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DYNAMICS OF A 4x6-METER THIN FILM ELLIPTICAL INFLATED MEMBRANE FOR SPACE APPLICATIONS

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Abstract

Dynamic characterization of a thin film inflatable elliptical structure is described in detail. A two-step finite element modeling approach in MSC/NASTRAN is utilized, consisting of (1) a nonlinear static pressurization procedure used to obtain the updated stiffness matrix, and (2) a modal "restart" eigen solution that uses the modified stiffness matrix.

Unique problems encountered in modeling of this large 4x6-meter lightweight inflatable are identified, including considerable difficulty in obtaining convergence in the nonlinear finite element pressurization solution. It was found that the extremely thin polyimide film material (.001 in or 1 mil) presents tremendous problems in obtaining a converged solution when internal pressure loading is applied. Approaches utilized to overcome these difficulties are described.

Comparison of finite element predictions for frequency and mode shapes of the inflated structure with closed-form solutions for a flat pre-tensioned membrane indicate reasonable agreement.

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Introduction and Background

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 (Figs. 1-2). A major advantage of using inflatable structures in space is their extremely light weight. An obvious second advantage is on-orbit deployability and subsequent space savings in the launch 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 (Ref. 1).

The Solar Orbital Transfer Vehicle (SOTV), discussed in Ref. 2, and Solar Thermal Upper Stage (STUS), described in Refs. 3-5, are possible technology demonstrator flights for solar thermal propulsion. The basic concept behind solar thermal propulsion is to utilize sunlight or solar energy as a means of heating a working fluid (propellant) to provide thrust at increased specific impulse. As described in Ref. 6, thrust is produced by expanding the heated propellant through a nozzle. No combustion occurs, and the thrust level is low. For this reason, solar thermal propulsive systems are mainly applicable for orbital transfer vehicles. The engine system envisioned for the STUS is designed to utilize hydrogen propellant to produce a thrust level of about 2 lbf. Two inflatable parabolic collectors could be used that would be rotated and gimballed for focusing sunlight into an absorber cavity (Fig. 1, from Ref. 5). The collectors would be inflated after separation of the upper stage from the launch vehicle.

Many investigators have considered the use of inflatable structures for space applications. Perhaps the earliest was Frei Otto (Ref. 7), who in 1962 published ideas for inflated tubular frames for use in structures such as orbiting platforms. A more recent proposed application involves the use of inflatable beam segments to replace

solid segments of the Space Shuttle remote manipulator system and thus reduce storage space and inertia of the arm (Ref. 8).

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 (Refs. 9-17), but very little work had been done in dynamics of inflatable structures until recent years. In 1988 Leonard (Ref. 18) 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 (Ref. 19). 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 20 describes an investigation of the dynamics of polyimide thin-film inflated cylinders, and Refs. 21-29 discuss recent dynamic tests/analyses and potential applications of inflatable solar concentrators.

Description of Inflatable Concentrator Investigated in the Current Study

In Fig. 3, a prototype elliptical, off-axis paraboloid 4x6-meter inflatable concentrator manufactured by SRS Technologies, Inc. is shown that consists of a pressurized lenticular supported by an aluminum fixture. The aluminum fixture will be supported by four I-beam stands for testing in a horizontal configuration. The inflatable is attached to the fixture by 204 silicon catenaries. The lenticular has a 226-in. major axis and a 164.08-in minor axis. 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 element is constructed of NASA Langley Research Center's CP-1 which is .001 in (1 mil) 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. It is noted that the particular application for the antenna/concentrator depends on the surface accuracy of the reflective lenticular surface. Use as an optical system would require greater surface accuracy than a solar concentrator for propulsion systems, for example.

In the case of solar thermal propulsion applications (Fig. 1), the collector assembly would focus sunlight into an absorber or secondary concentrator near the fixed ends of the struts. Solar energy stored in the absorber could be utilized to heat a propellant and generate thrust as described previously.

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 weighs approximately 3 lb.

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 element and a pretension applied to the catenaries, and 2. modal analysis utilizing the results of step 1. Such a procedure is needed due to the impossibility of active forces in an eigensolution. In step 1, the stiffness matrix of the model is updated to capture the tensioning of the thin film material caused by internal pressure. This two-step modeling and analysis methodology is described in detail in Ref. 29, where results are given for inflatable cylindrical beams.

The lenticular film was modeled using NASTRAN quadrilateral plate elements, each of which were .001 in. (1-mil) thick. Modulus, density, and Poisson's ratio as used were provided by the film manufacturers. The CP-1 film has $E=300$ ksi, $\nu=0.34$, and $\rho=0.0518$ lbm/in³. An internal pressure of 0.03 in. H₂O (.00108 psig) was applied to the lenticular element.

Modeling of the catenaries was done using silicon rod elements under a temperature load. The suggested temperature-loading pretension method was verified by comparing stress results to a rod with an applied force.

The Aluminum-5052 test fixture was also modeled using quadrilateral plate elements. The section of the aluminum plate with 3600 holes was modeled by altering the thickness accordingly to account for the adjusted density.

The steel I-beam stands were modeled using beam elements and multipoint constraints. A modal test was performed on a stand that was supported on three feet. The stands in the finite element model were cantilevered but were created with modes and mode shapes equivalent to that of the tested stand. Multipoint constraints were used to define a plate-sectioned rigid body in the place where the stand would be secured to the aluminum fixture. Fig. 4. shows the integrated finite element model.

Several parameter studies were performed to help diagnose problems and to aid in understanding of the solutions. Mode shapes and frequencies were compared while varying thickness, geometry, and material. Studies were also made on the effect of an induced strain or applied pressure. Drastic effects on mode shapes and frequencies would appear by changing only the geometry from elliptical-shaped to paraboloid-shaped. The introduction of curvature into the problem would not only affect system dynamics but also drastically increase computation time of the nonlinear static solution. It is interesting to point out that the strain of the paraboloid geometry (while averaging about 0.03%) did have a varying value across the membrane due to the applied pressure. The flat elliptical model had an induced uniform strain of 0.03%. But when a pressure was applied to the flat elliptical membrane giving a much greater and varying strain, the mode shapes were identical indicating that the mode shapes seem to be a function of geometry. The frequencies were not the same in this case. Ref. 30 shows that sag has played an

interesting role in cables and cable trusses as shown. Fundamental natural frequencies of cables with a small amount of sag can be as much as 300% more than those of a straight cable. Similar behavior may occur in membranes.

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 (1 mil or 1/1000 of one inch). The ratios of film thickness to overall geometric dimensions such as lenticular axes appear to be the critical parameters in the nonlinear pressurization analysis. For example, it was found that increasing the film thickness to 10 mils or 1/100 in. resulted in solutions that converged easily. The reason for this phenomenon appears to be that extremely thin films tend to have large displacements and large stiffness changes when pressure loading is applied. Obviously, increased thickness reduces the magnitude of these changes. Another issue in model convergence was fine-tuning the NASTRAN parameter 'kdiag'. A value of 'kdiag' helps convergence by initially adding a small value to the stiffness matrix diagonal terms and then is later removed. With this assistance, there was convergence of iterations early on that normally would have trouble converging. The value of 'kdiag' was continually decreased until successive results would have similar solutions indicating no necessary further change in the parameter.

After all the difficulties encountered in this modeling and analysis effort, it was satisfying to obtain reasonable results. The first natural frequency of the integrated model was 7.87 Hz, and the mode shape was characterized by an up-and-down bobbing of the inflatable through the ring fixture as shown in Fig. 5. With the exception of the 4th mode, the first seven modes exhibit rigid-body type modes due to the 204 catenaries that connect the inflatable to the fixture. Another example of these rigid-body type modes is shown in Fig. 6. These types of modes have frequencies not equal to zero but display motion in the directions of rigid body modes. A breathing mode of the entire inflatable occurs at 9.82 Hz, which is the 4th mode. The next system mode excluding the rigid-body type mode (mode 8) occurs at 13.44 Hz characterized as a 2nd-order breathing mode with node line along major axis of the inflatable. Table 1 shows some modes of the entire system. Some interesting curvature effects on the mode shape are apparent in mode 9 (13.98 Hz), Fig. 7. Coupled support structure and inflatable structure modes were seen for the first time at 26.15 Hz (mode 30) shown in Fig. 8.

Comparison of Finite Element Results to Closed-Form Solutions

The suggested method of applying a uniform strain to the membrane or a pretension to the catenaries is by using a change in temperature. This method was verified by comparing a catenary in strain to a catenary with an applied force. A 17.5-inch diameter membrane was tested

and then modeled in NASTRAN using this technique. Results of another finite element analysis for this test were replicated. A strain of 0.2% due to dry shrinkage and other effects was found by comparing the test data with the model results.

A finite element model of the 4x6-meter inflatable membrane was modified (converted to a flat 2-D ellipse) and re-analyzed in MSC/NASTRAN. In this analysis, the support stand and ring fixture were not included in the model to allow a focus on the critical aspects of the modeling process and to allow comparison to closed form solutions. The pressure load was replaced by a uniform temperature-induced strain. The catenaries were also removed and the perimeter of the ellipse was fixed in all directions. Hamidzadeh's closed-form solution had the following conditions: flat elliptical membrane, zero displacement on the boundary, uniform strain, and CP-1 properties. A nonlinear static analysis followed by a modal 'restart' was performed for this model as well.

The results are summarized in Table 2. The closed form solution compared well with the NASTRAN solution. The mode shapes were identical and the frequencies were on target. Slight differences in the frequencies can be attributed to approximate values for the Mathieu functions in the closed form solutions and slight geometric discrepancies in the NASTRAN model. A polynomial expansion for the Mathieu functions and modified Mathieu functions were used in calculating natural frequencies. The geometric dimensions in the NASTRAN model were slightly different than the design dimensions because the geometry followed that of the fabricated prototype.

Summary

Modeling of a large 4x6-m thin-film inflatable concentrator structure has been accomplished. Comparisons with modal tests will be made at a later time. This work is significant because of (1) general difficulty in accurately representing the nonlinear material and geometric characteristics of these structures, (2) the large size of this thin-film structure, and most importantly, (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 workarounds were required to obtain 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. The use of ABAQUS or other finite element packages should also be considered for inflatable structures.

Acknowledgments

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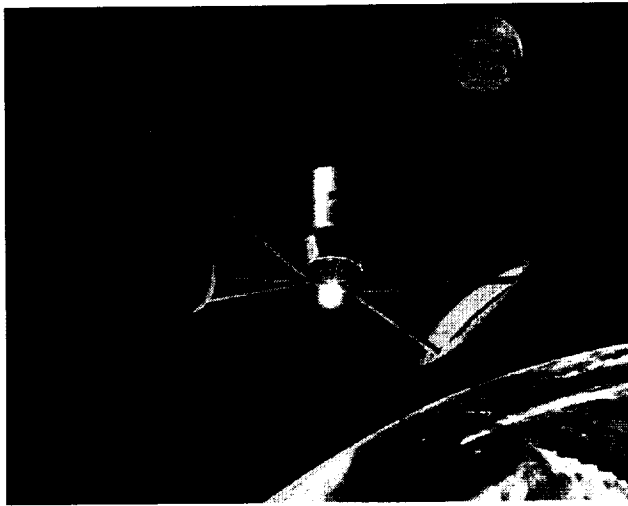


Figure 1. Concept for Solar Orbital Transfer Vehicle Utilizing Inflatable Solar Concentrators

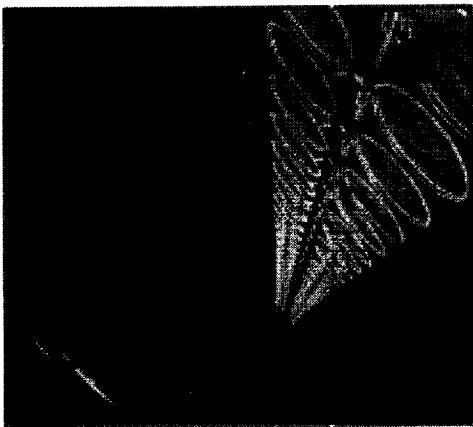


Figure 2. Space Solar Power Concept Based on Inflatable Structures

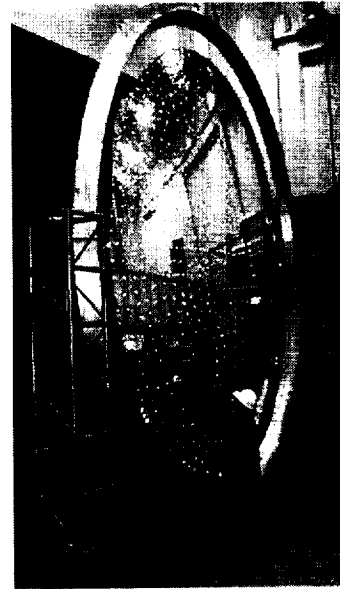


Figure 3. Vertically Supported 4x6-Meter Inflatable Concentrator with Aluminum Ring Fixture



Figure 4. Finite Element Model Representation of Inflatable Collector and Supporting Structure

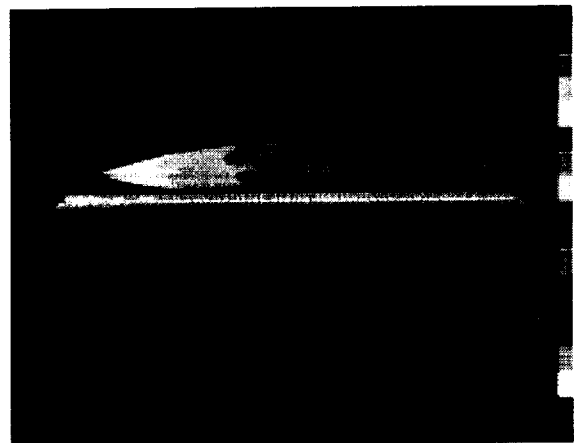


Figure 5. Fundamental Mode Shape Obtained in Finite Element Analysis (7.87 Hz)

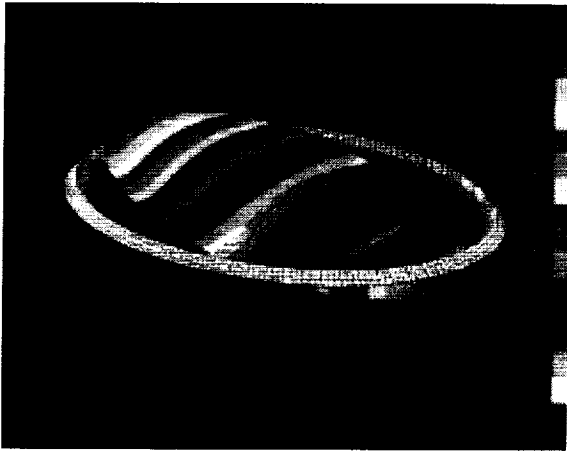


Figure 6. Rigid-Body Type Mode Shape Obtained in Finite Element Analysis (Mode 5, 10.34 Hz)



Figure 8. Coupling Between Support Structure and Inflatable at Mode 30 (26.15 Hz)







Mode Number	Freq (Hz)	Node Lines	Mode Number	Freq (Hz)	Node Lines
1	7.87	z-trans	7	11.18	z-rot
2	8.51	x-trans	8	13.44	
3	8.58	y-trans	9	13.98	
4	9.82		10	16.52	
5	10.34	y-rot	11	16.54	
6	10.95	x-rot	12	18.48	

Table 1. Frequency Results for Finite Element Analysis of Concentrator and Support








Mode Number	Closed Form Freq. (Hz)	NASTRAN Freq. (Hz)	Node Lines
1	4.1	4.2	
2	5.9	6.2	
3	7.0	7.3	
4	7.5	8.3	
5	8.2	9.0	

Table 2. Modes Predicted Using Finite Element Analysis and Closed Form Solutions for Flat Ellipse

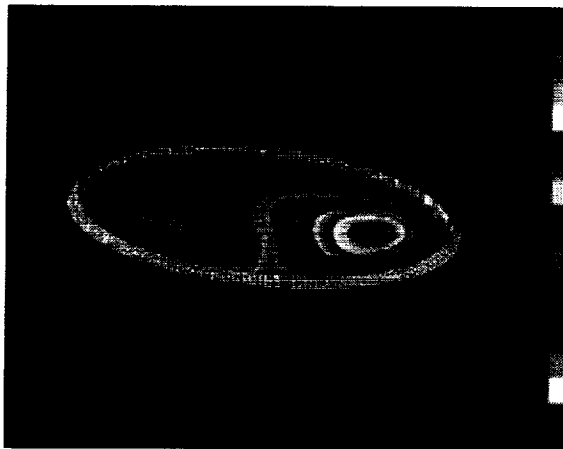


Figure 7. Mode 9 (13.98 Hz) Showing Geometric Curvature Effects on Mode Shape