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Comprehensive structural analysis and optimization of the electrostatic forming membrane reflector deployable antenna

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ABSTRACT

The electrostatic forming membrane reflector antenna (EFMRA) is a promising scheme to construct large-size, high-precision and lightweight space deployable reflector antennas. A set of comprehensive structural optimization design procedures is presented for EFMRA in this paper. This procedure consists of four steps: Firstly, a synthesized form-finding method is introduced for the AstroMesh structure which is the structural foundation of the EFMRA. Based on the nonlinear force density method, a fast iterative format is derived, using which we can get a initial state in which the tensions of the front rear cable networks and one electrode membrane are completely uniform, and all the nodes of the front networks are on the ideal paraboloid. Secondly, based on the finite element theory, a structure-electrostatic coupled analysis model is established to take the coupled field problems into consideration. Thirdly, a technique is proposed to optimize the initial reflective membrane geometry. The shape of the membrane is expressed by a set of polynomials, and the polynomial coefficients are optimized to obtain optimal geometry of the reflective membrane. Moreover, the controlling voltage adjustment model is established, which is solved by sensitivity analysis. At length, these proposed methods are applied to the structural optimization design of an EFMRA. The results validate the effectiveness of this comprehensive optimization procedure and the feasibility of designing the EFMRA to compensate the errors introduced from manufacturing process and environmental changes.

1. Introduction

Large deployable reflector antennas are widely used in various areas, such as remote sensing, deep-space probing, communication, reconnaissance, and environmental monitoring [1–6]. With the development of modern satellite technologies, there is now a higher performance requirement for space antennas, which tend to have large aperture, high accuracy and light weight. Light weight and high packing efficiency are indispensable requirements as the capacities of launch vehicles are always limited. A large aperture enables high signal resolution and high signal-to-noise ratio, and high accuracy enables both high spatial resolution and sensitivity [6,7].

The 10-m antenna aperture has been realized in both inflation and mesh reflector antennas, which can normally function on S/L wavebands [5,6,8–15]. Currently, such antennas cannot meet the requirement of high surface accuracy in the applications of meteorology radars and microwave radiometers, which always work on Ka or even higher wavebands. For example, NASA's NIS mission concept requires a space deployable 35-m diameter reflector that operates at 35 GHz with 0.21 mm RMS shape accuracy [4]. Therefore, many high precision deployable reflector antenna concepts have been developed in the past years, such as the PVDF inflatable antennas [16,17], membrane-shell reflectors [18,19], SMART antennas [20], electrostatic forming membrane reflector antenna and so on. The emergence of electrostatic forming technology provides a novel means to improve the surface accuracy [4,9,21].

The electrostatic forming technology is firstly proposed by Martin Yellin in 1977 [22]. This system mainly consists of polymer metal coating membrane and electrodes positioned behind the membrane. The electrodes can be wired together and connected to a bank of voltage supplies, and the membrane is linked to the ground with a zero electrical potential. As the variation of the voltages of the electrodes will affect the membrane shape, the membrane shape accuracy can be effectively controlled by adjusting the voltages of the distributed electrodes. In the past years, many prototypes have been developed for ground experiments [23–30]. In 2004, the first electrostatic forming membrane reflector antenna was jointly manufactured by SRS Company and Northrop Grumman Corp. [9,31,32]. This antenna mainly consists of the AstroMesh support structure, the curved polymer coating membrane, and the

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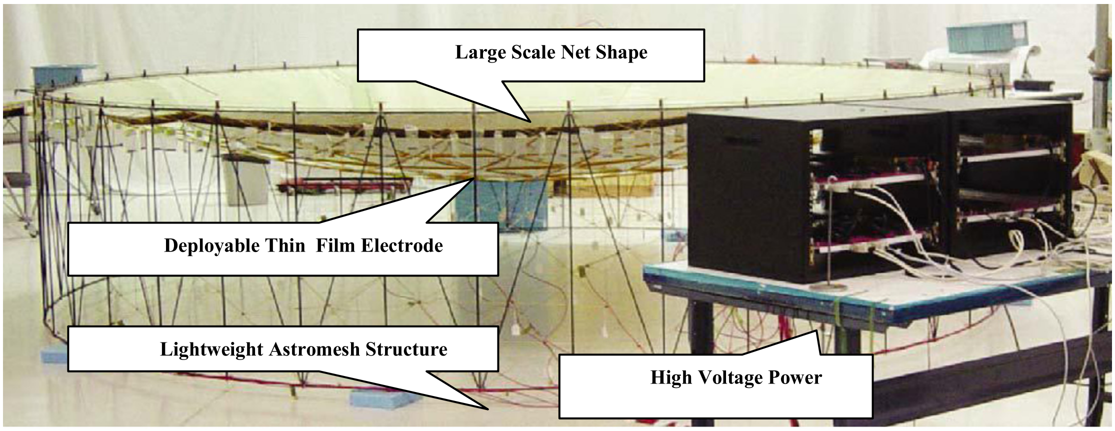
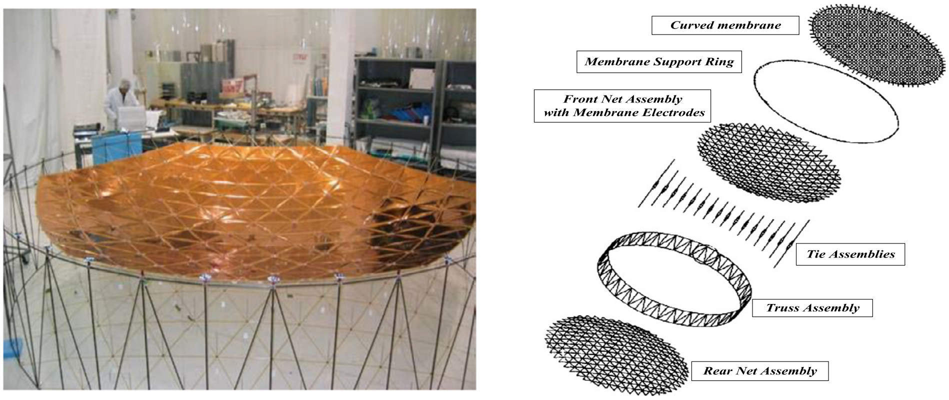


(a) Whole scene



(b) Electrode distribution

(c) Explode view

Fig. 1. Electrostatic forming membrane reflector antenna.

voltages controlling systems. The design concept of this forming membrane reflector deployable antenna is shown in Fig. 1 [9]. In this antenna, large-aperture mesh reflector is employed as a structural foundation, and each thin film electrode is attached to a triangle mesh on the front net of the mesh reflector and is wired to the high voltage power supply and control system. Adjacent electrodes are connected with insulating tapes to avoid the electronic discharge problem. Then, the voltages on each electrode are regulated to produce contraction/expansion forces to adjust the shape of the membrane reflector and compensate the distortions, thus obtaining high accuracy.

From the point of the view of the antenna structure components, the structural design of the electrostatic forming membrane reflector deployable antenna could be divided into the following three parts: form-finding design of the AstroMesh structure, which is also the structural foundation of this antenna; initial geometry design of the reflective membrane; solving of optimal control voltage. The aforementioned three subjects would be discussed in detail as follows:

The film electrodes are mounted on the AstroMesh structure which plays an important role in the whole EFMRA system. In fully deployable state, this structure is a tensioned cable-membrane network, which is very flexible and has very strong geometric nonlinearity due to the trivial flexural stiffness of the cables and membrane [7]. The shape of cable-membrane and its internal force distribution are interdependent. Previous studies showed that the stability of the structure increases with the tension distribution uniformity of cable-membrane network [33]. Furthermore, the faceted surface of tensioned film electrodes would also have some influence on the shape accuracy of the reflective membrane. In order to meet the shape requirement and tension uniformity, the method of finding the equilibrium configurations, which is form-finding for the cable-membrane structure design, has been investigated in previous studies.

In these studies, the form-finding process is generally divided into two steps, of which one is to carry on the form finding for the cable network and the other one is to slightly adjust the tension of the cables to compensate the shape precision loss due to the elastic deformation of the supporting structure. A mesh generation method to minimize the faceted errors was proposed, and the form-finding method which can minimize the ratio of maximum tension to minimum tension in the cable network was also presented based on the minimum norm method in Refs. [34,35]. Different design criterions, including the equal tension, the equal force-density, and the quasi-equal length of the front net, were implemented for a antenna of which the front net and the rear net are exactly identical based on the force density method in Refs. [36,37]. A numerical form-finding approach for calculating the uniformly tensioned cable net was proposed based on the assumption that the front cable net is exactly identical to the rear one in Ref. [39]. An iterative method to reduce the shape precision loss and the tension uniformity deterioration of the cable network was proposed by adjusting the boundary cables of the front networks in Ref. [33]. A non-iterative method to compensate the errors due to the elastic deformation of the supporting truss was presented based on the force density and finite element methods in Ref. [38]. In addition, a method using sequential quadratic programming to adjust the tensions of the whole cable networks to compensate