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Stochastic and sensitivity analysis of shape error of inflatable antenna reflectors

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A R T I C L E I N F O

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A B S T R A C T

Inflatable antennas are promising candidates to realize future satellite communications and space observations since they are lightweight, low-cost and small-packaged-volume. However, due to their high flexibility, inflatable reflectors are difficult to manufacture accurately, which may result in undesirable shape errors, and thus affect their performance negatively. In this paper, the stochastic characteristics of shape errors induced during manufacturing process are investigated using Latin hypercube sampling coupled with manufacture simulations. Four main random error sources are involved, including errors in membrane thickness, errors in elastic modulus of membrane, boundary deviations and pressure variations. Using regression and correlation analysis, a global sensitivity study is conducted to rank the importance of these error sources. This global sensitivity analysis is novel in that it can take into account the random variation and the interaction between error sources. Analyses are parametrically carried out with various focal-length-to-diameter ratios (F/D) and aperture sizes (D) of reflectors to investigate their effects on significance ranking of error sources. The research reveals that RMS (Root Mean Square) of shape error is a random quantity with an exponent probability distribution and features great dispersion; with the increase of F/D and D, both mean value and standard deviation of shape errors are increased; in the proposed range, the significance ranking of error sources is independent of F/D and D; boundary deviation imposes the greatest effect with a much higher weight than the others; pressure variation ranks the second; error in thickness and elastic modulus of membrane ranks the last with very close sensitivities to pressure variation. Finally, suggestions are given for the control of the shape accuracy of reflectors and allowable values of error sources are proposed from the perspective of reliability.

1. Introduction

In recent years, high requirements for future communications and observations have been posed for space antennas to obtain high gain and high directivity and to be operated in high frequency [1]. It is conceivable that the apertures of antennas are needed to be larger and more precise. Compared to rigid antennas, inflatable antennas (see Fig. 1) are more promising candidates to realize such requirements, since they could provide many advantages such as light weight, low cost and small packaged volume [2].

The performance of inflatable antennas hinges on the shape accuracy of the membrane reflectors. The tolerance of the reflector shape accuracy can be estimated at an RMS (Root Mean Square) between 1/50 and 1/20 of the wavelength of interest [3]. To achieve high accuracy, two primary types of inflatable reflectors with respect to different design concepts have been developed, namely, initially flat reflectors and initially curved reflectors.

The former ones are obtained by inflating an initially flat circular membrane. Many methods have been developed to reduce the deviation in the reflector shape from an exact parabola, such as adjusting the boundary position or initial stress [3,4]. However, these measures are not effective for large-size reflectors. For this reason, initially curved antennas became an attractive alternative. The exact parabolic reflectors can be obtained when the initial (uninflated) curved surfaces are determined properly [5–8]. In this paper, we will focus on the initially curved reflectors since it is more prospective for large aperture application.

It has been observed that, even though the initial curved reflectors are adopted and designed properly, it is still a difficult job to achieve the desired shape accuracy in practice because reflectors are typically flexible and easily affected by manufacture errors, such as membrane thickness, errors in elastic modulus of membrane, boundary deviations and pressure variations etc. Greschik [9] explored the effects of errors in the membrane thickness, errors in the membrane elastic modulus

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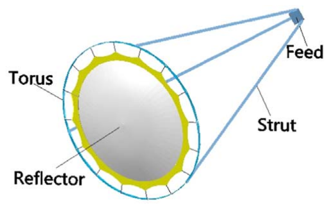

Fig. 1. Inflatable antenna.

and boundary deviations. Naboulsi [10] conducted a pressure tuning investigation. Coleman [11] carried out parametric studies on shape errors by varying the tendon forces, aperture size, and antenna reflector depth. The authors of this paper performed a local sensitivity analysis to distinguish the effects of error sources in manufacturing in Ref. [8]. These works provided useful solutions and advice in controlling the shape accuracy.

However, in the researches above, shape error analyses were treated as deterministic problems, which don't fit well with real-world engineering characteristics. Manufacture process, involving complicated labour and mechanical inputs, tend to be a random process, in which various uncertainties exist. Due to the absence of consideration about uncertainties, the existing sensitivity analyses were restricted to local sensitivity analyses. The local sensitivity measures the influence of parameters by varying one parameter at a time and keeping the other parameters constant. The procedure is repeated for all parameters one by one to study their effects [12]. It is easy to implement but features difficulties in exploring the effect of entire parameter spaces and identifying the interactions between parameters. In contrast, global sensitivity analyses are more reasonable since they perform analyses over the entire feasible region of input parameters and quantify the impact of parameters and their interactions on output variables [13].

In this paper, a stochastic analysis and global sensitivity analysis is presented for shape error of initially curved on-axis parabolic reflectors. The goal is to reveal the stochastic characteristics of shape errors and investigate the effect of each error sources under the consideration of randomness. Four main random error sources are involved, including errors in membrane thickness, errors in elastic modulus of membrane, boundary deviations and pressure variations. Furthermore, the allowable values of each error are suggested from the perspective of reliability.

The paper is organized as follows. In Section 2, a manufacture simulation method is adopted to obtain shape error of reflectors. In Section 3, the use of Latin hypercube sampling for the stochastic analysis is explained. Following it, a global sensitivity method is presented, which is based on regression and correlation analysis. In Section 4, stochastic analysis model of reflectors is established. In Section 5, stochastic and global sensitivity analyses are carried out with various focal-length-to-diameter ratios (F/D) and aperture size (D) of reflectors. And the results and discussion are reported. In Section 6, suggestions are given in controlling the shape accuracy and allowable values of error sources are proposed from the perspective of reliability. Finally, Section 7 presents concluding remarks.

2. Manufacture simulation method for reflectors

As introduced in Section 1, actual reflectors inevitably deviate from the design reflectors due to manufacture process. Therefore, we proposed a numerical method [8] to simulate the manufacture process, aiming at capturing the actual shapes of reflectors. The effects of manufacture error sources can be investigated by introducing them in the process of simulation.

The manufacture is sort of inverse process of design. Thus the process of design is firstly outlined as follows. First, a stress release analysis is carried out to solve for the initial (uninflated) reflector shape. To ensure the computed initial surface unwrinkled, inverse iterative method [8], is applied. After that, cutting pattern analysis is conducted. Since it is infeasible or overly expensive to mold the initial curved surface, the initial surface is usually assembled by a set of planar membranes. The aim of cutting pattern analysis is to solve for the pattern of planar membranes. It usually includes generation of cutting lines and flattening. In most cases, the cutting lines are generated as geodesic lines that extend from the vertex to the rim and divide the entire surface into several identical sub-surfaces (spatial gores). Subsequently, the sub-surfaces are flattened into planar gores. Because initial surfaces of antennas are not developable, this step is an approximate process.

The manufacture process is numerically simulated as follows.

Step1: Modeling of seamed surface.

As mentioned above, flattening is an approximate operation. That means the surface seamed from the set of flat gores is not exactly the initial surface provided by designers. This obviously leads to shape error. Hence, it is necessary to model the seamed surface.

In this paper, we do not need to consider the actual original sagged state and inflation process. The seamed surface model is only required to meet the following two requirements: the gores are not stretched or compressed, i.e., no stress or wrinkles are artificially induced; and there must be no gaps or overlaps between adjacent gores after seaming. To satisfy these requirements, a faceted surface model is proposed. It is based on the observation that stretching or compression can be prevented by converting a flat gore into a faceted surface.

To construct the assembled surface, each flat gore is divided into a group of panels. The division lines between two adjoining panels are designed and depicted as dashed lines in Fig. 2a. Each of them is generated starting from a radial boundary node and ending at the symmetric node of another radial boundary. These division lines form a group of parallel lines. Most of panels are trapezium.

The flat gore is transformed into a faceted sub-surface, which can be seen as a single curved surface, as illustrated in Fig. 2b. Considering the first requirement, only rotation and rigid-body movement of the panels are allowed in the transformation process. Aiming at satisfying the second requirement, the rotation angles are solved by a set of equations [8], which are in terms of profiles of panels. Finally, the seemed model is obtained (Fig. 2c).

The modeling method described above is feasible as long as the flat gores are identical.

Step 2: Simulation of inflation.

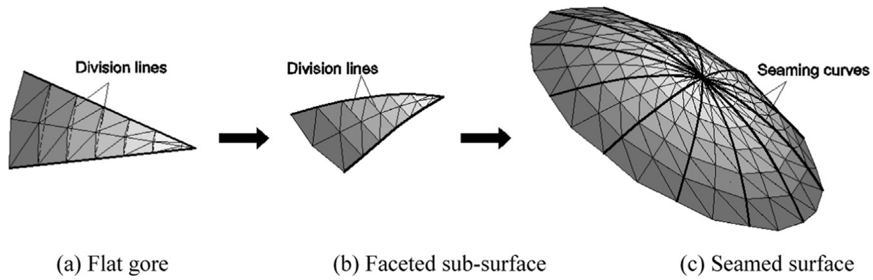

Fig. 2. Modeling the assembly of the initial surface.