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INTERNATIONAL JOURNAL OF

SPACE STRUCTURES

VOLUME 8 NOS. 1&2 1993

Editors

H. NOOSHIN

Z. S. MAKOWSKI

MULTI-SCIENCE PUBLISHING CO. LTD.
107 High Street, Brentwood, Essex CM14 4RX, England

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Concepts of Deployable Space Structures

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(Received 9 May 1991; revised version received 2 March 1992)

ABSTRACT: This paper presents several concepts of deployable space structures with emphasis on their relation to the basic principles of mechanics on which the concepts depend.

The following subjects are treated: the coilable longeron extendible mast and the theory of "Elastica" by Euler and Kirchhoff; the two-dimensionally deployable array and the theory of elastic surfaces ("Plate Elastica") by Miura and Tanizawa; the variable geometry truss and the theory of truss by Mobius; the tension truss antenna and the theory of truss.

1. INTRODUCTION

Creating a rational structural concept should be the first step in the process of designing a structure and it precedes the practical design step. As far as earth-bound structures are concerned, however, designers often tend to skip over the conceptual design step. It is because there is a lot of information on structural concepts and, in many cases, the only thing they have to do is to select a concept among feasible concepts.

As for space structures, whose environments and requirements are new and quite different from earth-bound structures, a designer has to begin with the creation of a rational structural concept. This is especially true in the case of deployable structures. In order to create a concept for a deployable structure, knowledge of geometry, mechanism, and kinematics are important. However, such knowledge is not sufficient for the present purpose.

The present author has been engaged for many years in the creation of concepts for deployable and related structures for space applications. He found that the really beautiful concepts depend either directly or indirectly on the well-known basic principles of mechanics. It is interesting to note that some of the concepts are directly obtained from minimum/maximum principles of mechanics.

The purpose of this paper is to show how the basic principles of mechanics played an important role when the present author first conceived and verified some concepts of deployable space structures, which have now become well established. This review may be helpful for researchers and engineers in this field.

2. COILABLE LONGERON MASTS AND ELASTICA

Elastica

Linear deployable structures constitute the basic building block for constructing space structures. They can be used independently, or to construct

Dimensions of deformation 1	Dimensions of deformation 2	Dimensions of deformation 3	Dimensions of body
Tensile or torsional deformation of bars	Bending deformation of bars in plane Euler	Bending and torsional deformation of bars in space Kirchhoff	1
	Tensile and shear deformation of plates in plane	Tensile, shear and bending deformation of plates in space Miura-Tanizawa	2
		Complex deformation of solid in space	3

Chart 1. Classification of Elastica.

composite planar and solid structures. Typical mechanisms based on linear deployable structures which can be observed in our daily life are telescopic automobile antennas, carpenter's reels, and foldable scales.

A group of space curves played a key role in the development of space depolyable structures which were used successfully for the early space missions such as Voyager. The curves are elastic curves called "Elastica". It is well known that the study of the Elastica was initiated by Euler [1] in his first book on variational calculus. Later, Kirchhoff treated the Elastica in three dimensions. Treaties by Kirchhoff are mentioned in the book "Theory of Elasticity" by Love [2].

As shown in Figure 1, a rod can be held so that it has a given twist, and its central-line forms a given helix, by a wrench of force K and couple R: the axis of the wrench coincides with the axis of the helix. The force and the couple of the wrench are applied to rigid pieces to which the ends of the rod are attached.

The following equations hold between the stiffness of the rod, the deformed configuration (helix), and the applied force and couple,

$$R = C\tau\cos\alpha/r - B\sin\alpha\cos^2\alpha/r^2 \quad (1)$$

$$K = C\tau\sin\alpha + B\cos^3\alpha/r \quad (2)$$

where B is the flexural rigidity, C is the torsional rigidity, τ is the twist of the rod, α and r are geometric parameters defined in Figure 1[2]. The important fact to be noted here is that the helical form can be maintained also by terminal forces alone, without any couple. In this case, the following equation holds.

$$R = B\cos^2\alpha/r^2\sin\alpha \quad (3)$$

With reference to deployable structures, this fact indicates the possibility that an elastic rod is stowed in a helical form simply by compressing it by terminal forces applied at the ends of the rod.

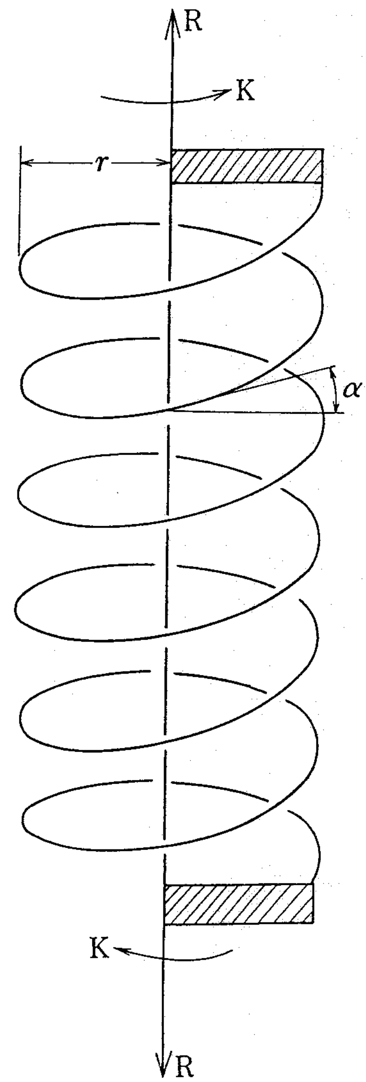

Figure 1. An elastic curve.

Coilable longeron masts for satellite application

A deployable structure using this phenomenon was first realized by the Astro Research Corpora-

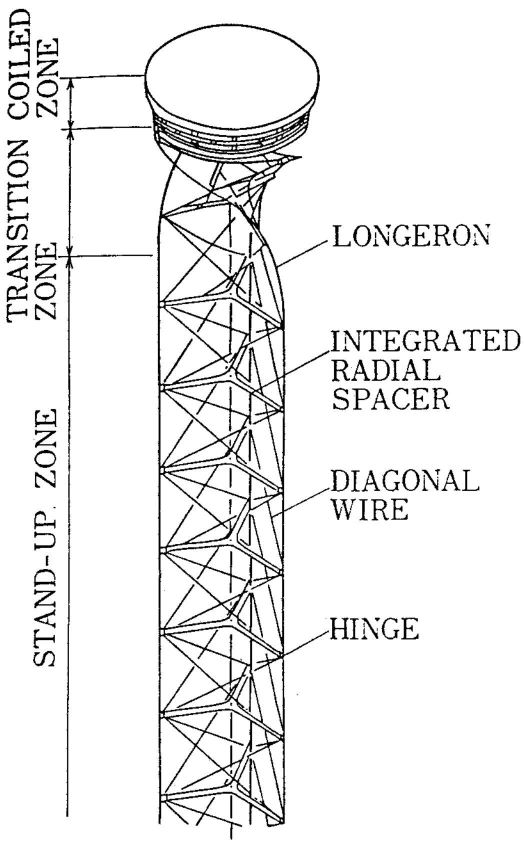

Figure 2. Simplex-mast.

tion, and the extendible mast called "Astromast" was successfully deployed in space on board the Voyager spacecraft [3]. Excited by the success of the Astromast, the author and his colleagues started a laboratory study of a similar concept. At the time we needed extendible masts for supporting payloads, to be installed in a scientific satellite much smaller than the Voyager spacecraft.

The modified concept, we called it the "Simplex-mast", is shown in Figure 2[4]. The principal components of the simplex mast are the coilable continuous longerons (rod), the integrated radial spacers, the diagonal bracing wires, the appropriate hinges, and the traction wire and its motor-driven reel. The three longerons are deformed to helical forms and finally stowed into a coil by the terminal forces applied by the traction wire in the direction of the axis of the mast. Since the elastic large deformation of this composite structure is very complicated, model experiments were necessary to understand the principal characteristics of this structure.

Several models with different design parameters were made and loading and unloading tests were carried out by an Instron-type testing machine. Figure 3 shows the load end-shortening curve and some of the observed deformation patterns in a continuous sequence of stowing and development tests of a model.

In Figure 3, the initial buckling starts from the lower end of the mast (photo. 2), and the first stable buckling configuration is seen in photo. 4. The first small snap-through occurs between photo. 4 and 5 and the second snap-through occurs between 6 and 7. After that, the deformation is

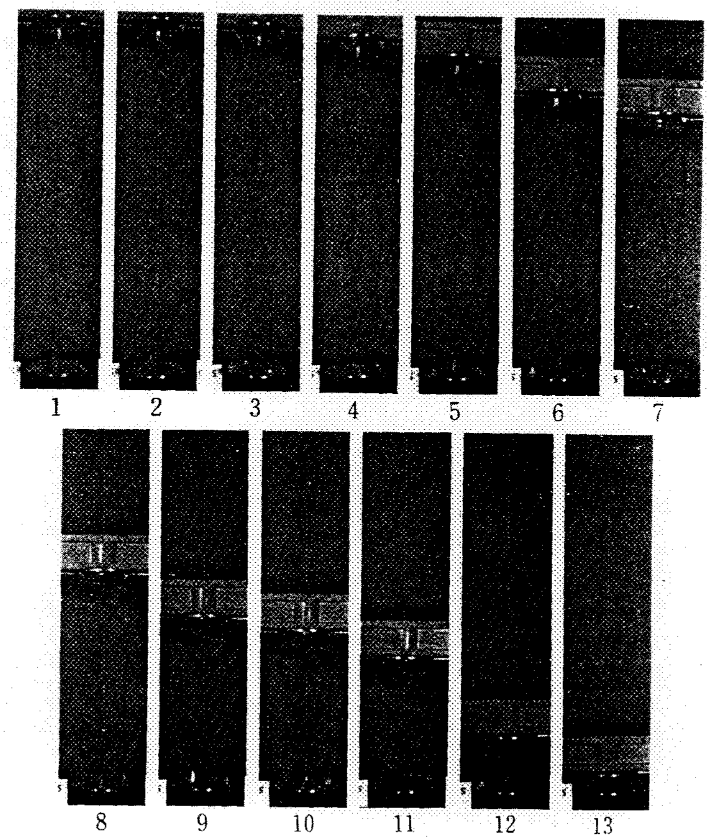

Figure 3. Deformation of Simplex-mast model.

characterized by the combination of a straight part, a transient helical part, and a fully collapsed coiled part, in this order. This configuration continues in a very stable state, therefore, it can be observed that the straight longeron is sucessively deformed to the transient helical form and then to the coil form. A variety of modes of deformation were observed in the models with different design parameters. Among them, the above-mentioned deformation pattern is preferable in view of the stable deployment/retraction as well as the bending stiffness of the mast. For extendible mast

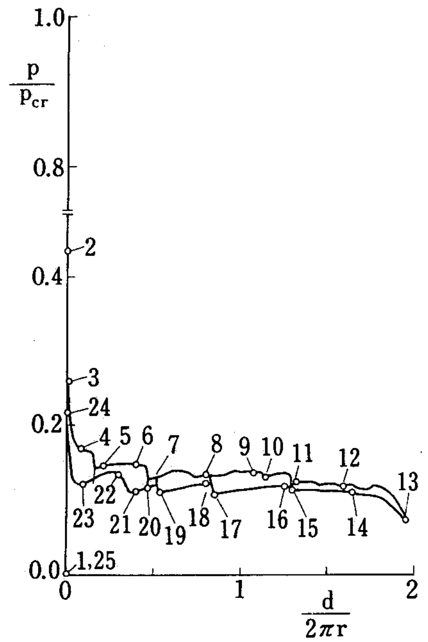

Figure 3. Continued

applications in space, we need the stiffness not only in the fully deployed state but also during the deployment process.

Extensive research and development efforts have ben done to apply the concept to a reliable, accurate, and compact extendible mast which meets severe specifications. The 5m and 3m long Simplex-mast were fabricated for the magnetometer experiment on board of the scientific satellite Akebono. Figure 4 shows a view of the ground testing of the Simplex-mast before launch.

3. PLANAR DEPLOYABLE STRUCTURES

Planar Elastica

Large planar structures are madatory for future space missions. Solar power satellites, space radars, solar sails are some typical examples. These planar structures can be constructed either by deploying a packaged structure or by assembling structural components, which may themselves be deployable. In the previous section, we have seen that the Elastica studied by Euler and Kirchhoff provided a hint for a rational method of packaging slender elastic bars, and it eventually led to the invention of the Astro-mast and the Simplex-mast. It is natural to think that, in the

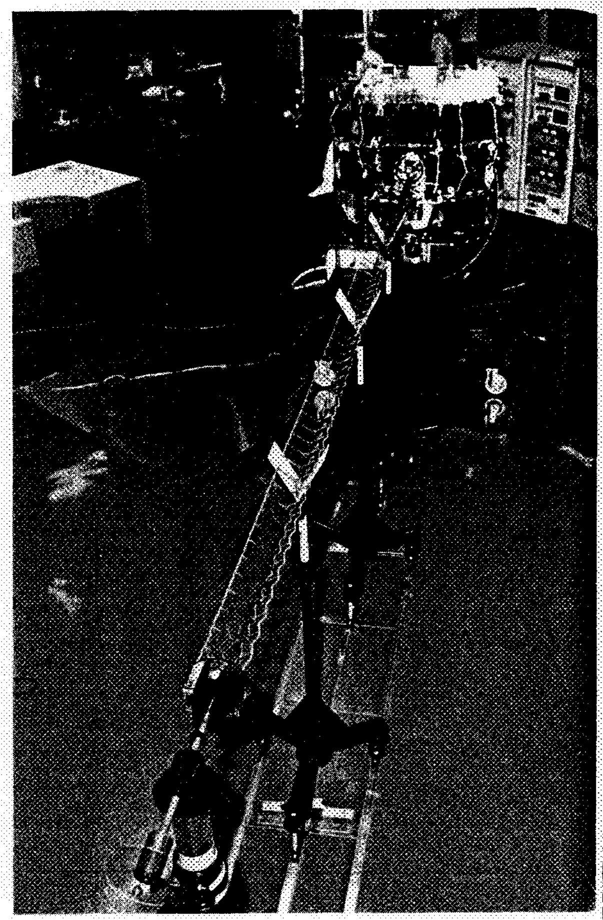

Figure 4. Deploying test of Simplex-mast on board Akebono satellite.

case of thin plates, the corresponding Elastica may also play a key role in the development of planar deployables. Chart 1 shows classification of Elastica for bodies of one, two and three dimensions presented by Konopasek [5]. The corresponding Elastica for the present problem comes under the area marked Miura-Tanizawa in this chart.

Depending on loading and boundary conditions, a wide variety of problems belonging to this category can be considered. Among them, the elastic deformation of a thin, infinite plate subjected to bi-axial compression may be a representative problem. This problem can be expressed by the finite deformation differential equation for a thin plate presented by von Kármán.

$$(D/t)\nabla^4 w = F_{,x_2x_2}w_{,x_1x_1} - 2F_{,x_1x_2}w_{,x_1x_2} \quad (4)$$

$$+ F_{,x_1x_1}w_{,x_2x_2}$$

$$\nabla^4 F = E\,[w_{,x_1x_2}{}^2 - w_{,x_1x_1}w_{,x_2x_2}]$$

where w,D and
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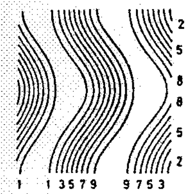

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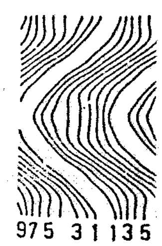
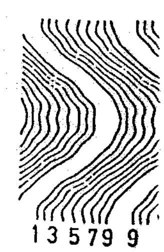


(1)



(6)

Figure 6. Deforn
fundamental regio

where w,D and t denote the normal displacement of the mid-surface, the bending rigidity and the plate thickness respectively. F is an Airy's stress function and is defined as follows:

$$\sigma_{x_1} = F_{,x_2x_2},\ \sigma_{x_2} = F_{,x_1x_1},\ \sigma_{x_1x_2} = -F_{,x_1x_2} \qquad (5)$$

The von Kármán-Tsien-Legget procedure, used for the post-buckling analysis of axially loaded circular cylinders, has been applied to solve this problem. The stress function F is obtained by the use of a Fourier expansion for the normal displacement. The displacement and the stress function are then substituted in the expression for the total potential energy, which is subsequently minimized with respect to the unknown deflection coefficients. Boundary conditions are imposed based on continuity requirements.

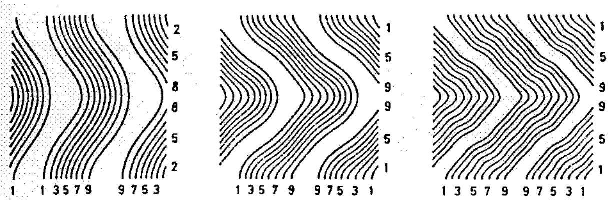


Figure 5. Deformation of infinite plate compressed bi-axially with increasing (left to right) end-shortening parameter (contour map) of the fundamental region.

Figure 5 shows one of the solutions in the form of contour map [6] as the end shortening is increased. The computation indicates that the bending deformation becomes dominant as the plate thickness decreases. For thin plates, the in-plate strain energy becomes large in comparison with the bending strain energy and hence, according to the principle of locally minimum potential energy, as the wall thickness is decreased, a deformation pattern with smaller in-plane strains and larger bending strains is produced. For an infinitely thin plate, therefore, the deformation should be completely inextensional within the mid-plane of the plate. This result is supported by the computed in-plane strains.

Figure 6 shows 10 other solutions, arbitraily selected from the computed data. These deformations feature sharp ridge lines, and are essentially inextensional within the mid-plane. Since the elastic plate problem is parallel to the elastic rod problem, this group of surfaces can be called "elastic surfaces", or "Plate Elastica". It is quite surprising that the elastic surfaces are by no means the smoothly curved surfaces expected by analogy with the rod problems. Becase of the property of inextensional deformation, these deformations can be visualized by models made of paper.

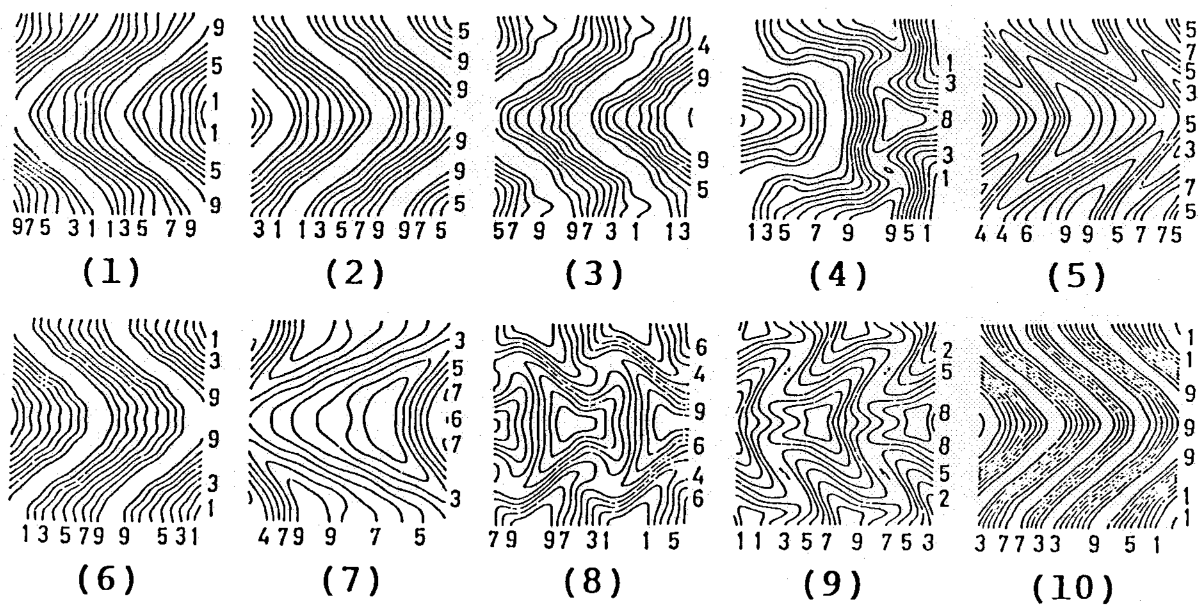


Figure 6. Deformation of infinite plate compressed bi-axially (arbitrary selected 10 solutions, contour map of the fundamental region).

When the least energy solution is sought among these solutions, we obtain the polyhedral surface based on a herringbone-shaped region which is further composed of four congruent parallelograms, as shown in Figure 7. This is exactly the surface presented by the author in relation to Yoshimura's buckling pattern for thin cylindrical shells [7]. A surface is developable if the sum of angles around an arbitrary point on the surface is 2π. As shown in Figure 7b, the sum of vertex angles of this polyhedral surface is 2π, therefore, it is developable. This surface is named "the developable double corrugation surface (DDC surface)".

The Fourier series representation of the DDC surface is as follows:

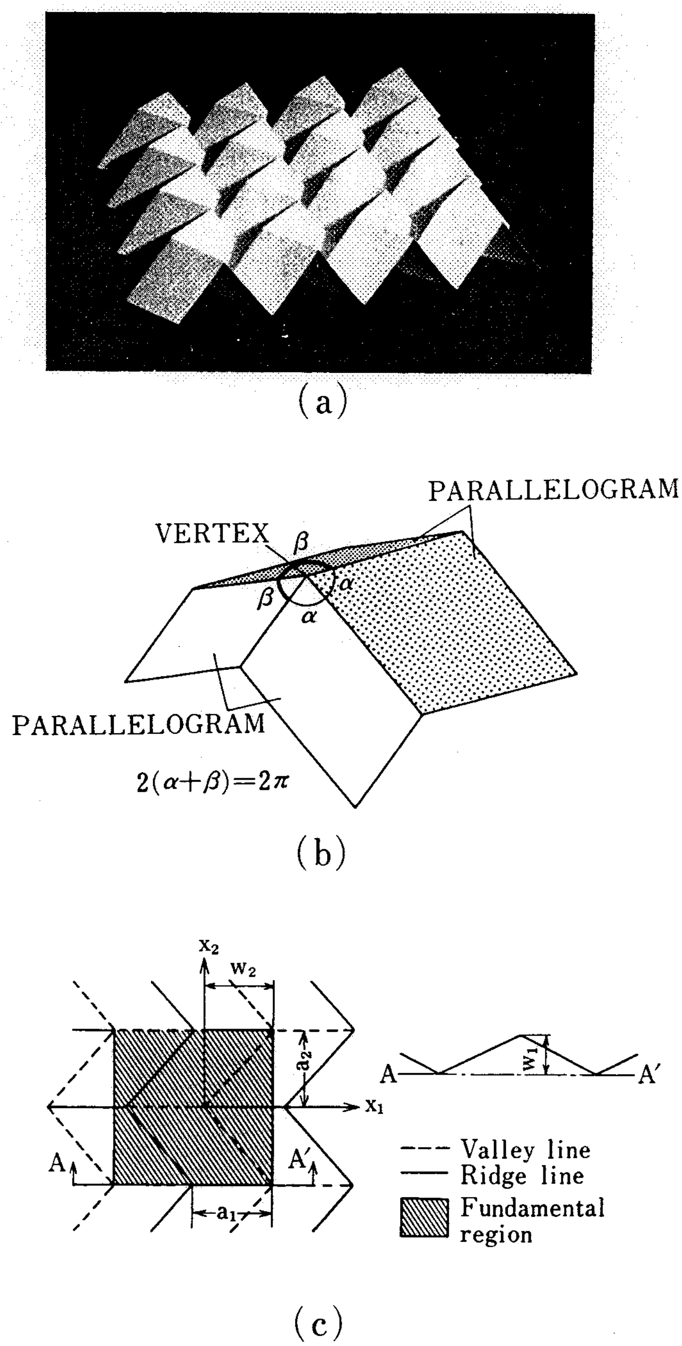


Figure 7. Developable double corrugation surface (DDC surface).

$$w/w_1 = \sum_{i,j} [A_{i,j}\sin(i\pi x_1/a_1) + B_{i,j}\cos(i\pi x_1/a_1)]\cos(j\pi x_2/a_2)$$

$$A_{i,j} = S_m \cdot mh(2-\delta_{no})/(m^2h^2-n^2) \cdot [1-\cos(mh\pi)\cos(n\pi)] \quad (6)$$

$$B_{i,j} = S_m \cdot mh(2-\delta_{no})/(m^2h^2-n^2) \cdot [\sin(mh\pi)\cos(n\pi)]$$

$$h = w_2/a_1$$

where $w_i(i=1,2)$ means twice the wave amplitude of the DDC surface in x direction and δ is the Kronecker delta (see Figure 7), S_m is the expansion coefficient of the triangular wave:

$$S_1=0.5,\ S_i=-2[1-\cos(i\pi)]/(\pi^2 i^2) \quad i \geq 2.$$

We know that the application of von Kármán's equation is limited to finite displacement. The numerical computation is naturally within that limit. Because the resulting surfaces are developable, there are no limits on the magnitude of the deformation. Therefore, by increasing the edge angles of the polyhedra, the DDC surface can be folded to the limit.

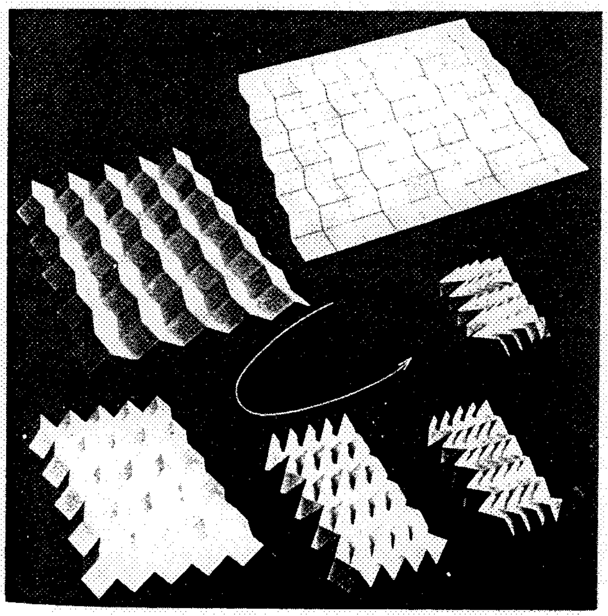


Figure 8. Folding a plate to DDC surface.

Planar deployable structures

The DDC surface leeds to a novel concept for planar deployable structures. By this concept, a plane can be folded in two mutually orthogonal directions at the same time, and in a uniform way.

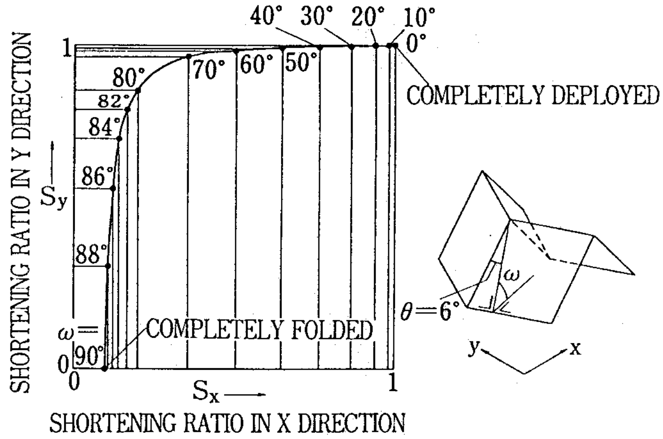


Figure 9. Locus of folding by DDC surface.

In Figure 8, a series of photographs of a paper model shows how a plane is folded up and contracts simultaneously lengthwise and widthwise. If an ideal paper of vanishing thickness is folded infinitesimally close, then it will fold into a point. This is the transformation of a plane into a point [8].

Another important characteristic of this deployable structure is that its contraction in the two mutually orthogonal directions are related throughout the folding process. A contraction in the x direction is always accompanied by a contraction in the y direction, and vice versa. If S_x and S_y represents the shortening ratios in the x and y directions, respectively, they are expressed by the following formulas.

$$S_x = \cos[\sin^{-1}(\cos\theta \cdot \sin\omega)]$$

$$S_y = \cos\omega/\cos[\sin^{-1}(\cos\theta \cdot \sin\omega)] \quad (7)$$

where θ and w are defined in Figure 9. The solid curve in this figure indicates the locus of (S_x, S_y) for decreasing ω. It can be observed that there are two distinct phases in the depolyment process. In the first phase deployment occurs primarily along the y direction, up to 80% of full extension with only 20% extension in the x direction. On the other hand, during the second phase deployment is primarily in the x direction. Nevertheless, on the whole, the deployment process is one of simple and continuous motion. In contrast, in the standard so-called orthogonal folding, the folds in the x and y directions are independent.

Now, the plan is under way to launch a two-

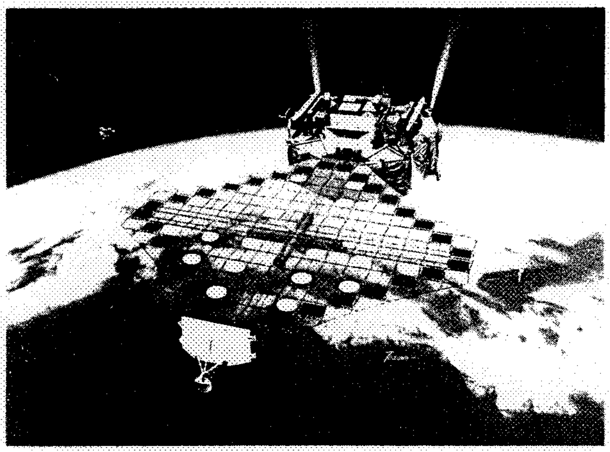


Figure 10. Two-dimensionally deployable array experiment on board Space Flyer Unit.

dimensional deployable array on board the Space Flyer Unit, scheduled for 1995 (Figure 10). The array utilizes the same folding principle described above. It is a thin membrane solar cell array which will be simultaneously deployed in two orthogonal directions, thus, it is called the "Two-dimensional Depolyable Array Experiment" (7). This concept of deploying large membranes is also suitable for the sails of solar sail spacecrafts.

4. VARIABLE GEOMETRY TRUSS AND ADAPTIVE STRUCTURES

Mobius theory on truss

For deployable structures, the two extreme configurations, that is, the packed and deployed configurations are important and the intermediate configuration is usually left out of consideration. After several years of research on deployable structures, the present author came to the conclusion that, if a structure can change its configuration step by step and can stay rigid at any step, it has very wide applications. That is, the possibility of structures which can be called variable geometry structures was envisaged. Because the majority of space structures are truss type structures, the variable geometry structure should be sought first in this category. Let it be called a variable geometry truss (VGT).

The concept of the VGT is based on the classical work by A.F. Mobius in 1837. Mobius's work is introduced by Timoshenko as follows [1]. "In his book on statics, Mobius discussed the problems of equilibrium of a system of bars hinged together and shows that if there are j hinges it is necessary to have no less than 2j−3 bars to form a rigid system in one plane and 3j−6 bars for a three-dimensional system. He also observes that, if a system has the number of bars essential for rigidity and if it be assumed that one bar, say that of length l(ab) between the joints a and b is removed, then the system will permit motion of the members as a mechanism. As a result of this relative movement, the distance between the joints a and b may be altered."

Variable geometry truss

Mobius description of the stability of the truss indicates that, if it is viewed from a new angle, the shape of the truss can be changed. Thus, if the length l(ab) between the joints a and b is changed, then, the shape of the truss is changed too. Of course, this does not cause any forces in truss members. The original thought of the variable geometry truss concept comes from this reasoning.

Let us obtain the condition under which a truss can change its configuration. As Mobius described, this condition is satisfied if a truss has the number of bars required for rigidity, in other words, if it is a statically determinate truss. Then,

$$m - 3j + 6 = 0 \tag{8}$$

where m is the number of bars (members) and j the number of joints. Because space structures are usually made by repeating large numbers of modules, the third term of the equation is negligible in comparison with other terms. Thus, the equation $m-3j=0$ is valid in an approximate sense, hence the number of members is three times the number of the joints. Because a member is connected to two joints, a joint collects six members on average.

It is found that there are only two configurations for the linear statically determinate spatial-truss structure shown in Figure 11. The configuration shown in Figure 11a consists of tetrahedral modules, while the configuration in Figure 11b consists of octahedral modules. Further-

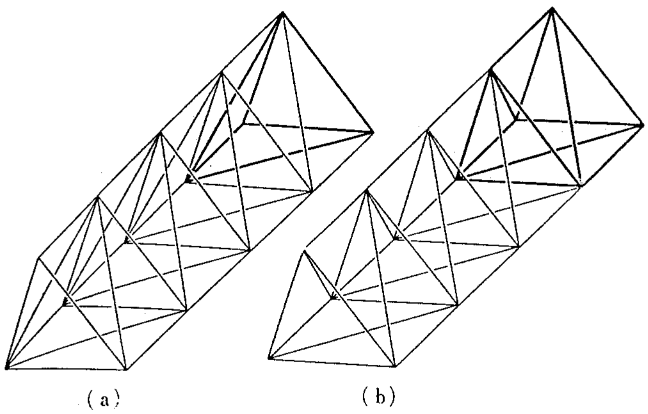


Figure 11. Linear statically determinate spatial trusses.

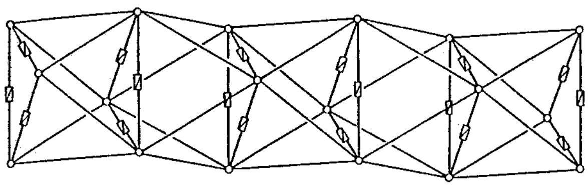


Figure 12. Variable geometry truss (VGT).

more, if an equilateral octahedral truss module is used, the truss shown in Figure 12 is obtained. This truss is a symmetry rich structure and is used for the following study.

The next problem is to determine the layout of the variable length members. A variety of VGTs of different characteristics will be obtained depending on the location of the variable length members. The truss shown in Figure 12, which is equipped with actuators in each lateral member, was originally developed by the ISAS group (Miura, Sakamaki and Suzuki [10]) and NASA group (Rhodes and Mikulas [11]) in the middle of the eighties. It has the unique property that the truss is completely collapsed if each lateral member increases its length to 3 times the original unit length. This is due to the relation between the face angle θ, shown in Figure 13, and the extension ratio k of the lateral members which are originally unit length.

$$\theta = \cos^{-1}(k/2\sqrt{3}\ \sqrt{1-k^2/4}) \qquad (9)$$

This layout of variable length members is selected for the present paper.

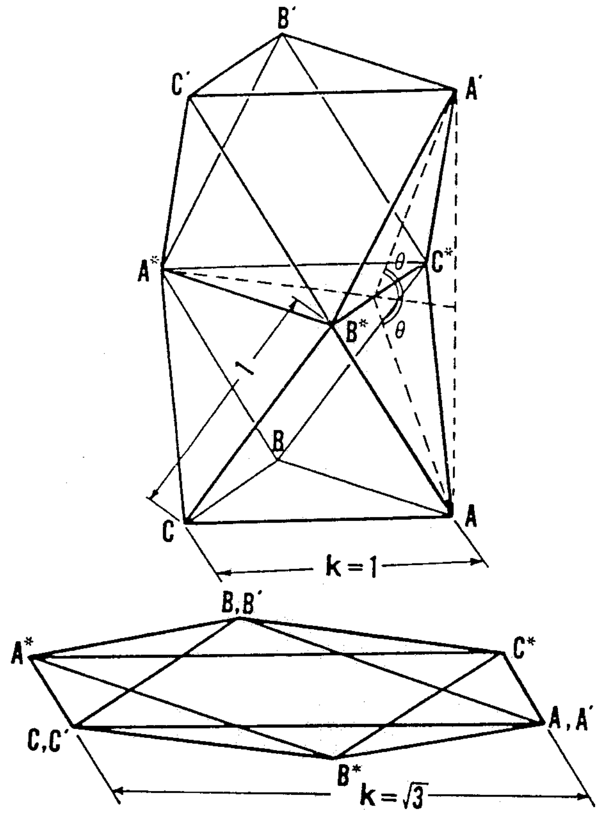


Figure 13. Geometry of folding a VGT unit.

Possible configurations and demonstration by a model

Some typical configurations of the VGT unit are presented in Figure 14. Conclusively, the VGT can simulate an arbitrary curve in three-dimensional space.

Figure 15 shows three configurations displayed by a 8-modules VGT conceptual model. The length of the diagonal members is 400 mm, and the length of the lateral members can change from 400 mm to 600 mm. Each lateral member is equipped with an actuator and is program controlled by a microcomputer.

The theoretical study and demonstration of the VGT concept presented the first clear example for the adaptive structure concept [13]. Adaptive structures are defined as structural systems whose geometric and inherent structural characteristics can be changed beneficially to meet mission requirements, either through remote commands and/or automatically in response to external stimulations.

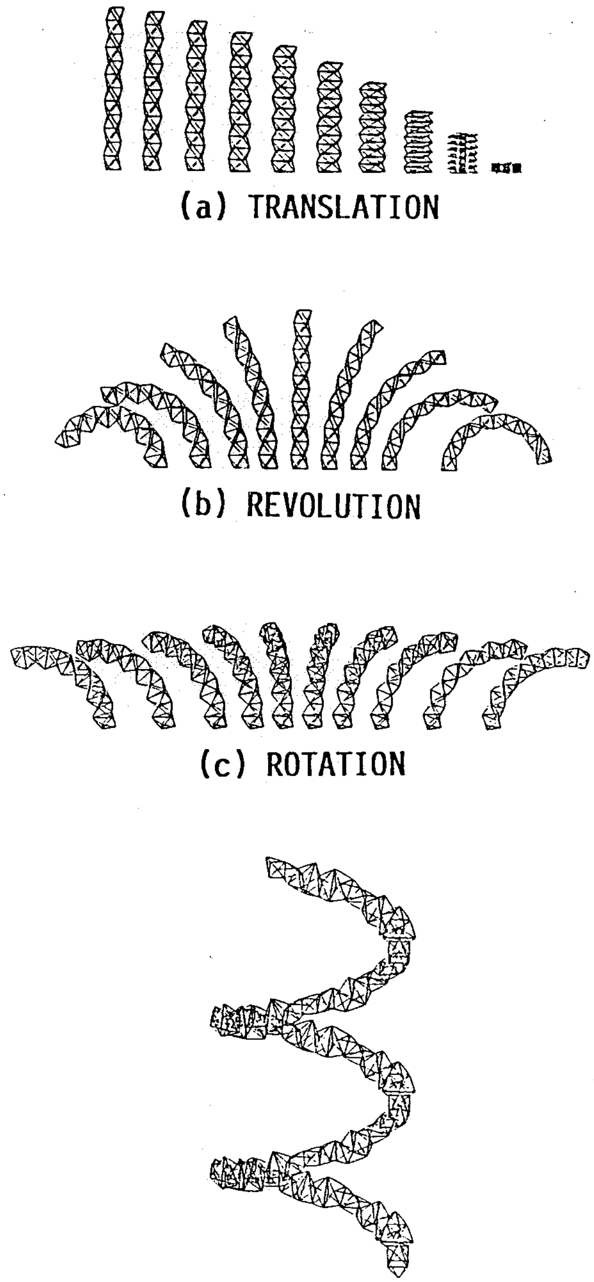


Figure 14. Typical configurations of VGT.

5. TENSION TRUSS ANTENNA

Tension truss concept

Various structural concepts have been proposed for space-borne large deployable antennas. Among them, antennas constructed by rigid spatial trusses or beams are prevalent. The wrap-rib antenna and the octet-truss antenna are a few examples. As the size of antennas increases, however, larger ones constructed by rigid members will meet serious difficulties caused by increasing weight, packing volume, and number of joints. So, the present author believes that antennas using primarily tensile members will play a major role in future lightweight, large space antennas.

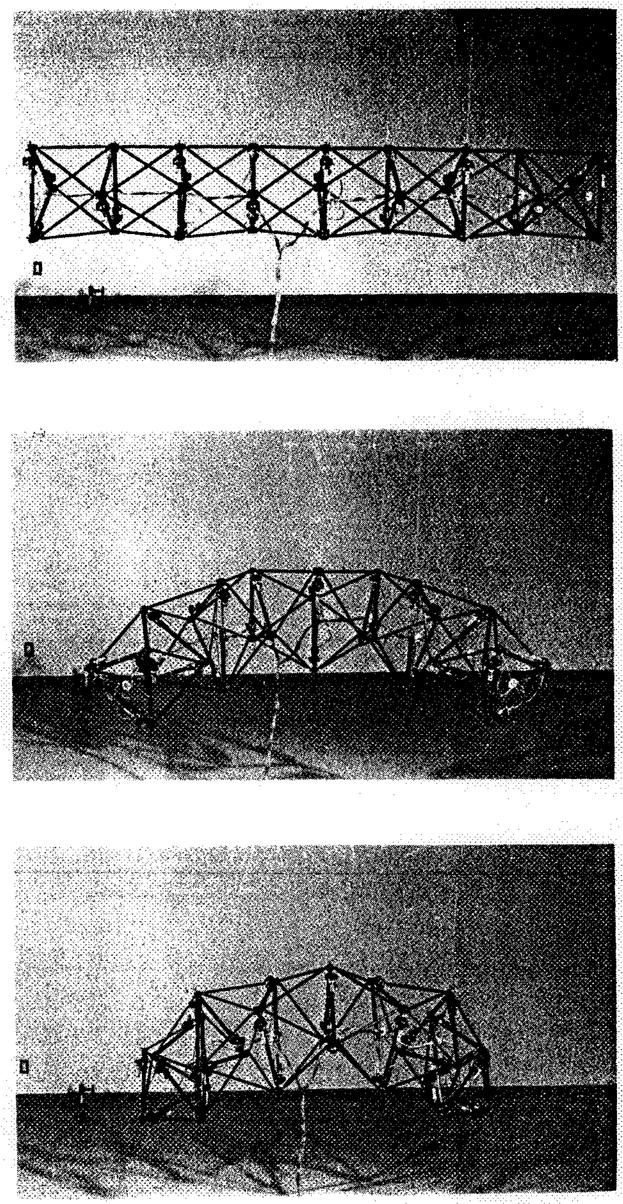


Figure 15. Demonstration by VGT model.

The problem of constructing an antenna reflector surface in three-dimensional space by a latticed tensile structure is, in terms of mathematics, establishing a finite set of lattice points describing, as closely as possible, a parabolic surface. For this

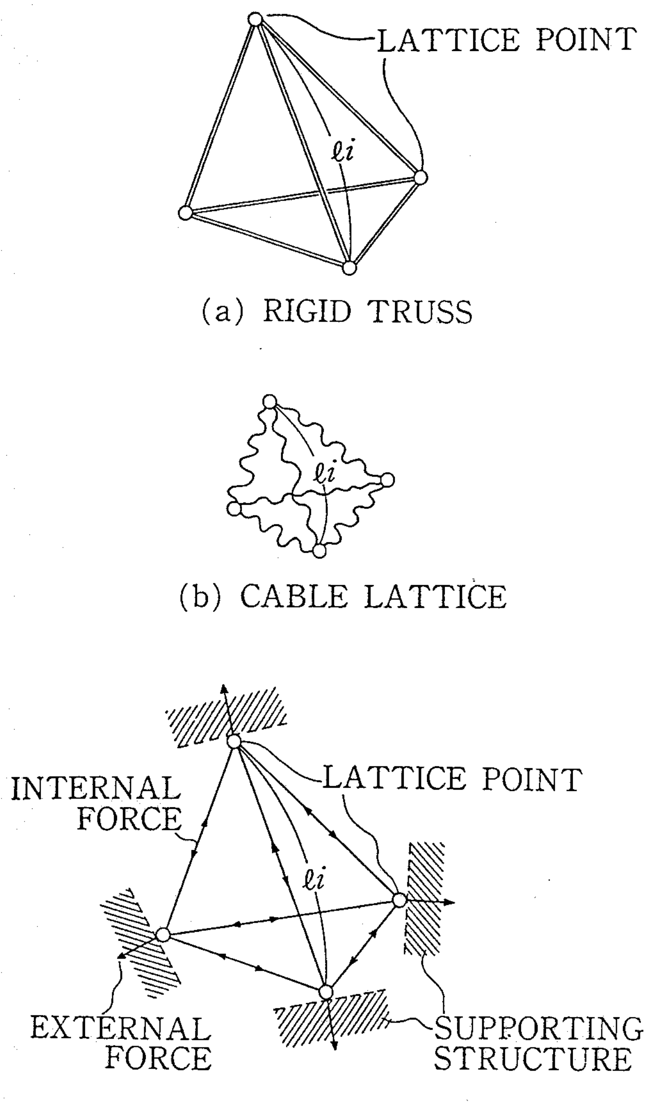


Figure 16. Concept of tension truss.

purpose, the present author presented a new concept called the tension truss antenna, which is a truss system consisting of tensile members.

Let us consider a tetrahedral truss, as shown in Figure 16. If each member of this truss is replaced by a flexible cable member of identical unstretched length, the cable lattice structure shown in Figure 16b is obtained. Then, if an appropriate force is applied to each node of the lattice, so that every cable member is in a state of tension, a three-dimensional rigid structure results, as shown in Figure 16c. It is clear that the lattice points determined by the configurations in Figures 16a and 16c are virtually identical to each other, because the length of corresponding members and their ways of combination are equal. Here, it has been assumed that strains in truss members are negligibly small.

Conclusively, a set of lattice points determined by a truss can be realized by means of a cable lattice structure activated by forces which are exerted by a supporting structure. It should be notèd that the shape of the cable lattice structure is primarily determined by geometric quantities only. The forces exerted from the supporting structure are used for stretching the cable members, and the effect of stretching on the geometry of the truss is always calculable and is of secondary importance. Thus, the concept of a tension-activated cable lattice structure is established. Since this structure is in essence a truss rather than a lattice structure, it can be called a "tension truss" [14].

The basic conditions for a tension truss are as follows:

1) Each member of the truss is made of a flexible cable and it must be in a state of tension in use.

2) The truss must be stable and statically determinate, that is,

$$m = 3j^* - r \tag{10}$$

where m is the total number of members, j^* is the total number of joints including fixed points, r is the number of restraints. The basis is given by Möbius as mentioned before.

Tension truss antenna

The tension truss concept can be applied to deployable parabolic structures. A geodesic truss dome, as shown in Figure 17 is an efficient

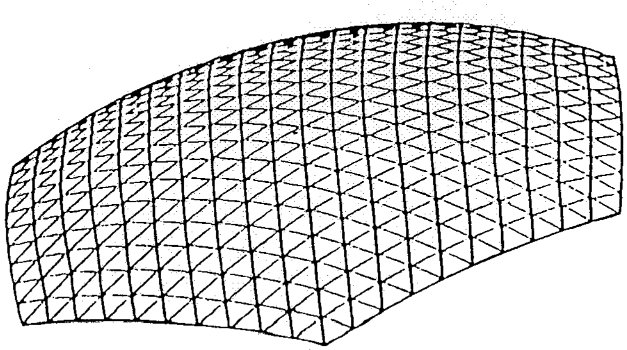


Figure 17. Geodesic truss dome.

lightweight truss and is erectable in space, so it becomes an obvious candidate for future space antennas. If a geodesic truss can be realized by a deployable tension truss, it may be useful.

The principal problem of this approach is to find a method of setting every member of the truss in a state of tension. Some useful hints for solving this problem come from observation of an air-supported membrane structure such as an air dome. An arbitrary unit element of the membrane of an air dome is in a state of tension governed by the following formulas:

$$T_1/R_1 + T_2/R_2 = P, \; 1/R_1 \times 1/R_2 > 0 \qquad (11)$$

where R_1, R_2 are the principal radii of curvature, T_1, T_2 are the tensile forces in the principal directions, and P is the internal pressure.

The latter part of Eq. (11) means that the surface has to have positive Gaussian curvature. Because the geodesic dome is a surface of positive Gaussian curvature, tensile forces can be produced everywhere if a force system simulating the internal pressure P of the air dome is provided. This is done by a number of concentrated forces applied to the nodes of the tension truss, as shown in Figure 18. These concentrated forces are supplied

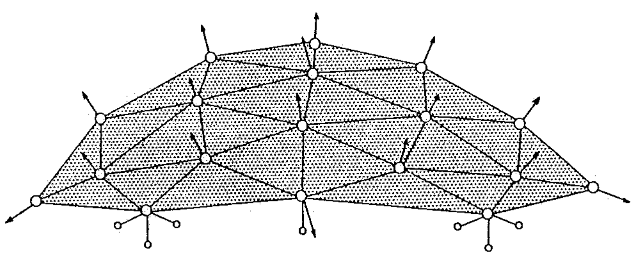


Figure 18. Principles of tension truss antenna.

by a supporting structure. It should be noted that these applied forces are not necessarily of definite values and directions, since the necessary condition is that the internal forces in the truss members are at least positive. The effect of stretching the members on the resulting surface can be calculated appropriately.

The condition of statical deterinacy and the necessary restraints must be examined before the truss is realized. With regards to truss geometry, there are various geometric schemes for subdividing a parabola into a lattice structure. One of the standard schemes has been proposed by Nayfeh

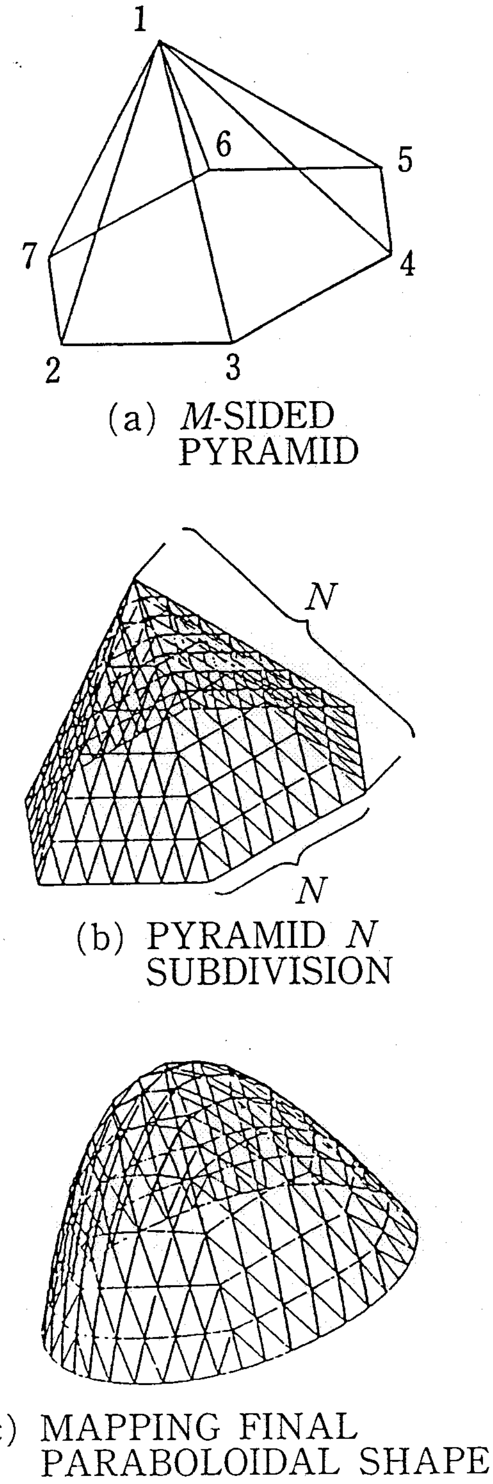


Figure 19. Geodesic scheme for subdividing a parabola to a tension truss.

and Hefzy [15] and is adopted here. The mapping procedure is illustrated in Figure 19. The number of triangles S in this model is given by

$$S = MN^2 \qquad (12)$$

the total number of members is

$$m = MN^2(1 + 3N)/2 \qquad (13)$$

and the total number of joints is

$$j^* = 1 + MN(1 + N)/2 \qquad (14)$$

The necessary number of restraints r for the statically determinate truss is thus obtained from Eq. (1) as follows:

$$r = 3 + MN \qquad (15)$$

The number of joints along the boundary is MN, and then there are 3MN degrees of freedom. Because 3MN is always larger than $r = 3 + MN$ ($M>2$, $N>0$), it follows that the necessary restraints can always be provided by the joints located at the boundary. Thus, the concept of tension truss antenna is established.

The most important feature of the tension truss antenna is that its shape is virtually predetermined by geometric quantities such as the length and arrangement of cable members of the truss. External forces are applied only for the purpose of giving the truss tensile forces to reproduce such predetermined shape. The effect of cable stretching on the shape is of secondary importance. Therefore, the concept of tension truss antenna is essentially different from those of current tension structure antennas such as the hoop-column antenna, whose shape is primarily determined by the equilibrium of forces.

Design of the tension truss antenna for Space-VLBI

Space-VLBI program in Japan needs a large, precision antenna more than 10 m in diameter. The antenna is used to receive radio wave from radio stars at 22., 5, and 1.6 Ghz bands in a circular polarization. The antenna must be stowed compactly within an envelope of 2200 mm × 5200 mm, and the weight should not exceed 200 kg.

After feasibility studies on a few proposed concepts, the modified version of the tension truss antenna was selected. As shown in Figure 20, the antenna structure consists of the supporting hub,

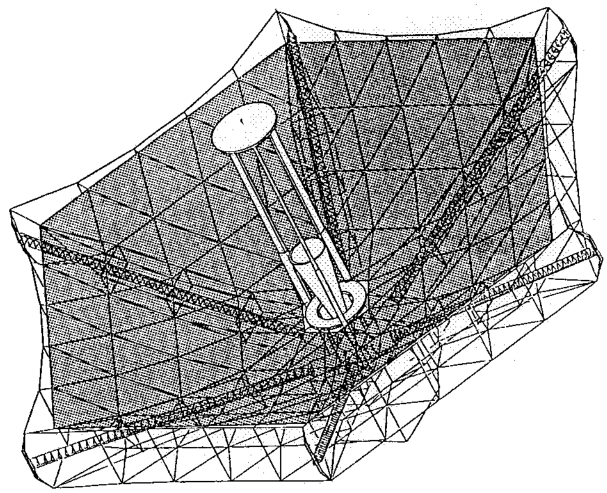


Figure 20. Tension truss antenna for VLBI mission.

the feed support column which deploys vertically from the hub, the six extendible columns which deploy radially from the hub, the cable assembly which is tensioned by the above columns, and the reflective metal mesh which is connected to the cable assembly.

The cable assembly consists of the tension truss, the secondary cable net which interpolates between the modes of the tension truss, and the reflecting mesh surface. This assembly is stretched between the terminal ends of radial columns and the central hub.

ACKNOWLEDGMENTS

One of the most crucial points in creating a new concept is the verification of the theoretical concept by means of a concrete model. Only through this step, one can clarify the central thought, generalize it, and modify it to meet with requirements. The design and fabrication of a conceptual model needs good craftsmanship as well as deep insight into the concept. In this respect, the author wishes to extend special thanks to Mr. M. Sakamaki of ISAS and Mr. K. Suzuki, President of Godo Works for their fine work.

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