STRUCTURAL MODELING OF A FIVE-METER THIN FILM INFLATABLE ANTENNA/CONCENTRATOR

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Introduction

Inflatable structures have been the subject of renewed interest in recent years for space applications such as communications antennas, solar thermal propulsion, and space solar power. A major advantage of using inflatable structures in space is their extremely light weight. An obvious second advantage is on-orbit deployability and related space savings in the launch

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configuration. A recent technology demonstrator flight for inflatable structures was the Inflatable Antenna Experiment (IAE) that was deployed on orbit from the Shuttle Orbiter. Although difficulty was encountered in the inflation/deployment phase, the flight was successful overall and provided valuable experience in the use of such structures[1].

Several papers on static structural analysis of inflated cylinders have been written, describing different techniques such as linear shell theory, and nonlinear and variational methods, but very little work had been done in dynamics of inflatable structures until recent years. In 1988 Leonard[2] indicated that elastic beam bending modes could be utilized in approximating lower-order frequencies of inflatable beams. Main, et al. wrote a very significant 1995 paper describing results of modal tests of inflated cantilever beams and the determination of effective material properties[3]. Changes in material properties for different pressures were also discussed, and the beam model was used in a more complex structure. The paper demonstrated that conventional finite element analysis packages could be very useful in the analysis of complex inflatable structures. Reference 4 describes an investigation of the dynamics of polyimide thin-film inflated cylinders, and Refs. 5-7 discuss recent dynamic tests/analyses and potential applications of inflatable solar concentrators.

The purposes of this paper are to discuss the methodology for dynamically characterizing a large 5-meter thin film inflatable reflector, and to discuss the test arrangement and results. Nonlinear finite element modal results are compared to modal test data. The work is significant and of considerable interest to researchers because of 1) the large size of the structure, making it useful for scaling studies, and 2) application of commercially available finite element software for modeling pressurized thin-film structures.

Description of Inflatable Collector

In Fig. 1, a prototype circular 5-m inflatable collector manufactured by SRS Technologies, Inc. is shown that consists of a pressurized lenticular/torus assembly supported by three solid composite struts. The lenticular has 4.82 m diameter while the torus has 6.40 m outside diameter and 61 cm cross-sectional diameter. This collector can function as a space-based antenna for communications, surveillance, and radiometry, or as a solar concentrator assembly for solar thermal propulsion systems. The inflatable lenticular and torus elements are constructed of NASA Langley Research Center's CP-1 and DuPont's Kapton polyimide films, respectively, each of which is 254 μm 25.4 μm thick. Silicon-backed Kapton is the adhesive used for joints in the inflatable structures. A reflective coating on the inner lenticular CP-1 film provides the means of collecting radio waves or solar energy.

The tapered composite struts for the prototype structure were formed by layering of a resin impregnated fabric, and have solid cross-sections varying from 20 cm diameter at the fixed ends to 10 cm diameter at the torus attach points. All three struts extend from the torus at 45 deg and toward a point 2.56 m from the torus/lenticular midplane. It is noted that for spaceflight configurations, the struts would likely be inflatable/rigidizable with hollow cross-sections. Following inflation and deployment in space, the struts would harden upon exposure to sunlight or another rigidizing agent. In the configuration of Fig. 1, the support struts are attached to a composite circular base plate.

Inflatable structures in general are extremely lightweight and the collector described in this paper is no exception. The thin-film inflatable part of the concentrator (in the deflated condition) has a mass of approximately 3.4 kg, and the total mass including the struts is on the order of 9.1 kg.

Test Configuration and Results

For modal testing, the inflatable structure with supporting struts was mounted on a stand (Fig. 1) by means of the circular base plate described in the previous section. The stand is a truss structure of composite beams anchored with three large metal plates resting on a concrete floor. The heavy metal plates were required due to the impossibility of bolting the stand directly to the floor.

Due to high flexibility of the polyimide film at any location on the inflated part of the collector, and based on previous experience, it was decided to utilize shaker excitation at a location on one of the struts (Fig. 1). It has been found that excitation applied directly on the inflatable surface, without special shaker adapters or thin film surface treatments, typically is not successful for modal measurements.

Accelerometers were used on the composite struts and support stand for measuring frequency response. However, in order to avoid mass-loading of the inflatable lenticular and torus elements, a non-contact scanning laser vibrometer was employed. Figure 2 shows the approximate location of the laser vibrometer relative to the test article for one series of measurements.

Modal data were obtained for the test configuration as described in this section at room temperature for inflation pressures of 420 Pa and 4.5 Pa (gage), in the torus and lenticular, respectively. As described in Ref. 5, modal parameters were successfully identified for the first five mode shapes of the integrated structure. The first five test frequencies are given in Table 1. The first several mode shapes of the assembly were largely controlled by the composite struts and were relatively insensitive to support stand dynamics. The fundamental experimental mode shape can be seen in Fig. 3, and is clearly characterized by side-to-side flexing of the struts.

Modeling Approach and Results

The finite element modeling technique involved two main steps: 1) nonlinear static analysis, in which the internal pressure loading was applied to the lenticular and torus elements, and 2) modal analysis utilizing the results of step 1. Such a procedure is needed to account for the internal pressure effects on the material stiffness. This two-step modeling and analysis methodology was utilized in the MSC/NASTRAN finite element code, and is described in detail in Ref. 7, where results are given for inflatable cylindrical beams.

The lenticular and torus films were modeled using NASTRAN quadrilateral plate elements, each of which was 256 μm thick. Plate elements of this thickness have extremely low bending stiffness, which approximates membrane behavior, but is believed to help stabilize the nonlinear static solution. Modulus, density, and Poisson's ratio as used were provided by the film manufacturers. The CP-1 film properties are $E=2.17$ GPa , $\nu=0.34$, and $\rho=1341$ kg/m^3, while for Kapton Type H film $E=2.96$ GPa, $\nu=0.34$, and $\rho=1417$ kg/ m^3. Internal pressures of 4.5 Pa and 420 Pa (relative or gage pressures) were applied to lenticular and torus elements, respectively, to account for pressure stiffening of the film. Modeling of the solid-section composite struts and the composite support stand was done using beam elements. Figure 4 shows the finite element model for the antenna assembly.

The mass properties of the inflatable components of the model are very interesting, and worthy of discussion. Of a total combined mass of 18.8 kg for the inflatable components, 13.8 kg, or 73 percent, was attributed to the internal air (air mass calculation based upon absolute pressure). Buoyancy force effects suggest the use of relative or gage pressure in the mass determination. However, modeling experience of the authors for a simple uniform inflated cylinder showed that use of absolute pressure in the computation of internal air mass provided excellent agreement with dynamic test data. Again, however, relative or gage pressure is used for stiffness modeling.

The greatest difficulty encountered in modeling and analysis was obtaining convergence of the nonlinear static pressurization solution in MSC/NASTRAN. This difficulty is due to the extremely thin polyimide material of which the inflatable components are constructed (256 μm). The ratios of film thickness to overall geometric dimensions such as torus cross-sectional diameter, torus major diameter, and lenticular diameter, appear to be the critical parameters in the nonlinear pressurization analysis.

It was discovered that the model had to be constrained at a large number of points on the film surface to obtain convergence of the pressurization solutions. The locations were determined by trial-and-error. These points were then released in the modal "restart" of NASTRAN, the second step in the analysis procedure. Reference 7 provides an extensive discussion of the convergence issue encountered in these modeling efforts, and describes the use of artificial constraints to aid convergence. An alternative approach to stabilizing the nonlinear pressurization computations is recommended by MSC/NASTRAN, in which artificial stiffness terms are added to the model in the early iterations. The extra stiffness terms are removed in later iterations.

A comparison between experimental and model frequency data can be found in Table 1. The first mode of the integrated model occurred at 1.45 Hz (Fig. 3), and the mode shape was characterized by side-to-side flexing of the composite struts with the inflatable components moving rigidly with the struts. This type behavior was also observed in testing, and the fundamental test and analytical modes compare very well, as seen in Fig. 3.

A finite element model of the five-meter torus with entrained lenticular was modified (reduced degrees of freedom in the torus-to-lenticular attachments) and re-analyzed in NE/NASTRAN. In this analysis, the support stand and struts were not included in the model to allow a focus on the critical aspects of the modeling process. However, the torus was restrained at the strut connect points for realism. The pressure load and boundary conditions used previously were retained, and both linear and nonlinear preload modal analyses were performed. The two-run methodology required by MSC/NASTRAN was accomplished more conveniently in NE/NASTRAN in one run. The preload portion of the analysis was accomplished in the first step, and release of the lenticular stabilizing boundary conditions (artificial constraints) was done for step 2. Modal analyses were performed for both linear and nonlinear preloads in step 1.

Comparison of the modal results for the linear and nonlinear preloads showed a pronounced change in the modal response between the two cases. This provided evidence that nonlinear modal solutions are needed for inflatable structures of this type. In both the linear and nonlinear cases, internal pressure was applied to the torus and lenticular, but for the linear analysis the stiffness matrix was not updated to account for the film deformation.

Conclusions

Modeling of a large 5-m thin-film inflatable collector structure has been accomplished, and comparisons made with test data. This work is significant because of 1) the large size of this thin-film structure, 2) general difficulty in accurately representing the nonlinear material and geometric characteristics of thin film inflatable structures, and 3) the accomplishment of a modeling methodology that realistically represents the internal pressure loading and the stiffness properties of the thin films in a modal solution.

It was shown that many difficulties were encountered in obtaining convergence of the nonlinear static pressurization procedure in MSC/NASTRAN. In this regard, MSC/NASTRAN was found to have limitations in its nonlinear analysis capability, particularly for large thin-film structures of the type investigated in this paper. NE/NASTRAN appears to be better suited for this analysis (though artificial constraints are still needed), and use of ABAQUS or other finite element packages should also be considered for inflatable structures.

Acknowledgments

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John Lassiter and Robert Engberg of Marshall Space Flight Center's Structures, Mechanics and Thermal Department conducted the dynamic testing and provided the modal test data cited in this paper.

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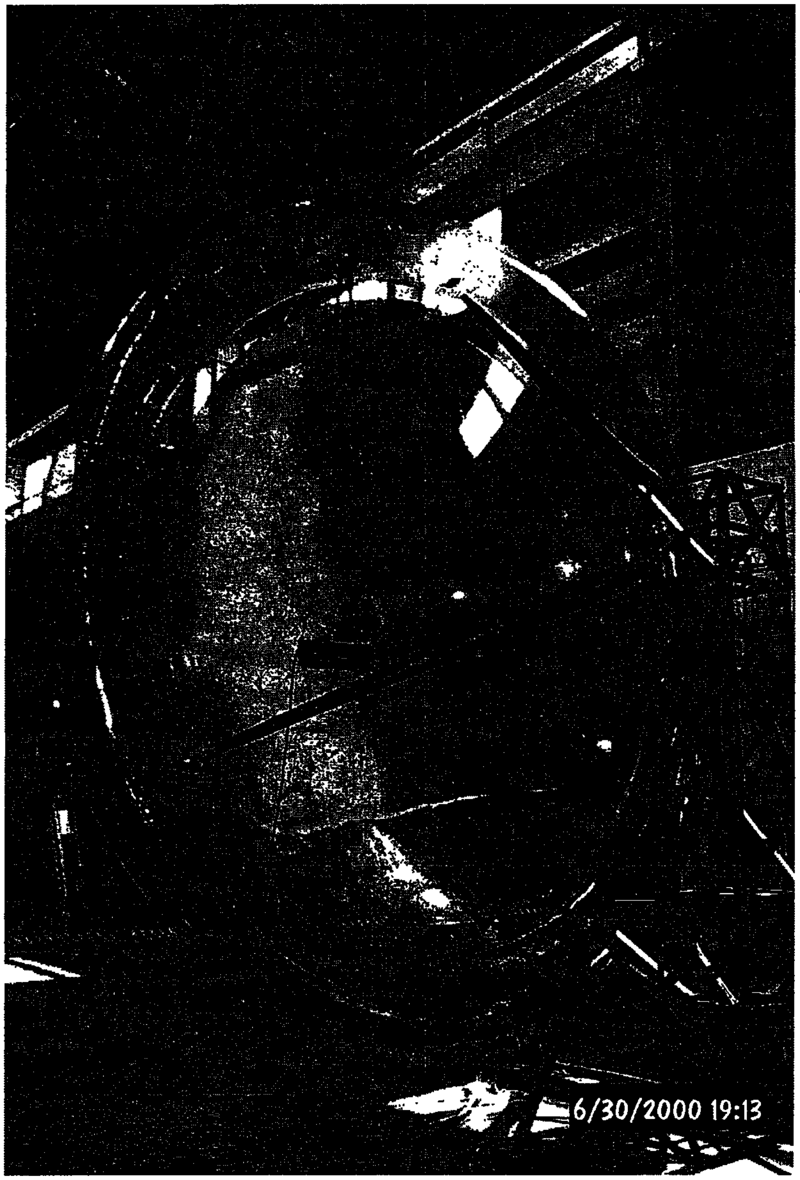
Mode Number	NASTRAN Nonlinear Analytical Freq. (Hz)	Experimental Freq. (Hz)	% Error
1	1.45	1.16	-25
2	2.05	2.37	14
3	2.52	3.21	21
4	3.56	4.17	15
5	4.86	5.31	8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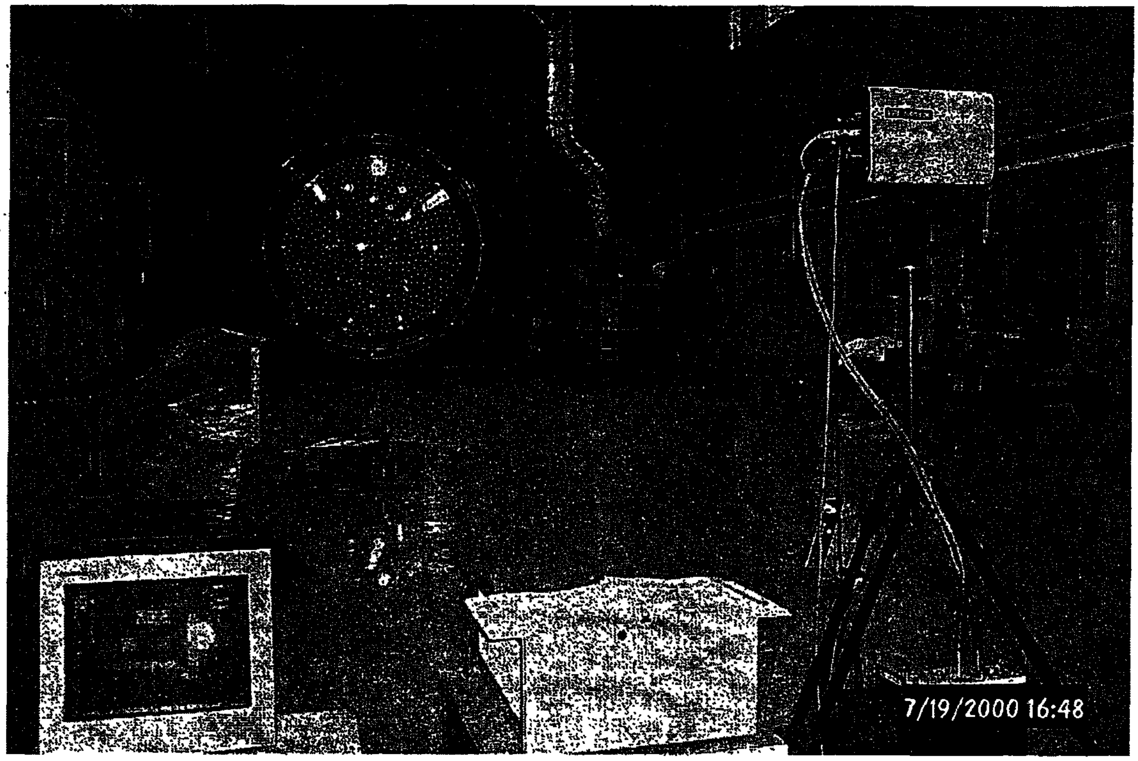
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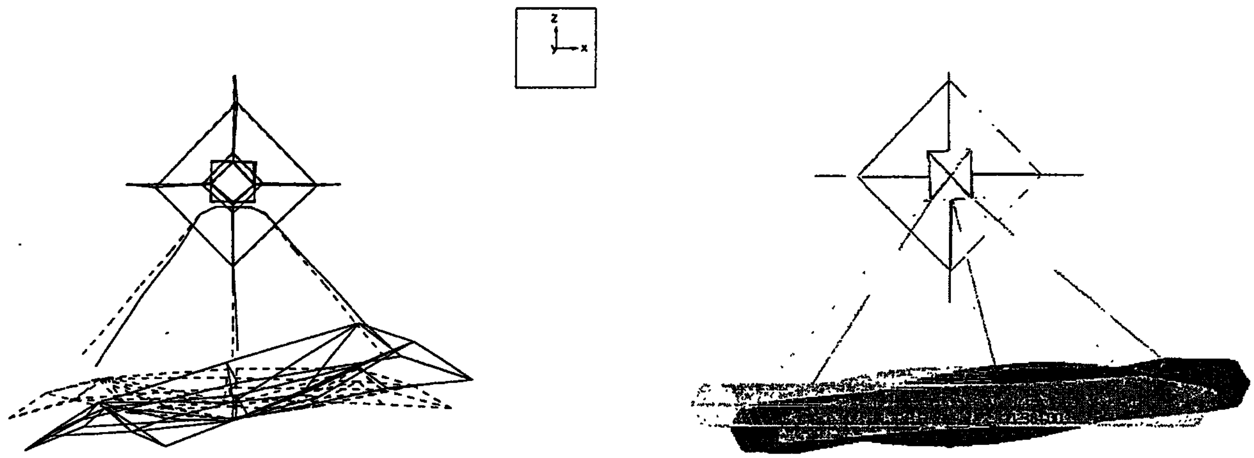
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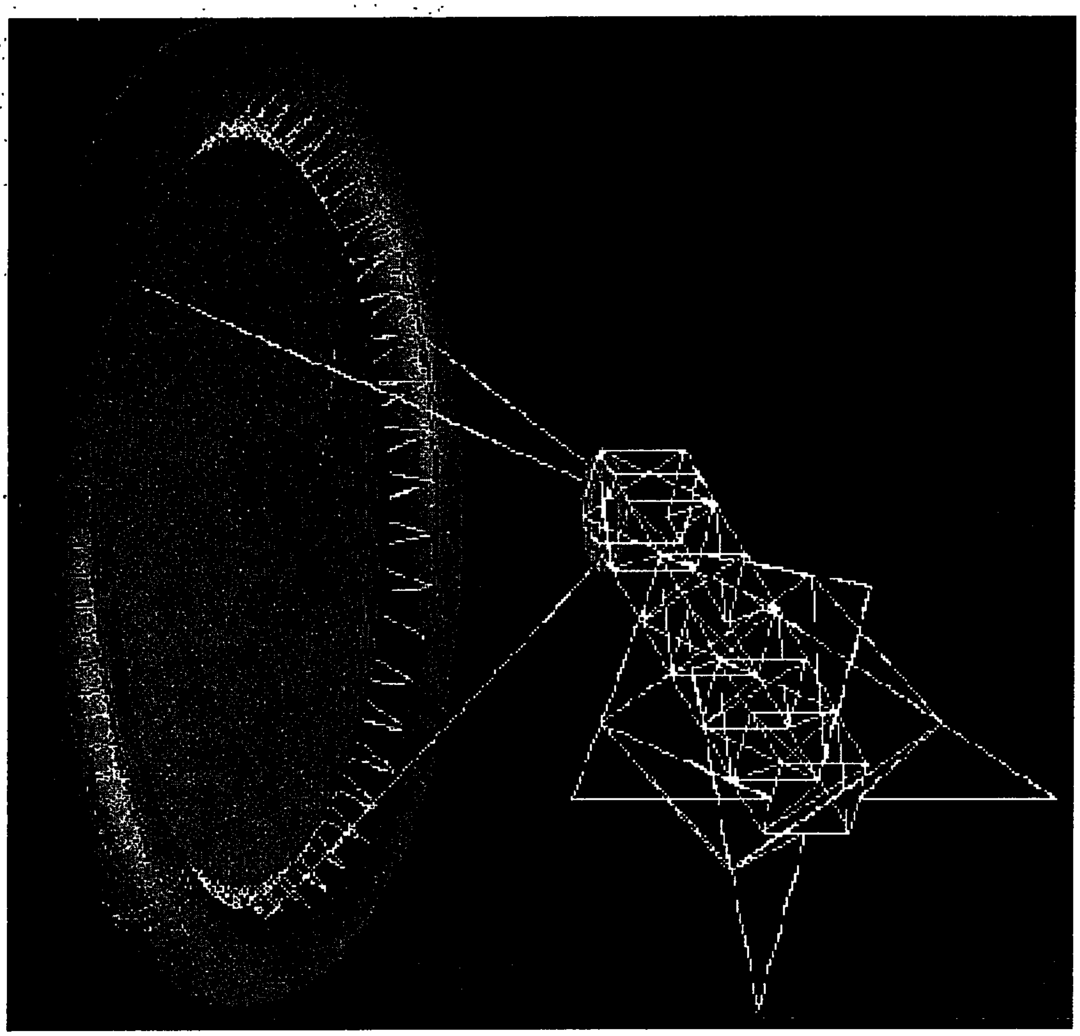

Table 1. Comparison of First Five Experimental and Analytical Frequencies

Figure 1. Five-Meter Inflatable Antenna/Concentrator with Tapered Composite Struts and Support Stand

Figure 2. Laser Vibrometer Configuration for Dynamic Measurements on Inflatable Components

Figure 3. Fundamental Mode Shapes from Test (Left) and NASTRAN Model (Right)

Figure 4. NASTRAN Finite Element Model of Antenna/Concentrator Assembly