Design and Development of an Inflatable Reflectarray Antenna

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With the development of inflatable technologies, inflatable structures used as large space antennas are becoming very possible for near-term space missions. This article discusses the development of an inflatable/self-rigidizable structure for a 3-m 32-GHz (Ka-band) reflectarray antenna. This reflectarray antenna uses a beam-scanning reflectarray antenna with circular-polarization technology. This technology uses a flat surface instead of a parabolic surface for the radio frequency component. A flat "natural" thin-membrane surface is much easier to accomplish and maintain than is a curved "non-natural" parabolic surface. An innovative inflatable/self-rigidizable technology, namely, a spring tape reinforced (STR) aluminum-laminate boom, has been developed by this research. An STR aluminum-laminate boom automatically rigidizes after it is deployed, with no space power, no curing agent, and no rigidization system required. Any small damage caused by micrometeoroids will not impact the membrane performance, and inflation air is no longer needed once the antenna is inflated. A detailed mechanical design, dynamic analysis, and deployment demonstration of the antenna are discussed in this article.

I. Introduction

With the advancing of space sciences, larger and larger apertures with very low launching masses and volumes are demanded by space scientists for future missions. Space inflatable technology will revolutionize future space structures to accommodate these demands. Inflatable structures used as supporting structures have been extensively investigated recently [1]. Major challenges include controlled deployment, space rigidization, dynamic modeling, and simulation. This article will discuss the mechanical design and hardware development of an inflatable 32-GHz (Ka-band) reflectarray antenna [2]. The electromagnetic component of this type of antenna is a flat membrane with a large number of copper patches. The membrane is supported by an inflatable/self-rigidizable frame structure. Booms of the inflatable/self-rigidizable structure can be flattened. The flattened booms are rolled up on two mandrels, and the membrane is rolled up a composite cylinder when the antenna is in a stowed configuration. After

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the antenna is launched into space, it is inflation-deployed, and the dynamics of the deployment are controlled by a deployment control system. As compared to other types of deployable antennas, this type of antenna offers much larger apertures, is extremely lightweight, and has high package efficiency. The new antenna radio frequency (RF) technology, namely, a beam-scanning reflectarray antenna with circular polarization [3], makes it possible to use a flat surface instead of a parabolic surface as the electromagnetic component. A flat "natural" thin-membrane surface is much easier to accomplish and maintain than is a curved "non-natural" parabolic surface. It is also believed that a flat surface has better reliability for a long-term space mission than does a thin-membrane parabolic surface.

This article will start by reviewing the previous versions of the inflatable reflectarray antenna. Details of the current model will then be presented. Functions of the major components and future development directions will also be discussed.

II. Previous Models of the Inflatable Reflectarray Antenna

Development of this technology originated from a 1-m 8.45-GHz (X-band) model of the inflatable reflectarray antenna.[5] The electromagnetic components of this unit are two layers of 1-m-diameter circular membranes that are supported by an inflatable structure. The inflatable structure is composed of a torus to support the electromagnetic membranes and a hexagonal ring to hold the feed. The torus and the hexagonal ring are connected by three struts. The inflatable structure is made of urethane-coated Kevlar. Urethane-coated Kevlar is a very strong material for holding pressure. The electromagnetic membrane is made of Kapton. The weight of the inflatable structure is 0.74 kg, and the weight of the electromagnetic film is 0.27 kg. The total weight of the whole antenna is only 1.08 kg.

Upon the great success of the RF test of the 1-m inflatable antenna, a 3-m technology-demonstration model of the inflatable reflectarray at Ka-band was also developed [4,5]. The RF test results of the 3-m antenna demonstrated an excellent radiation pattern characteristic. Figure 1 shows a drawing of the antenna. The configuration of this antenna is like a horseshoe, and its feed is supported by a hexagonal ring. The ring is connected by three asymmetrically located inflatable struts.

The reason for changing the configuration from circular to horseshoe is that, after the inflatable structure is deflated, the membrane and the deflated structure can be rolled up onto the rigid-tube

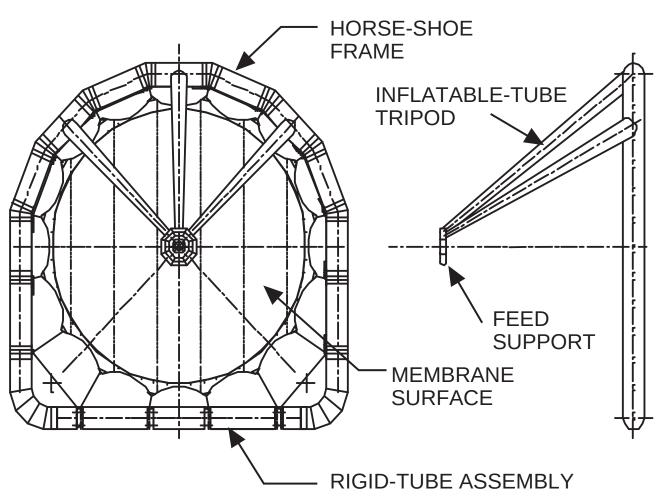

Fig. 1. Drawing of the 3-m inflatable reflectarray antenna.

[5] *Design, Fabrication, and Integration of a 1 Meter X-Band (8.4 GHz) Inflatable Microstrip Reflectarray Low Mass Technology Demonstrator*, Final Report, ILC Dover Inc., Frederica, Delaware, August 1997.

assembly without causing significant wrinkling to the membrane. The three struts, the hexagonal ring, and the horseshoe frame (excluding the rigid-tube assembly) are made of urethane-coated Kevlar, and the weight is 3.92 kg. The single-layer electromagnetic membrane is made of Kapton, and the weight is 2.55 kg. The rigid-tube assembly is made of aluminum, and the weight is 7.10 kg. The total weight of the antenna is only 13.57 kg.

However, this design has several disadvantages. The first disadvantage of this design is that the feed and its amplifiers are placed far away from the spacecraft, which is located just below the antenna (near the center of the rigid-tube assembly). These amplifiers will be difficult to protect thermally from extremely cold temperatures in space. RF blockage introduced by feed-supporting struts is also a disadvantage of this design. Vibration of the feed-supporting struts is another potential problem, plus the fact that with this design it is very difficult to implement space rigidization for future real space missions.

III. The Inflatable/Self-Rigidizable Reflectarray Antenna

In order to increase the readiness level for space application, a design trade-off study for the 3-m inflatable reflectarray antenna has been conducted [6]. The "movie screen with offset feed array" concept was identified as the best candidate for the reflectarray antenna structure. Based on the results of the design trade-off study, a new inflatable/self-rigidizable reflectarray antenna has been developed. The feed of this unit is offset located on the spacecraft, and the reflectarray surface is deployed by two inflatable booms. Figure 2 demonstrates the deployment process of the movie screen antenna. The deployment process involves only the pressurization and unrolling of two inflatable booms. Unlike other mechanically deployed antennas, it involves virtually no moving parts. This design clearly has the advantages of less weight, lower development cost, and better deployment reliability.

Figure 3 presents the schematic of the movie screen inflatable reflectarray antenna. Major components include the electromagnetic membrane, inflatable booms, flat panels, roll-up shells, crossbars, constant-force springs, mandrels, end caps, catenary systems, etc. The design consideration of each component will be discussed in the following subsections.

A. Electromagnetic Membrane

The most important component of the antenna is the electromagnetic membrane. The large circular portion of the membrane carries electromagnetic patches (approximately 200,000 patches). Figure 4 gives a close-up view of the electromagnetic patches. Membrane around the electromagnetic section is used to connect the electromagnetic area to the catenary system, which is attached to the supporting structure by constant-force springs. The whole supporting structure is designed to hold the membrane, to stretch the membrane, to avoid wrinkles on the membrane, and to maintain the flatness of the membrane.

Because of the unavailability of large-sized membrane material, the electromagnetic aperture is assembled from seven sections of membranes. Each membrane section consists of 5-mil-thick Kapton with 5-μm copper completely covering one side to serve as the ground lane and many etched square patches (also 5-μm copper) on the other side to serve as reflectarray elements. Originally we used 51-mm-wide double-sided adhesive tape covered by a 102-mm-wide Kapton adhesive tape to join the two sections. However, we observed slight separation along the seams 1 year after the assembling of the membrane. This could adversely affect the dimensional accuracy and thus the performance of the antenna.

To correct this problem, a flexible epoxy was used to bond the seven sections of membrane together. The flexible epoxy chosen is the two-part 3M Scotch-Weld Epoxy Adhesive 2216 Gray B/A. This adhesive is first applied to the bonding area of the membrane and then patched with a 4-in.-wide copper-coated Kapton strip. The reason for using copper-coated Kapton instead of clear Kapton is that it is easier to find adhesive to bind two metallic surfaces than to bind a metallic surface with Kapton.

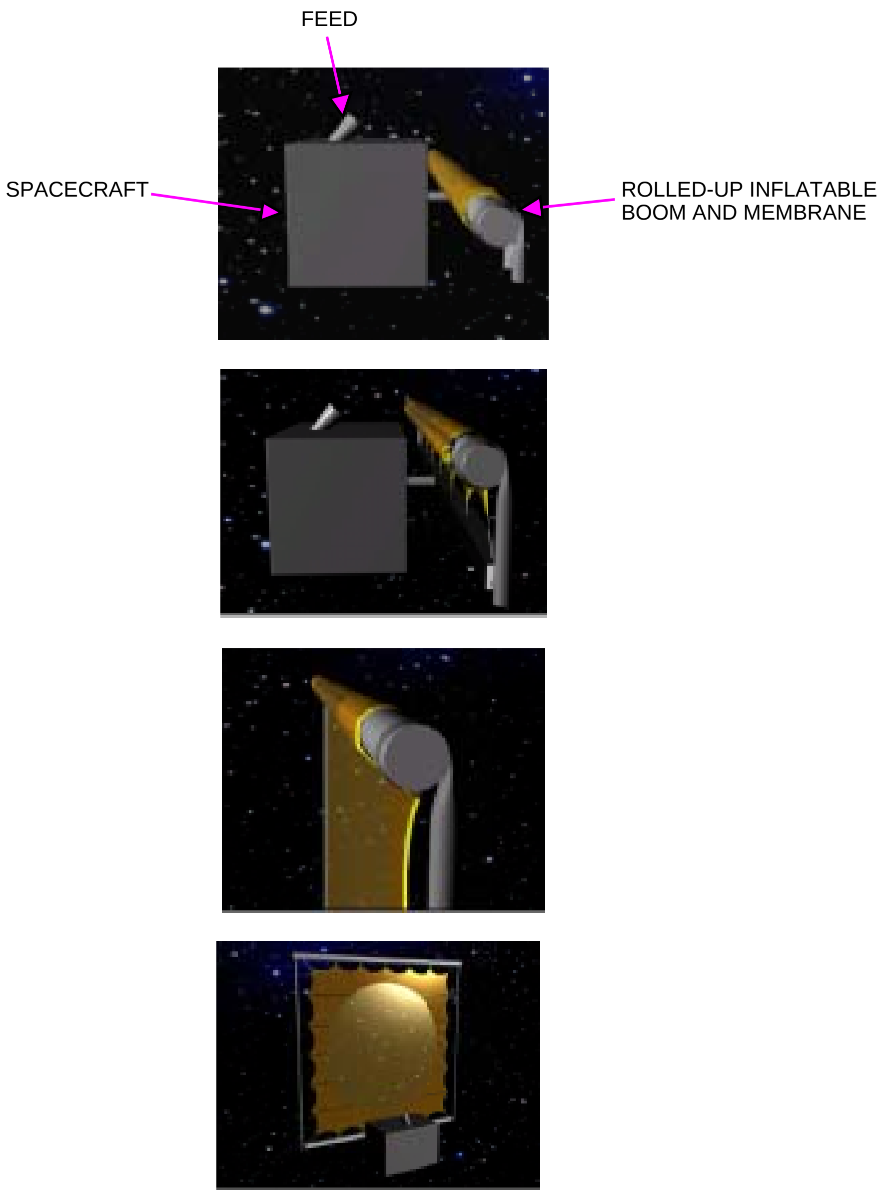

Fig. 2. Depiction of the process of inflation deployment.

B. Catenary System

A catenary system, which is composed of tensioning cord around the membrane, is used to attach the membrane to the structure and to uniformly tension it. Figure 5 shows where the catenary system is attached. The tensioning cord is pulled by constant-force springs that are connected either to crossbars or to flat panels.

In order to get an even stress distribution, the curvature of the catenary is a parabolic curve [7]. The thickness of the membrane is 5 mil. The tension stress of the membrane is pre-defined to be 620,528 N/m^2. Therefore, the distributed load onto the membrane is 79 N/m. The horizontal catenary (corresponding to Fig. 5) is identical to the vertical catenary. The inflatable components of the antenna are two inflatable/rigidizable booms. Because of the safety factor, each of these booms is allowed to take only a 156-N axial load. The span number should be minimized to reduce the number of crossbars and the weight of

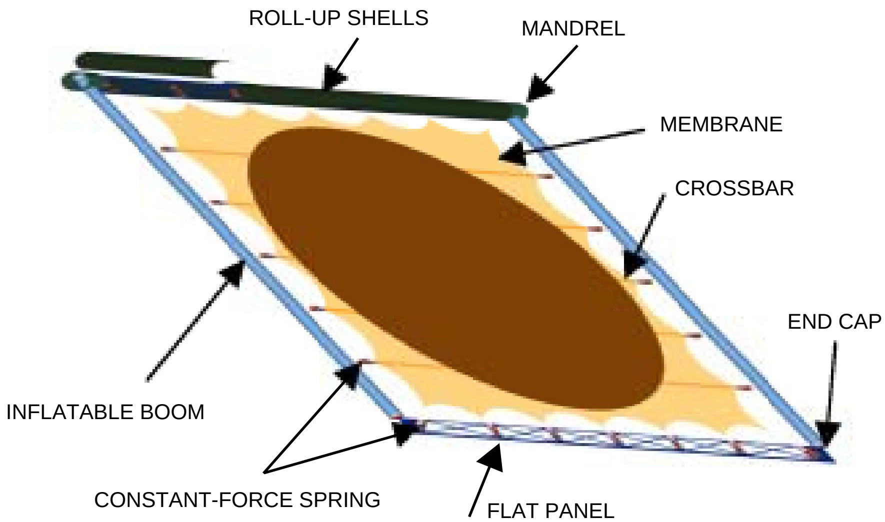

Fig. 3. Schematic of the movie screen inflatable reflectarray antenna.

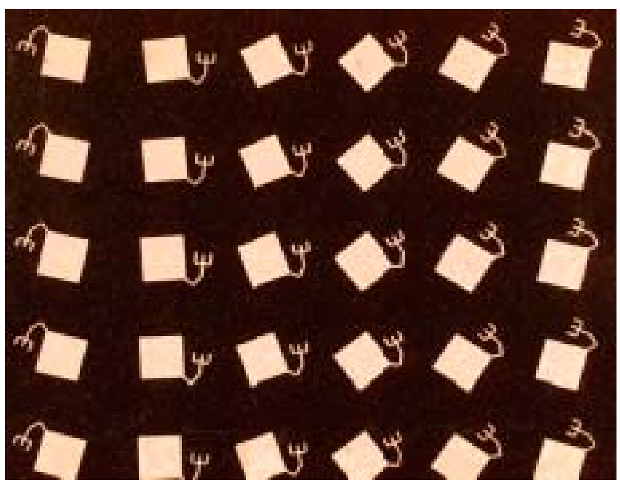

Fig. 4. Close-up of the electromagnetic patches.

the antenna. Decrease of the span number means increase of the width (indicated as L in Fig. 6) of each span, which results in increase of the maximum cord force and height (indicated as h in Fig. 6). Increase of height also means increase of the sizes of the catenary system and support frame and, consequently, of the weight of the antenna.

In order to find out the best set of these parameters, we calculated the force acting on each inflatable/rigidizable boom while the number of spans changed from 4 to 8 and the height of each span changed from 60 mm to 200 mm. The analysis results are given in Fig. 7. For the final selection between 6 spans and 7 spans, the maximum cord force and the cord angle at the end of each span were calculated for 6 spans (the height of each span is 140 mm) and 7 spans (the height of each span is 79 mm). The maximum cord force (at the end of each span) was calculated as 32 N for 6 spans and 33 N for 7 spans. The angle was calculated as 44.76 deg for 6 spans and 34.08 deg for 7 spans. Because less cord force and a larger cord angle at the end of each span are easier for implementation of the catenary system, 6 spans were selected for this antenna.

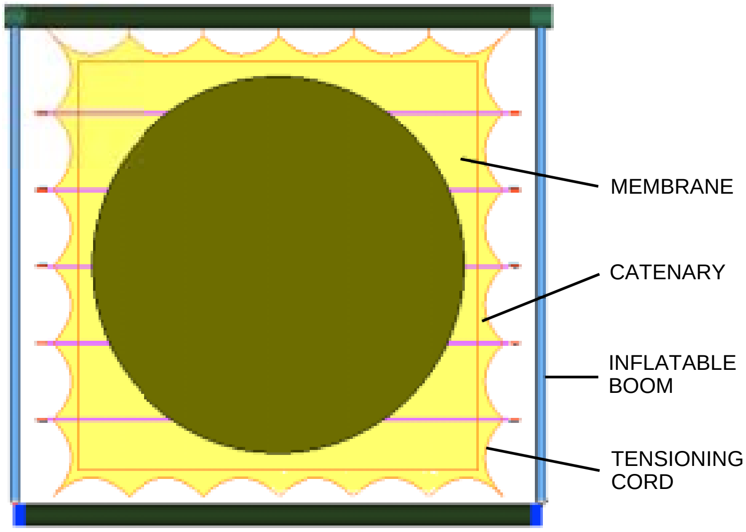

Fig. 5. Inflatable reflectarray antenna.

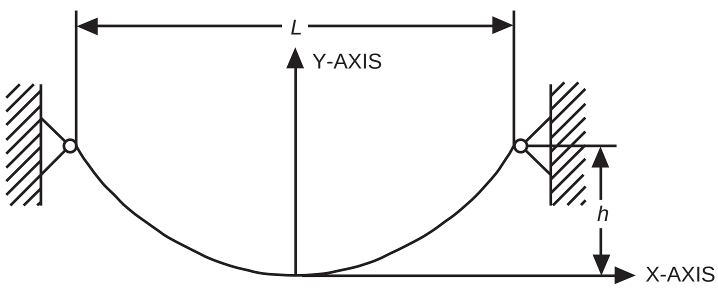

Fig. 6. One span of the catenary system.

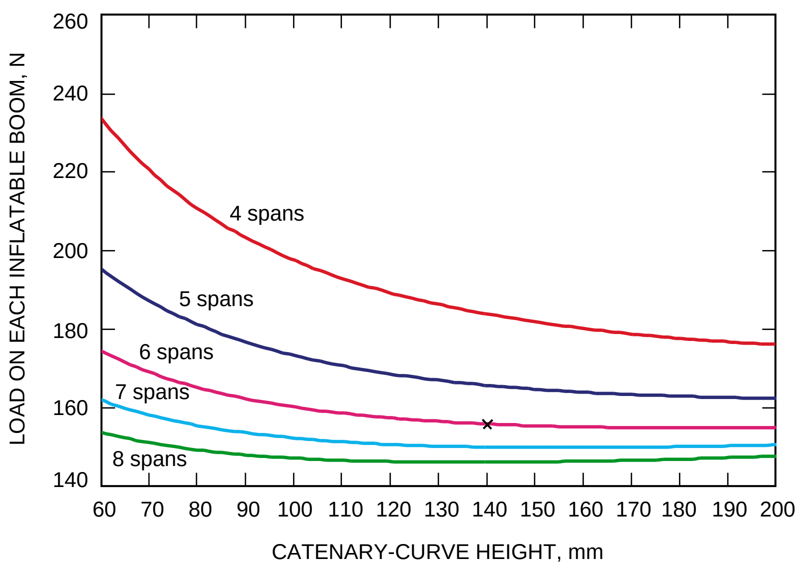

Fig. 7. Catenary analysis results.

After the outline of a catenary system is analyzed and determined, we need to actually implement the catenary system. Two methods of connecting the catenary system to the membrane were proposed and tested on a two-span-by-two-span membrane specimen. Figure 8 shows the schematic of the test setup. Pulling forces are applied by dead weights through pulleys. Locations of pulleys can be adjusted and, consequently, directions of forces can be precisely controlled.

The first catenary implementation method tested is named the tubing catenary system (TCS) and is illustrated in Fig. 9. For this method, very small and soft tubing is connected to the edge of the membrane, and the cord inside the tubing can then apply the tensioning force to the membrane. This method allows the cord to move freely inside the tubing. One can see from Fig. 9 that this method can stretch the membrane as flat as a mirror. It was also discovered during the tests that precise outline of the catenary is very critical to the flatness of the membrane. Wrinkles will show up at places where the outlines are not accurately cut. The advantage of this method is that it can achieve very good flatness. The disadvantage is the additional design complexity. Precisely cutting the outline of the membrane, connecting the tubing to the membrane without inducing any extra stress, and putting the cord into the tubing are very difficult tasks requiring careful planning and implementation. Another challenge is that the bonding between the tubing and the membrane must be made strong enough to withhold the pulling force. Several bonding methods for attaching the tubing and the membrane have been examined. The best method we found is to follow these steps: The first step is to cut the tubing open along the axial

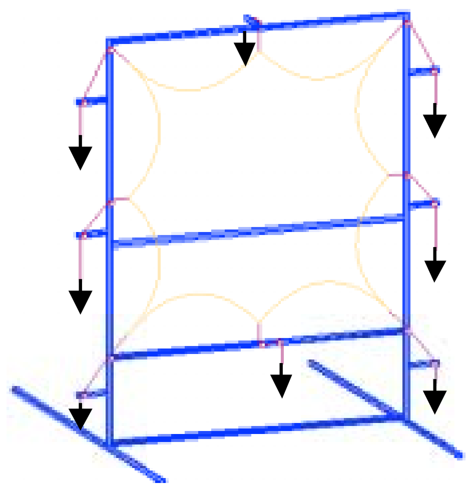

Fig. 8. Schematic of the catenary test setup.

Fig. 9. Tubing catenary system.

direction of the tubing. The second step is to insert the membrane edge into the cut of the tubing and to apply adhesive between the tubing cut surfaces and the membrane edge. The third step is to use Kapton adhesive tape to reinforce the connection.

The second catenary implementation method investigated is named the corner-reinforcing catenary system (CRCS) and is shown in Fig. 10. This method consists of the following steps: The first step is to increase the thickness of the material along the membrane edge for local reinforcement, which is shown by the darker area in Fig. 10. The second step is to reinforce the corners. The third step is to directly pull at these corners. The advantage of this method is the ease of implementation. The disadvantage of this method is that it counts on the membrane deformation to transfer loads from the corners to the center area. Basically, this method does not satisfy the assumption of the previously described catenary analysis. As a result, the membrane flatness is not as good as that of the tubing catenary method.

Another objective of this catenary study is to investigate the effects of the catenary systems on the dynamics of membrane structures. It is known that membrane does not have any out-of-plane stiffness. The out-of-plane stiffness of the membrane can be obtained only from the pre-tension of the membrane, namely differential stiffness. In other words, the dynamics of the membrane are heavily dependent on the membrane stress distribution and, therefore, the catenary system.

To study the effects of catenary systems on the dynamics of membranes, we conducted membrane dynamic tests. The out-of-plane membrane resonant frequencies of each of the two catenary systems were tested. Figure 11 presents a membrane with the tubing catenary system. A relatively small accelerometer was attached to the membrane. The membrane was excited by pushing the membrane and then suddenly releasing the pushing force. The process was repeated for a membrane with the corner-reinforcing catenary system. For both tests, the excitation and response points are both in the center of the membrane. Table 1 gives the first three resonant frequencies of these two tests. It can be seen from Table 1 that the membrane with the tubing catenary system has slightly higher resonant frequencies than does the membrane with the corner-reinforcing catenary system.

The equation of motion for a membrane with tension T is given as [8]

$$T\nabla^2 u = \rho \frac{\partial^2 u}{\partial t^2} \tag{1}$$

where ∇^2 is the Laplace operator and ρ is the mass per unit area of the membrane. If the membrane out-of-plane displacement, u, is expressed as the product of a function U of the spatial variables only and

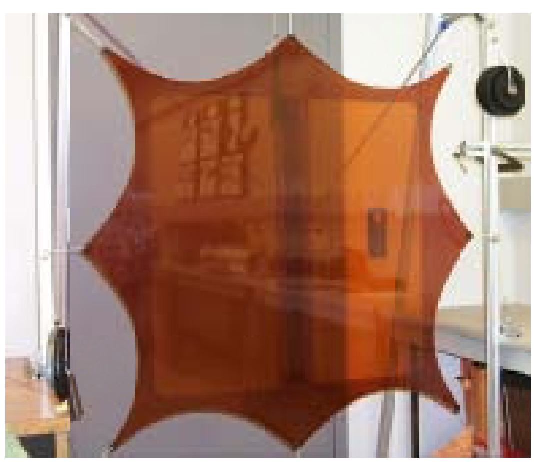

Fig. 10. Corner-reinforcing catenary system.

Fig. 11. Dynamic test setup.

Table 1. Resonant frequencies.

Mode number	TCS, Hz	CRCS, Hz
1	5.20	5.05
2	14.95	14.35
3	16.80	16.50

a function f that is dependent on time only, $u = Uf$. For free vibration, f is harmonic and of frequency ω. Equation (1) is reduced to

$$-T\nabla^2 W = \omega^2 \rho W \tag{2}$$

It can be concluded from Eq. (2) that the membrane resonant frequency is determined by membrane tension T.

Since a gossamer space structure can withstand only a relatively small pulling force imposed by the membrane, how one evenly distributes the stress through an effectively designed catenary system is crucial to the resonant frequency of the membrane. Although our two dynamic tests had the same test set-up, boundary conditions, and tensioning forces, the tubing catenary system had slightly higher first three resonant frequencies than did the corner-reinforcing catenary system. This is due mainly to the fact that the tubing catenary system results in more uniform stress distribution than does the corner-reinforcing catenary system.

C. Constant-Force Springs

The string of the catenary system is connected to 24 constant-force springs (10 on crossbars and 14 on flat panels). Since a constant-force spring provides a constant pulling force, the tension on the membrane does not depend on the elongation of the spring. Therefore, the elongation of the springs does not have to be accurately controlled. The use of the constant-force springs is not only convenient but also necessary. When the antenna experiences substantial temperature changes in space, the supporting structure and the membrane will expand or contract differently. Because of the constant-force springs, stress distribution in the membrane will not be affected by temperature changes in space. These springs are ideal for ensuring the uniform distribution of stresses in the membrane. Figure 12(a) shows how a constant-force spring is attached to a flat panel, and Fig. 12(b) shows how a constant-force spring is attached to a crossbar.

Single-strip constant-force springs were used first. In order to find the force and elongation relationships, tensile tests were performed. Due to the unavailability of the 62-N constant-force springs, two 31-N constant-force springs were used to substitute for the 62-N spring. Table 2 gives the tensile test results. Each setup tested two sets of springs (indicated as A and B). From Table 2, one can see that all those springs can work very well when their elongations are between 51 mm and 76 mm. Forces are still acceptable when elongations are between 76 mm and 127 mm.

However, the weight of each 44-N single-strip constant-force spring is 0.9 N, and the weight of each 31-N single-strip constant-force spring is 0.7 N. The total weight of these single-strip constant-force springs is 23 N. In order to reduce the weight, a new kind of spring, namely a double-strip constant-force spring has been developed by Vulcam Spring & MFG. Co. The weight of each 44-N double-strip constant-force spring is 0.2 N, and each 62-N double-strip constant-force spring is 0.3 N. As a result, the total weight of these double-strip constant-force springs is only 5.6 N. Table 3 gives tensile test results of these double-strip springs.

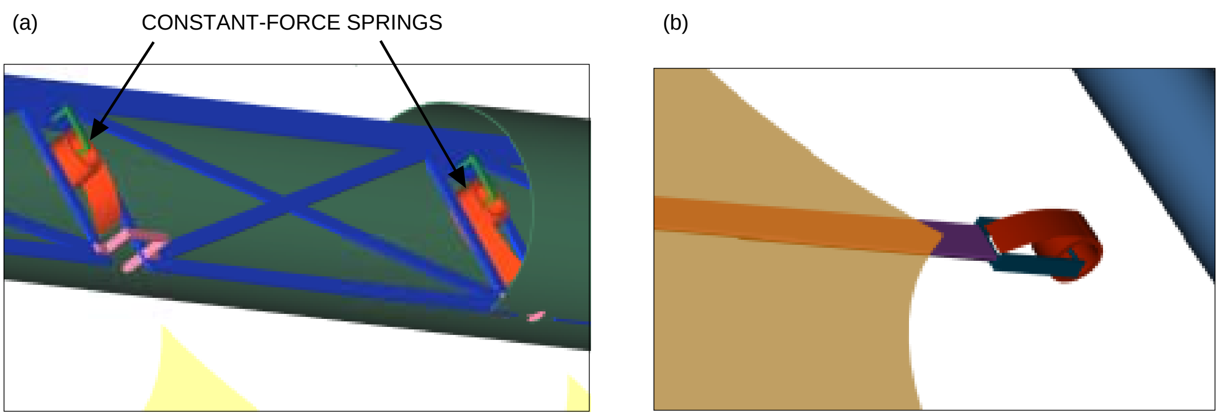

Fig. 12. Constant-force springs attached to a (a) flat panel and (b) crossbar.

Table 2. Tensile test results of single-strip springs.

Single-strip spring	Force, N			
	Spring	51 mm to 76 mm	76 mm to 102 mm	102 mm to 127 mm
One 44.5-N spring	A	44.5	48.0	46.3
	B	45.4	48.0	46.3
Two 31.1-N springs	A	62.3	66.7	68.5
	B	62.3	66.7	69.4

Table 3. Tensile test results of double-strip springs.

Single-strip spring	Force, N			
	Spring	25 mm to 51 mm	51 mm to 76 mm	76 mm to 102 mm
One 44.5-N spring	A	44.5	46.3	48.0
	B	44.5	46.3	48.0
One 62.3-N spring	A	62.3	66.7	68.5
	B	62.3	67.6	68.5

From Table 3, one can see that all the springs give the required forces when their elongations are between 51 mm and 76 mm. Forces are still acceptable when elongations are between 76 mm and 102 mm.

D. Flat Panel

Two flat panels are used at two ends of the antenna. They are made of carbon-fiber material, and extra material has been removed as much as possible to minimize the weight. Figure 13 presents the drawing of the flat panel. Flat panels are located inside the roll-up shells. Flat panels have two functions. The first one is to provide attachment points for constant-force springs; the second one is to resist bending loads created by constant-force springs.

E. Roll-Up Shells

Flat panels are covered by roll-up shells; Figs. 3 and 12(a) both show the roll-up shells. The carbon-fiber roll-up shells have two functions. One is to provide a surface for the electromagnetic membrane to be tightly rolled up, so the thin membrane will be able to survive the launching impact. These shells also act as structural members to provide bending and compression stiffness.

F. Crossbars

Because inflatable booms cannot take much bending load, crossbars are employed as compression members to stretch the electromagnetic membrane. Each crossbar is made of carbon-fiber tubing with an aluminum bracket at each end of the crossbar. Figure 14 shows how a constant-force spring is installed on the aluminum bracket and connected to the crossbar. Crossbars can be rolled up onto roll-up shells with the membrane.

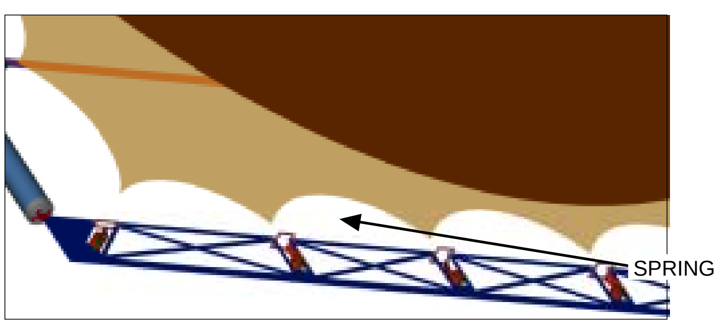

Fig. 13. Flat panel attached by constant-force springs.

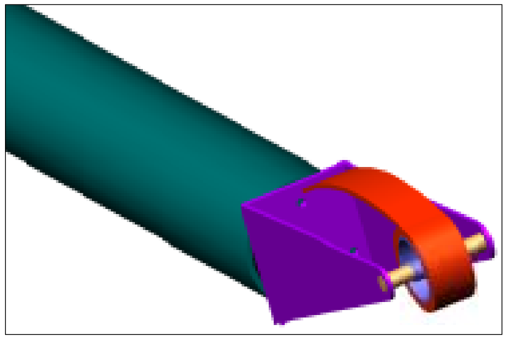

Fig. 14. Assembly of a constant-force spring and a bracket to the crossbar.

G. Mandrels

Mandrels have two functions. The first is to connect inflatable booms to flat panels and roll-up shells. Figure 15 shows how a mandrel is connected to an inflatable/self-rigidizable boom and a flat panel. The second function is to provide smooth circular surfaces for inflatable booms to roll up. It is found [9] that the axial buckling capability of an inflated boom is affected by the diameter of the mandrel while it is packaged. A mandrel is necessary to maintain the diameter of the bundle to avoid the boom damage caused by the packaging.

H. End Caps

End caps are needed for connecting the booms to the structure and keeping pressure inside inflatable/self-rigidizable booms during deployment. Each end cap is composed of an outer cap, inner cap, and o-rings, as shown in Fig. 16. Both the inner cap and the outer cap are machined out of aluminum. The inner cap and outer cap are pressed together by tightening a single bolt, which causes the o-rings to expand in the radial direction for sealing. The end caps have been tested up to 172,369 N/m^2, and they remained airtight. Figure 17 demonstrates how an end cap is assembled.

I. Constant-Force Spring Pre-Holding System

When the antenna is in its deployed configuration, the membrane is stretched by constant-force springs that lengthened about 51 mm. However, springs are not stretched when the antenna is packaged. During the deployment, inflatable booms would have to generate enough force to stretch the springs to their

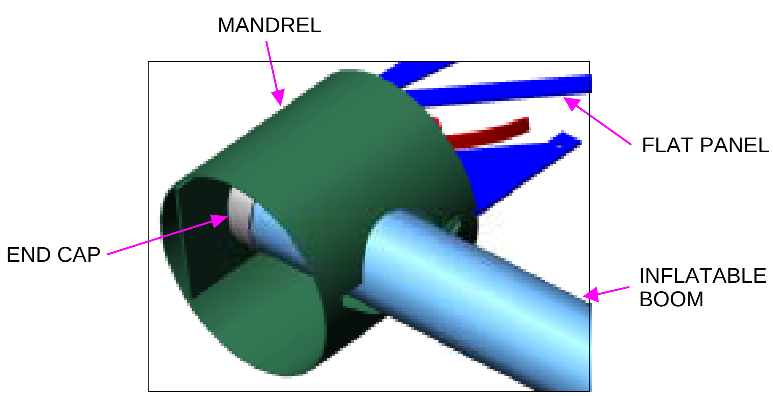

Fig. 15. A mandrel connected with an inflatable boom and a flat panel.

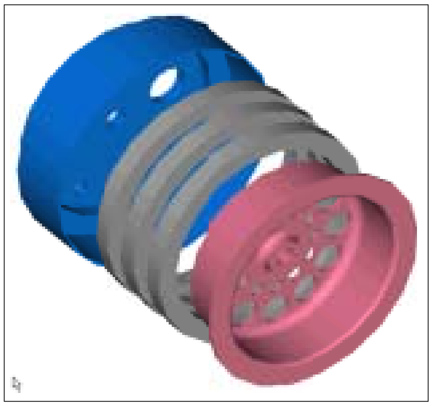

Fig. 16. Components of an end cap.

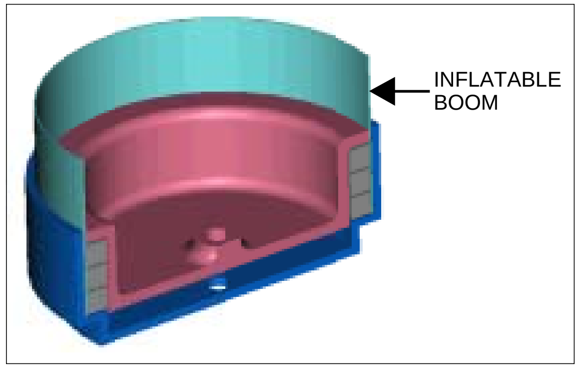

Fig. 17. Schematic of how an end cap is assembled to a boom.

extended length before the booms could be fully deployed if a spring pre-holding system were not provided. This could prevent booms from a successful deployment. Therefore, a constant-force spring pre-holding system has been developed to guarantee a successful deployment of the booms. This system is composed of two major components.

There are two flat panels: one is stationary, and the other is rotating during the deployment. The first component is a controllable string. While the antenna is in the stowed configuration, all constant-force springs attached to the stationary flat panel are lengthened and held by this string. As a result, these spring forces are contained, and inflatable booms can be deployed without any spring forces.

Every spring on the flat panel that is rotating during the deployment is held in position by a string attached to a locking pin. Figure 18 shows the schematic of this mechanism. The pin is placed in two brackets. The pin is pulled toward the walls of brackets by the string and is held in place by friction. When the membrane stretches the spring, the load on the pin is enough to overcome the friction force. The locking pin is pulled out by a small locking spring. The locking spring has to be a soft spring so the pin cannot be self-removed when it is held in place by the friction force.

After the booms are fully deployed, the controllable string attached to the stationary springs is released, and spring forces are loaded on to the membrane. This causes the membrane to move toward the stationary flat panel and to stretch the springs on the rotating flat panel. Consequently, locking pins on the rotating flat panel are released. Therefore, constant-force springs on both flat panels can apply forces to keep the membrane stretched.

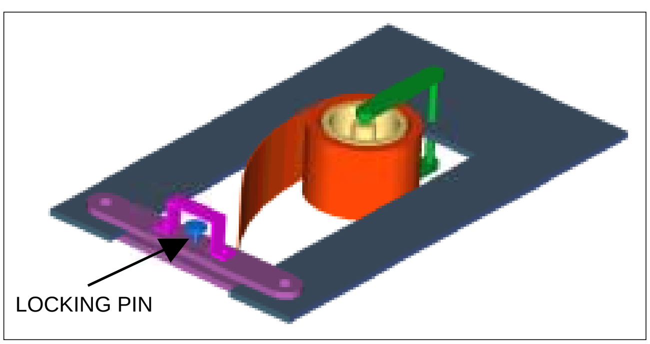

Fig. 18. Schematic of a spring holding mechanism.

IV. Inflatable/Self-Rigidizable Technology

The movie screen antenna represents a major improvement over the horse-shoe antenna. The movie screen antenna employs inflatable/self-rigidizable technology while the horse-shoe antenna uses only inflatable technology without the rigidization.

Technically, the word "inflatable" means the structure is deployed by pressurization. After a structure is deployed, pressure still has to be kept inside the structure to maintain the rigidity of the structure. Due to the material imperfections and/or small damages caused by micrometeoroids, small leaks are unavoidable. Large amounts of make-up gas would have to be carried into space for a long-term mission, which would be very costly or even unrealistic.

With the development of space inflatables, space rigidization is becoming a major research topic. Space rigidization—namely, inflatable/rigidizable structures—means that a structure is rigidized upon the completion of its inflation deployment. Several rigidization methods have been developed [1] and are briefly discussed as follows:

(1) Space-cured polymers. This method includes the development of some polymers that can be cured by space environments, such as a vacuum, ultraviolet light, infrared energy, and cold.

(2) Solvent loss system. This method uses a fabric that is impregnated with a volatile plasticizer (e.g., water). The volatile plasticizer leaves the fabric and makes it rigid as soon as the structure is deployed in the vacuum.

(3) Stretched aluminum laminate. The laminate is made of very thin aluminum foil with polyester films on both sides. While the polyester films provide tear resistance and gas seal, the aluminum foil is stretched by pressure just above the yielding point to provide the rigidity of the inflatable structure.

(4) Cold hibernated elastic/shape memory (CHEM). CHEM is formulated by incorporating shape memory polymers into open-cellular form. This material has a maximum deployed/stowed volume ratio of 30 and is self-expanding when heated up above its glass transition temperature. That means a space rigidizable structure made of CHEM does not need an inflation system to deploy.

Among the rigidization methods mentioned above, the stretched aluminum-laminate method is the only one that is not only inflatable/rigidizable but is also inflatable/self-rigidizable. Self-rigidizable means that the structure automatically rigidizes with no space power, no curing agent, and no rigidization system required. However, due to packaging constraints, only a very thin (no more than 0.1-mm) soft aluminum layer can be incorporated in the laminate. Consequently, an inflatable/rigidizable boom made of stretched aluminum laminate can take only very low axial loading. Before the stretched aluminum-laminate method can be employed in real space missions, the load-carrying capability must be improved.

A new inflatable/self-rigidizable method, namely, a spring tape reinforced (STR) aluminum-laminate boom, has been developed by this research for the movie screen antenna [10]. Figure 19(a) shows the buckling test setup of an STR aluminum-laminate boom. Figure 19(b) shows a 5-m-long STR aluminum-laminate boom, which is rolled up on a 165-mm-diameter mandrel. Figure 19(c) shows the cross-section of the STR aluminum-laminate boom. A typical STR boom consists of a tube that is formed with aluminum laminate. Four spring tapes are attached to the inside wall of the tube in the axial direction. At this time, the commercially available stainless-steel measuring tapes, commonly known as carpenter tapes, are used. With a wall thickness less than 0.1 mm, an STR boom can be easily flattened, rolled up (or folded up), and deployed by a relatively low inflation pressure. The buckling capability of an STR aluminum-laminate boom is significantly improved, due mainly to the high modulus of

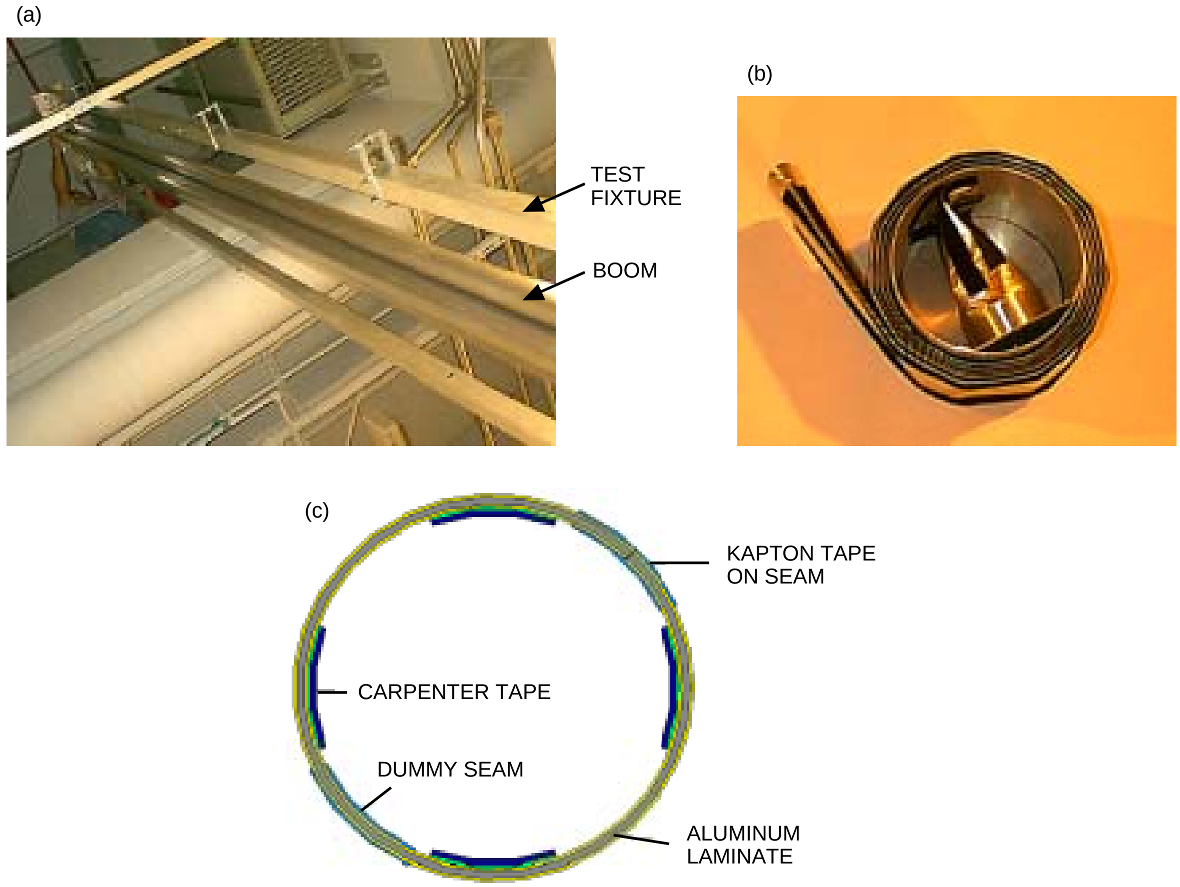

Fig. 19. Spring tape reinforced (STR) aluminum laminate boom: (a) buckling test setup, (b) 5-m-long boom rolled up on a 165-mm-diameter mandrel, and (c) cross-section of a typical boom.

elasticity and curved cross-sectional profile of the spring tapes. The length of an STR boom consequently can be significantly increased. It should be pointed out that spring tapes are very effective in resisting inward buckling, and the aluminum-laminate wall is very stable in resisting outward buckling. Therefore, these two components effectively complement each other in resisting local crippling of the boom. In addition, unlike the non-reinforced aluminum-laminate booms, an STR aluminum-laminate boom relies on the reinforcing tapes, not on pre-strain induced by high internal pressure, to attain its post-deployment stiffness. The required inflation pressure for an STR aluminum-laminate boom is relatively low. Several 5-m-long, 7.6-cm-diameter booms have been assembled and tested. The weight of each boom is only 0.9 kg. The axial buckling-load-carrying capability of this kind of boom can reach 74 kg (with pin–pin boundary conditions).

V. Dynamic Analysis

The structure of the antenna is relatively large and flimsy. The dynamic characteristics of the inflatable/self-rigidizable structure have been questioned. In order to investigate the response of the structure to the excitation introduced by spacecraft maneuvering, a finite-element model has been made, and a dynamic response analysis has been conducted. The membrane itself has very little out-of-plane bending stiffness. The-out-of plane stiffness of the membrane is from the pre-tensioning; it is a function of the membrane stress distribution and is called differential stiffness. Therefore, the dynamic response analysis of a membrane structure has three steps [11]. The first step is the static analysis to obtain the stress distribution; the second step is the modal analysis; and the third step is the response analysis.

A finite element with 568 nodes and 622 elements was assembled. The finite-element software NASTRAN was used for the analysis. First of all, a static analysis was performed to simulate the tensioning of the membrane and to obtain the differential stiffness. Stress distributions in both the x-direction (from the left to the right of the membrane) and the y-direction (from the bottom to the top of the membrane) were calculated, and they were within the range of ± 6895 N/m^2 of 620,528 N/m^2 (620,528 N/m^2 is the design goal). Modal analysis, incorporating differential stiffness induced by pre-tension of the membrane, was also performed. Figure 20 shows the first mode shape of the antenna.

After the modal analysis, transient analysis was conducted. A 1 percent critical damping, which was reduced from the dynamic test result of the inflatable/self-rigidizable boom, was used for the analysis. A 0.1-G step-function disturbance (lasting for 2 s) from the spacecraft attitude control was used as the excitation force. Figure 21 gives the responses of the membrane center as well as the spacecraft. It is concluded that the disturbance from the spacecraft attitude control can induce displacement of up to 0.065 cm at the center of the membrane; 0.065 cm is about 0.07 of the wavelength and can cause a 0.2-dB gain loss. It can also be concluded from Fig. 21 that the membrane motion will decay (i.e., be damped out) to less than 0.025 cm (0.027 wavelength; near-zero gain loss) in 18 s.

VI. Future Tasks

In order to prepare the inflatable/self-rigidizable reflectarray antenna for space missions, several tasks remain to be accomplished. A few important tasks that have been planned for the near future are briefly discussed in the following.

The first of these tasks is the antenna launch restraining system. During the launch, the antenna has to withstand high acceleration, vibration, and acoustic impact. In order for the antenna to survive the launch, a restraining system is essential to hold the packaged antenna in place. The second task is a structural thermal distortion investigation. The space thermal environment is very harsh and could cause distortion of the inflatable structure as well as of the electromagnetic membrane. Therefore, the structural thermal distortion needs to be studied. The third task is to study the effects of damping on the antenna's dynamic responses to spacecraft maneuvering. The sensitivities of damping locations will be investigated, and extra damping will be applied to the most effective places. The fourth task is to perform in-space deployment dynamics analysis. Due to gravity, deployment dynamics testing on Earth of a large inflatable space structure is very difficult and costly. Deployment dynamics analysis is, therefore, a necessary task for a space mission.

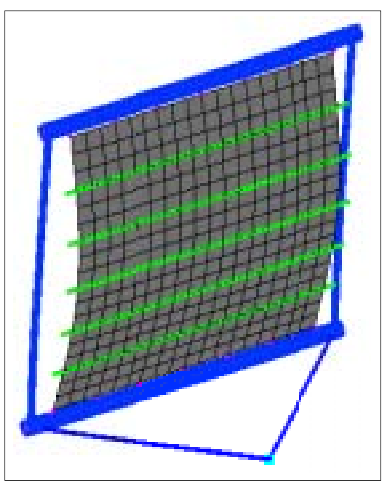

Fig. 20. First mode shape.

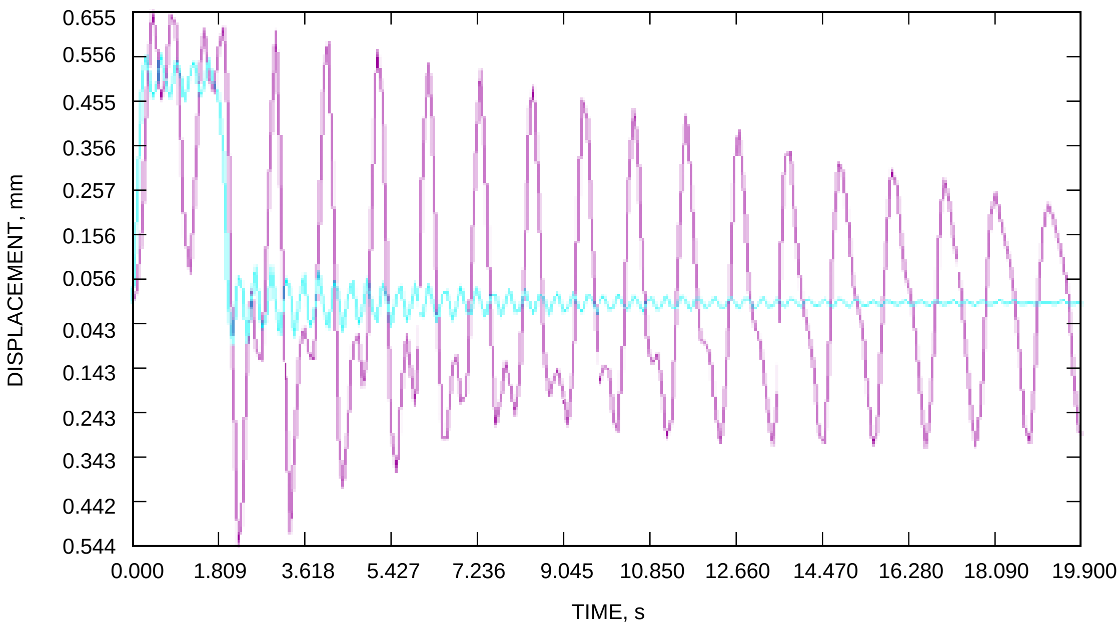

Fig. 21. Transient analysis results.

VII. Conclusions

For a space mission, the launch cost is always a significant portion of the life-cycle cost. Launch cost is usually directly proportional to the launch volume and mass. Space inflatable technology is one of the emerging space technologies that potentially can revolutionize the design and applications of large space structural systems.

This article presented the development of an inflatable structure for a 3-m Ka-band reflectarray antenna. This development took three stages. The first stage was a 1-m X-band inflatable antenna. The second stage was a 3-m (horse-shoe) Ka-band inflatable antenna. The third stage was a 3-m (movie screen) inflatable/self-rigidizable Ka-band antenna. Detailed design of the movie screen antenna as well as functions of each major component have been discussed. Dynamic response analysis of the antenna to spacecraft maneuvering also has been presented. The movie screen antenna used an inflatable/self-rigidizable technology so that any small leaks caused by material imperfection as well as micrometeoroid impact would not affect the membrane performance and so that inflation air would no longer be needed once the antenna was inflated. The differences among inflatable, inflatable/rigidizable, and inflatable/self-rigidizable have been discussed. An innovative inflatable/self-rigidizable technology, an STR aluminum-laminate boom, has been presented. Future remaining important tasks for the development of the inflatable reflectarray antenna also have been discussed.

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