Deployment Dynamics of Clover Type Solar Sail
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Abstract
ISAS/JAXA is studying a deployment method using centrifugal force for solar sail mission. In this paper, the clover type sail is investigated. The deployment sequence consists of two stages. In order to establish the analytical model of sail deployment, two kinds of experiments using a spinning table and an S-310 sounding rocket are conducted. In these experiments, the clover type sails of 2.5 m and 10 m diameters are deployed dynamically. These motions coincide with the motions by the numerical simulations using multi-particle model. On the other hand, the larger sail is supposed to be deployed statically as for actual spacecraft. We schedule to deploy the sail of 20 m diameter using a high altitude balloon. The mechanisms for first and second stage deployments are introduced and the results of numerical simulation using multi-particle model are shown.

1. Introduction
The solar sail mission concept is now being studied at Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA) for future applications to deep space explorations. The solar sail is a means of propulsion utilizing the momentum of photons from the sun to propel the spacecraft, which enables us to drastically enlarge the mission payload capacity within a limited spacecraft resources constrained mainly by a launch capacity.

The received force per unit area is only $4.6 \times 10^{-6}$ N/m² near the earth. Deployment method for very large thin membranes is quite important for solar sail vehicles. Some kinds of deployment methods have been investigated [1]-[4], and JAXA has studied the spinning type as shown in Fig.1. The sail rotates so that the shape be 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 centrifugal force is used for membrane deployment at the initial sequence after the launch as well as shape maintenance during the cruise phase.

Two types of the sail shapes are examined as shown in Fig. 2. We call them fan type [5] and clover type. This research analyzes the deployment motion of clover type sail. The clover type sail has four petals and its folding pattern seems to exploit the centrifugal force for deployment more effectively. Each petal consists of one triangle and two fan parts. Fig. 3 shows the two-stage deployment sequence. In folded configuration, each petal is line-shaped and rolled up around the satellite. In the first stage, rolling petals are extracted like a Yo-Yo despinner, and form a cross shape. The shape is maintained because the root is constrained as shown in (3). In the second stage, the constraint is released. The fan parts are inserted into the triangle parts as shown in (5). The fan parts are assumed to be deployed after the triangle parts are deployed.

This paper presents the deployment motions of clover type sails. If a sail is developed dynamically, the motion becomes complex, because Coriolis force as well as centrifugal force has large effect on it. Two kinds of experiments of second stage deployment have been conducted: drop test in a vacuum chamber [6] and drop test using a high altitude balloon [7]. In both experiments, the sail, whose shape is not equal to clover type completely, is deployed successfully as shown in Fig. 4. However, we could not monitor the motions well because of drop test.

In order to establish the motion models of the first and second stage deployments, we conducted two kinds of experiments using a spinning table and an S-310 sounding rocket as shown in Fig. 5. The diameter is 2.5
m and 10 m, respectively. The data is combined with the simulation results to tune analytical model of the membrane so as to get the precise behaviour. The size of the sail used to explore is at least 50 m. The larger sail is deployed, the larger angular momentum is required. If the large sail is deployed dynamically, it should re-wind around the center body. Thus a solar sail of an actual spacecraft is supposed to be deployed statically. The mechanism to control the sail deployment actively is required. We are planning the experiment using a high altitude balloon. In this experiment, the sail whose diameter is 20 m is deployed statically to validate the mechanisms. This paper introduces the experiment system.

Fig. 1  Image of solar sail spacecraft

Fig. 2  Sail shapes

(1) Fan type
(2) Clover type

Fig. 3  Deployment sequence of clover type sail

Fig. 4  Drop tests

(1) In a vacuum chamber  (2) Using a balloon

Fig. 5  Dynamic deployment experiments

2. Dynamic Deployment Using Spinning Table

2.1 Experiment Overview and Result

In this experiment, a sail attached on the center axis of spinning table is extracted via centrifugal force in no vacuum environment and no microgravity. The diameter of the axis is 9.0 cm. The spin rate is 2.0 Hz (constant). The membrane has a diameter of 2.5 m, and made of 7.5 µm thickness aluminized polyimide. The sail weight is 28.3 g.

Fig. 6 shows the images of first and second stage deployments. (1)-(6) are images at 0, 0.5, 1, 2, 3 and 4 s from the beginning of first or second stage deployments. At 3 s in the first stage deployment, the rolling petals are extracted entirely and form a cross shape. By air resistance, these petals do not re-wind around the center axis. At 0.5 s and 1 s in the second stage deployment, the triangle parts and fan parts are expanded, respectively. However, a part of sail is winded on the center axis in this process. At 4 s, the sail is deployed completely.
2.2 Simulation Model, Formulation and Result

As the simulation model, we use “multi-particle model” as shown in Fig. 7. In (a), each petal is regarded as a tether and it is devised into 50 concentrated masses. In (b), each petal is devised into 171 concentrated masses, considering its shape and folding lines. The weight of concentrated mass is defined by the occupied area. The concentrated masses are connected by springs and dampers. The spring constants are derived by the principle of virtual work, so as to rationally satisfy the relations of displacement energy.

The motions of concentrated mass \( i \) are formulated as follows.

\[
m_i \ddot{q}_i = C_i + \sum T_{ij} + \sum \frac{m_i D_{ijk}}{m_i + m_j + m_k} + m_i g
\]  

where \( C_i \) shows contact force between concentrated mass \( i \) and center axis, \( T_{ij} \) shows tension between concentrated mass \( i \) and \( j \), and \( D_{ijk} \) shows the air drag on the triangle area \( S_{ijk} \) consists of concentrated mass \( i, j \) and \( k \).

\[
T_{ij} = \left( k_{ij} \left( 1 - \frac{l_{ij}}{l_{ij}^0} \right) - c_{ij} \right) \frac{q_j - q_i}{l_{ij}}
\]  

\[
D_{ijk} = \frac{1}{2} \rho U_{ijk}^2 C_d S_{ijk} \frac{U_{ijk}^u}{U_{ijk}}
\]

Fig. 8 shows the results of first and second stage deployments. (1)-(6) show the same time of Fig. 6. The simulation motions of the first and second stage deployments are nearly equal to experiment results. Therefore the simulation models and formulations are validated to analyze the deployment motions.
experiment using ISAS S-310 sounding rocket has launched. The diameter is 310 mm and the length is about 7 m.

During the parabolic flight at the altitude of about 200 km, the membrane is extracted via centrifugal force by the spinning of the rocket. The membrane has a diameter of 10 m, and made of 7.5 µm thickness aluminized polyimide.

As shown in Fig. 9, the sail has center masses (70g×4) and tip masses (20g×8) in order to adjust the development time and prevent for sail winding on the rocket in second stage deployment. The sail is wrapped around the center axis. The center axis of the holders can rotate in one direction relative to the rocket axis, so that the sail should not re-wind around the rocket axis when the tip of the sails rotate faster than the sail fully extend in the first stage. The one direction rotation is realized by one-way clutches as shown in Fig. 10. They are set so as to transfer the spin angular momentum from rocket to sail, but not from sail to rocket.

At X+126, 25 seconds after the first stage deployment, the second stage deployment began. (b) contains the images at Y+25, 27, 30, 43 and 61. Fan parts have been developed in the first stage deployment. In the second stage deployment, clover shape was formed just after triangle parts are developed. At (6), the membrane became flat.

(c) shows the experiment data of angular velocities \(\omega_R\), \(\omega_0\) of rocket and one-way clutch mechanism. Both values of them are equal to 280 deg/s at first, and they are decreased as the membrane is extended in the first stage deployment. At Y+6.3, the one-way clutch starts to rotate relative to the rocket, so that the membrane should not re-wind the rocket. In this case \(\omega_k\) is increased and \(\omega_0\) is decreased, because the dynamical friction torque, 0.15 Nm, acts on rocket and one-way clutch mechanism. At Y+25, the second stage deployment starts, the one-way clutch sticks to the rocket and the sail winds the rocket so as to transfer the spin angular momentum from rocket. Thus, \(\omega_k\) and \(\omega_0\) are equal to each other and they are decreased. At Y+52, the sail is extended and one-way clutch mechanism rotates again. At Y+87, the one-way clutch mechanism sticks to the rocket by dynamical friction.

![Fig. 9 Center mass and tip mass](image)

![Fig. 10 One-way clutch](image)

3.2 Experiment Result

At 17:15, August 9, 2004 (Japan Standard Time), from Uchinoura Space Center in Kagoshima, Japan, S-310 #34 sounding rocket was launched. At X+101, 101 seconds after launching, the first stage deployment began as scheduled. Fig. 11 (a) shows images by the camera to see the panoramic view of the membrane. Each figure contains six images: (1)-(6) are images at Y+3, 6, 10, 11, 19 and 24 seconds after the beginning of the first stage deployment, respectively.

Rolling petals were extracted and form a cross shape at (2). However, the shape was not maintained because the insertions of fan parts were released just after (2). Thus fan parts have been developed before the beginning of the second stage deployment.

At (6), the membrane became flat.

![Fig. 11 Experiment results (S-310 rocket)](image)
3.3 Simulation Model and Formulation

In this experiment, not only the motion of concentrated mass $i$ but also those of rocket $R$ and one-way clutch mechanism $0$ need to be considered. The rocket including one-way clutch mechanism is regarded as a cylinder. These motions are formulated as follows.

$$\left( m_R + m_0 \right) \ddot{q}_R = - \sum \left( T_{0,i} + C_i \right) + \left( m_R + m_0 \right) g \tag{6}$$

$$I_R \cdot \ddot{\omega}_R + \omega_R \times \left( I_R \cdot \omega_R \right) + I_0 \cdot \ddot{\omega}_0 = - \sum q_i \times \left( T_{0,i} + C_i \right) \tag{7}$$

In case that one-way clutch mechanism and rocket rotate together, the constraint equation $\omega_R = \omega_0$ is satisfied. In case that one-way clutch mechanism rotates relative to rocket, the rocket motion is formulated as $I_R \cdot \omega_R = \tau$, where $\tau$ shows the torque of dynamic friction. Fig. 12 shows the stick and slip conditions of one-way clutch mechanism around rocket.

![Stick and slip conditions](image)

3.4 Simulation Result of Expected Motion

Fig. 13 shows the simulation data of the motion we have expected before the S-310 flight experiment. (a) and (b) show the motion sequence of first stage and second stage, respectively. (a) consists of three images at $Y+0$, $5$ and $10$. (b) consists of six images at $Y+25$, $25.1$, $25.4$, $26$, $37$ and $60$. (c) shows the graph of angular velocities of the rocket and one-way clutch mechanism.

After the membrane is extended fully at $Y+7$, relative rotation is realized by one-way clutch in the first stage deployment. The one-way clutch mechanism sticks to and slips on the rocket repeatedly, because its inertial moment is enough small. After the triangle parts are deployed, the fan parts are assumed to be developed in the second stage. The motion of left and right fan parts is not bilateral symmetry as shown in (b) (4). Because Coriolis force works on the left and right fans differently as shown in Fig. 14.

![Images of first stage deployment](image)

3.5 Simulation Result of Fan Released Motion

In S-310 flight experiment, fan parts are developed before the second stage deployment, because the insertions of fan parts are released. Considering it, the numerical simulation is conducted, and the result of the motion is shown in Fig. 15. (a) (1)-(6) and (b) (1)-(6) are images at the same time of Fig. 11 (a) and (b), at $Y+3$, $6$, $10$, $11$, $19$, $24$, $25$, $27$, $28$, $30$, $30$, $43$ and $61$, respectively. The membrane shape of the numerical simulation at the each time of (a) and (b) is nearly equal to those of the flight experiment at the same time. The error factors are the difference of release condition of fan parts, shortage of divided number of concentrated mass, disregard of the sail contact with each other, and disagreement of spring and damping constants and so on.
4. Static Deployment Using Balloon

4.1 Experiment Outline

The sail need to be deployed statically in order to apply to a spacecraft. We are planning the experiment using a balloon. In this experiment, the sail of 20 m diameter is deployed statically at the altitude of 35-40 km. Fig. 17 shows the experiment system. The motor on the gondola spins the cage and drum in order to deploy the tethered sail rolled up around the drum. The spin rate of the drum is 20 rpm (constant). The thrusters cancel the reaction force to keep the gondola attitude constant. The experiment system is hanged on the balloon. It is not a drop test. In order to cancel the effect of aerodynamic drag and gravity, the sail has center masses (1kg $\times$ 4) and tip masses (270g $\times$ 8). It is the other reasons in case of the experiment using S-310 rocket.

![Balloon and payload instrument](image)

**Fig. 16 Balloon and payload instrument**

**Fig. 17 Experiment system**

4.2 Mechanisms for First and Second Stage Deployments

Fig. 18 shows the mechanisms for static first and second stage deployment. The contact point of the sail and the drum is restricted by the cage as shown in (a). Thus the deployment length of each petal can be controlled by the relative rotational angle $\theta$ between the drum and the cage.

In the second stage deployment, two tethers are attached to a petal to develop statically. These tethers are restricted by the guide on the petal. Thus the deployment is adjusted by tether length as shown in (b). The tether length $L$ is controlled by reel mechanism actively. One petal has one reel mechanism. Four reel mechanisms are synchronized one another so as to develop a membrane symmetrically. With this mechanism, the insertion of fan part is not required. The problem that the fan parts are developed before second stage in S-310 flight experiment can be solved by this method.
4.3 Simulation Result

In the first and second stage deployments, the relative angle $\theta$ and the tether length $L$ are controlled linearly as follows.

$$\theta = \theta_{\text{max}} \frac{\text{time}}{T_1}, \quad L = L_{\text{max}} \frac{\text{time}}{T_2}$$

(8)

where $T_1$ and $T_2$ are control period for first and second stage deployments, respectively. They are defined as 90 s.

Fig. 19 shows the simulation results. (1)-(5) are figures at 0, 30, 60, 90 and 99 s from the beginning of first or second stage deployments. The first and second stage deployments are completed at 90 s by constraint equations (8). Because the sail is extracted statically, four petals do not re-wind around the center axis after 90 s in the first stage deployment. On the other hand, the sail is twisted around the center by the aerodynamic drag in the second stage deployment.

5. Conclusion

In this paper, the two kinds of experiments for dynamic deployment of clover type sail using a spinning table and an S-310 sounding rocket are shown. By comparison with the results of experiments and numerical simulations, the multi-particle model is validated to analyze the deployment motions. This paper also presented the mechanisms for static first and second deployment of larger sail using a high altitude balloon. These mechanisms can solve the problem that the fan parts are developed before the beginning of the second stage deployment.

References