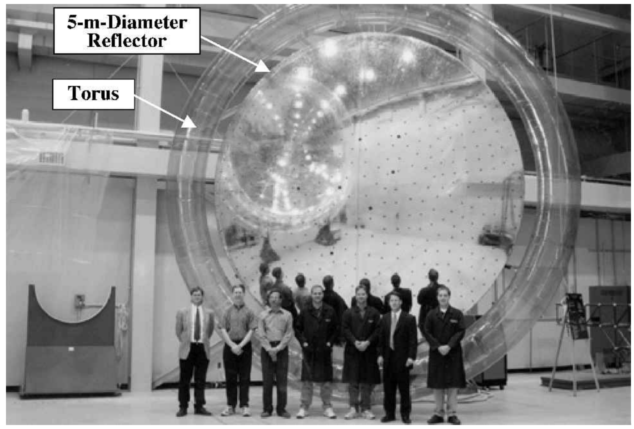
Photogrammetry (LaRC)

Photogrammetry is the science of calculating the three-dimensional coordinates of physical objects using photographs.[10] It is useful for measuring the static shape and/or motion of future ultralightweight and inflatable space structures. This technology combines the simplicity of taking photographs with good to excellent measurement precision. With time series of images (typically from video cameras), the technology is referred to as videogrammetry or videometrics and is used in many diverse engineering applications, such as to measure the deformation of aircraft wings in wind tunnels.[11] Research is underway at LaRC to apply photogrammetry and videogrammetry to gossamer space structures. Techniques are needed for measuring structures in both air and vacuum environments in one or more of the following three conditions: stationary, vibrating, and deploying.

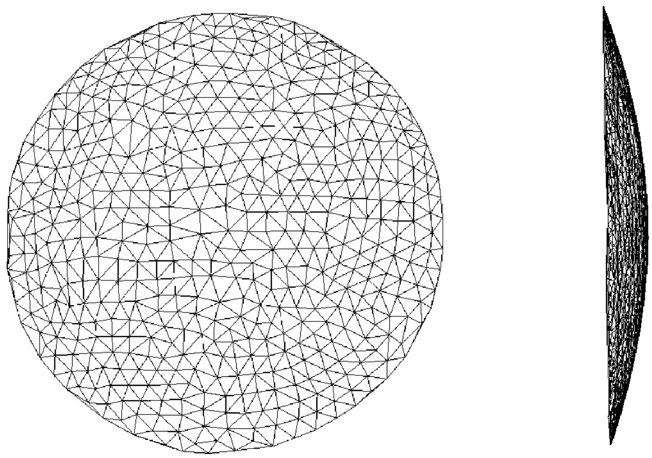
Figure 3a shows one of the test articles recently used in this research. This prototype structure is a 5-m-diam inflatable parabolic reflector attached with thin cords at its perimeter to an inflatable Kapton® torus. The total mass of the structure is approximately 4 kg. SRS Technologies of Huntsville, Alabama, manufactured this structure for NASA in 1996 under a research and technology development contract. In space, this concept can serve as either a radio-frequency antenna or as a solar concentrator for electrical power generation and/or propulsion. The photograph shows the rear, convex surface of the reflector, which is covered with more than 500 retroreflective targets for photogrammetry. The other side of the antenna (not visible) has three struts arranged in a tripod configuration for holding the antenna feed. In this work, the struts attach to a stiff support frame.

The static shape of the reflector was measured in the initial investigation. There were two main research objectives: to determine the photogrammetric measurement precision obtained using multiple consumer-grade digital cameras and to gain experience with new photogrammetry software packages. Photographs were taken from four different positions using four separate 2.1-megapixel consumer digital cameras. Using four different cameras simulated the future objective of measuring vibrating or deploying gossamer structures with multiple, time-synchronized cameras. To minimize air currents, the tests were conducted (at room temperature and pressure conditions) inside a 16-m-diam vacuum chamber at LaRC. Details of this project are documented elsewhere.[12]

Figure 3b shows the final results of the photogrammetric calculations. The software calculated this dense wireframe model using



a)



b)

Fig. 3 Photogrammetric measurement of 5-m inflatable antenna/solar concentrator at LaRC: a) test article and b) front and side views of photogrammetrically determined three-dimensional model of reflector surface.

Table 1 Measurement precision in millimeters for 521 targets on the antenna reflector surface

Direction	Minimum	Maximum	Mean	Standard deviation
X (horizontal)	0.076	0.584	0.229	0.102
Y (vertical)	0.381	1.041	0.457	0.102
Z (out of plane)	0.940	2.845	1.321	0.610
Root sum square	1.016	3.073	1.422	0.635

the photogrammetrically obtained three-dimensional points. With a least-squares analysis, the best parabolic surface representing the complete set of 521 measurement points was calculated. The focal length of this parabolic surface was 3.050 m, which compares closely with the design focal length of 3.048 m. The root-mean-square deviation over the entire 5-m-diam reflector surface from an ideal parabolic shape was approximately 1.5 mm.

Table 1 shows the corresponding measurement precisions of the calculated three-dimensional points at a 95% probability (2-sigma) level. This information is a byproduct of the photogrammetric calculations with the Bundle adjustment method (see Ref. 10). (Note that these precision values are good estimates of accuracy if systematic and gross errors are negligible.) The overall measurement precision is summarized by the mean values for each direction. The X direction is horizontal, Y is vertical, and Z is longitudinal. The cameras photographed a 6.5-m-wide test article, including the torus; therefore, these mean precision values correspond to 1:28,000 (1 part in 28,000) in the X direction, 1:14,000 in the Y direction, and 1:5000 in the Z direction. Additional tests conducted on the 5-m antenna showed that these precision values could be somewhat improved, as expected, by increasing the number of camera locations and/or the image resolution.

Laser Vibrometry (MSFC)

A laser vibrometer is a sophisticated instrument that measures the component of surface vibration velocity in the direction of the laser beam at any point on a structure that the laser illuminates. Laser vibrometry is a mature, though costly, measurement technology.[13] The vibrometer used at MSFC is a scanning vibrometer system, which can scan from point to point on the structure by moving internal mirrors under computer control. The obvious and primary benefit that a vibrometer provides is noncontacting response measurement. This approach avoids the undesirable mass-loading effects of traditional accelerometers. Even the added mass and stiffness of accelerometer cables can appreciably affect the dynamic response of an inflatable structure. This section discusses various experimental methods developed and used at MSFC over more than three years of testing ultralightweight and inflatable space structures with a laser vibrometer system.

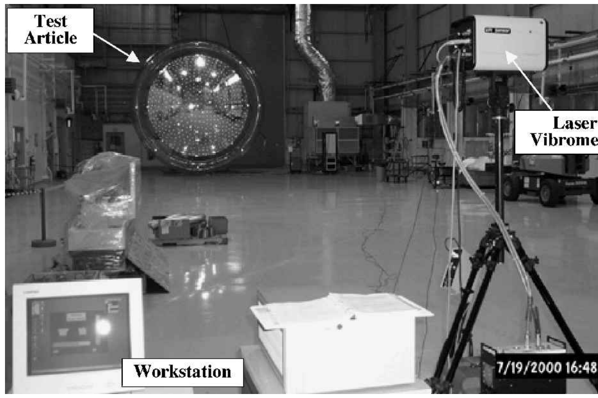
Figure 4a shows one laser position used in a recent modal test of the 5-m inflatable antenna/solar concentrator at MSFC.[14] (The structure was moved to LaRC following this modal test.) Note that the vibrometer can operate at long distances from the test article. Additional measurements were also made with the vibrometer at other locations relative to the structure. Figure 4b shows how the structure was excited with an electrodynamic shaker attached to one of the three struts. A dynamic force level of less than 1 N is sufficient to excite vibrations that are easily measured with the vibrometer. Figure 4c shows one of the mode shapes identified in the test.

The vibrometer system can be operated remotely via a serial computer interface. This capability was required in the modal test of an inflatable structure located inside a vacuum chamber. The vibrometer cannot operate in vacuum and had to be outside the chamber. At this facility, only one porthole was available to view the structure. This porthole was in a very inaccessible location. The solution was to place only the vibrometer and a minimum amount of test hardware near the porthole and to control the vibrometer with a personal computer located about 7 m away via the serial interface. (All inflatable structure dynamic tests have used this computer interface, including those that had no restrictions on where the vibrometer could be located.)

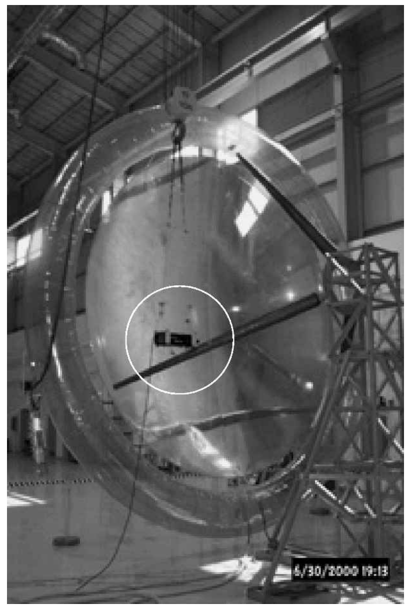
All of the inflatable structures tested at MSFC have been primarily constructed of thin-film materials that are transparent. A laser vibrometer must detect some reflected laser light from the structure to make the measurement, which will not occur if it is too transparent. Problems can also occur if the surface is too reflective, in which case all nonperpendicular laser beams deflect entirely away from their source. To circumvent this problem, retroreflective targets have been used in every modal test. A small section of adhesive retroreflective tape, approximately 1×1 cm, is attached at each response point. Such small pieces of tape, which are only 100 μm thick, have little effect on the structural dynamic response characteristics and have been used for tests with up to 60 response points. Small pieces of retroreflective tape have also often been placed perpendicular to the surface to permit measurements to be made in directions parallel to the surface of the structure. These perpendicular pieces of tape serve as "corner cubes." Of course, consideration must always be given to potential damage of an ultralightweight or inflatable structure when removing any type of surface preparation, especially for thin membranes.

For testing small subcomponents of inflatables or ultrathin membranes, the application of any reflective tape as a surface preparation could unacceptably alter the structural response. Other methods may need to be investigated to obtain adequate laser return signals. For example, to test ultrathin membranes, reflective tape could be avoided completely if the test article were constructed of an opaque material. (A diffuse white surface is best.) Selecting a specific type of membrane material to simplify making the vibration measurements may be feasible in certain research tests. A diffuse sprayed-on paint coating could also possibly be used. In this case, only a small area near each response point would be sprayed by carefully masking the surrounding area.

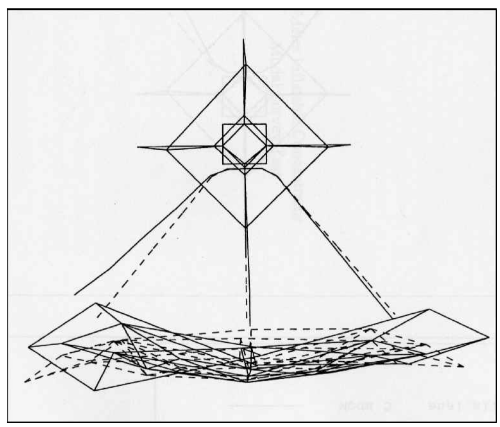
Another practical factor to consider is measurement errors that occur when the laser beam is not aligned with a coordinate axis of the structure. Recall that the vibrometer measures only the component of velocity in the direction of the laser beam. Positioning the vibrometer to be parallel with each coordinate axis at every response point is impractical for large structures with numerous points. These off-axis errors have been addressed using two different methods. The first method approximates the vibration component in the desired axis by multiplying the measured vibrometer response data by the appropriate direction cosine, which is a good approximation if the angle between the laser beam and the coordinate axis is relatively small, or if the motion at the measurement point is predominately in the direction of the coordinate axis. The other method is to position



a) Test configuration



b) Electrodynamic shaker on strut



c) Top view of identified bending mode at 4.17 Hz

Fig. 4 Modal test of 5-m inflatable antenna/solar concentrator using a scanning laser vibrometer at MSFC.

the laser vibrometer a long distance from the structure, aligned in the axis direction. The difficulty here is that the test requires a vacant facility substantially larger than the test article. Also, at long distances, it can be difficult to see the measurement targets at some locations. Another practical problem that occurs in many tests it that it is difficult to locate the vibrometer along one or more of the coordinate axis. For example, in the 5-m antenna modal test shown in Fig. 4, the vibrometer could not be easily located above the structure to measure the vertical component of vibration.

To allow three-dimensional velocity measurements to be obtained more easily and accurately with the vibrometer, MSFC recently purchased a commercial laser vibrometer interface (LVI). This package integrates with an existing suite of software that MSFC uses for large modal tests. The LVI controls the scanning of the laser, and coupled with the existing software, calculates frequency response functions (FRFs). To obtain FRFs along each axis, vibrometer measurements must be acquired for the same set of response points using three or more noncoplanar vibrometer locations. The LVI uses these data sets and least-squares analysis to calculate FRFs corresponding to each coordinate axis. Of course, if the measurements do not contain sufficient information in one of the axis directions, then the resulting data for that axis may be noisy.

Modal Tests of Inflatable Structures (MSFC)

MSFC has conducted modal tests of five full-scale inflatable structures ranging in size from approximately 2 to 6.5 m, as shown in Fig. 5. All of the structures were torus-supported concentrators with application to solar thermal propulsion systems or radio transmitter/receiver systems (antennas). These modal tests have been fully documented in test reports, and several have been described in technical papers and in a recently published book on gossamer spacecraft.[15–17] This section discusses some of the experiences and lessons learned in conducting the modal tests of these unique inflatable structures.

Both free–free and fixed-base boundary conditions have been used. In free–free tests, low-stiffness springs suspended the smaller inflatable concentrators for modal testing (Figs. 5a–5c). These springs had the lowest practical stiffness to minimize the suspension natural frequencies. However, there was still considerable coupling between the suspension system and the low-frequency test article dynamics. An alternative approach that MSFC is considering uses a commercially available active/passive suspension system that has been used successfully elsewhere, for example, at LaRC, for modal tests of a variety of heavier space structures. Those tests achieved vertical suspension frequencies on the order of 0.2 Hz, which closely approximates the unconstrained boundary conditions of Earth orbit. When suspending much lighter inflatable structures, however, the same system may not be able to achieve such good low-frequency performance due to the practical difficulty of removing all residual friction in the device.

The last two modal tests used fixed-base boundary conditions. Both inflatable structures were supported by three composite struts, and the ends of the struts opposite the torus and lenticular were connected to a circular interface plate using several bolts, nuts, and brackets. In the first test, shown in Fig. 5d, the interface plate was bolted to the floor with the struts cantilevered from it. However, the identified mode shapes showed that cantilevered conditions were not achieved. The excessive response was attributed to free play in the connection hardware. With lightweight structures, joints are more lightly loaded than with heavier structures so that free play can be more of a problem. In the second test, shown in Fig. 5e, the three struts connected to a fiberglass support stand. There was no pretest analytical model of the combined test article and stand, and so it was unknown if the test article dynamics would couple with the stand. Therefore, the stand and struts were instrumented with accelerometers. The identified mode shapes showed that the fixture was stiff enough to provide fixed-base boundary conditions for the first five modes. When good pretest analytical predictions are not available, the support fixture is included as part of the structure under test.

Space inflatables will use membrane materials that are only tens of micrometers or less in thickness. Their internal pressures will generally be as low as possible to minimize membrane stresses. These two conditions cause extremely low local stiffness, or, in other words, extremely high local flexibility. Therefore, applying a dynamic excitation force directly to an inflated component will typically produce insufficient forces for modal testing due to the high local flexibility. In all of the tests conducted at MSFC, an electrodynamic shaker was attached to a noninflated component such as a metal interface plate or a composite strut. Even in these cases, however, much smaller force levels than typically encountered in modal tests occur. Therefore, high-sensitivity load cells are used with inflatable structures. These sensors are 50 times more sensitive than those used in most other modal tests. Higher sensitivity allows better

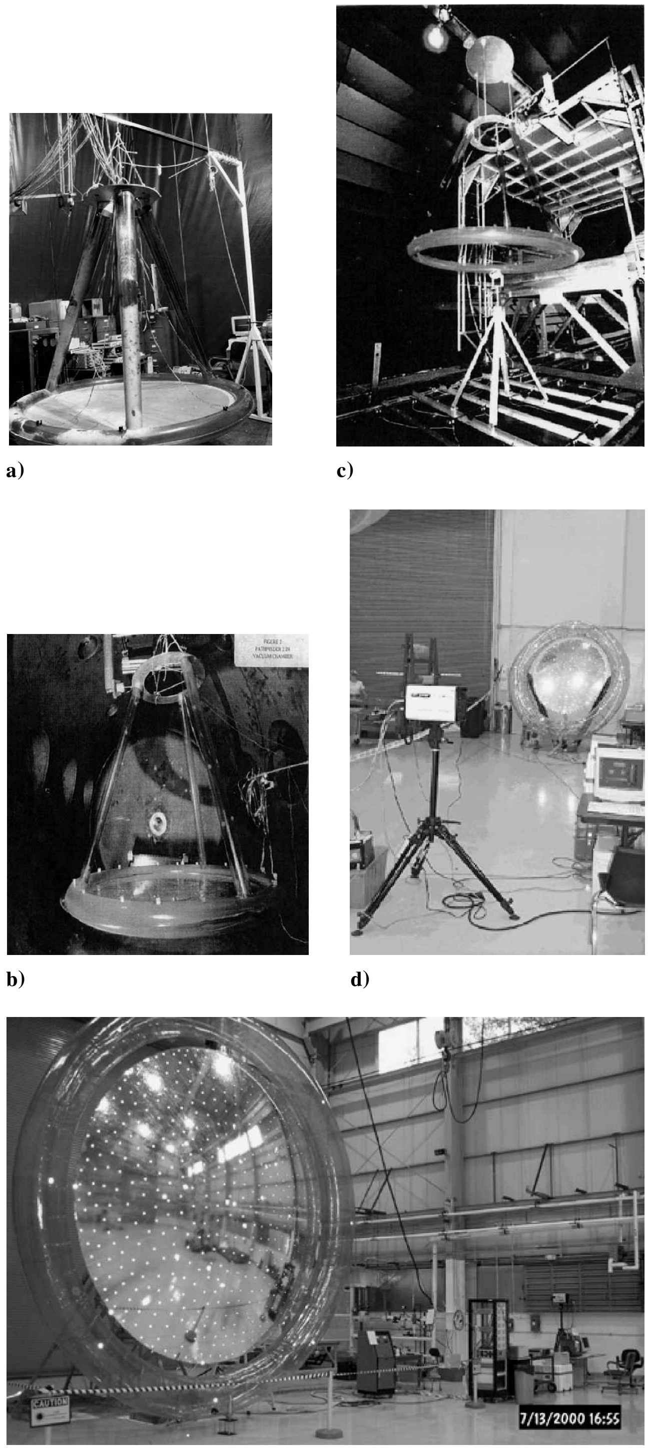


Fig. 5 Five inflatable solar concentrators tested at MSFC: a) Pathfinder 1, June 1997; b) Pathfinder 2, Oct. 1997; c) Pathfinder 3, Oct. 1998; d) TSC-6 2 × 3 m antenna, Aug. 1999; and e) antenna (5 m), July 2000.

resolution of smaller forces, which in turn allows better calculation of the FRFs.

The dynamics of lightweight inflatable structures are undesirably affected to some degree when using attached shakers. In the modal test of the 5-m antenna, for example, selection of the shaker location along the length of the strut was found to affect the resulting mode shapes of the structure significantly. With the shaker at approximately the center of the strut, the modes were far from being symmetric, whereas by moving the shaker closer to the end of the strut where it is stiffer, the modes became more symmetric and reasonable. Both MSFC and LaRC are investigating alternative methods of exciting inflatable structures for modal tests, in particular, using piezoelectric actuators bonded to the surface of the test article.

The extremely low weight and stiffness of inflatable structures make them particularly sensitive to extraneous disturbance forces, which can corrupt the dynamic response measurements. To date, all inflatable structures tested at MSFC have required a continuous resupply of gas to maintain a constant pressure due to leaks around seams or small holes. The flow of gas itself into and out of an inflatable is a source of unmeasured, extraneous dynamic excitation. In the test of the 5-m structure, the pressurization system could not be turned off long enough to acquire a complete set of FRFs at each response point without the structure deflating excessively. Therefore, data sets with both the air supply turned on and then off could not be obtained to assess the effects of this dynamic disturbance source. Other disturbances that must be minimized when testing inflatable structures include those from nearby vibration and acoustic sources, such as the ambient airflow in the laboratory from air conditioning systems.

The subject of nonlinear dynamic response is another important factor for inflatable structures. Considerable information exists on the analytical aspects of the nonlinear structural response of inflatables. However, there is not yet much corroborating experimental data available. In early tests at MSFC, sinusoidal sweeps were performed to identify those force levels that produced linear response of the structure and the force levels of greater magnitudes that produced nonlinear response. A significant result of these tests is the identification of the bifurcation process, which is the splitting of one mode into two at increasing force levels. Another result of these tests is the conclusion that the response of an inflatable due to any force level can be described as being chaotically modulated.[18]

In-Vacuum Modal Tests (MSFC)

Thin-film membranes vibrating in air will have lower natural frequencies and higher damping than when in vacuum conditions.[19] Therefore, modal vibration tests of these structures are conducted in vacuum chambers to approximate more closely the conditions of space. Gossamer structures larger than approximately 30 m cannot be tested in vacuum because of size limitations of existing facilities. Tests in vacuum conditions of larger structures can only occur using scale-model test articles.

As mentioned earlier, most laser vibrometers are not designed to operate in vacuum, and so they must remain outside the chamber. However, good vibrometer measurements can be obtained with the laser beam passing through a glass porthole of the chamber. If the chamber has multiple accessible portholes, the vibrometer can be moved from location to location, and the resulting data sets can be transformed into three-dimensional structural response measurements at each test point using the LVI system discussed earlier.

Moving the vibrometer to multiple viewing ports may not be possible with certain vacuum chambers. For example, in the modal test of the Pathfinder 3 structure conducted in vacuum in the large X-Ray Calibration Facility (XRCF) at MSFC, only one porthole was available. Figures 5c and 6 show this inflatable structure inside the chamber and the test configuration, respectively. To acquire vibrometer data in more than one axis, the test article needed to be rotated. The test objectives also required data acquisition at three different air pressure settings. Ideally, vibration data should be measured in both orientations of the structure, holding the ambient pressure constant to ensure that the measured vibration data in each axis corresponded to exactly the same operating conditions of the chamber. However,

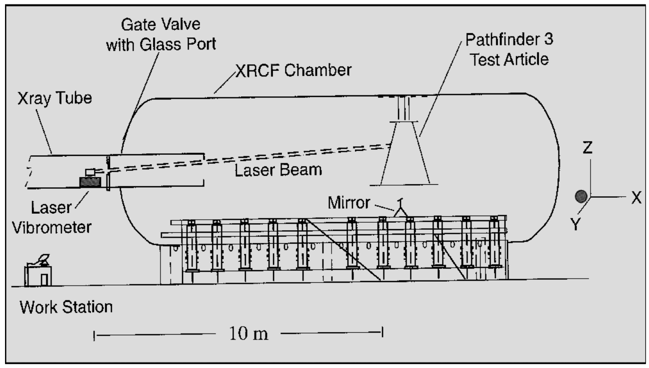


Fig. 6 Pathfinder 3 modal test configuration in vacuum chamber at MSFC.

to rotate the structure required that the chamber be depressurized, opened, then repressurized, which took more than 12 h to perform. To substantially reduce the overall testing time at some risk of data inconsistency, the decision was made to conduct the vibration tests in the first structural orientation at all three air pressures and then to repeat it for the second structural orientation. Additional details of this modal test of the Pathfinder 3 structure in the XRCF vacuum chamber are available elsewhere.[15]

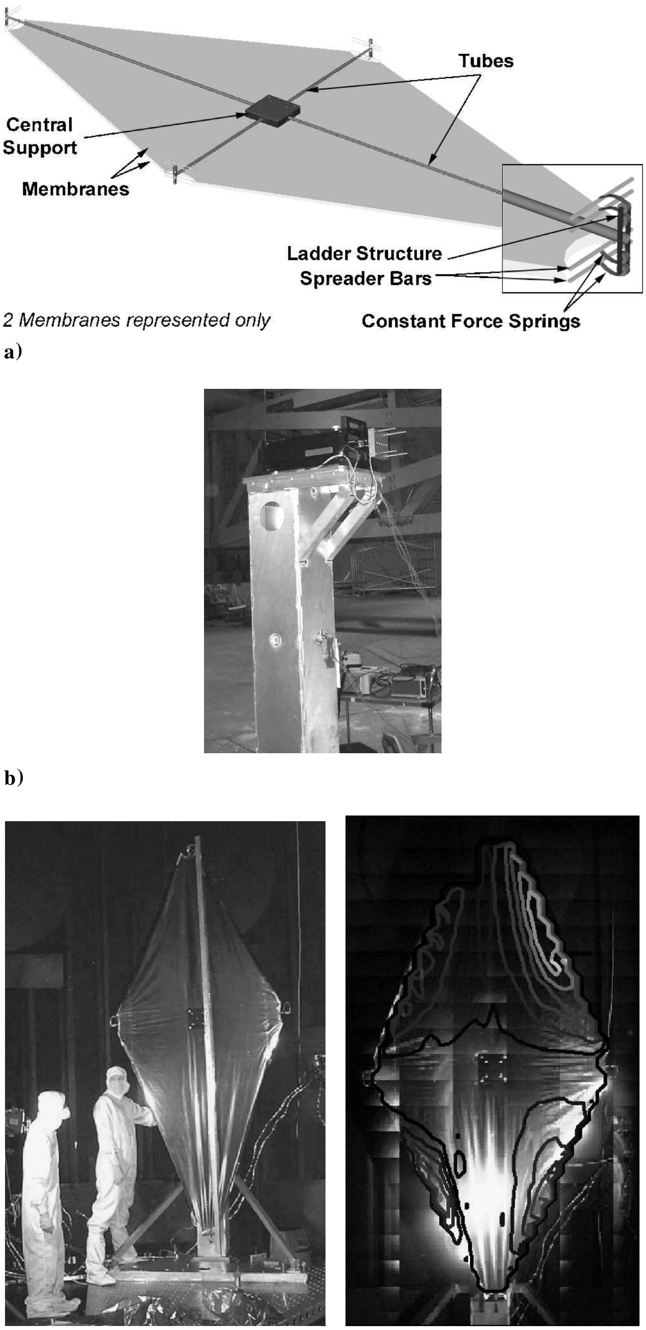
Several other potential problems can occur with modal vibration tests conducted in vacuum chambers. For example, shaker overheating could occur due to the lack of airflow that allows heat dissipation. Difficulties in supporting a shaker either by a fixture or a suspension device may also occur due to lack of space in small chambers. The application of piezoactuators for excitation of inflatable structures in dynamic tests will possibly eliminate this problem. At vacuum conditions, extraneous acoustic excitation will not occur due to the lack of air. However, some form of isolation may be required with ultralightweight structures to eliminate any unwanted excitation from structure-borne vibration that could come from vacuum pumps or other chamber machinery. Cleanliness and outgassing concerns are also often important when conducting tests in these facilities.

Tensioned Membranes (GSFC)

During the past two years, GSFC conducted two modal tests of a 1/10th-scale model of the Next Generation Space Telescope (NGST) sunshield to support structural analytical model validation. Because the sunshield surface is a thin membrane material, the tests were conducted in vacuum conditions to avoid the effects of air on the membranes. GSFC never conducted tests of this type before. Many lessons were learned during these two modal tests that are applicable to testing of other membrane structures.

Figure 7a shows the main components of the test article. They are a central aluminum mounting block, four aluminum support tubes with their corresponding tip hardware, and four membranes. The overall dimensions of the structure are 1.5×3.5 m. Each of the four membrane layers is 12.5-μm-thick Kapton film whose outer side has a reflective gold coating and whose inner side has a vapor-deposited aluminum coating. The model dimensions were selected using constant-thickness scaling laws. This approach keeps the membrane thickness the same for the full and sub-scale models. The membranes attach to the support tubes only at the corners using constant-force springs that apply a preload of 1.425 N to the membranes. The test article was oriented vertically in both modal tests to minimize gravity effects on the membranes. Tests were conducted with the long side of the membrane down and then with the short side down to compare the effects of gravity on the membrane response. A scanning laser vibrometer measured the out-of-plane vibration of the outer membrane.

The first modal test occurred in March 1999 in GSFC chamber 238, a 3.7×4.6 m vertical vacuum chamber. The sunshield was attached to a large steel block that hung from the top of the chamber by thin threaded rod. An electrodynamic shaker located outside the chamber provided the dynamic excitation with the connecting rod to the structure (stinger) feeding through a mechanical bellows in the chamber wall. The laser vibrometer system was also outside the



a)

b)

c) d)

Fig. 7 One-tenth-scale NGST sunshield modal test at GSFC: a) test article components, b) shaker location at top of support fixture, c) structure in vacuum chamber, and d) contour lines of identified mode shape at 1.8 Hz.

chamber with the sensor head positioned at a porthole to have a view of the sunshield. A drawback of this setup was that the excitation direction and the laser vibrometer line of sight could not be aligned. Also, the stinger connected to the steel block at an angle, which resulted in undesirable fixture modes being excited.

The second modal test occurred in July 2000 in the GFSC Space Environment Simulator, an 8.2 × 12.2 m vertical vacuum chamber. This test built on the lessons learned in the first test. The shaker was moved into the chamber so that the test article excitation could be better controlled. Also, a new rigid support fixture was designed whose modes of vibration were all higher in frequency than any of the sunshield modes of interest. (Sunshield modes of interest were in the range of 1–10 Hz.) The resulting setup was a towerlike fixture with an electrodynamic shaker mounted on top, as shown in Fig. 7b. The sunshield attached directly to the shaker armature with a triaxial force transducer sandwiched between them. The fixture, the sunshield central block, and the tube tips were instrumented with triaxial accelerometers. Figure 7c shows the test article and support fixture in the vacuum chamber. This larger chamber allowed the laser vibrometer, which was again located outside the chamber at a porthole, to have a field of view that encompassed the entire sunshield, which did not occur in the first modal test. To help minimize total testing costs, considerable preliminary testing was done in air outside the chamber to become familiar with the test setup and to allow the time in the chamber to be more productive.

A large amount of data was collected during almost two weeks in the chamber in this second test. The identified modes have reasonable agreement with the analytical predictions.[20] Figure 7d is a velocity contour plot of the 1.8-Hz mode from the laser vibrometer system. This is the lowest-frequency membrane mode of the short-side-down configuration. In this test series, all data were acquired at only one membrane tension level due to schedule limitations, and because the sunshield mounted directly to the shaker armature, the selected force transducer had to support a static shear load (the weight of the structure) and was, therefore, somewhat oversized for measuring the small dynamic forces exciting the lightweight membranes.

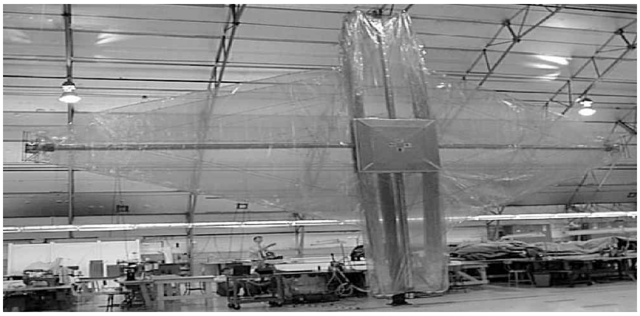
Deployment Tests (GSFC)

The in-space deployment process for a gossamer spacecraft will always be a mission-critical step. Therefore, understanding the deployment structural dynamics will typically be as important, or even more important, than understanding the postdeployment dynamic characteristics. In support of the development of the NGST sunshield, which will be a large, lightweight, multiple-membrane structure that deploys from a folded-up launch configuration, GSFC sponsored the design, manufacture, and ground deployment test of a one-half-scale model. This section discusses the test article and the deployment test, which was performed at ILC Dover, Inc. Other participants in the program were GSFC, JPL, and L'Garde, Inc. The ground test article had the following specifications: 1) one-half-scale model of NGST strawman design; 2) four membranes, two on each side of the supports; 3) 2.5-cm separation between membranes at support platform, increasing to 15.0 cm at the free edge; 4) lowest natural frequency greater than 0.2 Hz; 5) boom material of aluminum laminate, and membrane material of 12.5-μm-thick Kapton HN; 6) boom safety factor of four in Euler buckling; 7) 8-deg cant angle in the membrane ends; and 8) membrane wrinkling unimportant as long as the membranes do not touch.

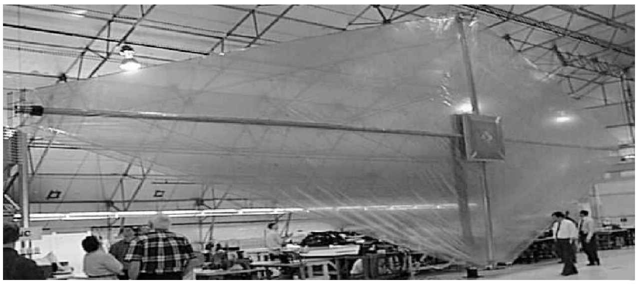
The goals of the deployment test were to evaluate the various characteristics of the deployment, such as the unfolding behavior of the membranes, the straightness and stiffness of the deployed booms, the impulse forces that would be imparted to the spacecraft, and the postdeployment system planarity. Also important was the need to verify that the packaging and deployment procedures would eliminate trapped gas and the threat of puncture during deployment.

Figure 8 shows the ground test article in both a partially deployed and then a fully deployed state. Details of the packaging and deployment sequence of the structure are as follows. The membranes were z folded in the lateral direction first, followed by the longitudinal direction, secured with membrane retainer clips, and then placed into membrane enclosures on the central container. The central container was mounted on a stiff support stand. The inflatable tubes were then attached to the container and membranes. Weight-relief lines were attached to both longitudinal tubes and the upper lateral tube. The lateral tubes were then pressurized and deployed simultaneously, after which weight-relief lines were also added to the membranes. The longitudinal tubes were then pressurized and deployed simultaneously. Finally, the tubes were depressurized. Over the course of the program, four deployments were performed.

A major lesson learned from the deployments was that the gravity effects were greater than anticipated. Longitudinal tube deflection required a vertical suspension line at the center span of the tube, and suspension lines were also added to prevent buckling in the longitudinal tubes at the low inflation pressures. The membranes tended to fall out of the folded stack during the deployment and resulted in switching from dispensing clips to a retainer dispensing design. There was also a problem with static electricity attraction between the membrane layers that was eliminated by adding a static-charge dissipative coating to the membranes.[21]



Partially deployed



Fully deployed

Fig. 8 Deployment demonstration of a one-half-scale NGST sunshield sponsored by GSFC.

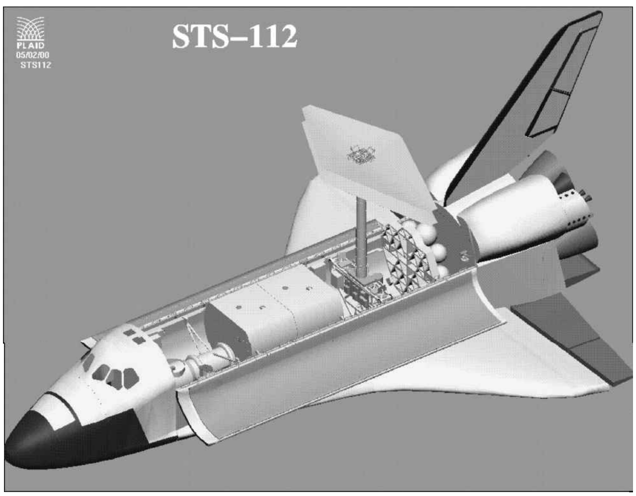


Fig. 9 ISIS experiment developed by GSFC.

Flight Experiment Support (GSFC)

Figure 9 shows the proposed Inflatable Sunshield in Space (ISIS) flight experiment, which GSFC and JPL have been developing during the past several years. Unfortunately, the ISIS experiment was recently canceled. Nevertheless, the research and development that occurred in planning and designing this flight experiment is excellent information concerning the issues that need to be addressed in any future flight experiment with large gossamer structures. This section summarizes the ISIS experiment and its structural-dynamics-related aspects.

The ISIS test article is a one-third-scale model of the GSFC strawman concept for the NGST sunshield.[22] The objectives of the experiment are to gather dynamic behavior data for a large thin-film membrane structure for analytical model correlation and to demonstrate controlled deployment and rigidization of a large inflatable sunshield in space. The experiment would provide important data on the dynamic response of such a structure in the absence of gravity and would be the first test in space of a large inflatable structure using controlled deployment.

The test article consists of a support structure and a thermal shield. The support structure is a cross-bay bridge mounted to a telescoping mast that supports a container and four inflatable booms arranged in a cross configuration. The thermal shield is four layers of 12.5-μm-thick Kapton membranes with vapor-deposited aluminum coatings. The membranes connect to the container and to the ends of the inflatable booms. Constant-force springs attach the membranes to the booms and keep the sunshield under constant tension. The inflatable, rigidizable composite booms consist of the following layers, starting with the innermost layer: a Kapton bladder for inflation, a graphite–epoxy layer that supplies the structural stiffness once heat cured in space, a Kapton outer restraint layer, and a multilayer-insulation sleeve. In the stowed configuration, each boom is flattened and rolled onto a cylinder attached to the tip hardware. Immediately before deployment, the booms are heated to approximately 20°C to soften them. During deployment, the booms inflate with nitrogen gas at 2.2×10^4 Pa, which causes the booms to unroll from the cylinders. After deployment, the booms are heated to a higher temperature, which causes the graphite–epoxy layer to cure and harden. After curing, the booms are allowed to cool down to ambient temperature. Once cooled, the nitrogen gas is vented.

Desired instrumentation for the experiment includes triaxial accelerometers, force transducers, thermistors, pressure transducers, and cameras. An encoder system conditions and digitizes the transducer signals. The digitized data are recorded on a laptop computer in the crew cabin. Triaxial accelerometers are located at the ends of the booms, inside the container, and at the base of the telescoping mast. Force transducers positioned between the container and mast measure the input force to the sunshield. Video from the shuttle cameras is recorded and photogrammetry techniques applied after the flight to obtain position information of the boom during deployment and of the outer layer of membranes during dynamic characterization tests. The space shuttle reaction control system (RCS) jets would provide the primary excitation for the experiment. In addition, some data would also be acquired during quiet times when all excitation is off.

The instrumentation selection process is more difficult for this flight experiment than for typical laboratory tests. There are additional restrictions on size, weight, and location for accelerometer placement because all instrumentation must be installed before deployment. All accelerometers must fit in the limited volume of the boom tip because the remainder of the boom is rolled up before deployment. This requirement also means that accelerometer cables must be as few in number and as flexible as possible to allow proper boom deployment. The accelerometers must also be as lightweight as possible to not mass load the boom significantly. However, small accelerometers that are sensitive enough to measure the anticipated shuttle background noise level of 10 μg are not available. Additionally, all instrumentation must survive launch loads and operate in the space environment.

Selection of the excitation source was also a difficult process. Various excitation systems and methods were investigated. We believed that designing and implementing a dedicated excitation system for the experiment was too prohibitive in cost and schedule. Analytical simulations based on preliminary impulse profile information showed that target modes would be sufficiently excited with RCS jet firings. Final simulations using more accurate impulse information have not yet been performed. Although the preliminary simulations showed that RCS excitation is acceptable, it is not an ideal situation and does have some issues that need to be addressed. The jet impulses are not as controllable as a typical shaker setup. The impulse duration must be a multiple of 80 ms, and it is not yet clear whether a pure translational input in the desired direction is possible. Also, the impulses are all at a fixed amplitude, making it more difficult to assess the linearity of the structural response.

Conclusions

Future ultralightweight and inflatable spacecraft, which will be folded and packaged for launch, will experience their maximum dynamic responses during deployment and operation in space. To date, there are no standardized ground test methods for validating the in-space structural dynamic behavior of these structures. Many factors combine to make such tests unusually difficult, including facility size limitations, gravity and air effects, low natural frequencies, nonlinearities, and the need for nontraditional structural measurement approaches, which typically must be noncontacting, optical methods. This paper discussed initial work recently conducted at three NASA centers (LaRC, MSFC, and GSFC) toward developing and conducting such ground test activities. Test articles included inflated, rigidized tubes (some with embedded piezoelectric actuators for active vibration control), several sizes of inflatable solar concentrators, and $\frac{1}{10}$th- and $\frac{1}{2}$-scale models of an NGST sunshield concept. Ground vibration tests were successfully conducted in ambient and vacuum conditions, using both laser vibrometry and photogrammetry optical measurement techniques, supplemented in some cases by traditional accelerometers. Plans for conducting an in-space structural dynamics test of a 1/3-scale NGST sunshield deployed from the Space Shuttle Orbiter (the ISIS experiment) were also summarized.

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