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Shape error study of inflatable antennas using a numerical model

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ABSTRACT

We conduct an in-depth study on the shape error of initially curved antennas to investigate errors that occur in the design and manufacturing processes. First, a numerical model is developed to simulate the actual surfaces. This model features a main advantage that it can predict the effects of cutting patterns on the shape error. The model is used to evaluate and optimize the design of cutting patterns. An error sensitivity analysis is performed to quantify and distinguish between the effects of error sources in manufacturing. The following sources are analyzed: errors in the elastic modulus of the membrane, pressure variations, and boundary deviations. The boundary deviation is found to be the most significant error source, and thus, boundary perturbation is recommended as an efficient error control measure. Finally, an inflatable antenna model is used to experimentally validate the numerical model. The experimental results display acceptable agreement with the numerical results. Thus, the developed numerical model and error control measure are shown to be feasible and efficient.

1. Introduction

There is currently a resurgence of interest in inflatable antennas (see Fig. 1), which has been motivated by growing reflector sizes. Inflatable antennas are preferred over traditional antenna reflectors when large-size antennas are required due to their light weight, low cost, and small packaged volume [1–3].

Antenna performance largely depends on the shape accuracy of reflectors, which typically have to be parabolic surfaces. The tolerance of the reflector surface accuracy can be estimated at an RMS (root mean square) between 1/50 and 1/20 of the wavelength of interest [4]. Such high accuracy is difficult to achieve. A significant amount of research has been conducted in this area, with a focus on design concepts, design methods, and accuracy analysis.

Two primary types of inflatable antennas have been developed to obtain the required parabolic profiles, namely, initially flat antennas and initially curved antennas.

The first type of antenna is obtained by inflating an initially flat circular membrane. Hencky [5] formulated the first description of the inflated shape of an antenna under several assumptions, and other contributions followed [6,7]. These works provided useful analytical solutions but also indicated that an initially flat reflector is not exactly parabolic in terms of its mechanical behavior. Many methods have been developed to reduce the deviation in the reflector shape from an exact parabola, such as adjusting the boundary position, pressure, or initial stress [4,8]. However, these measures are not effective for large-size antennas.

Thus, initially curved antennas have become an attractive alternative. An exactly parabolic surface can be produced if

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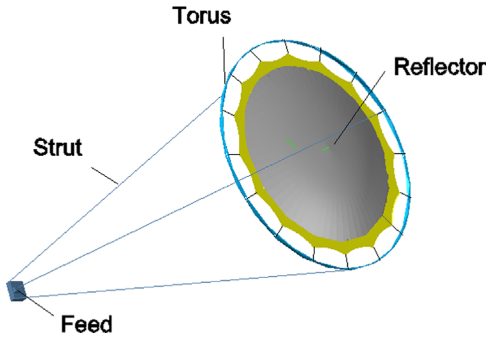

Fig. 1. Inflatable antenna.

the initial (uninflated) curved surface is designed properly. In early studies, the initial curved surface was designed to be an approximate target parabolic shape. This shape exhibited the same limitations as the initially flat antennas. Subsequent approaches solved for the initial shape required to obtain a desired inflated surface. Greschik [9] solved for a set of initially curved shapes by removing the strains from the inflated membranes. Xu and Guan [1] developed formulations to determine the initial shape. Zhao [10] developed a numerical analysis method to solve for the initial state. Bouzidi and Lecieux [11] defined the initial geometry of reflectors using an efficient optimization method simultaneously considering the optimal values of pressure. We previously used an inverse iteration method to solve for the initial shape [12]. The aforementioned methods are applicable to any reflector size.

In practice, it is infeasible or overly expensive to mold the initial curved surface. The surface must be approximated by assembling a set of planar membranes that are cut and seamed in a specified manner. The numbers and shapes of the flat membranes are determined by cutting pattern analysis. This analysis consists of two steps: generating the cutting lines on initial surfaces and flattening. Both steps have been studied in detail. Several types of surface lines are defined as cutting lines, including geodesic, planar section, irregular surface lines. Computational flattening techniques are typically classified in terms of two concepts: the minimum deformation principle and geometric transformation.

Unfortunately, initial surfaces of antennas are not developable; therefore all of the flattening methods are approximate. Thus, unexpected discrepancies occur between the actual and ideal shapes, and the magnitude of these discrepancies depends primarily on the cutting patterns, followed by the precision of the cutting analysis methods. Few studies [13] have considered the shape errors associated with cutting pattern analysis. These effects have not been investigated sufficiently.

As studies were carried out into the design method of antennas, error sources in the manufacturing process were identified to be important and worth further study. Reflectors are typically flexible and are easily deformed because of manufacturing errors, such as pressure variations and boundary deviations. Greschik [9] explored the effects of errors in the membrane thickness, errors in the membrane elastic modulus and boundary deviations. Naboulsi [14] conducted a pressure tuning investigation. Coleman [13] carried out parametric studies by varying the tendon forces, aperture size, and antenna reflector depth. However, further shape error analysis on the manufacturing process is still needed to improve accuracy.

In this paper, we perform a more in-depth study of the shape error of initially curved antennas to investigate the errors that occur in the design and manufacturing processes. First, a numerical model is developed to simulate the actual surfaces. This model has a main advantage that it can be used to predict the effects of cutting patterns on the accuracy of the surface generated. The model is used to evaluate and optimize the design of cutting patterns. The error analysis of manufacturing error sources can also be performed more accurately using this model.

The paper is organized as follows. In Section 2, the process of designing and manufacturing antennas is briefly introduced to better understand the new model and corresponding error analysis. In Section 3, the numerical model for the assembly of the flat gores is described along with the construction details. The numerical model can be generally applied to cutting patterns with identical gores. In Section 4, a geometric nonlinear finite element method is introduced to simulate inflation. In Section 5, the developed model is used to predict the effects of the cutting patterns. A parametric study is performed to determine the optimal number of gores. The effect of the construction details, seaming tapes, and central caps is also discussed. In Section 6, a sensitivity analysis is performed on the error sources in the manufacturing process, including errors in the membrane elastic modulus, pressure variations, and boundary deviations. Thus, the effects of each factor are quantified and distinguished in this study. An efficient and practical error control measures are also presented. In Section 7, an experiment is performed on an inflatable antenna with a 3 m aperture to verify the efficacy of the developed model and error control measure. Finally, concluding remarks and suggestions for future work are presented in Section 8.

2. Outline of design and manufacturing processes

The antenna design process typically consists of three steps (see Fig. 2).

Step 1: A stress release analysis is performed. The objective of this step is to solve for the initial (uninflated) reflector surface, given the desired ideal shape, the desired design pressure, and other parameters.

Step 2: Cutting lines on the initial surface are generated. In most cases, the cutting lines are geodesic lines that extend from the vertex to the rim and divide the entire surface into several identical sub-surfaces (spatial gores).

Step 3: The sub-surfaces are flattened into planar gores.

The procedure described above is feasible when the computed initial surface is smooth, i.e., unwrinkled. Some methods can ensure the computed initial surface unwrinkled. One of them, namely, inverse iterative method [12], is applied in this paper. The procedure is outlined below.