Prestress Optimal Design of Deployable Antenna Considering The Effect of Gravity

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***Abstract*—The prestress of deployable antenna reflector is designed for vacuum environment and tested on the ground. Which implies the effect of gravity has to be considered in order to get higher surface accuracy. In this paper, a new method for prestress design under gravity is proposed. A typical antenna mesh is simulated as an example. Results demonstrate the antenna mesh can be restored to the ideal shape after removing the gravity.**

Keywords-antenna reflector; prestress design; gravity effect;

I. INTRODUCTION

With the vigorous development of aerospace technology, the demand for large-scale space deployable antennas is becoming more and more urgent. In order to satisfy the requirements such as tiny signal transmission on the ground, greater capacity of information transmission, and the realization of high resolution of remote sensing, high accuracy of antenna mesh has become a key issue.

The mesh reflector of a deployable antenna is known as a cable net structure, which belongs to the family of flexible tension structures characterized by strong geometric nonlinearities. The initial stiffness and shape can be achieved by prestress design. The purpose is to find a surface sufficiently close to a desired profile under specific tension loads[1]. The prestress distribution plays a vital role on surface accuracy of mesh reflector antennas[2].

The prestress design of mesh reflector antennas is an extremely challenging problem resulting from the large scale and flexibility. However, some studies are put out only considering the cable-net[3,4]. An equal tension method is proposed to improve the stability of deployable antenna[5]. Two methods are proposed considering the coupling of supporting trusses and flexible cable nets in [6]. Shape control concepts for mesh reflectors have been explored by two ways as well [7,8].

However, these existing methods based on the force density method are only suitable in ideal environment. That means no gravity effect is taken into consideration. For a real antenna reflector, it should be adjusted on ground where gravity could not be ignored. Moreover, the influence for surface accuracy resulted by gravity increases as the size of the antenna increases. The main purpose of this paper is to propose a new method to optimize the prestress in the cable-net structure. From which a new model under gravity can be achieved to supply guidance in antenna adjustment. Simultaneously, this model also has the ability to recover to the desired surface in orbit.

II. PRESTRESS OPTIMAL DESIGN METHODS

A. Composition of a mesh reflector antenna

A deployed mesh reflector antenna is conceived with the concept of a tension truss, which is a light and inherently stiff structure that can be precisely and repeatedly deployed regardless of environment. As illustrated in Fig. 1, it is divided into three parts: a supporting truss, boundary cables, and a cable net reflector including surface cables and tension tie cables. The cable net reflector and the boundary cables together are named as the deployable cable net structure.

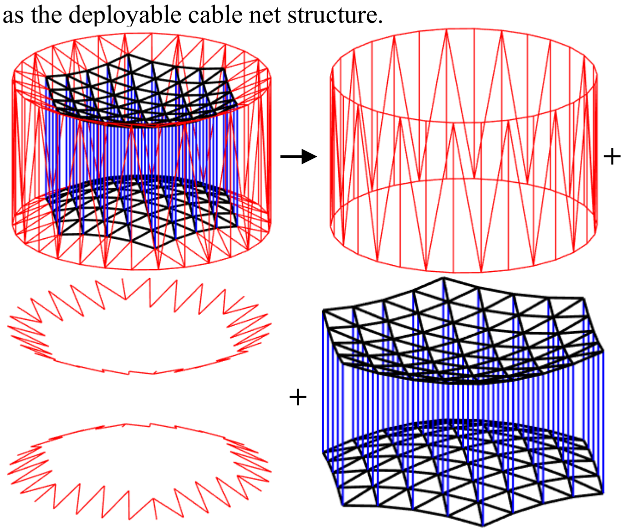

Figure 1. Composition of a mesh reflector antenna

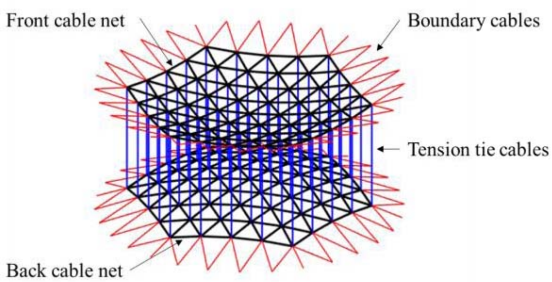

Figure 2. Schematic of a cable net structure

From the geometric viewpoint, a cable net structure can also be divided into: a front cable net, a back cable net, and tension tie cables, as shown in Fig. 2. Front and back cable nets are both doubly curved geodesic nets that are

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placed back-to-back. Tension tie cables evenly apply approximately normal forces between front and back cable nets to permanently preload them in tension to maintain the surface profile of the reflector.

B. Prestress design considering gravity effect

The prestress design of a cable net structure aims to determine cable tension distribution to obtain the required reflector surface accuracy. A unit of a cable net structure is shown in Fig. 3, where node *i* is connected to node *j* by a cable. The equilibrium equation of node i can be derived as follows:

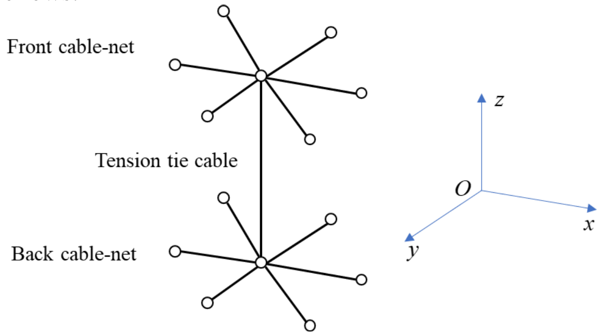

Figure 3. A cable-net unit

$$\begin{cases} \sum_j F_{ij}\dfrac{x_i - x_j}{l_{ij}} = 0 \\ \sum_j F_{ij}\dfrac{y_i - y_j}{l_{ij}} = 0 \\ \sum_j F_{ij}\dfrac{z_i - z_j}{l_{ij}} = \sum_j G_{ij} \end{cases} \tag{1}$$

where F_{ij} , G_{ij} and l_{ij} , respectively, represent the tension force, the gravity and the length of the cable between two adjacent nodes i and j of coordinates (x_i, y_i, z_i) and (x_j, y_j, z_j) . It can be rewritten in the form of matrix as follows[9]:

$$\begin{cases} \mathbf{C^T Q C x + C^T Q C_f x_f = 0} \\ \mathbf{C^T Q C y + C^T Q C_f y_f = 0} \\ \mathbf{C^T Q C z + C^T Q C_f z_f = G} \end{cases} \tag{2}$$

where $\boldsymbol{Q}$, $\boldsymbol{C}$ and $\boldsymbol{C_f}$, respectively, represent the force-density matrix, the topology matrix of free nodes and the topology matrix of boundary nodes. The boundary nodes are considered to be fixed.

With a given load and a given position of fixed points we get for each set of prescribed force densities exactly one equilibrium state with the shape

$$\begin{cases} \mathbf{x = -(C^T Q C)^{-1} C^T Q C_f x_f} \\ \mathbf{y = -(C^T Q C)^{-1} C^T Q C_f y_f} \\ \mathbf{z = (C^T Q C)^{-1} (G - C^T Q C_f z_f)} \end{cases} \tag{3}$$

Since the assumption of nodes located in the required parabolic surface, the nodal locations and topology of the cable net structure can be determined. Then the prestress design of the cable net structure can be expressed by the following optimization model:

$$\begin{cases} Find \quad Q = diag[q_1, q_2, \cdots, q_n] \\ Min \quad RMS = \sqrt{(\sum_{j=1}^{n} \Delta d_j^2)/n} \\ s.t. \quad C^T QCD + C^T QC_f D_f = b \end{cases} \tag{4}$$

where

$$D = \begin{bmatrix} \mathbf{x} & & \\ & \mathbf{y} & \\ & & \mathbf{z} \end{bmatrix} D_f = \begin{bmatrix} \mathbf{x}_f & & \\ & \mathbf{y}_f & \\ & & \mathbf{z}_f \end{bmatrix} b = \begin{bmatrix} 0 \\ 0 \\ G \end{bmatrix}$$

Δd_j is the displacement of the *j*th free node in the cable net reflector, n is the total number of free nodes in the cable net reflector and RMS is an abbreviation of root mean square.

It should be noticed that the length of cable changes in each iteration step so that the gravity matrix also changes in each step. However, the original lengths of all cables remain unchanged during the optimization process.

C. Prestress optimization

For a given antenna surface, the prestress can be designed through “(4)” with the influence of gravity at the same time. Nevertheless, the position of the antenna reflector is unknown. Specifically, when gravity is not taken into consideration, the design surface is simply the ideal surface P0 in orbit. But the design surface under gravity would deformed to P2, which means that the target surface is unknown during the optimization. The difference can be illustrated in Fig. 4. As gravity only work in z-direction, the influence of the coordinates in the x and y directions are ignored. There is a deviation Δz ,which is unknown, between the target shape under gravity and the ideal shape. But for every certain value of Δz_i , prestress can be designed by “(4)” for the *i*th target shape. Moreover, this under-gravity surface should have the ability to restore to ideal position in orbit as required. Gravity is removed after the design so that the shape would deform to a new position P2 as shown in Fig. 4. The smaller the gap between P0 and P2, the better it is. Obviously, all values of Δz for free nodes are negative and for boundary nodes the values are 0. The solution is to find a certain Δz with which prestress design can be solved. Then the surface is able to recover to ideal surface after removing the gravity. The overall algorithm is presented in the flowchart of Fig. 5.

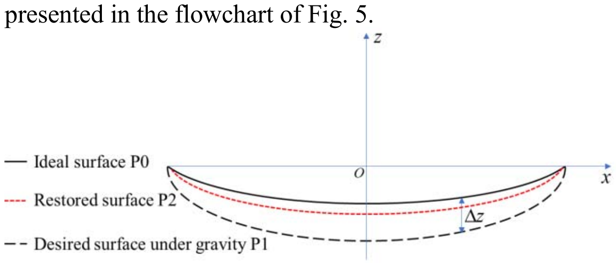

Figure 4. Schematic diagram of the relationship between the surfaces

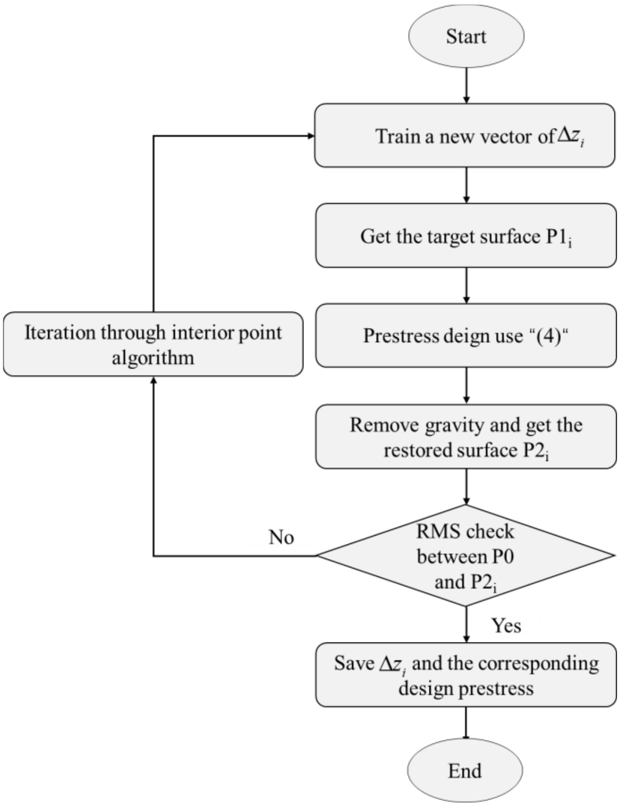

Figure 5. Algorithm of prestress optimization

The selection of the initial values of the iteration is a critical factor in the optimization. An improper selection of the initial value will cause the result to be a local optimum instead of a global optimum. And the iteration may not converge in worse cases.

III. NUMERICAL SIMULATION

A parabolic antenna with a spatial mesh reflector is shown in Fig. 1. The antenna specifications are as follows:

Diameter of aperture: 10,000 mm
Focal length of front cable net: 7,500 mm
Focal length of back cable net: 7,500 mm
Number of surface cables: 312 (=156×2)
Number of boundary cables: 108 (=54× 2)
Number of tension tie cables :61
Number of free nodes: 60 (=30×2)
Height: 2,000 mm
Type of facets: triangular
Elastic modulus of cables: 20 GPa
Radius of cables: 0.5mm
Density of cables: 1450kg/m^3

First, it is important to set the initial value of Δz, which can be expressed as

$$\Delta z = [\Delta z_1, \Delta z_2, \cdots, \Delta z_{n_f}, \underbrace{0, 0, \cdots 0}_{n_b}] \quad (5)$$

Where n_f and n_b represents the number of free nodes and boundary nodes respectively. With the help of finite element analysis in ANSYS, the minimum value of Δz is set to be -4mm. And all values of Δz is constrained to be negative. Second, the tension forces **F** of all cable are set to 10N initially. The iteration results are shown in Fig.6. It can be seen that the RMS error of front cable net is lowered from 11.07 mm to 0.66 mm.

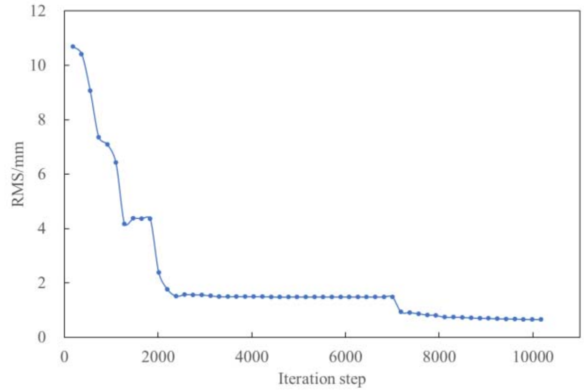

Figure 6. Iteration process of RMS error of the front cable ne

The deformation under gravity in z-direction is shown in Fig.7. The maximum nodal displacement is 3.79 mm. The prestress distribution of the cable net structure is shown in Table 1.

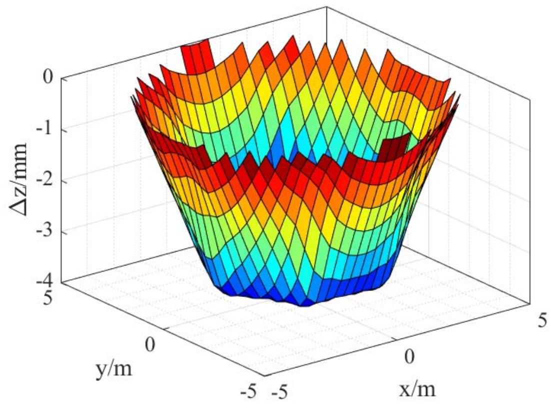

Figure 7. Deformation under gravity

TABLE I. PRESTRESS DISTRIBUTION OF THE CABLE NET STRUCTURE

Item	Prestress values in cables (N)		
	Maximum	***Minimum***	***Mean***
Front cable net	12.15	11.14	11.44
Back cable net	12.18	11.12	11.44
Tension tie cables	2.65	2.23	2.37

As shown in Fig.7, the distribution of Δz basically in line with the prediction of surface. Which confirms the validity of prestress optimization. On the other hand, the forces in Table.I show excellent uniformity that indicates a good stability in design result. The maximum and minimum stress ratios of the front cable net and the back cable net are 1.062 and 1.096 respectively. More importantly, the surface we find have the ability to restore to ideal surface when removing gravity. The RMS between two surfaces is 0.66mm which is acceptable in engineering. However, the algorithm iterated more than 10,000 times so that more efficient method should be explored in future work.

IV. CONCLUSION

A new method for prestress design of deployable antenna reflectors has been proposed. Because of all the adjustments for deployable antennas are executed on ground, the influence of gravity becomes a key factor affecting the antenna surface accuracy, and this is particularly evident when the antenna size increases.

A parabolic antenna is simulated to validate the method. Results show the surface we found can well return to the ideal surface after removing the gravity. The prestress design shows good stability as well.

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