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Manufacturing error sensitivity analysis and optimal design method of cable-network antenna structures

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ABSTRACT

Inevitable manufacturing errors and inconsistency between assumed and actual boundary conditions can affect the shape precision and cable tensions of a cable-network antenna, and even result in failure of the structure in service. In this paper, an analytical sensitivity analysis method of the shape precision and cable tensions with respect to the parameters carrying uncertainty was studied. Based on the sensitivity analysis, an optimal design procedure was proposed to alleviate the effects of the parameters that carry uncertainty. The validity of the calculated sensitivities is examined by those computed by a finite difference method. Comparison with a traditional design method shows that the presented design procedure can remarkably reduce the influence of the uncertainties on the antenna performance. Moreover, the results suggest that especially slender front net cables, thick tension ties, relatively slender boundary cables and high tension level can improve the ability of cable-network antenna structures to resist the effects of the uncertainties on the antenna performance.

1. Introduction

Cable-network structures, which are characterized by low mass, large scale and compact package volume, have found wide applications in architecture, space science and so on. The cable-network antennas have been used in various missions [1–3], such as SMAP (Soil Moisture Active & Passive) mission by Jet Propulsion Laboratory (JPL) [4]. Before a cable-network antenna is tensioned, it has no structural stiffness to take external loads or keep a certain shape. To obtain the anticipated stable shape and structural stiffness, cable-network structures should be properly tensioned. However, in the manufacturing process, errors that can result in deviations of the supporting node locations and imperfect cable lengths are introduced. Unavoidably, due to the manufacturing errors, the shape precision is possibly too low to meet the requirements and the critical stress may be exceeded. Therefore, to study the effects of the parameters carrying uncertainty on the antenna performance and alleviate the effects are of significant importance.

By using a finite-difference method (FDM) and Monte Carlo simulations, several studies for mesh antennas, domes and tensegrity structures have been performed regarding the effects of parameters that carry uncertainty. For example, Meguro [5] studied the surface precision degradation of mesh antennas due to cable length errors and module connection by FDM. Mehran [6] presented four methods to estimate the RMS error due to cable length error. The first one is a Monte Carlo simulation based method; the others are on the basis of finite element analysis. Tibert [7] investigated the effects of some random manufacturing errors on the performance of a tensegrity antenna by Monte Carlo technique. Hedgepeth [8] also

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used Monte Carlo technique for a nine ring geodesic dome with its rim fixed. The surface error of the dome with member length imperfection and tension tie force variation is computed. However, as for large cable-network antennas, the computational costs of both FDM and Monte Carlo simulations are very high, and it is very hard to find appropriate difference step size for FDM.

Although much work has been published concerning the effects of the parameters that carry uncertainty, no attention, to the authors' knowledge, has been paid to alleviate these effects. Moreover, much research has been done on the design of cable-network antennas aiming to obtain maximum surface precision and maximum–minimum tension ratio [9–15], but no studies have been performed on minimizing the effects of the parameters with uncertainty.

The present paper proposes a sensitivity analysis method, for examining the effects of the parameters on the shape precision and cable tensions as well as an optimal design approach for alleviating these effects. To begin with, the sensitivities of the structural performance with respect to (*w.r.t.*) the parameters with uncertainty are derived by directly differentiating the structural governing equation. Then, with the sensitivities, an optimal design procedure is proposed to alleviate the influence of the parameters carrying uncertainty by optimizing the cable tensions and cross-sectional areas. And finally, the application of the proposed method in a 3 m diameter cable-network antenna demonstrates the validity of the calculated sensitivities and shows that the effects of the parameters that carry uncertainty are remarkably alleviated. The effectiveness of the proposed design approach is verified by Monte Carlo simulations.

2. Sensitivity analysis of the parameters carrying uncertainty

Nodes in a cable-network structure are classified into two types: the supporting nodes and the free nodes (as shown in Fig. 1). A supporting node connects some cables with the supporting structure, while a free node connects different cables. In this section, two types of uncertainties introduced in the manufacturing and assembly process, the uncertainties in the supporting node locations and unstrained cable lengths, were essentially studied. The shape precision and cable tensions are expressed as a function of the free node coordinates that are related to the parameters carrying uncertainty by the governing equation.

2.1. Sensitivities of the shape precision w.r.t. the parameters with uncertainty

2.1.1. Expression of the shape precision

It is assumed that n_r of the free nodes have certain location precision requirements and their nominal locations are on the objective paraboloid. If node k is one of them, the z-direction deviation from its nominal location can be expressed as

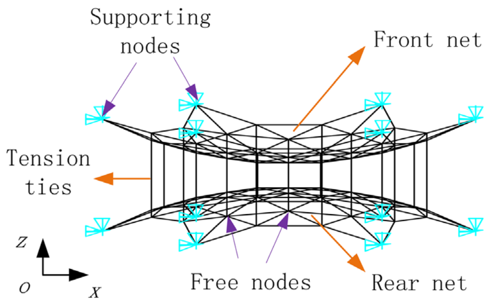

Fig. 1. A 3 m diameter cable-network antenna structure studied by Tibert.

$$\delta_k(Z_k) = \left[(Z_k^x - x_0)^2 + (Z_k^y - y_0)^2\right]/(4f) - Z_k^z + z_0, \quad (k = 1, 2, \cdots, n_r) \tag{1}$$

where $Z_k = \left[Z_k^x, Z_k^y, Z_k^z\right]^T$; Z_k^x, Z_k^y and Z_k^z are the x-, y- and z-coordinates of node k, respectively; x_0, y_0 and z_0 are the coordinates of the apex of the objective paraboloid; f denotes the focal length of the objective paraboloid. Here, the shape precision is written as the root-mean-square (RMS) error of the specified nodes

$$R = \sqrt{\sum_{k=1}^{n_r} (\delta_k)^2 / n_r}. \tag{2}$$

If the nodes are on their nominal locations, we get $\delta_k(\mathbf{Z}_k) = 0$ and $R = 0$.

2.1.2. Sensitivities of the RMS error w.r.t. the supporting node coordinates

Let n_f and $\mathbf{Z}_f$ denote the total number and coordinate vector of the supporting nodes, respectively, and Z_{fj}^{ii} represents the ii-coordinate $(ii = x, y, z)$ of the j-th $(j = 1, 2, \cdots, n_f)$ supporting node. Differentiating both sides of Eq. (2) gives the sensitivity of the RMS error *w.r.t.* Z_{fj}^{ii}

$$\frac{\partial R}{\partial Z_{fj}^{ii}} = \frac{1}{n_r R} \sum_{k=1}^{n_r} \left(\delta_k \frac{\partial \delta_k}{\partial Z_{fj}^{ii}} \right), (R \neq 0). \tag{3}$$

When the nodes are on their nominal value, $R = 0$, and Eq. (3) reaches a singularity. However, we can get the left derivative and right derivative of the RMS error *w.r.t.* Z_{fj}^{ii} in the following way. Now given an increment of ΔZ_{fj}^{ii} to Z_{fj}^{ii}, we obtain

$$\begin{aligned}
\frac{\Delta R}{\Delta Z_{fj}^{ii}} &= \frac{1}{\sqrt{n_r}\left(\Delta Z_{fj}^{ii}\right)} \left(\sqrt{\sum_{k=1}^{n_r} \left(\delta_k\left(\mathbf{Z}_k\left(Z_{fj}^{ii} + \Delta Z_{fj}^{ii}\right)\right)\right)^2} - \sqrt{\sum_{k=1}^{n_r} \left(\delta_k(\overline{\mathbf{Z}}_k)\right)^2} \right) \\
&= \frac{1}{\sqrt{n_r}\left(\Delta Z_{fj}^{ii}\right)} \sqrt{\sum_{k=1}^{n_r} \left(\delta_k\left(\mathbf{Z}_k\left(Z_{fj}^{ii} + \Delta Z_{fj}^{ii}\right)\right)\right)^2} \\
&= \frac{1}{\sqrt{n_r}\left(\Delta Z_{fj}^{ii}\right)} \sqrt{\sum_{k=1}^{n_r} \left(\delta_k\left(\mathbf{Z}_k\left(Z_{fj}^{ii} + \Delta Z_{fj}^{ii}\right)\right)^2 - \delta_k(\overline{\mathbf{Z}}_k)\right)^2}
\end{aligned} \tag{4}$$

where $\overline{\mathbf{Z}}_k = \left[\overline{Z}_k^x, \overline{Z}_k^y, \overline{Z}_k^z\right]^T$ is the nominal coordinate vector of