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Spontaneously deployable structure for space diffractive telescope*

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In order to satisfy the demands for diffractive telescopes in space exploration, a new deployable space diffractive telescope is designed. The structure and geometrical sizes of the spontaneously deployable telescope are preliminarily designated through the Serrurier truss principle and the optimized design theory. The finite element model of the deployable structure is established, and its deployed characteristics are analyzed. The prototype of the spontaneously deployable structure is constructed and some experiments are carried out to study its characteristics. Experimental results indicate that the deployable structure is 2.95 m in length, its repetitive deployed precision can reach less than 2 mm, the off-center error is less than 0.3 mm, and its deployed precision can be adjusted to micrometer level by actuators when it has deployed. It has simple structure, low mass, steady and reliable deployment, as well as higher precision for space diffractive telescopes.

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The diffractive imaging systems have superiority in space exploration for their excellent characteristics of big aperture, high resolution, low mass, deployable structure and easy replication. Most researches are focused on the manufacture of diffractive components and design of deployable structures[1]. Recent significant projects addressing larger diffractive imaging system applications include the Lawrence Livermore National Laboratory (LLNL) Eyeglass[2], a photon sieve telescope at the US Air Force Academy (USAFA)[3], the current Defense Advanced Research Projects Agency (DARPA) Membrane Optic Imager Real-Time Exploitation (MOIRE) program[4], and a Fresnel diffractive array imager (FDAI) at Centre National d'Etudes Spatiales (CNES) in France for astrophysics[5]. Moreover, Zheng et al[6] have designed a deployable structure for one big-aperture diffractive membrane through simulation. Most of these are concentrated on the manufacture of diffractive components and some small deployable structures, but big deployable structures for long-distance diffractive optics have rarely been found in open reports.

This paper demonstrates a deployable structure for diffractive telescopes. A 2.95-m-long deployable structure is designed for diffractive optical systems according to the Serrurier's truss principle and the optimized design theory. Also, a deployable prototype is constructed and some experiments are conducted. Experimental results indicate that the deployable structure can deploy repeatedly and satisfy the diffractive optical system's requirements appropriately.

The principle of diffractive imaging systems is that a diffractive membrane/mirror forms an entrance aperture that focuses incident illumination into a correcting lens which then removes the chromatic aberration introduced in the entrance aperture and corrects some off-axis aberrations[7,8]. Under the condition of high resolution, the diffractive imaging system with a big F number will normally make its diffractive membrane/mirror have a big distance from its correcting lens, resulting in that some deployable structures should be developed to support its diffractive membrane/mirror or correcting lens. Then the diffractive telescope will have a folded state before launch and deploy in orbit.

The diffractive optical system in this paper is shown in Fig.1, where the diffractive telescope should satisfy some indexes as follows: the diffractive mirror's aperture is 350 mm in diameter, the distance between its diffractive mirror and correcting lens, namely the deployable structure's deployed length, is 2.95 mm, and the diffractive telescope's total mass should be less than 15 kg. Some precision requirements should be satisfied as follows when the deployable diffractive telescope has been designed and deployed: the off-center error and tilt angle between its diffractive mirror and correcting lens should be less than 0.3 mm and 0.2°, respectively, and the deployable structure's repetitive deploy precision should be less than 2 mm.

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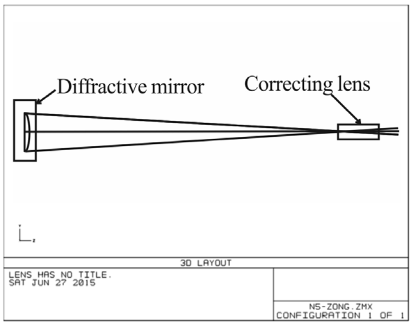


Fig.1 The diffractive optical system

When the diffractive mirror or correcting lens deploys alone from one side to the other, some biggish deformation will be generated because the distance between them in this paper is too big, which will affect the diffractive telescope's precision obviously. In order to reduce the position error, the method that deploys its diffractive mirror and correcting lens concurrently from middle to both sides will be adopted according to the Serrurier's truss principle[9,10].

Fig.2 shows a typical schematic of the Serrurier's truss principle. The diffractive mirror and correcting lens are both supported by several deployable trusses, one side of which is mounted on a rigid body, and the other is attached to a supporting ring. If the deployable trusses at both sides of the rigid body have suitable cross-section sizes under the ideal condition, the point *A* and point *B* in Fig.2 will generate equal deformation (namely $d_A=d_B$) in the perpendicular direction of the optical axis, through which the ideal deformed line A_1B_1 can be obtained. Also, this can be expressed in mathematical equation as follows:

$$d_A=\left(\frac{p_A b}{4Ea_A}\right)\left[\frac{4L_A^2}{b^2}+1\right]^{3/2}=$$

$$d_B=\left(\frac{p_B b}{4Ea_B}\right)\left[\frac{4L_B^2}{b^2}+1\right]^{3/2}, \qquad (1)$$

where *p* is the load applied on points *A* and *B*, namely, the weight of the diffractive mirror and correcting lens, *b* is the rigid body's height, *E* is the deployable truss's elastic modulus, *a* is the sectional area of the truss supporting *A* and *B*, and *L* is the cantilever's length at points *A* and *B*.

According to the Serrurier's truss principle and the diffractive telescope's precision requirements, tape spring hinges are adopted to design the deployable trusses used in this paper. The tape spring is a thin-walled straight strip of material with curved cross-section. Deployable structures made of tape springs have low mass, simple structure, high efficiency of enfoldment, and no mechanical joints, and they can deploy spontaneously without external driving forces[11]. The deployable trusses in this paper are constructed by some tape spring hinges and carbon fiber reinforced polymer (CFRP) struts, which are mounted on the simulated satellite, namely, the aforementioned rigid body, making the diffractive mirror and correcting lens deploy spontaneously.

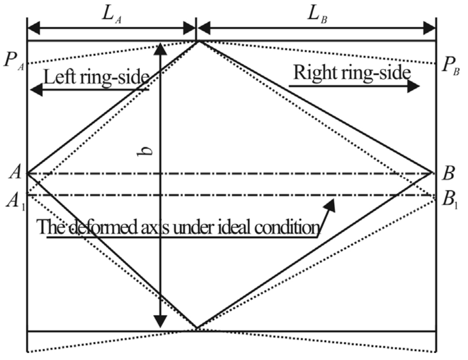
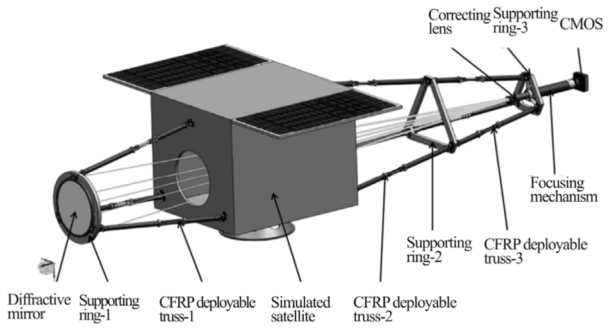
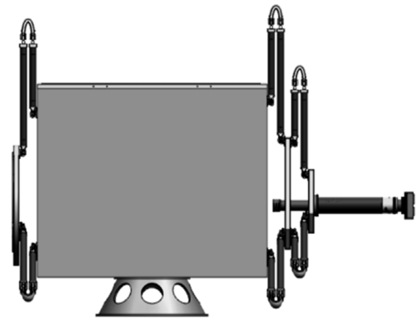


Fig.2 Schematic of Serrurier's truss theory

As the diffractive mirror's aperture and mass are much bigger than those of the correcting lens, according to the Serrurier's truss principle and optimized design theory, the left deployable structure supporting the diffractive mirror is designed as 815 mm in length with a single-decker, and the right deployable structure supporting the correcting lens is designed as 1 490 mm in length with a double-decker. The designed deployable diffractive telescope's prototype can be seen in Fig.3, and it has advantages of low mass, high efficiency of enfoldment and reliability.



(a) The deployed state



(b) The stowed state

Fig.3 Ensemble scheme of the deployable structure

As seen in Fig.3, the deployable structure is constructed by the CFRP deployable trusses, tape spring hinges, root joints and some supporting rings. The diffractive mirror and correcting lens are fixed on the supporting rings through screw thread, while the supporting rings are connected to the simulated satellite by using the CFRP deployable trusses. Frameworks of the deployable structure, such as the simulated satellite and supporting rings, are the parts that can't be folded, while the CFRP trusses constructed by root joints, CFRP struts and tape spring hinges can be folded repeatedly. The tape spring hinges used in this paper are formed by two tape springs in pairs for self-latching when deployed, the root joints are designed to guarantee the CFRP trusses can deploy in 180° regularly, and some torsional springs are used in the root joints to provide position limit and pretension.

The diffractive mirror using PMMA in this paper is 350 mm in diameter and manufactured through the diamond single-point turning method. According to the Serrurier's truss principle and optimized design, the CFRP trusses' external diameter is 28 mm with a 1.5 mm thickness, and the Mg-Al alloy supporting rings' thickness is 2.5 mm. The completely designed diffractive telescope has a total mass of 12.8 kg with a total deployed length of 2.95 m (including the simulated satellite's length). Meanwhile, in order to guarantee the deployed structure's rigidity and self-latching capability, the tape springs' parameters of thickness, width, subtended angle and cross-section radii are designed as 0.18 mm, 25 mm, 90° and 20 mm, respectively according to the elastic thin shell theory. The tape springs' critical moment is 1 925 Nmm, making it have preferable dynamical properties for the deployable structure, and the tape spring's moment-curvature relationship can be seen in Fig.4.

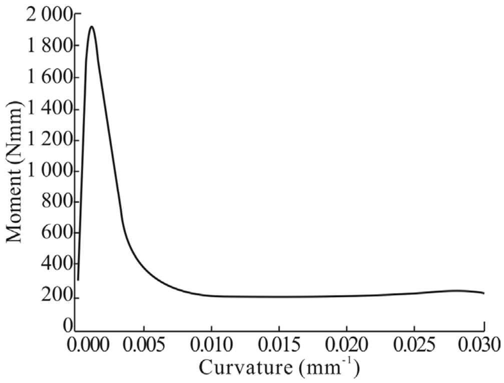


Fig.4 Moment-curvature relationship curve of the selected tape spring

Finite element models (FEM) of the deployable structures at both sides of the simulated satellite are established (see Fig.5 and Fig.6) to analyze their deployed characteristics after the diffractive telescope has been completely designed. Some simplifications are conducted to the FEM during the analysis, namely, the diffractive mirror, correcting lens and CMOS are all replaced by RB2 rigid elements defined with their masses. The diffractive telescope will be folded before launch, and then deploy spontaneously in orbit, keeping the deployed state when it works.

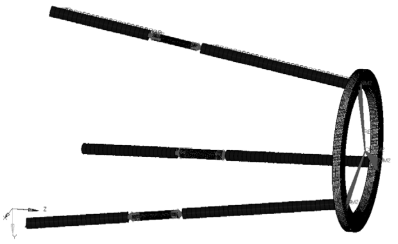


Fig.5 Finite element model of the left deployable structure

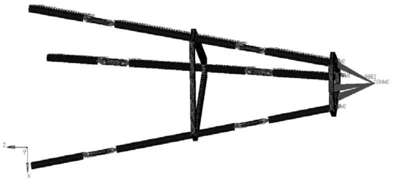


Fig.6 Finite element model of the right deployable structure

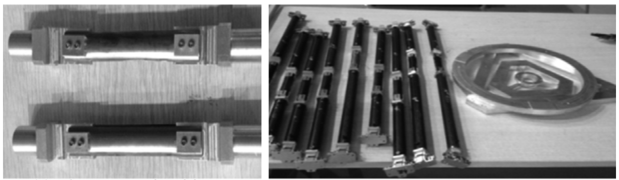
The MPC rigid nodes with six degrees of freedom can be constrained and tied to the CFRP deployable trusses' bottom whose sides are attached to the simulated satellite. The deployable structures' fundamental modes and deformations in the perpendicular direction of optical axis have been analyzed, and Tab.1 shows the results.

Tab.1 The analysis results of the deployable structures

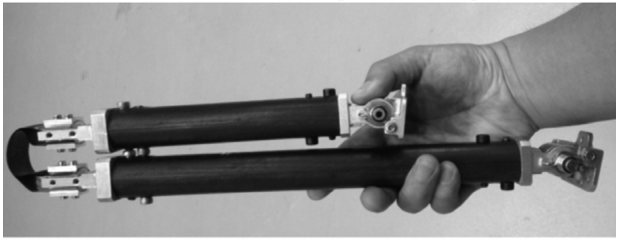
System	Fundamental frequency (Hz)	Static displacement in *X* orientation (mm)	The variation of tilt angle (°)
The left single-decker deployable system	12.2	1.453	0.04
The right double-decker deployable system	11.9	1.680	0.06

Some conclusions can be obtained from Tab.1. The fundamental modes of the deployable structures at both sides of the simulated satellite can satisfy the requirements when they have deployed in orbit, and their deformations in the perpendicular direction of optical axis are approximately equivalent with just a small error of 0.15 mm. Their tilt error is about 0.1°, which can satisfy the ground assembling very well. Some unpredictable and inevitable errors have been generated because some clearance exists in the root joints of the deployable CFRP trusses, and the FEM model has been simplified about that. In order to reduce deployed errors and guarantee the deployable diffractive telescope with a preferable precision, some actuators of LT3010A provided by Piezo LEGS with a 3 mm stroke and nanometer resolution are fixed between the diffractive mirror and its supporting ring, through which the diffractive mirror can be adjusted to the precise position as the optical system's requirements.

In order to verify the deployable structure's characteristics when it has deployed, its components, such as the deployable CFRP trusses, supporting rings and simulated satellite, are manufactured and assembled, as shown in Fig.7. After all the components have been assembled completely, the deployable structure's prototype is constructed and some experimental tests are conducted to evaluate the performance and precision of the structure[12].



(a) The tape spring hinges (b) Components of the deployable structure

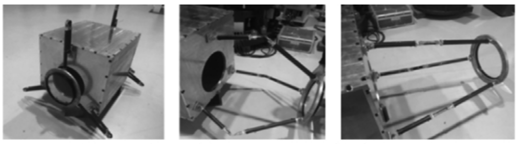


(c) The CFRP strut under folding state

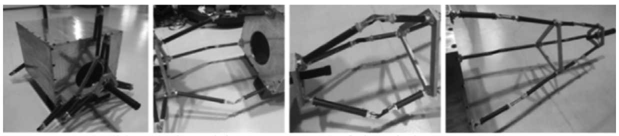
Fig.7 Pictures of components of the deployable structure

The experimental results show that the deployable structure can deploy spontaneously and reliably, and the left single-decker takes about 3 s to complete the deploy, while the right double-decker takes about 8 s to complete the deploy, with the order that the tier attached to the simulated satellite deploys first and the other one deploys next. The deployable structure's folded and deployed states at both sides of the simulated satellite can be seen in Fig.8.

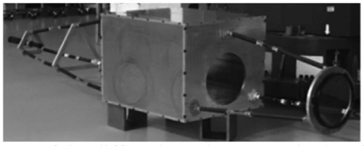
The deployable diffractive telescope has a very high efficiency of enfoldment, making it have a much smaller size in folded state than deployed state. High precision reflectors are bonded to the diffractive mirror's and correcting lens' mounting surfaces respectively[13], and the Leica P310 laser distance measurement equipment with a resolution of 0.1 mm and the Leica TM5100A transits with a resolution of 5 s and 0.001 mm are used to test the deployable structure's precision repeatedly. Experimental results indicate that the structure's deployed distance error, off-center error and tilt error between the diffractive mirror and correcting lens are less than 2 mm, 0.3 mm and 0.2°, respectively, but the off-center error would exceed 0.3 mm occasionally because of the clearance in the root joints. As to this condition, high precision reflectors should be bonded to the correcting lens' mounting surface, and a position monitor should be fixed on the diffractive mirror's mounting surface to monitor their position errors in real time. Also, the diffractive mirror's position can be adjusted slightly by the actuators fixed between the diffractive mirror and its supporting ring according to the monitoring results, making the off-center error between diffractive mirror and correcting lens reach micrometer level, satisfying the optical system's requirements very well.



(a) Deployoable processes of left structure



(b) Deployable processes of the right structure



(c) Prototype of the diffractive telescope's deployable structure

Fig.8 Prototype of the deployable structure

Some main factors affecting the diffractive telescope's deployed precision have been summarized as follows after taking a series of experiments. In order to make the root joints in the deployable CFRP trusses rotate smoothly, some clearance must be introduced between its pin roller and moving parts, which will generate inevitable errors to the deployable structure, containing a number of root joints in its deployable CFRP trusses. The three deployable CFRP trusses in the same tier with even a slight difference in length and deviation in their mounting angles can introduce inevitable errors to the deployable structure's precision.

This paper has designed a spontaneously deployable diffractive telescope with a total mass of 12.8 kg according to the Serrurier's truss principle. FEM analysis and experiments have been conducted to study the deployable structure's deployed characteristics, and the factors affecting its deployed precision also have been summarized. Experimental results indicate that the deployable structure can deploy spontaneously and repeatedly with low mass and simple structure, which can satisfy the optical system's requirements appropriately, providing some referenced value and technological supports for future design of the large aperture deployable diffractive telescopes.

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