Asymmetric Deployment Dynamics of Large Membrane
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Abstract
ISAS/JAXA is studying a deployment method using centrifugal force for solar sail mission. The larger sail is required to be deployed statically as for actual spacecraft. We scheduled to deploy the square sail of diameter 20m using a high altitude balloon. In this paper, the mechanisms for static first and second stage deployments are proposed and developed experiment system is introduced. And the operation and results are shown in detail.

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[1],[2]. One example is the mission for flying-by Jupiter and Trojan asteroids as shown in Fig.1. The solar sail is a means of propulsion utilizing the momentum of photons form the sun to propel the spacecraft. JAXA proposes the solar power sail (hybrid sail), which uses not only the light pressure but also light power for Ion engine.

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[3],[4], and JAXA has studied the spinning type as shown in Fig.2. 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.

Authors study clover shaped sail. This 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 by stoppers as shown in (3). In the second stage, it 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.

The dynamic second stage deployment of $\phi$4m sail was demonstrated using a high altitude balloon at 08/2003. The dynamic first and second stage deployments of $\phi$10m sail was performed successfully using an S-310 sounding rocket at 08/2004[5]. Before these flights, the ground experiments were conducted in a vacuum chamber and a spinning table respectively as shown in Fig.4.

The size of the sail used to explore is about 50m. 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 developed the mechanisms for static first and second stage deployments. To validate them, the experiment using a high altitude balloon is conducted[6]. In this experiment, the sail whose diameter is 20m is deployed statically. The size is the largest in the world. The preexamination on ice rink is also performed. In this paper, the operation and results of these experiments are reported in detail.
2. Experiment system

2.1 Experiment Outline

Fig. 5 shows the deployment system. It consists of a gondola and a drum. The thrusters on the gondola spin the system to deploy the membrane rolled up around the drum. The membrane is a square of diameter 20m. The deployment sequence of square sail is (1)-(5) in Fig. 3. The experiment system is hanged on the balloon whose volume is 200000m$^3$ as shown in Fig. 6. The experiment is performed at the altitude of 37km in order to decrease the aerodynamic drag. The top and side cameras shoot the deployment motion. The top camera and wireless radio is fixed over the gondola. The top camera can take image of the whole membrane. The wireless radio can communicate with ground station without membrane interference.

2.2 Mechanisms for First and Second Stage Deployments

Fig. 7 shows the mechanisms for static first and second stage deployments. At the first stage, the Yo-Yo despinner is restricted by stoppers as shown in (a). The stopper rotates relative to the drum slowly to deploy each petal statically by DC-motor 1. At the second stage, the deployment is adjusted by four tethers attached to the membrane. Each tether is restricted by the guide on each petal. Each length is controlled to deploy the sail statically and symmetrically by DC-motor 2 via a reel mechanism as shown in (b).
2.3 Modelling

Fig. 8 shows the analytical model of balloon experiment. When the weight of the membrane is smaller than that of tip mass, the motion in the deployment plane is described by the air drag of the membrane and the centrifugal force of the tip mass as shown in (a). The torque of each force on the spin axis is shown as follows.

\[
\text{Air drag: } -C_d \rho \pi \left( \frac{\phi}{2} \right)^5 \omega^2 / 5 \tag{1}
\]

\[
\text{Centrifugal force: } 4m\left( \frac{\phi}{2} \right) \omega^2 R \sin \psi \tag{2}
\]

where
- \( \psi \): torsion angle (phase delay) of membrane
- \( \phi \): diameter of membrane
- \( \omega \): spin rate
- \( m \): weight of tip mass
- \( R \): radius of drum
- \( C_d \): air resistance coefficient
- \( \rho \): air density

The torsion angle \( \psi \) is derived by the condition that the sum of Eqs. (1) and (2) is zero.

\[
\sin \psi = C_d \rho \pi \left( \frac{\phi}{2} \right)^5 / 20mR \tag{3}
\]

On the other hand, the gradient angle \( \theta \) out of the deployment plane is decided by the ratio of the gravity and the centrifugal force of the tip mass.

\[
\tan \theta = g / \omega^2 \left( \phi / 2 \right) \tag{4}
\]

Each parameters are defined by the conditions for satisfying \( \psi \leq 25 \text{deg} \) and \( \theta \leq 25 \text{deg} \).

- \( \phi = 20 \text{m} \), \( \omega \geq 0.25 \text{Hz} \), \( m = 1.5 \text{kg} \), \( R = 0.85 \text{m} \), \( C_d = 0.05 \) (including margin)
- \( \rho = 0.006235 \text{kg/m}^3 \) (at the altitude of 37km)

The membrane is designed as shown in Fig. 9.

2.4 Attitude Control System

The attitude control system spins the experiment system during the mission. There are two control modes for low and high spin rate. The low spin rate mode (0.3125Hz) is used during the first and second stage deployments. The high spin rate mode (0.375Hz) is set for analysis of the membrane motion after these deployments.

Gondola has two pairs of thrusters whose arm length is 3m. A pair of thrusters is consists of two CCW thrusters and one CW thruster. CCW and CW thrusters accelerate and decelerate the spin, respectively. The torques of CCW and CW thrusters are \( \tau_{\text{ccw}} = 403.2 \text{Nm} \) and \( \tau_{\text{cw}} = 164.1 \text{Nm} \) respectively. They are larger than the torque on air drag in the case of \( \omega = 0.40 \text{Hz} \) (124Nm). In both control modes, the data of piezoelectric gyro sensor is used for PD control.

This system selects the CFRP tanks. The capacity of each tank is 150 liter and the maximum pressure is 20MPa. It can decrease the total weight and space compared with the system using steel tanks.
3. Ice rink experiment

3.1 Scaling

The ground experiment on ice rink is planned in order to verify the sequences and mechanisms for static first and second stage deployments as shown in Fig. 11. In this experiment, AC-motor is used instead for the thrusters.

Fig. 12 shows the analytical model of ice rink experiment. Because the tip mass slips on the ice rink, the motion in the deployment plane is described by the dynamical friction in addition to the air drag and the centrifugal force. The torque of the dynamical friction on the spin axis is

\[
\text{Dynamical friction: } - \mu \frac{4m g (\phi / 2)^2}{20} \]

(5)

The torsion angle \(\psi\) is derived as follows.

\[
\sin \psi = C_d \rho \pi (\phi / 2)^2 / 20 m R + \mu g / \omega^2 R \]

(6)

On the other hand, the motion out of the deployment plane need not be considered because of the restraint of the ice rink. Each parameters are defined by the condition of \(\psi \leq 90\,\text{deg}\).

\(\phi = 10\,\text{m}, \omega = 0.18\,\text{Hz}, \ m = 10\,\text{kg}, \ R = 0.85\,\text{m},\)

\(C_d = 0.05\) (including margin)

\(\rho = 1.225\,\text{kg/m}^3\) (on the ground)

\(\mu = 0.03\) (measured value)

The value of air density on the ground is 200 times as large as that of at the altitude of 37km. Thus the size of the membrane needs to be decreased from \(\phi 20\)m to \(\phi 10\)m. The torque on air drag of this experiment is 154Nm. It is larger than that of balloon experiment (124Nm).

3.2 Result

The sequence of ice rink experiment is as follows.

0:00: AC-motor ON
3:00: DC-motor 1 ON (beginning of first stage)
5:18: DC-motor 1 OFF (end of first stage)
5:30: Stoppers are released.
7:00: DC-motor 2 ON (beginning of second stage)
7:00: DC-motor 2 OFF (end of second stage)

Fig. 13 shows the results. In this experiment the membrane of diameter 10m was deployed statically. Although the motions of four petals are independent of one another at the first stage, they are developed similarly. The time period of second stage deployment was shortened, because the torque of DC-motor 2 was not enough for the requirement. However, four petals were spread evenly. By the torsion angle \(\psi\), the air resistance coefficient was estimated: \(C_d = 0.02\).

These results show that these sequence and mechanisms are valid for the static first and second stage deployments.
4. Balloon experiment

4.1 Launch

The balloon was launched at 6:10, August 30, 2006. The accident was occurred at this time. The stoppers were released as shown in Fig. 15. Fig. 16 shows the release mechanism for stoppers. The tether was cut or untied by the shock of the launch.

The deployment motion was recorded on the tapes by the top and side cameras. Fig. 17 shows the images of the top camera. Because the stopper was released at launch, one petal is deployed like a Yo-Yo despinner just after thruster spin up at 9:21:33 as shown in (a). However, the other three petals were not deployed.

After DC-motor 1 ON at 9:22:26, the three petals are deployed dynamically in turn as shown in (b). It means that these petals were prevented from developing by the released stoppers before DC-motor 1 ON, and that the interferences were removed by the relative rotation.

After DC-motor 2 ON at 9:28:14, the membrane was deployed statically. After high spin rate mode ON at 9:30:25, the torsion of the membrane was larger as shown in (c). Fig. 18 shows the angles of reel mechanisms after DC-motor 2 ON. It shows that four petals were spread evenly.

Fig. 19 shows the images of the side camera. In this experiment, the first stage deployment was conducted dynamically without stoppers. The second stage deployment is performed statically. This is the first achievement. The size of the membrane is the largest in the world.

4.2 Operation

The experiment sequence is shown as follows.

- 9:12 : Arrival at altitude of 37km
- 9:13 : Top camera ON
- 9:14:09: Side camera ON
- 9:21:33: Low spin rate mode ON (0.3125Hz)
- 9:22:26: DC-Motor 1 ON
- 9:25:53: DC-Motor 1 OFF
- 9:28:14: DC-Motor 2 ON
- 9:30:25: High spin rate mode ON (0.375Hz)
- 9:31:14: DC-Motor 2 OFF
- 9:33:34: Low spin rate mode ON (0.3125Hz)
- 9:40 : Thruster OFF
- 9:42 : Side camera OFF
- 9:48 : Separation of balloon

Fig. 13  Results of ice rink experiment

Fig. 14  Launch

Fig. 15  Launch accident

Fig. 16  Release mechanism for stoppers

Fig. 17  Images of the top camera

Fig. 18  Angles of reel mechanisms after DC-motor 2 ON

Fig. 19  Images of the side camera

(a) After thruster spin up

(b) After DC-motor 1 ON
4.3 Gas Consumption

After the deployment, the gas was consumed by the low spin rate mode for recovery security. Fig. 20 shows the pressure in the tank during the mission. It shows that the pressure became zero finally.

4.4 Recovery

The experiment system was separated from the balloon at 9:48 after the experiment. It was dropped by the parachute on the ocean. It was searched by the helicopter and recovered by the ship successfully.

5. Conclusions

In this paper, the static deployment of large membrane for solar sail was shown. The mechanism for static deployment was developed and verified by the experiment on the ice rink.

In the experiment using a balloon,
(1) The membrane of diameter 20m was deployed.
(2) The size of the membrane is the largest in the world.
(3) The static deployment of the membrane is the first achievement in the world.
(4) The analytical model of the membrane is improved.
(5) Experiment under low air drag was realized.

References