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Shape adjustment optimization and experiment of cable-membrane reflectors

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ABSTRACT

Cable-membrane structures are widely employed for large space reflectors due to their lightweight, compact and easy package. In these structures, membranes are attached to cable net, serving as reflectors themselves or as supporting structures for other reflective surface. The cable length and membrane shape have to be carefully designed and fabricated to guarantee the desired reflector surface shape. However, due to inevitable error in cable length and membrane shape during the manufacture and assembly of cable-membrane reflectors, some cables have to be designed to be capable of length adjustment. By carefully adjusting the length of these cables, the degeneration in reflector shape precision due to this inevitable error can be effectively reduced. In the paper a shape adjustment algorithm for cable-membrane reflectors is proposed. Meanwhile, model updating is employed during shape adjustment to decrease the discrepancy of the numerical model with respect to the actual reflector. This discrepancy has to be considered because during attaching membranes to cable net, the accuracy of the membrane shape is hard to guarantee. Numerical examples and experimental results demonstrate the proposed method.

1. Introduction

In an effort to reduce launch and manufacturing costs, cable-membrane structures have been widely employed to construct ultra-lightweight space reflectors due to the fact that cable-membrane structures have the advantages of small-stowed volume, lightweight, low cost, and good thermal and damping properties [1]. In space applications, reflectors with large aperture and high shape precision are highly demanded since large aperture increases the signal-to-noise ratio and signal resolution, while the high-precision shape increases the sensitivity and spatial resolution. Reflector shape is required to be as close as possible to a perfect paraboloid and the shape precision is usually measured with the reflector surface root-mean-square (rms) error. For antenna reflectors, the demanded shape precision merely depends on the operation frequencies and is only a little fraction, say 1/50, of operation wavelengths. This is extremely rigorous for large reflectors. For instance, NASA's NEXRAD (Next-generation Radar) monitoring hurricanes, cyclones and severe storms requires a 35 m deployable reflector operating at 35 GHz with the shape rms error of 0.21 mm, equivalent to the thickness of three sheets of paper [2].

In order to achieve the needed shape precision, cable-membrane reflectors have to be designed to be capable of shape adjustment. With an elaborate shape adjustment, the degeneration in the reflector shape precision due to inevitable error in cable length and membrane shape can be effectively decreased. Furthermore, cable-membrane reflectors could nominally achieve the poor shape precision in the order of several millimeters because of the mechanical and thermal distortion in space [3]. Thus, shape adjustment is a key technology for high precision reflectors.

To reach this goal, some shape adjustment methods have been addressed. Some elements of the structure were designed with much high coefficients of thermal expansion than the main structure, and prescribing temperatures could be applied on these elements to improve the shape precision. Jenkins and Marker addressed the shape adjustment of inflatable membrane reflectors, which was achieved through enforced boundary displacements [4]. Hill and Wang studied the shape adjustment of membrane reflectors where a lot of distributed polyvinylidene fluoride actuators were utilized to change the reflector shape [3]. However, the most common way of shape adjustment is implemented by changing the length of some carefully selected cables of the reflector [5]. San et al. investigated the shape adjustment of inflatable reflectors, which was implemented by adjusting the length of the boundary cables and the inflatable pressure in the airtight membrane reflector [6]. DeSmidt et al.

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researched the shape adjustment of cable-membrane reflectors, using a gore/seam cable-based control system to reduce global rms errors due to thermal loading and inflation effects [7].

The most common type of space reflectors are the mesh reflectors with a lightweight metallic reflective mesh surface supported by cable net structure. The reflective mesh is stretched with a uniform tension by the cable net and is mechanically treated as membrane. The shape of this kind of reflectors can be adjusted by changing the length of some cables equipped with adjustment devices. In this paper we focus on the shape adjustment by changing the cable length. Some research has been done on the shape adjustment algorithms of mesh reflector. The approach using sensitivity matrix was commonly employed for shape adjustment where least-squares method was utilized to solve an over-determined system of linear equations to help avoid numerical conditioning problems [7–9]. If the discrepancy between the exact sensitivity matrix and the computed one is not negligible, shape adjustment procedure may not converge within allowable iteration or even diverge. The shape adjustment of tension truss antenna reflector was investigated by Tabata et al. also using the sensitivity matrix method [10]. In order to decrease the discrepancy between the exact sensitivity matrix and the computed one, an iterative approach was utilized to modify the matrix by simply utilizing the measured reflector position in the previous adjustment iteration instead of the computed reflector position. However, this is not an effective way of modifying the sensitivity matrix.

An optimization method for shape adjustment of mesh reflectors was proposed by Liu et al. [11], where the tensions of the adjustable cables were optimized to maximize the shape precision based on the nonlinear finite element model of the cable-beam reflector. Shape adjustment for space reflectors consisting of cable nets using mode adjustment method was investigated in Ref. [12] where the estimated reflector deformation and the mode shape of each mode were approximated by polynomials, and the linear finite element model was employed to obtain mode shapes. In these works, the influence of the reflective metal mesh was neglected and the discrepancy between the finite element model and the actual reflector was not involved.

An optimal method for shape adjustment of flexible reflectors was proposed by Yoon et al. [13], where the reflector deformation was expressed in terms of the adjustment inputs based on the linear finite element model, and then the adjustment inputs were optimally determined using the necessary condition for the existence of an extremum. However, usually it is hard to obtain this necessary condition when the nonlinear finite element model of reflectors was employed.

Cable-membrane reflectors are flexible and of strong geometric nonlinearity due to their large size and poor stiffness. In practical applications, the error in cutting and assembling cable segments and membrane pieces is relatively large, especially during attaching the membrane pieces to the cable net manually. This could lead to an obvious discrepancy of the numerical model relative to the actual reflector, deteriorating the adjustment algorithms and leading to a slow convergence procedure. Structural shape and tension distribution are critical for numerical models of cable-membrane reflectors. However, due to the hard work in measurement of the tension distribution, it is impossible to construct an accurate numerical model for cable-membrane reflectors with precisely direct measurements. In this situation, model updating provides a good way of decreasing the discrepancy [14].

The remainder of this paper is as follows: Section 2 performs the mechanical analysis of cable-membrane reflectors where the geometry of triangular membranes are described with their side length. Section 3 proposes a shape adjustment algorithm with model updating for cable-membrane reflectors to gradually decrease the discrepancy of the numerical model, improving the efficiency of shape adjustment. Section 4 presents numerical examples and experiment results to demonstrate the method. And some remarking conclusions are summarized in Section 5.

2. Mechanical analysis of cable-membrane reflector

The finite element method is employed to analyze the mechanical behavior of the cable-membrane reflector. Cable-membrane reflector is a tensile structure whose equilibrium position depends on its geometric parameters of cables and membranes. The geometric parameter for cable is the unstretched length and that for membrane is the side length of the triangular membrane in unstretched state since here only triangular membrane is involved. These parameters are readily to characterize cables and triangular membranes, and are easy to measure in practical applications. In order to calculate the equilibrium position of the reflector, the relation between its position and the geometric parameters will be developed.

2.1. Finite element analysis of cable

For an arbitrary cable with the end nodes 1 and 2, elastic modulus E_c, cross-sectional area A_c and unstressed length l in the cable-membrane reflector, its nodal position vectors are denoted by $\mathbf{x}_1 = [x_1, y_1, z_1]^{\mathrm{T}}$ and $\mathbf{x}_2 = [x_2, y_2, z_2]^{\mathrm{T}}$, respectively, subjected to the external forces $\mathbf{f}_1$ and $\mathbf{f}_2$, as shown in Fig. 1.

The total potential energy of the cable is

$$U_c = \int_0^l \frac{1}{2} E_c A_c \varepsilon_c^2 \mathrm{d}s - \mathbf{x}_c^{\mathrm{T}} \mathbf{f}_c \tag{1}$$

where ε_c is the axial strain of a point on the cable with the corresponding local coordinate $s \in [0, l]$, $\mathbf{f}_c = [\mathbf{f}_1^{\mathrm{T}}, \mathbf{f}_2^{\mathrm{T}}]^{\mathrm{T}}$ and $\mathbf{x}_c = [\mathbf{x}_1^{\mathrm{T}}, \mathbf{x}_2^{\mathrm{T}}]^{\mathrm{T}}$. The first item on the right-side of the equal sign is the elastic potential energy, and the second item is the potential energy of the external force, being opposite in sign from the external work expression because the potential energy of the external force is lost when the work is done by the external force.

The axial strain of the cable can be obtained as

$$\varepsilon_c = \frac{L}{l} - 1 \tag{2}$$

where $L = [(\mathbf{x}_1 - \mathbf{x}_2)^{\mathrm{T}}(\mathbf{x}_1 - \mathbf{x}_2)]^{1/2}$ is the stretched length of the cable. For small strain, (2) can be simplified as [15]:

$$\begin{aligned} \varepsilon_c &= \sqrt{\frac{(\mathbf{x}_1 - \mathbf{x}_2)^{\mathrm{T}}(\mathbf{x}_1 - \mathbf{x}_2)}{l^2}} - 1 \approx \frac{1}{2}\left(\frac{(\mathbf{x}_1 - \mathbf{x}_2)^{\mathrm{T}}(\mathbf{x}_1 - \mathbf{x}_2)}{l^2} - 1\right) \\ &= \frac{1}{2}\left(\frac{1}{l^2}\mathbf{x}_c^{\mathrm{T}}\mathbf{D}_c\mathbf{x}_c - 1\right) \end{aligned} \tag{3}$$

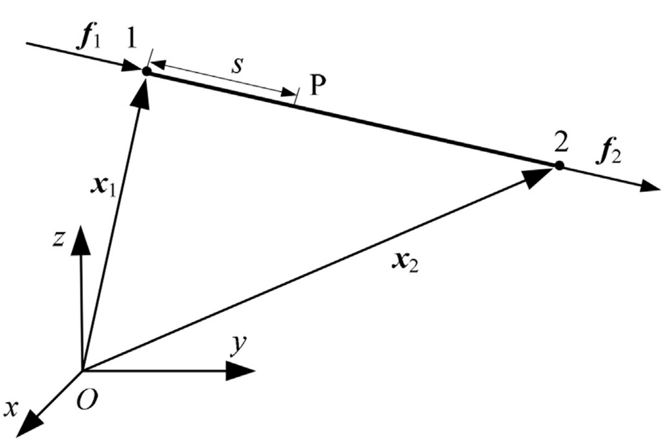

Fig. 1. A space cable in equilibrium.