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Inflatable Structure for a Three-Meter Reflectarray Antenna

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The application of inflatable/rigidizable structures technology has become feasible for near-term large space antennas. The development of one of such application of a 3-m Ka-band reflectarray antenna is discussed. This antenna employs the beam scanning and circular polarization technology that allows the use of a flat surface instead of a parabolic antenna surface. Structurally, a flat surface is comparatively easier to fabricate, package, and maintain than a curved parabolic surface. The development of this antenna was also supported by an innovative inflatable/self-rigidizable boom technology, namely spring tape reinforced aluminum laminate boom. A spring tape reinforced aluminum laminate boom automatically rigidizes after it is deployed by inflation pressure. The rigidization of this boom requires no space power, curing agent, or other added-on rigidization devices. Small damage caused by micrometeoroid impacts will not affect structural performance of the boom, and inflation air is no longer needed after the boom is deployed. Detailed mechanical design, dynamic analysis, and deployment demonstration of the antenna are discussed.

Nomenclature

H	=	height of a single catenary
L	=	length of a single catenary
T	=	tension force along the cable
$T_{\max}$	=	maximum tension force along the cable
T_0	=	horizontal component of the tension force along the cable
w	=	membrane stress
θ	=	angle of the cable

Introduction

MAINLY because of increasingly stringent mission cost constraints and the desire to perform more demanding science, larger apertures with very low launching masses and volumes are demanded by space scientists for future missions. Space inflatable/rigidizable structures technology, as suggested by many researchers, can potentially revolutionize future space structures and meet these demands.[1,2]

This paper will discuss the mechanical design and development of an inflatable Ka-band (32-GHz) reflectarray antenna.[3] The radio-frequency (RF) component of this antenna is a flat membrane with hundreds of thousand of copper patches. The membrane is supported by an inflatable/self-rigidizable frame structure. To stow the antenna for launch, the inflatable/self-rigidizable booms of this structure are first flattened. Then the two flattened booms are rolled up on individual mandrels, and the membrane itself is rolled up on a composite cylinder. After the stowed antenna is launched into space, the rolled-up booms are inflation deployed, and the dynamics of the deployment is controlled by the deployment control system. This boom deployment process concurrently pulls out the membrane.

Compared to other types of deployable antennas, this type of antenna offers a very large aperture with extremely lightweight and high package efficiency. The new antenna RF technology, namely, beam scanning reflectarray antenna with circular polarization,[4] made it possible to use a flat surface instead of a parabolic surface as the RF component. A flat thin-membrane surface is much easier to fabricate, package, and maintain its accurate shape than a curved parabolic surface.

This paper starts by reviewing previous versions of the inflatable reflectarray antenna. Details of the current self-rigidizable model will then be presented. Functions and designs of several major components will be discussed. Ground deployment test and dynamic analysis of the deployed antenna will be presented.

Previous Research on Inflatable Reflectarray Antennas

The first reflectarray antenna that used inflatable structures technology was a 1-m X-band engineering model[5] (see Fig. 1). The RF component of this X-band unit consists of two layers of 1-m-diam circular membranes that are separated by a large number of small foam separators. These two RF membranes are supported by an inflatable torus. A hexagonal ring is used to hold the feed. The torus and the hexagonal ring are connected by three inflatable struts. The inflatable structural components, that is, the torus and the struts, are all made of urethane-coated Kevlar. The RF membranes are made of Kapton membranes. The weight of the inflatable structure is 0.74 kg, and the weight of the RF membranes is 0.27 kg. The total weight of the whole antenna is only 1.08 kg.

After successful RF testing of the 1-m inflatable antenna, a 3-m technology demonstration model of the inflatable reflectarray at Ka-band was also developed.[6,7] Figure 2 shows the 3-m inflatable reflectarray antenna. The configuration of this larger antenna is shaped like a horseshoe, and its feed is supported by a hexagonal ring. The ring is connected by three asymmetrically located inflatable struts. Configuration was changed from circular to horseshoe to improve packaging such that, after the inflatable structure is deflated, the membrane and the deflated structure can be rolled up onto a rigid tube assembly without causing significant wrinkling to the membrane. The RF test results of the 3-m antenna demonstrated excellent radiation pattern characteristic. The three struts, hexagonal ring, as well as the horseshoe frame (excluding the rigid tube assembly) are

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all inflatable components made of urethane-coated Kevlar and have a total weigh of 3.92 kg. The single-layer RF membrane is made of Kapton and weighs 2.55 kg. The rigid tube assembly is made of aluminum and weighs 7.10 kg. The total weight of the antenna is 13.57 kg.

Although this Ka-band inflatable reflectarray successfully demonstrated excellent RF performance, it was determined that such a design still has several drawbacks. First, 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), such that it is difficult to protect the amplifiers from extremely cold temperature in space. Second, the feed support struts are long and cantilevered. This can potentially cause undesirable dynamic disturbances. The third drawback of the design is undesirable RF blockage by the feed support struts. Finally, for future real space missions all inflatable structural components in this design require in-space rigidization, which is not yet technically mutual at this time.

New Inflatable/Self-Rigidizable Reflectarray Antenna

Based on these early development efforts, a new architecture for the 3-m Ka-band inflatable reflectarray antenna was developed.[8] Figure 3 is the schematic of the "movie-screen" inflatable reflectarray antenna. Major components include inflatable booms, RF membrane, flat panels, roll-up shells, cross bars, constant force springs, mandrels, end caps, catenary systems, etc. Nonpatterned membrane around the RF section is used to connect the RF area to the catenary system, which is attached to the support structure by constant force springs. The support structure is designed to hold the membrane, to stretch the membrane, and to keep the membrane flat. The required rms for the surface accuracy is 0.1 mm. The feed of this unit is offset located on the spacecraft, and the reflectarray surface is deployed by two inflatable booms in a manner that is similar to the deployment of a movie screen. Figure 4 demonstrates the deployment process of the movie-screen antenna. The inflation deployment process of the antenna only involves the unrolling and pressurization of two inflatable booms. Compared to other mechanically deployed antennas, much fewer moving parts are employed by this inflatable structure. Fewer moving parts not only means less weight and less development cost but can also lead to better deployment reliability. Detailed designs of major components of the antenna are discussed in the following sections.

Inflatable/Self-Rigidizable Boom Technology

There is a major improvement of the movie-screen antenna from the horseshoe antenna. The movie-screen antenna employed inflatable/self-rigidizable technology, whereas the horseshoe antenna only used inflatable technology without rigidization.

Technically, the word "inflatable" means the structure is deployed by pressurization. After an inflatable structure is deployed, pressure is still required to be kept inside the structure to maintain the rigidity of the structure. Because of the material imperfections and/or small damages caused by micrometeoroids, pressure leaks are unavoidable. Large amount of make-up gas has to be carried to space for a long-term mission. This can be very costly or even not feasible. With the development of space inflatable technologies, space rigidization has become a major research topic in recent years. Space rigidization means that a structure is rigidized upon the completion of its inflation deployment.

One new inflatable/self-rigidizable method, namely, spring tape reinforced (STR) aluminum laminate boom, was developed at the Jet Propulsion Laboratory to support the movie-screen antenna.[9] Compared to other rigidization technologies, STR aluminum laminate boom automatically rigidizes after it is deployed with no space power, curing agent, or other rigidization system required. It is thus called self-rigidizable technology. A typical STR boom consists of a tube that is formed with aluminum laminate. For the STR booms developed for the 3-M Ka-band inflatable reflectarray antenna, 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, a STR boom can be easily flattened, rolled up (or folded up), and inflation deployed. The buckling capability of a STR aluminum laminate boom is very high mainly because of the high modulus of elasticity and curved cross-sectional profile of the spring tapes. Spring tapes are very effective in resisting inward buckling, and the aluminum laminate tube 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 nonreinforced aluminum laminate booms, a STR aluminum laminate boom relies on the reinforcing tapes, not prestrain induced by high internal pressure, to attain its postdeployment stiffness. The required inflation pressure for a STR aluminum laminate boom is relatively low. Several 5-m long, 7.6-cm-diam 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). Figure 5 shows a deployed 5-m-long STR aluminum laminate boom. Figure 6 is the picture of a 5-m-long STR aluminum laminate boom, which is rolled up on a 0.165-m-diam mandrel.

RF Membrane

The RF component of the antenna is the RF membrane. The large circular portion of the membrane carries RF patches (approximately 200,000 patches). Figure 7 gives the close-up view of the RF patches. Membrane around the RF section is used to connect the RF area to the catenary system, which is attached to the support structure by constant force springs. The whole support structure is only designed to hold the membrane, to stretch the membrane, and to keep the flatness of the membrane.

Because of the unavailability of wider-sized membrane material, the RF aperture is manufactured and assembled from seven strips of membranes. Each membrane strip consists of 0.127-mm-thick Kapton with 5-μm copper completely covering one side to serve as ground plane and many etched square patches (also 5-μm copper) on the other side to serve as reflectarray elements. Originally 5-cm-wide double-sided adhesive tape was used to join two strips, and the double-sided adhesive tape was covered by a 10-cm-wide Kapton adhesive tape. However, creeping was observed along the seams one year after the assembling of the membrane. Creep would degrade the dimension accuracy, which can significantly impact the antenna performance.

To resolve the creeping problem, a new method was developed to bind the membrane strips together. This method uses flexible epoxy, which made the membrane stronger with no creeping and kept the geometry intact. According to the results from the seam sample tests, the flexible epoxy adhesive chosen was 3M Scotch-weld two-part Epoxy adhesive (2216 B/A Gray). Adhesive is applied to the bounding area of the membrane, and this area is then patched with a 10-cm-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 to clear Kapton.

Catenary System

To maintain the proper functioning of antenna, the membrane must be kept flat. This requires pretensioning of the membrane through a catenary system.[10] The catenary system also provides physical connections between the membrane and the support structure. In addition, dynamic characteristic of the membrane structure is also dominated by the stress distribution in the membrane. Therefore, a catenary system is crucial to the performance of the antenna. Detailed analysis and design of the catenary system are discussed in the following.

Considering one span of the catenary system as shown in Fig. 8, in order to avoid wrinkles the distributed load must be constant. It is assumed that the distributed load is w per unit length. Figure 9 shows the free-body diagram of an infinitesimal element of the cord. At location x, the tension force along the cable is T, and the angle between the cable and the horizontal axis is θ. At location $x + \mathrm{d}x$, the tension force is $T + \mathrm{d}T$, and the angle is $\theta + \mathrm{d}\theta$. The equilibrium

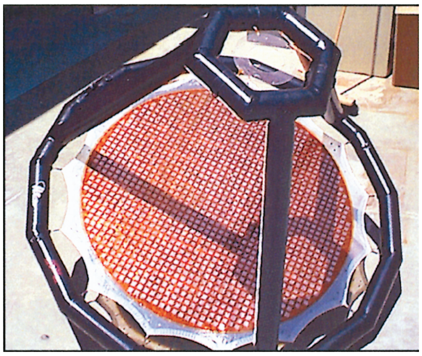

Fig. 1 One-meter X-band inflatable reflectarray antenna.

Fig. 2 Three-meter Ka-band inflatable reflectarray antenna.

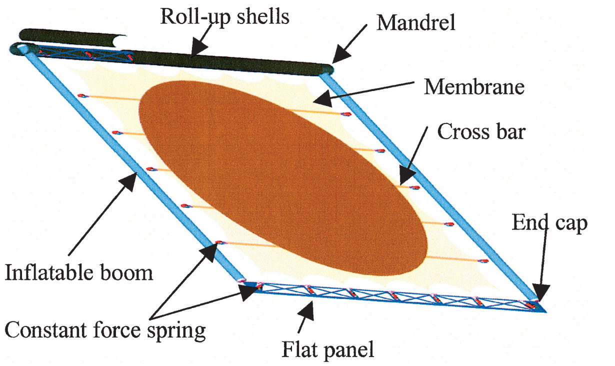

Fig. 3 Schematic of the movie-screen inflatable reflectarray antenna.

equations for both vertical and horizontal directions are given as

$$(T + \mathrm{d}T)\sin(\theta + \mathrm{d}\theta) = T\sin(\theta) + w\,\mathrm{d}x \tag{1}$$

$$(T + \mathrm{d}T)\cos(\theta + \mathrm{d}\theta) = T\cos(\theta) \tag{2}$$

Because $\mathrm{d}\theta$ is infinitesimal, Eqs. (1) and (2) can be simplified as

$$\mathrm{d}[T\sin(\theta)] = w\,\mathrm{d}x \tag{3}$$

$$\mathrm{d}[T\cos(\theta)] = 0 \tag{4}$$

Equation (3) means that the derivative of the vertical component of cable force T equals to the derivative of the distributed vertical load. Equation (4) expresses the fact that the horizontal component of the cable force T remains unchanged. The constant horizontal component of the cable force can be represented by T_0 and is given by

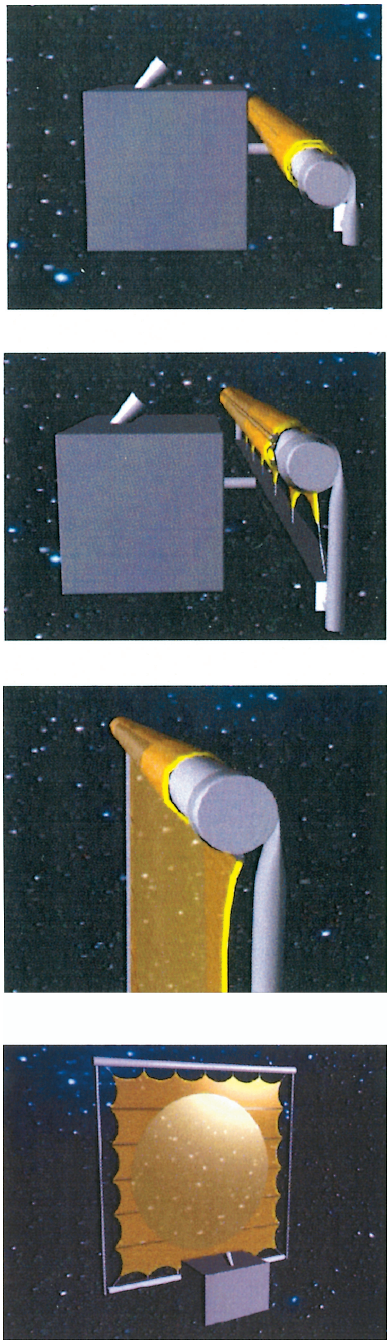

Fig. 4 Process of the inflation deployment.

$$T_0 = T\cos(\theta) \tag{5}$$

Introducing Eq. (5) into Eq. (3) leads to

$$\mathrm{d}[T_0\tan(\theta)] = w\,\mathrm{d}x \tag{6}$$

On the other hand, we have

$$\tan(\theta) = \frac{\mathrm{d}y}{\mathrm{d}x} \tag{7}$$

Therefore, Eq. (6) can be written in the form

$$\frac{\mathrm{d}^2 y}{\mathrm{d}x^2} = \frac{w}{T_0} \tag{8}$$

Equation (8) is the differential equation for the flexible cord.

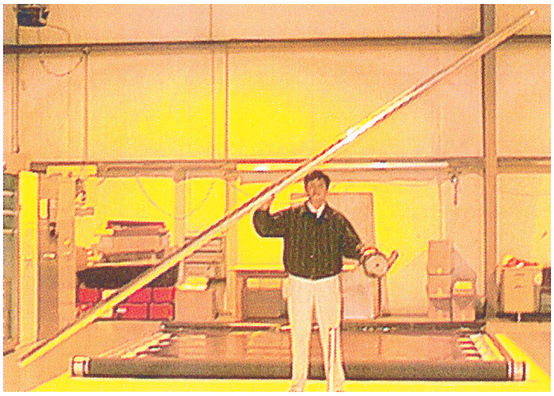

Fig. 5 Five-meter-long STR aluminum laminate boom.

Fig. 6 Five-meter-long STR boom rolled up on a 0.165-m-diam mandrel.

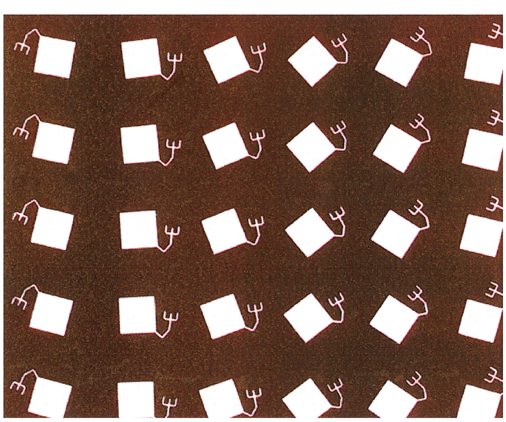

Fig. 7 Close-up of the RF patches (picture of a 2.5 × 3.0 mm membrane).

Assuming there is a coordinate system with its origin on the lowest point of the curve as shown in Fig. 8, we can integrate Eq. (8) twice with respect to x, while taking into account the fact that $\mathrm{d}y/\mathrm{d}x = 0$ and $y = 0$ at $x = 0$. This gives

$$y = wx^2 \big/ 2T_0 \tag{9}$$

Equation (9) represents the parabolic shape of the catenary as the function of the constant membrane stress w as well as the constant horizontal component of the cable force T_0.

The cable force as the function of x can be derived as

$$T = w\sqrt{L^4/64h^2 + x^2} \tag{10}$$

In Eq. (10), h and L are defined in Fig. 8.

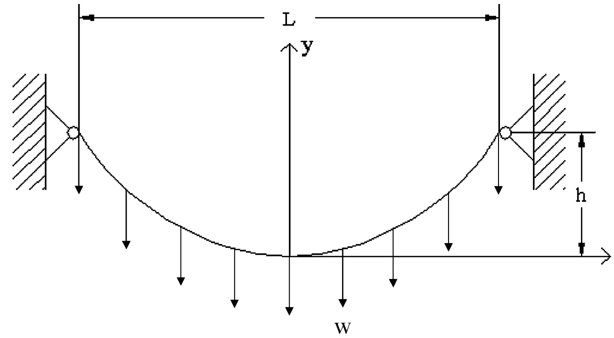

Fig. 8 One-span catenary system.

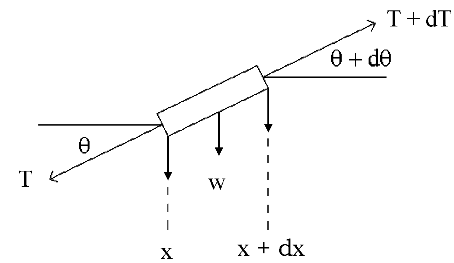

Fig. 9 Infinitesimal element of the cord.

The maximum cable force is located at $x = L/2$ and is equal to

$$T_{\max} = (wL/2)\sqrt{L^2/16h^2 + 1} \tag{11}$$

Equation (11) is used to perform the trade study among variables $T_{\max}$, L, and h for the reflectarray antenna. The size of the membrane shown in Fig. 3 is 3.1×3.1 m. The thickness of the membrane is 0.127 mm. The tension stress of the membrane is preselected to be 621 kPa. Therefore, the distributed load onto the membrane is 0.79 N/cm. The horizontal catenary is identical to the vertical catenary. The inflatable structural parts of the antenna are two inflatable/rigidizable booms. By considering the safety factor, each of these booms is allowed to take only 156 N in the axial direction. The force loaded to these booms is the summation of the cord force of each span in the axial direction of the boom. The span number is minimized to reduce the number of cross bars and the weight of the antenna. Decrease of the span number means the increase of the width (indicated as L in Fig. 8) of each span. Increase of the width of each span means the increase of the maximum cord force [see Eq. (11)] and height (indicated as h in Fig. 8). Increase of height also means the increase of the sizes of the catenary system and the support frame, consequently, the weight of the antenna.

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 four to eight and the height of each span changed from 5 to 20 cm. The analysis results are given in Fig. 10. It can be seen from Fig. 10 that, with 156 N axial boom force, only two design points can be selected. The first one is at six spans with the height of the catenary equalling to 14 cm. The second one is at seven spans with the height of the catenary equalling to 8 cm. For the purpose of helping the final selection between six and seven spans, the maximum cord force and the cord angle at the end of each span were calculated for six spans (height of each span is 14 cm) and seven spans (height of each span is 8 cm). The maximum cord force (at the end of each span) was calculated as 31.5 N for six spans and 32.7 N for seven spans. The angle was calculated as 44.76 deg for six spans and 34.08 deg for seven spans. Because less cord force and bigger cord angle at the end of each span is easier for the implementation of the catenary system, six spans were selected for this antenna.

Figure 11 shows the implementation of the catenary system. Tubing is attached to the edges of the membrane, and a string inside the tubing is used to connect the membrane to the support structure.

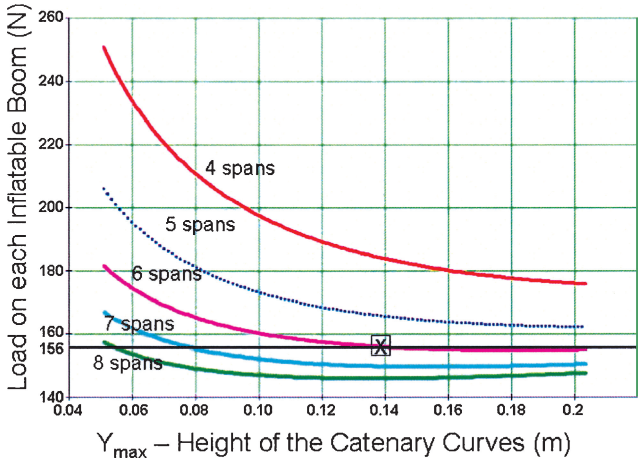

Fig. 10 Catenary analysis results.

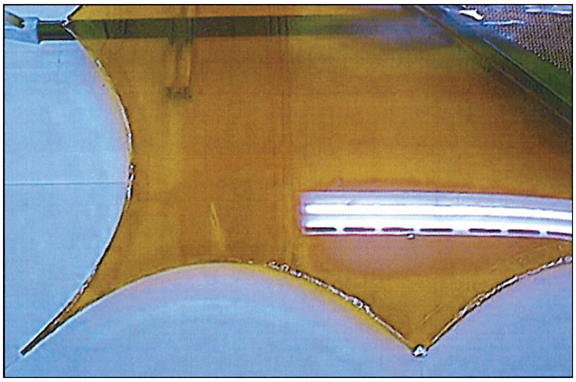

Fig. 11 Implementation of the catenary system.

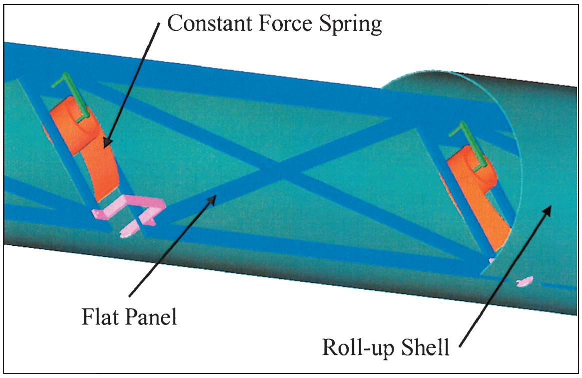

Fig. 12 Constant force springs attached to a flat panel.

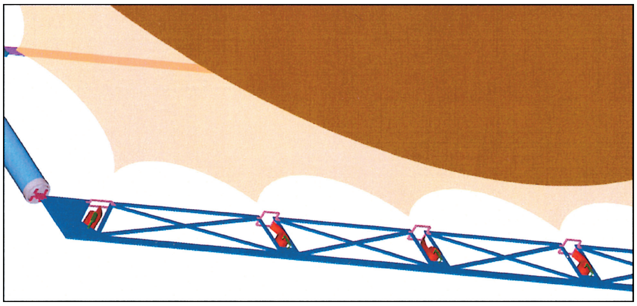

Fig. 13 Flat panel mounted with constant force springs (without showing roll-up shells).

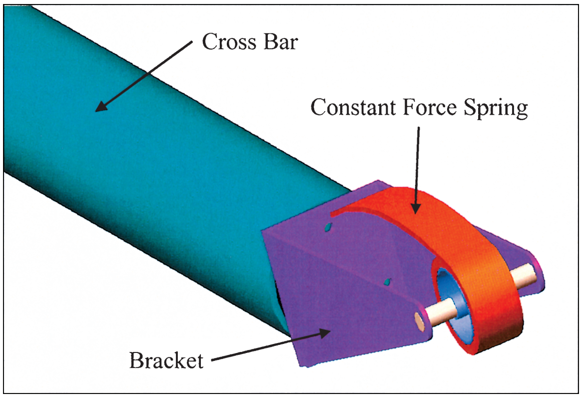

Fig. 14 Assembly of a constant force spring and a bracket to the cross bar.

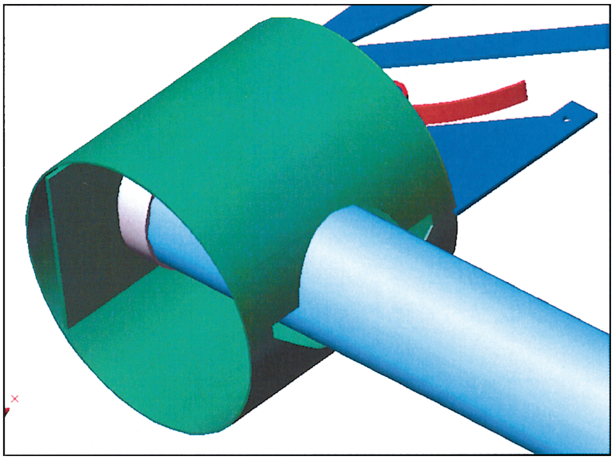

Fig. 15 Mandrel connected with an inflatable boom and a flat panel.

The string can freely slide inside the tubing. The tensioning cord is pulled by constant-force springs, which are connected either to cross bars or to flat panels.

Constant Force Springs

The string of the catenary system is connected to 24 constant force springs (10 on cross bars and 14 on flat panels). Because a constant force spring provides a constant pulling force, the tension on the membrane does not depend on the elongation of the spring, and the elongation of the springs does not have to be accurately adjusted. The use of the constant force springs is not only convenient but also necessary. When the antenna experiences substantial temperature changes in space, the support structure and the membrane can expand or contract differently. Because of the constant force springs, the stress distribution in the membrane will not be affected by these temperature changes. Figure 12 shows how a constant force spring is attached to a flat panel.

Flat Panel

Two flat panels are used at two ends of the antenna. They are made of carbon-fiber material with a latticed geometry to minimize weight. Figure 13 shows the picture of a portion of a flat panel mounted with constant force springs. Flat panels are located inside the roll-up shells and perform two functions. The first function is to provide attachment points for the constant force springs, and the second one is to resist bending loads created by the constant force springs.

Roll-Up Shells

Flat panels are covered by roll-up shells as shown in Fig. 12. The carbon-fiber roll-up shells have two functions. First, the shells provide a surface for the RF membrane to be tightly rolled up, and so the thin membrane will be able to survive the launching loads. The shells also act as structural members to provide bending and compression stiffness.

Cross Bars

Because the inflatable booms cannot take much bending loads, cross bars are employed as compression members to stretch the RF membrane as shown in Fig. 3. Each cross bar is made of carbon-fiber tubing with an aluminum bracket at each end. Figure 14 shows how a constant force spring is installed on the aluminum bracket and connected to the cross bar. Cross bars are rolled onto the roll-up shells with the membrane when the antenna is packaged.

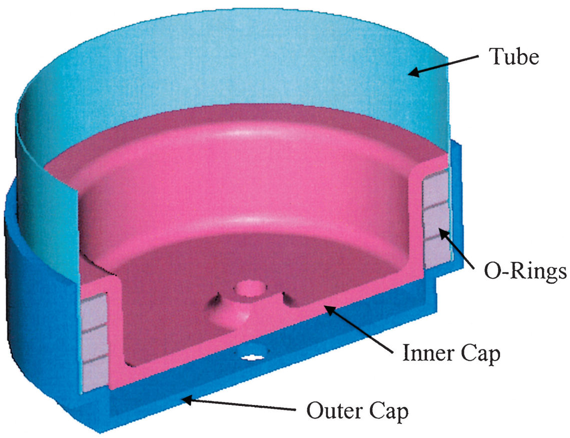

Fig. 16 Components of an end cap.

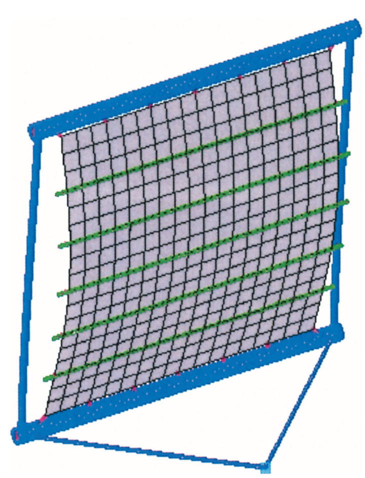

Fig. 17 First mode shape.

Mandrels

Figure 15 shows how a mandrel is connected to an inflatable/self-rigidizable boom and a flat panel. Mandrels have two functions. The first one is to connect the inflatable booms to the flat panels and roll-up shells. The second one is to provide circular surfaces for the inflatable booms to roll up around. It has been found[9] that the axial buckling capability of an inflatable/rigidizable boom after it is deployed is associated with the diameter of the mandrel about which it is packaged.

End Caps

End caps serve two purposes. They are used to connect the booms to the structure and to keep inflation pressure inside the booms during the deployment. Each end cap is composed of outer cap, inner cap, and o-rings. Both inner cap and outer cap are machined out of aluminum. Inner cap and outer cap are compressively attached together by a single bolt. The compressive bolt load causes the o-rings to expand in the radial direction, which, in turn, presses the boom skin against the wall of the outer cap. The end caps have been tested up to 25 psi, and they remained airtight. Figure 16 shows how an end cap is assembled to the boom.

Dynamic Analysis

The structure of the antenna is relatively large and flimsy. The dynamic characteristics of the inflatable/self-rigidizable structure needs to be studied. To investigate the response of the structure to the excitations introduced by the spacecraft maneuvering, a finite element model has been constructed and dynamic response analyses conducted. The membrane itself has very little out-of-plane bending stiffness. The out-of-plane stiffness comes from pretensioning. It is the 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 model with 568 nodes and 622 elements was assembled. The finite element software NASTRAN was used for the analysis. First, static analysis was performed to simulate the tensioning of the membrane and to obtain the differential stiffness resulting from this pretension. Stress distributions in both x direction (from left to right of the membrane) and y direction (from bottom to top of the membrane) were calculated and were within ± 7 kPa of the 621-kPa design goal. Modal analysis, incorporating differential stiffness induced by pretension of the membrane, was also performed. Figure 17 gives the first mode shape of the antenna.

After the modal analysis, a transient analysis was conducted. 1% critical damping, which was reduced from the dynamic test result

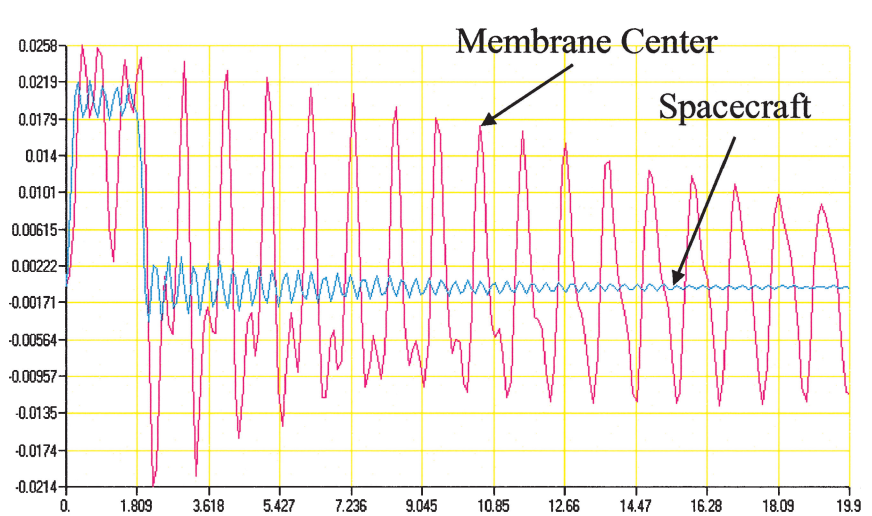

Fig. 18 Transient analysis results.

of the inflatable/self-rigidizable boom, was used for the analysis. 0.1-G step-function disturbance (lasted for 2 s) from spacecraft attitude control was used as the excitation force. Figure 18 gives the responses of the membrane center as well as the spacecraft. It is concluded that the disturbance from 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 0.2-dB gain loss. It can also be concluded from Fig. 18 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.

Demonstration of the Deployment

One of the most important tasks of this study was to build an engineering model to demonstrate the deployment process of this configuration. Figures 19 and 20 are pictures of this engineering model in its stowed configuration.

To have a smooth ground deployment demonstration, a structure was designed and built to support the antenna and eliminate some of the gravitational effects during the deployment. This support structure is composed of two tracks and five pairs of moving arms as shown in Fig. 21. Every moving mandrel has a roller attached to it, and the roller rotates on the track to eliminate resistance during the deployment as demonstrated by Fig. 22. Five pairs of arms were originally in a lower position. During the deployment, each pair of arms open up to support one of the cross bars right after that cross bar separated from the bundle. The arms are actuated by pneumatic cylinders.

Several deployment tests were successfully conducted, and Fig. 23 shows the process of the deployment, from packaged to fully deployed.

Fig. 19 Antenna in stowed configuration (side view).

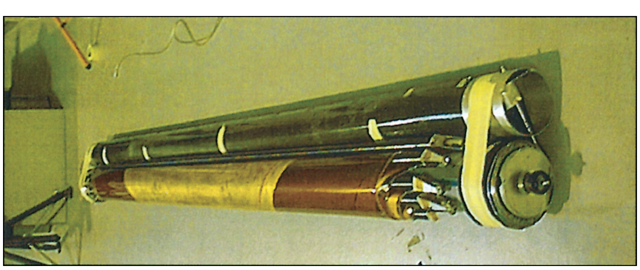

Fig. 20 Antenna in stowed configuration.

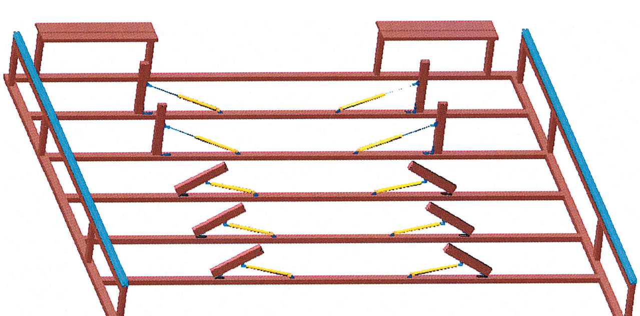

Fig. 21 Deployment support structure.

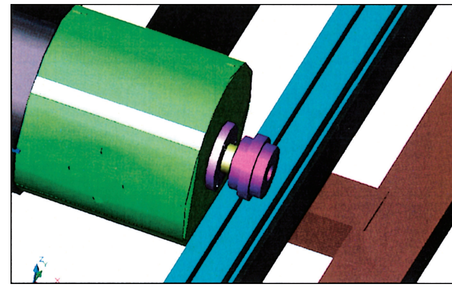

Fig. 22 Mandrel and roller on the track.

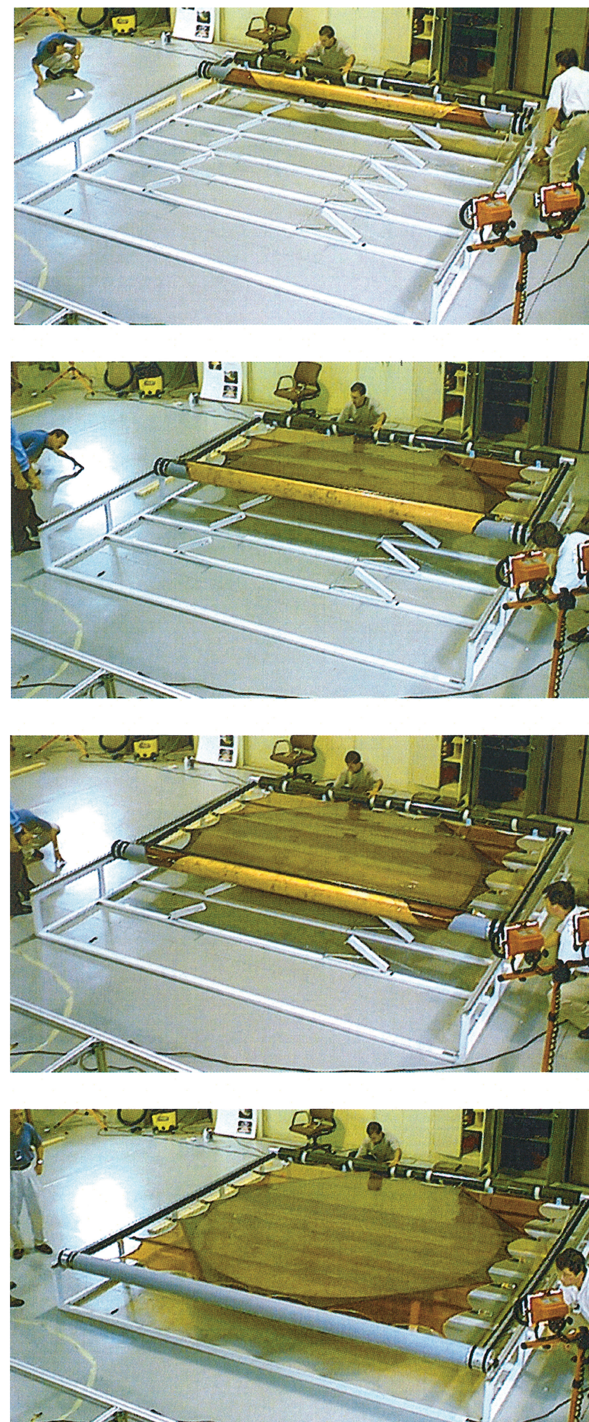

Fig. 23 Process of the deployment.

Conclusions

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

This paper describes the development of an inflatable structure for a 3-m Ka-band reflectarray antenna. This development had three stages. The first stage was a 1-m (circular) X-band inflatable antenna. The second stage was a 3-m (horseshoe) 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 analyses of the antenna have been presented. The deployment test has also been described.

It has been concluded that the movie-screen antenna, which uses an inflatable/self-rigidizable boom technology, is technologically ready for future space missions.

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References

[1] Lou, M., and Feria, V. A., "Development of Space Inflatable/Rigidizable Structures Technology," *Proceedings of Symposium on Deployable Structures: Theory and Applications*, International Union of Theoretical and Applied Mechanics, International Society for Shell and Spatial Structures, and British National Space Center, 1998.

[2] Jenkins, C., *Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications*, AIAA, Reston, VA, 2001.

[3] Huang, J., Feria, V. A., and Fang, H., "Improvement of the Three-Meter Ka-Band Inflatable Reflectarray Antenna," Inst. of Electrical and Electronics Engineers, AP-S/URSI, July 2001.

[4] Huang, J., and Pogorzelski, R. J., "A Ka-Band Microstrip Reflectarray with Elements Having Variable Rotation Angles," *IEEE Transactions on Antennas and Propagation*, Vol. 46, May 1998, pp. 650–656.

[5] "Design, Fabrication, and Integration of a 1 Meter X-Band (8.4 GHz) Inflatable Microstrip Reflectarray Low Mass Technology Demonstrator," ILC Dover, Inc., Final Rept., Contract 960929, Frederica, DE, Aug. 1997.

[6] Huang, J., and Feria, A., "Inflatable Microstrip Reflectarray Antennas at X and Ka-Band Frequencies," *Digest of IEEE AP-S/URSI Symposium*, Inst. of Electrical and Electronics Engineers, 1999, pp. 1670–1673.

[7] Feria, V. A., Huang, J., and Cadogan, D., "3-Meter Ka-Band Inflatable Microstrip Reflectarray," ESA AP 2000 Conf., Paper 1435, April 2000.

[8] Lin, J. K. H., Cadogan, D. P., Huang, J., and Feria, V. A., "An Inflatable Microstrip Reflectarray Concept for Ka-Band Applications," AIAA Paper 2000-1831, April 2000.

[9] Lou, M., Fang, H., and Hsia, L., "Development of Space Inflatable/Rigidizable STR Aluminum Laminate Booms," AIAA Paper 2000-5296, Sept. 2000.

[10] Fang, H., Lou, M., Hsia, L., and Leung, P., "Catenary Systems for Membrane Structures," AIAA Paper 2001-1342, April 2001.

[11] Fang, H., and Lou, M., "Analytical Characterization of Space Inflatable Structures—An Overview," AIAA Paper 99-1272, April 1999.

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