A flexible structure thermal induced bending vibration

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ABSTRACT

According to satellite structure with slender rods or thin-walled, drastic temperature changes on orbit cause structure vibration, and further thermal vibration and even thermal induced bending vibration. The paper describes a thermal machine two-way coupling analysis developed based on existing commercial software. A flexible structure was analysis using the method. The analysis results indicate the amount of displacement of the flexible structure on orbit changes over time providing a reference for the follow-up work. The thermal machine two-way coupling analysis proposed in the paper provides a new idea for thermal induced bending vibration analysis of the flexible structure of satellites.

Keywords: A thermal machine two-way coupling analysis, Flexible structure, Thermal induced bending vibration.

1. INTRODUCTION

At present, the large-scale and complex spacecraft structure is developing. Its flexible accessories have the characteristics of large size, light weight and complex structure, such as large solar panels, trusses, flexible antennas, etc.These structures are easy to be excited in a complex space environment and generate flexible vibration. When the spacecraft enters and leaves the shadow area of the orbit, the flexible appendages not only bend and deform, but also generate flexible vibration. Therefore, the impact of thermally induced motion of the flexible appendages on the spacecraft performance must be considered as an important factor.

In the past, the thermally induced vibration characteristics of structures have been studied. These studies are based on the assumption that the temperature change is independent of the structural response, and the thermally induced vibration is always stable.However, when considering the coupling of temperature change and structural response, the thermal-induced motion may become unstable[1-2]. In 1969, Beam illuminated one side of the open thin-walled beam under the ground environment and observed the thermal flutter of the beam [3]. This unstable thermally induced vibration phenomenon also frequently occurs in practical engineering.Apollo 15 At the edge of the lunar orbit, the two astronauts observed the thermal flutter of the pole, and the end of the pole was equipped with scientific instruments.The astronauts recorded this phenomenon with a camera. The oscillation lasted for 3.5 minutes, the oscillation period was about 5.5 seconds, and the amplitude of oscillation was 0.67 inches, about 1.7 cm. Apollo 15 is the first space mission to directly observe thermal flutter phenomenon. As a result, people realized the seriousness of thermal flutter of space structures, and gradually began relevant theoretical analysis and experimental test research [4-5].

Yu analyzed the thermal bending and thermal flutter phenomenon of the beam model with end mass, and firstly pointed out that when the direction of heat flow is at a certain angle with the rod, only bending deformation can cause thermal flutter without torsion [6]. In 1971 and 1973, Augusti, Jordan and Das et al. pointed out that this conclusion was correct, but the sun orientation given by them was incorrect [7-8]. Augusti deduced the stability criterion, and pointed out that the motion stability is not only related to the azimuth of the heat flow, but also related to the damping of the structure and the heat absorption rate of the surface. Seibert analyzed the thermally induced motion of Euler Bernoulli beam and Timoshenko beam based on the thermal-structural coupling method. When only one-dimensional heat conduction is considered, the analysis result is not significantly different from that of thermal-structural uncoupling, and points out that the magnitude of thermally induced vibration of the beam is related to the length-width ratio of the beam. Xue Mingde et al.of Tsinghua University used the finite element method to analyze the thermal flutter of the thin-walled beam structure, and believed that the coupling effect of the spacecraft body attitude angle change and the thermal deformation of the flexible attachment on the incident heat flow was the direct reason for the thermal flutter of the spacecraft [9-10].

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Through the above literature research, it is found that the research on the thermal-induced motion coupling modeling of spacecraft with flexible appendages needs to be in-depth, but there is no literature on the three-axis model and the system modeling based on the thermal-structural coupling assumption.On the basis of predecessors, this paper proposes a bi-directional coupled thermal engine analysis method, which is used to analyze a flexible structure.

2. THERMAL MACHINE TWO-WAY COUPLING SYSTEM

2.1 Principle of thermal machine two-way coupling analysis

The thermo-mechanical two-way coupling system is developed on the basis of MSC. Patran/Nastran/Sanda/Thermoica four mature pre-and post-processing and force-thermal solver software.Through the iterative control of the interaction between mechanical deformation and temperature field distribution, the thermal flutter simulation analysis of steady state and transient state in the thermal environment of orbit is realized. Some functions related to the processing and exchange of thermal data and structural data as well as the call of the whole complex process are developed, which mainly include four parts: the thermal-structural data conversion interface, the node displacement-thermal data conversion interface, the thermal system node offset algorithm, and the data exchange frequency control module.

The schematic diagram of the working principle of the heat-engine two-way coupling system is shown in Fig. 1.

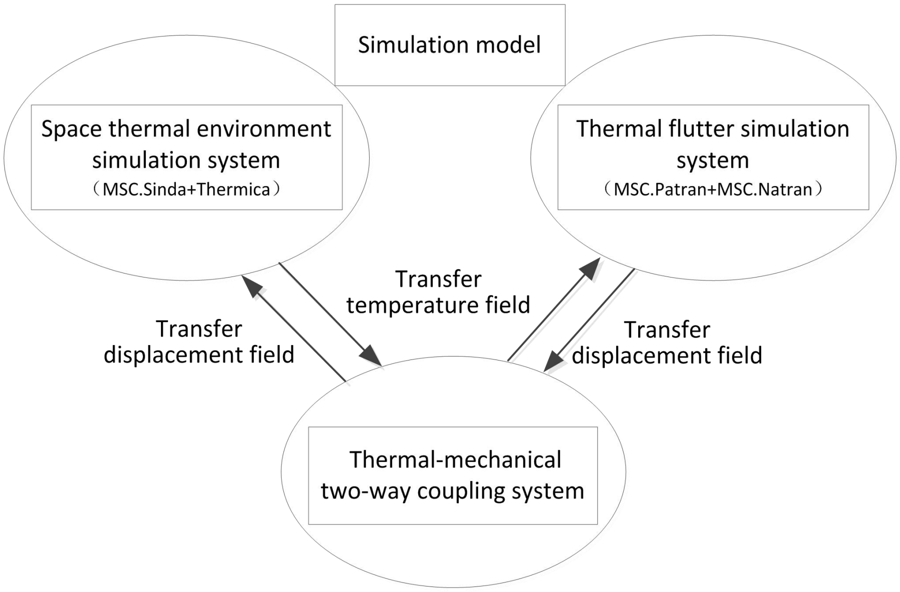


Fig. 1. Schematic diagram of working principle of thermo-mechanical two-way coupling system

2.2 Analysis method of thermo-mechanical two-way coupling system

2.2.1 Analysis model establishment

The mechanical analysis model of flexible structure is established by MSC. Patran. MSC Sinda uses MSC. Patran as the pre-processing software to pre-process the geometric model of the structure, so as to obtain the model required for thermal analysis. After the initial model of MSC Thermoica is generated by MSC Patran, the necessary parameters such as orbit data, attitude change data, etc. are defined by MSC Thermoica to calculate the orbital heat generated by radiation at different orbital positions during the satellite's in-orbit flight. The orbital heat information calculated by MSC Thermoica is directly imported into Sinda as the boundary condition for thermal environment calculation through the data interface between MSC Thermoica and MSC Sinda, The temperature distribution of satellite structure in the space environment can be obtained.

Patran is used as the pre-processing software of MSC Nastran to preprocess the geometric model of the structure, so as to obtain the model required for dynamic analysis, and MSC Nastran software is used to simulate the forced vibration of the satellite structure under different temperature loads.

2.2.2 Interpolation

The number of nodes in the thermal environment analysis model and the finite element model for dynamic analysis may be different, or even different mesh shapes and sizes may be used.Therefore, in the process of coupling calculation, it is necessary to use the thermal-mechanical two-way coupling system to automatically process or interpolate the grid values.

2.2.3 Thermo-mechanical two-way coupling analysis

The thermal environment data calculated by the space thermal environment simulation system is processed through the thermal-structural data conversion interface in the thermal-mechanical bidirectional coupling system, and then transferred to the thermal flutter simulation system. The thermal flutter simulation system takes it as a part of the input conditions, and carries out dynamic calculation after defining other parameter data.After dynamic calculation, the dynamic response results of the structure will be obtained. The node displacement-thermal data conversion interface interpolates the structural deformation data in the dynamic response, that is, the node displacement data. The thermal system node offset algorithm resets the node position, modifies the model data in the space thermal environment simulation system, and then performs the space thermal environment simulation based on the modified model data. This is done alternately to realize bidirectional coupling.

The data exchange frequency control module is mainly used to control the frequency of data exchange. The more data exchange times, the higher the calculation accuracy, but the higher the calculation cost.Therefore, according to the actual situation of the project, a reasonable control module is developed to control the data exchange frequency, so that the system can achieve the accuracy required by the project without too much calculation.

The conventional Patran, MSC Sinda and MSC Thermoica are used for thermal analysis during satellite flight to obtain the temperature changes of the structure at different times, and then the structural dynamic transient analysis is performed.In the process of structural dynamics analysis, if the amplitude is large, it will have a significant impact on the space heat flow. Therefore, it is necessary to stop the structural dynamics analysis after a short time of analysis, modify the model files of MSC Sinda and MSC Thermoica according to the deformed structure shape, recalculate the space heat flow and the space radiation matrix, and then recalculate the structure temperature distribution in the subsequent period of time, and change the structure according to the obtained temperature, Continue the structural dynamics analysis for Nastran restart. Similar analysis processes are carried out alternately until the end of the analysis. See Fig.2 for the flow chart of thermal-mechanical two-way coupling analysis.

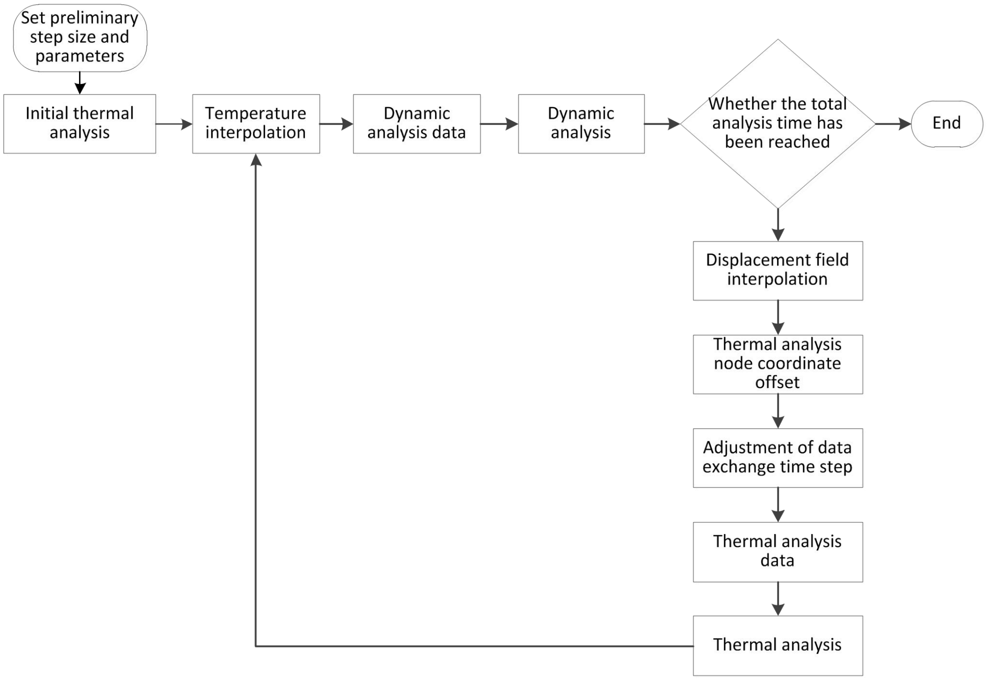


Fig. 2. Flow chart of thermal-mechanical two-way coupling analysis

3. BRIEF DESCRIPTION OF PHYSICAL MODEL OF FLEXIBLE STRUCTURE

The flexible structure is composed of chassis and root hinge, which can realize the functions of connecting and unlocking, expanding and locking support, and is installed on the satellite side wall panel. The simplified model of the flexible structure is shown in Fig. 3 below. The bi-directional coupling system of the heat engine is used to analyze the worst temperature changes that may occur in the front of the flexible structure and in the shadow area.

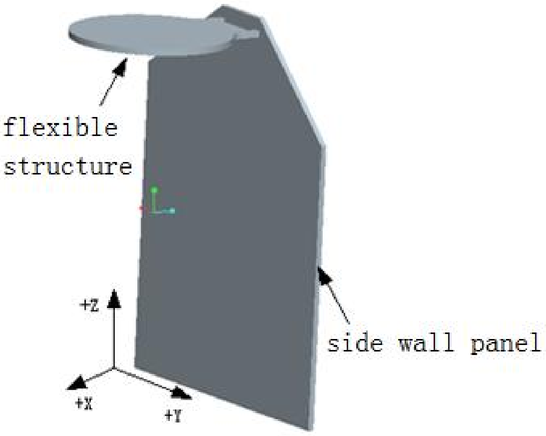
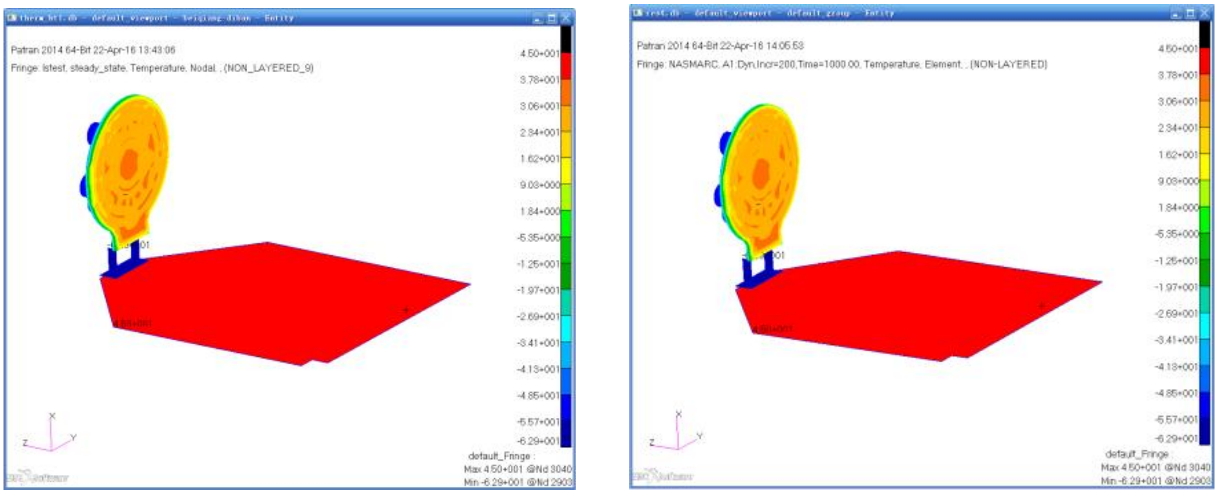


Fig. 3. Simplified schematic diagram of flexible structure deployment state

4. RESULTS AND ANALYSIS

4.1 Steady state analysis results and analysis

The temperature analysis results and the temperature distribution mapped from the stable temperature field to the mechanical model are shown in Fig. 4, The displacement nephogram under the stable state is shown in Fig. 5.From the analysis results, it is reasonable to reflect the steady-state temperature analysis and displacement of the antenna model. It can be seen from Fig. 5 that the maximum displacement of the flexible structure is 4.34mm during steady-state analysis.



(a) The temperature analysis result

(b) The temperature distribution mapped

Fig. 4. Steady state analysis results

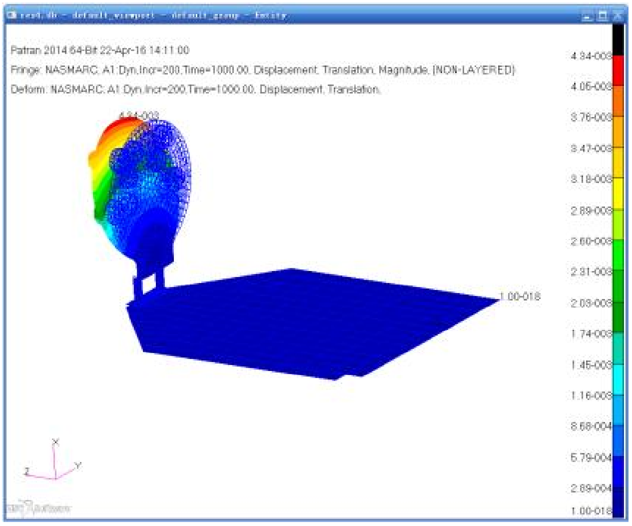

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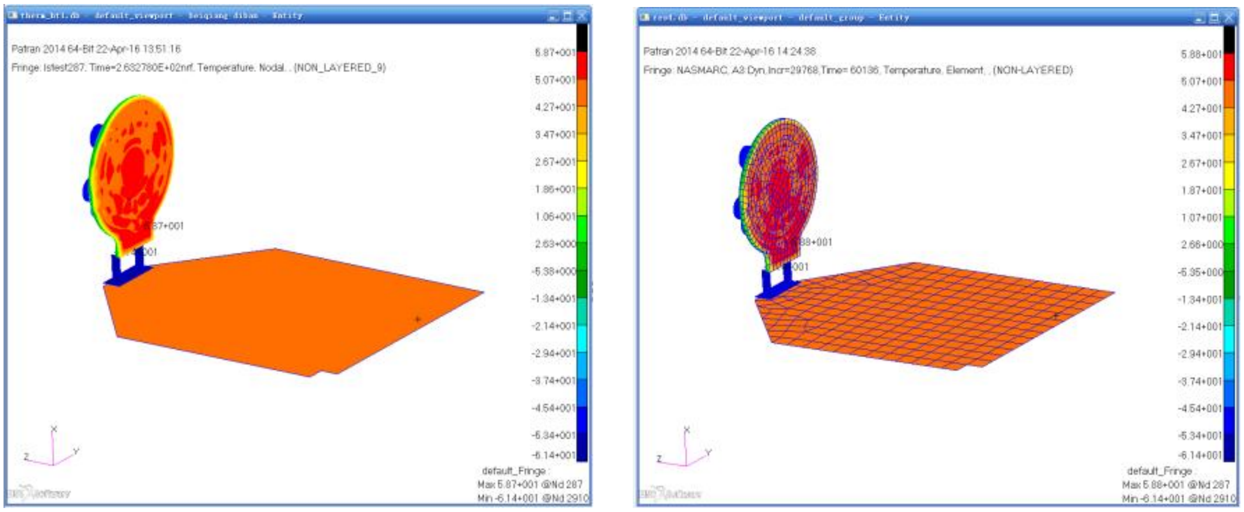
Fig. 5. The displacement nephogram under the stable state

4.2 Transient analysis results and analysis

The temperature analysis results of the flexible structure during the transient analysis and the temperature distribution of the temperature field mapped to the mechanical model are shown in the Fig. 6. The displacement nephogram under the transient state is shown in Fig. 7. From the analysis results, the temperature distribution and displacement of the antenna model are reasonably reflected.

Fig. 8 and Fig. 9 are the displacement versus time curves of the center and the most edge point of the antenna array. From the results in the figure, the maximum displacement at the center of the flexible structure is not more than 2.1mm, and the maximum displacement of the flexible structure is not more than 7.2mm. From the point of view of the transient allowable curve, it belongs to the convergence state, which means that the thermal flutter of the flexible structure in this paper will not occur.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(a) The temperature analysis result

(b) The temperature distribution mapped

Fig.6. Transient analysis results of flexible structures

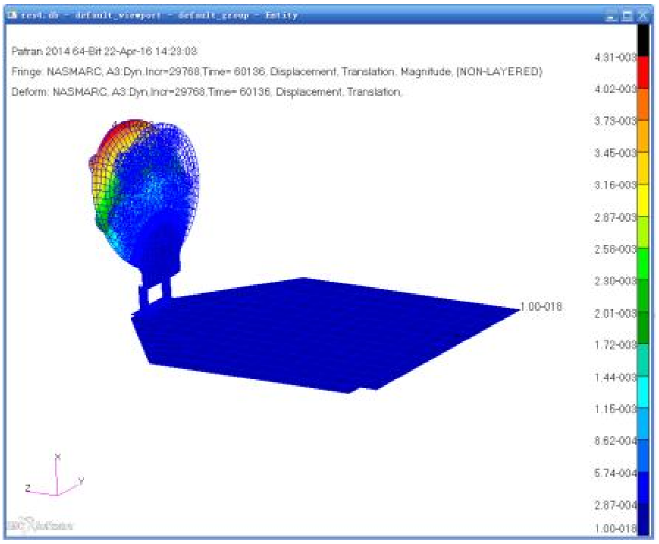

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Fig.7. The displacement nephogram under Transient state

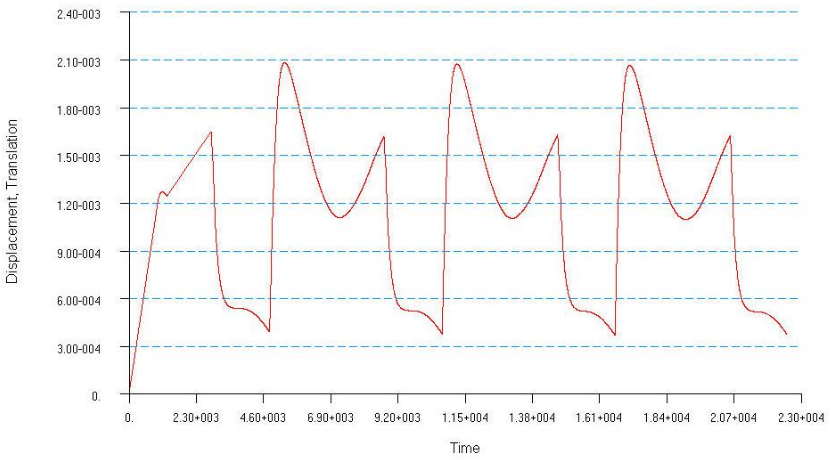

Fig.8. Displacement versus time curve of the center position of flexible structure

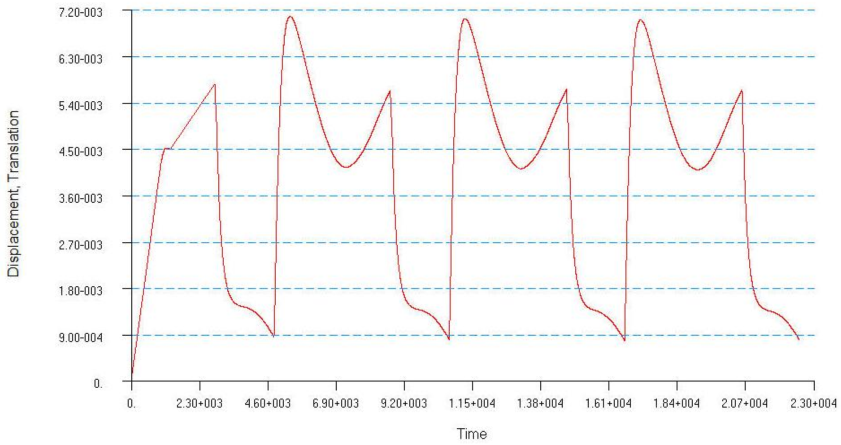

Fig.9. Displacement versus time curve of the most edge point of flexible structure

5. CONCLUSIONS

This paper introduces a bi-directional coupled thermal engine analysis method based on the existing commercial software. Using this method, the on-orbit thermo-mechanical coupling analysis of a satellite flexible structure is carried out, and the following conclusions can be drawn:

1. Through the thermal flutter analysis of flexible structures in this paper, the feasibility of the thermal-mechanical bi-directional coupling analysis method is verified;

2. The maximum displacement of the flexible structure is 7.2mm, and it is in the convergence state. Therefore, the flexible structure will not have thermal flutter;

3. The research method in this paper can provide a solution for the analysis of thermal flutter in orbit.

REFERENCES

[1] Goldman, R. L., Instability of a gravity gradient satellite due to thermal distortion[R]. NASA (1975).

[2] Merrick, V. K., Instability of slender thin-walled booms due to thermally induced bending moments[R]. NASA (1970).

[3] Beam, R. M., On the phenomenon of thermoelastic instability thermal flutter of booms with open cross section[R]. NASA (1969).

[4] Ko, K., Kim, J., Thermally induced vibrations of spinning composite structures[C]. 43rd Structures, Structural Dynamics, and Materials Conference, Reston, VA, American (2002).

[5] Ko, K., Kim, J., Thermally induced vibrations of spinning thin-walled composite beam[J]. AIAA Journal. 41(2): 296-303 (2003).

[6] Yu, Y., Thermally induced vibration and flutter of a flexible boom[J]. Journal of Spacecraft and Rockets. 6(8): 902-910 (1969).

[7] Augusti, G., Comment on Thermally induced vibration and flutter of flexible booms[J]. Journal of Spacecraft and Rockets. 8(2): 202-204 (1971).

[8] Jordan, P. F., Comment on "Thermally induced vibration and flutter of flexible boom[J]. Journal of Spacecraft and Rockets. 8(2): 204-205 (1971).

[9] Yao, H. M., Xue, M. D., Ding, Y., Thermally induced vibration analysis of large space structures using the finite element method[J]. Journal of Tsinghua University (Science And Technology), 42(11): 1524-1527 (2002). (In Chinese)

[10] Cheng, L. J., Xue, M. D., Tang, Y. H., Yao, H. M., Thermal-Dynamic Analysis of Large Scale Space Structures by FEM. Chinese Journal of Applied Mechanics. 21(2): 1-9 (2004). (In Chinese)