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ABSTRACT

The Next Generation Space Telescope (NGST) design requires a large sunshield to protect the large aperture mirror and instrument module from constant solar exposure at its L2 orbit. The structural dynamics of the sunshield must be modeled in order to predict disturbances to the observatory attitude control system and gauge effects on the line of site jitter. Models of large, non-linear membrane systems are not well understood and have not been successfully demonstrated. To answer questions about sunshield dynamic behavior and demonstrate controlled deployment, the NGST project is flying a Pathfinder experiment, the Inflatable Sunshield in Space (ISIS). This paper discusses in details the modeling and ground-testing efforts performed at the Goddard Space Flight Center to: validate analytical tools for characterizing the dynamic behavior of the deployed sunshield, qualify the experiment for the Space Shuttle, and verify the functionality of the system. Included in the discussion will be test parameters, test setups, problems encountered, and test results.

INTRODUCTION

Space inflatable technology development started in the 60's with the ECHO balloon reflectors (30m in diameter) that were put in orbit as a relay to broadcast television across the ocean. Several projects were then developed but the technology was put on hold later for material capability reasons. With the incredible progresses in material development, the technology is coming back now and it is competing with other mechanical type of structures. NASA and other private industries are putting significant resources into the development of this technology because of its wide range of applications: large reflectors, support structures for solar arrays, large antennas, sunshields, solar sails, etc. This technology is applicable and advantageous for large structures that must be lightweight and packaged in a small volume.

The government team developing the reference concepts for the Next Generation Space Telescope (NGST) has baselined an inflatable sunshield to passively cool optics and instruments. The reasons are simple: a very large aperture (32mx14m) sunshield has to be packaged in a relatively small volume (1.5x1.5x0.5m). In order to validate the concepts and reduce the risks of single point failure of sub-system, a flight experiment of a subscale of NGST sunshield (3 times smaller) has been implemented in the technology roadmap: the Inflatable Sunshield In Space (ISIS) flight experiment.[1-2]

The ISIS sunshield, in its deployed state, consists of two sub-systems: (1) the support structure and (2) the thermal shield. The support structure is composed of a container and four inflatable booms arranged in a cruciform shape. The thermal shield is composed – for ISIS – of four layers of thin film membranes (13 microns thick) made of VDA coated Kapton® attached at the root to the container and at the ends to the inflatable booms. Constant force springs at the interface between the booms and the membranes keep the shield under constant tension. References provide a detailed description of the design of the ISIS flight experiment.[3]

Constant thickness scaling laws[4] have been developed and used to dimension the ISIS sunshield keeping the thickness of the membranes constant. Besides validating technological concepts (packaging, deployment methods, film handling, rigidization process, etc), another important objective is to develop and validate numerical models representative of the dynamic behavior of the structure in the deployed state. These models will be used to characterize the performance and the stability of the NGST in space. A unique modeling technique[3] has been developed for thin film membrane systems under low tension. Ground testing methods are being elaborated as well on a smaller scale sunshield (10 times smaller than NGST sunshield) to validate the models and the modeling technique.

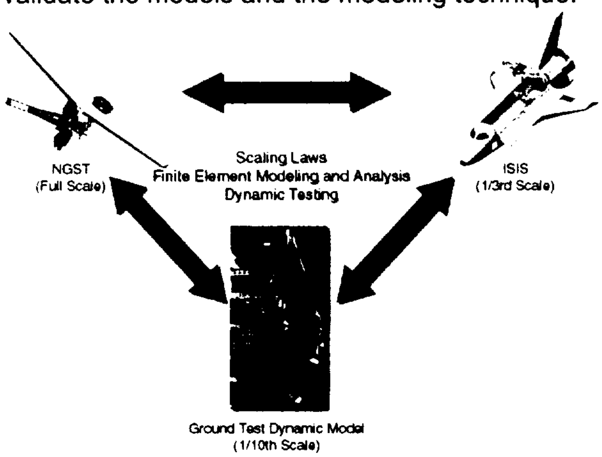

Fig. 1 Modeling, Analysis, and testing of Sunshield Concepts for the Next Generation Space Telescope (NGST).

Structural and thermal tests have been done on components to isolate their influence and to characterize their performance at the system level. The stowed configuration of ISIS has been modeled structurally and thermally to verify that the system can withstand Space Shuttle launch loads and that the inflatable booms, rigidizable with heat, will keep their soft state until they deploy. Qualification tests will be performed to verify analytical predictions as well as structural integrity of the payload. Tests and validation of deployment concepts and release mechanism have been performed in laboratory on engineering units. Objectives, models, tests, and results are presented in the following sections.

COMPONENT LEVEL ANALYSIS AND TESTING

The following sections describe component level analysis and testing performed on the ISIS inflatable booms and membranes.

Booms

The ISIS sunshield utilizes four inflatable booms for deployment of the sunshield and to provide structural support for the membranes in the deployed configuration. The four flight booms are 18, 14, and 6.5 (two booms) feet in length and have a diameter of 5.125 inches. The individual boom assemblies consist of an inflatable composite boom, its associated tip hardware, and a heat curing system. The composite booms are constructed from 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, a Kapton outer restraint layer, and an MLI sleeve. In the stowed configuration, the booms are flattened and rolled up on a cylinder attached to the tip hardware. Immediately prior to deployment, the booms are heated to approximately 20°C in order to aid their mobility. During deployment, the booms are inflated with Nitrogen gas at low pressure (3.2 psi) which causes the booms to unroll from the cylinder. After deployment, the booms are heated to a temperature range of 125 to 150°C which causes the graphite epoxy layer in the booms to cure and harden. The temperature must be maintained at this level for 30 to 45 minutes to ensure that the booms fully cure. After curing, the heaters are disabled, and the booms are allowed to cool down to ambient conditions. Once the booms cool to below 90°C, the Nitrogen gas is vented. Analyses and tests were performed to verify the thermal and structural performance of the booms and to validate analytical models. The following sections describe the thermal and structural test programs for the inflatable booms.

Thermal testing

Thermal vacuum (TV) testing of three inflatable boom segments representative of the ISIS booms was carried out to verify the thermal performance of the booms and to validate analytical models. The objectives of the thermal tests were to verify the performance of the inflatable booms in terms of the: (1) heater sizing, (2) effective emittance through the MLI (multi-layer insulation) covering the boom, (3) heat released during the graphite epoxy curing process, and (4) outgassing rate of contaminants diffusing through the boom MLI during curing. Since inflatable structures are a new technology, the tests also verified that the current boom design would inflate and cure properly while under vacuum conditions. The following sections describe the test articles, instrumentation, test setup and procedures, and test results from the thermal vacuum test program.

- Test articles

The test articles were three 11 foot long inflatable booms that represent the actual booms that will be flown on the ISIS experiment. Two of the booms will be tested in a deployed configuration, while the third boom will be tested in a stowed configuration. Except for their lengths, they are identical to the ISIS flight booms.

- Instrumentation

The temperature of the booms was measured using thermocouples and thermistors. The two deployed booms were instrumented with 51 thermocouples grouped in lots of 4 at 90° from each other along the entire length of the booms. Each of these booms was also instrumented with 3 thermistors. Nineteen thermocouples were attached to the stowed boom. A mass flow meter registered the amount of Nitrogen gas flow into the booms during inflation, and a convectron gauge measured boom pressure throughout the tests. The mass flow meter and pressure gauge were also used to monitor the leak rate as Nitrogen gas leaked / vented from the booms escaped into the TV chamber. Finally, TQCM's (Temperature-controlled quartz crystal microbalances) were used to measure the outgassing rates.

- Test setup and procedures

The thermal tests were conducted in the 12 foot vacuum chamber (Building 7, Facility 238) at NASA GSFC. The tests were divided into two phases. One deployed boom and the stowed boom were tested in each phase. The stowed boom and the first deployed boom tested were both wrapped with 7 layers of MLI blanket. For the second phase of testing, the booms were wrapped with 5 layers of MLI blanket. In each of the tests, the deployed boom was hung vertically in the TV chamber suspended from the top with low conductivity Kevlar fibers. The stowed boom was placed on the chamber floor and conductively isolated from the floor with G10 blocks. Both booms were surrounded by Kapton "tents" to prevent them from outgassing onto and contaminating the chamber walls. A scavenger plate was placed at an opening to each tent and maintained at –180°C (liquid nitrogen) to collect samples of contaminants outgassing from the booms. Three TQCM's were mounted along the deployed booms such that they penetrated the tent and had a direct view of the boom for measuring the outgassing rate during curing.

The first step in the test procedure involves pumping down the chamber. During the initial pump-down to vacuum, the deployed boom was pressurized slightly to 1 psi and leak-tested. Once under vacuum, the shroud was cooled to –80°C, and the boom was heated to 20°C. Although the –80°C sink is not a true representative of the orbit sink, it was desired to create a large gradient between the boom and the sink to promote radiative heat flow between the two. The initial 20°C boom data-point was taken to correlate the thermal model and to validate that the predicted cure heater power was accurate. At the 20°C plateau, the boom was fully pressurized to 3.2 psi and then heated up to the cure region of 125 to 150°C. The temperatures were maintained for 30 minutes to allow the cure to complete. Upon completion of cure, the heaters were disabled to allow the boom to cool down below 90°C. The boom was slowly vented to the chamber once it was below 90°C.

- Test results and model correlation

The first data point obtained from the TV tests was the 20°C plateau. This was done before the cure so that the thermal model could be correlated and the estimate of the anticipated heater power confirmed. The amount of heat required to cure the booms during the TV tests validated the thermal model and demonstrated that the heaters are adequately sized to cure the booms. The heaters were sized to deliver 0.1 Watts/in^2 of heater power to each boom while the test indicated that 0.013 Watts/in^2 was required to cure. It should be noted that the heater power for flight will not be the same as the heater power required in the TV test since the sink will be warmer on orbit and the four booms on orbit amount to more area being heated than the one test boom. However, after the thermal model from the test is correlated, it will be used in the flight model to predict the cure heater power.

Structural testing

Static and dynamic test data are required for verification of structural properties and validation of analytical models for the ISIS inflatable booms. One of the 11 foot rigidized inflatable booms that was cured in the TV tests completed at NASA GSFC in fall 1999 will serve as the test article in the structural characterization experiments. Static load tests will be performed by ILC Dover to determine the effective bending stiffness of the boom. In these tests, the boom will be oriented in the horizontal and fixed at one end. Loads will be applied to the free end of the boom and the corresponding displacements will be measured using an LVDT. Dynamic testing will be completed to verify the stiffness properties measured in the static tests and to characterize the damping behavior of the booms. For the dynamic tests, the boom will be tested in a vertical orientation with its free end located at the top. The supported end will be securely mounted to the floor to approximate a fixed-end boundary condition. The boom will be excited by applying a small initial displacement and then releasing it in a controlled fashion ("twang test"). A tri-axial accelerometer mounted on the tip piece at the free end of the boom will measure the response of the system. Additionally, accurate measurements will be taken for the masses of the inflatable boom, tip piece, and any additional hardware present during the tests.

Material tests

ILC Dover performed several tests on boom and membrane materials to ensure they could meet ISIS requirements. Tape and seam pull tests, boom deployment testing, boom burst testing and controlled deployment tests were performed. As these tests were performed by ILC Dover personnel, they are beyond the scope of this paper and will not be discussed.

Membranes

Two measurements have been performed at the component level on the membrane: (1) coupon testing to measure the Young's modulus of the material and (2) weight measurement to extract material density. No other tests such as dynamic testing of the membrane alone are planed because the tensioning and excitation systems would affect the integrity of the results.

SYSTEM LEVEL ANALYSIS AND TESTING

The ISIS experiment as a payload will be submitted to different environments that can be associated to three states: (1) the stowed configuration during launch phase, (2) the release of the restrain system and deployment phase, and (3) the dynamic data acquisition phase in the deployed configuration. The three states are critical for mission success. The following sections describe analyses and tests performed at the system level in these three states in order to validate the different aspects of the design.

Stowed configuration

The following sections describe the analyses and tests performed for the stowed configuration of the ISIS experiment, including: launch load verification analyses and tests and ascent venting tests.

Structural model and tests

A detailed Nastran finite element model of the ISIS payload in its stowed configuration, Fig. 2, was generated. It is composed of 20846 nodes and 25546 elements, and represents all the major structural components of the payload.

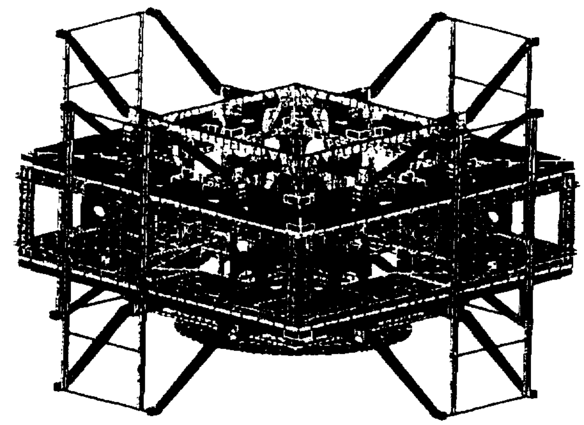

Fig. 2 Finite element model of ISIS in the stowed configuration.

Verification of the FEM was accomplished through identification of rigid body modes and SPC (single point constraint) force checks. The first analysis performed was a quasi-static analysis with 11g accelerations simultaneously applied along the three axes of the FEM global coordinate system. This static analysis is required for Space Shuttle safety to ensure that the stresses in the payload are acceptable during launch (positive margins of safety for yield and ultimate strength). Forces were also extracted from this static analysis to calculate/verify safety margins on fasteners and rivet joints. The upper marman band interface showed negative safety margin using Von Mises criteria. Design modifications and optimization were performed on this part to increase the safety margins.

A modal analysis was also performed to identify natural frequencies having a significant modal mass participation factor. The results of this dynamic analysis showed that the first significant mode is at 65Hz with a modal mass participation factor of 18%. To avoid having to undergo modal survey testing to recover both structural mode frequencies and mode shapes[5], one of the design requirement for the payload was to have the first significant mode be above 50Hz.

The FEM was used to verify the excitation levels and to predict measures expected for qualification tests. The payload will be submitted to two qualification tests: (1) a low-level sine-sweep (0.25g maximum acceleration) to confirm the dynamic characteristics of the ISIS payload with respect to base excitation, and (2) a qualification level random vibration (input spectrum given in ref 6) used to verify that the ISIS payload will keep its structural integrity during the launch phase.

Ascent venting test

Shuttle cargo bay venting during ascent from sea level to orbit represents a possible pressure build up in the membrane layers. This pressure drop from sea level pressure (approx. 14.7-psi) to a pressure of less than 0.5-psi takes approximately 100 seconds.[7] After this initial 100 seconds, the pressure drop-off continues at a slower rate until on-orbit steady state conditions (10^{-6} torr) are achieved. Without adequate venting paths in the folded membranes, a pressure-induced load caused by expanding gas between the membrane shelf and the membrane compression plate could create a condition where the boom and membrane launch restraint system inadvertently actuates or the membranes balloon out from their stowed position. The ISIS project shall perform an ascent-venting test to ensure adequate vent paths exist between the membrane layers. Testing will occur at the Goddard Space Flight Center Environmental Test Laboratory (Bldg. 7). The ISIS flight article with engineering model booms will be placed in an environmental chamber. The chamber will be evacuated at a rate that will simulate the shuttle cargo bay pressure drop during ascent to orbit. Once the chamber has reached the on-orbit pressure, a two-hour hold will take place. This hold will simulate the time on-orbit prior to boom and membrane release. After this two-hour hold, the boom and membrane launch restraint will be released. Through out the test, video data will be recorded. Success criteria for the test are no visible sign of membrane ballooning, the successful release of the launch restraint and successful inspection of the restraint mechanism to ensure no damage occurred during testing.

Additionally, the boom and membrane launch restraint and release mechanism will be qualified at hot and cold orbit extremes while in the environmental chamber. Predicted thermal extremes on-orbit are -450C cold and 150C hot. Qualification testing will be performed at cold temperature extreme -100C and hot temperature extreme +100C. After the ascent vent test is complete, the test article will be restowed and the restraint and release mechanism reset in the launch position. The environmental chamber will be evacuated to on-orbit conditions and wall temperature will be set to the cold condition. The launch restraint mechanism will be actuated. Following this actuation, the test article will be restowed and the environmental chamber will again be evacuated to on-orbit conditions and the wall temperature will be set to the hot case. Again, the launch restraint mechanism will be actuated. The actuations at hot and cold will be video recorded. Success criteria for this test are the successful release of the launch restraint and successful inspection of the restraint mechanism to ensure no damage occurred during testing.

Deployment phase

The sunshield deployment is a critical point in the on orbit operations: failure during this phase would jeopardize the whole experiment and objectives would not be fulfilled. Modeling this phase is a major effort that would not necessary represent reality due to the complexities involved into the design and restrain/release mechanisms as well as soft material behavior. In order to validate design and release mechanism concepts, tests have been performed on engineering models representing candidate concepts.

Restrain/Release mechanism tests

The functions of the restraint mechanism are (1) to keep the experiment stowed during the launch phase and (2) to release the membranes and tubes in a controlled fashion at the start of the deployment phase. Another critical function of this system is to guide the tubes during the initial stages of deployment to avoid collision between components. The overall restraint mechanism system consists of a set of four identical subsystems oriented 90 degrees from one to another on the sides of the experiment container. Each of the individual subsystems is composed of two main parts: (1) a pair (top and bottom) of rectangular shelves and compression trays for storing the membranes and (2) an inflatable tube tip assembly restraint. In the stowed configuration, two membranes are Z-folded and stored between each compression plate/shelf pair. Figure 3 presents a schematic of the restraint mechanism. Each inflatable tube is rolled around a spool attached to a tube tip assembly. This assembly is maintained in place with linear guides at the center of the spool and four cup/cone joints between the ladder structure and the arms pressing on the compression trays. Each subsystem is preloaded in the stowed configuration so that the ladder structure, tubes, and compression trays are fully constrained. A single wax-actuator per subsystem releases the preload and the spring-loaded system becomes free to deploy. Deployment is achieved using a controlled inflation system that provides pressure to inflate and deploy the rolled tubes. A damper-like device inside the spool slows the unrolling of each boom thus controlling the deployment rate.

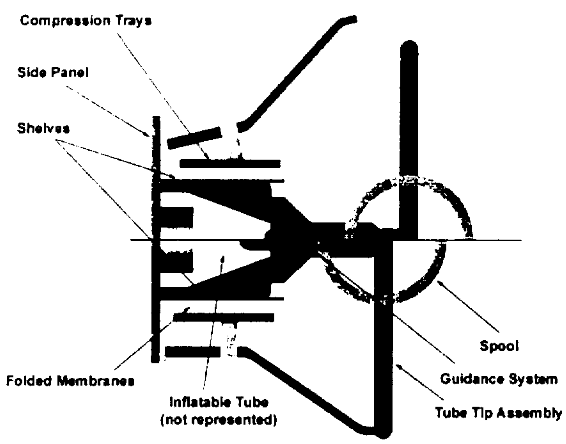

Fig. 3 Schematic of ISIS restraint mechanism.

A ground test of the restraint mechanism was carried out in order to validate the basic design of the system and to investigate alternate design concepts. Two release mechanism concepts have been tested. The difference between the two concepts involves the type of actuation used during initial deployment (immediately following release of the restraint system). The two types of actuation considered are inflation gas pressure and a loaded spring. These two systems have been implemented into an engineering model representing one quarter of the full-scale ISIS container. The model consists of a side panel, a set of shelves, a set of compression trays, an inflatable tube, and a guidance system. Since the inflatable tubes are not designed to withstand their own weight in a 1g environment, a g-negation system has been manufactured to reproduce on-orbit like conditions. This system allows the tube to translate freely along two directions as well as rotating about its axis of unrolling. To verify that gravity does not influence the results, tests were performed in several different orientations. The inflation system used for these tests had both flux and pressure control capabilities. Tests were carried out using several flux rates and nitrogen gas pressures representative of different deployment configurations. The two concepts were tested in a nominal configuration and both systems fulfill their function of releasing the deployable components. Catastrophic scenarios have been tested with both concepts such as uneven loads on the tube representing jammed membranes, unsymmetrical release of the compression trays, leakage of the tubes, and uneven preload on the four cup/cone joins. Both designs are robust enough to work in off-nominal conditions representing possible failure situations. The engineering model will be submitted to additional tests simulating the complete deployment sequence. Selection of the final concept will occur after this series of tests.

Deployment test

A system level test to demonstrate full deployment of the sunshield will be performed on both the engineering model and the flight unit. Ensuring the subsystems work together as planned, prior to launch, is essential. Deployment testing will take place at the sunshield manufacturer ILC Dover in Frederica, Delaware. For engineering model testing, the test article shall be mounted such that the long booms deploy horizontally and the short booms deploy vertically. As the booms cannot support their weight and the weight of the membranes, a pulley system shall be utilized to support the long booms during and after deployment. The deployment sequence shall being with a command set to the electronics system to release the boom and membrane launch restraint. Following release, a command shall be sent to the electronics system to begin inflation. Inflation is a software-controlled process with the ability to inflate the booms via ground commanding as a backup. Once fully deployed, the sunshield envelope shall be measured and data from the accelerometers shall be taken. After full deployment is complete, the engineering model is restowed and the complete deployment process is repeated. Subsequent to the second deployment test, the booms will be rigidized. A flight unit test will follow the same process as the first engineering model deployment. When the inspections are complete, the flight model will be restowed and prepared for launch.

Deployed configuration

Dynamic characterization of the deployed configuration of two scale sunshield models will be completed to validate analytical modeling and analysis techniques for the NGST sunshield. Test results will be obtained for the dynamic behavior of a one-tenth scale model on Earth and a one-third scale model on orbit. Ground testing of the one-tenth scale model in a vacuum chamber will provide the first set of data for validating modeling techniques and also allow for the study of gravity effects. Flight testing of the ISIS experiment in space will provide a second set of data for correlation with analysis under on-orbit environmental conditions. The following sections describe the modeling and analysis techniques developed to predict the behavior of the sunshields, and the ground tests of the one-tenth scale dynamic model used for modeling technique validation.

Structural modeling and analysis

Large thin film membrane structures under low tensile loads are new concepts for space applications that have not been developed neither modeled before. The following paragraphs describe the modeling issue relative to the dynamics of these structures and the approaches developed to solve the problems encountered.

- Modeling Technique

Thin film membranes in a stress free state do not have any bending stiffness. Membrane structures can be stress stiffened by applying tensile loads. In the case of the sunshields considered here, the structural stiffness is derived from the tensile loading applied by the constant force springs at the membrane corners. The finite element models must therefore reproduce the effective stiffness due to preloading in order to perform the dynamic analyses. Another difficulty encountered in the analysis of thin film membranes is the modeling of wrinkles. Laboratory experiments demonstrate that thin film membranes subject to discrete tensile loads exhibit global wrinkling patterns along straight lines emanating from load points. Wrinkles form in regions where minor principle stresses are negative. The membrane is essentially buckled and has zero bending stiffness in these regions. Plate/membrane elements cannot be used to calculate the dynamic response of wrinkled membranes because negative stresses result in spurious negative eigenvalues. A unique modeling technique has been implemented in order to model pretensioned, wrinkled membranes.[8] The membrane is meshed with a network of cables (preloaded bar elements) that is mapped to the wrinkle pattern of the structure. The preloading of the structure is performed using geometric nonlinear solutions with extraction of the updated stiffness matrix representing the state of stress in the cables. For dynamic analysis, the stiffness matrix extracted from the nonlinear static solution is exchanged during the solution process before the calculation of eigenvalues. This process has been implemented for modal, frequency response, and transient response analyses. The analyses were completed using UAI/NASTRAN version 20.0.[8,9]

- Models

Two finite element models using the cable modeling technique have been generated representing the ground test article (1/10th scale of NGST sunshield) and ISIS (Fig. 4). These models are very similar; the only difference besides the dimensions are (1) the container that is a block for the 1/10th scale ground test article and (2) the boom tip assembly. For ISIS, the container is not very detailed because it is a very stiff part where local vibration modes are way above the modes of interest. The boom tip assemblies (ladder structures) are modeled with weightless bars and a concentrated mass. The inflatable booms (for ISIS) and the aluminum tubes (for the 1/10th scale test article) are modeled with bar elements. The constant force springs are modeled in two different ways with respect to the type of analysis. For static analysis (preload of the structure) they are modeled with forces applying tension to the membrane and compression to the booms. For dynamics, they are modeled with rigid elements. Membrane layers are modeled with a mesh of bar elements. For each model, the boundary conditions represent the bolt pattern located on the base plate of the canister: six degrees of freedom are fixed at each grid point.

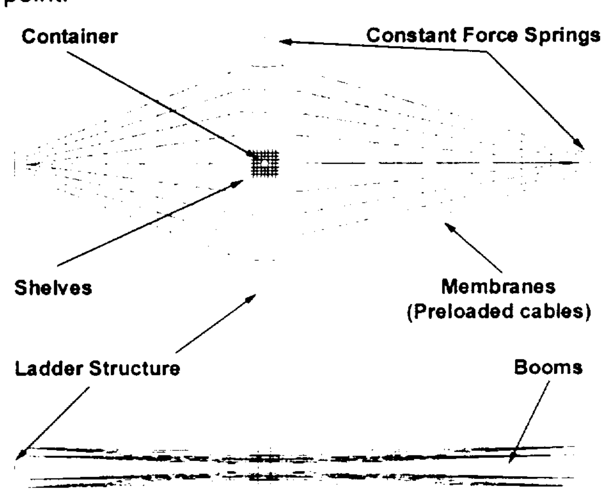

Fig. 4 Finite element model of ISIS in the deployed configuration.

• Simulations

The finite element models generated are used to perform three types of dynamic analyses: (1) modal, (2) frequency response, and (3) transient response.

The modal analysis extracts the natural frequencies of the structure as well as the mode shapes. For each mode, the modal mass participation is calculated to identify important modes (with high participation factors). These results provide information about the frequency range of interest and the frequency steps/accuracy needed for the other simulations.

The frequency response analysis calculates the response of the structure (accelerations where the sensors are located) over a specific frequency range. With respect to the damping coefficient set in the model, the calculation provides amplification factors, and forces generated at the interface (boundary conditions). The plots generated are also used to verify the modes selected are indeed present (acceleration peaks at specific frequencies). The combination of acceleration plots at different locations allows for identification of the mode shapes.

The transient response analysis is a time domain calculation of the response of the structure. Space Shuttle acceleration profiles are applied to the ISIS sunshield and accelerations are calculated at the locations of the instrumentation (tip of the booms). These data are transformed from time domain into frequency domain using Fast Fourier Transform (FFT) algorithms and become comparable to the frequency response plots. Other data processing algorithms provide different plots such as Power Spectral Density (PSD) allowing the identification of high-energy vibration modes. This type of simulation is representative of on orbit operations and is used to verify and validate Space Shuttle maneuvers and analytical post flight data processing tools.

Ground Testing

The main objectives of the ground dynamic tests are: (1) to gather data for characterizing the dynamic behavior of the one-tenth-scale model for correlation with analytical models and (2) to validate instrumentation, excitation, and data processing routines for the ISIS Flight experiment. The following sections describe the test article, results and lessons learned from a preliminary test series, the test setup, instrumentation, and test plans.

• Test Article

The ground test article is a one-tenth-scale model of the NGST sunshield yardstick design. It was scaled down from the full-scale concepts using constant thickness scaling laws. The main components of the test article are a central mounting block, four support tubes with their corresponding tip hardware, and four 0.5 mil thick Kapton® membranes. Figure 5 presents a schematic of the sunshield test article. The central block and support tubes are both made of aluminum. At the tip of each tube is mounted a composite ladder structure that maintains a constant distance between the membrane layers. The membranes are attached at the corners to the constant force springs using a composite spreader bar. At the root, the membranes are clamped to the central block between thin aluminum plates that maintain a constant spacing between the layers. The static envelope of the test article is 3.4 m long by 1.52 m wide by 0.1 m thick, and the overall weight is 4.1 kg (approximately 9 lbs.). The test article was used in an initial series of dynamic tests carried out in spring 1999.

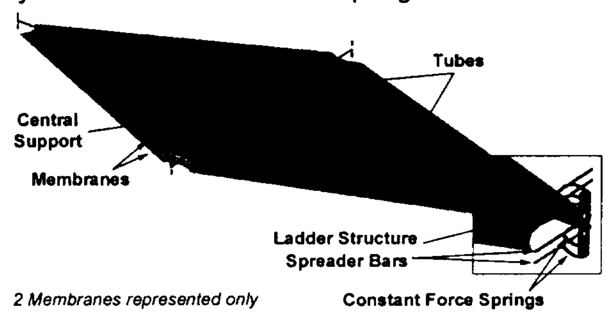

Fig. 5 One-tenth scale sunshield dynamic test article.

• Preliminary Dynamic Testing

A preliminary series of dynamic tests using the one-tenth-scale sunshield in a two-membrane configuration were completed in March 1999. The test setup for this series involved attaching the test article to a massive mounting block that was suspended from the top of the 12 foot vacuum chamber at NASA GSFC by four flexible rods. Figure 6 presents a schematic of the test set-up for the preliminary dynamic test series. The sunshield and mounting block were excited by a shaker located outside the chamber via an extension rod. The intention was to excite the mounting block in the direction normal to the sunshield membrane layers; however, the geometry of the chamber ports resulted in an off-axis excitation direction that induced both lateral and normal forces on the sunshield/mounting block. Additionally, coupling between the fundamental modes of the test article and support block complicated the response of the system. Accelerations at the tip of each support tube along the direction normal to the membranes and forces at the sunshield / mounting block interface were measured. Several important lessons were learned from this test series: (1) support structure frequencies need to be adequately isolated from test article frequencies to avoid dynamic coupling, (2) off-axis excitation significantly degrades the quality of measurements and complicates data post-processing, and (3) three-axis accelerometers should be used in order to characterize both normal and lateral accelerations. These lessons have been incorporated into the design of a new test setup for a follow-up dynamic test series described in detail in the following sections.

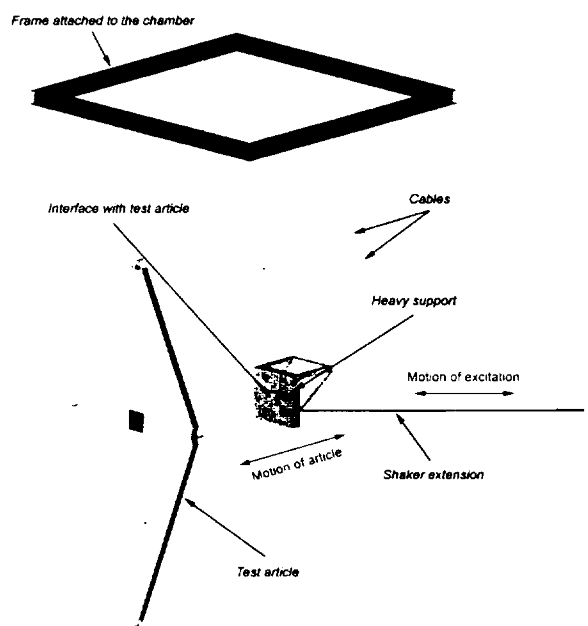

Fig. 6 Test setup for preliminary dynamic test series.

- Follow-up dynamic testing

A new test fixture has been designed to perform dynamic testing of the one-tenth-scale sunshield. It is a stand-alone structure that can be used in any lab or can be easily integrated into the 12-foot thermal vacuum chamber at NASA GSFC. The test fixture consists of two main components: a test stand and a controlled excitation system.

The test stand is a stiff framework of welded aluminum members designed to support the excitation system and test article. The primary sub-assemblies of the stand include the test platform, column, support legs, base plate, and I-beam standoffs for vacuum chamber integration. The test platform is located at the top of the column and provides a mounting interface for the excitation system and test article. The column has a 10 in. square cross-section and a height of 80in. Two support legs are located between the column and base plate to increase the rigidity of the structure. The base of the stand is sized to interface with the mounting points in the 12 ft thermal vacuum chamber at GSFC and has overall dimensions of approximately 70 in x 30 in. The total weight of the test stand (excluding the excitation system and test article) is 238 kg (525 lbs) and the center of gravity is located on the front face of the column at the height of the support leg attachment points. Finite element analysis of the structure predicts a fundamental frequency of 23.6 Hz for the structure assuming a 100 lb. combined weight for the excitation system and test article. This mode involves a first cantilever bending mode of the support column. Note that the frequency range of interest for the one-tenth scale sunshield is 0.5 – 10 Hz, which is sufficiently separated from the first mode of the test stand to ensure that no dynamic coupling will occur.

The excitation system consists of an electromagnetic shaker and its associated amplifier and controller. The shaker is a long stoke linear actuator (Electro-Seis Model 113, APS Dynamics, Carlisbad, CA). The large six in. peak-to-peak displacement capability of the shaker allows the system to provide adequate excitation for both low frequency modal survey and long duration impulse (half-sine profile, 0.08s minimum – 0.8 s maximum duration) testing. The shaker is integrated at the top of the column on the test platform, and the test article is attached directly to the shaker armature. Minor modifications to the materials used in select parts in the shaker, along with use of a contamination bag and cold trap, allows the system to be operated in vacuum without exceeding chamber contamination requirements.

- Instrumentation

The instrumentation suite for the tests consists of accelerometers and force gages to determine frequency response characteristics and damping; and, a laser vibrometer to capture the mode shapes. Table 1 presents a list of the accelerometer and force gage locations. The laser vibrometer will scan individual points on the outer membrane layer during sine sweep excitation for determination of the natural frequencies of the system. During sine dwell excitation a full scan of one-half of the shield will be performed to recover velocity contours that can be interpreted as mode shapes of the outer membrane. The outer membrane layer facing the laser vibrometer will be marked at specific locations representing nodes of the finite element model. The velocity data recovered at these points will be used for model correlation.

Table 1: Baseline instrumentation for the one-tenth scale sunshield dynamic model.

Sensor	Location	Channels
Tri-axis accelerometer	Long tip	3
Tri-axis accelerometer	Medium tip	3
Tri-axis accelerometer	Short tip 1	3
Tri-axis accelerometer	Short tip 2	3
Tri-axis accelerometer	Central Block	3
Single axis accelerometer	Excitation block	1
Tri-axis load cell	Support interface	12
		28 (total)

- Test Plan

The test plan is organized to meet the overall objectives of the ground dynamic tests which are to provide data for correlation with analytical models and to validate the instrumentation, excitation, and postprocessing methods planned for the ISIS flight experiment. There are three main types of tests planned: (1) modal survey, (2) mode shape recovery, and (3) STS impulse maneuver simulation. The modal survey and mode shape recovery tests will provide data for the natural frequencies, damping, and mode shapes of the one-tenth scale test article for correlation with analytical models. The STS impulse maneuver tests will subject the test article to scaled half-sine impulses with peak accelerations and duration's representative of planned Space Shuttle (STS) maneuvers that will excite the one-third scale sunshield on-orbit. These tests will verify that impulse excitation will excite the structure sufficiently to extract key data for the dynamic characteristics of the system.

Tests will be carried out both in air and in a vacuum environment. Testing in air will be performed to verify the performance of the instrumentation and excitation system and to provide a measure of the influence of air damping on the dynamic characteristics of the test article. Each test planned to be completed in vacuum will be done first in air to validate, and modify if needed, the test set-up and procedures. Additional testing of sunshield configurations that do not require a vacuum environment will also be completed. An important objective of these tests is to characterize the dynamic behavior of the support tubes so that their behavior can be isolated from that of the membranes. Additionally, the fundamental frequency of the test stand will be verified. For these tests, the laser vibrometer will be located such that a full scan of the shield is possible. The 12 ft. thermal vacuum chamber (Facility 238) located on site at NASA Goddard Space Flight Center will be utilized for vacuum environment dynamic testing of the one-tenth scale sunshield. Figure 7 presents a schematic of the test setup for the follow-up test series. The location of the test article in the chamber has been defined such that approximately one-half of the outer-membrane layer will be scanned with the laser vibrometer. The field of view of the laser vibrometer is limited by the size of the observation porthole (show in Fig. 7), which necessitates the use of two test orientations to recover mode shapes for both the long and short sides of the membranes.

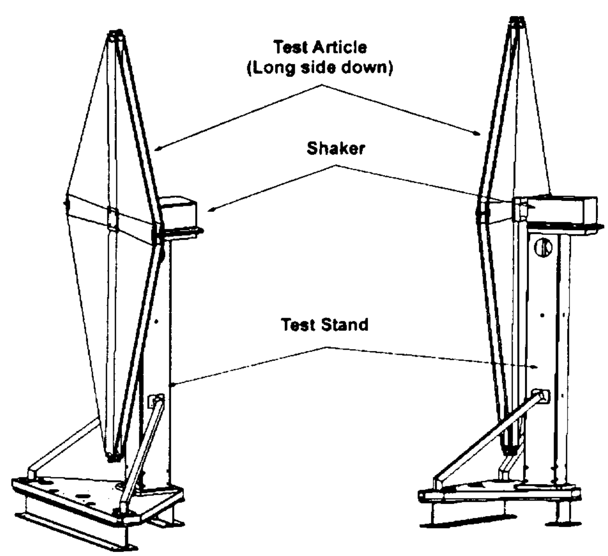

Fig. 7 Test setup for ground dynamic test series.

CONCLUSION

This paper has presented an overview of the analysis and ground testing program for the Inflatable Sunshield in Space (ISIS) flight experiment. The experiment has been characterized at both the component and system levels to verify the design and predict the on-orbit performance of the system. Key areas of the analysis and test program described include: (1) thermal and structural tests to verify inflatable boom performance, (2) ascent venting tests, (3) restraint mechanism and system deployment tests, and (4) analysis and tests to predict system dynamics in the deployed configuration. Results from the ISIS experiment will provide invaluable resources for use in design of the sunshield for the Next Generation Space Telescope.

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