Design and Mechanical Characteristics of Support Structure for Modular Deployable Antenna

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Abstract: A new configuration of support structure for modular space deployable antenna is proposed, and its mechanical characteristics are studied to meet the urgent needs of large-scale, high-precision, and high-rigidity development of space deployable antenna. On the basis of the basic theory of mechanism, the overall scheme design and detailed design of support structure are developed, and a 3-D model of modular deployable antenna consisting of 19 hexagonal prism modules is established. In accordance with strut stability theory, a static analysis model of support structure is established, and the value range of pretightening force in cables is obtained. A dynamic analysis model of the antenna structure is established, and the modal analysis is conducted. The natural frequency influencing factors and sensitivity analysis are performed. A principle prototype of support structure is developed, and the deployment function test and verification are conducted. Results show that the pretightening cables have a great influence on the structural stiffness, and the structural stiffness is increased by about 2.01 times after the pretightening cables are deployed. The natural frequency is sensitive to the material density and elastic modulus of members and the size parameters of chord beams and diagonal beams. The developed principle prototype in this paper is deployed smoothly and gently, verifying the feasibility of the structural design. Research results provide theoretical reference and technical support for the basic research and engineering application of modular deployable antenna.

Key words: deployable antenna; modular structure; statics; dynamics; sensitivity; modal analysis

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0 Introduction

Space deployable antenna is a new space structure generated with the rapid development of aerospace science and technology and plays an important role in many major aerospace missions[1-2]. As the "ears" and "eyes" of satellite system[3], space deployable antenna is widely used in mobile communication[4], deep space exploration[5], military reconnaissance, earth observation, navigation, remote sensing, and other fields[6-7]. It is a key aerospace equipment for satellite system and ground signal transmission. Deployable antennas are developing toward large-scale to improve the satellite communication distance, communication capacity, and remote sensing resolution. Large-aperture deployable antennas with deployment scales of tens of meters or even hundreds of meters have become one of the frontiers and hotspots in the international aerospace research[8-9].

The mesh deployable antenna is one of the most widely used and actively researched structure in space deployable antennas, which has the advan-

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tages of high storage rate, good rigidity, and light weight[10]. In accordance with the different structures of basic deployment units, mesh deployable antennas can be divided into three structural types: Tetrahedron, ring truss, and hexagonal prism modularization. Tetrahedral deployable antenna was studied previously. The Condor-E satellite launched by Russia was equipped with a tetrahedral modular antenna[11]. The deployed aperture of the antenna was 6 m, and the size of the stowed antenna was 0.5 m. After it was unfolded, the antenna had a parabolic structure. The China Academy of Space Technology launched a tetrahedral antenna mounted on the C-Star of Environment-1[12-13], and its deployed size was 6 m×2.8 m, and the surface accuracy was better than 3 mm. Guan et al.[14] and Yan et al.[15] developed a prototype of truss antenna with tetrahedral module unit, and the developed aperture of the prototype is 2.1 m. Ring truss antenna has been widely used in recent years. A single-layer ring antenna was applied to the SMAP satellite launched by the United States[16-17]. The antenna aperture was 6 m and the weight of the antenna structure was 13 kg. The China Academy of Space Technology[18-19] developed a ring truss deployable antenna with a deployment aperture of 15.6 m for communication technology test satellite No.1. The antenna used a quadrilateral mechanism as the deployable module unit. Shi et al.[20-21] proposed a deployable antenna with a double-layer ring truss, where the inner and outer support structures are composed of crank-slider mechanisms, and a prototype with a diameter of 2 m was tested. Japan Aerospace Exploration Agency (JAXA)[22-24] first investigated the hexagonal prism modular deployable antenna. The Engineering Test Satellite Ⅷ (ETS-Ⅷ) launched in 2006 was equipped with two such antennas with a size of 19 m×17 m, each consisting of 14 hexagonal prism modules with an aperture of 4.8 m and an effective aperture of 13 m. To meet the demand of communication satellites for deployable antennas with larger aperture, JAXA[25-26] proposed a trifold rib deployable antenna structure scheme, which consists of seven hexagonal prism modules. Each module is 14.4 m in size after deployment, and the aperture after overall deployment reaches 30 m. Yue et al.[27] proposed a hexagonal prism module unit driven by telescopic rods, each module mainly consists of six quadrilateral units. A prototype of paraboloid antenna with a deployment size of 5 m×2.88 m is designed by using this module unit.

The tetrahedral deployable antenna has a large area density due to the tight arrangement of its members, and this type of antenna is suitable for satellites with deployment aperture of 5—10 m class and high requirements for surface accuracy. The structural quality does not increase proportionally with the increase in the aperture because the support structure of the ring antenna is distributed around the antenna[28]. This antenna is suitable for satellites of 10—15 m class. If the antenna aperture continues to increase, the surface accuracy of the antenna will be reduced and difficult to adjust due to the lack of direct support of rigid structure on the reflective mesh surface[29]. Hexagonal prism modular antenna is an ideal structural form to meet the needs of large aperture antennas in the future due to its flexible structure and good expansibility. However, only one type of antenna has been applied in orbit at present due to its late start, indicating that more extensive and in-depth research is needed for this type of antenna.

In this research, a new configuration of support structure for modular deployable antenna is proposed. The proposed antenna consists of 19 hexagonal prism modules, and its structural design and mechanical characteristics are studied. The rest of this paper is organized as follows. Section 1 describes the structural design, introduces the overall structural scheme, and presents the detailed design of rib unit, single module, multimodules, and other structures. Section 2 establishes a structural static model, obtains the influence relationship between pretightening cables and support structure, and deduces the range of pretightening force in cables. Section 3 establishes a dynamic analysis model and performs the influence factors and sensitivity analysis of natural frequency. Section 4 develops a set of principle prototype and verifies the feasibility of the structural scheme and principle by the deploying function test. Section 5 provides the conclusions.

1 Design of Support Structure for Modular Deployable Antenna

1.1 Antenna structure scheme

Nature has gone through a long period of survival of the fittest, and a variety of organisms have evolved in the most appropriate manner. On this basis, human beings have developed a number of scientific and technological achievements by applying biomimetic principles. In biology, the hexagonal modular structure of honeycomb is characterized by the least material required, the highest tightness, and the strongest structure, as shown in Fig.1(a). In organic chemistry, benzene ring has a hexagonal structure, which makes its molecular structure highly stable, as shown in Fig.1(b). During the crystallization of snowflakes, water molecules attract each other, forming a stable hexagonal structure, as shown in Fig.1(c). Inspired by the above hexagonal structure and using the modular design idea, a configuration scheme of support structure for hexagonal prism modular deployable antenna is proposed. The antenna structure is shown in Fig.2.

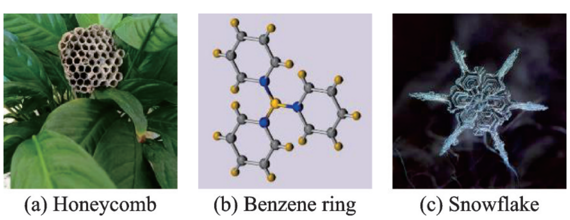


Fig.1 Hexagon module prototype

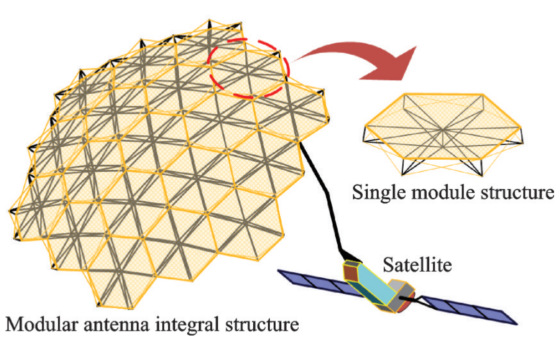


Fig.2 Modular antenna system

Modular deployable antenna consists of mesh surface and support structure. The support structure is located below the mesh surface. The mesh surface is tensioned into a paraboloid shape after the antenna is fully deployed. The signal can be transmitted and received by using the geometric property of paraboloid with focus convergence. The working schematic is shown in Fig.3. The proposed antenna consists of 19 hexagonal prism modules that are arranged in layers. The first layer consists of a single module, the second layer has six modules, and the third layer has 12 modules. The topology principle is shown in Fig.4.

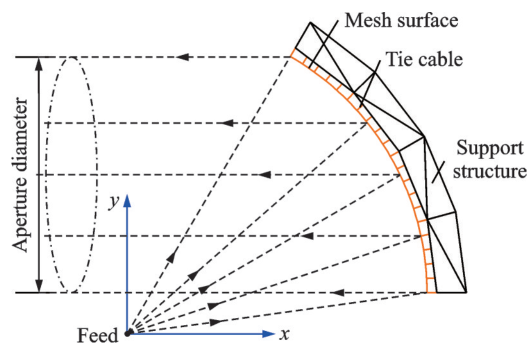


Fig.3 Schematic of working process

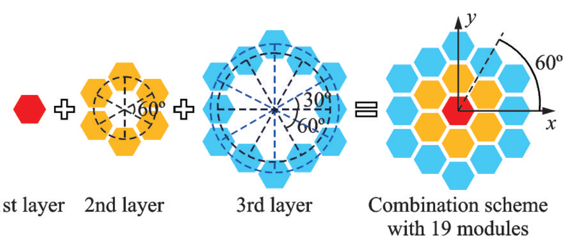


Fig.4 Topology principle of modular antenna

1.2 Structure composition and deployment principle

1.2.1 Structure composition

Each module is composed of two main parts: A mesh surface and cable network and a support structure to improve the modularity of the whole structure, as shown in Fig.5. The mesh surface and cable network is a flexible mesh structure composed of front net, mesh surface, and rear net. The mesh surface is the working part of the antenna system that plays the signal transmission function. It is woven by metal molybdenum wires, and its shape is paraboloid. The front net is used to connect the

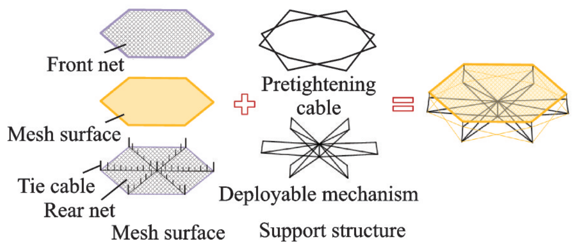


Fig.5 Structure of a module

mesh surface. The rear net mainly acts as a carrier, providing tension and support for the front net and the mesh surface. Many tie cables are installed on the specific nodes of the rear net. The tie cables are used to connect the front and rear nets, and play a role in adjusting and tensioning the antenna working surface to ensure the surface accuracy of the antenna. The whole mesh surface and cable network structure unfolds with the support structure when the satellite is in orbit to form a set shape. The support structure is the skeleton of the antenna, which deploys, supports, and positions the mesh surface and cable network structure, and provides sufficient rigidity and accuracy. The support structure is mainly composed of deployable mechanism and pretightening cables, and the deployable mechanism is the core structure that plays a supporting role. Pretightening cables are installed on the periphery of the module and are mainly used to improve the stiffness of the mechanism after deployment.

1.2.2 Deployment principle

As shown in Fig.6, the support mechanism of each module is composed of six rib units with the same structure, and the rib units are radially distributed with the center of the module as the rotation center. The rib unit is the minimum deployable unit of support structure, which is a planar multilink mechanism. The mechanism diagram is shown in Fig.6(b). The mechanism consists of eight components, in which the central beam can be regarded as a fixed frame, and the central beam remains unchanged during the deployment. The slider is an active part and slides up and down along the central beam. The rest of the beams are connected by hinges. The mechanism includes two low pairs, moving pairs, and rotating pairs, and no high pairs are

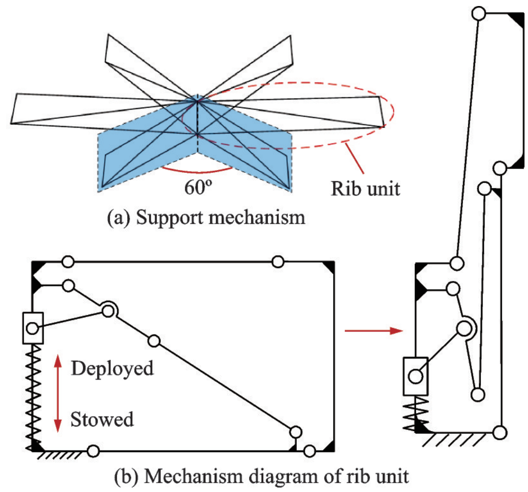


Fig.6 Composition principle of support mechanism

found. Therefore, the freedom of the mechanism is

$$F = 3n - 2p_l - p_h = 3 \times 7 - 2 \times 10 - 0 = 1 \quad (1)$$

where n is the number of free components in the rib unit, p_l the number of low pairs in the mechanism, and p_h the number of high pairs in the mechanism.

As shown in Eq.(1), the rib unit has one degree of freedom, so only one actuator is needed to ensure its definite motion law.

1.3 Antenna structure design

1.3.1 Rib unit design

In accordance with the above scheme and principle, the structure design of rib unit is conducted, and the 3D model of rib unit is established, as shown in Fig.7. The deployed size of the rib unit is about 600 mm, which is mainly composed of a central beam, a slider, a support beam, an upper beam, a lower beam, an outer beam, a small diagonal beam, and a large diagonal beam. When the rib unit is stowed, the host spring is compressed and stores elastic potential energy, and then drives the slider upward movement and the support beam movement. Under the action of the support beam, the large and small diagonal beams are gradually opened, thereby driving the whole mechanism to deploy. The upper beam is used to fix the cable net, and the tie cables on the rear cable net are installed on the upper beam. The rest of the beams play a supporting and connecting role. An auxiliary driving spring plate is arranged at the hinge of the plinth to improve the reliability of mechanism deployment.

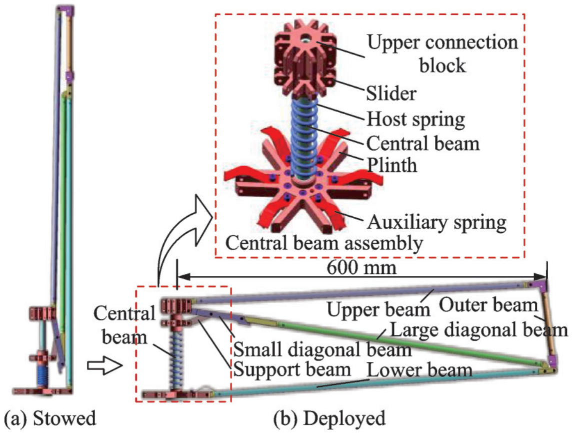


Fig.7 Three-dimensional model of rib unit

1.3.2 Single module structure design

In the single module, six rib units share the same central beam and slider. Under the action of the same driving spring, the slider moves along the central beam and drives the support beams of six rib units to realize their linkage, thereby ensuring that the whole hexagonal prism module is deployed synchronously, as shown in Fig.8. When a single module is stowed, it has a small volume and a slender column shape. During the deploying process, the volume and aperture gradually increase, and the rib units are smoothly linked and do not interfere with each other. When fully deployed, the aperture of the hexagonal prism reaches 1.2 m, and all rib units are deployed to the predetermined positions. The independent design idea of hexagonal prism module makes its structure more universal and improves the interchangeability of modular antenna.

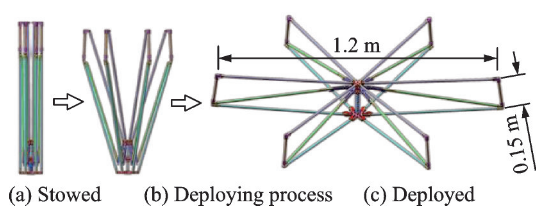


Fig.8 Three-dimensional model of module

1.3.3 Overall structural design

Adjacent modules are connected through the connecting nodes installed on the outer beams, as shown in Fig.9. The concave-convex notch design is used to realize structural positioning between adjacent connecting nodes, and bolts are used for connection, so as to ensure the accuracy, reliability, and convenience of assembly and disassembly between modules.

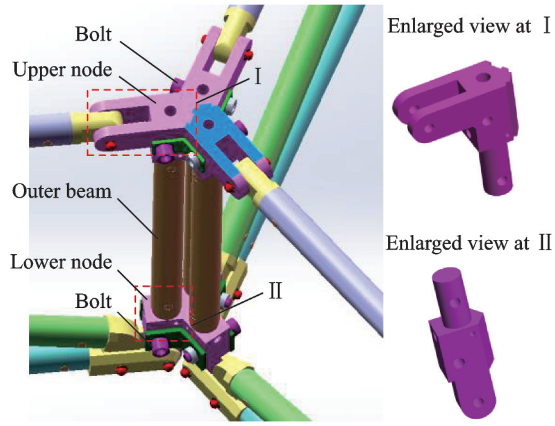


Fig.9 Assembly of adjacent modules

In accordance with the topological principle in Fig.3, the three-layer support structure of modular deployable antenna is composed of 19 hexagonal prism modules, as shown in Fig.10. When the antenna is stowed, the support structure is a regular column, and each module is folded separately without interference between modules. The size of the stowed antenna is 0.41 m×0.7 m. Each module is connected accurately after deployment, and the size of the deployed structure is 4.8 m×5.2 m. The structure as a whole is a 3-D space curved shape, indicating that the antenna support structure meets the expected design requirements.

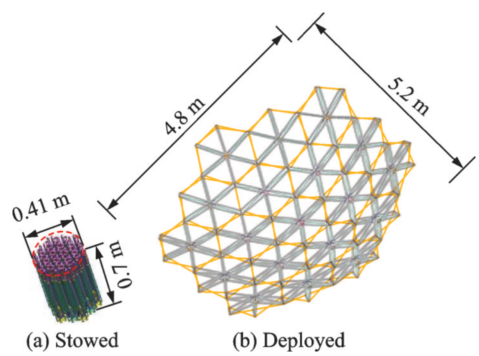


Fig.10 Support structure of modular deployable antenna

Storage rate is an important technical index used to characterize the folding ratio of structures. According to Ref.[30], the storage rate of support structure for deployable antenna is usually obtained from the ratio of the diameter of the structure in the stowed state to that in the deployed state. The storage rate of mesh antenna is usually 0.06—0.22. The smaller the storage rate is, the greater the change of aperture in the process of structure from folding to unfolding is. The storage rate of the support structure for designed modular deployable antenna is about 0.08, which shows that the antenna support structure has a high storage rate and the potential to develop into a larger aperture deployable antenna.

2 Static Analysis of Deployable Antenna Structure

The structure design shows that the support structure of modular deployable antenna is a rigid-flexible coupling system composed of flexible pretightening cables and rigid deployable mechanism. The single module is used as the configuration unit, and the flexible pretightening cables with cross distribution are installed between adjacent rib units to improve the stiffness of the structure after deployment, as shown in Fig.11.

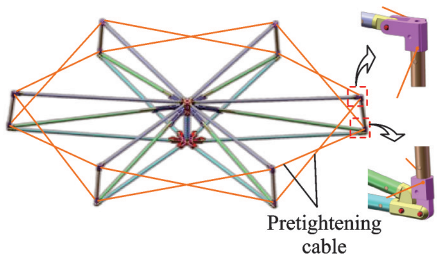


Fig.11 Model of support structure for single module (with pretightening cables)

The cables are arranged on two sides of the outer beams and play a fixed role in the rib units to ensure the angle requirements between the adjacent rib units. The stiffness of the support structure and the stability of the antenna are improved by applying a certain pretightening force on the pretightening cable to ensure the accuracy of the antenna working surface.

Under the tension of the pretightening cables, the outer beam, the diagonal beam, the upper beam, and the lower beam are in the compression state. The preload is one of the key parameters. If the preload is extremely small, the stiffness of the structure is difficult to ensure. Extremely large preload easily makes the compression beam unstable. The value of prestressing force has an important influence on structural stiffness and stability. Therefore, establishing the static model of the antenna support structure, obtaining the interaction relationship between the compression critical force of the antenna rod and the cable preload, and obtaining the value range of the cable preload under the condition of ensuring the stability of the antenna beams are extremely important for the design and research of the structure.

2.1 Antenna structure design

The stability of compression bar is one of the important basic theories in material mechanics. In the support structure of modular deployable antenna, except the moving pair at the slider, all the other beams are connected by double-headed hinges. The structure of the beam is simplified, and a stress analysis model of the compressive deformation of the double-hinge beam is established, as shown in Fig.12.

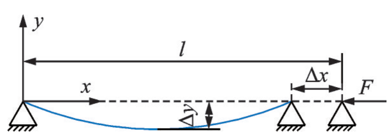


Fig.12 Compression schematic of antenna beam

In accordance with the small deformation assumption in material mechanics, the differential equation of deflection curve is as follows

$$\frac{d^2 y}{dx^2}=-\frac{F}{EI}y \tag{2}$$

where E is the elastic modulus of the beam, I the moment of inertia of the beam, and EI the bending stiffness of the antenna beam.

The beam of antenna support structure is a hollow structure, and its inertia moment can be expressed by the inner and outer diameter (d and D) of hollow beam as follows

$$I=\frac{\pi(D^4-d^4)}{64} \tag{3}$$

The general solution of the differential equation can be expressed as

$$y=A\sin\frac{F}{EI}x+B\cos\frac{F}{EI}x \tag{4}$$

where A and B are undetermined coefficients.

The boundary conditions for a beam under slight bending are as follows

$$\begin{cases}x_1=0\\ y_1=0\end{cases} \tag{5}$$

$$\begin{cases}x_2=l-\Delta x\\ y_2=0\end{cases} \tag{6}$$

Substituting the boundary conditions into Eq.(4), the solution of the differential equation of the deflection curve is

$$y=\Delta y\sin\frac{\pi x}{l-\Delta x} \tag{7}$$

Thus, the relationship between the deformation of beam axis and load is

$$F=\frac{\pi^2}{(l-\Delta x)^2}EI \tag{8}$$

The following condition needs to be met to ensure the stability of the beam, then we have

$$\lim\Delta x=0 \tag{9}$$

Thus, the Euler formula for stable critical load of the antenna support beam can be written as

$$F_{cr}=\frac{\pi^2}{l^2}EI \tag{10}$$

2.2 Static modeling

In accordance with the right-hand rule, the Cartesian coordinate system with coordinate origin located in the center of the antenna module base is established. Two adjacent triangular prism units in a single module are selected as the research objects, and the static model of unit nodes is established.

In the modeling process, the deployable mechanism is simplified, and the upper joint of the outer beam is regarded as a node, which is regarded as the overlap point of the outer beam, the upper beam and the cable, and the lower joint of the outer beam is treated in the same manner. The deployable mechanism can be regarded as a static balance structure when deployed and locked. As shown in Fig.13, the stress analysis diagram of the upper and lower nodes (points A and B) of the outer beam of the antenna rib unit is established, and the stress relationship between the related cables and beams is established.

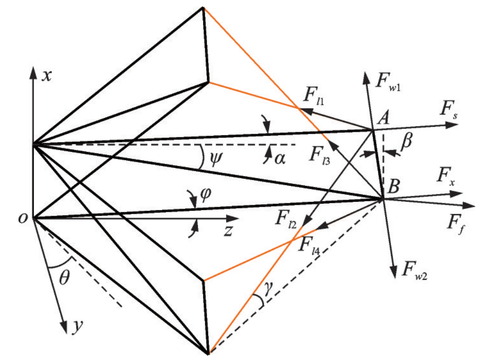


Fig.13 Force analysis model of antenna structure node

The static equilibrium equations at nodes A and B are established as follows

$$\begin{cases}\sum F_{AX}=F_{w1}c\beta+F_s s\alpha-(F_{l1}+F_{l2})s\gamma c\beta=0\\ \sum F_{AY}=F_{l2}c\gamma c\theta-F_{l1}c\gamma c\theta=0\\ \sum F_{AZ}=-F_{w1}s\beta+F_s c\alpha-(F_{l1}+F_{l2})c\gamma s\theta=0\\ \sum F_{BX}=-F_{w2}c\beta-F_f s\psi+F_x s\varphi+\\ \qquad (F_{l3}+F_{l4})s\gamma c\beta=0\\ \sum F_{BY}=(F_{l4}-F_{l3})c\gamma c\theta=0\\ \sum F_{BZ}=F_{w2}s\beta+F_f c\psi+F_x c\varphi-\\ \qquad (F_{l4}+F_{l3})F_{l3}c\gamma s\theta=0\end{cases} \tag{11}$$

where α, ψ, φ are the angles between the z axis and the upper beam, the diagonal beam, and the lower beam, respectively; β is the angle between the outer beam and the x axis, θ the angle between the rib unit plane and the xoy coordinate plane, and γ the angle between the pretightening cable and the connecting line of the lower nodes of the outer beams; si, ci, and ti ($i=\alpha$, β, γ, $\cdots$) represent the sine, cosine and tangent values of the corresponding angle, and the relevant expressions in the following formulas have the same meaning.

Each support beam of the antenna module is in a compression state under the action of deployment driving force and the cable pretightening force, so the beam only provides the support force. Considering that the space deployable antenna works in the microgravity space environment, the mass of cables and beams is not involved in static modeling.

The single module of modular deployable antenna mechanism is approximately a standard hexagonal prism, and 12 cables are arranged around the antenna module in a crossing circle. Two crossing cables should have equal preload, thereby meeting the following requirements

$$F_{l1}=F_{l2}=F_{l3}=F_{l4}=F_l \tag{12}$$

Among them, F_{w1} and F_{w2} are the support forces of the outer beam of the antenna mechanism, which are provided by the same beam. Thus

$$F_{w1}=F_{w2}=F_w \tag{13}$$

Therefore, Eq.(11) can be simplified as

$$\begin{cases} F_w \mathrm{c}\beta + F_s \mathrm{s}\alpha - 2F_l \mathrm{s}\gamma \mathrm{c}\beta = 0 \\ -F_w \mathrm{s}\beta + F_s \mathrm{c}\alpha - 2F_l \mathrm{c}\gamma \mathrm{s}\theta = 0 \\ -F_w \mathrm{c}\beta - F_f \mathrm{s}\psi + F_x \mathrm{s}\varphi + 2F_l \mathrm{s}\gamma \mathrm{c}\beta = 0 \\ F_w \mathrm{s}\beta + F_f \mathrm{c}\psi + F_x \mathrm{c}\varphi - 2F_l \mathrm{c}\gamma \mathrm{s}\theta = 0 \end{cases} \tag{14}$$

The support forces of upper beam, outer beam, lower beam, and the diagonal beam are calculated as follows

$$F_s = 2F_l \frac{\mathrm{s}\gamma \mathrm{c}\beta \mathrm{t}\beta + \mathrm{c}\gamma \mathrm{s}\theta}{\mathrm{c}\alpha + \mathrm{s}\alpha \mathrm{t}\beta} \tag{15}$$

$$F_w = 2F_l \frac{\mathrm{s}\gamma \mathrm{c}\beta - \mathrm{c}\gamma \mathrm{s}\theta \mathrm{t}\alpha}{\mathrm{s}\beta \mathrm{t}\alpha + \mathrm{c}\beta} \tag{16}$$

$$F_x = \frac{F_l \left[\frac{(2\mathrm{s}\gamma \mathrm{c}\beta - \mathrm{c}\gamma \mathrm{t}\alpha)(1 - \mathrm{t}\beta \mathrm{t}\psi)}{(\mathrm{t}\beta \mathrm{t}\alpha + 1)} + \mathrm{c}\gamma \mathrm{t}\psi - 2\mathrm{s}\gamma \mathrm{c}\beta \right]}{\mathrm{c}\varphi \mathrm{t}\psi + \mathrm{s}\varphi} \tag{17}$$

$$F_f = \frac{F_l \left[\frac{(\mathrm{c}\gamma \mathrm{t}\alpha - 2\mathrm{s}\gamma \mathrm{c}\beta)(1 + \mathrm{t}\beta \mathrm{t}\varphi)}{(\mathrm{t}\alpha \mathrm{t}\beta + 1)} + 2\mathrm{s}\gamma \mathrm{c}\beta + \mathrm{c}\gamma \mathrm{t}\varphi \right]}{\mathrm{c}\psi \mathrm{t}\varphi + \mathrm{s}\psi} \tag{18}$$

Configuring the pretightening cables of deployable mechanism should be solved on the premise of ensuring the stability of each beams. Therefore, ensuring that $F_s<F_{scr}$, $F_w<F_{wcr}$, $F_x<F_{xcr}$, and $F_f<F_{fcr}$ is necessary, where F_{scr}, F_{wcr}, F_{xcr}, and F_{fcr} are the instability critical forces of upper beam, outer beam, lower beam, and diagonal beam, respectively. On the basis of the above theory, the value range of crossing cable pretension of modular deployable antenna can be expressed as

$$0 < F_l < \min\{F_{Sl}, F_{wl}, F_{xl}, F_{fl}\} \tag{19}$$

where F_{Sl}, F_{wl}, F_{xl} and F_{fl} respectively represent the pretightening force of the cross cable when the upper beam, outer beam, lower beam and diagonal beam are unstable. They could be specifically expressed as

$$F_{Sl} = \frac{\pi^2 E_S I_S (\mathrm{c}\alpha + \mathrm{s}\alpha \mathrm{t}\beta)}{2l_S^2 (\mathrm{s}\gamma \mathrm{c}\beta \mathrm{t}\beta + \mathrm{c}\gamma \mathrm{s}\theta)} \tag{20}$$

$$F_{wl} = \frac{\pi^2 E_w I_w (\mathrm{s}\beta \mathrm{t}\alpha + \mathrm{c}\beta)}{2l_w^2 (\mathrm{s}\gamma \mathrm{c}\beta - \mathrm{c}\gamma \mathrm{s}\theta \mathrm{t}\alpha)} \tag{21}$$

$$F_{xl} = \frac{\pi^2 E_x I_x (\mathrm{c}\varphi \mathrm{t}\psi + \mathrm{s}\varphi)}{l_x^2 \left[\frac{(2\mathrm{s}\gamma \mathrm{c}\beta - \mathrm{c}\gamma \mathrm{t}\alpha)(1 - \mathrm{t}\beta \mathrm{t}\psi)}{\mathrm{t}\alpha \mathrm{t}\beta + 1} + \mathrm{c}\gamma \mathrm{t}\psi - 2\mathrm{s}\gamma \mathrm{c}\beta \right]} \tag{22}$$

$$F_{fl} = \frac{\pi^2 E_f I_f (\mathrm{c}\varphi \mathrm{t}\psi + \mathrm{s}\varphi)}{l_f^2 \left[\frac{(\mathrm{c}\gamma \mathrm{t}\alpha - 2\mathrm{s}\gamma \mathrm{c}\beta)(1 + \mathrm{t}\beta \mathrm{t}\psi)}{\mathrm{t}\alpha \mathrm{t}\beta + 1} + \mathrm{c}\gamma \mathrm{t}\psi + 2\mathrm{s}\gamma \mathrm{c}\beta \right]} \tag{23}$$

where $E_S I_S$ is the flexural rigidity of upper beam, $E_w I_w$ the flexural rigidity of outer beam, $E_x I_x$ the flexural rigidity of lower beam, $E_f I_f$ the flexural rigidity of diagonal beam, l_S the length of upper beam, l_w the length of outer beam, l_x the length of lower beam, and l_f the length of diagonal beam.

The value range of crossing cable pretension force can be obtained, which provides a theoretical basis for the value of cable pretension force in the subsequent analysis of antenna structure dynamics characteristics.

3 Dynamic Modeling and Analysis

3.1 Dynamic model

The finite element model of support structure with 19 modules is established on the finite element simulation software. During the modeling process, the antenna support structure is simplified appropriately, and the deployable mechanism is regarded as a stable structure with rigid connection after deployed and locked. Beam188 is used to simulate the beams. The cable is simplified as tension beam element, which is simulated by Link180. The upper and lower joints of central beam and the remaining corner blocks of the support structure are simplified as concentrated mass nodes and simulated by

Mass21. The beam material is aluminum alloy, with elastic modulus of 70 GPa, density of 2 840 kg/m^3 and Poisson's ratio of 0.31. The length of the module is 600 mm, and the size of each beam can be obtained from the structural design. On the basis of the geometric modeling and kinematic analysis of the support structure, the coordinate of each node of the structure is obtained[31]. The space deployable antenna is connected with the satellite body through the extension arm when it is applied to the satellite system, the degree of freedom of the support structure is constrained, and a fixed constraint is added at the outer beam outside the support structure. The finite element model of support structure is established, as shown in Fig.14.

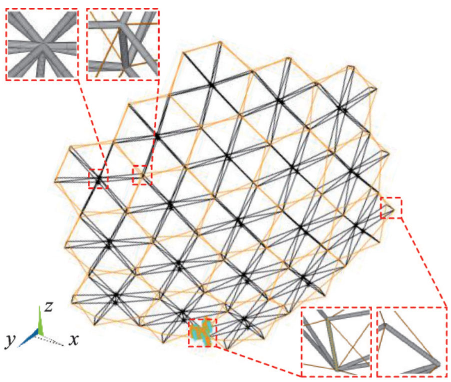


Fig.14 Finite element model of support structure

3.2 Modal analysis

Modal analysis can reflect the strength of support structure, which is the basis of the research on dynamic characteristics of space deployable antenna. Modal analysis can also help to improve the natural frequency or working condition of antenna structure to avoid system resonance. Therefore, modal analysis of support structure for modular deployable antenna is of great importance.

The natural frequencies of support structures without cable and with cable are calculated in this section to verify the contribution of crossing cable to the antenna structure. On the basis of statics theory, the value range of pretightening force is $0 < F_l < \min\{540.03\ \text{N}, 21\ 611.40\ \text{N}, 1\ 282.34\ \text{N}, 970.26\ \text{N}\}$, that is, the maximum value of the pretightening force of cable is 540.03 N. Therefore, the cable preload is set to 100 N during the modal analysis of the structure with cable to ensure its stability. The comparison results of the modal analysis of support structure without and with crossing cables are obtained, as shown in Tables 1 and 2.

Table 1 Modal analysis results of support structures without crossing cables

Modal order	f/Hz	Vibration mode
1	0.368	Bending around z axis
2	1.306	Bending around y axis
3	3.998	Torsion around z axis
4	4.555	Shrinkage around y axis
5	7.013	Torsion around z axis
6	9.335	Bending around y axis

Table 2 Modal analysis results of support structures with crossing cables

Modal order	f/Hz	Vibration mode
1	0.373	Bending around z axis
2	1.417	Bending around y axis
3	4.107	Torsion around z axis
4	9.716	Bending around y axis
5	15.355	Torsion around z axis
6	22.610	Localized mode

The increase in the first 3-order natural frequency of the structure with crossing cables is unremarkable compared with that of the structure without crossing cables by comparing the first 6-order modal analysis results of the two structures. The reason is that the first 3-order modes of the two structures all show the overall rigid body deformation, so the contribution of the cable to the structural stability is unremarkable. In the modes from the fourth order and after, the structure begins to exhibit local deformation. At this time, the cable has an inhibitory effect on the local deformation of the structure. Therefore, the natural frequency of the structure with crossing cables is significantly higher than that of the structure without crossing cables. The analysis results of the two cases show that the natural frequency of the structure with crossing cables is increased by 101.6% on average compared with that of the structure without cables, indicating that the stiffness of support structure is significantly improved by the configuration of crossing cable. Therefore, a structure with crossing cables is adopted in the subsequent dynamic studies.

In the range of cable pretightening force (0—540.03 N), different pretightening force values are selected, and dynamic simulation analysis is conducted to obtain the influence of different cable pretightening forces on the natural frequency of antenna structure, as shown in Fig.15. The results show that the first 6-order natural frequencies of the structure do not change obviously when the cable pretightening force is different in this interval. This condition shows that the contribution of pretightening force to the stiffness of support structure is the same, and the antenna support structure can be deployed and locked into a structural state. Therefore, the cable pretightening force is taken as 100 N in the subsequent analysis.

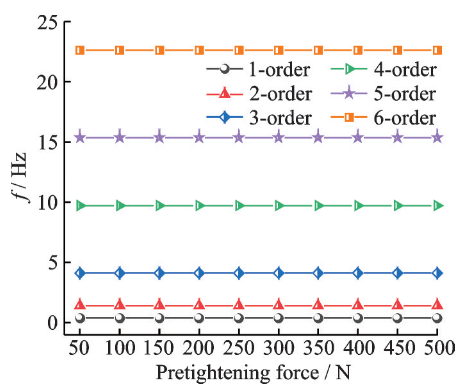


Fig.15 Influence of cable pretightening on natural frequency

3.3 Analysis of the influencing factors of natural frequency

The support structure of modular deployable antenna is composed of many types of beams, and different beam parameters affect the dynamic behavior of support structure. Analyzing the dynamic influence factors of support structure is of great theoretical importance for understanding the dynamic performance of antenna structure and conducting structural optimization design. In this section, the natural frequency of the structure is analyzed, and the influence rule of the parameters on the natural frequency is studied by changing the material properties and geometric parameters of the structure.

3.3.1 Influence of cable diameter on natural frequency

The above analysis results show that the crossing cables contribute greatly to improving the stiffness of support structure for modular deployable antenna. When the cable pretightening force is constant, the influence of cable diameter on the natural frequency of support structure is analyzed, and the results are shown in Fig.16.

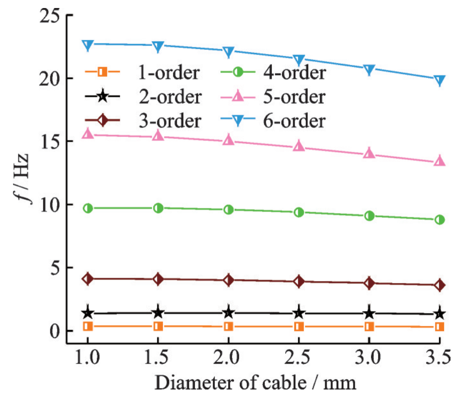


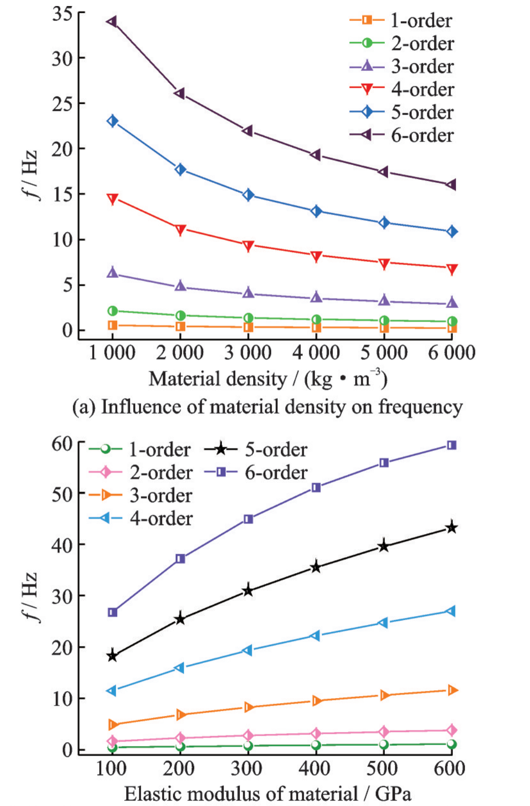
Fig.16 Influence of cable diameter on frequency

The results show that the first 6-order natural frequencies of support structure all decrease with the increase in the cable diameter, and the 5-order has the largest decrease of 13.91%. The negative effect of the cable diameter on the natural frequency is because the antenna becomes a relatively stable structure when deployed and locked. Increasing the cable diameter is equivalent to influencing the mass matrix of the structure, but has minimal influence on the stiffness matrix, so the natural frequency decreases.

3.3.2 Influence of material properties on natural frequency

Considering the rocket carrying capacity and space working environment, spacecraft has strict requirements for the selection of materials. Density and elastic modulus are two important properties of materials and have a great influence on the dynamic behavior of the antenna structure. The effects of different material properties on the natural frequency of support structure are studied by taking density and elastic modulus as analysis variables, as shown in Fig.17.

The results show that the material density and elastic modulus have obvious influence on the natu-



(a) Influence of material density on frequency

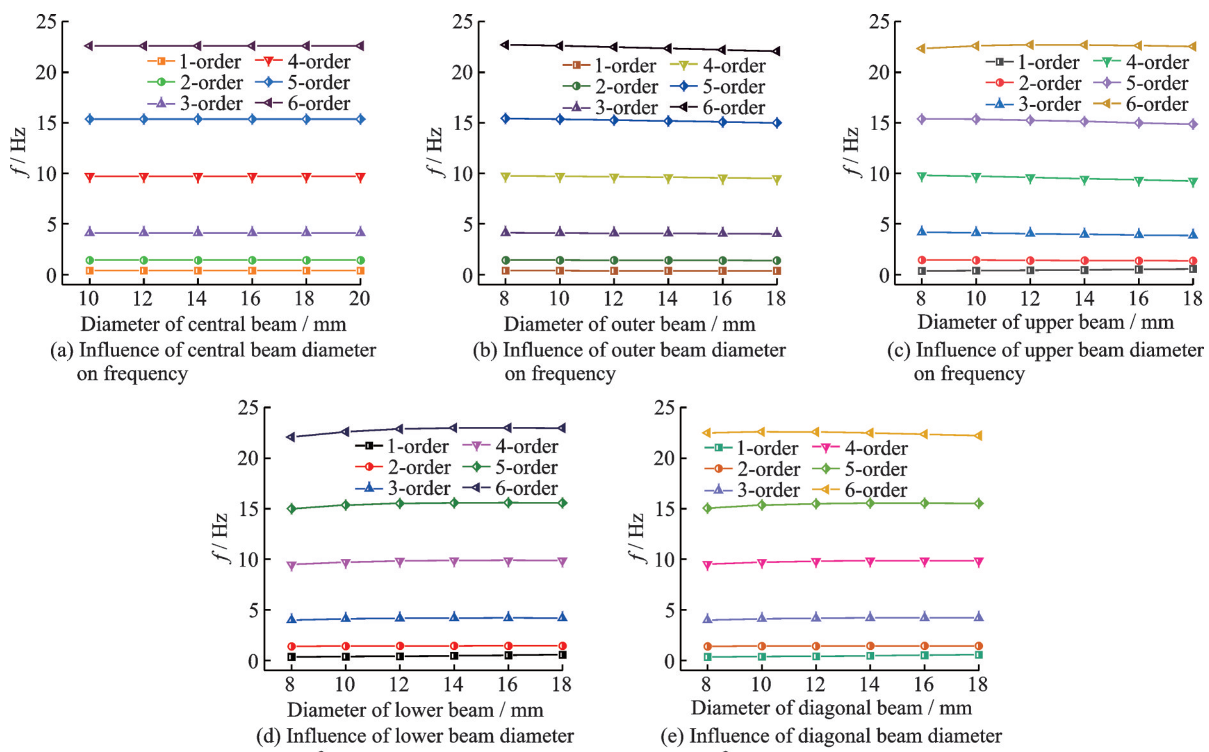
(b) Influence of the elastic modulus of material on frequency

Fig.17 Influence of material properties on frequency

ral frequency of the structure. When the density increases from 1 000 kg/m^3 to 6 000 kg/m^3, the natural frequency decreases by more than 50%. When the elastic modulus is adjusted from 100 GPa to 600 GPa, the natural frequency of each order is increased by more than 120%. Materials with low density and high elastic modulus contribute greatly to improving the stiffness and stability of support structures for modular deployable antenna.

3.3.3 Influence of beam diameters on natural frequency

The beams of deployable mechanism for modular deployable antenna mainly include center beam, outer beam, upper beam, lower beam, and diagonal beam. The axes of small diagonal beam and large diagonal beam coincide after the support structure is deployed, so the two beams are regarded as the same beam. Fig.18 shows the influence of the geometric parameters of beams on the natural frequency of the structure.



(a) Influence of central beam diameter on frequency

(b) Influence of outer beam diameter on frequency

(c) Influence of upper beam diameter on frequency

(d) Influence of lower beam diameter on frequency

(e) Influence of diagonal beam diameter on frequency

Fig.18 Influence of beam diameters on natural frequency

The analysis results show that:

(1) As shown in Fig.18(a), the first 6-order vibration frequency of structure decreases slightly with the increase in diameter of the central beam, and the maximum change rate is the first-order frequency, which is only 0.03%. This condition is be-

cause after the antenna is deployed, the whole structure is similar to a cantilever beam under the constraint of the satellite system extension arm, and the section moment of inertia of the structure has a great influence on the stiffness. On the one hand, the increase in the center beam diameter makes minimal contribution to the beam section. On the other hand, it increases the weight of the antenna, so the natural frequency of the structure decreases slightly.

(2) As shown in Fig.18(b), the first 6-order natural frequencies of the structure decrease with the increase in outer beam diameter, with the decreasing amplitude of 2.48%, 2.25%, 2.61%, 2.61%, 2.90%, and 2.85%. The influence law of the outer beam and central beam is similar to that of the central beam because they are in the vertical state and have the same contribution to the beam section. However, the change rate is larger than that of the central beam because one central beam corresponds to six outer beams. The increase in the diameter of the outer beam improves the quality of the antenna structure more obviously, so the vibration frequency of the structure decreases more obviously.

(3) As shown in Fig.18(c), the change in the upper beam diameter has the greatest influence on the first-order natural frequency of the structure, with an increase of 57.81%. However, it has minimal influence on the other orders, and the change range is less than 10%. The 2-, 3-, 4-, and 5-order frequencies decrease slightly, and the 6-order frequency increases slightly. The change in the upper beam diameter has different effects on the natural frequencies of the antenna structure.

(4) As shown in Fig.18(d), the increase in the lower beam diameter increases the section moment of inertia of the structure, which has a positive influence on the natural frequency. This parameter has the greatest influence on the 1-order natural frequency, with an increase of 62.24%, and the other orders are not significantly improved.

(5) As shown in Fig.18(e), the contribution of diagonal beam to the structural section is similar to that of the lower beam. The other frequencies show an upward trend, except that the 6-order frequency decreases slightly, and the 1-order frequency increases the most significantly, which is 65.65%.

3.4 Sensitivity analysis of influencing factors

The above analysis shows that the changes in multiple parameters affect the natural frequency of the support structure of modular deployable antenna. The sensitivity analysis is conducted to better understand the influence of various parameters on the natural frequency.

According to Ref.[32], the sensitivity of the natural frequency of support structure to the structural parameters can be expressed as

$$\eta\left(f_i/x_j\right)=\lim_{\Delta x_j\to 0}\frac{\Delta f_i/f_i}{\Delta x_j/x_j}\quad f_i\neq 0,x_j\neq 0 \tag{24}$$

where f_i is the ith-order natural frequency of the modular antenna structure, x_j a certain parameter of the modular antenna structure, and Δx_j and Δf_i are the variation of parameter and variation of natural frequency, respectively.

On the basis of the above theoretical calculation, the sensitivity of the natural frequency of support structure to the structural parameters is obtained, and the results are shown in Table 3. In the calculation results, the negative value indicates that the natural frequency of the antenna structure decreases with the increase in the parameters, and the positive value indicates that the natural frequency of the antenna structure increases with the increase in the parameters. The larger the absolute value of sensitivity, the more significant the influence of a certain parameter of support structure on the natural frequency of the corresponding order of the structure. The calculation results show that:

(1) Among the natural frequencies of each order, the most positive sensitivity is the 1-order natural frequency with a sensitivity of 0.525 2 to the diagonal beam diameter, followed by the 1-order frequency with a sensitivity of 0.498 0 to the lower beam diameter. The most negative sensitivity is the 1-order frequency to material density, and the sensitivity is −0.106 8. The results quantitatively reflect

Table 3 Sensitivity of the natural frequency of support structure to structural parameters

Structural parameter	Sensitivity of natural frequency					
	1-order	2-order	3-order	4-order	5-order	6-order
Elastic modulus of material	0.289 1	0.258 6	0.276 0	0.270 2	0.274 3	0.243 1
Material density	−0.106 8	−0.106 7	−0.106 1	−0.105 9	−0.105 5	−0.105 7
Cable diameter	−0.054 7	−0.015 9	−0.048 8	−0.037 3	−0.055 6	−0.049 0
Central beam diameter	−0.000 4	−0.000 2	$-9.739\ 7\times10^{-5}$	−0.000 2	−0.000 1	−0.000 2
Outer beam diameter	−0.019 7	−0.018 0	−0.020 9	−0.021 0	−0.023 2	−0.022 8
Upper beam diameter	0.462 5	−0.045 9	−0.063 1	−0.045 8	−0.026 7	0.007 7
Lower beam diameter	0.498 0	0.035 9	0.037 9	0.033 2	0.030 1	0.032 6
Diagonal beam diameter	0.525 2	0.025 7	0.042 0	0.027 5	0.024 2	−0.009 7

the influence degree of each parameter of the support structure on the natural frequency of the structure.

(2) The first six natural frequencies of support structure are positively sensitive to the elastic modulus of the beam and the diameter of lower beam because the two variables have a positive influence on the overall stiffness matrix and the sectional moment of inertia of the structure. The natural frequency of the structure is negatively sensitive to the material density, cable diameter, central beam diameter, and outer beam diameter because the four variables have great influence on the structure quality and minimal influence on the stiffness matrix of the structure. The 1-order frequency can be greatly increased by increasing the diameters of the upper beam, the lower beam, and the diagonal beam. At the same time, a small increase in the 1-order natural frequency can be achieved by appropriately reducing the diameters of the central beam, the outer beam, and the crossing cable.

From the analysis results of this section, three schemes are obtained to improve the stiffness of the modular deployable antenna support structure. Firstly, by configuring the pretightening cables, the antenna structure forms a more stable rigid-flexible coupling system. Secondly, materials with low density and high elastic modulus such as carbon fiber, aluminum alloy and titanium alloy can be selected as the materials of deployable antenna structure. Finally, the structural dynamic performance can also be improved by reasonably allocating the geometric parameters and material parameters of each member.

4 Prototype Development and Experimental Verification

4.1 Prototype development

A prototype is developed to verify the feasibility of the proposed structure. From the above analysis, the low density material can improve the stiffness of support structure. The proposed scheme is unsuitable for in-orbit application. On the basis of previous research experience, hard aluminum alloy is selected as the prototype material, which has the characteristics of low density, light weight, and high strength.

From the influence of the geometrical parameters of center beam and outer beam on the natural frequency of structure, the rigidity of the structure will be reduced if the quality of support structure is increased. Therefore, hollow structure is used to control the prototype quality. The diameter of the central beam is 12 mm, the diameter of the other beam is 10 mm, and the wall thickness is 1 mm. The main beam dimensions are shown in Table 4.

Table 4 Dimensions of main beams of the prototype mm

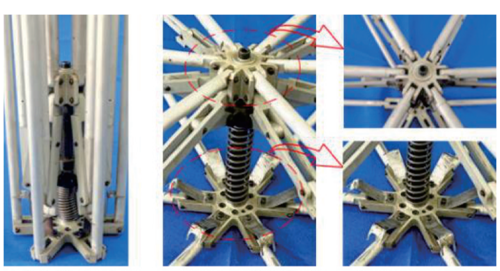
Central beam	Outer beam	Upper beam	Lower beam	Small diagonal beam	Large diagonal beam	Support beam
150	150	554	563	86	499	38

The reasonable processing and assembly of the central beam, diagonal beam, and pretightening cable of support structure is the difficulty of prototype development. The main reasons are as follows: (1) Central beam is the component with the most functions in the module. On the one hand, it should be used as a fixed frame to support the movements of the upper beam, the lower beam, the diagonal beam, and the slider. On the other hand, it serves as the support structure of the main driving spring and the auxiliary spring. (2) Diagonal beam is the most likely component to cause structural interference in the mechanism. The angle between the small diagonal beam and large diagonal beam is extremely small after the rib unit is completely stowed, and the conventional beam with circular section is difficult to meet the requirements. (3) Pretightening cables mainly ensure the included angle accuracy of rib units and improve the structural rigidity. The installation of pretightening cables and ensuring that each section has a certain pretensioned force are extremely important. Therefore, this paper mainly introduces the design of the above three key components.

4.1.1 Central beam design

The central beam is mainly composed of upper connection block, center beam, spring, slider, and lower connection block, as shown in Fig.19. The upper and lower connection blocks are similar in structure and are petal-shaped. They are used to connect the upper beam and the lower beam of rib units, respectively. The upper and lower connection blocks are connected by center beam. The center beam is also used as the support structure of the main drive spring and slider.

Two structures, stop and pin, are used for circumferential positioning between the upper connection block and upper beam, and between the lower connection block and lower beam, respectively. These structures are applied to ensure the installation accuracy of the upper connection block and the center beam, and the lower connection block and the center beam, except for the centering with cylindrical surface. Axial positioning is accomplished with shoulders.

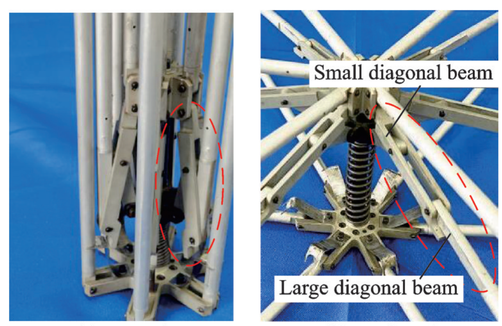


(a) Stowed (b) Deployed

Fig.19 Central beam structure

4.1.2 Diagonal beam design

The space volume occupied by the large and small diagonal beams will have a great influence on the antenna storage rate. The two components after folded must be fitted as close as possible without interference to improve the storage rate and reduce the volume after stowed. For this reason, the small diagonal beam in the middle position is designed as a flat sheet rather than a simple cylindrical structure. The joint of the large diagonal beam is set as a long flat shape, so that it can be folded into the interior of the small diagonal beam under the folded state, so as to minimize the volume after stowed. The structure of the two components is shown in Fig.20.



(a) Stowed (b) Deployed

Fig.20 Diagonal beam structure

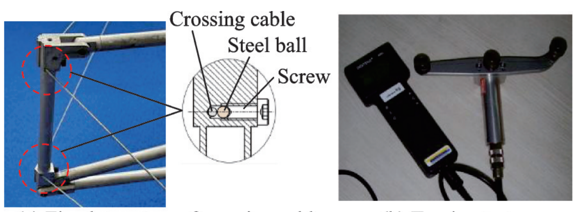
4.1.3 Crossing cable installation

A set of large tooling is designed to ensure the angle of rib unit and tension the crossing cable, as shown in Fig.21. The main structure of the tooling base is welded by square steel pipe with section size of 100 mm×100 mm, and 20 mm-thick processing steel plates are welded on the upper and lower surfaces, fully ensuring that the base has sufficient stiffness. The welding deformation is eliminated by annealing treatment. The upper surface and the positioning holes on the upper surface are processed once by a large CNC machine tool by taking the processed lower surface as the reference plane, thereby fully guaranteeing the flatness of the upper surface of the base, the parallelism of the upper and lower surfaces, and the accuracy of the positioning holes. The rib unit is clamped by the upright post, which has sufficient rigidity and will not be deformed.

(a) Module assembly tooling (b) Upright post

Fig.21 Diagonal beam structure

The pretightening cable is formed by two wire ropes alternating up and down, which are divided into 12 sections by six rib units of the module. The tension of each section of the wire rope is exerted by a tension tester. The cable tension in the module is measured with a rope tension tester developed by German Schmitt Company. The screw and steel ball are used to lock the cable after meeting the requirements, so as to effectively ensure the consistency of the internal tension of the cable. The measurement and locking process is shown in Fig.22.

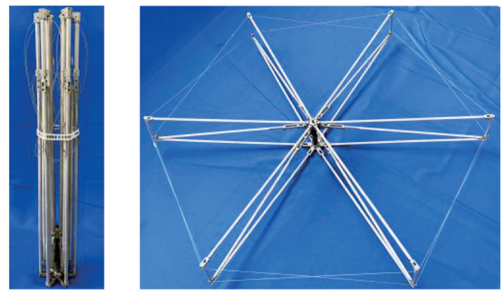


(a) Fixed structure of crossing cable (b) Tension tester

Fig.22 Fixing and measurement of cable

4.1.4 Single module prototype

The installed single module prototype is shown in Fig.23, and the size of the prototype after deployment is about 1 m×1.2 m. The single module prototype can be successfully deployed from the fully stowed state to the maximum aperture after trial assembly and evaluation. No interference occurs in the deployment process, and each rib unit is smoothly linked. The deployed cables are all tensioned as expected, and the angle of each rib unit is ensured accurately. The whole structure of the single module prototype has good stability and high reliability, and meets the expected design requirements.

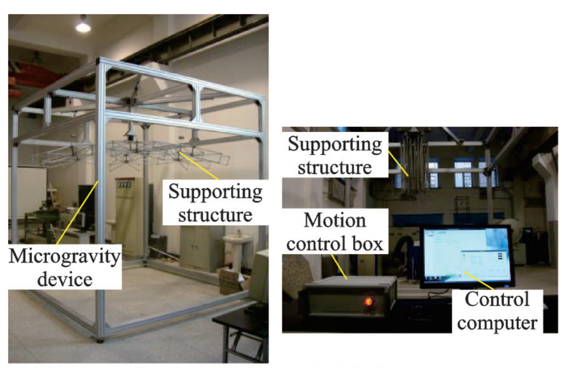


(a) Stowed (b) Deployed

Fig.23 Single module prototype

4.2 Deployment function test

In this paper, a prototype of support structure for deployable antenna composed of seven modules is taken as an example to test the mechanism deployment function. The support structure is suspended on a microgravity test device to simulate the weightlessness environment of space deployable antenna, as shown in Fig.24(a). A motion control system composed of motion control box, upper computer, and motor is used in the experiment to ensure the smooth deployment of support structure, as shown in Fig.24(b). The parameters of the motor are set in the host computer. The motion control box controls the rotational speed of the servo motor. The motor rotates to release the rope. The rope connects each module, and the slider slides to release the spring elastic potential energy, so as to ensure the smooth deployment of the whole support structure under the condition of controllable speed.



(a) Microgravity test device (b) Motion control system

Fig.24 Experimental setting scene

After several tests, the mechanism can be smoothly deployed in each test process. The test process is shown in Fig.25. No jamming occurs in the deployment process, and the mechanism can be locked after fully deployed. In the deployment process, the mechanism under the control of the slow-release device slowly unfolds and is relatively stable, and the mechanism deployment speed is controllable. The above test results show that the proposed support structure is feasible in terms of the mechanism principle and design scheme.

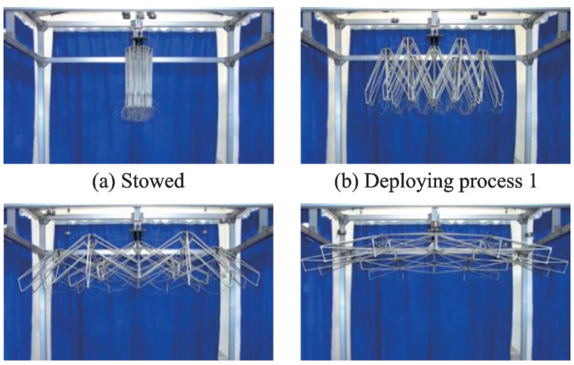

(a) Stowed (b) Deploying process 1 (c) Deploying process 2 (d) Deployed

Fig.25 Deployment test of support structure

5 Conclusions

(1) A new configuration of support structure for modular deployable antenna is proposed. The antenna is composed of 19 hexagonal prism modules, and the structure has high storage rate and high rigidity. This configuration enriches the types of mesh deployable antenna and provides a new design idea for the development of large aperture antenna.

(2) The static analysis model of support structure is established, and the value range of the pretension force of crossing cable is obtained with the critical force of antenna support structure as constraint condition. The dynamic analysis shows that the configuration of crossing cable increases the natural frequency of support structure by more than 2.01 times, indicating that the configuration of crossing cable has an important effect on improving the structural stiffness.

(3) The analysis of the influencing factors of natural frequency and the calculation results of structural parameter sensitivity show that the diameters of the upper beam, the lower beam, and the diagonal beam have a great influence on the natural frequency of support structure. The results provide a theoretical basis for the follow-up optimization of the dynamic performance of support structure for modular deployable antenna.

(4) The support structure prototype for modular deployable antenna is developed, and functional test experiment is conducted. The prototype is connected reliably, the deployment process is smooth, and the linkage between modules is stable, verifying the feasibility of the mechanism principle and design scheme of the proposed support structure.

(5) Taking the rib unit as the minimum deployable mechanism unit and arraying it are feasible to obtain a single module unit and multimodule support structure. The antenna aperture can be changed through the combination of different modules because the proposed structure contains many modules. The proposed antenna has great application potential and economic value to meet the application requirements of a variety of functions.

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模块化可展开天线支撑结构设计与力学特性研究

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摘要: 为满足空间可展开天线大型化、高精度、高刚度发展的迫切需求,提出一种模块化空间可展开天线支撑结构新构型,并对其进行了力学特性研究。首先,基于机构学基本理论,开展了天线总体结构方案设计和结构详细设计,建立了由19个六棱柱模块组成的模块化可展开天线三维模型。其次,根据压杆稳定理论,建立了天线支撑结构静力学分析模型,得到了拉索预紧力的取值范围。再次,建立了天线结构动力学分析模型,进行了模态分析,开展了固有频率影响因素及灵敏度分析与研究。最后,研制了一套天线支撑结构原理样机,并进行了展开功能试验与验证。研究结果表明:预紧拉索对结构刚度的影响较大,配置预紧拉索后结构刚度提高了约2.01倍;固有频率对杆件材料密度和弹性模量、弦杆及斜腹杆尺寸参数较为敏感;研制的原理样机展开平稳、顺畅,验证了结构设计的正确性。研究结果为模块化可展开天线的基础研究及工程应用提供了理论参考和技术支撑。

关键词: 可展开天线;模块化结构;静力学;动力学;灵敏度;模态分析