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Design and analysis of combined hinges using multi-tape spring

Z Han[1*], L Dong[1] and R Hao[1]

[1] School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang, China

[*] E-mail：hanzeguang1@163.com

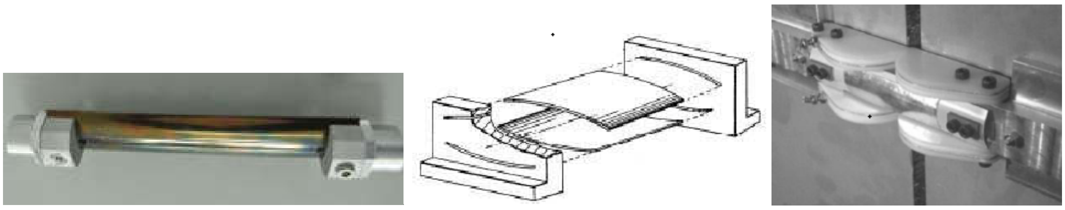
Abstract. In the space folding mechanism, the function of rotation can be provided by the traditional hinge, and additional driving and locking functions are completed by the unfolded and locking mechanism. Thus, such a mechanism is not only of high quality and volume, but also of complex structure. In this paper, a kind of folding hinge mechanism, which is composed of three springs for the expansion of solar canvas, has been designed and analysed. It can perform automatic expansion by the strain energy accumulated after bending and automatic locking by its inherent critical bending moment. The additional locking devices are not required. By using ABAQUS, the influence of tape spring's space layout and bending mode on the bending moment of the combined hinge with three springs in unfolding process has been researched. An optimal combined hinge which has better bending performance is then obtained. The problem of dead point which may exist in the process of expansion in this kind of hinge was successfully avoided.

1. Introduction

In the space folding mechanism, the function of rotation can be provided by the traditional hinge, and additional driving and locking functions are completed by the unfolded and locking mechanism. Thus, such a mechanism is not only of high quality and volume, but also of complex structure. Therefore, the development of light-weight, small-volume space folding mechanism has become a hot research topic.

The tape spring is a kind of single-layer open cylindrical shell structure similar to a steel tape gauge. It has special mechanical properties and can be automatically expanded by the strain energy accumulated after bending and automatically locked by its inherent critical bending moment. The additional locking devices are not required. Thus, the tape spring has been widely used in aerospace [1, 2]. Multi-tape spring combined hinges are used in large space deployable mechanisms, such as solar panels, spatial deployable antennas, and so on.

At present, the spatial deployable hinge based on the tape spring has several forms shown in figure 1. This kind of tape spring mainly composed of two tape springs has high stiffness, but there is an impact phenomenon at the end of expansion [3, 4]. Therefore, after finding out the optimal geometric parameters of a single belt spring, a new type of hinge consisting of three tape springs has been designed. The optimum spatial layout combination has been obtained after analyzing, and using a foundation for the design of the solar panel expansion mechanism for space.



(a) Single spring hinge (b) Multi-tape spring combined hinge1 (c) Multi-tape spring combined hinge2

Figure 1. Several deployable hinge structures based on tape spring.

2. Theoretical introduction of single tape spring

Professor Pellegrino, University of Cambridge, has studied the bending process of a single spring and he found the moment-angle diagram of the bending process with spring which is shown in figure 2. The moment increases linearly to the maximum value $M_+^{\max}$ during reverse bending, and then jumps to the steady moment M_+^*. Similar to reverse bending, the moment increases linearly to the maximum value $\left|M_-^{\max}\right|$ in forward bending. And then it reduces linearly to the steady moment $\left|M_-^*\right|$. And it leaves the value unchanged [5].

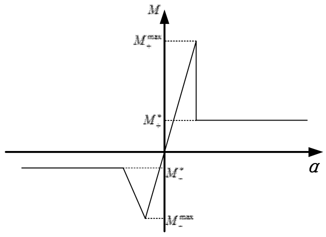


Figure 2. Relationship between bending moment and bending angle of single tape.

Assuming that the shape of the bending region after bending is close to a cylinder, the curvature of the cross section of the bending region changes from 1 / R to 0, and the curvature of the length direction from 0 to 1 /R[5-8]. The steady-state bending moment formula for the expansion process of single tape spring is:

$$\left.\begin{aligned} M_+^* &= \frac{Et^3(1+\mu)\theta}{12(1-\mu^2)} \\ M_-^* &= \frac{Et^3(\mu-1)\theta}{12(1-\mu^2)} \end{aligned}\right\} \qquad (1)$$

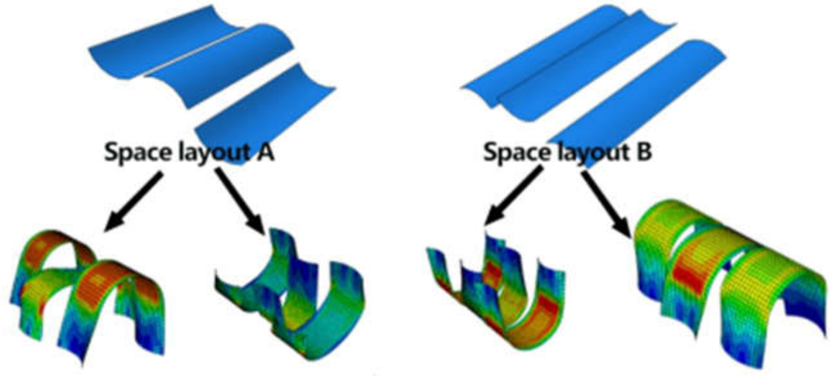
In the formula (1), M_+^* is the steady bending moment of the reverse bending, M_-^* is the steady bending moment of forward bending. E is the elastic modulus of the material of tape spring, ì is the Poisson's ratio, and t is the thickness of the tape spring.

3. Design and simulation of combined hinge

3.1. Design of combined hinges

Because the stiffness of single tape spring is poor, the driving ability and locking ability of unfolded spring are also weak. In general, the multi-tape spring combination hinge is used in engineering. On the one hand, it can improve the unrolling driving ability of the combined hinge, and on the other hand, it can greatly improve the ability of resisting the impact of the end after the hinge is unfolded [9].

In order to combine forward bending and reverse bending well, a combined hinge with three tape springs has been designed. The cross section arc direction of the two tape springs on both sides is the same, and the cross section arc direction of the middle band spring is opposite to that of both sides. There are two kinds of space layout for the three tape springs. There are two bending modes for each space layout. All spatial layouts and bending modes are shown in figure 3. The connection between the three tape springs and the solar panels will be described in detail later.



Bending mode 1 Bending mode 2 Bending mode 3 Bending mode 4

Figure 3. Spatial layout and bending mode of hinges.

For convenience of expression, the case of reverse bending of two springs on both sides and forward bending of one tape spring in the middle is defined as reverse bending. The forward bending of two tape springs on both sides and the reverse bending of one tape spring in the middle is defined as forward bending.

(a) Bending mode 1: Reverse bending on the basis of spatial layout A.
(b) Bending mode 2: Forward bending on the basis of spatial layout A.
(c) Bending mode 3: Reverse bending on the basis of spatial layout B.
(d) Bending mode 4: Forward bending on the basis of spatial layout B.

3.2. Finite element analysis of combined hinges

Taking bending mode 2 as an example, the whole structure of the combined hinge will be introduced and the finite element analysis of the working state of the combined hinge is also done.

The whole structure diagram of the combined hinge is shown in figure. 4. The combined hinge is composed of two parts: the spring and the chuck. The two ends of the side-by-side three tape springs are clamped by two chucks. In practice, the other end of the chuck will be connected to the solar canvas.

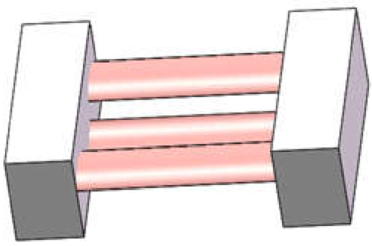


Figure 4. A schematic diagram of the whole structure of the combined hinge.

Due to the fact that only three tape springs are deformed during the operation of the hinge, the model can be simplified in ABAQUS, and the mechanical analysis of the three tape springs can be carried out after the equivalent model is established. The spatial layout of the three tape springs is shown in fig.5. The reference points RP1，RP2，RP3，RP4，RP5 and RP6 are respectively the center of the circular arcs across the two ends of the spring, and the six reference points are located on the same plane. Z to the view, RP2, RP4, RP6 are on the same line, and RP1, RP3, and RP5 are on the same line. The MPC node is established to couple the RP4 with three cross-sections at one end and the RP3 with three cross-sections at the other end, so that the synchronous constraint on the three tape springs can be carried out by imposing constraints on the RP3 and RP4, and the bending and unfolding of the hinge can be carried out. The 90 degree angular displacement of rotation around X was applied on RP3 and RP4 respectively to carry out the forward bending of hinges.

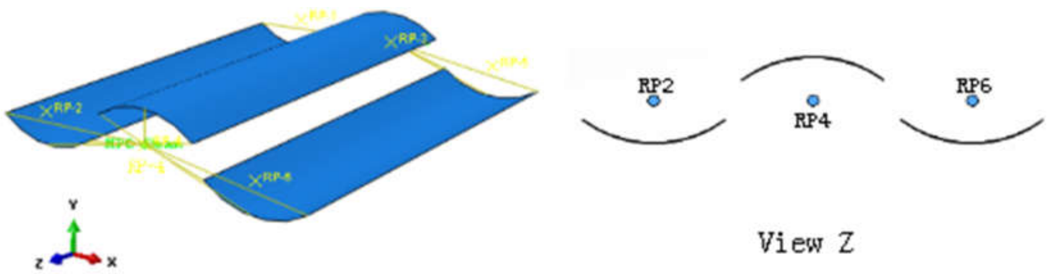
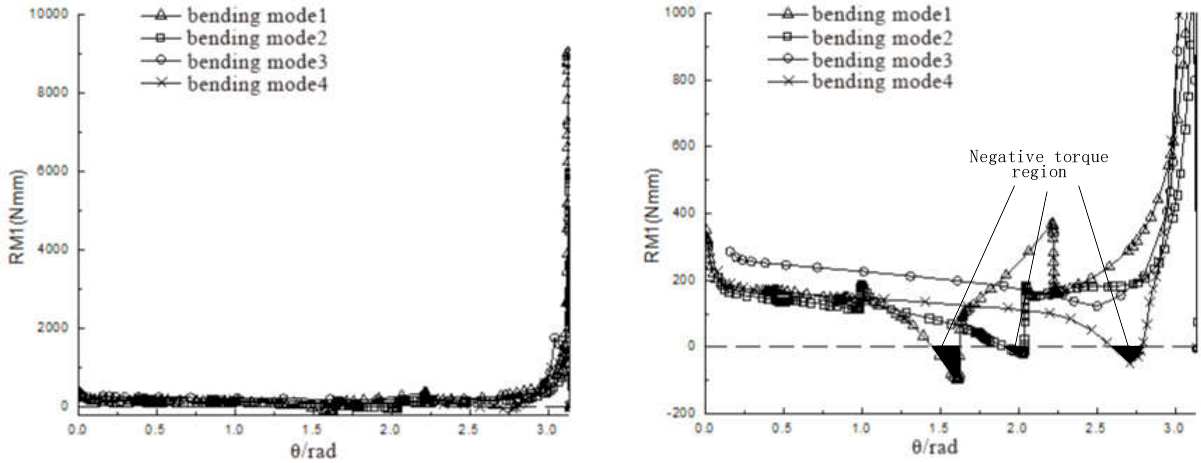


Figure 5. Equivalent model.

For the other three kinds of combined hinge, the simplified method and constraint conditions of the model are similar to that of bending mode 1, so there is no more repetition.

3.3. Effect of different spatial layout and bending mode on bending properties of combined hinges
The results of the finite element analysis of the expansion process of the combined hinges under four bending modes are shown in figure 6(a). Figure 6(b) is a magnification of the part near the X axis in fig. 6(a)



(a)Moment-rotation Diagram (b) Enlarged drawing

Figure 6. FEM analysis of combined hinge.

As shown in figure 6(b), the critical moment and the steady moment of the combined hinge are larger than those of the single belt spring, but combination hinges with some kinds of bending mode produce negative moments during expansion. That is, the driving moment of the hinge expansion process is negative, which is not conducive to the unfolding of the combined hinge. This shows that the dead center will occur on the hinge. The combination hinge will not be further expanded after it has expanded to the center point.

By comparing the torque variation of hinge expansion process with four bending modes, the following results can be obtained:

(1) With bending mode 1: The critical moment of the hinge is larger (9040N·mm), which indicates that the hinge has stronger self-locking ability. But, throughout the whole development process, the bending moment is not stable enough, and the moment is negative between 85.5°and 93°, and the minimum is -98.1146Nmm, which is very unfavorable to the expansion of the combined hinge.

(2) With bending mode 2: The critical moment of the hinge is 5995N·mm, and the moment is negative between 111.66°and 116.53°, and the minimum is -17.6423N·mm. Although its minimum negative torque is not small enough, the bending moment of the whole development process is not stable.

(3) With bending mode 3: The critical moment of the hinge is small (1764N·mm), and the moment value of the unfolding process is the most stable in the three bending modes, which is consistent with the theoretical analysis of the steady moment, and there is no negative moment in the unfolding process.

(4) With bending mode 4: The critical moment of the hinge is minimum (1119 N·mm), and the moment value of the unfolding process is more stable than that of the bending mode 1. However, there is also negative bending moment between 155 °and 160 °, with a minimum of -50 N·mm.

So, the hinge shown in bending mode 3 is an optimal solution.

4. Conclusion

The application of tape spring in aerospace is a major breakthrough in the research of space folding structure. Compared to the traditional deployable hinges, the proposed hinge is lighter in mass, better in unfolding performance and larger in unfolding torque, and self-locking can be achieved after unrolling. The finite element analysis method presented in this paper can also be verified by the theoretical calculation formula of single tape spring, and it can also be applied to the simulation analysis of other similar structures.

In this paper, the expansion process of multi-tape spring combined hinge has been mainly researched. The problem of dead point in the process of hinge expansion aiming is found and solved. The obtained conclusions are as follows:

(1) The bending and unfolding performances of multi-tape spring combined hinge are much better than that of single tape spring.

(2) The reverse bending performance of single tape spring is better than that of forward bending.

(3) When the number, material and shape of a single spring are fixed, the spatial distribution and bending mode of the spring are the main factors affecting the bending moment during the expansion process of the multi-tape spring combination hinge.

(4) The self-locking ability of multi-tape spring combination hinge in spatial layout mode is stronger. The unfolded process of the combined hinge based on spatial layout b is stable and when it bends reversely there is no dead point. It is a more optimized structure form and it has great engineering application value.

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