Design and Analysis of Large Space Membrane Sunshield Structure Based on Origami

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Abstract: This paper proposes a self-deploying membrane sunshield structure to satisfy the requirements of lightweight, easy unfolding with high expansion ratio, and not requiring the driving power. Four equal length tape springs are used to unfold the Kapton membrane folded with leaf-in and circumferential and the folding ratio is calculated. In order to prevent the problems of hook and damage during the unfolding process, stress and trajectories of the membrane as well as the tape spring modal distribution of the skeleton are analyzed. Finally, a test prototype completes to verify the feasibility of the designment. The results show that by applying the tape springs as the driving method, the membrane unfolding process is smooth, and the membrane will not be damaged. The maximum stress at the membrane crease is about 42.3 MPa which is lower than the allowable stress of the material and the folding ratio reaches 69.4.

Key words: sunshield structure; self-deployable; tape spring; membrane; origami; finite element method

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0 Introduction

Sunshield structures, including sun shade, lens hood, visor, etc., are widely used in many typical space optical structures to shield internal opto-mechanical structures from external heat flow and space stray light from outer space[1]. It can improve the accuracy of the detection or observation system by maintaining a stable low-temperature working environment.

The geometry of the sunshield structure affects the temperature distribution and stray light level significantly by inhibiting the external heat flux and stray light entering into the optical structures[2]. With the increasing demands of deep space and earth observation, the development of large-aperture high-resolution optical system, and the envelope size limitation and launch cost control of carrier rocket fairing, the characteristics of large size, light weight, high storage ratio and high reliability are required for space shading structure. For different application scenarios, there are different corresponding shading structures with diverse expansion drive methods, shape and size. The regular expansion drive methods include inflatable expansion[3], motor driven expansion[3-4], shape memory effect expansion and elastic expansion[5]. The typical expansion shapes are cylindrical[4], conical[5], planar[3] and beveled cylinder[5]. The starshade sunshield is a large planar structure that uses motor-driven cables for deployment[4]. The primordial inflation explorer uses elastic deployment, with a deployment structure consisting of four layers[6]. The sunshield for the X-ray telescope is cylindrical in shape, with a deployment height of up to 24 meters and driven by extension arms[7]. The cone-shaped sunshield for the Atlas V 400 vehicle is deployed using an inflation method[3], as shown in Fig.1.

Membrane structures are widely used in large

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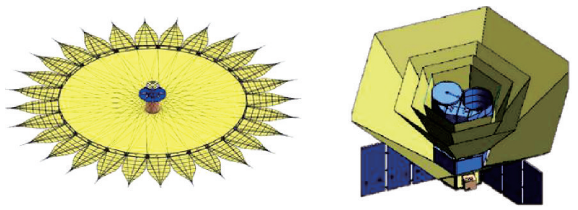


(a) Deployed sunflower configuration[4]

(b) Primordial inflation explorer[6]

(c) Thermal shield on the Atlas V 400 vehicle[3]

(d) International X-ray observatory[7]

Fig.1 Different kinds of sunshield structures

space deployable structures because of their light weight and high folding ratio. The James Webb Telescope, launched in late 2021, applies a large four-layer thin membrane shade whose deploying size is 21.197 m×14.625 m[8]. It reduces the cold surface temperature to 30 K successfully without the help of refrigeration.

The membrane structure is prone to twist or tear, and these characteristics make the unfolding process difficult to control[9] or even make the whole mission failure. Therefore, the unfolding of membrane shading structure should be orderly and controllable. Using complete paper, origami only forms various space shapes by folding and bending. The most typical character of origami structure is that the process of unfolding is smooth and orderly, and the stress is only concentrated in the crease position, which is suitable for the needs of large membrane unfolding and storage. The trajectory and stress concentration of the membrane during the unfolding process can be simulated through the CAE software at the design stage. Many scholars have carried out research on origami model. Meloni et al.[10] summarized the latest applications in major origami-based engineering fields and discussed the challenges and limitations of current design processes and computational tools. According to the results of simulation analysis, Lin et al.[11] established deployment performance evaluation system. Liyanage et al.[12] put forward how can overcome the adverse effects caused by the membrane thickness while achieving a compact folding state.

At present, the inflation-driven deployment and the motor-driven deployment are main driving modes of space deployment structures. The inflation-driven expansion needs to carry extra gas and air pump which may cause the risk of air leakage. The motor-driven needs more additional structures and higher circuit reliability requirements. Tape spring is a single layer of open cylindrical shell structure which mainly used in measuring length of steel tape. Many institutions tend to apply tape springs in space structures such as deployable antenna[13], deployable wind panel[14], deployable sunshield[15], and space deployable telescope[16] due to its characteristics of light weight, compact storage, no external force driving, fast expansion speed and maintaining locked by relying on its own stiffness. In recent years, carbon fiber, glass fiber and other composite tape springs[17] are gradually developed according to the demand.

Combined low stress origami structure with self-expanding and self-locking tape spring, an in-plane self-expanding large-storage-ratio lightweight membrane sunshade can be designed. Compared with existing deployable sunshade structures, this design does not require an additional driving mechanism, and its deployment not only is reliable and lightweight, but also has a larger storage ratio. Through the finite element simulation of the deployment process of the membrane, the motion trajectory of the membrane, the stress variation and the modal distribution of the unfolding skeleton are monitored, and a scaled prototype is made to verify the physical model.

1 Structure Design

1.1 Design scheme

Since the membrane is folded around the centrosome in the receiving state, the folded state of the tape spring is compatible with the folded mode of the membrane. Thus, an efficient membrane-cantilever composite structure is formed. The structure is a regular quadrilateral plane, mainly composed of four equal length tape spring skeletons, tape spring storage box, membrane storage box and Kapton membrane. Fig.2 shows the overall design configuration of the shading structure. The tape spring storage box and the membrane storage box share the same mounting surface, and the end of the tape spring is fixed with the four corners of the membrane. After unlocking, the membrane is unfolded from four corners by the self-unfolding characteristic of the tape spring and maintained by the self-locking property of the tape spring after the unfolding process is completed.

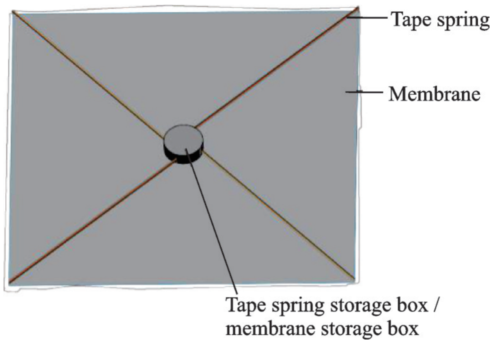


Fig.2 Overall structure diagram of sunshield structures

1.2 Membrane folding method

To minimize the folding model, the folded parts need to overlap as much as possible. Therefore, a regular polygon with center symmetry is the best choice. Leaf-in folded structure is inspired by the leaf of beech tree in nature[18]. "Leaf-in" means that the tips of the leaves meet at a certain point (point A). As shown in Fig.3, the solid black line is the mountain fold and the dashed black line is the valley fold. The gray part is one of the "leaves". In Fig.3, O is the center of the circle, the regular quadrilateral is divided into n parts ($n=4$), the fold angle $\alpha=45°$, the number of layers $s=6$, and the height of each layer is h. The relationship between α and n is as follows

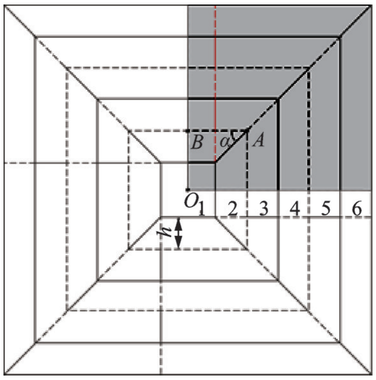
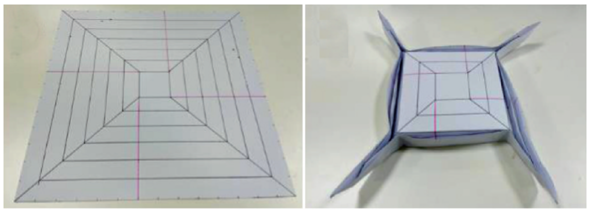


Fig.3 Leaf-in pattern

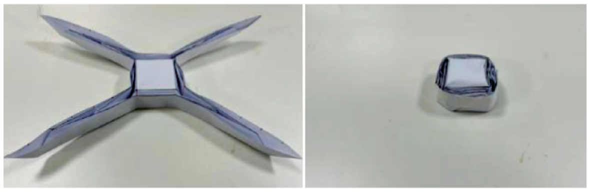
$$\alpha=\frac{\pi}{2}-\frac{\pi}{n} \tag{1}$$

It is worth mentioning that, it will produce an infinitely long surface and all the "leaves" continue side by side in a straight line when $n \rightarrow \infty$. This is known as the Miura's folded configuration[19].

The sunshield membrane structure is a regular quadrilateral plane before folding. The regular quadrilateral membrane is folded into a center symmetric configuration by means of in-leaf folding, and then the folded structure is coiled around the centrosome[20], as shown in Fig.4.



(a) Unfolded paper (b) Folding process 20%



(c) Folding process 80% (d) Folding completion

Fig.4 Square module with leaf-in and circumferential folding

1.3 Tape spring frame

The tape spring skeleton structure is illustrated in Fig.5, which is composed of a central rotor, a storage box, four tape springs and four free-end restriction blocks. Four tape springs are uniformly fixed on the central rotor along the tangent direction and regularly coiled around the central rotor in the storage state. The tape spring skeleton then expands outward from the four corners by the self-unfolding property of the tape spring after unlocking and can keep locked after fully deployed.

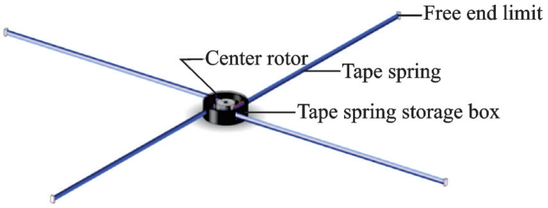


Fig.5 Schematic diagram of tape spring frame

1.4 Calculation of folding ratio

The folding ratio is an important parameter to evaluate the performance of deployable structures. Because the storage box height of the protective membrane structure is fixed, it is not considered when calculating. Only the in-plane storage ratio λ is considered, shown as

$$\lambda=\frac{S_1}{S_0} \tag{2}$$

where S_1 is the membrane area after fully expanded, and S_0 the membrane before commencement of the initial area. From the geometric structure in Fig.3, we can get that

$$S_1=(2\cdot h\cdot s)^2 \tag{3}$$

$$S_0=(2\cdot h)^2 \tag{4}$$

So, the folding ratio is

$$\lambda=\frac{S_1}{S_0}=s^2 \tag{5}$$

It can be seen that the folding ratio of the folding method is only related to the number of folded layers. Theoretically speaking, when the unfolding area is fixed, the more the folding layers are, the higher the folding ratio is and the higher the storage efficiency is.

In practice, a minimum folding ratio of the membrane should be reserved according to its thickness considering the stress of the membrane. When the multilayer membrane is wound, the inner membrane will be wrinkled due to the different winding radius of the inner and outer layers, which further affects the storage size and causes the actual folding ratio to be smaller than the theoretical value. At present, scholars have optimized the shape and position of creases to reduce the influence of wrinkle[21].

If each fold is calculated according to the thickest position, it can be known that the theoretical value of unilateral thickness increase is

$$d'=\begin{cases}2r'\left\{\dfrac{s-1}{2}+\sum\limits_{i=1}^{s}\left[s-(2i-1)\right]\right\} & s=2j+1\\[2ex] 2r'\left[\dfrac{s-1}{2}+\sum\limits_{i=1}^{s}(s-2i)\right] & s=2j\end{cases} \tag{6}$$

where r' is the minimum folding radius of the membrane, which is related to the thickness of the membrane. The storage ratio after winding is

$$\lambda=\frac{S_1}{S_0'}=\frac{(2\cdot h\cdot s)^2}{(2\cdot h+2\cdot d')^2} \tag{7}$$

2 Simulation of Shading Structure

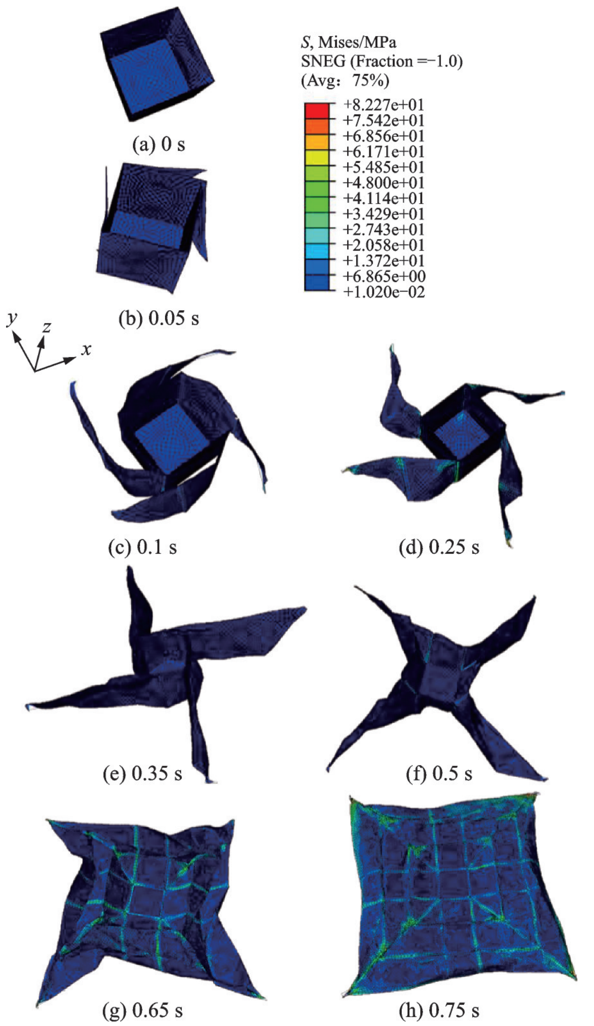
2.1 Membrane deployment simulation

The MATLAB program is used to control the whole folding process. The coordinates of all nodes (*Node) and the number of each element (*Element) are automatically generated, which are written into the ".INP" file according to the prescribed format, and then are imported into ABAQUS to get the folded model. The size of whole model is 1 m× 1 m, containing 14 841 nodes and 14 700 elements. The S4R element type is used to analyze the unfolding of the folded and coiled membrane, and the U1, U2, UR1 and UR2 degrees of freedom of the bottom surface are constrained. The contact type is general. Since the four tape springs unfold synchronously, they exert the same driving effect on the four corners of the membrane, so the displacement load of the same size is applied to the four corners. The main material properties used in the analysis are given in Table 1.

Table 1 Material properties

Material property	Value
Elastic modulus / ($\mathrm{N\cdot mm^{-2}}$)	5 200
Poisson's ratio	0.38
Density / ($\mathrm{kg\cdot m^{-3}}$)	1 390

The unfolding process and stress distribution are calculated using the Abaqus/Explicit solver, as shown in Fig.6. It can be seen that the unfolding process of leaf-in folding combined with surround fold-



(a) 0 s

(b) 0.05 s

(c) 0.1 s

(d) 0.25 s

(e) 0.35 s

(f) 0.5 s

(g) 0.65 s

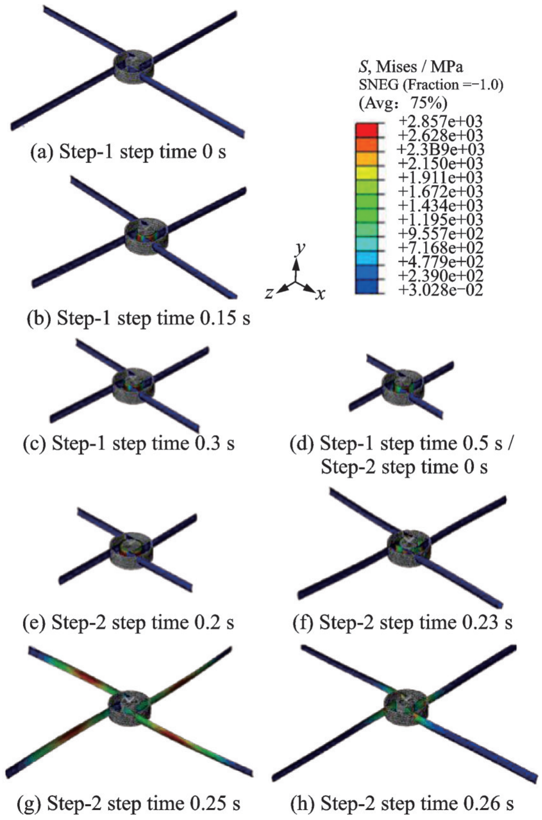
(h) 0.75 s

Fig.6 Membrane finite element analysis of unfolding process

ing is smooth and orderly, and the stress mainly concentrates on the crease position and the stress points at the four corners. The maximum stress at the crease is about 42.3 MPa, and the maximum stress at the crease is about 80 MPa, which compared to the allowable stress of the material (the allowable stress of the base Kapton membrane is more than 100 MPa) with the risk of tearing. In practical application, the strength and service life of the membrane can be improved by setting stress unloading device at four corners and local strengthening at the crease position.

2. 2 Simulation of tape spring expansion

When analyzing the self-expansion of the tape spring, the storage box is set as a rigid body and fixed for the convenience of calculation. Fig. 7 explains the whole process of loading and unlocking. The degrees of freedom of the central rotor in U1, U2, U3, UR1 and UR3 directions are constrained. In Step-1, a rotational load is applied in UR2 direction to coil the tape spring around the central rotor, and this load is deactivated in Step-2. It can be seen from Fig.7 that there is an inertial impact along the unfolding direction, which will cause a small elastic deformation and certain vibration of the tape spring, especially when it expands to the limit position.



(a) Step-1 step time 0 s

(b) Step-1 step time 0.15 s

(c) Step-1 step time 0.3 s

(d) Step-1 step time 0.5 s / Step-2 step time 0 s

(e) Step-2 step time 0.2 s

(f) Step-2 step time 0.23 s

(g) Step-2 step time 0.25 s

(h) Step-2 step time 0.26 s

Fig.7 Tape spring finite element analysis of unfolding process

2. 3 Modal analysis of tape spring skeleton

For modal analysis of the expanded skeleton, the tape spring storage box is regarded as a rigid body, and the degrees of freedom in all directions are constrained, namely U1=U2=U3=UR1=UR2=UR3=0. The linear perturbation analysis step is adopted, and the type is set as frequency. The modal shapes of the first six orders of output are shown in Fig.8.

According to the displacement cloud diagram of the first six modals, it can be seen that the end of

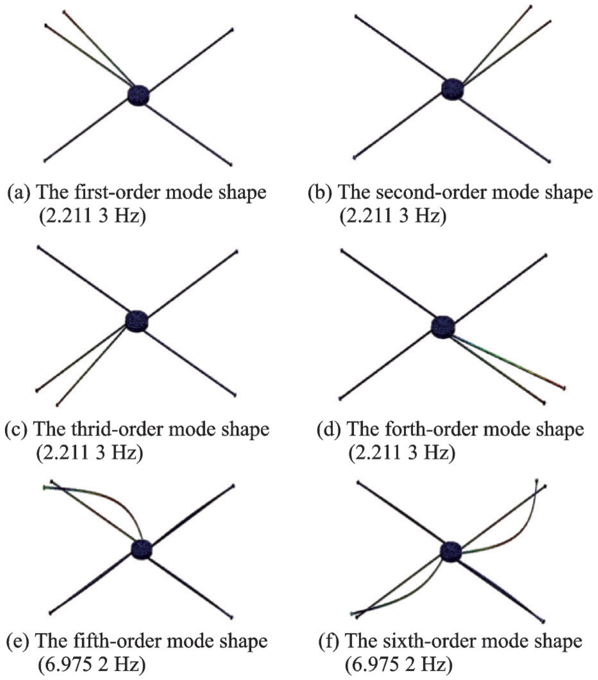


Fig.8 The first six modes of the tape spring measure

the tape spring produces a large displacement, and with the increase of the natural frequency, the middle of the tape spring will appear a large elastic deformation.

3 Physical Model

According to the design parameters of the deployable shading structure, the 3D printing technology is used to make the physical model of this design. Four tape springs with a length of 70 cm are used as the unfolding skeleton, and the end of the tape spring is fixed with the four corners of the unfolding membrane. The size of the unfolding membrane is 1 m×1 m. Fig.9 shows a schematic diagram of the folded state.

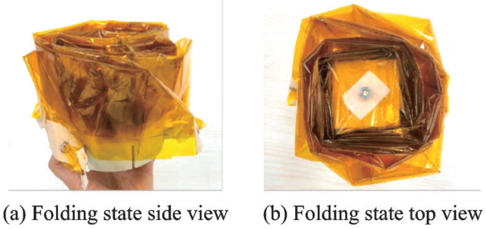

(a) Folding state side view (b) Folding state top view

Fig.9 Schematic diagram of folded state

In order to prevent the four corners of the membrane from tearing, a stress unloading ring structure (Fig.10) is added at the four corners of the membrane.

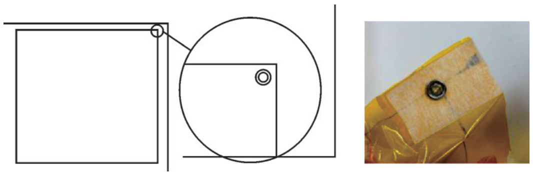


Fig.10 Stress unloading ring

The limit of the fixed tape spring is removed, and the mechanism is unlocked. The unfolding process is shown in Fig.11.

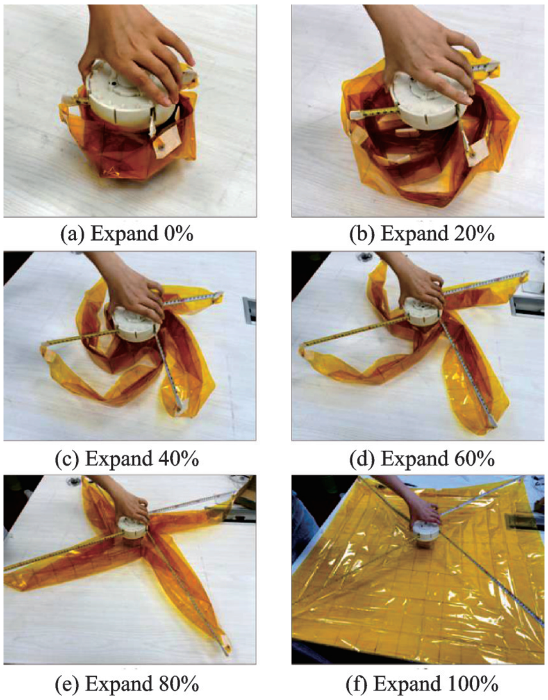


Fig.11 Unfolding process of sunshield structure

It can be seen that the membrane expands with the action of the tape spring extending outwardly, which is basically consistent with the simulation results, the plane shape is maintained after the unfolding is completed, and no winding or tearing phenomenon occurs during the process.

Measurement of dimensions in both post-expansion and pre-expansion states. Before folding, the membrane is a square with a side length of approximately 1 m and an area of about 1 m^2. When folded, the membrane is about a square with a side length of 0.12 m and an area of about 0.014 4 m^2. After calculation, the storage ratio is about 69.4.

4 Conclusions

A plane deployable sunshade structure is designed by combining a low-stress origami model with a self-unfolding tape spring mechanism. It can not only meet the shading requirements of the optical system, but also expand reliably and occupy less space when folding. The self-weight of the tape spring and membrane design can also meet the requirements of lightweight, which can greatly save the emission cost.

(1) The simulation results show that the unfolding process is orderly and controllable, and the stress level is low.

(2) The expansion of the tape spring will be accompanied by a certain impact. According to the deformation results and expansion tests, the impact force will have a certain impact on the membrane, but will not lead to damage or rupture of the membrane. The crease position and the four corners can be strengthened to improve the strength of the membrane.

(3) In engineering applications, it also needs to consider the locking and unlocking method. And if want to further reduce the storage volume and achieve a greater storage ratio, it can do so by optimizing the location of the folds, reducing the folding thickness, and minimizing the creases during winding.

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Author contributions Ms. **QI Lingtong** contributed to the discussion and background of the study, designed the experiment and the simulation, complied the models and wrote the manuscript. Dr. **SUN Liwei** contributed to the design and discussion of the study and manuscript revision. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

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基于折纸的大型空间薄膜遮阳结构设计与分析

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摘要:提出了一种轻质、展开顺畅、收纳比高且不需要额外驱动动力的新型自展开薄膜遮阳结构。利用4根等长的带状弹簧驱动叶内环绕折叠的聚酰亚胺薄膜,并计算了收纳比。为了防止薄膜在展开过程中出现钩挂和破损的问题,对薄膜展开的轨迹、薄膜的应力分布以及带状弹簧骨架的模态分布进行了有限元仿真,并制作了测试样机以验证设计的可行性。结果显示,利用带状弹簧驱动薄膜展开,展开过程顺利,带状弹簧展开时的冲击不会造成薄膜损伤,薄膜折痕处的最大应力约为42.3 MPa,低于材料的许用应力,且收纳比达到了69.4。

关键词:遮阳结构;自展开;带状弹簧;薄膜;折纸工程学;有限元法