Journal of Mechanical Engineering Science and Technology ISSN 2580-0817
Vol. 8, No. 1, July 2024, pp. 27-38 27

Static and Modal Analysis of a Box Structured Satellite Deployment Mechanism with Self-Actuated Torsion Joint

Dongping Sheng[1]*, Renzhe Ma[2], Chun Su[1]

[1]*Changzhou Institute of Technology, Changzhou, 213032, China*
[2]*University of Leeds, Woodhouse Lane, Leeds, United Kingdom, LS29JT*
**Corresponding author: shengdp@czu.cn*

Article history:
Received: 17 January 2024 / Received in revised form: 5 February 2024 / Accepted: 1 March 2024
Available online 12 March 2024

ABSTRACT

A brand-new satellite deployment mechanism with boxed structure and self-actuated torsion joints is proposed and an effective method to verify the feasibility of this mechanism is established in this paper. This mechanism has the characteristics of high base frequency, high ratio of deployed and folded space occupation ratio. In order to meet the design requirements, the related analysis and optimization need to be conducted, and several conclusions are obtained. Firstly, the modal analysis of deployment mechanism at folded and fully deployed state is analyzed, and the result showed that the proper wall thickness is the key parameter to satisfy the design requirement and an optimized value could be obtained; Secondly, the heat deformation analysis result showed that the material plays an more important roll on affecting the thermal deformation than structure parameter; Thirdly, Under the torsional moment of the joints, the stress distribution of the deployment mechanism under different folding angle is investigated, it could be clearly found that the maximum stress is always located on the bonded area of the rod and joint, and the maximum stress is increased with the opening angle generally. By combined analysis including thermal, static, and modal, the related characteristics are obtained which could be used for structure optimization and provide an effective solution for the design of box structured satellite unfolding mechanism with self-actuated torsional joints.

Keywords: *Deployment mechanism, modal, satellite, self-actuated joints, static*

I. Introduction

Based on the rapid development of commercial space satellite field, the demand for small satellites with diversified functions, rapid development and fast demand response is increasing day by day, and there are multiple transportation cases in the production and manufacturing process of small satellites. During satellite testing and installation, for large-size solar wings, large component sizes, low stiffness and structural deformation are easy to occur under the influence of gravity during assembly or engineering tests on the ground. Therefore, traditional deployable mechanisms are widely used. However, the traditional mechanisms also have defects, such as complex structure, relatively high cost, low work efficiency and the rise of operational difficulty.

At present, the research on space folding mechanism in satellite deployment device mainly includes: The space folding mechanism in the satellite deployment device mainly includes truss type [1],[2] and hinge type [3],[4]. Typical applications include the "Ocean Satellite" of the United States, ESA’s European Remote Sensing Satellite-1 and Japan's ‘Advanced Land Observation Satellite’, and their deployment antennas were trussed structures. Although the structure has high rigidity conditions, the structure is relatively complex, the weight is relatively heavy, and the launch cost is relatively high. The advanced

DOI:10.17977/um016v8i12024p027

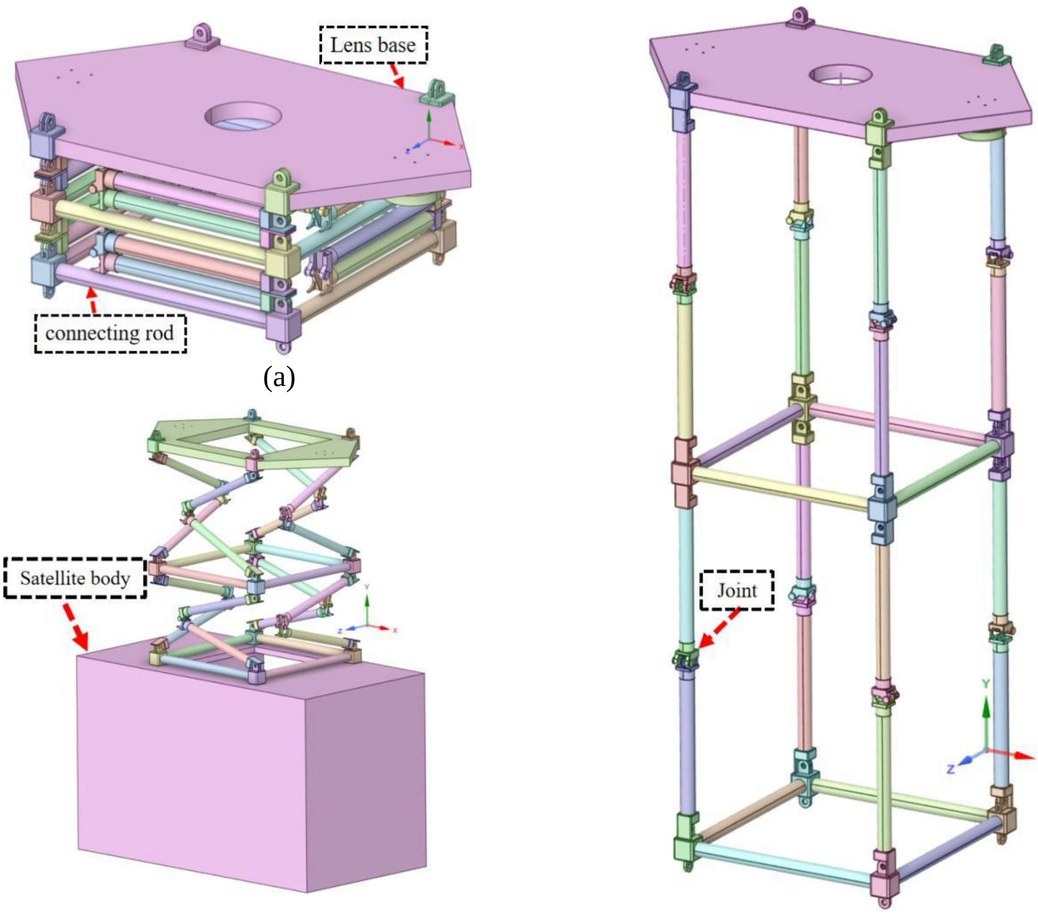
synthetic aperture radar (ASAR) antenna on ESA's Environmental Satellite was a flat deployable antenna with all the hinges on the back of the antenna when deployed. But, in the process of unfolding, it was necessary to adopt the method of segmental unfolding to carry out active control [5]. It should be noted that the single-board expansion solar wing was successfully applied on China’s satellite named ‘Science Experiment No.1’ [6],[7], and the working principle of this structure was to lock the solar panel on the side wall ofthe satellite before the satellite was launched, and then expand the solar panel after the satellite was in orbit which could be used to improve the utilization rate of the solar panel by adjusting the position. For high-power spacecraft, the multi-plate spread solar wing is used. This structure combines the advantages of the paddle type and the single plate and can realize the flexible configuration of the structure. However, different from the single plate, the power of the multi-plate structure was significantly increased [8], [9]. In thespace exploration project of the United States, the space folding mechanism was widely used in the development and construction of satellites [10], space stations and probes. Arita [11] proposed a new available deployable structure “deployable cube”, which is a bistable structure applying buckling actively and developed a prototype of the deployable cube for a cube sat. Choi [12] presented a high precise deployment mechanism for a deployable space telescope to facilitate satellite miniaturization. which was designed with a passive deployment mechanism utilizing a spring hinge. In particular, the customized modules and an assembly jig were specifically designed to reduce alignment errors. A 3D model for calculations of optical parameters of a metal-knitted mesh textile was presented as a structural element of deployable antenna reflectors for space satellites [13]. The model was based on geometrical-optics ray tracing upon diffuse scattering of a broadband light source at a complex knitted mesh structure with different inclinations to the radiative source. A new design methodology for ultra-light-weight solar array paddles was established [14], which was defined as ‘an integrated structure’ and proposed a hinge-less, ultra-light-weight deployable solar array paddle as a functional/structural integrated structure. A study performed on hinged-rod structural systems and their geometry and foldability was presented [15], and in this study, the basic principles enable the synthesis ofrod structures with a foldability feature and new concepts of foldable and deployable rod structures were discussed, which were derived from the foldability condition and were suitable for applications in large space structures. The detailed design of a conical ring constructed with V-fold bars was presented [16], which has the characteristics of low mass,high deployed stiffness, scalability to large dimensions, and potential for modularity.

In this paper, a box structured satellite with unfolding mechanism based on self-actuated torsion joint is designed and the method to verify the feasibility is proposed. The related analysis and simulation of the folding mechanism are carried out by the Finite Element Analysis (FEA), including modal analysis, thermal analysis and static strength analysis based on ANSYS. Through multi-angle and double-parameter analysis, the modal and static characteristics of the structure are obtained, and the optimal design of the structure is carried out based on the related analysis, which provides a reliable solution for the design analysis and optimal design of this kind of box structured folding mechanism.

II. Materials and Methods

Physical Model

Satellite deployment mechanism mainly contains self-actuated torsional joint, connecting rod and load base. Torsional joints, bonded with connecting rod joint, is acted as power source to drive the folded mechanism to deploy. Load base is installed on the end of the folding mechanism, and deep space probe is installed on load base. The deployment mechanism is fixed on satellite body at the folded state, and unfolded when satellite is in orbit. The process of unfolding is shown in Figure 1.



(b) (c)

Fig.1. Process of unfolding. (a) Fully folded; (b) Half deployed; (c) Fully deployed

1. Self-actuated Torsion Joint

Since the deployment mechanism is normally one-time unfolding function, and no external power is needed to drive or retract for simplifying the design and save the cost. As of this requirement, the self-actuated joint with the function of high precision and self-position locking is designed, as shown in Figure 2.

Additionally, it can be seen from Figure 2(a), the connecting rod is bonded with joint and paralleled with each other at folded state. With the process of unfolding, the angle between the rods increased from 0 to 180 degree finally, as shown in Figure 2(c). For the purpose of high strength and low mass, titanium alloy is used for design and prototype.

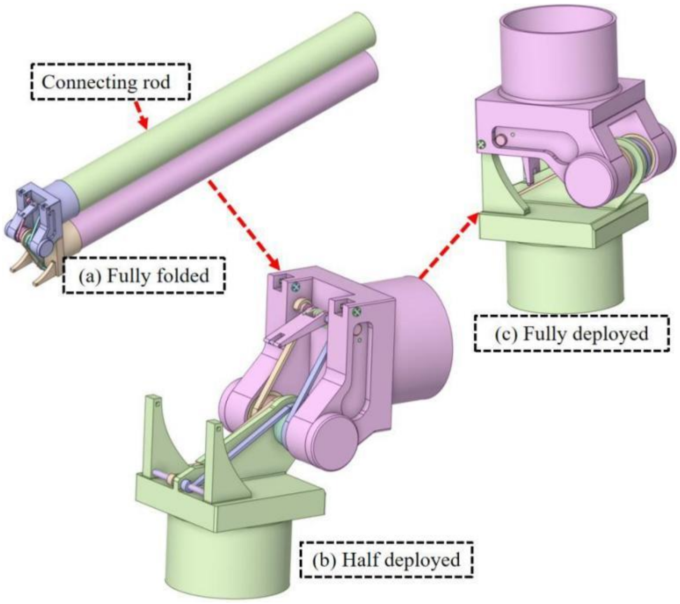


Fig. 2. Unfolding process of joint

2. Connecting Rod and Load Base

The connecting rod, shown in Figure 1 and Figure 2, is made of epoxy carbon braided composite material, which has lighter weight and higher stiffness, and this rod is installed together with the joint. Additionally, as the thermal expansion coefficient of epoxy carbon braided composite material is small, the thermal deformation of the whole truss can be effectively reduced.

The load base, as shown in Figure 1, is mainly used to carry the detector. Its shape is designed as hexagonal plate with threaded holes on both sides for initial fixing, and a hollow in the middle is used for installing the detector. Additionally, it should be noted thattitanium alloy is chosen as the material for design and prototype, which can effectively reduce the weight of the structure and ensure the stiffness.

III. Result and Discussion

Modal and Static Analysis

1. Modal Analysis

1) Model Analysis at Folded State

The modal characteristics of deployment mechanism at folded conditions is necessary for the first stage of the design, and the model needs to be meshed first before analysis, as shown in Figure 3. Additionally, the four mounting holes at the bottom of the mechanism are set to be fixed, and each self-actuated joint is set as a joint with a certain torsional moment based on the test value which is mentioned in Section III.3.

In order to analyze the mechanism systematically, the wall thickness and the material of rod are chosen as parameters to be optimized. Considering the outer diameter is controlled by global geometry limitation and set as 7.5 mm, the wall thickness of the connecting rod is set to be 1 mm, 2.5 mm, and 3.5 mm, respectively. The material of the connecting rod has three options, including epoxy carbon braided (395 GPa) prepreg, epoxycarbon braided (230

GPa) prepreg, and epoxy carbon braided (230 GPa) infiltrates, and three different materials are numbered by 1, 2, and 3, respectively in Table 1.

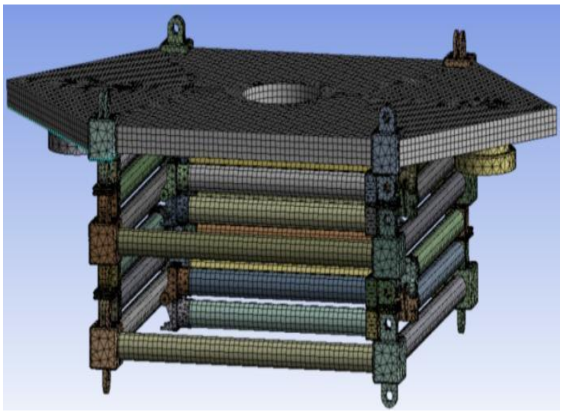
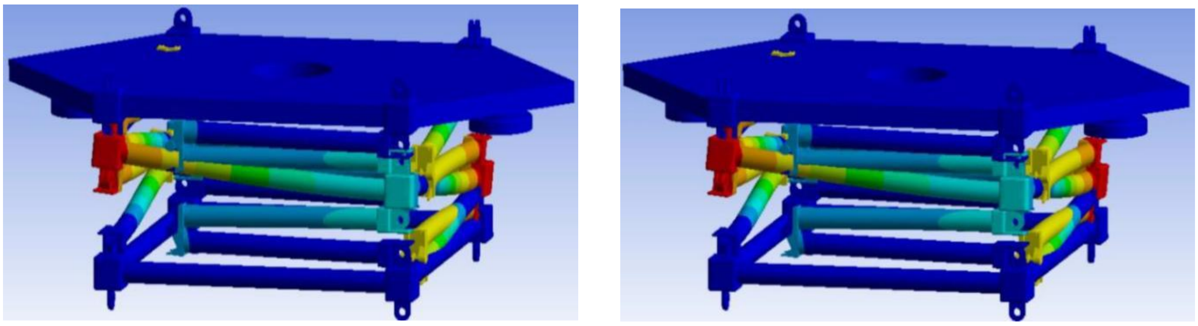
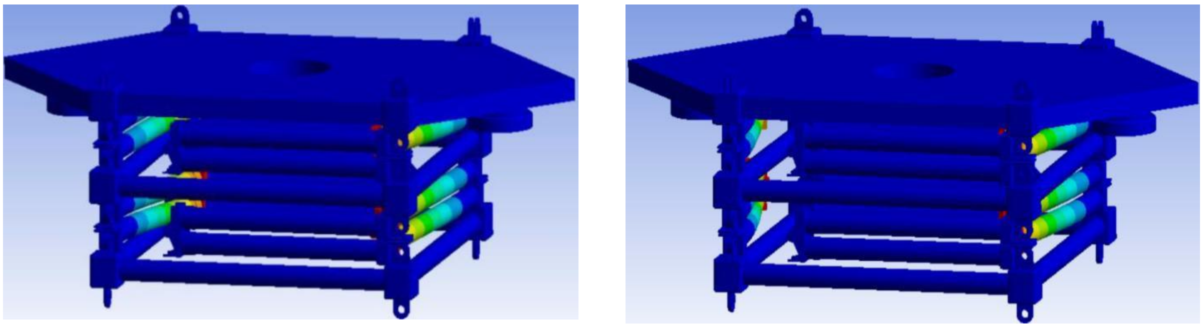


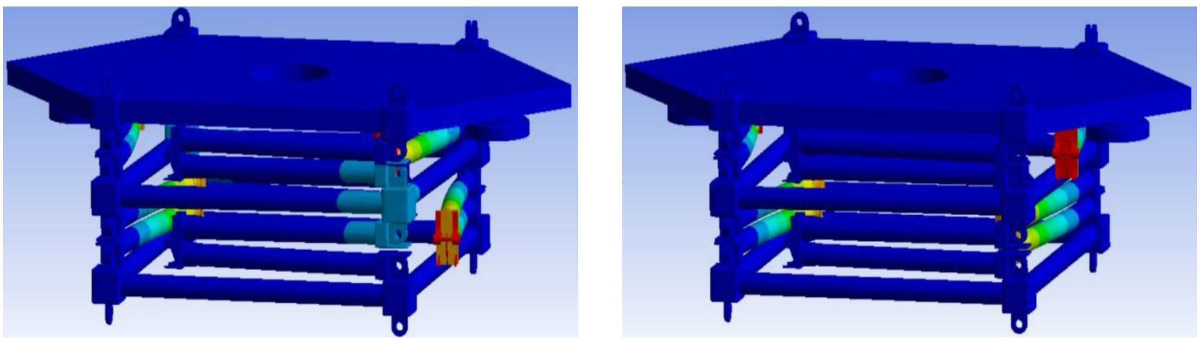
Fig. 3. Meshing model at folded state



(a) (b)



(c) (d)



(e) (f)

Fig.4. Vibration shape of top six order. (a) First order; (b) Second order; (c) Third order; (d) Forthorder; (e) Fifth order; (f) Sixth order

Vol. 8, No. 1, July 2024, pp. 27-38

Figure 4 shows the vibration shape of the first six order with a wall thickness of 2.5 mm at folded state. It could be seen that the vibration almost focused on the connecting rod located on the center of the mechanism, the load base and connecting rods at the bottom have no deformation. Figure 5 shows a diagram of first six natural frequency distributions. It could be seen that the first order frequency is about 116 Hz, and the sixth order frequency is increased to 181 Hz gradually. Additionally, it could be observed that the frequency under different orders is increased smoothly without any abrupt change, which represents the deployment mechanism has the characteristics of the continuity under the fully folded condition.

In order to investigate the dynamics of the deployment mechanism with different wall thickness and different materials under fully folded state systematically, a group of parameters is set, and first two natural frequencies are obtained, as shown in Table 1. It could be found that the changing of the material doesn't change natural frequency much, but the changing of wall thickness could change the frequency significantly. According to design technical specification, the first order natural frequency should not less than 110 Hz at the folded state, which means the wall thickness of the connecting rod should not less than 2.5 mm. By parametric study, under the parameters of material and wall thickness, the optimum parameter group could be obtained and reduce the design boundary.

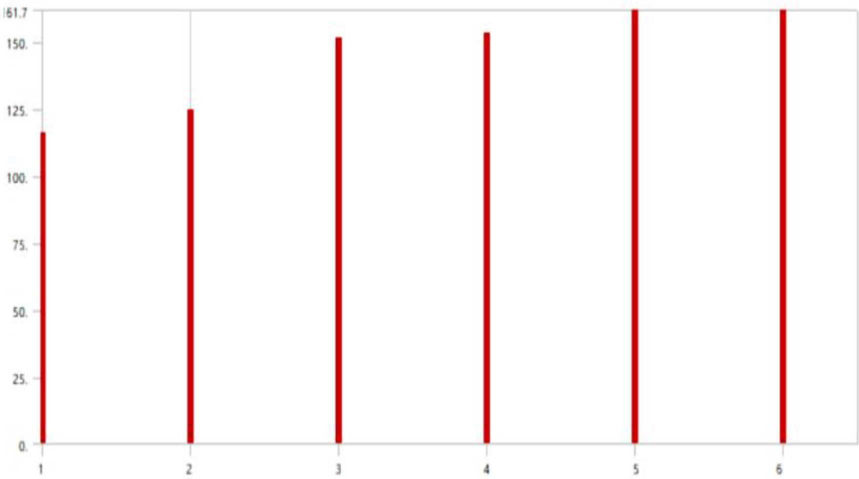


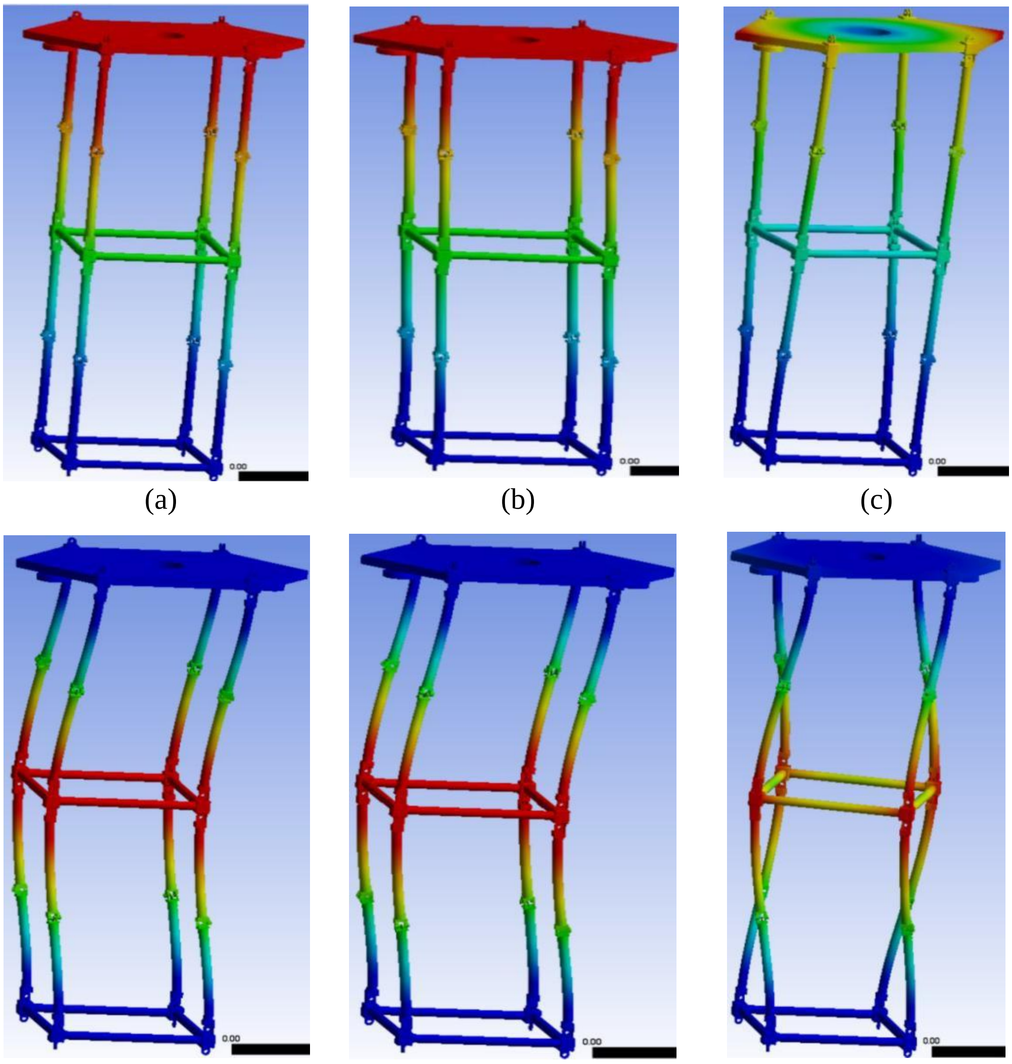
Fig.5. The first six order modal diagrams at folded state

Table 1. First two natural frequencies with different wall thickness and different materials at folded state

Material item	First two natural frequency					
	First order (Hz)			Second order (Hz)		
	2.5mm	1mm	3.5mm	2.5mm	1mm	3.5mm
1	115.92	99.166	112.64	124.21	102.97	119.66
2	101.30	88.976	102.00	106.25	92.052	107.44
3	101.91	89.796	102.52	107.20	93.094	108.32

2) Model Analysis at Fully Deployed State

Similarly, the model analysis of the mechanism under fully deployed state needs to be studied as well. Figure 6 shows the vibration shape of the first six order with the wall thickness of 2.5 mm at fully deployed state. It could be found that, different from section III.1.1, the vibration shape mainly includes swing at two horizontal direction and twist along the longitudinal axis, which represents that the connecting point of torsional joint and connecting rod would suffer maximum deformation and stress.



(a) (b) (c)

(d) (e) (f)

Fig.6. Vibration shapes under different order. (a) First order; (b) Second order; (c) Third order; (d)Forth order; (e) Fifth order; (f) Sixth order

Figure 7 shows a diagram of the first six natural frequency distributions. It could be observed that the first order frequency is about 8.4 Hz and the fourth order frequency is risen to 87 Hz abruptly which is quite different from the result when deployment mechanism is under the fully folded condition. This phenomenon is consistent with the research [17], [18] and needs to be concerned and checked if the design of mechanism satisfies the design requirement.

Vol. 8, No. 1, July 2024, pp. 27-38

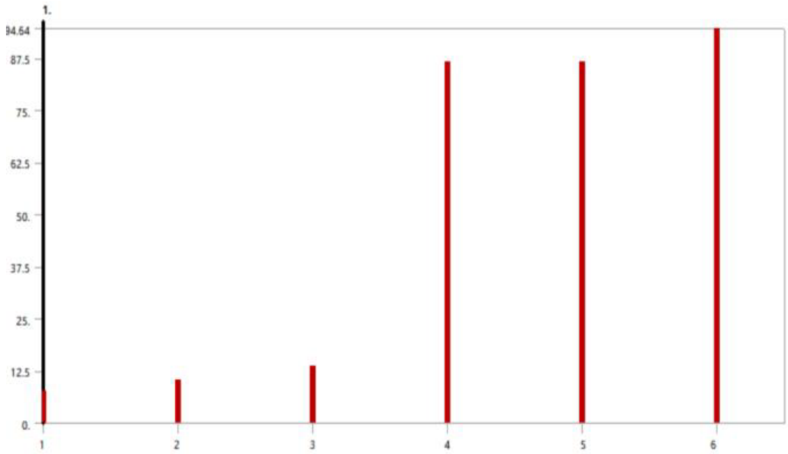


Fig. 7. The first six order modal diagrams at fully deployed condition

With the same purpose, Table 2 shows the first two natural frequency of the deployment mechanism with different wall thickness and different materials under fully deployed state. It could be found that the changing of the material affects the natural frequency more significant than the folded state, and the changing of wall thickness also change the natural frequency dramatically. According to design technical specification, the first order natural frequency should not less than 8 Hz at fully deployed state, which means the wall thickness of the connecting rod should not less than 2.5 mm as well.

Table 2. First two natural frequencies with different wall thickness and different materials at fully deployed state

Material item	First two natural frequency					
	First order (Hz)			Second order (Hz)		
	2.5 mm	1 mm	3.5 mm	2.5 mm	1 mm	3.5 mm
1	8.4772	7.0679	9.1407	11.955	9.6867	12.840
2	7.5365	6.2263	13.2340	10.513	8.4673	13.251
3	7.5701	6.2422	8.2060	10.388	8.3650	11.206

3. Thermal Analysis

When the satellite works in space, the ambient temperature around the folding mechanism will change in a large range. Obviously, the huge temperature difference generated could generate a great impact on the service life of the folding machine. In addition, due to the change in external ambient temperature, the thermal deformation of the folding mechanism will also be caused, which can affect the positioning accuracy and stability of the folding machine significantly. Therefore, it is necessary to analyze the thermal deformation of the folding mechanism after unfolding. Additionally, based on the practical application, the space temperature of the folding mechanism during operation changes is considered in the range of -90℃ - 90℃.

By the similar boundary condition, the thermal deformation in the temperature range of -90℃~90℃ is obtained in Figure 8. It could be found that the maximum deformation happens on load base at the axial direction which would affect the distance accuracy between lens and detector significantly. It could be concluded that thermal analysis is a crucial parameter during the device with high precision requirements and needs to be designed and combined with other parameters.

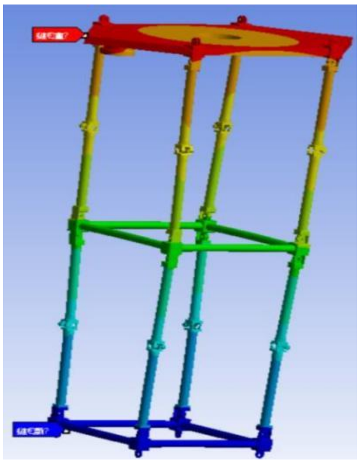


Fig.8. Total thermal deformation under fully deployed condition

With the purpose of obtaining the thermal deformation of the mechanism withdifferent material and wall thickness, the maximum deformation at fully deployed state is calculated as well, as shown in Table 3. As can be seen from Table 3, the affection of maximum deformation with different materials is higher than that with different wall thickness, which means the material is a more sensitive parameter to affect the mechanism accuracy comparing with the wall thickness and this conclusion could be verified by the related research [19].

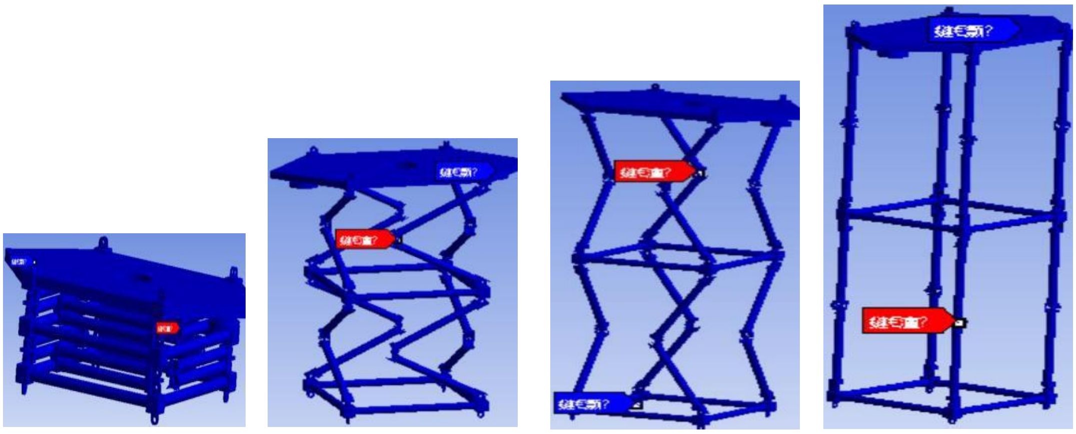
Table 3. Maximum formation with different wall thickness at fully deployed state

Material item	Maximum deformation		
	2.5 mm	1 mm	3.5 mm
1	0.37988	0.37988	0.3808
2	0.36732	0.36732	0.3787
3	0.36762	0.36762	0.3688

2. Static Analysis

During the process of mechanism deployment, the self-actuated joints drive the two paralleled rods at the starting position to rotate based on the axis of the joint, as shown in Figure 2, and the initial torsion is 0.9 Nm and the final torsion is 0.3 Nm respectively which are obtained by field test. The maximum stress and location need to be found out and checked compulsorily.

To obtain the stress distribution of the folding mechanism, the four mounting holes at bottom are set to be fixed and the displacement at axial direction of load base is set to be fixed as well. Besides, the torsional moment of the joints is set according to the different angles. The stress distributions of the deployment mechanism under different folding angles are obtained and shown in Figure 9; it could be clearly found that the maximum stress is always located on the connecting area of the rod and joint, which could be confirmed by the relevant study [20]. In other words, this connecting area belongs to the critical points and needs to be double-checked during the practical design.



(a) (b) (c) (d)

Fig.9. Stress distribution under different folding angle. (a) 0 degrees; (b) 60 degrees; (c) 120 degrees; (d) 180 degrees

Table 4 shows the maximum stress with different wall thickness at different deployment angles. It could be found that, with the increase of the angle, the maximum stress is also increased generally. Taking 2.5 mm wall thickness rod as example, the maximum stress is 97 MPa at 0 degree and 276 MPa when joint reached limited position.As the static design safety factor is set to be 2, it means the 2.5 mm and 3.5 mm wall thickness connecting rod could satisfy the design requirement. Combine the analysis in section III.1 and III.2, and considering from the angle of cost and parameter feasibility, the 2.5 mm wall thickness is chosen as the final design.

Table 4. Maximum stress with different wall thickness at different

Angle (°)	Maximum stress (MPa)		
	1 mm	2.5 mm	3.5 mm
0	137.3	97.3	86.2
30	82.7	43.1	33.2
60	89.1	44.9	34.6
90	206.1	174.9	144.9
120	255.5	197.5	167.5
150	302.1	227.1	207.1
180	366.9	276.9	231.8

IV. Conclusions

In this paper, a box structured satellite unfolding mechanism with a brand-new and self-actuated torsion joints is proposed, and the effective method to verify the feasibilityand optimization of the design is established. The system structure characteristics including static strength, thermal deformation and model frequency are investigated systematically under different parameter combinations, including wall thickness and material types. The analysis enables us to draw the following conclusions: (1) The modal analysis of deployment mechanism at folded and fully deployed state are analyzed, and first six order frequency and vibration shape are obtained. The result showed that, both under folded and fully deployed state, an optimum wall thickness couldbe obtained which plays as a key parameter to satisfy the design requirement and should not less than a certain value normally; (2) Although the protection of heat shield, the large temperature difference can cause the unacceptable deformation. The result of the thermal analysis shows that the material plays a more important role in affecting the thermal deformation than the structure parameter, and the value needs to be checked with the other factors, such as manufacture errors and stress deformation; (3) Under the torsional moment of the joints, the stress distribution of the deployment mechanism under different folding angle is investigated systematically, it could be clearly found that the maximum stress is always located on the connecting area of the rod and joint.Besides, the maximum stress is increased with the opening angle generally, and the minimum wall thickness of the rod is required according to design specification; (4) The optimal structure parameter and material type could be obtained by the above combined analysis, which offers an effective way for the design of box structured unfolding mechanism from the point of strength, deformation and natural frequency.

Acknowledgment

This work is Supported by the National Key Laboratory of Science and Technology on Helicopter Transmission (Nanjing University of Aeronautics and Astronautics) (Grant No. HTL-O-20K01) and Changzhou Science and Technology Planning Project (CE20225067).

References

[1] B.E. Campbell, and W. Hawkins, "A 11-meter deployable truss for the sea sat radar antenna," in *Proceedings of the 12th Aerospace Mechanisms Symposium*, Washington D.C, pp, 77-88, Apr. 1979.

[2] L.H. Jurgen, E.C. Christian, and W. Rudolf, "Design and verification of mechanisms for a large foldable antenna," in *Proceedings of the 23rd Aerospace Mechanisms Symposium*. Huntsville: Marshall Space Flight Center, pp.113-126, Mar., 1989.

[3] C. Compostizo, M. Domingo, and E. Urgoiti, "Low release force and high direct preload latches," in Proceedings of the *7th European Space Mechanisms and Tribology Symposium*, Noordwijk: ESTEC, pp. 61-66, 1997.

[4] D. Wright, "Design, integration and testing of an advanced synthetic aperture radar," in *Proceedings of the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*. Cambridge: IUTAM and IASS, pp. 467-476, 2000, doi: 10.1007/978-94-015-9514-8_48.

[5] X.R. Ma, D.Y. Yu, and J. Sun, "The researching evolvement of spacecraft deployment and driving mechanism," *Journal of Astronautics*, vol. 27, no. 6. pp. 1123-1131, Nov., 2006.

[6] Z.Q. Liu, S. L. Yang, and H. L. Pu, "Development and trend of space solar array technology," *Spacecraft Engineering*, vol. 27, no. 6. pp. 112-118, Dec., 2012, doi: 10.3969/j.issn.1673-8748.2012.06.018

[7] Y.Z. Dong, Y.Liu, and G.D. Wang, "Application status and future demand of materials for spacecraft structures," *Spacecraft Environment Engineering*, vol. 27, no. 1, pp. 41-44, Feb., 2010, doi: 10.3969/j.issn.1673-1379.2010.01.007

[8] X.G. Deng, S.Z. Zhou, and R. S. Xiong, “A optimize design bending mechanism of toroidalfocusing mirror,” *Acta Photonica Sinica*, vol. 35, no. 5, pp. 797-800, May, 2006.

[9] R.Q. Liu, D.K. Tian, and Z.Q. Deng, “Research actuality and prospect of structure for spacedeployable antenna,” *Mechanical Design*, vol. 27, no. 9, pp. 1-10, Sep., 2010, doi: 10.13841/j.cnki.jxsj.2010.09.018.

[10] T. Feng, Y.Z. Ji, and Y. Xiao, “Overview of Space-borne perimeter truss antenna and its application,” *Space Electronic Technology*, vol. 12, no. 2, pp. 22-28, 2015, doi: 10. 3969/j.issn.1674-7135.2015.02.007.

[11] S. Arita, I. Fukuta, and Y. Yamagiwa, “A proposal of new deployable space structure applying buckling,” in *AIAA/ ASCE/AHS/ASC Structures, Structural Dynamicsand Materials Conference*. Kissimmee, pp. 4741-4750, 2018, doi: 10.2514/6.2018-1952.

[12] J. Choi, D. Lee, and K. Hwang, “Design fabrication and evaluation of a passive deployment mechanism for deployable space telescope,” *Advances in Mechanical Engineering*, vol. 11, no. 5, pp. 1-14, May, 2019, doi: 10.1177/168781401985225.

[13] G. Latynsevsv, “Geometrical-optics computer model of metal-knitted mesh for calculations of solar pressure on space deployable antenna reflectors,” *Applied Optics*, vol. 58, no. 14, pp. 3815-3822, 2019, doi: 10.1364/AO.58.003815.

[14] I Yaguchi, and A Meguro, “A new design concept of light-weight and deployable membrane structures for space applications,” in *the Proceedings of the JSME Annual Meeting*, pp. 2056-2062, Sep., 2010. doi:10.1299/jsmemecjo.2010.5.0_401.

[15] L. Datashvili, “Foldability of hinged-rod systems applicable to deployable space Structures,” *Ceas Space Journal*, vol. 5, pp. 157-168, Nov., 2013. doi: 10.1007/s12567-013-0052-7.

[16] N. Medzmarlashvili, E. Medemariashvile, and D. Tsigna, “Possible options for jointly deploying a ring provided with v-fold bars and a flexible pre-stressed center,” *Ceas Space Journal*, vol. 5, pp. 203-210, Jun., 2013, doi:10.1007/s12567-013-0037-6.

[17] R. Dilip, and T. S. Nishchitha, “An analysis and design of the mechanisms used to deploy solar arrays aboard a small satellite using latest technology,”. *Eur. Chem. Bull*, vol. 12, no. 3, pp. 4008-4014, 2023, doi:10.31838/ecb/2023.12.s3.467.

[18] X. Wang, B. Li, and L. Li, “Modal optimization analysis of large-scale modular deployable structure for SAR”, in *International Conference on Mechanical Design: Advances in Mechanical Design (ICMD)*, vol. 55, pp. 1389-1400, 2017.

[19] J. S. Tao, and X. X. Lin, “Thermal analysis of large communication satellite platform in geostationary transfer orbit,” *Spacecraft Environment Engineering*, 2021, vol. 38, no. 5, pp. 495-502, 2021, doi:10.12126/see.2021.05.001.

[20] Y. Yuan, and H, Wang, “Static analysis and topology optimization of satellites deployment mechanism hinges,” in *2nd China International SAR Symposium (CISS)*, 2021, doi: 10.23919/CISS51089.2021.9652205.