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Development of Deployment System for Small Size Solar Sail Mission

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JAXA is studying solar power sail as a new propulsion engine for deep space explorations. In this paper, the sail shape and equipment layout for small-sized solar power sail mission are proposed. The deployment method, sequence and mechanism are also introduced. The deployment motions are analyzed by numerical simulations using multi-particle models in order to verify the deployment. They are compared with the results calculated by finite element method models.

Key Words: Solar Sail, Deployment System, Multi-particle Model

1. Introduction

Solar sail is a propulsion engine using no fuel because it can receive photon momentum. Japan Exploration Agency (JAXA) proposes solar power sail as a new propulsion engine for deep space explorations. It can be a hybrid engine, if the ion-propulsion engines, whose specific impulse is very high, are driven by the solar cells on the membrane.

JAXA is studying two missions to demonstrate solar power sail as shown in Fig. 1. Small-sized solar power sail in the early 2010s is the front-loading measures for risk reduction. The minimum success criteria are the deployment of the sail whose diameter is 20m and electric power supply using the solar cells on the membrane. The full success criteria are the acceleration and navigation using photon sail for the first time. On the other hand, the medium-sized solar power sail in the mid-2010s integrates ion-propulsion engines with solar power sail of diameter 50m. The destinations of the spacecraft are the Jupiter and the Trojan asteroids.

Some kinds of deployment methods have been investigated[1,2]. JAXA is studying the spinning type, in which the membrane is deployed and maintained flat by the centrifugal force. This method is expected to be realized with simpler and lighter-weight mechanism than other ways, because it does not require rigid structural elements. The authors have been demonstrating it. The dynamic deployment of ϕ10m sail was performed successfully using an S-310 sounding rocket at 08/2004[3]. The static deployment of ϕ20m sail was demonstrated using a high altitude balloon at 08/2006[4].

In this paper, the sail shape and equipment layout for small-sized solar power sail mission are proposed. The deployment method, sequence and mechanism are also introduced. The deployment motions are analyzed by numerical simulations using multi-particle models in order to verify the deployment. They are compared with the results calculated by finite element method models.

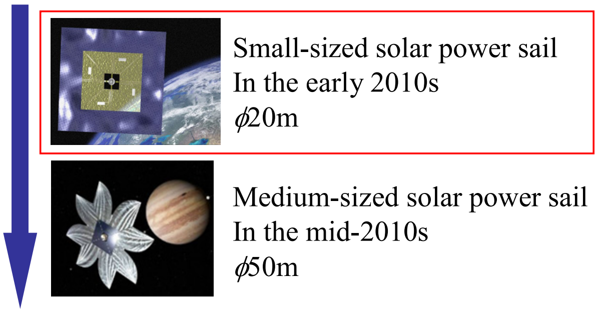


Fig. 1. Solar power sail missions

2. Proposals for Small-Sized Solar Power Sail

2.1. Sail

The sail shape and equipment layout is proposed as shown in Fig. 2.

Membrane: The shape of the membrane is a square whose diagonal is 20m. It consists of four trapezoid petals. The direction of folded lines is normal to that of centrifugal force. It is made of polyimide whose thickness is 7.5μm. It is simple and easy to product relatively.

Tether: The membrane should not be contact on the main body after the deployment. They are connected by tethers.

Tip mass: Four masses are attached on the four tips of the membrane. It adjusts the centrifugal force and the inertial momentum of the membrane.

Solar cell: Solar cells are attached on the membrane partly. The area ratio is 10%.

Steering device: Eight variable reflectance elements are loaded near the tips of the membrane. The control of the spin direction and rate can be performed using them as shown in Fig. 3[5].

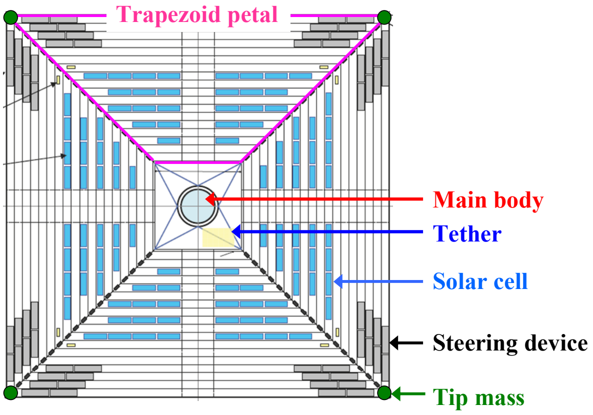


Fig. 2. Sail shape and equipment layout

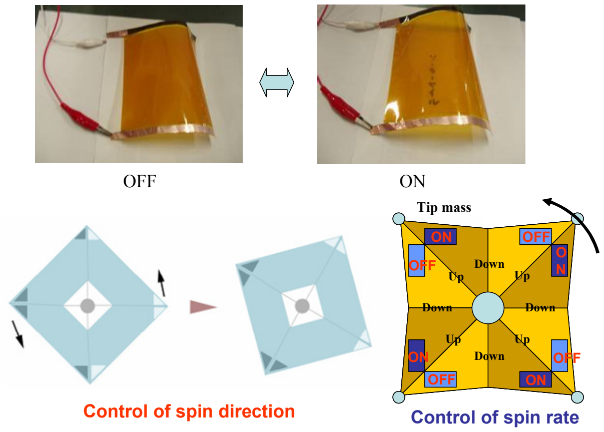


Fig. 3. Steering device

2.2. Deployment

The deployment method of the sail is proposed as shown in Fig. 4. It consists of two stages. In folded configuration, each petal is line-shaped and rolled up around the satellite as shown in (1). In the first stage, the rolling petals are extracted like a Yo-Yo despinner, and form a cross shape. The shape is maintained by stoppers as shown in (3). In the second stage, the stopper is released and each petal is developed to form a square shape. If the first stage deployment is performed dynamically, each petal should be twisted around the main body just after the deployment. Therefore it needs to be deployed statically at the first stage. On the other hand, it is supposed to be deployed dynamically at the second stage.

This paper introduces two types of deployment mechanism. Fig. 5 shows a continuous deployment mechanism. The Yo-Yo despinner is restricted by a stopper. Each stopper rotates relative to the main body slowly to deploy each petal continuously at the first stage. The second stage deployment is started by releasing four stoppers after the first stage deployment. Fig. 6 shows a divided deployment mechanism. Each petal is held by several stoppers, which are aligned properly. It was deployed step by step at the first stage by releasing stoppers 1-5 in number order. It was deployed dynamically at the second stage by releasing stopper 6. This mechanism is simple relatively. The deployment motion at the first stage is, however, complicated.

The deployment sequence is defined as follows.

1) Separation from rocket with slow spin (2rpm)
2) Release of launch lock
3) Spin up using RCS (2rpm -> 36rpm)
4) First stage deployment (36rpm -> 14rpm)
5) Second stage deployment (14rpm -> 5rpm)
6) Spin down using RCS (5rpm -> 2rpm)
7) Control of spin direction and rate using steering devices

The spin rate is decreased at the first and second stages, because the inertial momentum of the sail is increased.

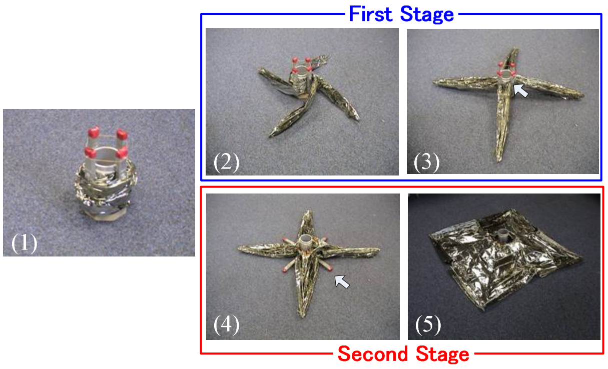
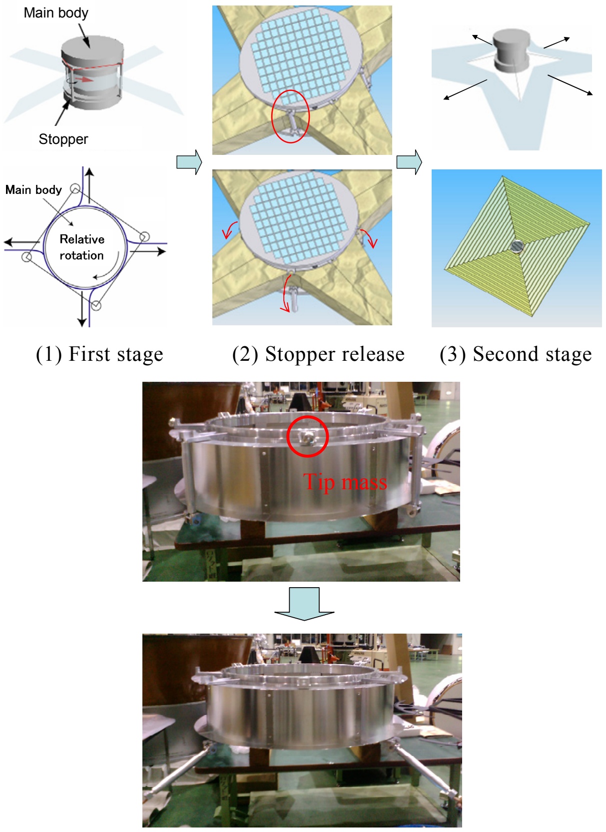
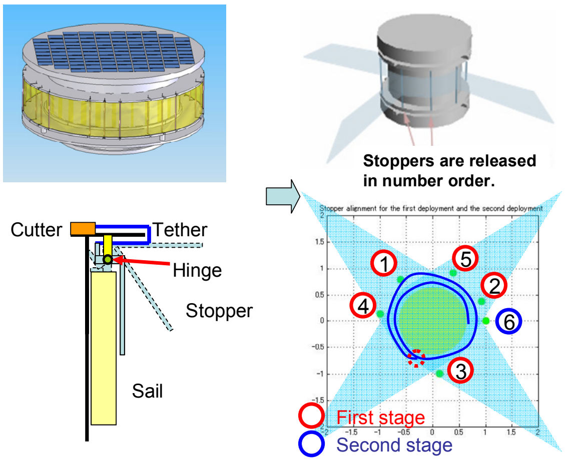


Fig. 4. Deployment method



(1) First stage (2) Stopper release (3) Second stage

Fig. 5. Continuous deployment mechanism



(1) Folded sail (2) Stopper release

Fig. 6. Divided deployment mechanism

3. Deployment motion analysis by numerical simulations

3.1. Modeling

Analytical models of the first and second stage deployments are shown in Fig. 7. The parameters of the main body and the sail are set as follows.

<Main body> rigid cylinder model
Weight: 285kg
Inertial moment:

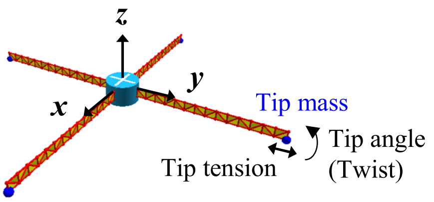
$$\{I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{yz}, I_{zx}\} = \{45.1, 44.2, 63.8, 0.58, 0.35, -1.63\}[\mathrm{kgm}^2]$$

Diameter: 1.26m
Offset of center of mass:

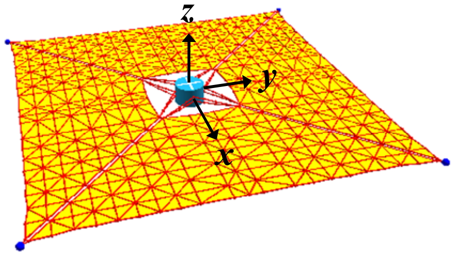
$$\{x, y, z\} = \{9.28, -3.73, -50.0\}[\mathrm{mm}]$$

<Sail> multi-particle model
Weight: 17kg
(including four tip masses whose weight is 0.5kg*4)
Inside diagonal: 4.5m
Outside diagonal: 20m
Young's modulus: 3.2GPa

Tip angles (in-plan and out-of-plane) are defined as shown in Fig. 8.



(a) First stage



(b) Second stage

Fig. 7. Analytical model

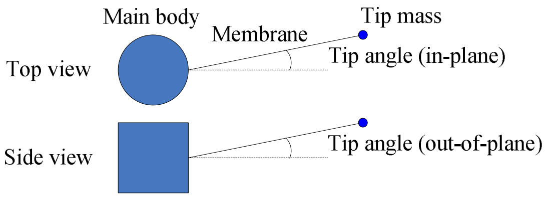


Fig. 8. Definition of tip angles

3.2. Results of numerical simulations

Considering the deployment sequence, the nominal conditions of numerical simulation for the first and second stages are set as follows.

<First stage deployment>
Initial spin rate: 36rpm
Initial nutation angle: 5deg
Damping: none
Deployment method: continuous deployment (120sec)

<Second stage deployment>
Initial spin rate: 7.7rpm
Initial nutation angle: 5deg
Deployment unbalance: none
Damping: 0.0000002 (tether)
Deployment method: dynamic deployment

Fig. 9 shows the pictures of deployment motion at the first and second stages.
These conditions are changed as follows. The graphs of spin rate, attitude angle and tip angles (in-plane and out-of-plane) of the first and second stages are shown in Figs. 10 and 11.

<First stage deployment>
(a) In the case of nominal condition.

The spin rate is decreased because the inertial momentum of the sail is increased during the continuous deployment (0-120sec), and it becomes constant after the deployment. The attitude angle and tip angles (in-plane and out-of-plane) are oscillating. They are not converged because the sail damping is not considered. The tip angle (in-plane) is increased just after the continuous deployment (120sec). It is, however, not more than 20deg. Then each stopper does not collide with each petal if it was released. The tip tension is also oscillating. The average is nearly equal to the centrifugal force of the tip mass.

(b) In the case using FEM (finite element method) model.

In this model, each branch is modeled by the finite Timoshenko beam elements with variable element length. The axial, bending, transverse-shear and torsional stiffness of each branch are taken into account in this model. The number of the beam element is fixed during the first stage deployment. The unstressed length of each beam element elongates gradually, so that the length of the branch is extended during the deployment. The difference between these models is that the FEM model can consider the effect of the bending of the branch while the multi-particle model can not. There is another difference. The multi-particle model employs the explicit Runge-Kutta-Gill scheme for numerical time integration. The FEM model employs the energy-momentum method[6,7].

The spin rate, attitude angle and tip angle (in-plane) calculated by FEM model are nearly equal to those calculated by multi-particle model, respectively. On the other hand, tip angles (out-of-plane and twist) become zero due to bending stiffness. The amplitude of tip tension in FEM model is smaller than in multi-particle mode by considering beam elements.

(c) In the case that the deployment is divided into 5 and that stoppers are released every 800 seconds.

The spin rate, attitude angle and tip angles (in-plane and out-of-plane) are oscillating drastically just after every stopper is released. There is a possibility that the petals collide with each other, since the maximum amplitude of the tip angle (in-plane) is 120deg. The oscillation amplitudes can be decreased if the division number is increased or dampers are included. The deployment mechanism becomes, however, complicated.

These results show that continuous deployment at the first stage is feasible considering the initial nutation, the height offset and the deployment unbalance. On the other hand, the feasibility of divided deployment is dependent on the division number and dampers.

<Second stage deployment>

(a) In the case of nominal condition.

The sail is expanded dynamically in a few seconds. The spin rate, attitude angle and tip angles (in-plane and out-of-plane) are changed dramatically just after the deployment start. The sail does not collide with the main body and the oscillation amplitudes of them are decreased with time by tether damping. The average of tip angle (out-of-plane) is not zero due to tilt angle.

(b) In the case using FEM (finite element method) model.

This model is the finite element plane stress model based on the tension field theory. The membrane is assumed to be isotropic and to be unable to bear compressive stress. At the moment that the principal stress gets negative, the stress is set to be zero. The essential difference between the multi-particle model and the FEM model is as follows; The multi-particle model assumes that the stress in the direction along each spring depends only on the strain in the same direction, so that the elasticity matrix (stress-strain relation matrix) is approximated to be diagonal. On the other hand, the FEM model can take into account the effect of the strain in the orthogonal direction because it is the plane stress model[8].

The spin rate, attitude angle and tip angles (in-plane and out-of-plane) calculated by FEM model are nearly equal to those calculated by multi-particle model, respectively.

(c) In the case of no tilt angle.

The attitude angle and tip angle (out-of-plane) are decreased. The average of tip angle (out-of-plane) is zero in this case.

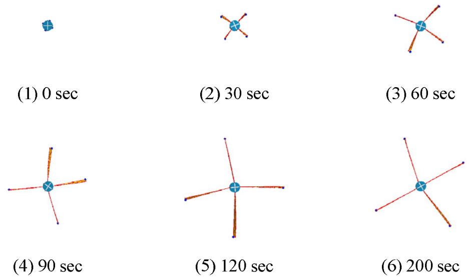
(d) In the case of no offset of center of mass.

The attitude angle and tip angle (out-of-plane) just after the deployment start. It shows that tilt angle and offset of center of mass are coupling.

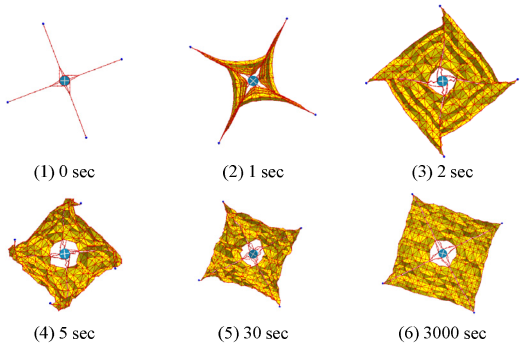
(e) In the case that the connection method using tethers are changed as shown in Fig. 12.

The spin rate, attitude angle and tip angles (in-plane and out-of-plane) are converged slowly.

These results show that dynamic deployment at the second stage is feasible considering the initial nutation, the height offset and the deployment unbalance. The spin rate, attitude angle, tip angles (in-plane and out-of-plane) can be converged by adjusting the connection method using tethers.

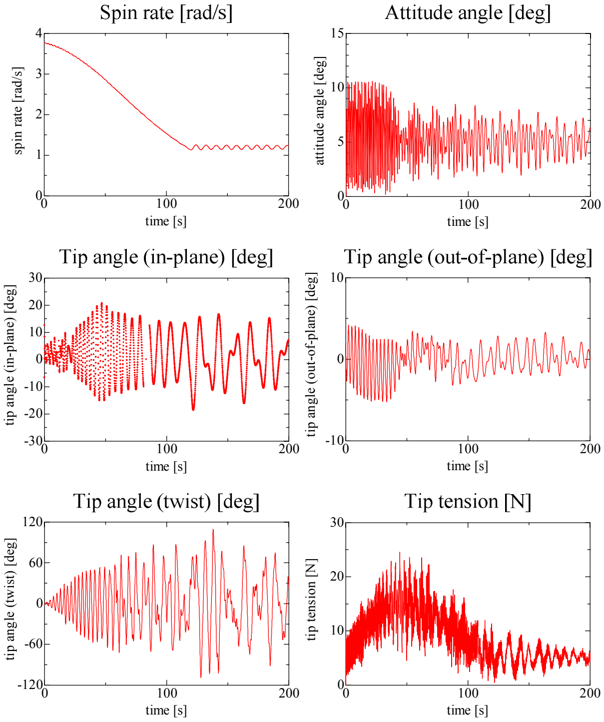


(a) First stage deployment

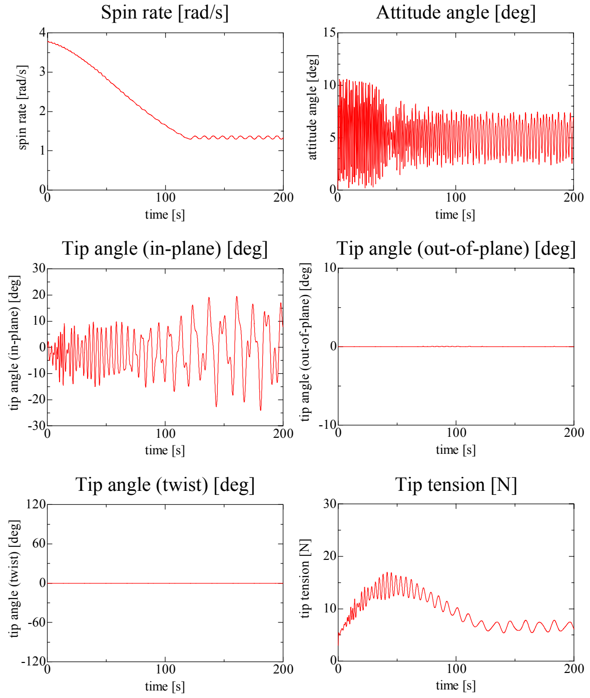


(b) Second stage deployment

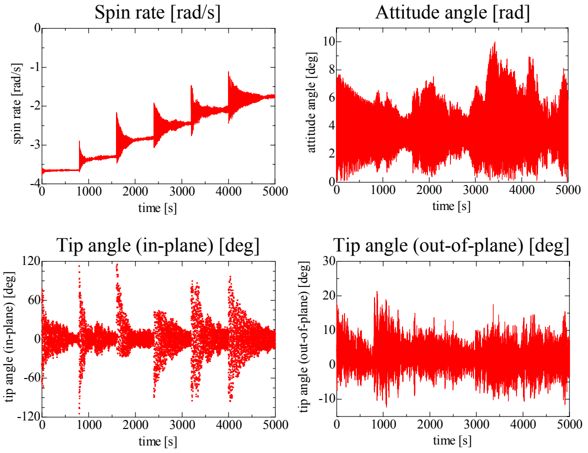
Fig. 9. Pictures of deployment motion



(a) Nominal

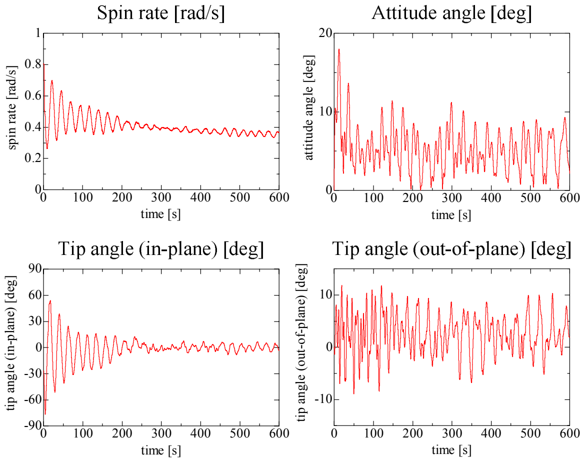


(b) FEM model

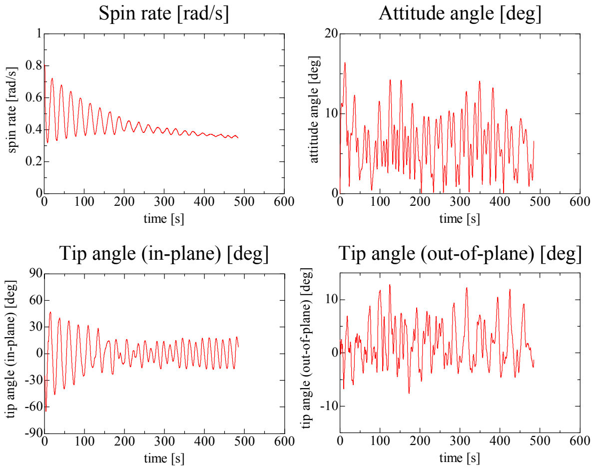


(c) Divided deployment

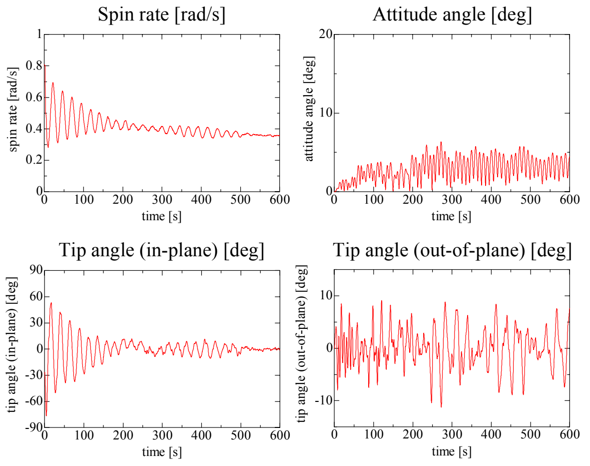
Fig. 10. Results of first stage deployment



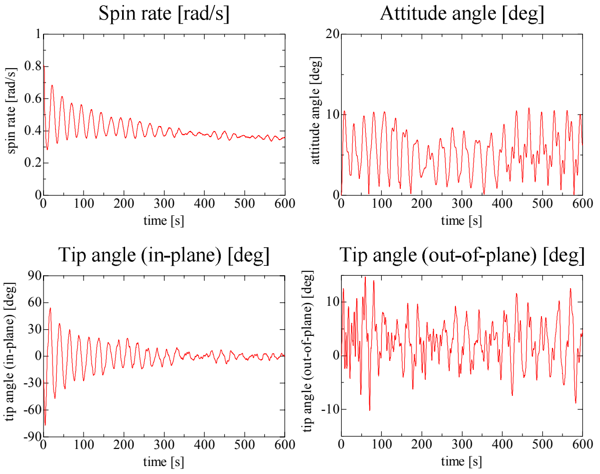
(a) Nominal



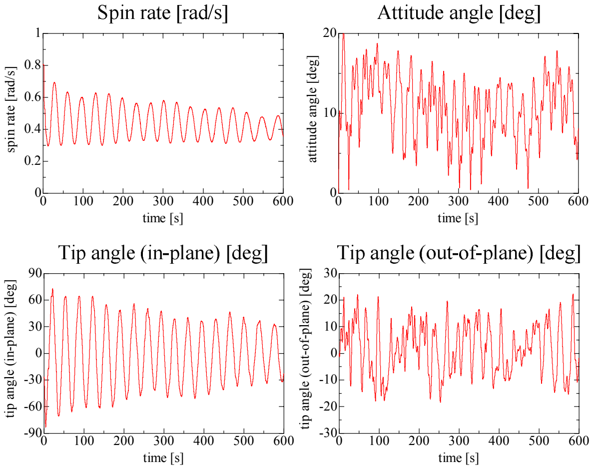
(b) FEM



(c) No tilt angle



(d) No offset of center of mass



(e) Tether

Fig. 11. Results of second stage deployment

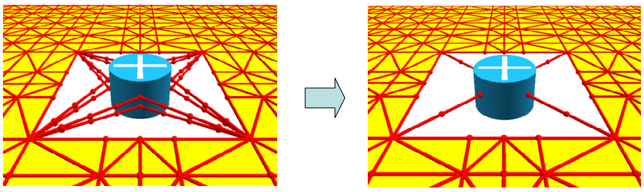


Fig. 12. Connection method using tethers

4. Conclusions

The square-shaped sail and its equipment layout were proposed for small-sized solar power sail mission. The two-stage deployment was also proposed. The mechanisms of continuous deployment and divided deployment were introduced. Numerical simulations using multi-particle models showed that continuous deployment at the first stage and dynamic deployment at the second stage were feasible. The motions analyzed by multi-particle models are well accorded with those analyzed by FEM models.

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