Acta Astronautica 97 (2014) 164–171

Contents lists available at ScienceDirect

Acta Astronautica

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

Shape adjustment of cable mesh reflector antennas considering modeling uncertainties

Jingli Du*, Hong Bao, Chuanzhen Cui

Key Laboratory of Electronic Equipment Structure Design of Ministry of Education, Xidian University, Xi'an, Shaanxi 710071, China

ARTICLE INFO

Article history:
Received 27 March 2013
Received in revised form
24 November 2013
Accepted 4 January 2014
Available online 11 January 2014

Keywords:
Shape adjustment
Cable mesh structures
Worst-case optimization
Modeling uncertainties

ABSTRACT

Cable mesh antennas are the most important implement to construct large space antennas nowadays. Reflector surface of cable mesh antennas has to be carefully adjusted to achieve required accuracy, which is an effective way to compensate manufacturing and assembly errors or other imperfections. In this paper shape adjustment of cable mesh antennas is addressed. The required displacement of the reflector surface is determined with respect to a modified paraboloid whose axial vertex offset is also considered as a variable. Then the adjustment problem is solved by minimizing the RMS error with respect to the desired paraboloid using minimal norm least squares method. To deal with the modeling uncertainties, the adjustment is achieved by solving a simple worst-case optimization problem instead of directly using the least squares method. A numerical example demonstrates the worst-case method is of good convergence and accuracy, and is robust to perturbations.

1. Introduction

Space antennas aim at being capable of large diameter, light weight and high precision. Large diameter is essential for antennas to achieve high gain or high directivity. Light weight is attributed to limited delivery capacity of rockets. Thus, space antennas are usually launched in a stowed, compact state so that they can be accommodated and can withstand launch loads. Despite these, high precision is in urgent demand, which only depends on operation frequencies. Reflector surface RMS error is usually a little fraction, say 1/50, of operation wavelengths. Several types of antennas have been studied and developed including solid surface antennas, inflatable antennas and cable mesh antennas [1]. Among these, cable mesh antennas are excellent candidates for space antennas to satisfy the above three requirements. For example, the ETS-VIII satellite has two 17 m × 19 m cable mesh antennas for satellite communication [2], TerreStar satellite possesses an 18 m cable mesh antenna for global communications [3].

Cable mesh antennas in deployed state are usually very flexible and have strong geometric nonlinearity due to their large size and poor stiffness. As is well known, the shape and internal force distribution of cable structures are highly coupled. The unavoidable manufacturing and assembly errors and external environment loads will lead to errors in cable mesh shape and internal force distribution. Therefore, these antennas are deliberately designed to be adjustable by changing length of some special cables to obtain desired surface precision or other requirements, facilitating manufacture of the antennas.

Many researches on shape adjustment of cable mesh antennas have been carried out. Tanaka and Natori investigated the shape control of a cable mesh space antenna, in which the adjustment procedures using a direct method and a mode method were presented to increase the surface precision by altering the length of tie cables or boundary cables of the mesh reflector [4]. Mitsugi et al. proposed the basic idea of shape adjustment of statically determinant tension truss antennas by using the sensitivity matrix of

* Corresponding author. Tel./fax: +86 29 88203040.
E-mail address: jldu@mail.xidian.edu.cn (J. Du).

0094-5765/$ - see front matter © 2014 IAA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actaastro.2014.01.001

surface error with respective to cable length variation [5]. These studies employed the small deformation assumption and did not account for the geometric nonlinearity of cables. To overcome this problem, Tabata et al. proposed to recalculate the sensitivity matrix in each shape adjustment iteration [6]. Xu and Luo also presented an iterative procedure to implement nonlinear shape adjustment [7]. These works focused on achieving specified displacements of the mesh reflector, but they did not discuss the displacement determination.

Optimization methods can also be employed for shape adjustment. Di et al. presented a multi-objective optimization model aiming at minimizing the surface error and the number of adjustable cables of a cable mesh antenna [8]. Jager proposed a mixed integer linear programming optimization model to control the shape of tensegrities [9]. However, optimization methods usually need a large amount of computation especially when there is a lack of gradient information.

An accurate mechanical model is essential for all these shape adjustment methods. However, there are divergences between the actual behaviour of an antenna and its nominal model due to inevitable modeling uncertainties, such as the manufacturing and assembly error, measurement error of nodal position and modeling simplification. These uncertainties will deteriorate the adjustment algorithms, leading to a slow convergence procedure or even a divergence. These literatures did not account for the effect of uncertainties.

Shape adjustment is an indispensable procedure in the assembly of cable mesh antennas. In this paper, we discuss the determination of the required displacement for shape adjustment and propose a simple worst-case optimization model to take into consideration the modeling uncertainties. The organization of the paper is as follows: Section 2 performs the mechanical analysis of cable mesh antennas and obtains the sensitivity matrix of reflector surface displacement. Section 3 proposes a method to determine the displacement for the reflector surface to deform to a required paraboloid. Section 4 presents a worst-case optimization model to deal with modeling uncertainties in shape adjustment. A numerical example is presented in Section 5 to demonstrate the validity of the method. And some remarking conclusions are summarized in Section 6.

2. Mechanical analysis of cable mesh antennas

Force density method [10] is an efficient way of analyzing the equilibrium state of structures consisting of cables and/or bars for which it is easy to define a force density. However, it is difficult for other types of structures, such as antenna structures involving beams. For this reason, the finite element method is employed. To better account for the geometric nonlinearity of flexible antennas and the effect of cable length variation during shape adjustment, a line cable element is first derived. Illustrated in Fig. 1 is a space cable element in equilibrium state with the axial stiffness EA and the unstressed element length L. The nodal position vectors of the element are denoted by $\mathbf{x}_1$ and $\mathbf{x}_2$ in the global frame, respectively, with the corresponding nodal forces $\mathbf{F}_1$ and $\mathbf{F}_2$. According to Hooke's law, nodal force $\mathbf{F}_1$ can be expressed as a function of the relative nodal position,

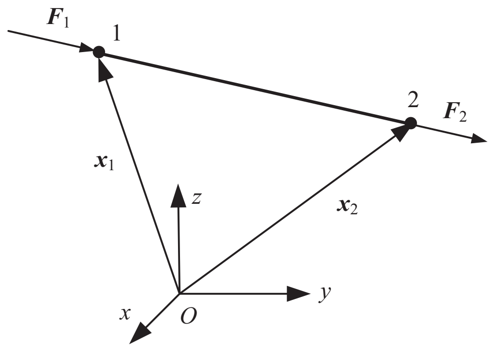

Fig. 1. Cable element in equilibrium state.

$\mathbf{x}_1$–$\mathbf{x}_2$, and the unstressed element length, L, as following:

$$\mathbf{F}_1 = -\mu \frac{EA}{L}(L_e - L)\frac{\mathbf{x}_2 - \mathbf{x}_1}{L_e} \tag{1}$$

where $L_e = [(\mathbf{x}_2 - \mathbf{x}_1)^{\mathrm{T}}(\mathbf{x}_2 - \mathbf{x}_1)]^{1/2}$ is the stressed element length and

$$\mu = \begin{cases} 1 & \text{if } L_e > L \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

to account for the fact that cables can only be tensioned but not compressed.

By neglecting higher order terms, the first-order Taylor expansion of (1) is obtained as

$$\Delta\mathbf{F}_1 = \frac{\partial \mathbf{F}_1}{\partial(\mathbf{x}_1 - \mathbf{x}_2)}(\Delta\mathbf{x}_1 - \Delta\mathbf{x}_2) + \frac{\partial \mathbf{F}_1}{\partial L}\Delta L \tag{3}$$

where

$$\frac{\partial \mathbf{F}_1}{\partial(\mathbf{x}_1 - \mathbf{x}_2)} = \mu \frac{EA}{L_e}\frac{1}{L_e^2}(\mathbf{x}_1 - \mathbf{x}_2)(\mathbf{x}_1 - \mathbf{x}_2)^{\mathrm{T}} + \mu \frac{EA}{L_e}\frac{L_e - L}{L}\mathbf{I}_3 \tag{4}$$

$$\frac{\partial \mathbf{F}_1}{\partial L} = -\mu \frac{EA}{L^2}(\mathbf{x}_1 - \mathbf{x}_2) \tag{5}$$

Here the element length is also treated as a variable to facilitate the analysis of cable adjustment. We can note from (4) that the first term corresponds to the axial stiffness of the element in the global frame and the second term to the geometric stiffness due to the element tension.

Noting $\Delta\mathbf{F}_2 = -\Delta\mathbf{F}_1$ leads to

$$\Delta\mathbf{F}_k = \mathbf{K}_{ck}\Delta\mathbf{u}_k + \mathbf{K}_{sk}\Delta L \tag{6}$$

where

$$\Delta\mathbf{F}_k = \begin{bmatrix} \Delta\mathbf{F}_1 \\ \Delta\mathbf{F}_2 \end{bmatrix}, \ \Delta\mathbf{u}_k = \begin{bmatrix} \Delta\mathbf{u}_1 \\ \Delta\mathbf{u}_2 \end{bmatrix} = \begin{bmatrix} \Delta\mathbf{x}_1 \\ \Delta\mathbf{x}_2 \end{bmatrix}, \mathbf{K}_{ck} = \begin{bmatrix} \mathbf{k}_{ck} & -\mathbf{k}_{ck} \\ -\mathbf{k}_{ck} & \mathbf{k}_{ck} \end{bmatrix},$$

$$\mathbf{K}_{sk} = \begin{bmatrix} \mathbf{k}_{sk} \\ -\mathbf{k}_{sk} \end{bmatrix}, \mathbf{k}_{ck} = \frac{\partial \mathbf{F}_1}{\partial(\mathbf{x}_1 - \mathbf{x}_2)}, \mathbf{k}_{sk} = \frac{\partial \mathbf{F}_1}{\partial L}$$

Thus, the incremental nodal force $\Delta\mathbf{F}_k$ is related to the increments of nodal displacement $\Delta\mathbf{u}_k$ and cable length ΔL.

The trusses of antennas can be modeled using the common beam elements [11]. Following the standard finite element analysis procedure we can establish the static model of cable mesh antennas as following:

$$\Delta\mathbf{F} = \mathbf{K}_c\Delta\mathbf{u} + \mathbf{K}_s\Delta\mathbf{L} \tag{7}$$