Advanced Materials Research *Online: 2012-01-24*
ISSN: 1662-8985, Vols. 457-458, pp 1337-1341
doi:10.4028/www.scientific.net/AMR.457-458.1337

Kinematics Modeling and Driving Spring Design of Truss Structure for Deployable Truss Antenna

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Keywords: Deployable truss antenna, Truss structure, Kinematics modeling, Driving spring, Geometry modeling, Homogeneous coordinate transformation

Abstract. To design a truss structure of deployable truss antenna with 7 modules and ensure that the truss structure can be deployed successfully in space environment, kinematics equation of single module with homogeneous coordinate transformation method is built based on the structure and deployment principle of truss structure. By using dynamics software ADAMS, simulation analysis on the deployment is carried out and the driving force of single module is obtained in the ground condition. On this basis, driving spring is designed, and all the important design parameters are obtained. The analytical results show that the driving spring can meet the requirement of deployment in the ground condition. So it can be deployed in orbit (0G). This method can be taken as the theoretical basis for the design and deployment experiment of truss structure.

Introduction

Space deployable antenna is one of the important research areas of space deployable structure, and it is widely used in the field of military, aerospace and information etc. With the development of mobile communication, deep space exploration and military observation etc, people have proposed higher requirements. To cover larger communication range, reduce the size of ground terminal and get higher observation accuracy, the aperture of deployable antenna must be increased with the developing trend. So in the future the space deployable antenna should have the characteristics of maximization, high precision and lightweight.

Deployable truss antenna with modular idea [1] is a new type of deployable structure, which has many advantages such as high deployment precision, good flexibility of structural topology and short manufacturing schedule etc. Engineering Test Satellite Ⅷ (ETS-Ⅷ) designed by National Space Development Agency (NASDA) is one of the typical representatives of this class antenna [2]. It is a geostationary satellite to develop new technology for advanced satellite communication. This satellite is equipped with two sets of deployable truss structure whose diameter would be about 20m. The antenna can realize telecommunication with hand-held terminal. However, it also has a few disadvantages such as complex structure and large mass. In terms of lightweight design, this paper improves the structure of this antenna, and proposes a deployable truss antenna with the same size module. To ensure the antenna can be deployed successfully, the driving spring must be designed rigorously. Owing to the same structural parameters of all the modules, this paper estimates the driving force of multi-module from a single module. The organization of this paper is as follows. The structure of deployable truss antenna and deployment principle of module are shown in section 2. Section 3 concerns how to build the kinematics model of single module and calculate the driving force. In section 4, the driving spring is design. The paper is concluded in section 5, summarizing the present work.

Structure and Deployment Principle of Truss Structure

Deployable truss structure includes two important parts: mesh surface and truss structure [3], as shown in Fig.1. Mesh surface is the working part of the antenna and is formed by cables which correct the shape of the surface. The surface accuracy of metal reflective mesh directly affects working performance of the antenna. Truss structure is the module framework, which can provide high stiffness.

The deployable truss structure proposed by this paper is composed of 7 modules, as shown in Fig.2. The size of this antenna is 3m×3.1m. Because each module has the same size, there are few types of beams. One of the outstanding characteristics of this structure is that there is just only a single outer beam between the connection points. It reduces the structural mass effectively.

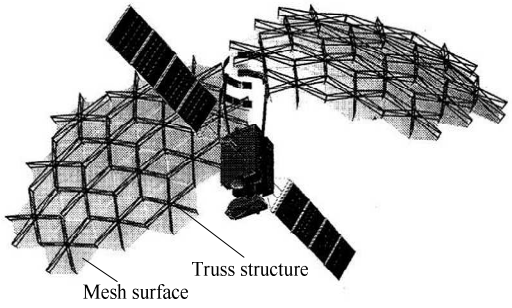


Fig. 1 Deployable truss antenna with 13m diameter of ETS-Ⅷ

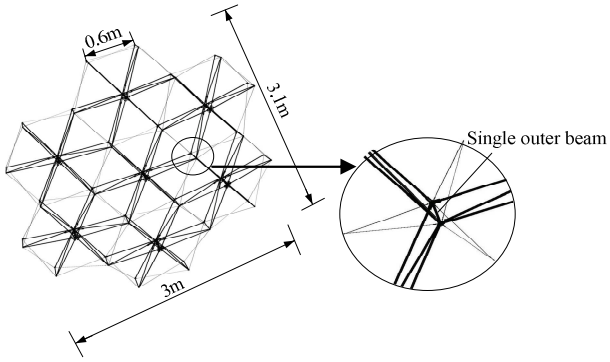
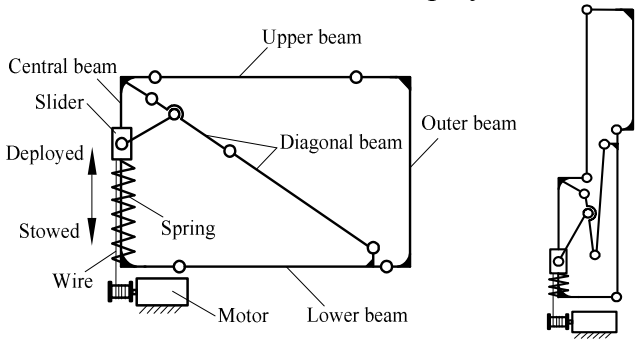


Fig. 2 Truss structure of deployable truss antenna

The module is similar to a regular umbrella [4] and it is composed of hinges, spring, wires, motor and beams etc (see Fig.3). Each truss structure of module consists of six basic frames located in a radial direction from the central beam. The deployment force is generated by the spring which is installed in the central beam. The module can be deployed and stowed by the slider, which is attached to the diagonal beam and spring, and slides along the center beam. During the process of deployment, the motor installed in the bottom of the module controls the speed of the deployment through drive cable, until the module realizes deployment state completely.



(a) Deployed state (b) Stowed state

Fig. 3 Structure of basic frame

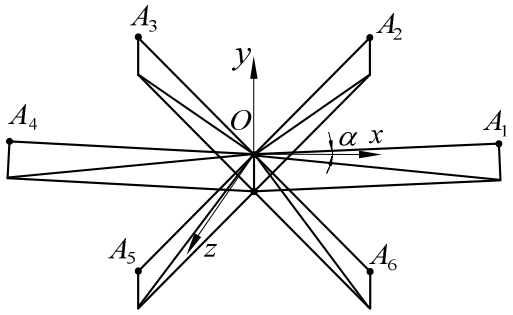


Fig. 4 Geometry model of single module

Kinematics Modeling of Truss Structure

A proper driving force is very important to the deployment of truss structure. If the truss structure can be deployed in the ground condition, it must be deployed in the space. So at first this paper builds the kinematics model of single module. Then by using dynamics software ADAMS, simulation analysis on the deployment is carried out and the driving force of single module is obtained in the ground condition.

As shown in Fig.4, the basic coordinate system $\sigma = [O; x, y]$ is established on the upper point of central beam. *y*-axis direction of coordinate system is from the bottom of central beam axis to the top. *x*-axis direction is from the origin *O* to the outside. *y*-axis and *x*-axis are all in the A_1Oy plane. The order of six points is as follows: $A_1 \sim A_6$. Suppose counterclockwise direction is positive direction [5].

The mesh surface must be a parabolic surface, however, the truss structure composed of the same modules is a spherical surface, so there are two different surfaces [6]. In order to ensure the two surfaces to have the least shape difference, a fitting method is used to reduce this difference, so the upper and lower beams must be a certain tilt angle.

Homogeneous coordinate of A_1 can be expressed as:

$$A_1 = \begin{bmatrix} l\cos\alpha & l\sin\alpha & 0 & 1 \end{bmatrix}^{\mathrm{T}}. \tag{1}$$

where l is the truss length, $l = \overline{OA_1}$; α is a inclination angle.

Owing to the symmetric of six basic frames, the angle of two planes which are composed of two adjacent connection points and y-axis is $\pi/3$. Homogeneous coordinate of each connection point can be expressed as:

$$A_i = \mathrm{Rot}(y,\phi_j)A_1 = \begin{bmatrix} \cos\phi_j & 0 & \sin\phi_j & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\phi_j & 0 & \cos\phi_j & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} l\cos\alpha \\ l\sin\alpha \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} l\cos\alpha\cos\phi_j \\ l\sin\alpha \\ -l\cos\alpha\sin\phi_j \\ 1 \end{bmatrix}. \tag{2}$$

where ϕ_j is rotation transformation angle, $\phi_j = j\pi/3$, $j = 0,1,\cdots,5$, $i = j+1$.

So the geometry model of single module can be obtained by (2). It contains the coordinates of all the points.

The kinematics equation of single module can be derived as follows:

$$\dot{A}_i = \mathrm{Rot}(y,\phi_j)\dot{A}_1 = \begin{bmatrix} l\sin\alpha\cos\phi_j\dot{\alpha} \\ -l\cos\alpha\dot{\alpha} \\ -l\sin\alpha\sin\phi_j\dot{\alpha} \\ 1 \end{bmatrix}. \tag{3}$$

Using dynamics software ADAMS, simulation analysis on the deployment is carried out.

As shown in Fig.5, the maximum working load is about 170N, which means when the slider is in the bottom of the module the spring must have enough deployment force to overcome the constraint force. When the truss structure is deployed completely, the spring still need to provide a little force. We suppose the minimum working load is 5N.

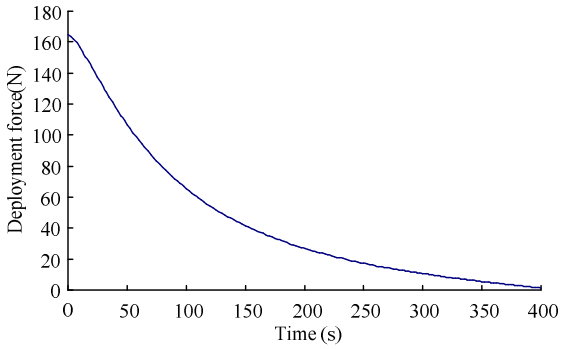


Fig. 5 Kinematic analysis result

Driving Spring Design of Truss Structure

According to the curve of simulation, maximum working load is obtained. Suppose initial conditions of cylinder helix spring are as follows:

Minimum working load $P_1 = 5$ N; maximum working load $P_n = 170$ N; working stroke $h = 48.7 \pm 1$ mm; outer diameter $D_2 \leqslant 30$mm [7].

Initial spring stiffness:

$$P' = (P_n - P_1)/h = 3.39\ \mathrm{N/mm}. \tag{4}$$

Limit working load:

$$P_j \geqslant 1.25P_n = 212.5\,\text{N}. \tag{5}$$

Combining (4) and (5), calculation table of spring can be got from handbook of mechanical design. The design parameters are listed in Table 1.

Table 1 Calculation table of spring

Design parameters	Values
Diameter d/mm	2.5
Pitch Diameter D/mm	20
Limit Load P_j/N	215.03
Deformation of One-Loop f_j/mm	4.46
Stiffness of One-Loop $P_d^{'}$/ N• mm^{-1}	48.2

The main design parameters of spring are effective loop n, total loop n_1, spring stiffness $P^{'}$, deformation of limit working load F_j, pitch t, free height H_0, outer diameter D_2, inner diameter D_1, helix angle α, developed length L. The results are as follows:

$$\begin{cases} n = P_d^{'} \big/ P^{'} = 14.5 \\ n_1 = n + 2 = 16.5 \\ P^{'} = P_d^{'} \big/ n = 3.32N/mm \\ F_j = nf_j = 64.67mm \\ t = F_j \big/ n + d = 6.96mm \\ H_0 = nt + 1.5d = 105mm \\ D_2 = D + d = 22.5mm \\ D_1 = D + d = 17.5mm \\ \alpha = \arctan \dfrac{t}{\pi D} = 6.32^{\circ} \\ L = \dfrac{\pi D n_1}{\cos\alpha} = 1197.1mm \end{cases} \tag{6}$$

On the basis of calculation results, the driving spring must be checked. The checking parameters include height of minimum load H_1, height of maximum load H_n, height of limit load H_j, practical working stroke h, range of working area $P_1 \big/ P_j$ and $P_n \big/ P_j$. The results are as follows:

$$\begin{cases} H_1 = H_0 - P_1 \big/ P^{'} = 103.49mm \\ H_n = H_0 - P_n \big/ P^{'} = 53.79mm \\ H_j = H_0 - P_j \big/ P^{'} = 40.23mm \\ h = H_1 - H_n = 49.7 = 48.7 \pm 1mm \\ P_1 \big/ P_j = 0.02,\ P_n \big/ P_j = 0.79 \end{cases} \tag{7}$$

From (7), we can see that practical working stroke h is 48.7 ± 1mm, so the driving spring can meet the design requirement.

Summary

This paper proposes a design scheme of truss structure of deployable truss antenna with 7 modules. The structural characteristics of truss structure are introduced. Based on the homogeneous coordinate transformation method, kinematics equation of single module is established. By using dynamics software ADAMS, simulation analysis on the deployment is carried out. According to the result of simulation, the theoretical value of deployment force is obtained. By calculating the minimum working load and maximum working load and other initial conditions of cylinder helix spring, the main design parameters of driving spring are got. At last, correctness of the spring designed is proven. So the presented method can be applied to the design of truss structure.

Acknowledgements

This project is supported by the National Natural Science Foundation of China (No.50935002 and No.11002039), and the Program of Introducing Talents of Discipline to Universities (No. B07018). The authors wish to express their gratitude to Kui Li for his support to this study. Especially, the effort of Lu Jin to polish the English is much appreciated.

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