On-Ground Dynamics Simulator for Spinning Solar Sail

Shinichi Inagawa¹ and Saburo Matunaga¹
¹Mechanical and Aerospace Engineering, Tokyo Institute of Technology, Japan

Abstract

The authors developed on-ground dynamics simulator for a class of spinning solar sail studied by ISAS/JAXA. Using the simulator, we estimated the dynamics behavior of the main body of the spinning solar sail and the damping characteristics after deployment in order to contribute the design of attitude control method for the spinning solar sail. In this paper, the purpose, the dynamics simulator and its functional test results are described. The on-ground experiment indicated that the dynamics behavior of the main body is changed according to the connection way between the main body and the membrane.

1. Introduction

Solar sail is considered as an interplanetary cruising method, and a large deployed sail produces necessary thrust by the light pressure of the sun with no chemical propellant. Therefore, it attracts attention as one of the long-distance space cruising systems for interplanetary exploration, and several space organizations around the world have been studying the solar sail.

In Japan, ISAS/JAXA studies a spinning solar sail [1] in which centrifugal force generated by a main satellite rotation is used for deploying the sail and keeping its shape. Figure 1 shows an image of the spinning solar sail. The authors also proposed one type of spinning solar sail [2-5]. Several on-ground experiments on dynamics behavior of sail deployment have been conducted. Okuizumi et al. [6] in ISAS/JAXA conducted a series of experiments in vacuum chamber as shown in Figure 2. In this experiment, the size of the sail was reduced due to size limitation of the vacuum chamber, and spin rate of the satellite model was much faster than one of the full scale model to increase the centrifugal force for deploying the sail and keeping the sail shape. Mori et al. [7] in ISAS/JAXA conducted a series of experiments on ice using a full scale model to check the feasibility of a sail deployment system as shown in Figure 3. In this experiment, the air resistance greatly acts on the sail. So, it is difficult to simulate the behavior of the solar sail after the sail deployment. Moreover, these experiments cannot confirm rotational dynamics of the sail for a long period.

The authors developed an on-ground dynamics simulator for a class of spinning solar sail to estimate the dynamics behavior of the main
body of the spinning solar sail and damping characteristics after sail deployment and to contribute the design of attitude control method for the spinning solar sail. In this paper, the purpose, sub-systems and functional test results of the on-ground dynamics simulator are described.

Figure 1 Image of the spinning solar sail

Figure 2 Experiment in vacuum chamber

Figure 3 Experiment on ice

2. Purpose of the Developed On-Ground Dynamics Simulator

Figure 4 shows a shape of spinning solar sail which is studied in JAXA. It consists of a main body in the center and a deployed membrane (sail) connecting to the main body with tethers. The centrifugal force caused by rotation of the sail is used for deploying its membrane and keeping the shape. The tethers connecting the main body with the membrane are used to prevent the main body from winding the membrane when deploying.

Mori et al. [1] in ISAS/JAXA conducted a numerical simulation for dynamics of the main body at the membrane deployment as shown in Figure 5, which shows that the spin rate of main body is vibrated due to the interaction with the membrane dynamics through the tethers. This result was obtained in the case of one-tether connection as shown in Figure 6. Figure 7 shows another result in the case of two-tether connection as shown in Figure 8. Comparing Figure 5 with Figure 7, we can see that there are great differences in convergence time of the spin rate, and the results are dependent on the tether connection type, and that the spin rate fluctuation can be damped by an appropriate tether connection.

Figure 4 Shape of spinning solar sail

Figure 5 Spin rate in case of one-tether connection

Figure 6 One-tether connection
For the design of the solar sail, it is necessary to estimate the damping coefficient of the fluctuation in several tether connection types. The dynamics behaviors of the main body and the membrane are dependent not only on the connection type, but also on the relative displacement of the main body due to the change of the tether length or the position of tether connected points and on external disturbances such as thruster firing, solar radiation and so on.

Thus, the authors developed an on-ground dynamics simulator to simulate and measure the dynamics of spinning solar sail after membrane deployment.

3. On-ground dynamics simulator

Considering the dynamics behavior after membrane deployment observed by several numerical simulations, the authors selected a configuration of the on-ground dynamics simulator as shown in Figure 9. It consists of two rigid bodies and tethers. The membrane (sail) is regarded as a rigid body, because inertia moment ratio of the main body to the membrane is 1:12 (after deployment in full-scale model), and, in the numerical simulations, the shape of the deployed membrane is kept when stable centrifugal force acts on the membrane. It isn't necessary that the size of the simulated membrane is equal to one of the full-scale model. On the other hand, it is preferable that the positions of tether connected points between the main body and the membrane can be changed. Thus, the size of the simulated main body is equal one of the full-scale model (φ1.5m), and the simulated membrane is designed to be matched to the position of tether connected points in the full-scale model.

The developed dynamics simulator is shown in Figure 10, and a system block diagram of the dynamics simulator is shown in Figure 11. In order to spin up, the membrane part is connected with a motor through a turn mechanism. The main body part is floated by air and can rotate and translate on the flat floor (glass) with very small friction, and the main body part follows the spinning membrane part through the tethers. Three personal computers (PC) are used to handle with data obtained several sensors and cameras with wireless LAN in real time.

Figure 12 shows a structure configuration of the simulator. The motor to rotate the membrane part through the turn mechanism is fixed in a support frame. The membrane part is connected with the main body part by the tethers.
The main body part uses DISC (Dynamics and Intelligent control Simulator for satellite Cluster) [8] developed by the authors as shown in Figure 13, and Table 1 shows its specification. The feature of DISC is to simulate two-dimensional microgravity environment by air float on the flat floor. DISC has eight thrusters to control rotational and translational motions which can also be used to simulate an external disturbance.

The membrane part consists of four beams and a center plate supporting the beams. These beams are used to determine the position of tether connected points. The membrane part can rotate by the motor, and the spin rate can be achieved in the range of 0.1 to 0.5 rad/s. The membrane part can also be separated from the motor by the turn mechanism as shown in Figure 14. Solenoids are turned on and the cores are removed from a plate of the membrane part. Then the membrane part is separated from the motor.

The tethers that connect the main body part and the membrane one are made of Kevlar which has the high mechanical strength and high heat resistance. Indeed, its mechanical strength is five times as large as one of steel at same weight. The end of tethers is fixed in the way as shown in Figure 15. It corresponds to the pinned support.

---

**Table 1** DISC specification

<table>
<thead>
<tr>
<th>Weight</th>
<th>42 [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size L×W×H</td>
<td>0.6 [m]×0.6 [m]×0.47 [m]</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>2.3 [kgm²]</td>
</tr>
<tr>
<td>Pressure in Air Tank</td>
<td>100 [kgf/m²]</td>
</tr>
<tr>
<td>Volume of Air Tank</td>
<td>8.6 [l]</td>
</tr>
<tr>
<td>Control Cycle</td>
<td>60 [ms]</td>
</tr>
<tr>
<td>Communication Rate</td>
<td>5.0 [Mbps]</td>
</tr>
<tr>
<td>Thrust</td>
<td>1.8 [N]</td>
</tr>
<tr>
<td>Time of Experiment</td>
<td>5.0 [min]</td>
</tr>
</tbody>
</table>

---

**References**

1. [8] DISC (Dynamics and Intelligent control Simulator for satellite Cluster) was developed by the authors.
4. Experiment and Result

The developed on-ground dynamics simulator has three kinds of sensors; two gyro sensors, four tension sensors and six cameras. The mounting position is shown in Figure 16. The gyro sensor is a fiber optical one. Each gyro sensor is mounted on the main body part and the membrane one, respectively. The resolution of the gyro sensor is 0.002 rad/s which satisfies measurement requirement in the case that the spin rate of the solar sail is 0.1 to 0.5 rad/s. The tension sensors measure tether tensions. The cameras are installed on a ceiling, the main body part and the membrane part.

The following experiment procedure is adopted.
1) Motor mode: the motor rotates the membrane part and keeps the specified spin rate until the main body part follows the membrane part stably.
2) Separation mode: the solenoids of the turn mechanism are turned on and the membrane part is separated from the motor.
3) Free mode: a two-rigid-body system connected by tethers is in motion.

The dynamics behavior of the system in all processes is observed in two connection types (Figures 6 and 8). Figures 17 - 20 show the spin rate and in-plane tip angle in case of the one-tether connection and the two-tether connection, respectively, where the in-plane tip angle is an angle between a radial vector of the main body and a direction vector of the membrane corner as shown in Figure 21. The spin rate is 0.3 rad/s in the motor mode, and the sytem are separated at 40s (one-tether) or 16s (two-tether), then the mode is changed to the free mode. The in-plane tip angle data are analyzed from the camera movies.
These results show that the tether connection influences the dynamics of the system. In case of one-tether connection, the spin rate of the main body part greatly fluctuates compared to one of the membrane part. In-plane tip angle, the vibration frequency is 0.3Hz in the motor mode and 0.15Hz in free mode, and the maximum vibration degree is 10 deg in motor mode and 5 deg in free mode. The tip angle does not seem to converge in the experiment. In the corresponding numerical simulation, the vibration frequency is 0.07Hz, so the experimental result of 0.15Hz is twice as fast.

In case of two-tether connection, the spin rate fluctuation are drastically damped, and the in-plane tip angle changes at the same time of the mode change, but in free mode, it is almost constant. In the corresponding numerical simulation, the convergence time of the spin rate fluctuation is about 200s. In the experiment, the membrane part is strictly followed the main body movement.

In motor mode, the membrane vibrates in motion, because motor transmission yields to impulse load when the motor spin up the main body, and there are misalignments of the setup. In free mode, the spin rate can not be kept in constant and be decreased because of friction in the turn mechanism.

5. Conclusion

The authors developed the on-ground dynamics simulator for the dynamics of spinning solar sail after sail deployment. The dynamics of the main body and the membrane were observed in two types of tether connection. The on-ground experiment indicated that the dynamics behavior of the main body is changed according to the connection way between the main body and the membrane. It was confirmed that this result was similar to one of the numerical simulation.

References