Optimization and experiment of an electrostatic forming membrane reflector in space

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Abstract

An electrostatic forming membrane reflector with AstroMesh structural support is a new concept for space-borne deployable antennas. A membrane shape-control optimization model is proposed in this study for electrode design to achieve high reflector precision. In this model, the electrode number, channel number, and voltages are considered design variables, the membrane reflector precision is an objective function, and the positivity and uniformity of membrane stress are constraints. A technology that combines a gradient method and genetic algorithm is proposed to solve the optimization model. This technology includes continuous and discrete design variables with different values and dimensions. The validity and effectiveness of the optimization model are demonstrated via the numerical example of a 5 m membrane reflector and a 0.55 m experimental prototype.

Keywords: Electrode design; Electrostatic forming membrane reflector; Optimization model; Shape control

1. Introduction

Given the developments in space technologies, demand for satellite antennas with large diameters and high reflector precision have increased [1-4]. However, owing to available space structures, large-diameter deployable antennas usually work in a low frequency, such as L/S bands, which cannot be used for high frequencies. As a concept proposed in Ref. [5], an electrostatic forming membrane reflector with AstroMesh structural support is designed to satisfy the large diameter and high frequency requirements. High reflector precision can be achieved with an electrostatic forming membrane by applying electrostatic forces between the electrodes and surface membrane. The electrodes mounted to the front net of the AstroMesh support can be individually controlled with independent power supplies from different channels. The design concept for an electrostatic forming membrane reflector is shown in Fig. 1.

In the design of an electrostatic forming membrane reflector, a key technology is electrode optimization design [6], which requires a reasonable number of electrodes; Furthermore, the number of control channels and the values of electrode voltages also need to be optimized. Some methods have been used in the actuator layout of domain control, such as linear quadratic regulator [7], controllability Gramian method [8], and en masse elimination algorithm [9]. However, few works have investigated the electrode optimization of electrostatic forming membrane reflector.

In this paper, a membrane shape control optimization model is presented for electrode optimization design. The static behavior of the electrostatic forming membrane is analyzed by using the nonlinear finite element method (FEM). To determine the electrode voltages, we propose an optimization model wherein the number of voltage channels and the corresponding voltages are the design variables. The optimization aims to achieve a high membrane reflector precision by considering that the membrane stress is positive and uniform. In the optimization procedure, the design variables are iterated simultaneously. They contain the discrete integers for the electrode and channel numbers. Furthermore, continuous voltages are optimized, thus making the optimization model a mixed...
problem. To solve this mixed problem, a technology that combines a gradient method, as well as a genetic algorithm (GA), is applied in the procedure. This technology can increase the optimization efficiency and achieve high reflector precision requirements.

The remainder of this paper is organized as follows. Sec. 2 outlines the proposed optimization model with the solution technology. Sec. 3 presents the utilization of an electrostatic forming membrane reflector to demonstrate the validity and effectiveness of the proposed model. Sec. 4 summarizes the major achievements of this study.

2. Optimization model of electrode design

2.1 Nonlinear FEM analysis formula

The electrostatic forming membrane reflector utilized in this study consists of a membrane surface, a membrane support ring, adjustable cables, and a flexible steel ring. The top view of the structure is shown in Fig. 2.

This reflector structure combines the elements of membrane, cable, and beam. Nonlinear FEM is employed to describe its stiffness equation [10]:

\[
[K_L + K_{NL}]\{\Delta X\} = \{F_T + F_E\},
\]

where \(K_L\) and \(K_{NL}\) are the linear and nonlinear stiffness matrices, respectively; \(\{\Delta X\}\) is the nodal displacement vector; \(F_T\) and \(F_E\) are the thermal load vector and electrostatic force vector, respectively.

As for a large electrostatic membrane reflector, the aperture is far larger than the distance between the membrane and electrodes; on the basis of this assumption, the force per unit area between the membrane and electrode is subject to parallel plate capacitor relationship [11]:

\[
p = \frac{U^2\varepsilon_{perm}}{2L^2},
\]

where \(U\) is the voltage between the membrane and electrodes; \(\varepsilon_{perm}\) is the permittivity; \(L\) is the distance between the membrane and electrodes and can be considered constant compared with reflector deformation [5].

The membrane surface is under an electrostatic force, which is normal to the surface. In the global coordinate system, the electrostatic force vector of each membrane element is defined as follows:

\[
\{F_E^i\} = \frac{1}{3}Ap\{\cos^2\gamma, \cos^2\beta, \cos^2\alpha, \cos^2\gamma, \\
\cos^2\beta, \cos^2\alpha, \cos^2\gamma, \cos^2\beta, \cos^2\alpha\}^T,
\]

where \(A\) is the membrane area; \(p\) is the membrane force in Eq. (2); \(\alpha\), \(\beta\), and \(\gamma\) are the inclination angles of the membrane element with respect to \(XOY\) plane, \(XOZ\) plane, and \(YOZ\) plane of the global coordinate system, respectively.

Eq. (3) can be rewritten as follows:

\[
\{F^E\} = \frac{1}{3}AqU^2\{\cos^2\gamma, \cos^2\beta, \cos^2\alpha, \cos^2\gamma, \\
\cos^2\beta, \cos^2\alpha, \cos^2\gamma, \cos^2\beta, \cos^2\alpha\}^T,
\]

where \(q = \varepsilon_{perm}/2L^2\).

By assembling the element stiffness matrices, we can write the electrostatic force on the membrane surface as follows:

\[
\{F_E\} = \sum_{i=1}^{k} \{F^E_i\} = [B_e]\{U\}^2,
\]

where \(k\) is the total number of membrane elements, \([B_e]\) is the load coefficient matrix, \(\{U\}\) is the membrane element voltage vector determined by the channel voltage vector \(\{U\} = [U_1, U_2, \ldots, U_n]\) according to the control location, \(\{U\}^2\) is the square of each entity of the vector \(\{U\}\), and \(n\) is the number of voltage channels.

Substituting Eq. (5) into Eq. (1), we can express the stiffness equation as follows:

\[
[K_L + K_{NL}]\{\Delta X\} = \{F_T + [B_e]\{U\}^2\}.
\]

The membrane surface deformation can be obtained by solving Eq. (6), and the membrane stress can also be calculated.

2.2 Electrode design optimization model

In the electrode design, the membrane reflector precision is optimized, which demands that the electrode and channel numbers should be few as possible to prevent decreasing the weight, cost, and energy for launching.

(1) Design variables

The electrode layout is given in Fig. 3. The electrodes are composed of many regular electrode elements, and several adjacent elements may form a group that should be electrically connected (Fig. 3). Each electrode group is connected to a