The Influence of an Out-of-plane Curvature of the Solar Cells on the Shape of a Spin-type Solar Power Sail

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A squared spin-type solar power sail is currently being considered at JAXA. This solar power sail has thin-film solar cells attached to the surface of its membrane. These solar cells present an inherent out-of-plane curvature which modifies the length of the membrane, and consequently the shape of the whole structure. This study shows using numerical simulations how this curvature affects the shape and stiffness of the membrane, and how the whole solar sail shape changes.

スピン型ソーラー電力セイルにおける反りによる形状と剛性の変化が面外変形に与える影響

JAXA では，スピン型ソーラー電力セイルについて検討を進めている．ソーラー電力セイルは膜面に薄膜太陽電池が貼り付けられたものである．また，薄膜太陽電池は，反ることが確認されており，これにより膜の長さが変化することで，セイル全体の形状が変化することが考えられる．本研究は数値計算により，薄膜太陽電池の反りなどによる膜の長さと剛性の変化により，膜面全体の形状がどのように変化するのかを確かめ，その結果を報告する．

I Introduction

Solar Power Sail is a spacecraft which is accelerated by solar radiation pressure on an expanded membrane in space. A solar power sail generates electricity from thin film solar cell on the membrane in addition to acceleration by solar pressure. Solar sail Demonstrator IKAROS is the world's first solar sail which was launched by the Japan Aerospace Exploration Agency (JAXA) on May 21, 2010 and demonstrated space navigation of the solar sail. [1]

IKAROS is a Spin-type Solar Power Sail. Figure 1 shows the shape and layout drawing membrane device in the IKAROS.

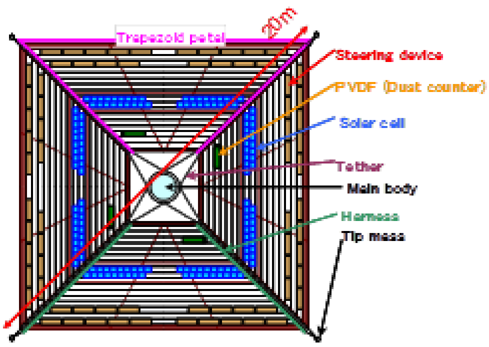
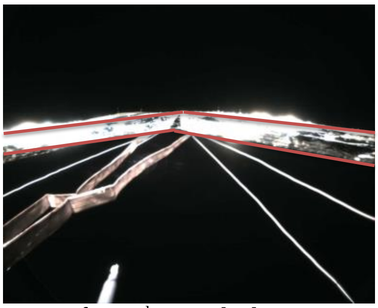


Fig. 1 IKAROS Configuration

IKAROS consists of four trapezoidal membranes called "Petal" connecting small pieces called "Brige". The several membrane devices are attached to membrane surface in IKAROS. Petals are attached to main body with the tethers. Four tip masses are connected to the edge of the Petal by tethers. The centrifugal forces acting on tip mass support the deployment and the expansion. Thin-film solar cells are warped by temperature change because of a multi-layer structure. IKAROS was confirmed by the twisted and warped a petal from IKAROS flight data（Fig.2）.



After 2nd stage deployment

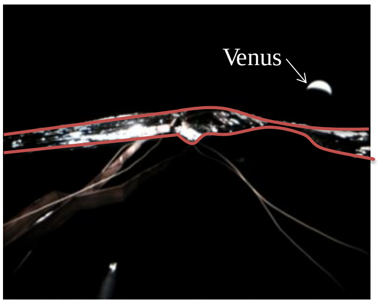


Image of the Venus taken by IKAROS fly by

Fig.2 IKAROS Flight data

Membrane surface was flat after 2nd stage deployment. Membrane surface was twisted in a passing the planet of Venus.

JAXA is now planning an outer solar system exploration mission to a Jovian Trojan asteroid using a solar power sail larger than IKAROS of the membrane's configuration. [3].The next solar power sail has a large membrane and one side of a membrane is 50 m. Also, thin film solar cells are attached on a large part of the membrane.

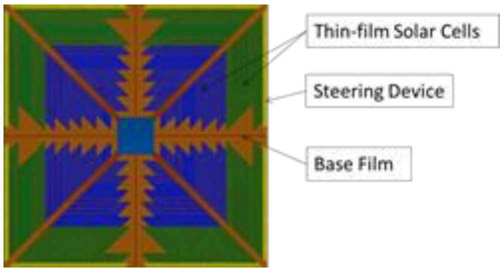


Fig. 3 Next Solar Power Sail Membrane Surface

The curvatures of thin-film solar cells attached to the Petal are considered to change a size of the Petal. This curvature of thin-film solar cell affects the stiffness of the membrane. This study shows using numerical simulations how this curvature affects the shape and stiffness of the membrane, and how the whole solar sail shape changes.

II Multi Particle Model

This study simulated the motion of membrane with multi-particle model. In the multi-particle model, each element of the membrane is substituted by particles connected by springs and dampers. The multi-particle method has the advantage that it is easy to change the analysis model and lower computational cost compared to the finite element model. [3]

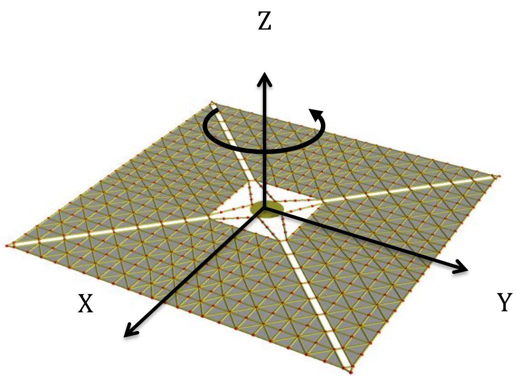


Fig. 4 Multi particle model

The thin-film solar cell is necessary to consider the warp. In the case of a warping thin-film solar cell, the moment of inertia of area is changed. The arc model is applied to the warped shape to calculate moment of inertia of area, as shown in Fig. 5.

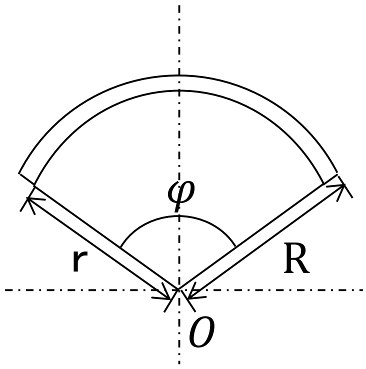


Fig. 5 The shape of arc model

Fig. 5 shows a comparison between the flat model and the arc model. It can be seen that the moment of inertia of area is greatly increased for more warped. In the analysis, the thin-film solar cell is expressed by a rotational spring and the effect of a warp is expressed by the increasing bending stiffness in the range of Fig. 6. [4]

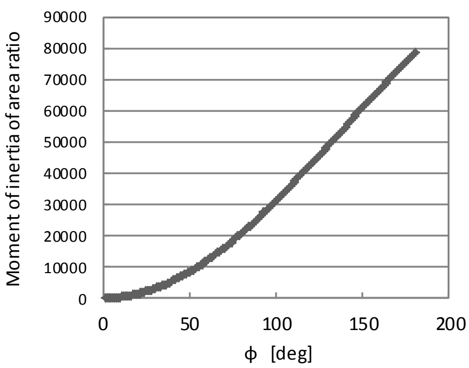


Fig. 6 The moment of inertia of area of comparison between a flat and arc

Ⅲ Simulation Result

In this study, the direction of the curvature of the thin-film solar cell was set to two types which were curvature in the circumferential direction and curvature in the radial direction. Spin rates were set to 0.055 rpm and 1.0 rpm. Figure.7 shows outline figure of a curvature direction.

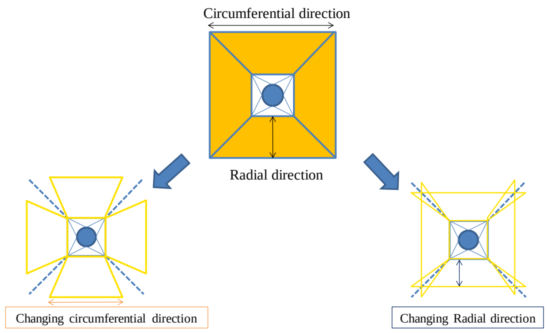


Fig. 7 Image of a curvature direction

High and low compressive stiffness was used.Table.1 shows analysis parameters in this study.

Table1 Condition for this simulation.

No	Compressive stiffness	Curvature direction
1	High	Radial
2	High	Circumferential
3	High	Circumferential
4	Low	Radial
5	Low	Circumferential
6	Low	Circumferential

The bending stiffness in the circumferential direction of thin-film solar cells are assumed to be sufficiently strong because of they are attached in a nested arrangement. Figure.8 shows the simulation result in the case of the warping in the radial direction.

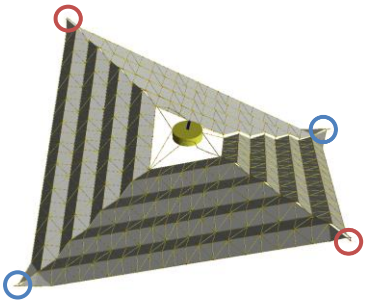


Fig. 8 Saddle-type shape

When petal are warping in the radial direction without changing petal length, solar sail become a shape to divide tip mass into two on a diagonal. Such a shape was defined as a saddle type. Figure.9 and figure.10 show the simulation result in the case of the warping in the circumferential direction.

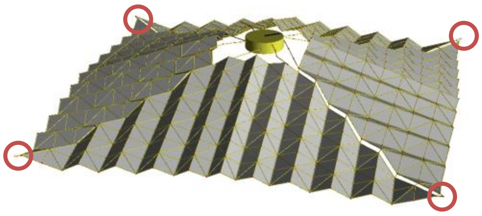


Fig. 9 Umbrella-type shape

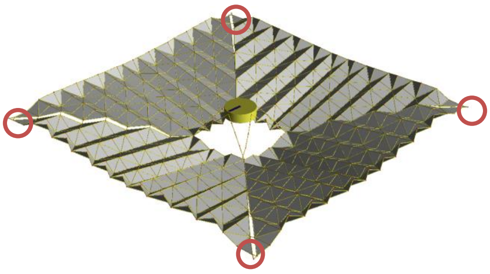


Fig. 10 Umbrella-type shape

When petals are shrunk in the circumferential direction, solar sail become a shape to move in the same direction four tip mass. Such a shape was defined as a umbrella type. The reason for appearing these shapes can be considered to be easily geometric. The changing a membrane by the curvature of the thin-film solar cells can be considered to change the apparent length of the membrane. If the thin-film solar cells are warped in radial direction, the membrane in circumferential direction is left over.

Then, the membrane moves out of the plane to make up for the length of the membrane in the circumferential direction. Therefore, when thin-film solar cells are shrunk in the radial direction, the saddle type appears. On the other hand, in case of the curvature of thin-film solar cells in the circumferential direction, the membrane in radial direction is left over. In case of the curvature of thin-film solar cells in the in the circumferential direction, the membrane moves a center position and membrane in radial direction moves out of plane. Then, the umbrella type appears.

Next, the simulation was performed by changing the compression rigidity. The results show Figure.11, 12 and 13.

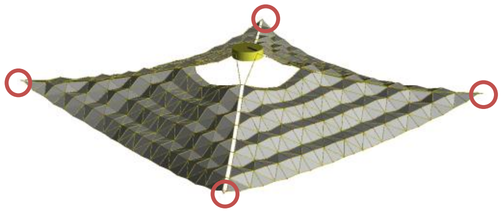


Fig. 11 Saddle-type shape

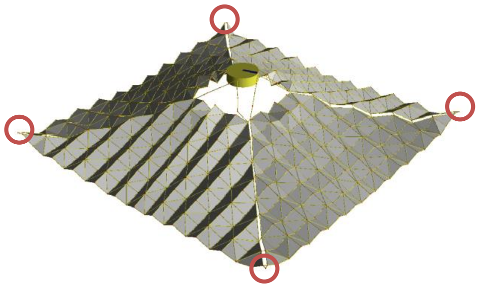


Fig. 12 Umbrella-type shape

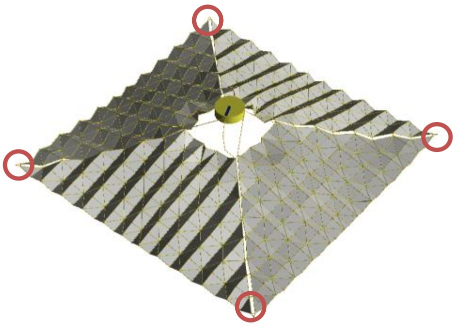


Fig. 13 Umbrella-type shape

The shape of the saddle type could not be seen in this calculation condition. In this reason, a phenomenon caused by the warping thin-film solar cells are resolved by shrinking little by little between each particles

IV Conclusion

In this study, we investigate how the whole solar power sail shape by membrane device influence. Simulation result shows that the solar power sail shape was changed by the effect of the curvature of thin-film solar cells. When petal are shrunk in the circumferential direction, overall shape is an "umbrella-type". When petal are shrunk in the radial direction, overall shape is a "saddle-type" . When the compressive rigidity is weak, the shape change in solar power sail was not appeared.

References

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