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Dynamic Analysis of Reflector Structure for a Solid-Surface Deployable Antenna

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Abstract:

Solid-surface reflector is widely used in satellite aperture antenna based on its high surface accuracy. Compared with traditional single-blade solid-plane antennas which rotate along orthogonal two-axis, single-axis-rotation antenna greatly reduces the number of kinematic pairs and improves the deploying reliability of such deployable structures. This paper establishes a deploying dynamic model and a finite element model based on a 10-meter-aperture single-axis-rotation deployable surface antenna. The feasibility of the antenna design is verified by ADAMS dynamics simulation, and the folded-state in launch vehicle and the deployed-state in orbit service are also studied by ANSYS. The natural frequencies and vibration modes of the structure in two states are obtained, and the dynamic characteristics meet the requirements. It has an important reference value for design analysis and parameter research for this kind of solid-surface deployable antenna.

Keywords: *Solid-surface reflector, Deployable structure, Dynamics, Deploying Simulation, Modal analysis.*

I. INTRODUCTION

The solid-surface reflector, compared with the cable-net reflector [1] and the inflatable membrane reflector [2], can maintain very high surface accuracy [3] by the structural stiffness of the solid surface itself. It has been widely utilized in the aperture antenna [4-7] for satellites. However, the package performance is not as good as the other two styles because of the solid-surface reflector structural style. Hence, the reflector aperture is limited so as to affect the gain improvement and the application range. Therefore, the deployable solid-surface reflector is an effective way to increase the aperture and develop the package performance for antennas.

In previous research of deployable solid-surface reflector antenna, the centrosymmetric petal-type rotation storage [8-14] is a main form for the deployable mechanism. Thereinto, there are several kinds of deployable solid-surface reflector with rotations along two orthogonal axes such as Large Petal-type Space Mirror (LPSM) [9,10] and New Petal-type Deployable Solid Surface Antenna(NPDSSA) [11] and the deployable solid-surface reflector with rotation along single axis such as the 10-meter aperture Millimetron Telescope [15] proposed by Lebedev Physical Institute-Astro Space Center, ASC-LPI. Compared to the biaxial deployment mechanism, the uniaxial deployment mechanism can be deeply cut down the number of revolute joints. Then, the number of interactions between the members can largely decreasebased on the smooth deployment. Thus, thedeployment reliability of this deployable solid-surface reflector with uniaxial deployment mechanism can be leveled up.

For this reason, this paper has focused on a 10-meter aperture deployable solid-surface reflector antenna with uniaxial deployment mechanism. The deployment kinetic model and finite element model have been designed and established to explore the structural dynamics in folded state during launching and in deploying state in orbit. The mode analyses of folded state and deployed state have been carried out to study the dynamic properties of deployable solid-surface reflector. Several designing technology points have been concluded for following applications.

II. REFLECTOR DESIGN

The main structure of the deployable solid-surface antenna is a parabolic reflector with an aperture of 10 meters. The reflector is divided into a central disk andtwenty identical parabolic petals around disk. Each petal is connected with the central disk through an L-type supporting arm which can rotate around a specific spatial axis. This centrosymmetric petal-type deployable structure with uniaxial revolute mechanism is shown in Fig. 1.

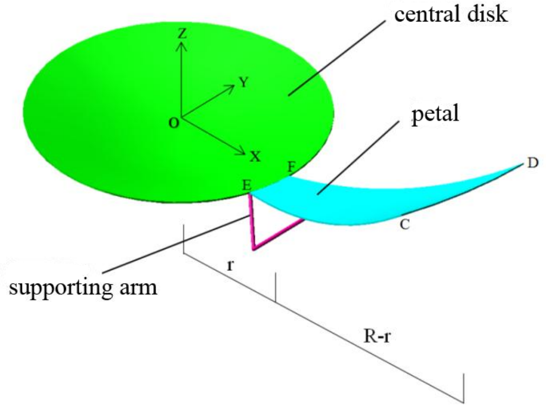
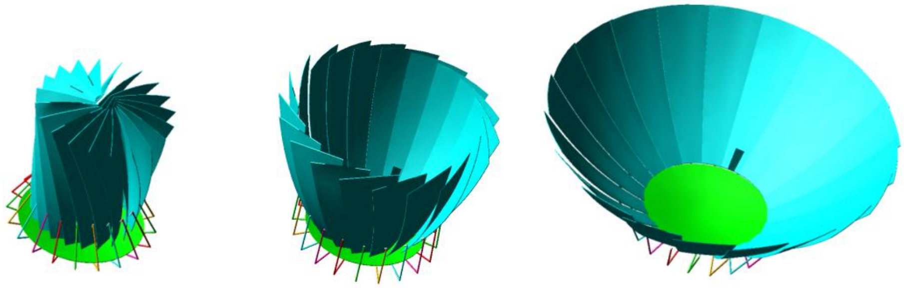


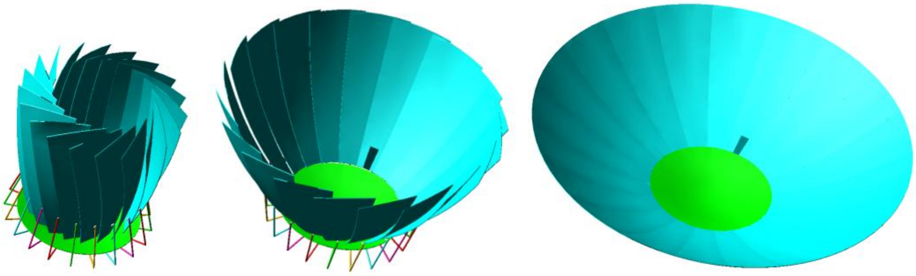
Fig1: Schematic diagram of reflector model

The Cartesian coordinate system O-XYZ is set on the vertex O(0, 0, 0) of parabolic surface. The antenna focus length is f = 3000mm and the aperture is D = 10000mm. The parabolic surface equation is $x^2 + y^2 = 12000\ z$. The surface CDEF is the main petal which is symmetry along Plane XOZ. The projecting radius on Plane XOY of central disk is defined as r. The main petal has the projecting radius range as [r, R] with r = 600mmand R = 5000mm. The outer end of the L-type supporting arm is fixed on the main petal while its inner end is set on the revolute joint around the spatial axis.

Based on the design above, the deploying kinetic model is established by software ADAMS. The torsion spring is set in each revolute joint pin with a pre-torqued angle to drive the petal deploying from folded state to deployed state. The deploying process of this reflector antenna is shown in Fig. 2. It is illustrated that this antenna model has a smooth deploying process and this model design is reasonable and feasible.



(a) 0 s (c) 0.4 s (e) 0.8 s



(b) 0.2 s (d) 0.6 s (f) 1.0 s

Fig2: Deploying process of ADAMS model

III. FINITE ELEMENT MODELS

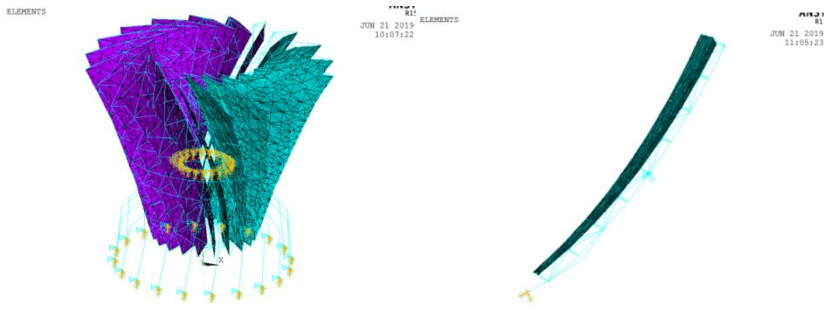
Compared with this smooth deploying process, the reflector structural dynamic properties in folded state during launching and in deployed state in orbit are much more important. It should be avoided to occur theresonance damage or the uncontrollable flexibility. This deployable solid-surface reflector with twenty petals can be treated as the cantilever thin plate structure, which has a small stiffness and has a great influence on the structural dynamic performance. According to these two states of the deployable reflector structure, the finite element models are established and the dynamic mode analyses are carried out based on software ANSYS.

Theelement sizes and material properties of this reflector structure are listed in TABLE I. The petal is designed with the back brace truss to develop the stiffness. The truss elements use the circular tube while the supporting arms are defined as the BEAM188 with square tube. The petal surfaces are defined as the SHELL181. The deployable reflector in folded state is locked by the constraint rope.

TABLE I. Component size and material properties

Element	Material	Section size	Elastic Modulus MPa	Shear ModulusMPa	Poison ratio	Densitykg/m^3
Back truss for petals	Carbon fibre tube	circular diameter 40mm thickness 2mm	$E= 4.5e^4$	$G= 4.5e^3$	0.34	527
Petal reflector	M55Carbon/ epoxy material	thickness 30mm	$E_{11}= 3e^5$ $E_{22}= 6e^3$ $E_{33}= 6e^3$	$G_{12}= 4.5e^3$ $G_{13}= 4.5e^3$ $G_{23}= 3.5e^3$	0.34	160
Supporting arm	Carbon fibre tube	square 50mm*50mm,thickness 5mm	$E= 4.5e^4$	$G= 4.5e^3$	0.34	527
Constraint rope	IM7 Carbon fibre	diameter 2mm pretension 5N	$E= 10e^4$		0.34	1600

The finite element model and element mesh of the whole structure in folded state are shown in Fig. 3(a). Considering the central disk directly fixed to the satellite, the boundary conditions of the antenna structure in folded state can be reduced to three translational degrees of freedom and two rotational degrees of freedom of the proximal node of each support arm with releasing the rotational degree of freedom around the rotation axis.At the same time, the constraint ropeis set at the innermost side of the petal to ensure that the relative circular and radial motion of the petal does not occur in folded state. The corresponding nodes of the petal constrain two translational degrees of freedom and three rotational degrees of freedom with only releasing the UZ translational degrees of freedom.



(a) folded state (b) deployed state

Fig3: Finite element model of deployable reflector structure

Since each petal of the surface is independent in deployed state, the finite element model of onepetal is established based on the central symmetry of the reflector structure as shown in Fig. 3(b). The lower nodes of each supporting arm are fixed and each petal back truss is restrained by the construct limit device.

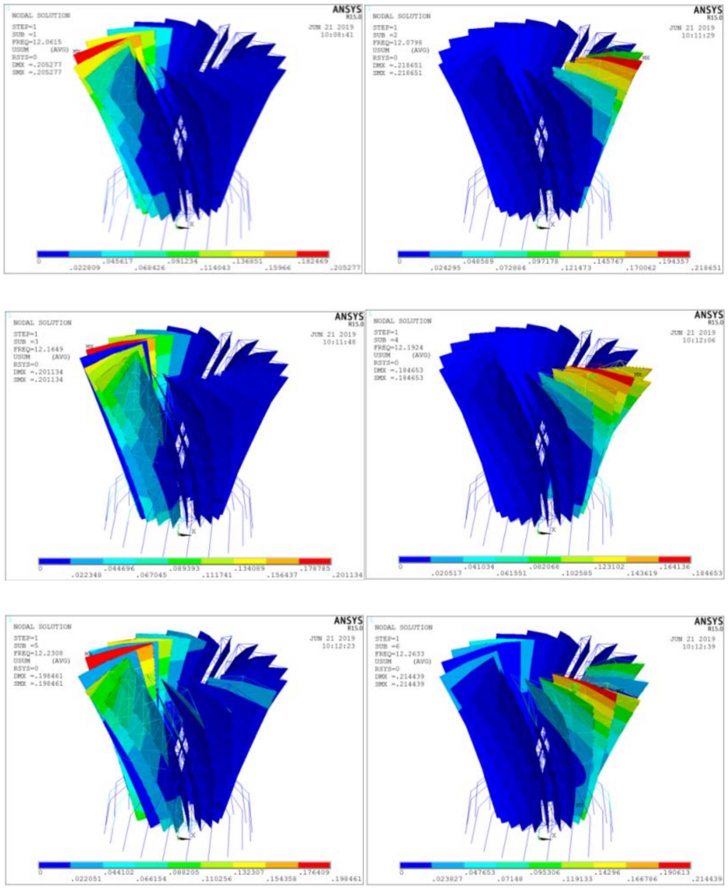
IV. MODE ANALYSES

Based on the finite element models, the dynamic mode analyses of the deployable reflector structure in folded and deployed state are carried out.

The first ten natural frequencies and mode shapes of the folded reflector are obtained as shown in TABLE II and Fig. 4.

TABLE II. First 10 natural frequencies of reflector structure in folded state

No.	Frequency Hz	No.	Frequency Hz
1	12.061	6	12.263
2	12.080	7	12.269
3	12.165	8	12.292
4	12.192	9	12.316
5	12.231	10	12.322



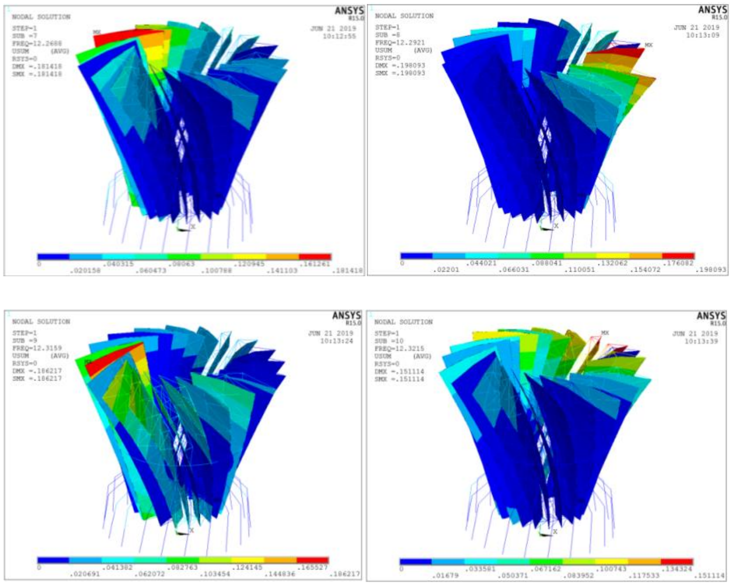


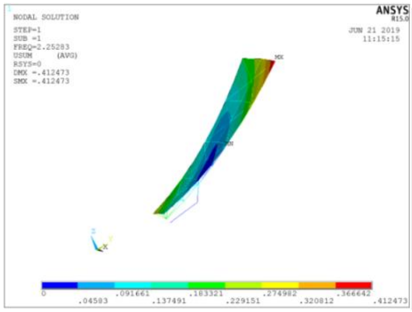
Fig4: First 10 mode shapes of reflector structure in folded state

According to the mode analysis results, the first natural frequency of the folded reflector structure is 12.061Hz. The first ten modes of the structure are close and it shows the local vibration of the petal free end. The frequency distribution is dense, which is beneficial for the effective vibration isolation measures during launching to avoid the resonance damage. It is also shown that this fundamental frequency is higher than the Millimetron Telescope reflector [15]. The dynamic performance of the folded reflector structure is better and can meet the requirements.

The first ten natural frequencies and mode shapes of the deployed reflector are obtained as shown in TABLE III and Fig. 5.

TABLE III. First 10 natural frequencies of reflector structure in deployed state

No.	Frequency Hz	No.	Frequency Hz
1	2.2528	6	121.26
2	13.022	7	167.23
3	15.333	8	218.52
4	52.763	9	225.05
5	103.16	10	269.60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R15.0
JUN 21 2019
11:15:15
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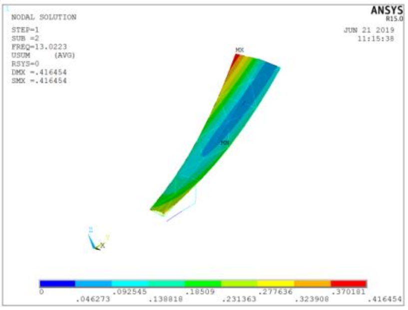
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R15.0
JUN 21 2019
11:15:38
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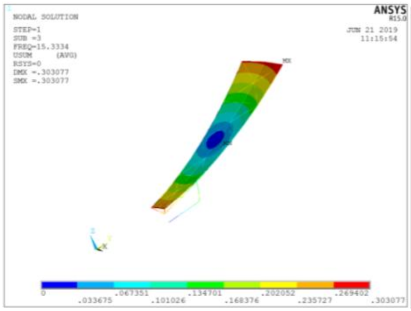
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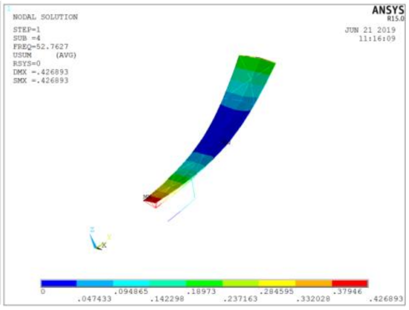
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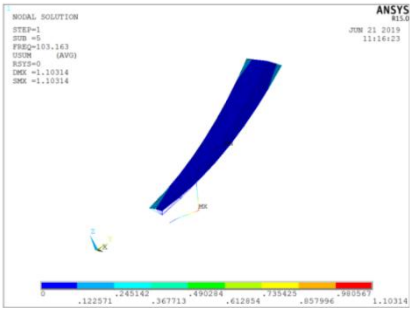
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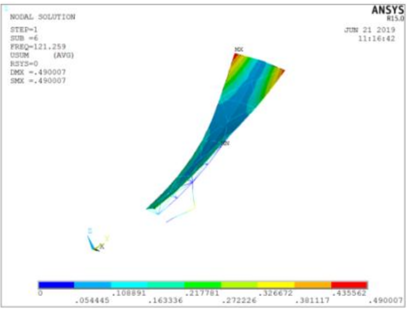
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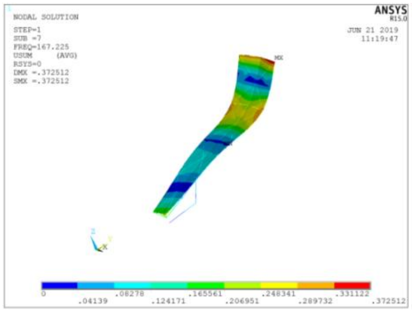
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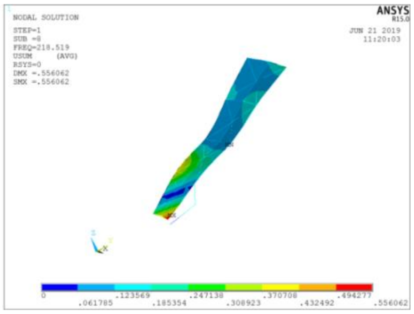
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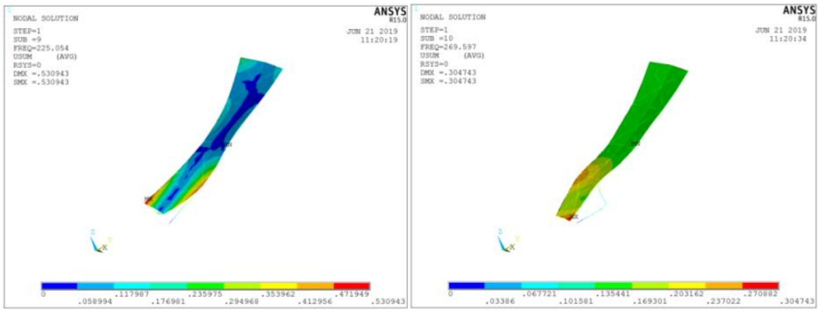

Fig5: First 10 mode shapes of reflector structure in deployed state

Based on the results, the first natural frequency of the deployed reflector is 2.2528 Hz and it meets the requirements of structural dynamics in orbit. The results show that the high-order modes of the deployed reflector present very complex vibration modes and the back truss not only improves the structure stiffness but also develop the vibration mode. Moreover, the frequency of the first ten orders is relatively scattered, which is easy for the subsequent modal identification and control.

On the basis ofaforementioned dynamic analyses, it is shown that both folded and deployed state can meet the requirements for antenna structure.It is ensured that folded state in launching and deployed state in orbit have good structural dynamic performance.

V. CONCLUSION

In this paper, the deployable solid-surface reflector with uniaxial rotation is designed.The deployment process of the antenna is simulated and analyzed by ADAMS. The deployment process is smooth and the petals do not interfere with each other.The dynamic mode analyses of the deployable reflector structure in folded and deployed state are carried out by ANSYS. The natural frequency and vibration mode in the two states are obtained.The analysis results show that the design is reasonable and feasible andmeets the design requirements. It has important reference value for the design analysis and parameter research for this kind of deployable petal-type solid-surface reflector antenna.

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