DYNAMIC AND STATIC DEPLOYMENT MOTIONS OF SPIN 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 analyze the motion of the dynamic deployment, S-310 flight experiment is conducted. In this experiment, the clover type sail of 10 m diameter is deployed dynamically. Numerical simulations by multi-particle model are also conducted to analyze the complicated motion. The experiment and simulation results are compared with each other to validate the analytical model. On the other hand, we schedule to conduct a balloon experiment. The clover type sail of 20 m diameter is deployed statically. The mechanisms for first stage and second stage deployments are introduced.

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 form 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 4.6×10^{-6} N/m^2 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.

The deployment motion becomes complex, because Coriolis force as well as centrifugal force works on it. Three kinds of experiments have been conducted: drop test in a vacuum chamber (ϕ0.9m) [5], drop test using a high altitude balloon (ϕ4m) [6], and spinning table test (ϕ2.5m). The size of the sail used to explore is at least 50 m. The larger sail deployment need to be examined. Then we carried out the S-310 flight experiment to deploy the sail whose diameter is 10 m in high vacuum environment and microgravity. This data is combined with the simulation results to tune analytical model of the membrane so as to get the precise behaviour.

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 using a 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.

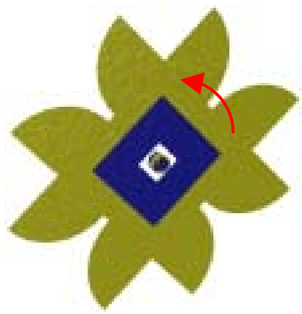


Fig. 1. Image of solar sail spacecraft

2. SAIL SHAPE AND DEPLOYMENT SEQUENCE

Two types of the sail shapes are examined as shown in Fig. 2. We call them fan type [7] and clover type. This research analyzes the deployment motion of clover type sail. The clover type sail has 4 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). Te fan parts are assumed to be deployed after the triangle parts are deployed.

(1) Fan type (2) Clover type

Fig. 2. Sail shapes

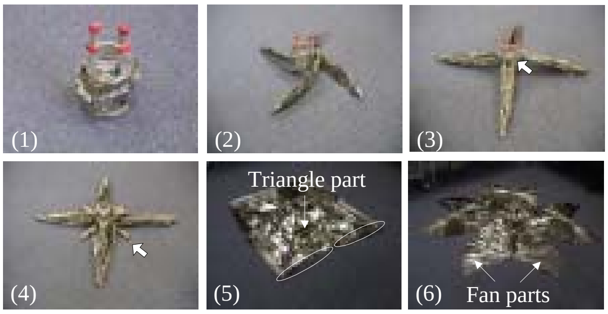


Fig. 3. Deployment sequence of clover type sail

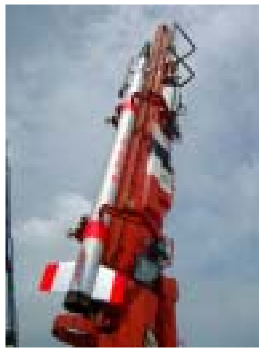
3. DYNAMIC DEPLOYMENT USING S-310 ROCKET

3.1 Experiment Overview

The dynamic deployment of membrane larger than 3 m on the ground is difficult since aerodynamic drag and gravity affect the motion greatly. A zero-gravity flight experiment using ISAS S-310 sounding rocket has planned in the summer, 2004. Fig. 4 shows an S-310 sounding rocket whose diameter is 310 mm, the length about 7 m.

During the parabolic flight at the altitude of about 200 km, clover type and fan type membranes are extracted via centrifugal force by the spinning of the rocket as shown in Fig. 5. The spin rate after the Yo-Yo despin is expected to range from 0.7 Hz to 1.3 Hz. Both the membranes have a diameter of 10 m, and made of 7.5 μm thickness aluminized polyimide. The duration of experiment is defined by the maximum dynamic pressure the sails experience. We defined the ratio of dynamic pressure force to centrifugal force must be less than 0.1, that leads to the maximum dynamics pressure of 8.0×10^{-3} N/m^2. This value corresponds to the duration of about 3 minutes around the peak of the parabolic flight.

The dynamics is observed by 4 onboard cameras. Two of those cameras are located near the center of the membranes, and their FOV are directed toward radius direction. Another two cameras are placed at the side of tail fins, and FOV is set to see the panoramic view of membrane. Moreover, various sensors, such as a gyro and a geomagnetic sensor, measured the attitude to know the behaviour of the deployment.



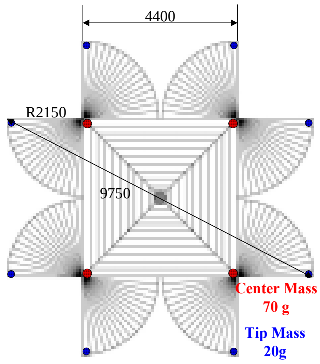


Fig. 4. S-310 sounding rocket Fig. 6. Clover type sail

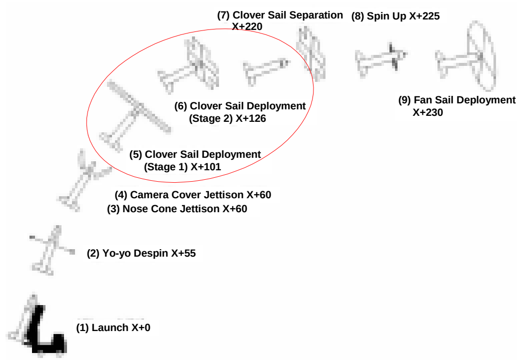


Fig. 5. S-310 #34 flight sequence

3.2 Clover Type Sail

Figs. 6 and 7 show the clover type sail and holder, respectively. The clover type sail has center masses (70g×4) and tip masses (20g×8). The centrifugal force of the sail is increased and the development time can be adjusted by these masses. The holder weight is 5 kg including sail weight 1.1 kg. 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, and they are set so as to transfer the spin angular momentum from rocket to sail, but not from sail to rocket.

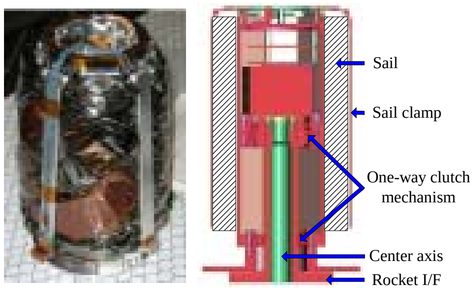
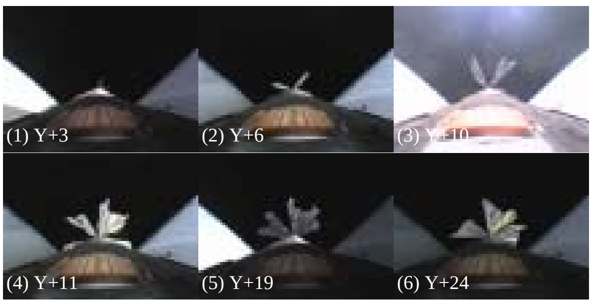


Fig. 7. Clover type sail holder

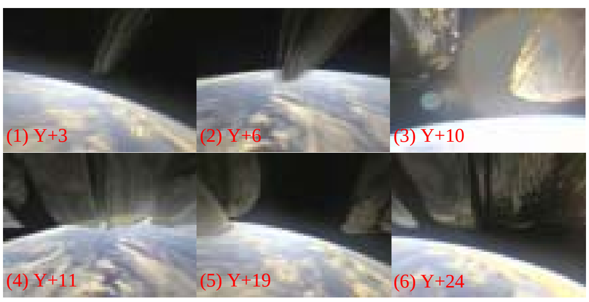
3.3 Experiment Result

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. 8 (a) shows images by the camera to see the panoramic view of the membrane and Fig. 8 (b) are images by the camera directed toward radius direction. Each figure contains 6 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.



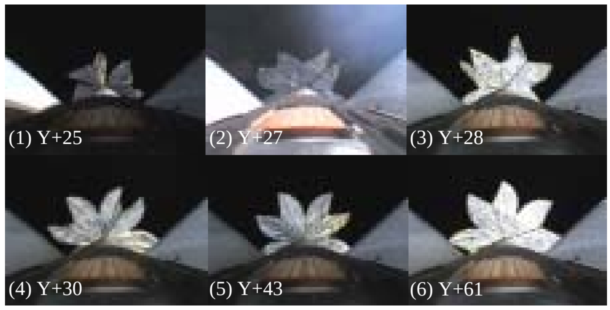
(a) Panoramic view



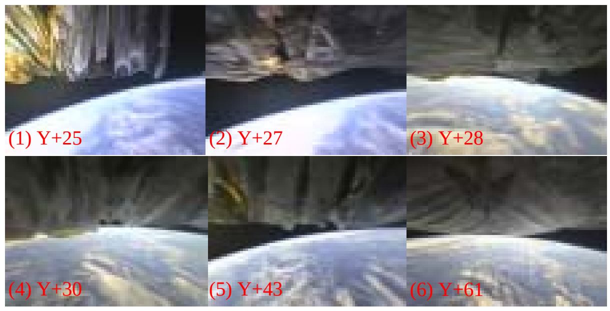
(b) Radius direction view
Fig. 8. Images of the first stage deployment

At X+126, 25 seconds after the first stage deployment, the second stage deployment began. Fig. 9 contains the images at Y+25, 27, 28, 30, 43 and 61. The images by the camera placed at the side of tail fins are shown in (a), and those by the camera located near the center of the membranes in (b).

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.



(a) Panoramic view



(b) Radius direction view
Fig. 9. Images of the second stage deployment

At X+220, 119 seconds after the beginning of the first stage deployment, clover type sail was separated as scheduled. Fig. 10 shows the images at Y+122, 128 and 137, by the camera attached at the side of tail fins.
The clover type sail is ejected forward at 2.0-2.4 m/s. The clover shape is maintained by the centrifugal force.

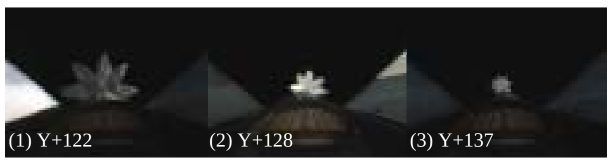


Fig. 10. Images after clover type sail separation

Fig. 11 shows the experimental data of angular velocities ω_R, ω_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 ω_R is increased and ω_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 development 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, ω_0 and ω_R 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.

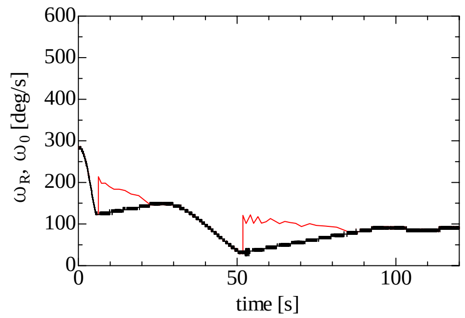
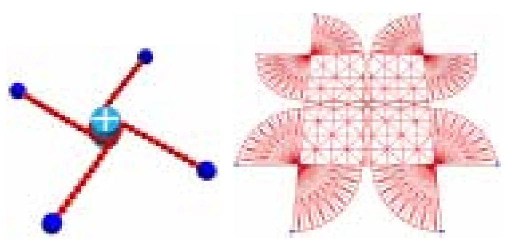


Fig. 11. Angular velocities (experimental data)

4. SIMULATION

4.1 Modelling and Formulation

In this section, numerical simulation is conducted and its result is compared with the data of S-310 flight experiment in order to validate the analytical model. We use "multi-particle model" as shown in Fig. 12. In (a), each petal is regarded as a tether and it is devised into 50 concentrated masses. In (b), a sail is devised into 492 concentrated masses, considering its shape and folding lines. The concentrated masses are assumed to be 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 rocket including one-way clutch mechanism is regarded as a cylinder.



(a) First-stage model (b) Second-stage model

Fig. 12. Analytical models

The motions of concentrated mass i, rocket R and one-way clutch mechanism 0 are formulated as follows.

$$m_i \ddot{\mathbf{q}}_i = \sum_j \mathbf{T}_{i,j} + \mathbf{C}_i \tag{1}$$

$$(m_R + m_0)\ddot{\mathbf{q}}_R = -\sum_i \left(\mathbf{T}_{0,i} + \mathbf{C}_i\right) \tag{2}$$

$$\mathbf{I}_R \cdot \dot{\boldsymbol{\omega}}_R + \mathbf{I}_0 \cdot \dot{\boldsymbol{\omega}}_0 = -\sum_i \mathbf{q}_i \times \left(\mathbf{T}_{0,i} + \mathbf{C}_i\right) \tag{3}$$

where $\mathbf{T}_{i,j}$ shows tension between concentrated mass i and j, $\mathbf{C}_i$ shows contact force between concentrated mass i and rocket. In case that one-way clutch mechanism and rocket rotate together, the constraint equation $\boldsymbol{\omega}_R = \boldsymbol{\omega}_0$ is satisfied. In case that one-way clutch mechanism rotates relative to rocket, the rocket motion is formulated as $\mathbf{I}_R \cdot \dot{\boldsymbol{\omega}}_R = \boldsymbol{\tau}$, where $\boldsymbol{\tau}$ shows the torque of dynamic friction. Fig. 13 shows the stick and slip conditions of one-way clutch mechanism around rocket.

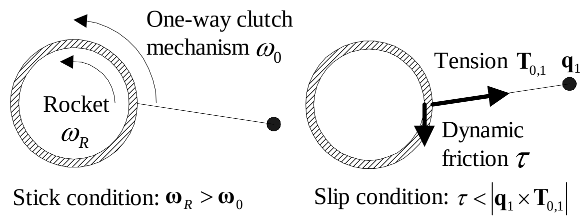
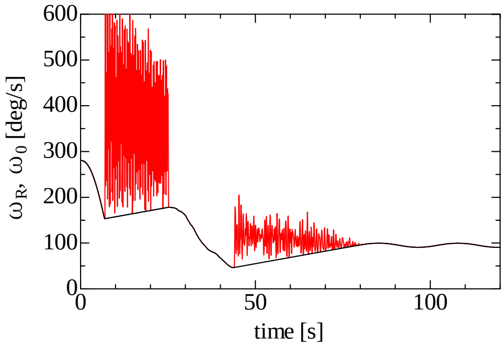


Fig. 13. Stick and slip conditions

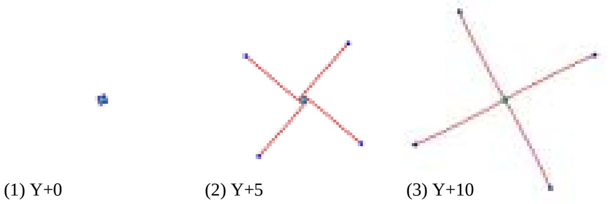
4.2 Expected Motion

Fig. 14 shows the simulation data of the motion we have expected before the S-310 flight experiment. (a) shows the graph of angular velocities of the rocket and one-way clutch mechanism. (b) and (c) show the motion sequence of first stage and second stage, respectively. (b) consists of three images at Y+0, 5 and 10. (c) consists of six images at Y+25, 25.1, 25.4, 26, 37 and 60.

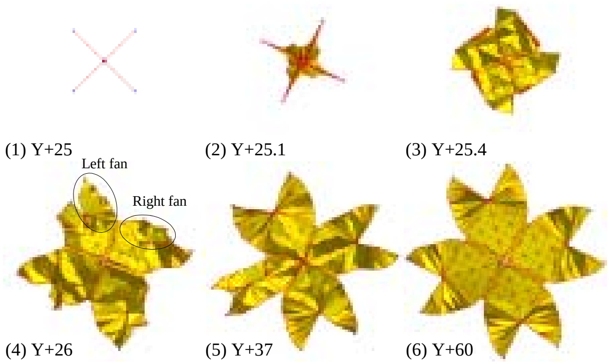
After the membrane is extended fully at Y+7, relative rotation is realized by one-way clutch in the first stage deployment. The one-way clutch mechanism sticks to and slips on the rocket repeatedly, because its inertial moment is enough small. After the triangle parts are deployed, the fan parts are assumed to be developed in the second stage. The motion of left and right fan parts is not bilateral symmetry as shown in (c) (4). Because Coriolis force works on the left and right fans differently as shown in Fig. 15.



(a) Angular velocities



(b) Images of first stage deployment



(c) Images of second stage deployment
Fig. 14. Expected motion

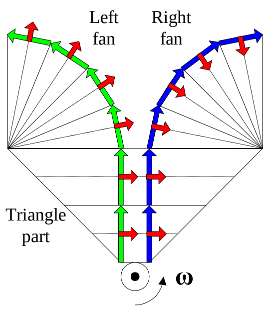
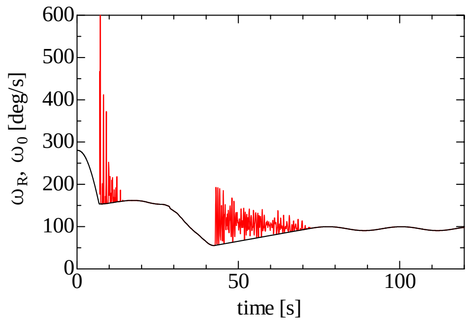


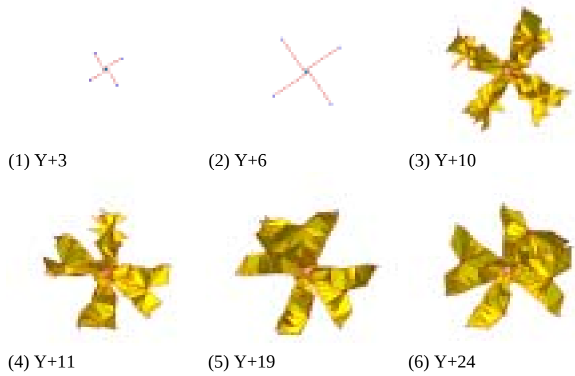
Fig. 15. Coriolis force

4.3 Fan Released Motion

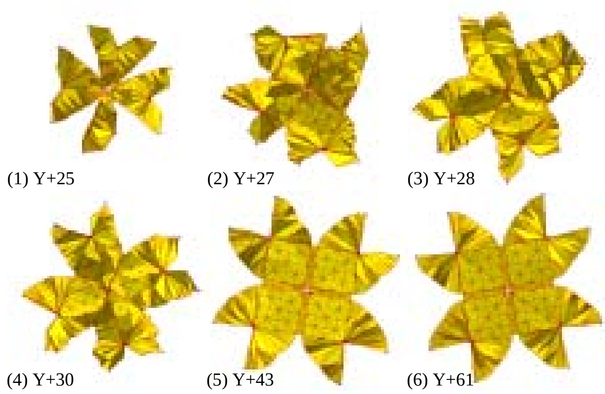
In S-310 flight experiment, fan parts are developed before the second stage deployment, because the insertions of fan parts are released. Considering it, the numerical simulation is conducted, and the result of the motion is shown in Fig. 16. The (b) (1)-(6) and (c) (1)-(6) are images at the same time of Figs. 8 and 9, at Y+3, 6, 10, 11, 19, 24, 25, 27, 28, 30, 43 and 61, respectively. The membrane shape of the numerical simulation at the each time of (b) and (c) 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.



(a) Angular velocities



(b) Images of first stage deployment



(c) Images of second stage deployment
Fig. 16. Fan released motion

5. STATIC DEPLOYMENT USING BALLOON

5.1 Outline

In S-310 flight experiment, the sail is deployed dynamically. However, 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. 18 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 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. Some weights are attached to the membrane to increase centrifugal force.

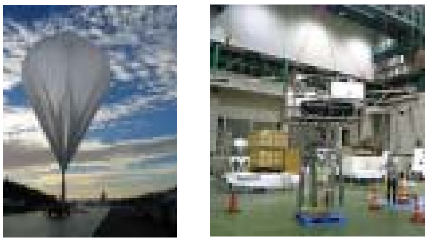


Fig. 17. Balloon and payload instrument

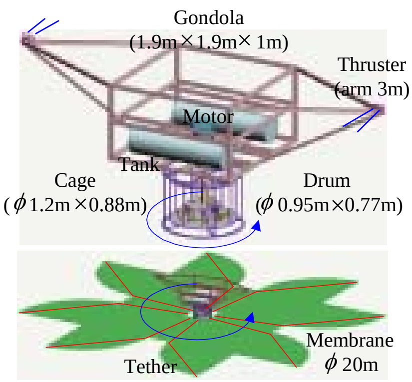


Fig. 18. Experiment system

5.2 First Stage Deployment

Fig. 19 shows the mechanism for first stage deployment. The contact point of the sail and the drum is restricted by the cage. Thus the deployment length of each petal can be controlled by the relative rotational angle θ between the drum and the cage.

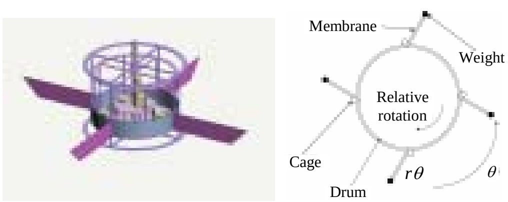


Fig. 19. Mechanism for first stage deployment

5.3 Second Stage Deployment

Two tethers are attached to a petal to develop statically in the second stage deployment. These tethers are restricted by the guide on the petal. Thus the deployment is adjusted by tether length as shown in Fig. 20. The tether length 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 part is developed before second stage in S-310 flight experiment can be solved by this method.

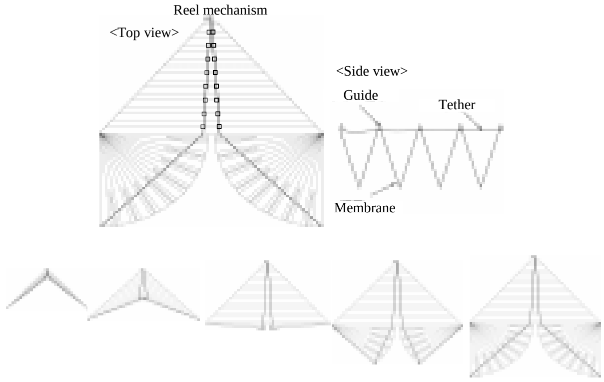


Fig. 20. Mechanism for second stage deployment

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