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Simulation and Analysis of Flexible Solar Panels' Deployment and Locking Processes

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Abstract: To predict the attitude of satellite during the whole deployment process and evaluate the locking impact, a numerical flexible model of a certain satellite associated with four flexible honeycomb solar panels was established. The flexible solar panel was modeled by the finite element analysis (FEA), and the motion equations were derived by Lagrangian formulation. The locking process was based on the method of Hertzian contact, which enables one to predict the locking impact on the satellite and the subsequent oscillation of solar panels. The results reveal that locking operation has great impact on the attitude of the satellite, and the angular acceleration of satellite reaches $22.03\,^{\circ}/\mathrm{s}^2$ at the locking moment; the flexible solar panels model is feasible to predict the accurate response of the satellite during deployment and the oscillation of solar panels; the instantly impulsive force occurred during locking process is about 1.5 kN and the changing time is nearly 0.32 s. It provides an effective approach to present the flexible solar panels' deployment process and evaluate the locking impact.
Key words: flexible solar panels; deployment; locking impact; simulation
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Introduction

Solar panels are ones of the critical subassemblies for a satellite, providing the necessary energy for satellite orbiting. These structures are originally in stowed configurations when launched and are deployed into their full size in space. The deployment process of solar panels is a highly dynamic movement, which was predicted to have great impact on the attitude of satellite[1]. In the end of the deployment, a locking operation is performed to ensure relatively moving the bodies locked in the proper positions. The operation will result in a redistribution of the total momentum, thus lead to impulsive forces and moments on the system. The induced impulsive forces may incur a large vibration in the lightweight flexible solar panels and may also cause damage to the mechanical components. Therefore, it is of importance scientific focus to predict the attitude change of satellite in the process of solar panels deployment and evaluate the locking impact.

It is really difficult and costly to simulate the orbiting deployment of solar panels by means of experiments on the ground because of the influence of gravity and the air resistance[2,3]. In literature, Walter[4] analyzed the deployment mechanisms of solar panel of a satellite based on the multi-body software Adams, both the satellite and the solar panel were built as rigid bodies. Oskar *et al*[5,6] preformed the simulation of deployment of flexible solar panels. Bai *et al*[7] analyzed the attitude effects in the process of flexible solar panels deployment and locking. However, there is no available paper on modeling of flexible honeycomb solar panels, the locking operation at the joints and the solar panels oscillations resulting from the locking impact. This paper establishes a numerical model of a certain flexible satellite and solar panels. The solar panels' deployment process and locking impact are simulated when the satellite flies into orbit. Especially, it is focused on the analysis of the attitude of satellite and the flexible solar panels oscillation resulting from the locking impact.

1 System Description and Modeling

The presented satellite associated with flexible solar panels is a typical large flexible multi-body system. The model consists of the central body of the satellite, along with a yoke and four flexible bodies of solar panels, which are connected by revolute joints and deployment structures. The whole deployment process lasts 100 real-time second. The deployment contains the two deployment phases, primary deployment and secondary deployment as shown in Fig. 1. The deployment process continues until the whole solar panels are deployed completely and the deployed state is locked by the locking structures.

1.1 Deployment and Locking Structures

The geometrical models of deployment and locking structures are designed as shown in Fig. 2 at stowed and deployed positions, respectively. The male-articulation

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and the female-articulation are connected by a revolute joint. Deployment spring attached to the joint has certain preload torque providing the energy to drive the solar panels movement. The locking frame is connected to female-articulation by a revolute constraint, on which positioned a locking spring to provide the locking energy. Locking arm is fixed to locking frame. During the process of the deployment, the male-articulation and the female-articulation rotate relatively driven by the preloaded deployment spring. The deployment process commences relative rotation of the panels over two inter-panel hinges along the panel fold lines. Meanwhile, the locking arm glides on the surface of male-articulation driven by the preloaded locking spring. Eventually, the deployment and locking processes are accomplished when the locking arm glides into the locking groove in male-articulation.

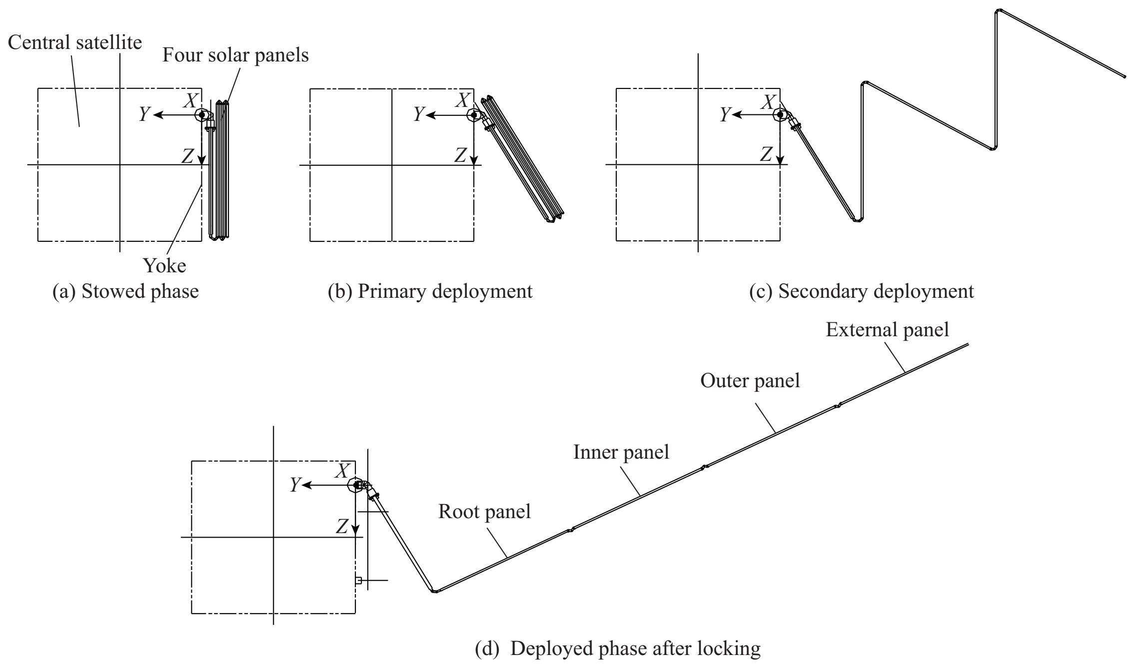


Fig. 1 The whole deployment process of solar panels for a certain satellite

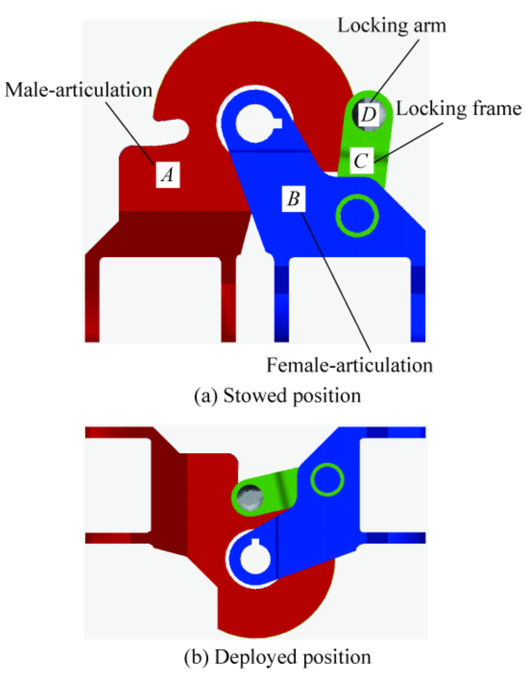
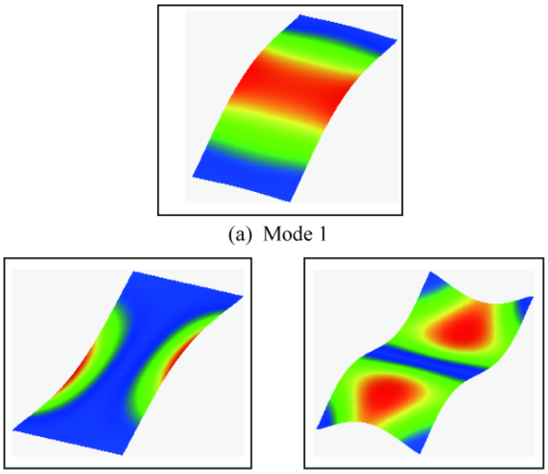


Fig. 2 Deployment and locking structures at stowed and deployed positions

1.2 Flexible Solar Panels

The solar panel is made of an aluminum honeycomb with carbon fibre face sheet (carbon fibre reinforced plastics) on both sides, which is characterized by large dimensions, low mass to size ratio, large inertias and relatively low structural rigidity[8]. It should be modeled as flexible body in accord with the engineering application. In Adams, flexible bodies are defined by importing modal data as calculated by external FEA program[9]. Modal flexibility assigns a set of mode shapes (frequently eigenvectors) to a flexible body. The flexible body modeling element designates a system state variable to each eigenvector and calculates the relative amplitude of each eigenvector during a time analysis. Modal neutral file (MNF) is used to transfer frequency and amplitude data from a FEA code to Adams environment. Craig-Bampton modes, required for defining constraint connections to flexible bodies, are transferred from the FEA code by defining master nodes. For each master node, constraint mode information is stored in the MNF. The model is based on equivalent method[10]. Nastran is adopted to generate FEA model of a panel as it is good at modeling composite laminate material. The first three modes of a flexible solar panel are calculated, as shown in Fig. 3. The four corner nodes were selected as master nodes. The flexible solar panel's damping is applied by default. Each solar panel has the same geometric dimension of 3 m×1.8 m×0.25 m and the physical parameter mass of 16 kg.



(a) Mode 1

(b) Mode 2 (c) Mode 3

Fig. 3 First three modes of a solar panel (5.9 Hz, 13.8 Hz, 17.8 Hz)

1.3 Initial and Boundary Conditions Application

The deployment is simulated using the multibody program Adams as it can realistically simulate the space environment. Boundary conditions are applied on the model involving three types:

(1) Constraints. Revolute joints between male-articulation and female-articulation, locking frame and female-articulation; the coupled joint between revolute joints to ensure the deployment is synchrony.

(2) Force. The deployment drive force—deployment spring, the locking drive force—locking spring. The torque of deployment and locking spring is

$$T = -C\mathrm{d}\theta/\mathrm{d}t - K(\theta - \theta_0) + T_0,$$

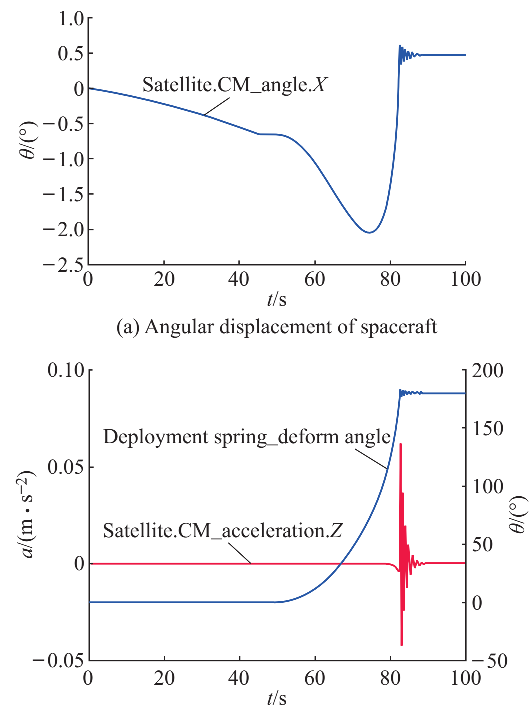
where, T is the working torque; C is the damping coefficient; K is the stiffness coefficient; θ is the deform angle; T_0 is the preload torque; θ_0 is the initial angle at the preload torque. The parameters of the deployment spring are $K = 0.44$ (N·mm)/°, $C = 1$ (μN·ms)/°, $T_0 = 0.16$ N·m, $\theta_0 = 0°$.

(3) The contact phenomenon during impact is determined by Hertzian contact stress between locking arm and female-articulation. The contact type is solid-to-solid. The stiffness of contact force is 10 GN/m; the penetration depth is 0.2 mm.

2 Results and Analysis

2.1 Change of Satellite Attitude

Figure 4(a) shows the angular displacement of center of mass (CM) of the satellite in direction X. The variation of the angular displacement during the primary deployment is quite steady along single direction, while during secondary deployment the angular displacement is relatively large and the direction changes. When it comes to locking, the angular displacement reaches 2.05°. After that, the angular displacement declines because of the locking impact and the solar panels oscillation. Finally, as the angular momentum keeps conservation, the angular displacement of spacecraft tends to stability. Figure 4(b) shows the deployment angle and the acceleration of spacecraft. The locking impact on the attitude of spacecraft can be distinctly detected, the acceleration of center of mass reached 62.1 mm/s^2. Figure 5 is the strain change of flexible panels at the locking moment. And Table 1 shows the maximum change of the physic quantity described the attitude of satellite along directions.



(a) Angular displacement of spaceraft

(b) Acceleration of spacecraft

Fig. 4 Attitudes of satellite during the whole deployment process

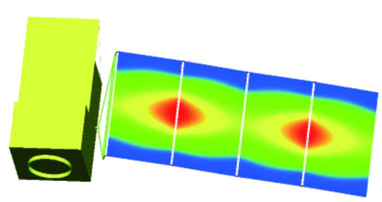


Fig. 5 Strain of flexible panels at the locking time

Table 1 Maximum change of the physic quantity described the attitude of satellite

Attitude	X-direction	Y-direction	Z-direction
Displacement/m	2.55×10^{-4}	0.1108	0.0304
Velocity/$(\mathrm{m\cdot s^{-1}})$	2.02×10^{-5}	0.0062	0.0042
Acceleration/$(\mathrm{m\cdot s^{-2}})$	9.25×10^{-5}	0.0357	0.0621
Angular displacement/(°)	2.05	0.026	0.092
Angular velocity /$(^\circ\cdot\mathrm{s^{-1}})$	1.60	6.99×10^{-4}	0.005
Angular acceleration /$(^\circ\cdot\mathrm{s^{-2}})$	22.033	0.09	0.035

2.2 Oscillations of Flexible Solar Panels

The velocity of CM of outer panels and external panel is shown in Fig. 6. The extracted simulation time is from the secondary deployment to the end of the whole deployment, namely, from 50 to 100 s. During the secondary deployment before locking impact happened, the velocity of CM of external panel is greater than that of outer panel. After locking, the curve is completely overlapped, as shown in Fig. 6. It reveals that the two panels turn into a single flexible cantilever beam and provide another demonstration, the designed locking structures are capable. The oscillations of flexible solar panels are clearly shown in the Fig. 6. The amplitude and the frequency of the oscillation are related to the preload of locking spring, the stiffness and a damping of contact force, and the damping of the solar panels.

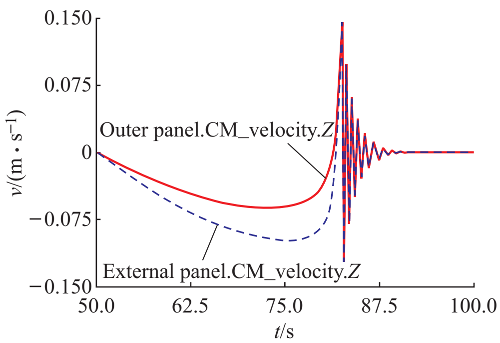


Fig. 6 The oscillations of flexible solar panels

2.3 Locking Impact Analysis

Figure 7 shows the locking impact during the deployment process. In the primary deployment and the phase of secondary deployment before locking moment, the contact force is nearly zero. It is the stage that the locking arm gilding on the surface of male-articulation. Then the locking impact happens at the moment of the locking arm gilding into the locking groove of male-articulation. The contact force has an instant step, the maximum force reaches 870.1 N. Under the combined drive forces of groove squeezing and the locking spring, the locking arm oscillates in the groove, and the contact force is −715.2 N when it arrives at the root of groove. The internal is only 0.32 s. Due to the damping of locking spring and the solar panels, the contact force comes to zero after a decline process. The factors to determine on the locking impact are the preload torque of deployment spring, the geometry characteristic of the groove of female-articulation and the damping of flexible solar panels.

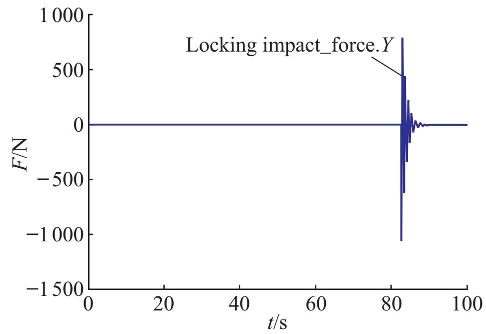


Fig. 7 Locking impact

3 Conclusion

The paper has presented the methodology on modeling and simulating the deployment and locking processes of flexible solar panels for a satellite. It revealed that the deployment process of flexible solar panels impacts the attitude of satellite. In term of the model presented in the paper, several conclusions are drawn from the simulation and analysis:

In the deployment of solar panels, the attitude of the satellite angular displacement change reached 2.05°. The locking movement has great impact on the attitude of satellite. The angular velocity and angular acceleration are 1.6 °/s and 20.5 °/s^2, respectively. The locking impact should be therefore included during the analysis the deployment of solar array. Solar panels considered as flexible model is necessary to predict the accurate response of the satellite during deployment the oscillation of the solar panels after locking. The instantly impulsive force occurred during locking process is about 1.5 kN and the changing time is nearly 0.32 s. It is related to the preload torque of deployment spring, the geometry characteristic of the groove of female-articulation and the damping of flexible solar panels.

The method is an effect approach for the solution of highly dynamic mechanical problems. It can be employed in solar panel array design, and the deployment and locking structure optimization. It also provides a guidance to control the attitude motion of solar panel array in the initial stage when a certain satellite flies into orbit.

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