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Dynamic analysis of spinning solar sails at deployment process

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Abstract The spinning deployment process of solar sails is analyzed in this study. A simplified model is established by considering the out-of-plane and in-plane motions of solar sails. The influences of structure parameters, initial conditions, and feedback control parameters are also analyzed. A method to build the geometric model of a solar sail is presented by analyzing the folding process of solar sails. The finite element model of solar sails is then established, which contains continuous cables and sail membranes. The dynamics of the second-stage deployment of solar sails are simulated by using ABAQUS software. The influences of the rotational speed and out-of-plane movement of the hub are analyzed by different tip masses, initial velocities, and control parameters. Compared with the results from theoretical models, simulation results show good agreements.

1. Introduction

Solar sails have gained widespread attention for several decades because of their significant advantages, including small package volume, low energy consumption, and low cost.[1–4] The development of a solar sail spacecraft involves a wide range of technologies, and the manner in which to deploy a large area sail in space is a key design issue.[5] Among the proposed several deployment methods, the spinning deployment of solar sails is an ideal technique that utilizes centrifugal force to deploy sail membranes.[6] As a successful case, the Japan Aerospace Exploration Agency launched a spinning-deployable spacecraft named IKAROS on May 21, 2010.[7] IKAROS succeeded in deploying a 20 m span solar sail from a wrapped status and managed to pass by Venus with the help of solar radiation pressure.[8]

Given the high flexibility of the membrane structure, rigorous control strategies must be used to avoid the entanglements or yo-yo-like oscillations caused by the repeated coiling and uncoiling of membranes to and from the hub.[9–11] Gardsback et al.[12] reviewed the existing control strategies for the centrifugal deployment of space webs. They concluded that stable deployment can be obtained by using the method of applying torque to the center hub, namely, the Melnikov–Koshelev law.[10] Gardsback and Tibert presented a simplified hub-cable-mass model to qualitatively analyze the deployment dynamics in which out-of-plane motions were neglected.[13] Finite element (FE) calculation using LSDYNA was proposed

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to simulate the dynamical response of the real deployment system.[14] Shirasawa et al. applied the Multi-Particle Method (MPM) to the dynamic analysis of IKAROS, and approximated the solar membrane by using the network of springs with lumped masses.[15] Haraguchi et al. used the model of MPM to validate the control laws for the spinning deployment of a solar sail system.[16,17]

A two-step deployment strategy was applied for the IKAROS. First, the four folded arms were slowly released from the tip by rotating the stopper relative to the hub. At the second stage, the four stoppers were released to deploy the entire membrane. A large disturbance at the beginning of the second-stage deployment was observed, which caused significant oscillations during the second-stage deployment.[18] Miyazaki et al. developed an FE model to analyze the nutation motion at first-stage deployment.[18,19] Severe out-of-plane oscillations were also observed at the beginning of the second stage during the ground simulation tests conducted by Zhou et al.[20]

This study aims to analyze the deployment dynamics during the second stage under the initial perturbation of the instantaneous spreading out of the membrane. Following the work of Gardsback and Tibert[13], a simplified hub-cable-mass model, including out-of-plane motion, is established to qualitatively analyze the effect of control parameters. An FE model of the solar sail is then established. This model contains continuous cables and sail membranes. The second-stage deployment of a solar sail is simulated by using ABAQUS software. The influences of the rotational speed and out-of-plane movement of the hub are analyzed under different tip masses, initial velocities, and other factors.

2. Analytical model analysis

At the end of first-stage deployment, the membrane arms together with the center hub rotate stably with the same rotational speed. At the beginning of the second-stage deployment, the membrane is instantaneously deployed when the stopper is released. For the conservation of angular momentum, the rotational speed of the membrane becomes lower than that of the center hub, thus causing the in-plane oscillations of the system. When the membrane is spread from a zigzag folding pattern to a plane, out-of-plane motion is produced. To stabilize the deploying process, the system is controlled by applying a torque to the center hub with torque control law. This law implies that the torque increases when the hub angular velocity decreases and vice versa. To estimate the oscillations and control method, a simple analytical model is used to describe the deployment dynamics qualitatively. The development of our analytical model follows the model presented by Gardsback and Tibert.[13] The out-of-plane motions are included in our analytical model. The following assumptions are also made:

The cables were supposed to be straight and were deployed symmetrically relative to the central axis.

The motion of the membrane, cable, and tip mass is dominated by the cable and tip mass. The effect of membrane motion is equivalent to the additional mass at cable tip.

Each part of the sail motion is the same (symmetric).

(1) The mass of the hub is higher than the sum of attached membrane, cable, and tip mass; hence, the hub is assumed fixed except its rational freedom in OZ axis.
(2) The motion of the membrane, cable, and tip mass is dominated by the cable and tip mass. The effect of membrane motion is equivalent to the additional mass at cable tip.
(3) Each part of the sail motion is the same (symmetric).

The analytical model is described in Fig. 1. With the assumption of symmetric motion, only one part of the sail is considered for analysis. The entire sail consists of four parts. The coordinate system $OXYZ$ is fixed with the center hub of the solar sail. In this model, the center hub is only free in its rotational motion by the OZ axis. The distance from the tip to the center hub edge is the length of the cable. This model can describe the relative position and motion of the center and sails by lengths, angles, and velocities. The system can be described by three degrees of freedom, the angular velocity of center hub ω, the relative in-plane rotational angle of the cable ϕ, and the out-of-plane rotational angle ψ. In this study, r is the hub radius and L is the cable length.

2.1. Equations of system dynamics

According to Lagrange's law of motion, the dynamic equations of the system can be described as follows[20]:

$$\ddot{\phi}=\frac{r(\dot{\omega}\cos\phi-\omega^2\sin\phi)+L\dot{\omega}\cos\psi+2(\dot{\phi}-\omega)(L\dot{\psi}\sin\psi+\dot{L}\cos\psi)}{L\cos\psi} \tag{1}$$

$$\ddot{\psi}=\frac{g\cos\psi-2\dot{L}\dot{\phi}-mL(\omega-\dot{\phi})^2\sin\psi\cos\psi-r\omega^2\sin\psi\cos\phi-r\dot{\omega}\sin\psi\sin\phi}{L} \tag{2}$$

$$\begin{aligned}F=m[&r\omega^2\cos\phi\cos\psi+r\dot{\omega}\sin\phi\cos\psi+L(\omega-\dot{\phi})^2\\ &\times\cos^2\psi-\ddot{L}+L\dot{\psi}^2+g\sin\psi]\end{aligned} \tag{3}$$

where g is the gravity coefficient for ground tests, which is zero on orbit; m is the equivalent mass of the membrane, cable, and tip mass system, and F is the tension force in the cable. The equivalent mass is determined by total inertial moment of the membrane, cable, and tip mass system.

During the deployment, an external moment M is applied to the center hub by the actuators that are installed on the hub edge. Accordingly, the hub dynamic equation can be described as

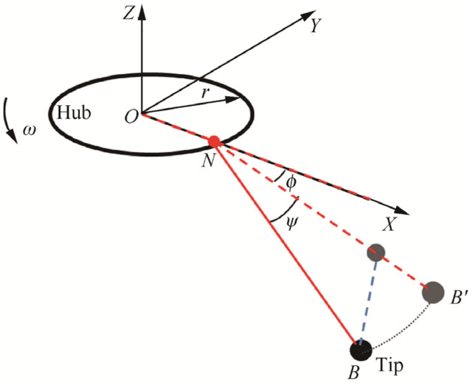

Fig. 1 Analytical model for a point mass.

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