Asymmetric Deployment Analysis of Spin-type Solar Power Sail with Improved Multi-Particle Method

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Solar Sail Demonstrator "IKAROS" has been successful in a technology demonstration in space. At the centrifuge deployment of IKAROS, it has been confirmed that their 4 trapezoid membranes deploy asymmetrically. This phenomenon has a negative effect for the spacecraft attitude and the sail deployment. The multi-particle model, which defines the sail as a mass point, a spring and a damper, is limited to the deployment analysis which is taken into account the stress. In this study, it is investigated that the cause of the asymmetrically phenomenon by using the improved multi-particle model which is introduced a few additional elastic parameters.

改良多粒子法を用いたスピン型ソーラー電力セイルの非対称展開解析

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2010 年 **5** 月に打ち上げられた小型ソーラー電力セイル実証機"**IKAROS**"はマストを要しないスピン型ソーラーセイルタイプであり、世界で初めて宇宙空間での技術実証に成功した。**IKAROS** の遠心力展開時、**4** 枚の台形膜面が対称に展開しない非対称性が確認された。このような現象は、探査機姿勢や膜面展開への悪影響から、原因究明が重要である。薄膜構造物の解析手法として、薄膜をバネマスに置き換える多粒子法が提案されているが、応力がかかった展開運動については予測に限界があると考えられる。本研究では、弾性パラメータを増やすことにより改良を加えた多粒子法を用いて、本現象の発生原因の解明を行う。

Nomenclature

F	=	inertial force of element
K	=	spring constant
α	=	compression ratio
β	=	attenuation coefficient
L	=	distance between particles
L_0	=	natural distance between particles
$\boldsymbol{\varepsilon}$	=	total distortion
$\boldsymbol{B}$	=	strain displacement conversion
$\boldsymbol{u}$	=	displacement vector of element
u_A	=	directional vector of element A
u_B	=	x directional vector of element B
v_B	=	y directional vector of element B
x_A	=	x directional displacement of A
x_B	=	x directional displacement of B
y_B	=	y directional displacement of B
$\boldsymbol{\sigma}$	=	stress vector
$\boldsymbol{D}$	=	stress strain conversion matrix
E	=	Young's modulus
ν	=	Poisson coefficient
V	=	volume of element
$\boldsymbol{K}$	=	spring constant vector
t	=	thickness of sail
S	=	area of triangle element
δ_i	=	displacement of element
f_i	=	direction force of element i
k_i	=	spring constant of element i
F_i	=	inertial force of element i

I. Introduction

A solar power sail is a spacecraft which can make the altitude control and solar power generation possible by deploying a thin-film in space. Recently, the technology of the solar sail is actively researched. Solar Sail Demonstrator IKAROS (Fig.1), which was launched on May 21, 2010 was a successful technology demonstration. The main successes are as follows: First, deployment of a large sail membrane; second, generation of electricity by thin-film solar cells; third, demonstration of photon propulsion; fourth, demonstration of guidance, navigation and control techniques for solar sail propulsion.

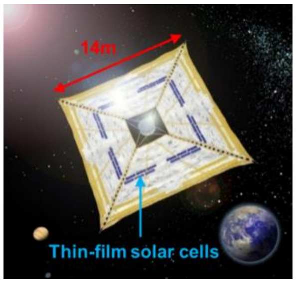


Fig.1 IKAROS

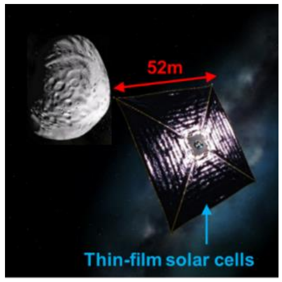


Fig.2 Next solar sail

IKAROS is a spinning type solar sail equipped with a large solar sail that is kept extended by the centrifugal force generated by the spinning of the spacecraft. To be compared with a mast type, it is possible to design a lightweight when the scale of the sail becomes big. In contrast, because the solar sail deploys by only using a centrifugal force and the sail shape depends on the spin rate, it is difficult to estimate the sail shape.

The deployment of IKAROS has two stages. At the first deployment, the four folded sails are extended such as a cross shape. At the Second deployment, the sail is deployed the square shape by removing the restraint bars of the main body. During the actual operation, the pictures taken by the monitor cameras (Fig.3) revealed the late deploying of two parts of the sail for 27seconds. In addition, from the flight data of IKAROS, it is confirmed that the spin rate of the main body is converged in the 60seconds after starting the deployment.(Fig.4) This means that the in-plane vibration is also converged at the same time. On the other hand, it is impossible to reproduce this phenomenon by using the Multi Particle Method (MPM) which is widely used for the thin-firm analysis. As shown in Fig.4, the spin rate of the MPM analysis is not able to be confirmed the convergence. Because MPM is the simplified model which is composed the sail as mass points, springs, and dampers, it can be considered this method has a limitation of the large movement analysis such as the deployment.

However, the convergence of the in-plane vibration of the sail is the important factor to design solar power sails. If the vibration is continued for a long time, it has a bad influence on the operation such as the collision between the main body and the sail, the loss of the sail control and so on. Besides on, the next solar power sail is designed a bigger size than IKAROS. For this reason, the effect will be also expected to be larger. Therefore, in order to reproduce the convergence of the in-plane vibration, Improved MPM which has a stiffness matrix included an asymmetric section is introduced in this study.

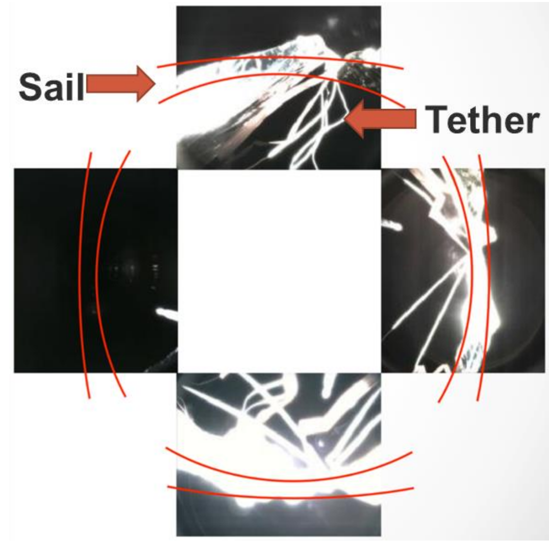


Fig.3 Asymmetric deployment of IKAROS

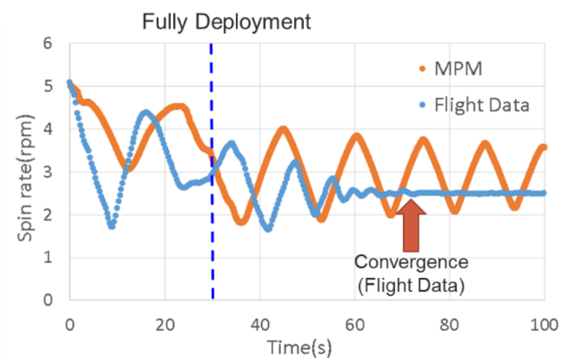


Fig.4 Comparison of Flight data and MPM

II. Analysis Method

A. Multi Particle Method

In multi-particle model as shown in Figure 5, each element of the membrane is assumed to be isotropic and substituted by particles connected by springs and dampers. To be compared with a calculation time of a normal CAE software, it is possible to significantly reduce the long calculation time required for thin-film structures analysis.

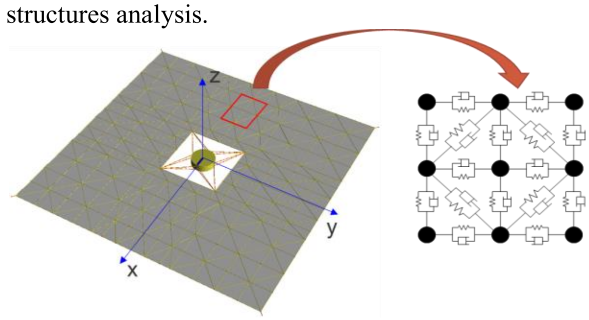


Fig.5 Concept of Multi Particle Method

The inter-particle force F can be obtained as follow;

$$F = \begin{cases} K(L-L_0) + \beta K\dot{L} & (L \geq L_0) \\ K\alpha(L-L_0) + \alpha\beta K\dot{L} & (L < L_0) \end{cases} \quad (1)$$

By dividing the sail into triangular elements, these weights are distributed to each node. On the assumption that is equivalent to the strain energy which is derived from physical properties and elastic energy determined from the displacement of the mass, spring constant K is calculated. Coefficient α of dumping β is derived from the ratio of the spring constant. Assuming that the membrane resistance a compression slightly, nonlinear spring model using coefficients of compression stiffness are employed.

B. Improved MPM

MPM has a disadvantage that it cannot simulate the effect of the displacement in one direction given in other directions because it represents the spring constant as a diagonal matrix from the approximation of the three directions. By contrast, Improved MPM which has been suggested by Yuichi Tsuda is used for this deployment analysis.[1] In this paper, the stiffness matrix is introduced as a representative math formula. Improved MPM allows to reflect an influence of the displacement in all directions to the sail by assuming that it is also including a component in the triangle shape. Firstly, the sail is defined as nodes and elements as shown in Fig.6.

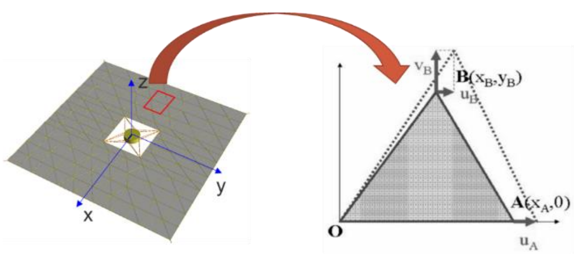


Fig.6 Concept of Improved MPM

When u_A, u_B, v_B are defined as the displacement of each node, **ε** and **B** can be calculated as follows:

$$\boldsymbol{\varepsilon} = \mathbf{Bu} = \mathbf{B}\begin{bmatrix} u_A \\ u_B \\ v_B \end{bmatrix} \quad (2)$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{x_A} & 0 & 0 \\ 0 & 0 & \frac{1}{y_B} \\ -\frac{x_B}{x_A y_B} & \frac{1}{y_B} & 0 \end{bmatrix} \quad (3)$$

By assuming elements of an isotropic material sail, the relationship between **σ** and **D** is obtained from the theoretical strength of materials as follows:

$$\boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon} = \boldsymbol{D}\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \quad (4)$$

$$\mathbf{D} = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \quad (5)$$

By assuming that the displacement of the vertex **F** is corresponded to u = $(u_A\ u_B\ v_A)^T$, the equation of the external force and the internal one on the sail can be represented as follows:

$$(d\mathbf{u})^T \boldsymbol{F} = \int d\boldsymbol{\varepsilon}^T \boldsymbol{\sigma} dV \quad (6)$$

$$\mathbf{F} = \left(\int \boldsymbol{B}^T \boldsymbol{D}\boldsymbol{B} dV\right)\mathbf{u} = \mathbf{Ku} \quad (7)$$

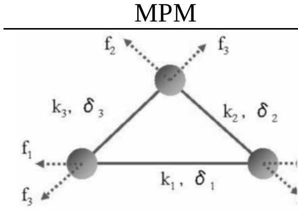
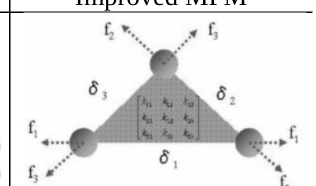
Assuming the sail thickness is a uniform from (2)-(5), K can be represented as follows:

$$\mathbf{K} = \int \boldsymbol{B}^T \boldsymbol{D}\boldsymbol{B} dV \approx \boldsymbol{B}^T \boldsymbol{D}\boldsymbol{B} tS \quad (8)$$

$$= \frac{tE}{2(1-\nu^2)}\begin{bmatrix} \frac{y_B}{x_A} + \frac{1-\nu}{2}\frac{x_B{}^2}{x_A y_B} & -\frac{1-\nu}{2}\frac{x_B}{y_B} & \nu \\ -\frac{1-\nu}{2}\frac{x_B}{y_B} & \frac{1-\nu}{2}\frac{x_A}{y_B} & 0 \\ \nu & 0 & \frac{x_A}{y_B} \end{bmatrix} \quad (9)$$

From the theory, MPM is calculated with the equation of the motion only by the displacement in one direction. On the other hand, Improved MPM is possible to reflect the equation of the motion displacement in all directions as shown in Table1. As a result, a simulation of a strict model can be performed.

Table1. Comparison of MPM and Improved MPM

MPM	Improved MPM
	
$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} k_1 & & \\ & k_2 & \\ & & k_3 \end{bmatrix}\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{bmatrix}$	$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix}\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \end{bmatrix}$
Diagonal matrix	Symmetric matrix

III. Analysis Configuration

IKAROS is connected to four trapezoidal membranes of which the length of outer circumference is 14m. (Fig.7) A trapezoidal membrane is called a petal in this paper. In order to deploy the sail by using the centrifugal force of the spin, it is equipped with four tip masses of 0.5kg in each tip interval of the petals. In the stage of the Second deployment, the four folded petals are fully extended by continuing to spin at 5rpm in the initial condition.(Fig.8) Then, the sail is deployed a square shape by removing the restraint bars of the main body.

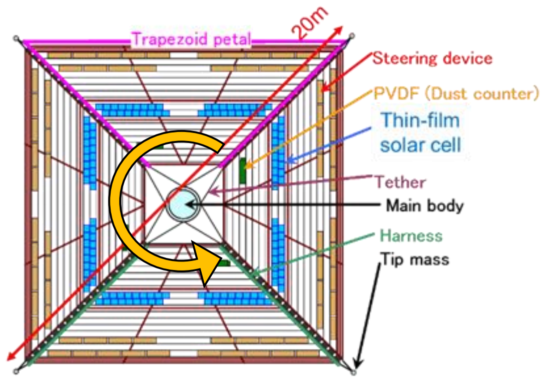


Fig.7 IKAROS Configuration

In this analysis configuration, 1280 triangular faces which are composed of elements of 530mm are used as the whole solar power sail. The number of triangular faces is not enough to express the detailed condition of the sail such as a wrinkle. But the purpose in this study is to evaluate the convergence of the spin rate in the deployment. It is obvious that the effect of the spin rate which is generated by wrinkles is much smaller than the deployment dynamics. Therefore, the number of triangular faces is sufficient to simulate the convergence of the spin rate. The effect of the wrinkle is the outside of the object of the discussion in this study.

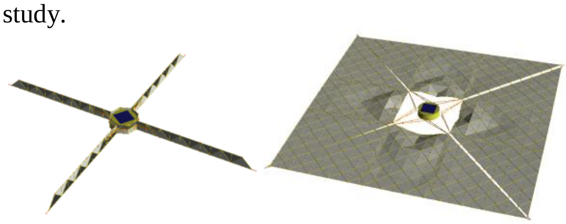


Fig.8 Analysis Condition
(Left: Initial, Right: After deployment)

IV. Analysis Result

A. Comparison of MPM and Improved MPM

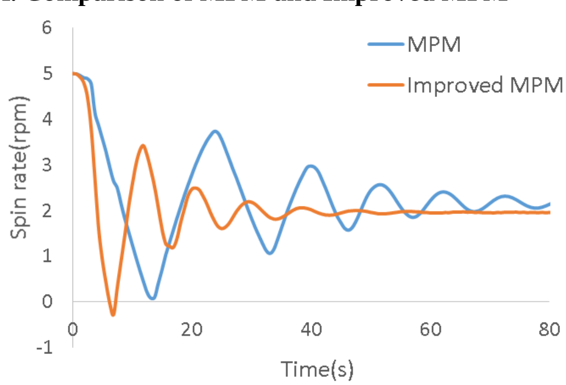


Fig.9 Comparison of MPM and Improved MPM

Fig.9 is shown the comparison of the spin rate transition of MPM and Improved MPM in the symmetric deployment. It can be confirmed the spin rate of Improved MPM is converged at the 50seconds. On the other hand, the spin rate of MPM cannot be seen a tendency the convergence at the 80seconds. From this result, since the stiffness matrix of Improved MPM has an asymmetric section, it can be clearly confirmed the effect of the faster convergence.

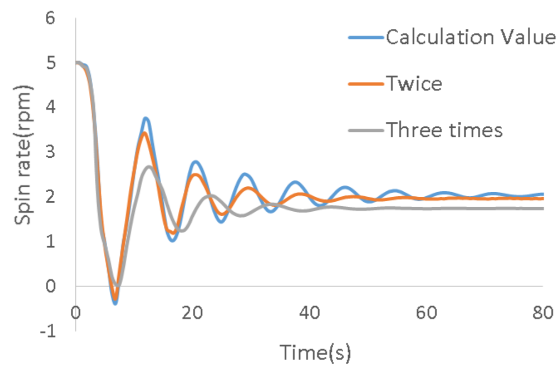


Fig.10 Comparison of Damping value

Fig.10 is shown the comparison of the damping value of the Improved MPM. In this analysis, the damping value of the nominal calculation, twice and three times are investigated. From this result, it can be considered the convergence time and the amplitude of the spin rate depend on the damping value. Therefore, the damping value of the membrane can be acquired by comparing with the flight data of IKAROS.

B. Simulation of Actual Condition

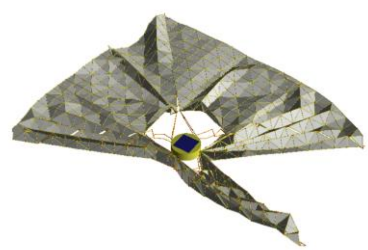


Fig.11 Asymmetric deployment of Improved MPM

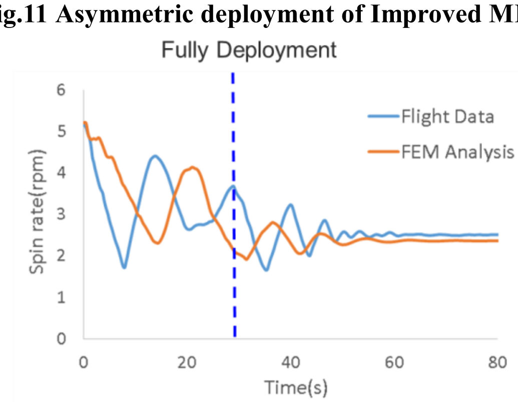


Fig.12 Comparison of Flight data and Improved MPM

Fig.11 is shown the simulation image that the two petals are given the restraint of the deployment till 27seconds. Fig.12 is shown the comparison of the flight data and Improved MPM as well. In this analysis of Improved MPM, the damping value of the sail is applied 2.4 times the nominal damping value. From this result, there is a slight deference of the frequency of the spin rate. However, it can be seen the much consistent of the convergence time and the amplitude of the spin rate with the flight data of IKAROS. In conclusion, Improved MPM is an effective method for designing the future solar power sail about a deployment analysis and deciding a damping value.

V. Conclusion

In this study, since MPM analysis cannot reproduce the actual in-plane vibration of IKAROS, Improved MPM which contains an asymmetric section in the stiffness matrix is introduced to compare with the flight data of IKAROS

From the result of the analysis, it can be clearly confirmed the convergence of the spin rate by using Improved MPM. On the other hand, MPM required a much longer time to converge the spin rate. Besides on, it can be considered the convergence time and the amplitude of the spin rate depend on the damping value of Improved MPM. Then, the comparison of the flight data and Improved MPM of the actual condition is conducted. From the result, there is a slight deference of the frequency of the spin rate. However, it can be seen the much consistent of the amplitude of the spin rate with the flight data of IKAROS. In conclusion, Improved MPM is an effective method for designing the future solar power sail about a deployment analysis and deciding a damping value.

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