Ninth International Conference on
THIN-WALLED STRUCTURES – ICTWS2023
Sydney, Australia, Nov 29 – Dec 1, 2023

PARAMETRIC STUDY FOR SINGLY-CURVED PARABOLIC CYLINDRICAL INFLATABLE STRUCTURE

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Keywords: Inflatable antenna structure; Singly-curved parabolic cylinder; Membrane reflector; Parametric study.

Abstract. *For the large singly-curved parabolic cylindrical reflector, the stowage space limitations demand fully inflatable structures that attain higher packaging efficiency. The present study is novel in incorporating inflatable cylindrical booms to shape a singly-curved parabolic cylindrical reflector. The approach can meet the higher packaging efficiency requirement, avoiding hinges while being fully inflatable. The presented structural concept and FE modeling provided a base by performing modal analysis. Parametric study based on membrane length to width ratio, width to focal length ratio, the effect of applied loading and membrane thickness on the natural frequency of parabolic cylindrical membrane surface. The analysis provided a specific size ratio for the Kapton membrane reflector eliminating resonance for the frequency range. A developed proof-of-concept model of an inflatable cylindrical torus with multiple gores attains the desired singly-curved parabolic shape. How the change in the number of gores affects the shape accuracy is also included. An assembly of reflector and torus is inflated from a fully folded configuration as a proof-of-concept model.*

1 INTRODUCTION

Deployable solid parabolic reflectors have shown their broader utility on the ground and in space missions, including synthetic aperture radar antenna [1], DART system [2] and precipitation radar antenna reflector [3]. The concept behind the deployable is to get a small packaging volume at launch and a larger deployed configuration in space. Efforts in designing singly-curved reflectors are limited to using solid frame hinge support configuration with actuators to minimize structural wrinkles [4]. The effect of gravity and boundary support conditions was examined experimentally using photogrammetry on a scaled model of a singly-curved reflector [5]. However, the model was supported by flexures. Flat solid beams and extension arms were used to generate a parabolic boundary in a suspension cable-supported stretchable reflective membrane [6].

For the broadband-surveillance search radar system, [7] tested and validated a doubly curved reflector antenna to understand its system behaviour. In the same field, [8] introduced a parabolic cylindrical mesh reflector concept and tested it for feed source broadband RF results. For higher deployment stiffness and packaging efficiency, thin-shell deployable reflectors with collapsible stiffeners were described in the literature [9, 10] as being able to be folded elastically and deployed using the stored elastic energy without an onboard power source. Further improvement was made using a rollable structure that significantly improved packaged volume with few hinges [11]. The rib design for an inflatable deployable reflector was proposed [12] to improve the overall surface accuracy of the structure.

The research so far in singly-curved/doubly-curved parabolic reflectors and mesh reflector antennae solves wrinkling and shape accuracy problems by introducing some mechanical connections and flexural hinges. However, limited stowage space demands inflatable structures that can be stowed in limited stowage space and are lighter in weight. In that regard, recent research [13] proposed collective z-folding strategy for planar reflector and inflatable torus assembly. In current paper, authors have presented a novel approach to achieve a singly-curved parabolic cylindrical shape of the reflector by an inflatable torus. The concept is introduced, and the Finite Element model is presented with compatibility analysis in section 2. Section 3 shows the parametric study performed for a singly-curved parabolic cylindrical reflector, including the effect of L/D, F/D, Poisson's ratio and membrane thickness variations. Section 4 conceptualizes the experimental approach to develop a singly-curved inflatable torus-reflector assembly. Section 5 concludes the paper.

2 FINITE ELEMENT MODEL OF A SINGLY CURVED PARABOLIC CYLINDRICAL MEMBRANE REFLECTOR

Primary work is designing a reflector that meets the design requirements based on structural parameters. The parabolic cylindrical reflector surface is a part of the paraboloid obtained by cutting a cylinder from a parabolic surface [12], [14]. However, a concept of the system with loading and end moments for a nonuniform shape might be helpful in developing an inflatable antenna structure. Motivated by this idea, a novel concept of parabolic cylindrical inflatable booms as connecting elements is proposed. By inflating booms, the reflector gains the desired parabolic cylindrical shape. Before developing a physical antenna assembly, a presumed perfectly desired reflector profile is analyzed numerically. This section described numerical model development for a singly curved parabolic cylindrical reflector.

Figure 1(a) is the schematic of a parabolic cylindrical membrane reflector. Assuming no bending effect and shaping process on a plate, forming a parabolic cylinder with a Length (L) of 2 meters, width (D) of 1.1 meters and membrane thickness being 25 µm. The focal length to get and maintain the parabolic cylinder shape is 0.7 m. This thin-film membrane reflector can be treated as a beam subjected to end moments and loads.

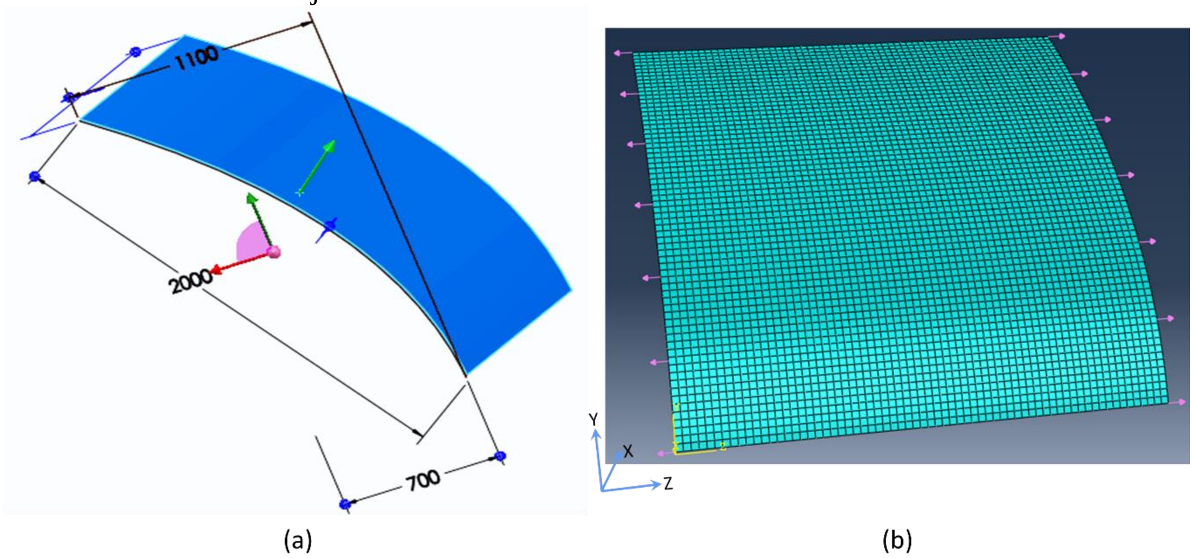

Figure 1: (a) The schematic of the singly curved parabolic cylinder with a focal distance to width (F/D) ratio less than one (b) Finite element model with boundary conditions and loading

The study of physical systems and the analytical solutions of their partial differential equations for dynamic behaviour leads to the complexity due to the boundary conditions. For the detailed study, a numerical method is used to solve the problem of complex domains. A finite element tool, ABAQUS, is used to analyze the non-linear behaviour of a singly-curved reflector. A profile of the singly-curved parabolic cylinder (2000 mm × 1100 mm, focal length 700 mm) is discretized into a finite number of elements using iso-parametric quad shell elements with reduced integration. Boundary conditions are as follows: free edges (top and bottom, figure 1(b)) are kept free while the sides are restrained for all degrees of freedom except translation in Z-axis and rotation about Y-axis.

2.1 Mesh convergence study

The convergence of the FE model has been checked for the following membrane properties. The Kapton membrane properties were obtained experimentally [15].

Table 1: Properties of experimentally tested Kapton thin-films.

Parameter	Value
Young's modulus (Gpa)	3.330
Yield stress (Mpa)	63.01
Material density (kg/m^3)	1420
Membrane thickness (μm)	25

The mesh convergence study is carried out by observing the maximum deflection of the membrane model, stress distribution and total computational time for the first natural frequency. Global mesh size is changed from as high as 200 to the lowest value of 5 units. The mesh elements and total deflection plot (figure 2) show that the use of 4623 quad-elements gives a close solution. The graph also represents similar behaviour. With a smaller number of elements, the deformation is much higher in magnitude and with an increased number of elements, the magnitude becomes stable. It won't change over 0.5% with very fine mesh designs. The fine-meshed model has no improvement in displacement outputs even after compromising on computational time for convergence (refer to table 2).

Table 2: Data comparison for mesh convergence study.

No. of elements	Max. deformation (cm)	Frequency (Hz)	Stress (N/mm^2)	Computational time (seconds)
100	0.78	18.86	62.812	7
272	0.32	12.13	63.187	8
420	0.47	14.14	63.093	10
1640	0.492	14.15	63.075	12
2720	0.532	14.18	63.066	15
4623	0.545	14.17	63.062	18
9300	0.53	14.15	63.062	26
19400	0.53	14.15	63.062	41

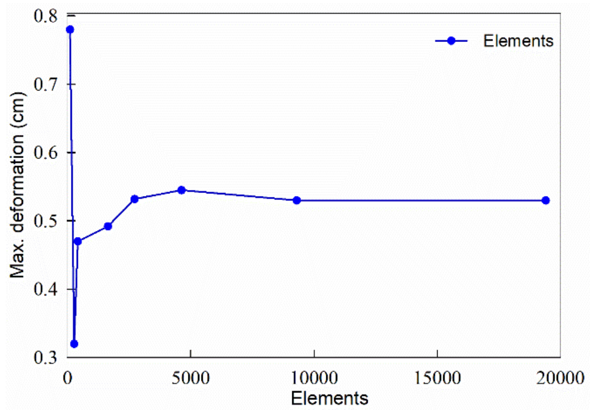

Figure 2: Mesh convergence for finite element model

2.2 Modal analysis

Among two iteration methods, subspace iteration and Lanczos, A fast and efficient Lanczos eigensolver system is used. A pre-stress modal analysis is preferred to evaluate the natural frequency and the respective shape to every frequency (known as mode shapes) of a structure. Pre-stress modal analysis is performed for two types of conditions: first, the initial static analysis involves small-deflection effects, then we use pre-stress modal analysis from a linear base analysis, and for applying this procedure, the essential condition must be satisfied, i.e., the deflection should be sufficiently small, and the analysis should be linear. Second, if these conditions are not satisfied, i.e., deflection in the structure is large, then prior static analysis is used.

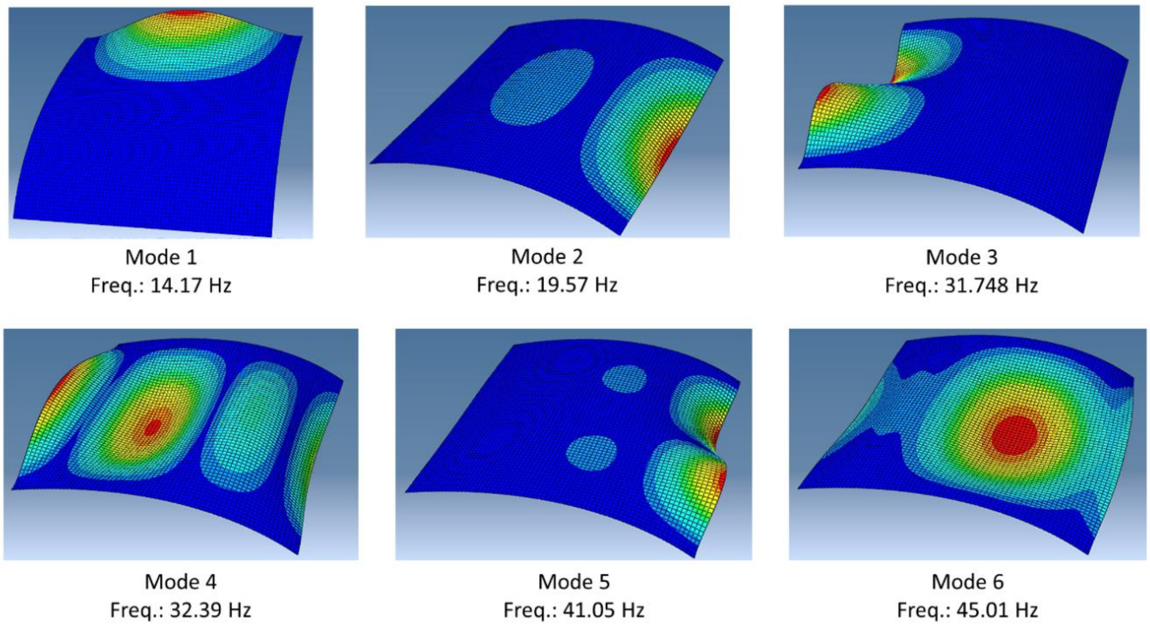

Figure 3: The first six mode shapes for singly-curved parabolic cylindrical membrane reflector

So, we have performed a pre-stress modal analysis from a linear base analysis. In that case, a two-step procedure is a must. The first step performs static analysis by pre-stressing the structure; the second is modal analysis. For the static pre-stress analysis, all the boundary conditions remain the same; however, the rotational DOF is also restrained. A small pre-stress magnitude, 0.5 N, is applied to the side edges as a uniform load in an outward direction. This pre-stress will induce small out-of-plane displacement in the shell elements, and the structure behaves like a membrane. After pre-stressing, modal analysis is performed by neglecting loading and dealing with only boundary conditions. The Lanczos eigen solver is used to derive the first 20 modes of a singly-curved parabolic cylinder for numerical analysis. Out of these, the first six modes are crucial from a modal analysis point of view. Hence, they are extracted, and natural frequencies of vibration of the system are obtained for each mode shape. The next section analyses these six mode shapes (figure 3) for system-affecting parameters.

3 PARAMETRIC STUDY: GEOMETRIC AND MATERIAL ASPECTS

This section presents a detailed analysis of the factors affecting the performance of the singly curved cylindrical parabolic inflatable structure. These directly affecting parameters include dimension and focal length; membrane thickness and Poisson's ratio; and loading. The effect of the length to width (L/D) ratio and focal-length to membrane width (F/D) ratio on natural frequencies, stress and surface deflection are presented, followed by the effect of applied loading and membrane thickness on the same parameters.

3.1 L/D ratio

Based on the predetermined dimensions, the ratio of length (L) to width (D) for a parabolic reflector is 1.81. The aspect ratios are changed in equal proportion to observe the effect of larger-size structures on natural frequencies, stresses and surface deflection. Element sizes are the same for all models, resulting in a varied total number of elements corresponding to the aspect ratio. After performing the mesh sensitivity analysis using different quad elements, S4R, four-node quad elements with reduced integration are used for the whole model over any other elements with fine meshing. The model shape effectively divides the global quad meshing task into simpler sub-tasks, and the Bresenham algorithm for lines inspires this uniform distribution of quad-shape elements. The uniform distribution of elements allows controlling the anisotropy nature of quad elements, which is not the case with other meshing approaches.

Considering the importance of an inflatable structure, the effects of aspect ratio on the natural vibration modes have been investigated. An aspect ratio is defined as the length (L) to the width (D) ratio of the planar profile projection on a flat surface of a singly-curved cylindrical, parabolic reflector. This study considers five different aspect ratios, i.e., L/D = 1.81, 3.62, 5.43, 7.27 and 9.05. The eigen frequencies with different aspect ratios are presented in table 3 for six mode shapes of vibration. It is observed that higher mode shapes influence the eigenfrequency. In the case of in- and out-of-plane mode shapes, the eigenfrequencies decrease as the L/D ratio increases. The prominent change in length compare to width for different aspect ratios leads to this. Moreover, the decrease in eigen frequencies for increased eigen frequencies is due to the increased mass on the spread surface of a singly-curved cylindrical parabolic reflector.

Table 3: Eigenfrequency for different L/D ratios of a singly-curved parabolic cylindrical reflector.

Mode Shapes	L/D (1.81)	3.62	5.43	7.27	9.05
1	0.38	0.27	0.22	0.19	0.17
2	0.62	0.44	0.37	0.32	0.29
3	0.69	0.49	0.41	0.36	0.32
4	0.85	0.62	0.52	0.46	0.42
5	1.06	0.79	0.67	0.58	0.51
6	1.08	0.8	0.68	0.59	0.53

A few natural frequencies are also presented in the table below. It is observed that the natural frequencies reduce for particular mode shapes even though the L/D ratio increases. It is because the width is kept mostly the same with each model while the length is varied. The effect of various L/D ratios is also checked for deflection and stress variation. As seen from table 5, the stress values remain constant for applied loading, however, the membrane deflection is prominently increased with the increased structure's overall dimension. It is seen from the literature as well that with upscaling, the deflection and out-of-plane displacement becomes more crucial. Controlling these demands a more complex design with multiple support for reflectors in the form of a web-cable guarded design and multiple anchor points to maintain the desired shape of the structure. However, these design modifications are out-of-scope of this paper and hence not covered.

Table 4: Comparison of natural frequencies for different L/D ratios.

Mode Shapes	L/D (1.81)	3.62	5.43	7.27	9.05
1	5.82	2.84	1.91	1.45	1.17
2	15.29	7.83	5.41	4.17	3.41
3	18.93	9.84	6.78	5.19	4.22
4	25.82	15.41	10.91	8.55	7.09
5	45.73	25.16	17.79	13.53	10.56
6	46.2	25.77	18.63	13.86	11.42

Table 5: Stress and deflection for different L/D ratios.

L/D ratio	Stress (MPa)	Deflection (cm)
1.81	101.9	0.72
3.62	102.4	0.98
5.43	102.5	1.25
7.27	100.7	1.91
9.05	101.1	3.30

3.2 F/D ratio

Since the parabolic reflector has dynamic characteristics, various models are analyzed for mode variations and various sizes of reflectors. One of the parametric studies varies the depth of the reflector. The reflector depth is governed by one of the geometric parameters, the focal length of an inflatable antenna structure (F) and the reflector width (D). The F/D ratio (reflector depth ratio) expresses the effect. If the width of the reflector is kept fixed for certain limited dimensions, the focal length (F) is the controlling parameter. Four F/D ratios are examined by varying F: 0.16, 0.21, 0.32 and 0.64. Figure 4 represents the eigenfrequencies for the first six modes of reflectors. The figure shows that, for lower F/D ratio, the eigen frequency parameters of all mode shapes have lower values compared to higher values at higher ratios. Moreover, with an increased mode shape, the eigenfrequency eventually coincides. For the given mode shape of the reflector, the eigen frequency monotonically increases with an increase in focal length F and approaches a certain constant value. The natural frequencies of these mode shapes at different F/D ratios, tabulated here (table 6), say that the difference in natural frequency is not significant for varied F/D ratios. The difference in the natural frequencies between the highest and lowest focal length to width ratio is not exceeding 12% for said mode shape.

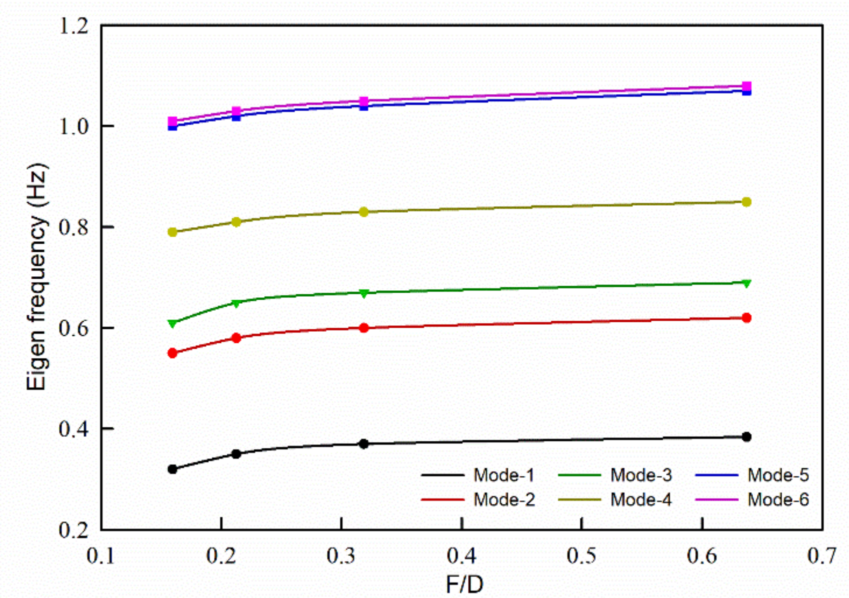

Figure 4: The first six eigen frequency parameters (modes) over varied ratio F/D

Table 6: Comparison of natural frequencies for different F/D ratios.

Mode Shapes	F/D (0.16)	0.21	0.32	0.64
1	5.17	5.37	5.56	5.82
2	13.91	14.13	14.6	15.29
3	16.87	17.63	18.12	18.93
4	25.47	26.23	27.54	28.82
5	39.56	41.80	43.90	45.73
6	41.47	43.23	44.14	46.21

3.3 Membrane thickness

Thickness is one of the crucial factors to consider while designing the inflatable structure; henceforth, membrane thickness's effect on natural frequencies is discussed here. Section properties in finite element tool are used to assign the thickness to the model. The range of Kapton membrane selected for analysis starts from as low as 12.5 µm up to 75 µm, including commonly used membrane sizes 25 µm and 50 µm. The dynamic effect of thickness variation on natural frequency is analyzed, and found that the excitation frequency never equals the system's natural frequency, which leads to resonance and system failure. The results plotted for first six modes of frequencies in figure 5 shows that natural frequencies decrease with an increase in membrane thickness. The reason behind this is the distribution of mass molecules over the membrane region, which lowers the frequencies. In other words, the mass density dominates the natural frequency.

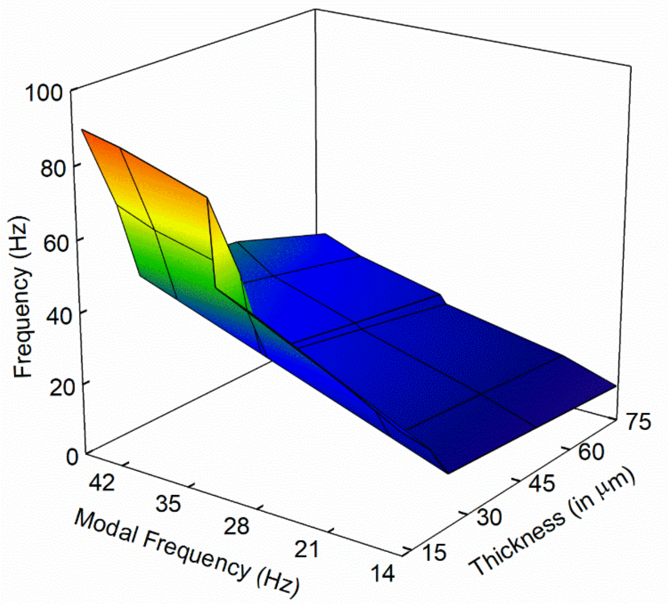

Figure 5: Effect of membrane thickness on first six mode shapes

3.4 Poisson's ratio

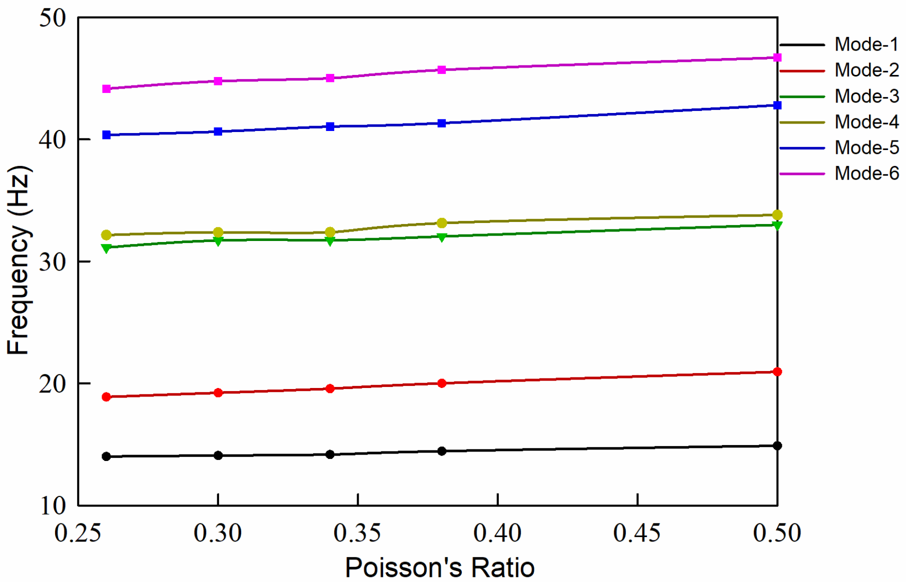

Figure 6: Poisson's ratio effect on natural frequency of membrane reflector

The Poisson's ratio of material is associated with the material flexural stiffness and thus influences the wrinkling deformation. The wrinkled membrane under vibration affects the natural frequency of the system. A membrane under uniaxial tension contracts in an orthogonal direction with wrinkles and consists of two components; one induced by wrinkles and the other by Poisson's ratio. Results of the variation of Poisson's ratio on the natural frequency of the cylindrical parabolic reflector are produced in figure 6. The results show that the frequency reduces for an increased Poisson's ratio. However, the change is inadequate for altering the membrane functionality. However, considering the application of the membrane reflector for inflatable antenna structure, limiting the Poisson's ratio within range of 0.30-0.34 is desirable.

4 EXPERIMENTAL CONCEPTUALIZATION

The analysis performed in previous sections, i.e., static, modal, and parametric study, are related to the singly-curved parabolic cylindrical reflector. As discussed earlier, the Kapton-made thin-film membrane reflector has no bending stiffness; hence, a supporting torus is required. For an inflatable concept, an inflatable torus should be designed to attain the singly curved parabolic shape in a fully inflated condition. This section details about getting the parabolic cylinder shape of a torus and the experimental conceptualization of a singly-curved parabolic cylindrical rim-reflector assembly.

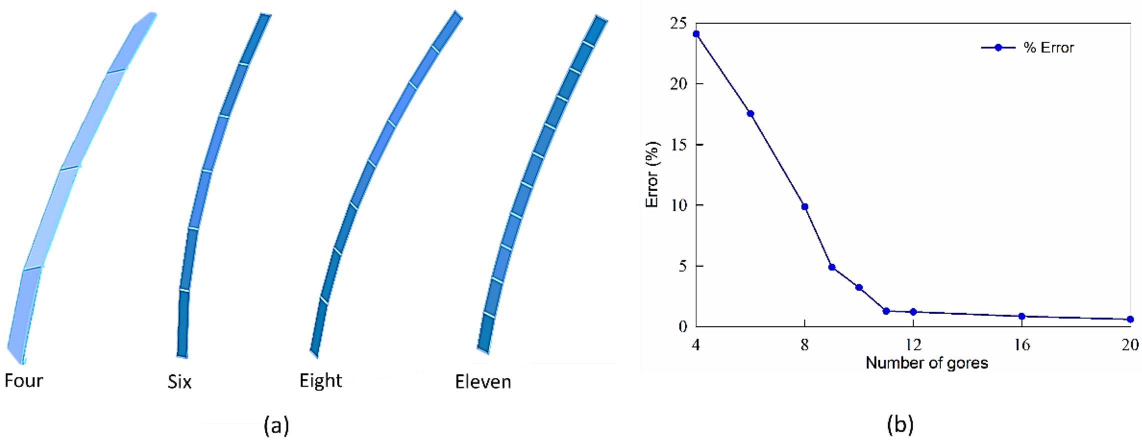

Figure 7: (a) Singly curved parabolic inflatable torus sides with design changes by a varying number of gores, (b) Effect of number of gores on profile accuracy for torus sides

Firstly, the model of a singly-curved torus is prepared in design software and optimized for the number of gores required to get the exact parabolic shape by air inflation from a fully flat configuration. The simplest way to get a parabolic shape is to cut the torus into four equal size pieces (gores). With an infinite number of gores, one can get a circular shape. Hence, the number of gores and the angle at which they should be cut have been chosen wisely so that an inflated configuration supports the reflector and keeps the reflector as wrinkle-free as possible. In this regard, the authors prepared various torus models with varied gores. Figure 7(a) presents a couple of such models, while figure 7(b) is the percentage error for designed profiles compared to an ideal parabolic profile of inflated cylindrical torus sides. It is clear from the figure that, with the increase in the number of gores, less error-prone results can be obtained. However, while considering the challenges during physical model development: including cutting patterns for individual gores, angle and seeming of gores, a model with eleven gores is selected as a final design. It is a balanced profile with approximately a 1.27% deviation from the actual profile.

A desired parabolic shape for torus sides can be obtained by selecting the optimum number of gores. Yet, to get a singly-curved parabolic cylindrical reflector, a more robust inflatable design is required. Tensioning the membrane from the side and inflating the torus to get the desired shape is insufficient to achieve reflector shape, as only two torus profiles on each side of the reflector cannot serve the purpose. A couple of literature [4], [11] presented concepts of rigid rod and clamp systems, solid frames for reflectors, etc. However, these concepts involve total solid or hybrid deployable structural concepts. The approach used and presented by the authors is for a fully inflatable structure. While designing the assembly, a compactly folded inflatable structure is kept in mind where the stowage volume occupied on the ground should be as low as possible. This work employs an inflatable supporting structure (a pipe-shaped connecting rod). It serves two purposes: first, it provides a passage for air to pass through; hence, a single-point inflation is possible which help to inflate the torus sides. Second, it keeps the two inflated tours sides separated and parallel to each other, which helps in maintaining the singly-curved parabolic cylindrical reflector shape.

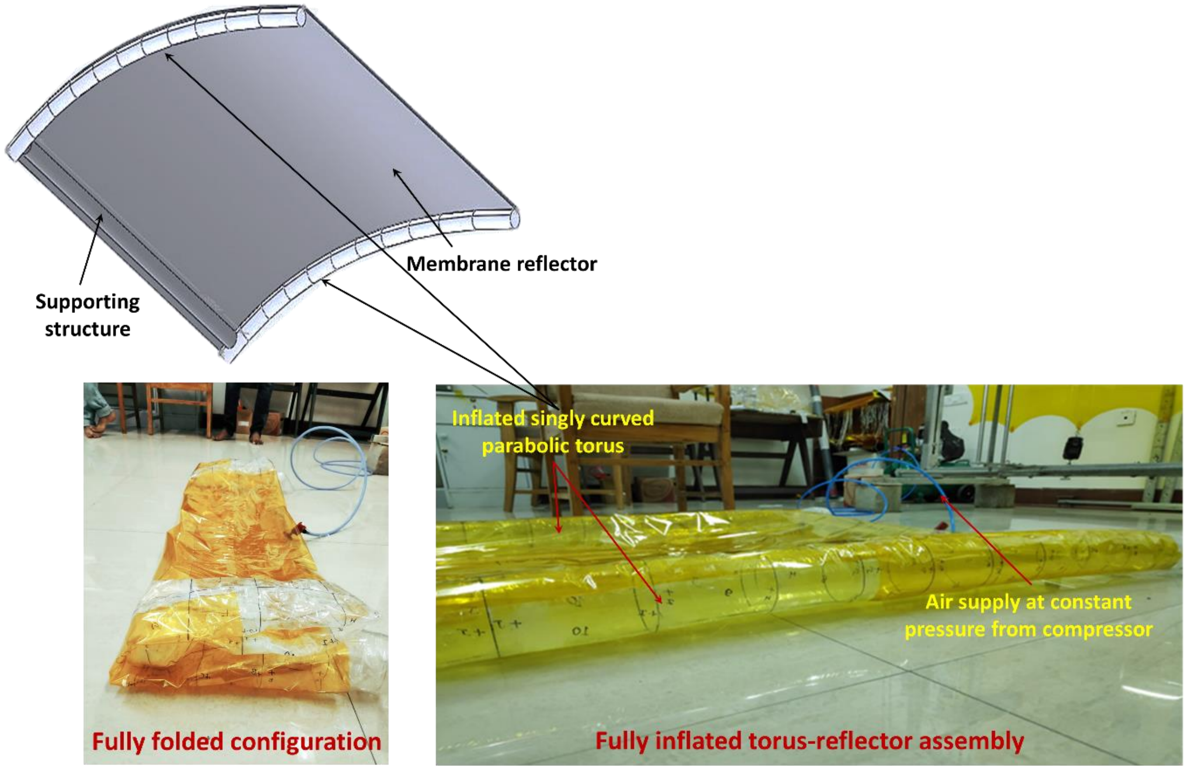

Figure 8: A physical prototype of a singly curved parabolic reflector assembly. Two cylindrical parts of the torus are connected with a supporting structure, which passes the gas flow and keeps the torus in desired shape post inflation.

The torus of the actual size is cut into eleven gores with different sizes and shapes, in and out of the angle of each gore. While preparing these gores, utmost care is taken to avoid unnecessary cuts and creases. The membrane reflector is cut from Kapton 25 µm thin-film roll. The connection between the torus and reflector is made using Kapton tape. The tap is not the exact solution, but for model conceptualization, tape with similar material properties can work. The Middle of the supporting cylinder is connected to the air supply. The single air inlet point inflates the torus uniformly; thus, the connected reflector attains its singly-curved parabolic cylindrical shape. The fully folded and inflated reflector assembly is shown in figure 8. Experimental non-linear vibration testing of these ultra-large inflatable reflector assemblies is still challenging.

5 CONCLUSION

For the larger singly-curved parabolic membrane reflectors, the concept of inflatable is more suitable. A novel idea of a singly-curved parabolic cylindrical inflatable structure follows a parametric study. For the said dimensions of the reflector part, an FE model is prepared by incorporating experimentally tested Kapton membrane properties and validated for mesh convergence before jumping to the modal analysis and parametric study based on these mode shapes. For the extracted first six modes of natural frequency, it was found that the L/D ratio of 1.81 and the F/D ratio of 0.64 are most appropriate for desired frequency values of greater than 20 Hz and 25 µm Kapton. Moreover, the stress and deflection are directly proportional to the load; hence, there should be some proportional limit to maintain the desired reflector profile. The later part comprises developing a proof-of-concept model of an inflatable cylindrical torus that attains a singly-curved parabola shape. Dividing the torus into eleven gores proved the most optimum solution for shape accuracy with a 1.27% error. Moreover, adding cylinder-shaped supporting connector elements helps the structure maintain its shape post inflation.

ACKNOWLEDGMENT

This work was supported by the Department of Science and Technology, Ministry of Science and Technology, Govt. of India under Indo-Sri Lanka joint research grant [No. DST/INT/SL/P-27/2016].

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