Study of Asynchronous Solar Sail Deployment Using Finite Element Method

By Go ONO1), Kengo SHINTAKU2), Yoji SHIRASAWA3), Osamu MORI3), Yasuyuki MIYAZAKI4) and Saburo MATUNAGA3)

1) Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan
2) Department of Mechanical and Aerospace, Tokyo Institute of Technology, Tokyo, Japan
3) Japan Aerospace Exploration Agency, Sagamihara, Japan
4) Department of Aerospace Engineering, Nihon University, Funabashi, Japan

(Received June 19th, 2013)

Solar sails are a form of spacecraft which deploys a large sail in space and uses solar radiation pressure for propulsion. IKAROS is a spinning solar sail developed by JAXA and was launched in 2010. As demonstrated with IKAROS, it is extremely effective to place various devices, such as thin-film solar cells for power generation, on the sail membrane of a solar sail. Such devices, however, contribute to the thickness of the sail, and may hinder the deployment of the sail. In this paper, the sail deployment method of IKAROS is reviewed and its dynamics, which may result in an asynchronous deployment of the sail, is investigated.

Key Words: Solar Sail, Sail Deployment, IKAROS

Nomenclature

\[ I \]: elasticity matrix
\[ E \]: Young’s modulus
\[ \nu \]: Poisson’s ratio
\[ \alpha \]: sail compressive stiffness ratio

1. Introduction

Solar sails are a form of spacecraft which deploys a large sail in space and uses solar radiation pressure (SRP) for propulsion. Since they do not require any propellant for propulsion, they are expected to be a promising technology for future deep space exploration. Moreover, the sail membrane of a solar sail can be advantageous for many purposes. For example, “IKAROS” shown in Fig. 1, which is a solar sail spacecraft developed by Japan Aerospace Exploration Agency (JAXA), had several devices on its sail. Such devices include thin-film solar cells for power generation, reflectivity control devices for attitude control, and ALADDIN (Arrayed large-Area Dust Detector for Interplanetary Space) for scientific observation.

Fig. 1. Spinning solar sail IKAROS.

As demonstrated by IKAROS, it is extremely effective to place various devices on a sail membrane. It is certain that future solar sails will be in such a configuration to exploit the large surface area of its sail.

At JAXA, for instance, another solar sail mission, which aims to explore Jupiter and its Trojan asteroids, is currently under consideration.2) The sail of this spacecraft will majorly consist of thin-film solar cells. This enables the spacecraft to generate sufficient power to operate electric propulsion at a considerable distance of 5 AU from the Sun. The greatest difference between the sail of IKAROS and that in the next mission is the thickness. As opposed to the former, which was majorly composed of 7.5µm polyimide resin, most part of the latter is expected to be considerably thicker due to the thin-film solar cells.

A sail must be folded up and stored compactly prior to a launch, and then deployed in space somehow. This is one of the most difficult and critical tasks for solar sails. IKAROS deployed its sail using the centrifugal force due to spinning. In this deployment method, however, a high thickness of a sail may hinder the deployment. The objectives of this study are to review the sail deployment method of IKAROS and to understand its dynamics more deeply regarding a thick sail and an asynchronous deployment.

2. Sail Deployment Method of IKAROS

The deployment method of IKAROS consisted of two stages.3) In the first stage, after releasing tip masses, the sail folded up and wreathed around the main body of IKAROS was extracted gradually. A cross-shape was formed as the sail was held by rotation guides at four points. In the second stage, the rotation guides were released simultaneously, and the sail was dynamically deployed.
Prior to the launch of IKAROS, the sail deployment dynamics was investigated with several approaches such as high-altitude balloons, sounding rockets and numerical calculations. Consequently, it was concluded that the deployment method shown in Fig. 2 was sufficiently reliable, and it was in fact conducted with IKAROS. It is, nevertheless, known that the elastic energy of the sail does not monotonically decrease during the second stage of the deployment sequence. Hence the sail may get stuck and trapped in a local minimum, and the deployment may fail halfway through. It is believed that this phenomenon was not a concern with IKAROS since its sail was very thin. The phenomenon, however, becomes problematic as the thickness of a sail increases.

3. Compressive Stiffness

An important parameter for the sail deployment is the compressive stiffness of a sail. As can be seen in Fig. 2, the sail folded up into a strip-shape is fastened to the main body of the spacecraft with the rotation guides at four points at the end of the first stage deployment. A crease created due to this fastening is called a ‘double-crease’. At these four points, the sail must be compressed slightly in an in-plane direction for the sail to be deployed as shown in Fig. 3.

A high compressive stiffness of the sail, therefore, hinders the sail deployment. In general, a thick sail has difficulty deploying because it has a high compressive stiffness.

4. Simulation Conditions

In this study, a numerical analysis is made using the finite element method (FEM). Nonlinear Elasto-Dynamic Analysis (NEDA) code based on the energy momentum method, which preserves the total energy, linear momentum and angular momentum, has been developed by Miyazaki. In this model, the bending stiffness of several devices on the sail, the crease stiffness of folding lines, and the compressive stiffness of the sail are taken into account. Major conditions used in the analysis are shown in Table 1. They are based on the design of IKAROS.

<table>
<thead>
<tr>
<th>Initial Spin Rate</th>
<th>5 [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft Mass</td>
<td>291.24 [kg]</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>(47.93, 47.49, 66.48) [kgm²]</td>
</tr>
<tr>
<td>(I_{xx}, I_{yy}, I_{zz})</td>
<td>((-6.3e-4, 4.6e-5, 1.6e-3) [kgm²])</td>
</tr>
<tr>
<td>Sail Size</td>
<td>20 [m]</td>
</tr>
<tr>
<td>(Diagonal Length)</td>
<td></td>
</tr>
<tr>
<td>Mass of Each Tip Mass</td>
<td>0.5 [kg]</td>
</tr>
<tr>
<td>Sail Mass</td>
<td>15.0 [kg]</td>
</tr>
<tr>
<td>Sail Thickness</td>
<td>7.5 [μm]</td>
</tr>
<tr>
<td>Sail Folding Width</td>
<td>0.28 [m]</td>
</tr>
<tr>
<td>Sail Density</td>
<td>1420 [kgm⁻³]</td>
</tr>
<tr>
<td>Sail Young Modulus</td>
<td>3.2 [GPa]</td>
</tr>
<tr>
<td>Sail Poisson Ratio</td>
<td>0.4</td>
</tr>
<tr>
<td>Sail Damping Coefficient</td>
<td>3.9e-5 [s]</td>
</tr>
<tr>
<td>Sail Compressive Stiffness Ratio</td>
<td>1.0e-6</td>
</tr>
</tbody>
</table>

In the simulation, a damping that is proportional to the stress rate is assumed. The damping is required because the kinetic energy of the sail is considered to have a large influence on whether the sail gets stuck in the middle of the deployment, while the sail damping coefficient affects the sail deployment rate in the radial direction. Since the simulation result agrees with flight data with a value of 3.9e-5 [s], such a value is also used in this study.

The sail compressive stiffness ratio, α, is the ratio of the in-plane stiffness of the sail membrane under compression to that under stretch. In the stiffness reduction model, an elasticity matrix is defined as shown in Eq. (1).

\[
\Gamma = \frac{\frac{a_1}{1-a_2 \alpha}}{a_3 a_2} = \begin{bmatrix}
\frac{a_1}{a_3}
\end{bmatrix}
\]

(1)

The parameters \(a_1\) and \(a_2\) represent taut, wrinkle and slack states, and are given as follows:

A) Taut : \((a_1, a_2) = (1, 1)\)
B) Wrinkle: \((a_1, a_2) = (\alpha, 1)\)
C) Slack : \((a_1, a_2) = (\alpha, \alpha)\)

\(\alpha\) generally has a small value because the sail membrane has little stiffness for compression.

In this study, the compressive stiffness of the sail is varied in order to investigate its influence on the sail deployment. It is chosen to vary the compressive stiffness instead of the
thickness of the sail because the mass of the sail changes with respect to the thickness. The compressive stiffness generally increases according to increasing thickness. The dynamics of the sail deployment can be, therefore, analysed adequately by varying the compressive stiffness.

5. Simulation with Various Compressive Stiffness Values

5.1. Nominal compressive stiffness

Fig. 4 shows a successful sail deployment of IKAROS simulated with the conditions in Table 1. Since the compressive stiffness is small enough, the sail deploys easily.

![Simulation of sail deployment of IKAROS (Case 0).](image)

As can be seen, the deployment of the sail on one side of each petal is delayed due to the Coriolis effect as the spacecraft and the sail are rotating anti-clockwise. This result indicates that the double-crease created on this edge of each petal must be overcome for the sail to be deployed successfully. This dynamics of the sail deployment is dependent on the compressive stiffness of the sail, which is, therefore, an important parameter.

5.2. Increased compressive stiffness

Simulation results with the compressive stiffness increased from 500 to 100 times are as follows. In Fig. 5, a final state of the sail from where no more progress is made with the deployment is shown for each case.

![Simulation with increased compressive stiffness.](image)

As shown in Fig.5, the deployment is incomplete and finished prematurely due to the increased compressive stiffness. The sail gets stuck during the deployment and trapped in a local minimum of elastic energy. The magnitude of the compressive stiffness is directly reflected on the sail area successfully deployed.

5.3. Potential energy history

In Fig. 6, histories of potential energy of a petal are plotted against time. The potential energy denotes the sum of the strain energy, bending energy and crease stiffness energy of the folding lines.

![Potential energy histories (Case 0, 1, 2, and 3).](image)

Peaks of the potential energy can be observed between 1 and 3 seconds since the start of the sail deployment. Considering the sail deployment dynamics explained in Chapter 5.1, these peaks are due to a stress applied to the sail when overcoming the double-crease. The fact that the potential energy in Case 0 is very low shows that the sail is easily deployed. The potential energy history justifies the result shown in Fig. 4.

Of particular interest, although the height of the peaks for Case 1 and 2 are high and similar, it suddenly drops for Case 3. This demonstrates that the sail deployment is failed because of the high compressive stiffness at the double-crease in Case 1 and 2 whereas a barrier of potential energy due to the double-crease is overcome in Case 3.

There is, nevertheless, another local minimum of energy subsequent to the double-crease. It can be verified with Case 3 in which the sail gets stuck in the middle of each petal as shown in Fig. 5.

Fig. 7 shows energy per unit volume at the moment when the sail deployment gets stuck. A part of the sail with high energy per unit volume indicates where the sail is stuck. As can be seen, the energy is high at the double-crease in Case 1. This result proves that the energy barrier of the double-crease cannot be overcome when the compressive stiffness is high.

On the other hand, the energy in the middle of each petal is high in Case 3. The sail is trapped in another local minimum subsequent to the double-crease.
In Case 0 to 3, the sail deployment is commenced from a symmetrical shape. In order to investigate the dynamics regarding the sail deployment more deeply, further analysis is made with an asymmetrical initial shape of the sail as shown in Fig. 8.

In this simulation, the compressive stiffness is increased by 200 times. Angles of each petal are defined as angles formed by vectors from the centre of the main body of the spacecraft to each tip mass. The initial values of these angles are set to be 150 deg, 70 deg, 70 deg, and 70 deg.

Fig. 9 shows potential energy histories of each petal in Case 4. The peak of Petal 1 is, for example, significantly lower than that in Case 2 shown in Fig. 6 although the magnitude of the compressive stiffness is unchanged. This is due to the asymmetrical initial shape with the large angle of Petal 1. The initial angle which is greater than 90 deg mitigates the difficulty overcoming the double-crease.

Moreover, it is interesting to note that the height of peaks differs widely between Petal 2, 3 and 4 even though the initial angles are the same.

Fig. 10 shows histories of petal angles. As can be seen, the angle histories oscillate notably. This shows very interesting dynamics of the sail deployment. Conventionally, it was believed that the order of deployment of each petal depends on the initial angle of a corresponding petal. It is intuitive that a petal with a large initial angle deploys earlier than that with a small initial angle. This is because the compressive stresses are higher when the angle is small. Furthermore, it was thought that a petal with a very small initial angle may get stuck and fail to deploy due to the compressive stiffness at the double-crease being too high to be overcome.

Fig. 10, however, contradicts these hypotheses. A remarkable point shown in Fig. 10 is that the in-plane oscillation of petals may give a better chance to deploy to every petal. The initial angles of Petal 2, 3 and 4 are, for instance, as small as 70 deg. There are, however, moments when the angles become greater than 100 deg due to the
in-plane oscillation. At these moments, the corresponding petals may have a chance to deploy successfully. This is a phenomenon which cannot be observed in a deployment from a symmetrical initial shape.

Secondly, the deployment of the sail in the second stage deployment was asynchronous. The deployment of one of the petals delayed significantly.

The analyses made in this paper do not resolve these phenomena. As mentioned above, the sail of IKAROS was thin, and the compressive stiffness is expected to be small enough. Simulation results shown in Fig. 4 and 6 demonstrate that the compressive stiffness does not hinder the sail deployment of IKAROS. The reasons why the two unexpected phenomena were caused are currently under investigation.

8. Conclusions

Firstly in this paper, the sail deployment dynamics of the deployment method of IKAROS is reviewed for a thick sail membrane. The simulation results show that a high compressive stiffness hinders the deployment, and the sail may get stuck and trapped in a local minimum of energy. Secondly, the sail deployment from an asymmetrical initial shape is investigated. It is proved that the barrier of energy due to the double-crease can be overcome with a large initial petal angle. Moreover, the histories of petal angles demonstrate that such a deployment may result in an asynchronous deployment of a sail. There is a possibility that the variations of petal angles due to the in-plane oscillation gives a good chance to deploy to every petal. This result suggests that an asynchronous deployment may be superior to a synchronous deployment. Conventionally, a synchronous deployment from a symmetrical initial shape was always assumed to be desirable. The analyses made in this paper, however, indicate that it may be a preferred alternative to make the cross-shape at the end of the first stage deployment asymmetrical intentionally in order to raise the probability of a successful deployment.

References