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Surface accuracy analysis of large deployable antennas

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ABSTRACT

This paper performs an analysis to the systematic surface figure error influenced by three factors including errors of faceted paraboloids, fabrication imperfection and random thermal strains in orbit. Firstly, the computational formulas for root-mean-square surface deviations caused by these factors are presented respectively. The stochastic finite element method is applied to derive the computational formulas of fabrication imperfection and random thermal strains, by which the sensitivity of surface accuracy to component imperfection can be revealed. Then the Monte Carlo simulation method is introduced to obtain the surface figure by sampling test on random errors. Finally, the analytical method is applied to the research on the surface figure error of AstroMesh deployable reflector. The results show that the deviations between the root-mean-square surface errors calculated by the proposed formulas with less consuming time and those by the Monte Carlo simulation method are less than 2%, which indicates that the proposed method is efficient and receivable enough to analyze systematic surface figure error of a large deployable antenna. Moreover, further investigations on the relationship between surface RMS deviation and the antenna parameters including aperture and the number of subdivisions are presented in the end.

1. Introduction

Large deployable antennas, such as Rigid-Rib Antenna (RRA) [1], Wrap-Rib Antenna (WRA) [2], Spring-Back Antenna (SBA) [3], Tension Truss Antenna [4,5] and Astro-Mesh Antenna [6,7], have been widely employed in geostationary orbit communications satellites, tracking and data relay satellites, and electronic reconnaissance satellites etc. Meanwhile as the further development of applications of satellites in earth explorations, radio astronomy, deep space observations and land remote sensing, the demand for larger aperture and higher frequency deployable antennas is on the rapid increase [8].

Large deployable antennas are distinguished by flexibility, less stowed volume, good heat stability and capability of being applied to both low- and high-frequency missions [9]. However, a significant drawback to these antennas is the limited deployed surface accuracy of reflectors, which has imposed a restriction on the ability to reflect RF communications at shorter wavelengths. Furthermore, one of the most important parameters to characterize the antenna performance is the maximum gain which is inversely proportional to the square of the root-mean-square (RMS) deviation of the actual surface from the desired one [10]. Thus it is essential to analyze the surface accuracy of a reflector at its design stage.

Up to now, many representative large deployable antennas have been extensively applied in such renowned projects like AstroMesh and ETS-VIII [11]. They are composed of the supporting truss and cable net with a reflecting mesh or membrane. In principle, the reflecting surface is divided into many flat facets with zero Gaussian curvature due to their lack of shear and bending rigidity. Therefore, the practical reflector assembled by these facets exhibits the minimum

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theoretical error which is known as the design error. Hedgepeth [12], investigated a thorough study about RMS deviations of faceted mesh antennas. Agrawal et al. [13] studied the RMS surface deviation between the best-fit paraboloid with flat facets and a sphere.

In addition, the random errors of member length, cable tension and coefficient of thermal expansion (CTE) are unavoidable in the manufacturing process which will degrade the surface accuracy. Although the minimum theoretical error has been taken into account during the design of a reflector, few publications deal with the random errors. As a consequence of the growing demands for great performance antennas of high surface accuracy and large size, investigations on the systematic surface figure error influenced by random errors are extremely urgent. Based on the Rayleigh–Ritz principle, Hedgepeth [14], established the relationship between the statistical errors and natural frequencies of a reflector structure assembled by tetrahedral truss with the virtual mass per unit area. As reported in [12], Hedgepeth also derived an approximate expression for estimating surface errors caused by random member-length imperfection of the truss configurations including tetrahedral truss, geodesic dome, radial rib and pretensioned truss. The strain obtained by superposition principle may lead to an increase in surface error. Moreover the computational error of this method may grow out of control when the antenna has a large number of elements. Mobrem [15] described four useful methods for analyzing the RMS deviations of reflectors influenced by the manufacturing tolerances: Monte Carlo simulation method (MCSM), inverse frequency squared method, direct method and normal mode method. And these methods were applied into a Synthetic Aperture Radar (SAR) antenna and a 12-meter AstroMesh deployable antenna. The author pointed out that the former two methods were used in the overall behavior of the structure in considering manufacturing errors while the latter two were used when the sensitivity of surface distortion to individual member error were required. Furthermore, the random thermal strains affected by random CTE must be taken into consideration, because the satellite will be subjected to extreme temperatures at the moment of exiting or entering Earth's umbral shadow [16].

The available researches mainly focus on the effects of a single error factor on surface accuracy without considering these errors systematically. And general expressions for random errors are absented. Furthermore, the existing several analytical methods for random errors are limited by the antenna aperture and desired high accuracy. In this paper, a new method based on stochastic finite element method (SFEM) is proposed to analyze systematical surface figure error of large deployable antennas. The SFEM is used to deal with the random errors problem, which is an extension of the classical deterministic finite element approach to the stochastic framework [17]. The general and explicit expressions of the RMS surface deviations due to the minimum theoretical error, manufacture error and in-orbit random thermal strains formulated respectively. Thanks to the SFEM, the connection between the RMS deviation and probability distribution parameters of structural statistical error is developed. By MCSM, one of proven techniques to deal with problems which are complex, nonlinear, or involves more than just a couple uncertain parameters, is applied to be a key reference to the random error research, since the real errors with the statistical property of a complex system are difficult to measure, and the process of sampling is extravagant expenditure. Afterwards, the application of the computational formulas and MCSM to analyze the surface accuracy of an AstroMesh deployable reflector is carried out.

The remainder of this paper is organized as follows: Section 2 describes the formulas of RMS surface deviation caused by faceted reflector. Then, random errors of large deployable antennas including fabrication errors and in-orbit random thermal strains are investigated based on SFEM in Section 3. In Section 4, numerical simulation studies are presented. Finally, conclusions are summarized in Section 5.

2. Surface error of faceted reflector

Agrawal et al. [13] derived the equation for the deviation caused by the general flat facet, shown in Fig. 1, located on a revolution surface. They pointed out that if the reflector under consideration shown in Fig. 2 is shallow, it can be closely approximated by a sphere with the radius R given by

$$R = 2F + \frac{D^2}{32F} \tag{1}$$

where D is the aperture of the reflector, and F is the focal length.

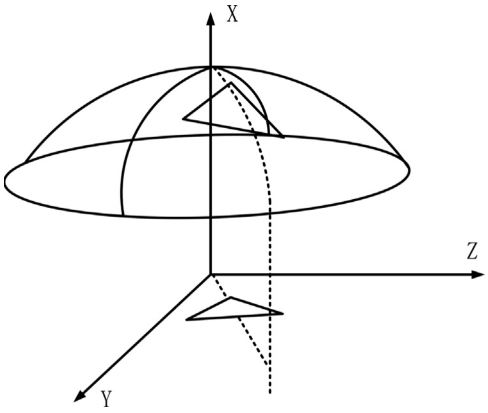

Fig. 1. Geometry of general triangle located on a revolution surface [13].

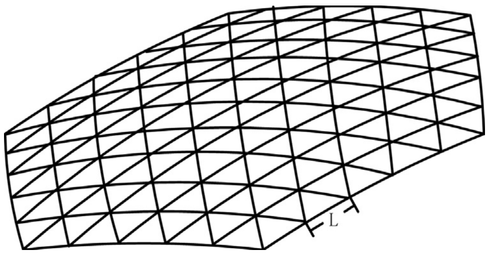

Fig. 2. Shallow spherical dish approximated with flat facets [13].