Geometric optimization of planar membrane reflector used in gossamer space structure

S. D. Shinde¹, M. Soni², S. H. Upadhyay³, S. Sakhare⁴ and K. S. Singh⁵

¹,²,³Smart Material and Structures Laboratory, Mechanical and Industrial Engineering Department, Indian Institute of Technology (IIT), Roorkee, 247667, India.
⁴⁵Space Applications Centre-Indian Space Research Organisation, Ahmedabad, 380015, India.
*Email: sanjay.upadhyay@me.iitr.ac.in

Abstract. In recent trends membrane reflector has increased its applications in space missions due its significant advantage such as light in weight, higher folding and packaging efficiency, ease of deployment, low on-Board volume requirement. Geometry of the membrane reflector has significant influence on its the stress distribution and area of deformation, subsequently determining the stiffness and geometrical parameters of its supporting structures. The present study uses a Taguchi optimization method of orthogonal array for investigating the membrane geometry parameter and its effect on membrane reflector.

1. Introduction

Light in weight, higher folding and packaging efficiency, ease of deployment which makes gossamer structures best suit for the space applications. Membrane Reflector antenna is one the type of gossamer structure which used for efficiently distributing the electromagnetic waves in predefined manner. Such structures can be potentially used in near term space missions, as it giving an additional benefit such as reduction in total system mass and deployment complexity also reducing the size of launch vehicle [1]. As the reflector aperture area has direct relation with the gain from the antenna, hence the size and geometric specification of the reflector is important contributing factor in designing of large size space reflector antenna [2]. Hedgepeth et al. discussed the design requirements of large structures which are deployed, erected, assembled, or fabricated in space with high stability and accuracy [3].

Geometry and boundary support of membrane structure has significant influence on the material stresses, deformation areas and RF gain of antenna performance. M.J. Coleman et al. has investigated the influence of boundary support on performance characteristic of inflatable parabolic reflector antenna [4]. Circular membrane reflector with inflatable supporting structure has been developed by D P Cadogan et al. Polyamide is used as a membrane material for investigating the antenna characteristics with 16 catenary points [5].

Flow chart of the optimization process for different cutting pattern for membrane structure given by Kim J.Y et. al. Actual stresses and design stresses are used as key parameter for obtaining optimum cutting pattern [6]. Liu Z. et. al discussed the planar rectangular as well as circular membrane reflector antennas developed by Jet Propulsion library (JPL). Synthetic aperture radar antenna with a three-layer membrane reflector was developed by Canadian Space agency in 2007. Cutting pattern analysis for inflatable parabolic antenna with planar gores was carried out by Xu Y at. al. Shape analysis of inflatable parabolic reflector can be carry out by membrane theory and elastic mechanics [7-9].

Many researchers have used a planar membrane reflector with inflatable torus (or supporting) structure but detailed geometry optimization study was not done till date. The geometry and number of attachment
point of the membrane reflector has significant influence on the membrane supporting structure in terms of stiffness and its geometric parameters. The presented study uses a square membrane reflector with four and eight holding points with variation in geometry associated with changes in holding point is analyzed for material stresses and deformation area. The analysis is made under the assumption of deformation at the loading point should be less than 0.01 mm. The present work uses a Taguchi method of orthogonal array for finding the optimum geometric shape of square membrane reflector.

2. Methodology

2.1. Geometry and Material Specification

A square membrane of 500 mm side made of Kapton material has been selected for the investigation due to its inherent property of best suit to the space environmental conditions, Material properties of Kapton material are shown in Table 1. By keeping the reflector effective area for of 500 mm × 500 mm, outer geometry of the membrane is made of shape to facilitate ease of holding with its supporting structure and provide uniform stress distribution in the membrane reflector. The outer geometry of the membrane is highly dependent on the number of holding points. The holding points are increase from 4 to 8 and variation in geometry parameter is made to finding out material stresses, area of deformation and mass of membrane reflector. Currently membrane reflector with 4 and 8 holding points are presented in this manuscript. For four holding point, the geometry parameters are i. Pin length (P1), ii. Radius of Curvature (P2), iii. Corner Distance (P3) as shown in Figure 1. The one more parameter in eight holding points is added which is periphery distance(P4) as shown in Figure 2.

Table 1: Material property of Kapton material

| Property                      | Kapton VN, 25 µm |
|-------------------------------|------------------|
| Density (Kg/m³)               | 1420             |
| Poisson’s ratio               | 0.34             |
| Young’s Modulus (MPa)         | 2500             |
| Yield point at 3% (MPa)       | 69               |
| Ultimate Elongation (%)       | 72               |

Figure 1: Membrane reflector with four holding point configuration
2.2. Taguchi Orthogonal Array
Taguchi method of orthogonal array is one of the widely used as optimization technique which gives the information about conducting minimum number of experiment. This method is derived from the full factorial design approach. Taguchi Orthogonal Array gives the parameter variation table with minimum number of possible combination affecting the performance of the system [10]. For four holding point the three parameter are checked at 5 levels which gives the 25 experiment combination as per Taguchi orthogonal array method as shown in Table 2, and Table 4. Similarly, for eight holding point the four parameters are analyzed at four levels leads to 16 experiment combinations as shown in Table 3, and Table 5. The values of parameters and levels are selected for minimum material condition for the outer geometry of the membrane ultimately reducing the mass of membrane structure. The tension forces applied at the holding points are increased gradually till the 0.01mm of deformation and stress results are recorded.

Table 2: Parameter and Level for four holding point configuration

| Four Holding Points | Pin length | Radius of Arc | Conner Distance |
|---------------------|------------|---------------|-----------------|
| Level 1             | 16         | 800           | 55              |
| Level 2             | 18         | 900           | 65              |
| Level 3             | 20         | 1000          | 75              |
| Level 4             | 22         | 1100          | 85              |
| Level 5             | 24         | 1200          | 95              |

Table 3: Parameter and Level for eight holding point configuration

| Eight Holding Points | Pin length | Radius of Arc | Conner Distance | Periphery Distance |
|----------------------|------------|---------------|-----------------|--------------------|
| Level 1              | 18         | 225           | 60              | 50                 |
| Level 2              | 20         | 250           | 70              | 60                 |
| Level 3              | 22         | 275           | 80              | 70                 |
| Level 4              | 24         | 300           | 90              | 80                 |
Table 4: Taguchi array for four holding points

| Run | P1  | P2  | P3  |
|-----|-----|-----|-----|
| 1   | 16  | 800 | 55  |
| 2   | 16  | 900 | 65  |
| 3   | 16  | 1000| 75  |
| 4   | 16  | 1100| 85  |
| 5   | 16  | 1200| 95  |
| 6   | 18  | 800 | 65  |
| 7   | 18  | 900 | 75  |
| 8   | 18  | 1000| 85  |
| 9   | 18  | 1100| 95  |
| 10  | 18  | 1200| 55  |
| 11  | 20  | 800 | 75  |
| 12  | 20  | 900 | 85  |
| 13  | 20  | 1000| 95  |
| 14  | 20  | 1100| 55  |
| 15  | 20  | 1200| 65  |
| 16  | 22  | 800 | 85  |
| 17  | 22  | 900 | 95  |
| 18  | 22  | 1000| 55  |
| 19  | 22  | 1100| 65  |
| 20  | 22  | 1200| 75  |
| 21  | 24  | 800 | 95  |
| 22  | 24  | 900 | 55  |
| 23  | 24  | 1000| 65  |
| 24  | 24  | 1100| 75  |
| 25  | 24  | 1200| 85  |

Table 5: Taguchi array for eight holding points

| Run | P1  | P2  | P3  | P4  |
|-----|-----|-----|-----|-----|
| 1   | 18  | 225 | 60  | 50  |
| 2   | 18  | 250 | 70  | 60  |
| 3   | 18  | 275 | 80  | 70  |
| 4   | 18  | 300 | 90  | 80  |
| 5   | 20  | 225 | 60  | 60  |
| 6   | 20  | 250 | 70  | 70  |
| 7   | 20  | 275 | 80  | 80  |
| 8   | 20  | 300 | 90  | 50  |
| 9   | 22  | 225 | 60  | 70  |
| 10  | 22  | 250 | 70  | 80  |
| 11  | 22  | 275 | 80  | 60  |
| 12  | 22  | 300 | 90  | 50  |
| 13  | 24  | 225 | 60  | 80  |
| 14  | 24  | 250 | 70  | 50  |
| 15  | 24  | 275 | 80  | 60  |
| 16  | 24  | 300 | 90  | 70  |

Above geometrical parameter was investigated for combination given in Taguchi Orthogonal Array for stress distribution and mass criteria with the targeted or required deformation of 0.01 mm at the periphery of the membrane is shown in Table 4, and Table 5. The force values for required deformation are also found in each run of simulation in Abaqus Ver.2016 software [11].

3. Result and Discussion

For each run of the Taguchi Orthogonal Array, mass properties along with stress distribution and deformation area are investigated. The preliminary result shows that the stress distribution become more evenly and area of deformation are also reduced as the holding points are changed from four to eight. The graph for stress distribution along with the diagonal path of square membrane for each run of Taguchi orthogonal Array is plotted and it is observed that for four holding point the maximum and minimum stresses at periphery of 500 mm × 500 mm membrane was 0.2065 MPa and 0.16886 MPa for Run number 20 and 21 respectively. The minimum mass is observed for Run 11 of 10.3 gm with stress level of 0.2029 MPa as shown in Figure 4.
Similarly, for the eight holding points the maximum and minimum stresses at the periphery of membrane 500 mm × 500 mm was 0.2367 MPa and 0.1889 MPa for the Run number 1 and 15 respectively. The minimum mass of 10.2 gm is also observed at Run 1. From the preliminary results it
is observed that geometry has significant influence on mass property, stress distribution and force required for holding the membrane reflector. The deformation areas also reduced with increased in holding point. The force required for minimum mass array run geometry combination for membrane is found to be 0.48 N and 0.32 N respectively for four and eight holding points. These forces are the key factor for determining the stiffness and geometric parameters of the support structure.

4. Conclusion

With use of Taguchi orthogonal array parameter optimization technique, the geometry optimization was done for four and eight holding point of square membrane reflector. The values of stresses and forces required for targeted deformation was analyzed and it is observed that geometry has significance influence on these parameters. Further study with increased holding points in subsequent steps are needed for finding the best suit for geometry configuration and holding point needed.

Acknowledgments

The authors thankfully acknowledge the financial support provided by Space Applications Centre (SAC/ISRO) under respond project, Government of India. (Project Grant Number ISR-1248-MID)

References

[1] Chmielewski A B 2001 Overview of Gossamer Stuctures Gossamer Spacecraft:Membrane and Inflatable structures Technology for Space Applications, edited by Paul Zarchan, Progress in Astronautics and Aeronautics AIAA Virginia 1-33
[2] Romanofsky R R, Lambert, Welch B W, Bbyk 2006 The Potential for Gossamer Deployable Antenna System in Ka-Band Exploration and science Communications Architectures Twelth Ka and BroadbandCommunications Conference, Italy
[3] Hedgepeth J 1891 Critical requirements for the design of large space structures Conference on Large Space Platforms: Toward Permanent Manned Occupancy in Space 443
[4] Coleman M J and Baginski F 2012 Effect of Boundary Support and Reflector Diamension on Inflatable Parabolic Antenna Performance Journal of Spacecraft and Rockets, 49, 5
[5] Cadogan D P, Lin J K, Grahne M S 1999 The development of inflatable space radar reflectarrays Proceedings of the 40th AIAA/ ASME/ ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit Saint Louis Missouri
[6] Kim J Y and Lee J B 2012 A new technique for optimum cutting pattern generation of membrane structures Engineering Structures, 24, 745–756
[7] Liu Z, Qiu H, Li X, Yang S 2017 Review of Large Spacecraft Deployable Membrane Antenna Structures Chinese Journal of Mechanical Engineering 1447–1459
[8] Xu Y, Guan F, 2012 Structure design and mechanical measurement of inflatable antenna Acta Astronautica, 13–25
[9] Lee, K and Lee, S W 2006 Analysis of gossamer structures using assumed-strain solid-shell finite elements Journal of spacecraft and rockets, 43, 1301-1307
[10] Cimbala J M 2014 Taguchi Orthogonal Arrays Penn State University
[11] Aabaqs, Simulia Ver. 2016 Johnston Rhode Island United States