Acta Astronautica 151 (2018) 160–172

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Structural design and optimization of large cable–rib tension deployable antenna structure with dynamic constraint

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ARTICLE INFO

Keywords:
Space antenna
Deployable structure
Structural optimization
Dynamic characteristics
Experimental testing

ABSTRACT

The large deployable antenna has continuously received research interest in space technology. The design of such large structure has certain inherent challenges, such as limited mass and volume because of the inadequate capabilities of launchers. This constraint affects different aspects, including shapes, dimensions, and stiffness requirements. This study explores a new large cable–rib deployable antenna structure with radial ribs and tensioned cables. This structure has the advantages of high stiffness/mass ratio, which is suitable for constructing large-scale deployable antennas. A structural optimization method with a dynamic constraint for the maximum stiffness/mass ratio is proposed; this method is based on structural design formulas and the dynamic model of the deployable antenna structure. A genetic algorithm is introduced for parameter optimization with frequency constraint. Numerical examples are conducted to demonstrate the effectiveness of the proposed optimization method. By using these analysis methods, a 1.8 m prototype is fabricated and tested. Afterward, the feasibility and dynamic characteristics of the proposed cable–rib tension deployable structure are validated.

1. Introduction

Recently, the increasing demand for high-gain and high-resolution antennas motivates the enlargement of the antenna aperture. However, constrained by carrying capabilities of launchers and fairing dimensions, the mass and stiffness of antennas are restricted. Deployable structures, which are folded in launch and deployed in orbit, offer an ideal solution for building antennas with large apertures (greater than 10 m) and medium baselines (from 15 m to 50 m) [1].

Various deployable antenna structure designs have been proposed and can be classified as modular [2,3], radial [4,5], and truss structures [6–8]. By supporting parabolic surfaces, deployable structures offer the rigidity to resist deformation and vibration. However, the increase in the diameter of these antennas limits their deployed stiffness, which restricts the surface accuracy of data communications.

To improve the stiffness of the large deployable antenna structure, previous researchers have performed lots work on its structural design. Datashvili [9] proposed a double-scissor ring truss structure, which has two scissor pairs on the top and bottom vertical support bars. A modal analysis showed the high rigidity of the structure. A 1.6 m prototype was processed to verify feasibility. Medzmariashvili et al. [10] designed a conical ring deployable structure, which is fully deployed to form a conical ring shape. The vertical support bar of the deployable structure is connected with two sets of V-fold bars with different lengths. Tests were conducted to verify the high rigidity of the structure. Dai et al. [11] proposed a double-ring deployable truss that is based on a Pactruss structure [12]. The detailed deployment mechanisms and geometrical model were introduced. The dynamic structure was analyzed and compared with the single-ring truss, and the superiority of the double-ring deployable truss was verified. However, these methods increase the total weight of the structure due to the additional bars and hinges.

Therefore, innovative deployable structural systems are needed. Instead of conventional struts, cables are applied increasingly to build large deployable structures with light weight and adequate stiffness [13–15]. The cable–rib tension deployable structure was proposed by Semler et al. [16]. Therefore, this structure is not introduced in detail in the present study. Determining the geometric shape of the cable–rib tension deployable structure and the section parameters of all of its members is a crucial design problem. The geometric shape of the deployable structure, which includes the number and the length of radial ribs, are critical influencing factors in the deployment and performance of the whole system. The section parameters, namely, the thickness and radius of the radial ribs and cables, directly influence the mass and stiffness of the deployable structure.

Existing studies on the optimization of deployable antennas focus on the pretension and accuracy optimization of the cable network. Deng

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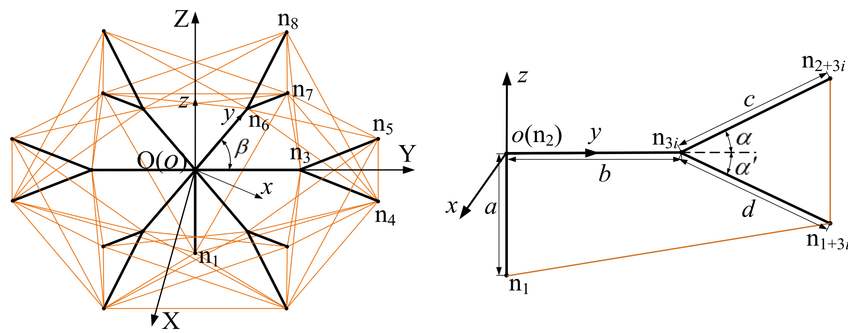
https://doi.org/10.1016/j.actaastro.2018.05.055
Received 6 December 2017; Received in revised form 23 April 2018; Accepted 29 May 2018
Available online 01 June 2018



(a) Global coordinate system (b) Local coordinate system

Fig. 1. Coordinate system of cable–rib tension deployable structure (Yellow lines represent the cables.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al. [17] proposed a pretension design method for the cable surface, and the relationships between multi-source errors and tension uncertainty were established. With an anti-optimization strategy, the minimization surface RMS errors of the cable surface could be obtained under uncertainty. Morterolle et al. [18] obtained an optimized node positioning and uniform tension with geometrical constraints using force density. The accuracy of the cable network was evaluated by calculating the systematic surface error. The nodal forces of the tied cables were used to position the network on the desired surface. Finally, different surfaces were tested to verify the efficiency of this method. In [19], Yuan et al. presented two new methods that adopt a definition of the RMS errors between a deployable mesh reflector and its desired working surface to optimize surface accuracy. The RMS error of the mesh could be further reduced in comparison with the traditional mesh surface design method. Zong et al. [20] proposed a cable surface sensitivity analysis method and obtained the sensitivity of the parameters that caused uncertainty in shape accuracy and cable tensions. Moreover, an optimal procedure was designed to reduce the effects of uncertainty on structural performance. However, studies that focus on structural parameter optimization with frequency constraint is limited for large-scale deployable structures. The natural frequencies of these structures are sensitive to shape changes. Moreover, structural optimization with frequency constraint allows a designer to improve the dynamic characteristics of the deployable structure.

For the cable–rib tension deployable structure, our research group has conducted several works to determine the pretension of the tensioned cables [21]. This paper introduces our recent work on the specific structural design and parameter optimization of the cable–rib tension deployable structure. The same dynamics modeling and genetic algorithm methods are used because the same deployable structure is investigated. In this paper, to meet the demands of satellite communications services and earth observation missions, a novel cable–rib tension deployable structure is presented. Detailed structural design is presented; the deployable structure comprises multiple deployable radial ribs and tensioned cables and is suitable for building large-scale deployable antennas. The nonlinear finite element method is applied to analyze the dynamic behavior, and a structural optimization model with frequency constraint is subsequently established. Genetic algorithm is applied to obtain the optimal sectional dimensions of each element. A 1.8 m group experimental prototype is fabricated and tested to verify the feasibility and dynamic characteristic of the proposed cable–rib deployable structure.

This paper is organized as follows. Section 2 presents the corresponding geometric and dynamic modeling methods of the cable–rib tension deployable structure. Section 3 investigates the design of the basic deployable unit; the number of deployable units, height of deployable structure, and length of radial ribs are formulated, and the stiffnesses of deployable structures with and without cables are compared. Section 4 introduces the detailed structural optimization procedure. In Section 5, a 1.8 m ground experimental prototype is fabricated and subjected to verification experiments. Finally, Section 6 provides the conclusion and suggestions for future work.

2. Analysis method

The cable–rib tension deployable structure has certain members that are under compression (radial ribs) and tension (cables). The nonlinear finite element method (FEM) is applied to establish an effective dynamic model and only nodal connectivity is needed as the initial input to implement structural dynamics and modal analysis. Therefore, a precise corresponding geometric model is required to obtain nodal connectivity. The geometric and FEM models are separately discussed in the succeeding section.

2.1. Geometric model

The spatial coordinates of nodes under a homogeneous coordinate system are essential in establishing the dynamic model of the deployable antenna structure. As shown in Fig. 1, the cable–rib structure has symmetrically distributed radial ribs and tensioned cables with identical geometries. Thus, a transformation matrix is used to obtain the relationship of different units and establish the geometric model of the whole deployment structure.

First, the global coordinate system $O–XYZ$ is defined as demonstrated in Fig. 1(a); the Z direction points upward along the vertical center beam, the Y direction extends along the radial rib, and the X direction is defined according to the right-hand rule. Meanwhile, as shown in Fig. 1(b), the local coordinate system $o–xyz$ is established in a single unit, the y direction of each unit extends along the radial rib direction; all the z axes point upward, and the x axes are defined according to the right-hand rule. The spatial coordinates of nodes n_1, n_2, n_3, n_4, n_5 in the local coordinate system can be obtained according to the geometric relation shown in Fig. 1.

$$\begin{cases} n_1 = (0 \quad 0 - a) \\ n_2 = (0 \quad 0 \quad 0) \\ n_3 = (0 \quad b \quad 0) \\ n_4 = (0 \quad b + d\cos\alpha' \quad - d\cos\alpha') \\ n_5 = (0 \quad b + c\cos\alpha \quad c\cos\alpha) \end{cases} \tag{1}$$

Each radial rib unit is labeled counter-clockwise. Thus, only the rotation around the z-axis exists between adjacent units, and the rotational angle is the angle $\beta = 2\pi/n$ (n is the number of units.) of adjacent coordinate systems. A transformation matrix is used for the conversions between the global and local coordinate systems. Besides, the transformation matrix between adjacent radial rib coordinate systems is given by the following expression: