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Study of unfurlable mechanism for space radars

Santoshkumar Ganeshnavar
sganeshnavar2@gmail.com
Electronics And Radar Development Establishment (DRDO), Bengaluru, Karnataka

Shreeshial B
bshreeshial@gmail.com
Electronics And Radar Development Establishment (DRDO), Bengaluru, Karnataka

Ajai Kumar Shrivastava
ajai.kr.shrivastava@lrde.drdo.in
Electronics And Radar Development Establishment (DRDO), Bengaluru, Karnataka

Sivakumar S.
sivakumar.s@lrde.drdo.in
Electronics And Radar Development Establishment (DRDO), Bengaluru, Karnataka

Jai Kumar V
Jaikumar.v@lrde.drdo.in
Electronics And Radar Development Establishment (DRDO), Bengaluru, Karnataka

ABSTRACT

Unfurlable rim truss antennae are considered to be the most suitable for developing large size aperture structures for space antenna. They have largely deployed to stowed volume ratio, precision, and reliability in its operation. The mechanism is capable of altering its configuration from a stowed to deployed shape to meet specific operational requirements of space-borne radar. The proposed study of unfurlable mechanism for paraboloid reflector antenna is made up number of parallelogram units comprised of links with appropriate hinge joints, which concatenate in a repeatable fashion to form the desired structure. This study include geometric modeling, kinematic simulation and preliminary structural analysis of unfurlable rim truss.

Keywords: *Unfurlable mechanism, Rim truss, Offset fed paraboloid reflector, Simulation*

1. INTRODUCTION

Large unfurlable antennae have been built for spaceborne radars with different structural schemes, most of them can be classified as radial structures, modular structures, and rim truss. Among these, rim truss antenna with the advantage of high thermo-elastic stability and deployment reliability is investigated for the past few years. Miyasaka, A. and Hommat M. [1] have designed deployable rim truss mechanisms which are extensively used to fulfill the requirement of large aperture antenna in space environment than one can be carried to space orbit. Pei Li et.al [2] have presented research work on geometrical modeling and dynamic behaviour of support rim structure for mesh deployable antenna and it can be observed that the deployable rim truss has circular contour to support prime focus parabolic reflector system and for that of offset fed parabolic reflector system it is required have elliptical contour deployable support structure. Mark W. Thomson [3] has explained the concept used in deployable reflectors developed by AstroMesh Corporation. Xiaozhi Qi, et.al [4] have discussed on the detail geometrical modeling process for both axis symmetric parabolic reflector and offset fed parabolic reflector antenna. L. Datashvili [5] has done research to develop the concept of double pantograph based peripheral ring which satisfies the demand of significantly less mass and smaller folded volume while maintaining stability and deployment reliability. Zhang Yiqun et.al [6] studied kinematic simulation of Deployable Polyhedral Truss (DPT) used especially for large aperture antennae. S. Laxminarayan et.al [7] has used ADAMS software to carry out the kinematic analysis of deployable polyhedral truss of 18 bays. All the units rim truss structure has a single degree of freedom; one translation motion input is given to the telescopic diagonal member of the first unit. The motion of the first unit is transmitted to the next and subsequent units through gears. For offset fed parabolic reflector antenna, the support unfurlable rim truss structure has an elliptical shape, so each hinge has different angles to connect vertical and horizontal links of deployable rim truss. So the objective of this study is geometric modeling, kinematic simulation and preliminary structural analysis of unfurlable rim truss for offset fed paraboloid reflector antenna.

The proposed study of an unfurlable mechanism for paraboloid reflector antenna is made up of a number of parallelogram units known as bays comprised of links with appropriate hinge joints, which concatenate in a repeatable fashion to form the desired structure. Each of these bays undergoes determined relative motion between the links to transform the mechanism from an initially compact state to unfurlable state. In the present development, the rimtruss has 30 bays forming a 30 equal sided polygon. Each bay is connected to the adjacent bays through revolute joints. A cable is routed through all the diagonal members of the rim truss elements. One end of the cable is fixed and the other end is pulled by a motor. The diagonal elements are of longer length when stowed and short when deployed. Hence when the cable is pulled or spooled over a pulley by a motor, as the diagonal elements become shorter and shorter the antenna will deploy to the desired size. The unfurlable mechanism is stowed during launch and is capable of being deployed in the space orbit.

2. PROPOSAL OF UNFURLABLE MECHANISM

The basic deployable unit which consists of two horizontal members, two vertical members, and one diagonal member. Each unit has four rotary joints and one translation joint at the diagonal member.

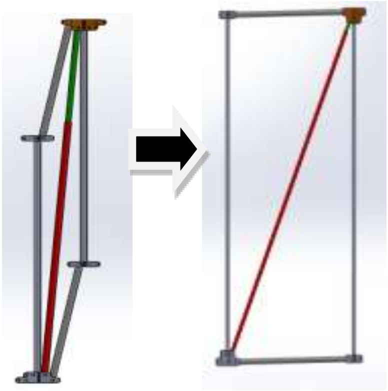


Fig. 1: Basic Deployable unit

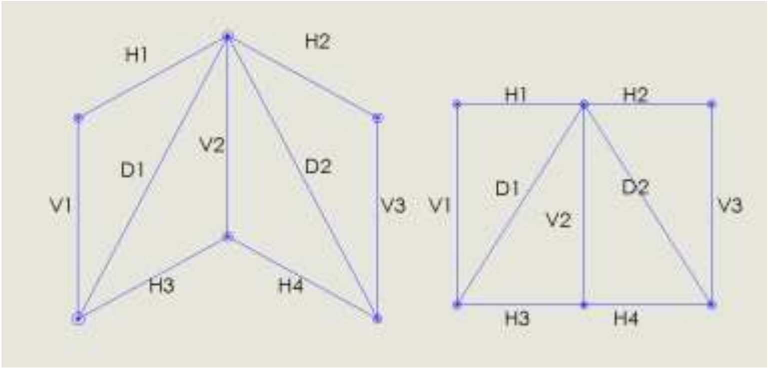


Fig. 2: Sequence of Deployable Units

The lengths of six links in each deployable unit follow relationship listed below:
H1=H2=H3=H4
V1=V2=V3
D1=D2
From the figure 2, when the deployable unit is stowed the horizontal struts H1 and H2 become parallel with vertical strut V2. In deployed condition, the diagonal member D1 collapses and makes an angle to vertical strut and strut H1 becomes parallel with strut H3 in fully deployed condition. The vertical link is a common link between adjacent units to form the profile of parabolic reflector.

3. GEOMETRIC MODELING OF RIM TRUSS UNIT

The axis-symmetric parabolic reflector has a circular contour and the offset fed parabolic reflector has an elliptic contour. So the design of support deployable rim truss should have a circular contour to support axis symmetric reflector and elliptical contour for that of offset fed parabolic reflector. Usually, the multiple units of a deployable mechanism such as horizontal, vertical and diagonal links are designed with the same geometric parameters to build required deployable rim truss. The fundamental principle for assembling circular rim truss is regular polygon which approximates a circle. Figure 3 shows the regular polygon inscribed in a circle. Let n, α, β and R be the number of edges of the polygon, the angle between the adjacent sides, excluded angle of the polygon and the radius of reflector respectively. β is the shortest length from the origin of reflector length connecting links on the surrounding rim truss. The design parameters for joints connecting links of rim truss are simple as the angle between adjacent sides of the regular polygon are equal. This angle between two consecutive sides of the polygon is obtained as:

$$\alpha = 180 - \beta = 180 - 360/n$$

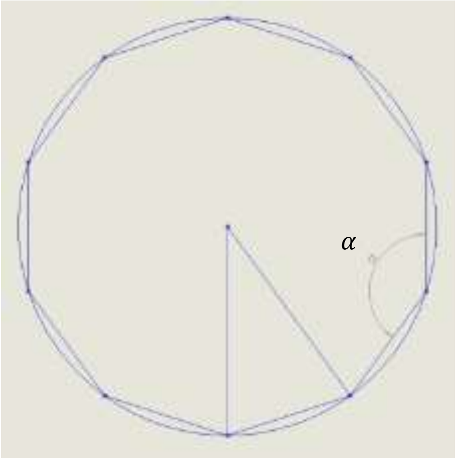


Fig. 3: Regular polygon inscribed in a circle

In case of offset parabolic reflector antenna, the outside contour of deployable support truss has elliptical contour, so the calculation of angles between each side of a regular polygon inscribed inside an ellipse is relatively complex as angles between each side in the polygon are not same. To calculate angles between each side, an example of dodecagon inscribed in an ellipse is considered. The quarter arc of an ellipse is chosen to analyze calculation process because of elliptical symmetry as shown in figure 4.

Fig. 4: Angle between the chords in an elliptical arch

The coordinates of all the nodes which satisfy standard ellipse equations are determined initially, and it is known that all chords are of equal length, and the following equations are obtained.
$P_0P_1 = P_1P_2 = P_2P_3$

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

The coordinates of each node are determined by using the above equation, which gives one solution. The different angles between the chords shown in Fig. 4 are determined by solving below listed equations,

$$\alpha_0 = \tan^{-1}\frac{y_1}{a - x_1}$$

$$\alpha_1 = \cos^{-1}\frac{|P_0P_1|^2 + |P_1P_2|^2 - |P_0P_2|^2}{2|P_0P_1||P_1P_2|}$$

$$\alpha_3 = \tan^{-1}\frac{x_2}{b - y_2}$$

$$\alpha_1 = \cos^{-1}\frac{|P_1P_2|^2 + |P_2P_3|^2 - |P_1P_3|^2}{2|P_1P_2||P_2P_3|}$$

The different joints which connect links of deployable rim truss are required to be designed as per the different angles obtained. Offset fed parabolic reflector supported flexible cable net system can be attached top and bottom support of vertical link rim in truss mechanism.

When the antenna is in a folded condition, groups of similar hinges extend to the maximum length, and all similar hinge groups come closer, the diameter of an antenna becomes least and it can be accommodated in limited space available in the launch vehicle. Once antenna reaches target point, the rope which runs through diagonal links is shortened and wounded on its spool by an electrical motor, at this stage, both hinges come together in one plane, the diameter of the antenna starts increasing till it reaches its maximum value for its operational requirements in space orbit.

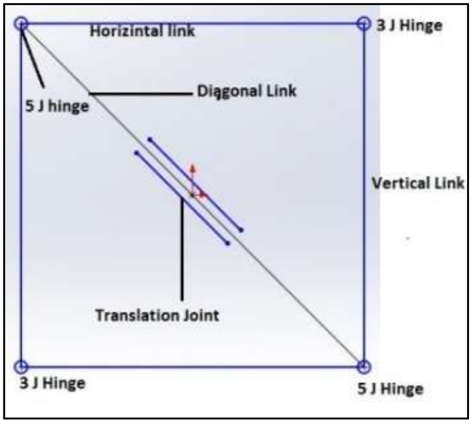


Fig. 5: CAD model of basic unit

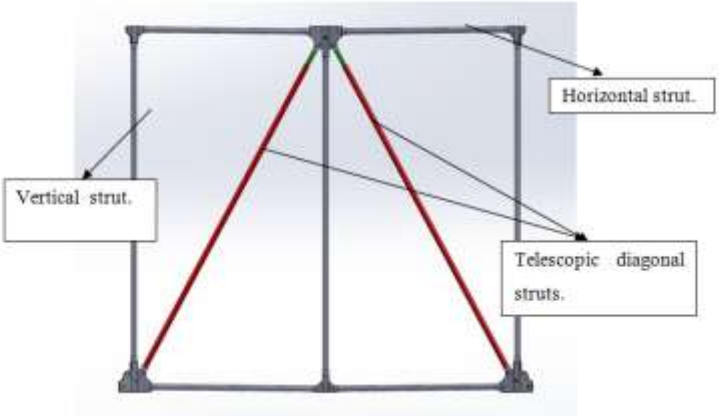


Fig. 6: Free body diagram of basic unit

The connection of one bay to next bay is considering two units is shown **Error! Reference source not found.**. The two units of the deployable mechanism are in fully deployed condition. Revolute pair with which all the links are connected to each other. All diagonal members of a parallelogram units have two links with a translation joint, wire rope is inserted inside all diagonal members of the mechanism which connected end to end so that the wire rope passes through all diagonals to drive the rim truss mechanism from stowed in the deployed condition.

3.1 Vertical and Horizontal struts

From the concept of astromesh deployable rim truss, stowed height of the antenna is summation of lengths of horizontal strut and vertical strut. If a and b are the lengths of horizontal and vertical strut respectively the total height of antenna h can be given as follows:

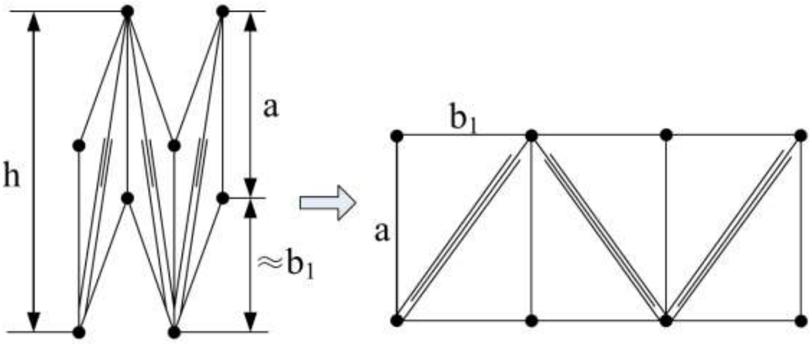


Fig. 7: Schematic diagram of a mechanism

$$h= a + b$$

The length of vertical strut is equal to height of antenna in deployed condition. So the length of horizontal strut is found out by limiting stowed height. Diameter of the strut is equal to each other and is determined by limiting the stowed diameter of the antenna. Figure 8 shows the evaluation parameters of rim truss mechanism. In case of stowed condition of an antenna, all horizontal, vertical and diagonal struts become parallel to each other and are arranged on periphery of ellipse, let d' be diameter of the all struts, each bay contains an average of four struts, therefore the maximum stowed diameter d can be approximately calculated as follows:

$$d = 4d'/\sin(180^0/n)$$

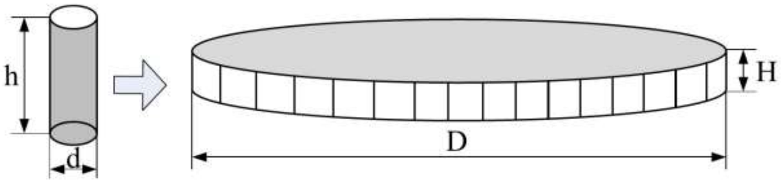


Fig. 8: Parameter evaluation of rim truss

3.2 Diagonal telescopic members

The length of a diagonal member of rim truss varies as the antenna is stowed from the deployed configuration and vice versa. So diagonal member is formed with a telescopic structure which has piston-cylinder type arrangement, as the antenna is stowed the piston member extends from cylinder tube and while deploying it goes inside the cylinder tube. Figure 9 shows the diagonal telescopic member.

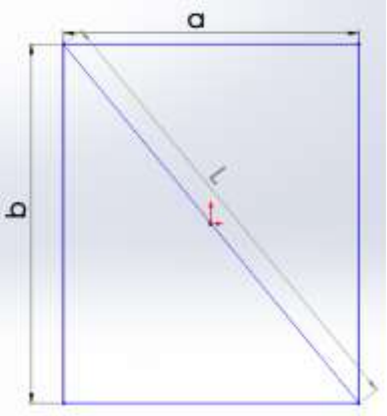


Fig. 9: Deployed Basic Unit

The length diagonal tube diagonal telescopic structure in fully deployed condition is determined as,

$$L^2= a^2+b^2$$

3.3 Hinges

There are two types of hinges to be used for the design of rim truss, one is five joint hinges and other is three joint hinges. A number of hinges to be used depends upon the aperture diameter of rim and length of the horizontal strut. The stowed diameter of the antenna depends upon the size of these two hinges. Five joint hinges connect two horizontal links, two diagonal links, and one vertical link. Three joint hinges connect two horizontal links and one vertical link. As shown in **Error! Reference source not found.** Thus the number of five-dimensional hinges and three-dimensional hinges are equal.

There are thirty 5J and 3J hinges are to be designed to form 30 bays rim truss mechanism. Following three parameters of hinge affects the dimension of the antenna in both stowed and deployed condition.

- Angle to connect the adjacent horizontal strut
- The overall width of the hinge
- The positioning of the hole in the hinge.

Figures 10 and 11 show the 5J hinge and 3J hinge indicating above listed parameters. The angle of hinge depends upon the number of equal divisions in a reference ellipse.

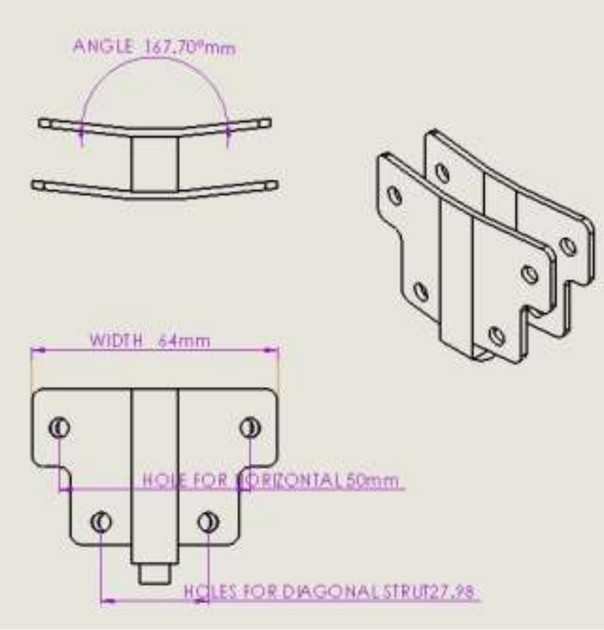


Fig. 10: 5J Hinge

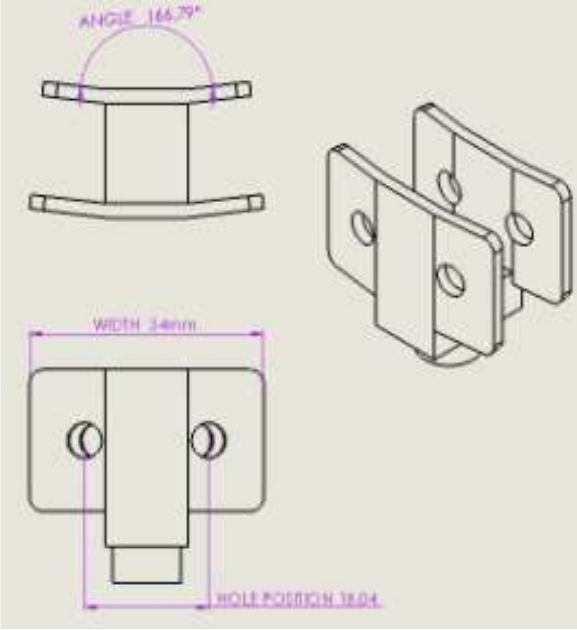
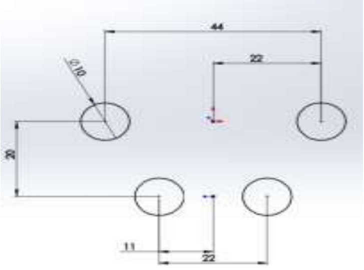
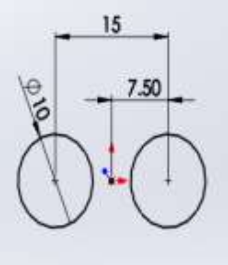
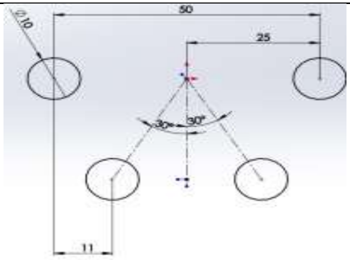
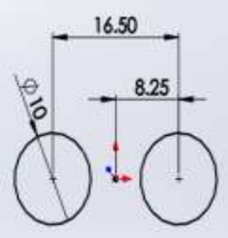
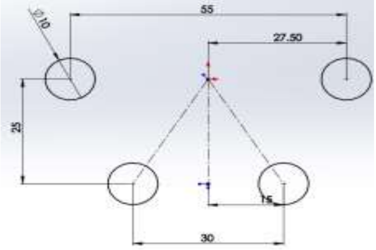
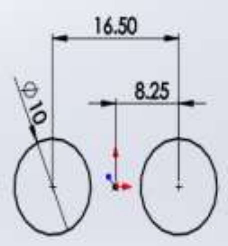


Fig. 11: 3J Hinge

Table 1: Different holes orientations in hinges

S. No.	5J description	3J description	Stowed Dia(mm)	Remark
1			345	Interference between diagonal and vertical member is found in a stowed condition
2			375	With no interference in a stowed condition
3			405	No interference in stowed condition

The width of Hinges: The overall width of 5J hinge directly affects the stowed diameter of the deployable antenna, as the similar hinges come together when the antenna is stowed. So the summation of the overall width of fifteen hinges must not exceed the perimeter antenna in the stowed condition.

For 400mm stowed diameter of an antenna, the overall width for 5J hinges are determined as follows,
The width of fifteen 5J hinges + clearance between consecutive 5J hinge = perimeter of the stowed antenna.
i.e. 15 (W+C) = ∏ d

Where, W= overall width of the 5J hinge, C=clearance between each hinge and d=stowed diameter of an antenna.
Considering clearance of about 5mm,
15 W= (3.142*400)-15*5
Therefore width W=78.8mm

The position of holes in hinges: Holes position in hinges connects the horizontal, vertical and diagonal members of the rim truss. These holes are oriented in hinges such that the stowed diameter of the antenna should be well within the design constraints. Three different orientations are tried, stowed diameter is observed as listed in table-5.2. Among three different orientations, the second one is found to have stowed diameter well within the required limit.

4. 3-D MODEL OF DEPLOYABLE RIM TRUSS

By knowing all required dimensions of hinges, horizontal, vertical strut and diagonal strut, the 3-D model of rim truss is built in SOLIDWORKS CAD software. **Error! Reference source not found.** shows the 3-D model in deployed and stowed condition.

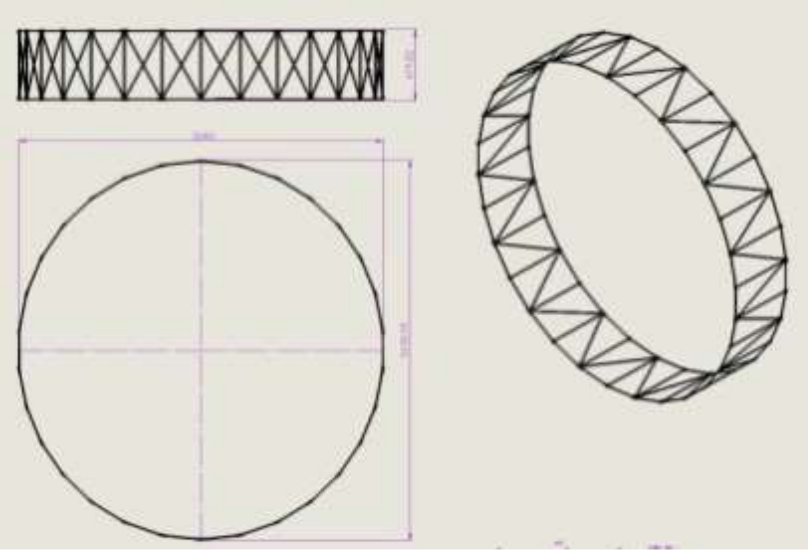


Fig. 12: Deployed View of Rim Truss

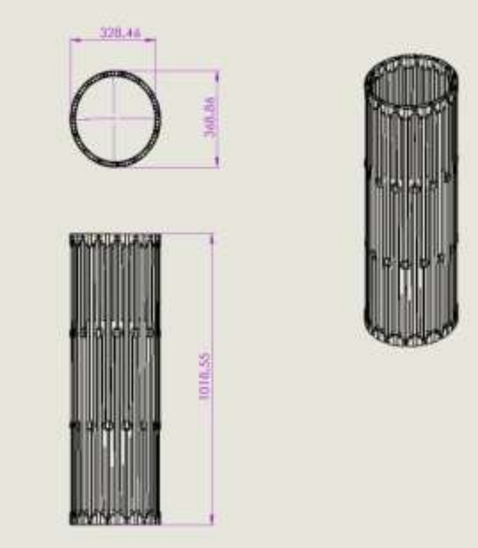


Fig. 13: Stowed View of Rim truss

5. KINEMATIC SIMULATION

The following assumptions are made for the kinematic study of the rim truss mechanism

- The links of deployable rim truss are rigid
- The friction and clearances in joints and neglected
- The axial deformation of drive cable due to tension is negligible.

The deployable rim truss containing 30 bays is modeled in SOLIDWORKS modeling software. As the system has a single degree of freedom, one translation motion input is given to the telescopic member of the first bay. The motion of the first bay is transmitted to the next and subsequent bays through gears.

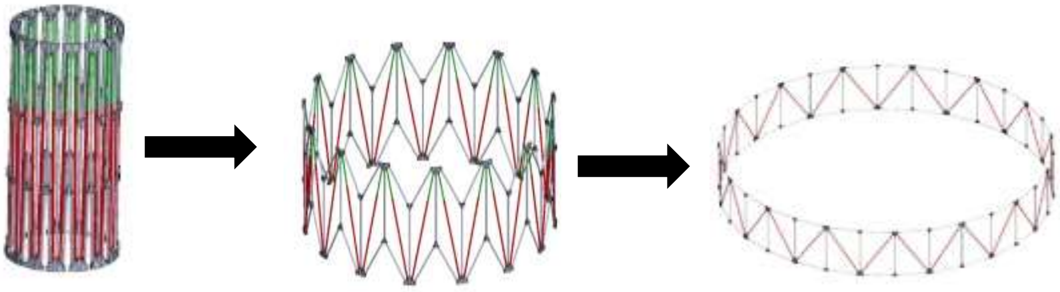


Fig. 14: Deployment Sequence of Rim truss

Path trajectories are shown in Figure 15 and 16. It can be observed from the trajectories of center point of 5 J links are radial straight lines from the fixed link, so the all 5J links are constringed to move in plane and the trajectory of point which lies on the major axis of the rim truss is the longest and which can be calculated by subtracting stowed diameter from

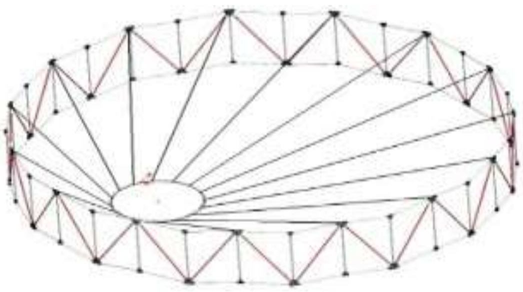


Fig. 15: Path trajectory of 5J Hinges

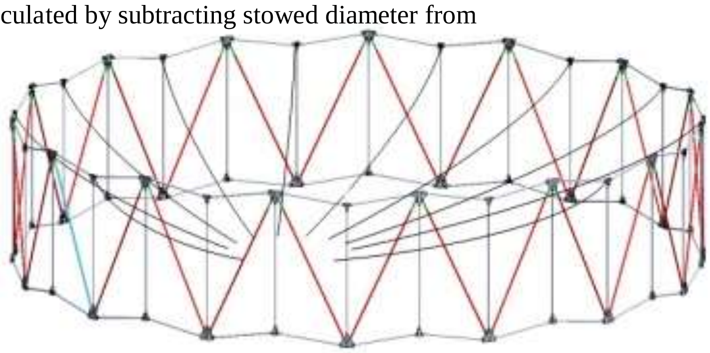


Fig. 16: Path trajectory of 3J hinges

Figure 16 shows the path trajectories of points on the 3J link when the rim truss starts deploying all 3J links move to the different plane as the horizontal links rotate by an angle 90^0. The new plane to which all 3J links move is at a distance equal to the length of the horizontal link.

6. MODAL ANALYSIS

Modal analysis is carried out to determine the fundamental frequency of structure in stowed and deployed state.

6.1 Modal analysis in stowed condition

The natural frequencies obtained are listed in table 2**Error! Reference source not found.** Six mode shapes are extracted for the analysis and first three mode shapes are shown in 17.

Table 2: Natural Frequencies in Stowed Condition

S. No.	Mode no.	Natural Frequency (Hz)
1	1	63.135
2	2	65.673
3	3	71.285
4	4	73.442
5	5	78.563

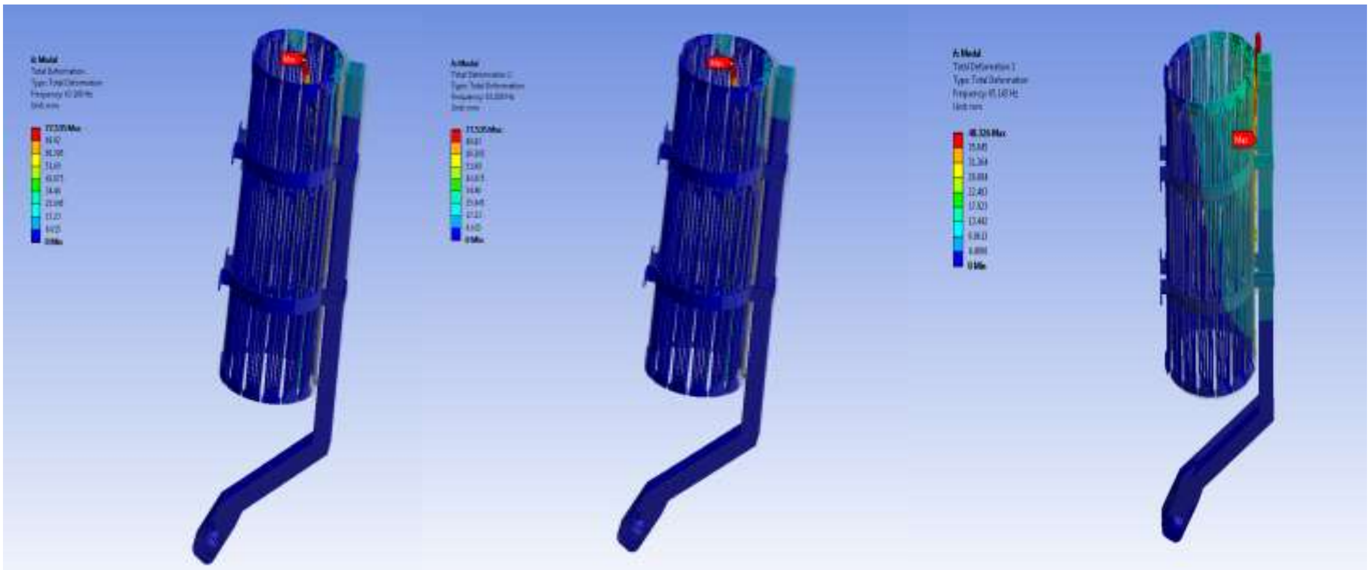


Fig. 17: First 3 mode shapes in stowed condition

The antenna in stowed condition is required to have fundamental frequency of 40Hz to avoid resonance during launch phase. The fundamental frequency obtained is 63.135 Hz and resonance is avoided.

6.2 Modal analysis in deployed condition

The six modes are extracted and respective natural frequencies are obtained as shown in

Table 3: Natural Frequencies in Deployed condition

Sl.no	Mode no.	Natural Frequency (Hz)
1	1	1.0928
2	2	1.3837
3	3	2.5546
4	4	3.4828
5	5	3.8819

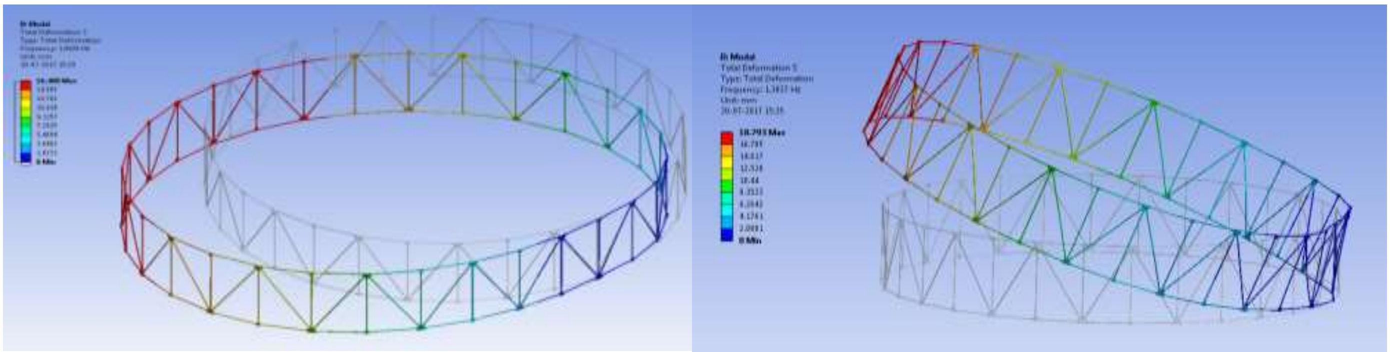


Fig. 18: Mode shapes in deployed condition

7. CONCLUSION

The detail geometric modeling of unfurlable rim truss mechanism for offset feed paraboloid reflector has been discussed. The supporting rim truss has an elliptical shape and each hinges connecting the horizontal strut has different angles. The dimension of hinges used in the design of rim truss directly affects the stowed diameter of an antenna. Three different types of hinges are modeled and respective stowed diameter of an antenna is compared and suitable hinges are chosen. The ability of so designed deployable rim truss changing from compact or stowed configuration to deployed configuration is studied in SOLIDWORKS motion simulation software. It is found that the presented concept of rim truss can be stowed to diameter of 375mm from 3000mm deployed diameter. Modal analysis is carried out to determine the natural frequencies of the antenna structure, the fundamental frequency in stowed condition is found to be 63.13Hz which is 1.6% higher than desired natural frequency to avoid resonance during launch.

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