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Mathematical relationship between mean cable tensions and structural parameters of deployable reflectors

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ABSTRACT

The main purpose of the paper is to investigate the effects of structural parameters of deployable reflectors on their mean cable tensions. The proportional relations between spatial and plane cable nets are firstly explored on the basis of projection principle. By the means of obtained proportional relations, the analytical expressions between the mean spatial cable tensions and structural parameters of deployable reflectors including aperture, subdivision number and focal length are then derived. In the following, a modified plane projection method is proposed for pretension design of offset reflectors. Finally, numerical simulations are taken to verify the analytical expressions, as well as the modified plane projection method. The results show that the mean spatial cable tensions are predicted accurately by the analytical expressions, and uniform tension distribution is obtained by the modified plane projection method. With the applications of the analytical expressions and the modified plane projection method, the cable tensions can be controlled more flexible and convenient in engineering applications.

1. Introduction

With the development of modern science and technology, the demands of mobile communication have increased rapidly. New requirements to provide high data rate service to very small user terminal have led to the need for large aperture reflectors with high gain in turn [1]. Cable net deployable antennas, as one of the most widely used solutions of large aperture antennas nowadays, whose aperture have already reached more than 20 meters and still far from the structural limit, will develop towards the larger aperture inevitably.

The cable net deployable antenna is a form-active structure [2], and form-finding analysis is necessary for structural design to obtain the initial configuration shape. According to Dieringer [3], the definition of form-finding analysis is to find a shape of equilibrium of forces in a given boundary with respect to a certain stress state. In 2012, Veenendaal and Blockz categorized form-finding methods in three main families [4]: stiffness matrix method, geometric stiffness method and dynamic equilibrium method. The stiffness matrix method, including material properties, is falling into disuse, because of the hugely computational cost and dissatisfied convergence. The commonest geometric stiffness methods are the force density method and its extensions and variations [5–8], which transform the nonlinear equilibrium equations into linear equations with a concept of "force density", then the equilibrium equations are solved by numerical method to obtain equilibrium tension distribution. The typical dynamic equilibrium method is dynamic relaxation method proposed by Barnes [9–11]. The method traces all processes of system vibration, and records the maximum kinetic energy positions as the structural equilibrium status. Besides the above methods, other methods are also put forward, such as inverse iteration algorithm [12], genetic algorithm [13,14], "geotensoid" method [15] and the method via static modeling and quadratic programming [16], etc.

Due to the feature of many cables and less restraint nodes, the cable net deployable reflectors are statically indeterminate. So the tension distribution is a multi-solution problem in the equilibrium state. For form-finding analysis of large-scale cable net reflectors, an equilibrium tension distribution is not the only requirement anymore, because the equilibrium tension distribution has become easy to obtain by form-finding analysis after years of research. The requirement of pretension design has been changed from shape control into both shape control and performance control. That is, the cable pretensions obtained by form-finding analysis have to satisfy both the basic requirement to keep the shape in equilibrium state and the engineering requirements, such as uniform tensions and well controlled tensions. However, the existing methods just keep the cable net reflectors in shape, but do not reflect the internal relationship between the tension distribution and the structural parameters of cable net deployable reflectors, such as

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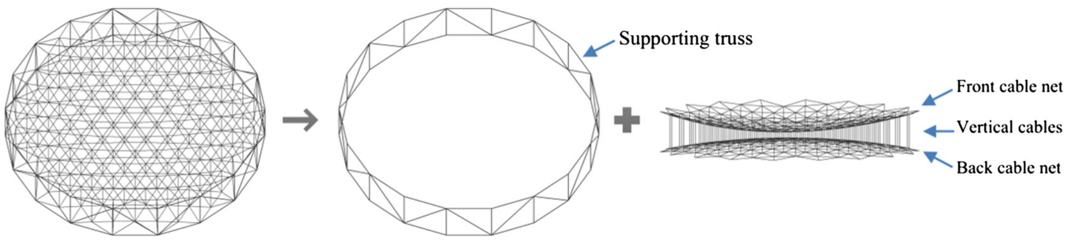

Fig. 1. Composition of a hoop truss reflector antenna.

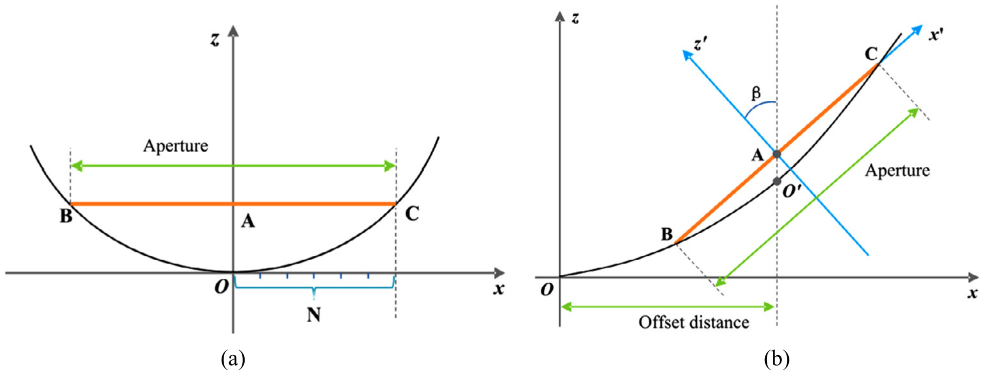

Fig. 2. Reflectors geometry definitions: (a) axi-symmetric reflectors; (b) offset reflectors.

aperture, subdivision number, and focal length etc. Therefore, they are unable to predict and analyze the pretension distribution in the initial design stage, neither they can control the reflector in a good performance.

In this paper, we base on a new pretension design method called plane projection method (PPM) [17] to reveal the mathematical relationship between mean cable tensions and structural parameters of deployable reflectors. To describe the work in detail, this paper is structured as follows: Section 2 describes the procedure of the PPM; Section 3 researches the internal relationship between the mean tensions of spatial cable nets and the structural parameters, such as aperture, subdivision number, and focal length etc., then deduces the analytical expressions of the internal relationship; Section 4 proposes a modified plane projection method (MPPM) for pretension design of offset reflectors on the basis of the proposed analytical relationship. In Section 5, numerical simulations are taken to verify the analytical expressions, as well as the MPPM. Finally, the work is summarized in Section 6.

2. Plane projection method

As shown in Fig. 1, hoop truss reflector antennas consist of four parts: supporting truss, front cable net, vertical cables (tension ties) and back cable net.

The tensions of plane cable net structure projected by front cable net are denoted as F_k^p $(k = 1, 2, \ldots, r)$, r is the number of cable elements of plane cable net structure, cable lengths of plane cable net structure are denoted as l_k^p $(k = 1, 2, \ldots, r)$. Similarly, tensions of front cable net are denoted as F_k^s, cable lengths are denoted as l_k^s; tensions of back cable net are denoted as F_k^b, cable lengths are denoted as l_k^b. According to the PPM, the following derivations are obtained.

Projecting the plane cable tensions, F_k^p, onto spatial cable net structure, the tensions of front cable net are obtained:

$$F_k^s = \frac{l_k^s}{l_k^p} \times F_k^p \quad (k = 1, 2, \cdots, r) \tag{1}$$

Similarly, the tensions of back cable net are given by:

$$F_k^b = \frac{l_k^b}{l_k^p} \times F_k^p \times \rho_{ij} \quad (k = 1, 2, \cdots, r) \tag{2}$$

where ρ_{ij} is the ratio of back cable tension to front cable tension in projection plane, relating to the nodal positions. i, j are nodes connected to cable k. The z-axis of the coordinate system is set parallelly to the vertical cables. Denoting z-direction coordinates of the ith node of front and back cable net as z_i^s and z_i^b respectively, ρ_{ij} is expressed in a typical form as follows.

$$\rho_{ij} = \frac{z_j^s - z_i^s}{z_i^b - z_j^b} \tag{3}$$

For axi-symmetric reflectors, denoting the focal lengths of front and back cable net paraboloid as p^s and p^b respectively, a simplified expression is obtained.

$$\rho_{ij} = \frac{p^b}{p^s} \tag{4}$$

The number of vertical cables is denoted as r_v, the tension of cable connected to node i is denoted as F_i^v. In the projection plane, the length of cable connected to node i is denoted as l_{it}^p, cable tension is denoted as F_{it}^p, and z-direction coordinates of two cable ends are denoted as z_i and z_{it}, where $t = 1, 2, \ldots, m$, m is the number of cables connecting to the node i. According to the equilibrium condition, the expression of vertical cable tensions is as follows:

$$F_i^v = \sum_{t=1}^{m} \left(F_{it}^p \times \frac{z_{it} - z_i}{l_{it}^p} \right) \quad (i = 1, 2, \cdots, r_v) \tag{5}$$

3. Relationship between mean cable tensions and structural parameters

According to the symmetry, the parabolic reflectors are categorized into two main families: axi-symmetric and offset reflectors, as show in Fig. 2.