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Original Paper

Evaluation of Crease Effects on Out-of-plane Stiffness of Solar Sails

By Tadashi NISHIZAWA[1)], Hiraku SAKAMOTO[1)], Masaaki OKUMA[1)], Hiroshi FURUYA[2)], Yasutaka SATO[2)], Nobukatsu OKUIZUMI[3)], Yoji SHIRASAWA[3)] and Osamu MORI[3)]

[1)]*Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, Tokyo, Japan*
[2)]*Department of Built Environment, Tokyo Institute of Technology, Yokohama, Japan*
[3)]*Japan Aerospace Exploration Agency (JAXA), Sagamihara, Japan*

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This study estimates the effect of creases, or plastic wrinkle lines, on the out-of-plane stiffness of solar sails. A method to simulate the crease effects using reduced-order finite-element (FE) models is proposed, and is applied to a practical solar sail architecture. A detailed crease shape is determined by a geometrically nonlinear FE analysis using a simple model first; the effect of creases is then replaced by beam elements. This method substantially reduces the computational effort required for the FE analysis of a solar sail model. The result suggests the significant impact of creases on membrane's out-of-plane stiffness when the tension level in the membrane is small.

Key Words: IKAROS, Finite Element Method, Wrinkle, Crease

Nomenclature

T	:	tension per unit length
h	:	crease height
S	:	strain energy stored in the sail

1. Introduction

1.1. Background

In 2010, Japan Aerospace Exploration Agency (JAXA) launched the world-first solar sail "IKAROS", shown in Fig. 1, and succeeded the deployment of its large membrane sail and the demonstration of photon propulsion in an interplanetary orbit[1)]. IKAROS is the spin-type solar sail that has no compressive structures to apply tensions in the sail. Instead, the sail is deployed and tensioned by centrifugal forces. The sail size is 20m in diagonal length, and the sail has a square shape made of four trapezoidal membranes. The sail is made of polyimide membrane and its thickness is 7.5μm.

All missions of IKAROS were succeeded; however, some problems became evident during the operation of IKAROS.

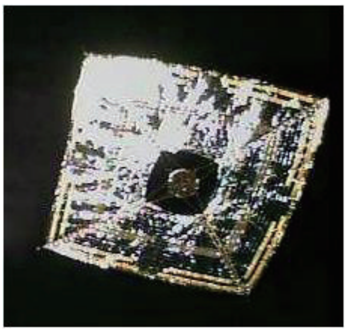

Fig. 1. Picture of "IKAROS" taken in orbit (© JAXA).

One of the problems is about the prediction of out-of-plane stiffness of membrane. IKAROS sent to the ground a considerable amount of images of its sail membrane taken by onboard cameras. These images are different from the pre-flight prediction based on numerical models, with respect to the following two points [2)].

(1) Many local out-of-plane deformations are observed on the sail membrane.
(2) The sail membrane does not significantly deflect even under the radiation pressure.

The item (2) suggests that the out-of-plane stiffness of the membrane has been increased. And the reason of the increase of the out-of-plane stiffness may be explained as the result of the increase of the second moment of area, caused by the local out-of-plane deformations of the membrane described in the item (1). However this effect has not been properly investigated during the development of IKAROS.

In order to design future solar sails, the out-of-plane stiffness of sail membranes should be estimated before the launch, since it determines the requirements for the attitude and orbital control systems. To predict the out-of-plane stiffness of the large sail, a geometrical nonlinear finite-element (FE) analysis using shell elements is often required. However, it is quite difficult to analyze the deformation of the membrane under radiation pressure considering geometrical nonlinearity because it needs heavy computation load to follow many local buckling. In addition, detailed crease shape is difficult to apply to the solar sail model. This is because solar sail size is 10m order, on the other hand, the crease height is 1mm order. So the crease amplitude is very small compared to the solar sail size. Thus, a practical analysis method to estimate the out-of-plane stiffness of sail membranes is needed for the design of future solar sails.

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To estimate the out-of-plane stiffness of a solar sail membrane, the following three factors that appear on the sail should be considered:

(i) Wrinkles
(ii) Creases (plastic wrinkles)
(iii) Deformations of devices attached on the sail

Wrinkles in the item (i) are defined as the elastic deformations of the membrane. By contrast, creases in (ii) are the plastic deformations of membrane caused during the folding process. Deformations of devices, in the item (iii), are the curls of devices caused by thermal and/or radiation effects. These three factors should be compared, and dominant factors should be reflected in the solar sail models. In order to realize the comparison, however, modeling method of "creases" on a membrane, (ii), has not been sufficiently investigated. To this end, this paper aims at estimating the effect of membrane creases on the out-of-plane stiffness of practical solar sails without requiring a large computational effort.

1.2. Past research

Many numerical analyses have been conducted regarding the structures of IKAROS; however, all of them assumed that the sail is a tension field and the sail itself does not have a bending stiffness. Miyazaki et al.[3] added spring-like elements along the crease lines in the FE model of IKAROS, in order to analyze the effect of creases during the deployment of the sail. But the effect of the creases on the out-of-plane stiffness after the sail's deployment has not been investigated.

Miyazaki et al.[4] used analytical models of a creased membrane to investigate the effect of initial plastic deformations to the deployed shape of the membrane. They successfully obtained the out-of-plane crease shape; however, their analysis is limited to one-dimensional models, and applicability to a practical solar sail analysis is not discussed.

Papa et al.[5] conducted the analysis of square membrane, creased according to the Miura-ori folding pattern. Geometrically nonlinear analysis is conducted to investigate the stress distribution and the load-displacement relationship when in-plane, diagonal loads are applied at the corners. However, unlike the present study, they only focused on the in-plane characteristics of creased membranes.

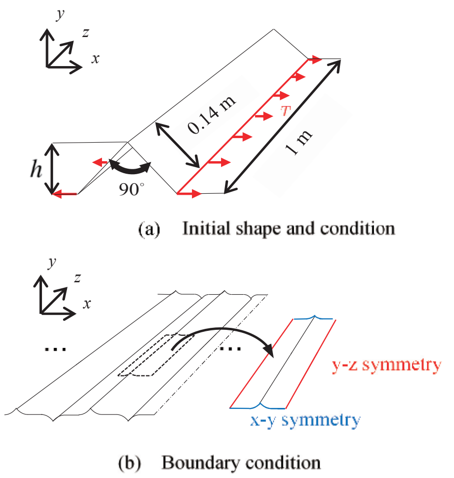

Fig. 2. Detailed model of a creased rectangular membrane.

Woo et al.[6] investigated the dynamic response of creased membranes. The creased square membranes are modeled using nonlinear orthotropic material, and tensioned at the four-corner. In this study, the dynamic response in the out-of-plane direction is considered; however, the tension applied in their sail is so high that the effect of creases only appears as the result of the change of stress distribution throughout the membrane. By contrast, the present study focuses on the effect of crease shape under extremely low tension level.

1.3. Objective and organization

The objective of this paper is to develop a method to estimate the crease effect on the out-of-plane stiffness of a practical solar sail. As mentioned before, there are two difficulties to estimate the out-of-plane stiffness of the membrane sail using conventional method: difficulty about heavy computation load and modeling of the detailed crease shape.

To solve these difficulties, following approach is conducted in the present study. First, eigenvalue analysis is conducted instead of applying radiation pressure. Then, the out-of-plane stiffness is evaluated by natural frequency, which makes computation loads lighter. Second, crease effect is modeled by using beam element so that second moment of area is equal to the detailed crease shape. As a result, the division number of FE meshes will be reduced. Section 2 describes the reduced-order modeling method and the evaluation of its applicability. Section 3 discusses the result of evaluation by applying the proposed reduced-order modeling method to a realistic solar sail.

2. Reduced-order Modeling of Membrane Creases

This section describes the proposed reduced-order model method of membrane crease. In this paper, this reduced-order modeling is named "Simplified creased model". Then, the model validity of this model is evaluated by comparing to the Detailed crease model

2.1. Modeling method of "Simplified crease model"

Detailed crease shapes are modeled by adding beam sections to the flat membrane along the crease line. The beam element is added so that total second moment of area, including both of membrane and beam, is equal to that of detailed crease shapes. The second moment of area of Detailed crease model is calculated from the result of FE analysis. The following subsections describe more details.

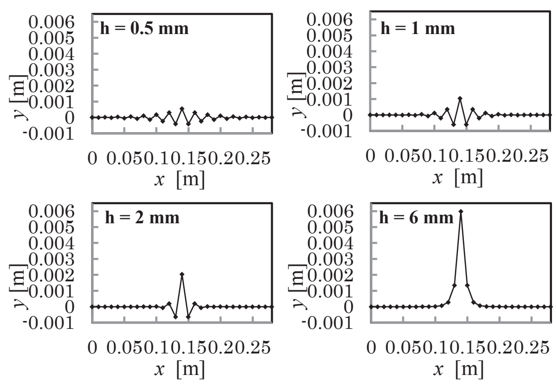

Fig. 3. Node points of crease section.

2.1.1. Extracting the nodal point of detailed crease shape (FE analysis)

To extract the nodal point of detailed crease shape, FE analysis of a simple rectangular membrane is conducted using ABAQUS. In this analysis quasi-static analysis is conducted. Then "NLGeom" option is used to account for geometry nonlinearity and "STABILIZE" option is used for stabilizing computation. To account on the bending stiffness of the membrane properly, a shell element (S4R) is used to model the membrane.

Initial shape of the membrane is assumed to be L-shaped, as illustrated in Fig. 2(a), which represents the plastic deformation of the membrane along the crease line. The width of the membrane is chosen as the same size as crease interval of IKAROS. And tension T is applied to the long direction of the edge. Fig. 2(b) shows the boundary conditions for the rectangular membrane. Longer edge is tensioned and narrower edge is restricted to symmetry boundaries. These boundary conditions represent that the rectangular membrane is a part of infinitely creased membrane. Other analysis conditions are shown in Table 1.

2.1.2. Calculation of second moment of area from detailed crease sections

Fig. 3 shows the nodal coordinates of the crease section computed in the FE analysis. In this analysis, each crease height h varies from 0.50 mm to 10.0 mm. When the crease height is small, some peaks of ripples are observed as shown in Fig. 3. These peaks corresponds to wrinkling phenomena of the membrane around the intentional crease line, but the peaks are unrealistically nonsmooth because of the coarse mesh. Meshes could be refined, which is not conducted in this paper, since the effect of these small ripples on the membrane is not significant in the following analyses. Then from these nodal coordinate, the second moment of area of the detailed creased membrane is calculated.

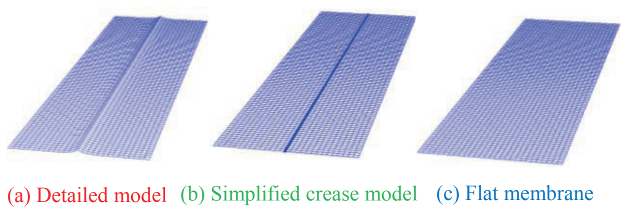

Fig. 4. Examples of FE modes.

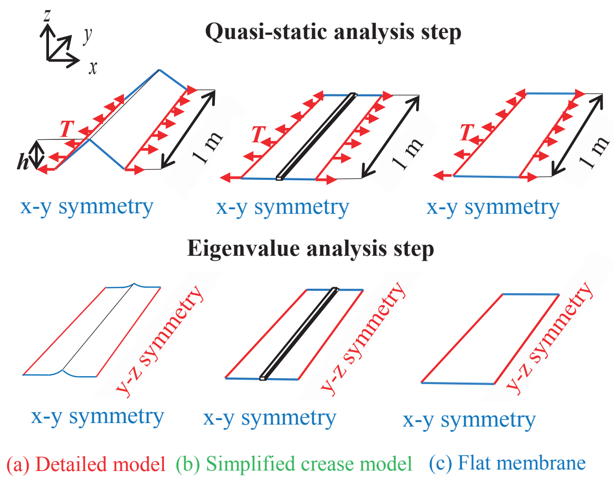

Fig. 5. Boundary condition.

2.2. Evaluation of model validity of "Simplified crease model"

To evaluate model validity of simplified crease model, FE analysis is conducted. This analysis consists of two steps, and the three models are compared. From the analysis, the applicability of the simplified crease model for order estimation is confirmed.

2.2.1. Analysis condition

This analysis consists of two steps: quasi-static analysis and eigenvalue analysis. In the quasi-static analysis step, geometrical nonlinearity is considered and tension are applied on the membrane along the longer edge. Then eigenvalue analysis is conducted using the tangent stiffness matrix in the equilibrium state.

There are three types of analytical model. Detailed crease model, Simplified crease model, and Flat membrane. Fig. 4 shows the examples of each model. The Detailed crease model is L-shape membrane at first, and deployed by applying tension along the longer edge. Simplified crease model is consisted of beam and membrane made by modeling method explained before. Flat membrane is only the rectangular membrane. This model is made for comparing to other models.

Boundary condition is shown in Fig. 5. In the first step, the longer side is tensioned, and the narrow side is symmetry condition for all models. In the next step, all boundary is constrained to symmetry. Model properties of rectangular membrane are shown in Table. 1. A shell element (S4R) is used for membrane, and beam elements (B31) is used for crease in Simplified crease model. In ABAQUS, S4R is 4-node, quadrilateral, stress / displacement shell element with reduced integration and a large-strain formulation. B31 is 2-node linear beam element. The density of beam section used for crease in Simplified crease model is set to 0, so that the total mass of all models is the same.

2.2.2. Analysis result

Fig. 6 shows the result of eigenvalue analysis of the FE model of the rectangular membranes under tension. The abscissa is tension T [N/m] per unit length, and the ordinate is a natural frequency of the membranes. A mode frequency for the first bending mode is used for comparison. Fig. 7 shows the

Table 1. Model properties of rectangular membrane.

	Membrane	Crease
Section	Shell (S4R)	Beam (B31)
Material properties	E = 3.0GPa $\nu = 0.3$ $\rho = 1420\ \mathrm{kg/m^3}$ Thickness: 7.5μm	E = 3.0GPa $\nu = 0.3$ $\rho = 0\ \mathrm{kg/m^3}$
Mesh size	0.001 m	
Number of element	2900 (for Detailed crease model and Flat membrane model) 2800 (for Simplified crease model)	

mode shapes of each model, and the colors of the membranes show the displacement of the mode shape. These mode shapes are the first bending mode of each model for three different crease heights.

In the plot shown in Fig. 6, the red line is the Detailed crease model, the green broken line is the Simplified crease model, and the blue dotted line is the Flat membrane model. Under high tension, the height of crease is small, and the height of crease getting higher as the applied tension is smaller.

In the Flat membrane, its natural frequency behaves linearly on the double-logarithmic plot in Fig. 6. On the other hand, the Detailed crease model behaves differently. Under high tension,

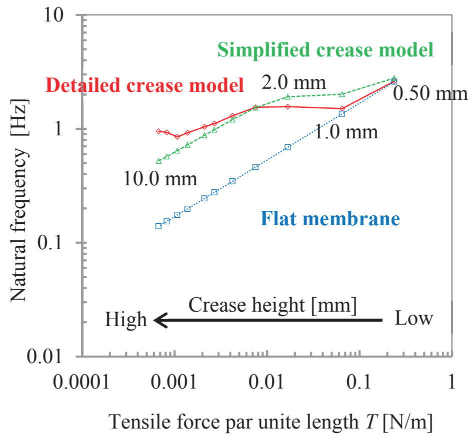

Fig. 6. Comparison of natural frequency among the three models.

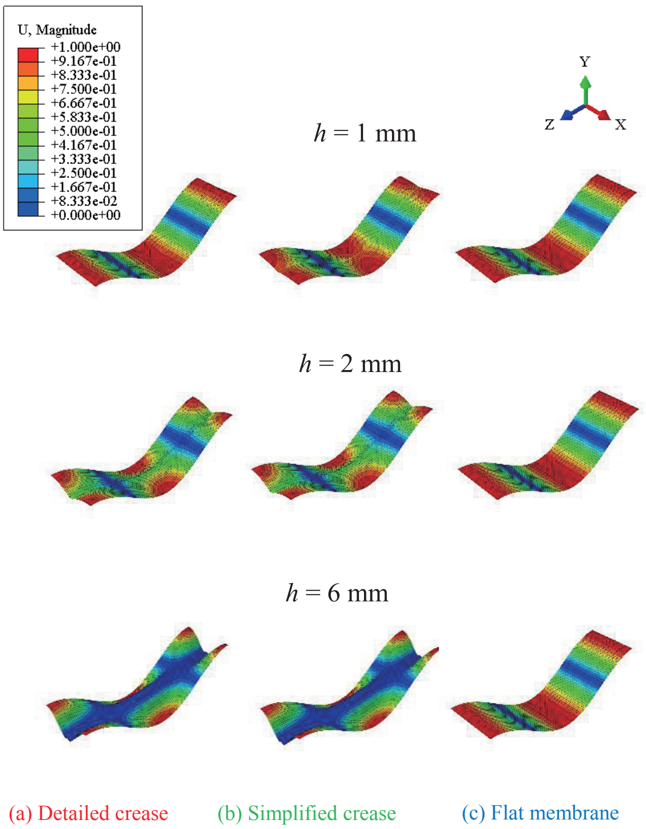

Fig. 7. Mode shapes of each model.

the Detailed crease model has the similar natural frequency with the Flat membrane model. However, as the tension reduces, the crease effects become evident in the natural frequency. For example, when $T = 6.73 \times 10^{-4}$[N/m], the natural frequency of the detailed model is 0.951 Hz, which is 7.04 times larger than the Flat membrane.

Comparing the Detailed crease model to the Simplified crease model, where the beam element is added on the flat membrane, the natural frequency changes similarly with respect to variable tensions; in addition, the mode shapes are also quite similar, as shown in Fig. 7.

In Fig. 6, when the applied tension is small (around 0.001N/m), the natural frequencies of the Detailed crease model slightly increase. This is because of a sudden increase of second moment of area of Detailed crease model due to remain the initial folded shape of the model as the applied tension decrease. However, as discussed later, the crease heights of these area are unrealistically high (8~10 mm) compared to the realistic crease height (2~3mm in maximum). Thus, the authors concluded that Simplified crease model can be used for order estimation within the range of crease heights which should be considered for the design of solar sails. As discussed in Section 3, the tension applied to the membrane in this analysis is, in fact, still much higher than the tension in the IKAROS's sail under the low spin operation. Moreover, in the actual membrane, the crease does not exceed a certain height when a strong tension is applied once, and then unloaded. Thus, another assumption about the crease heights is added in Section 3.

3. Evaluation of Crease Effect in Solar Sail Size

In this section, simplified method is applied to the solar sail size, and the crease effect is evaluated quantitatively by comparing the natural frequencies of the sail.

3.1. Modeling method

The solar sail model with creases is constructed as follows. In IKAROS, the centrifugal force due to spin is applied

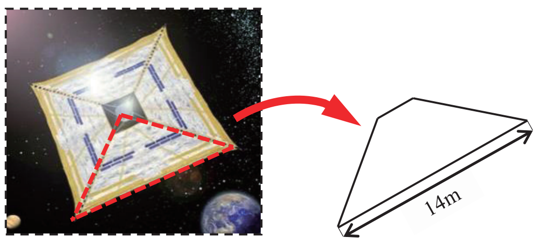

Fig. 8. Modeling area of FE solar sail.

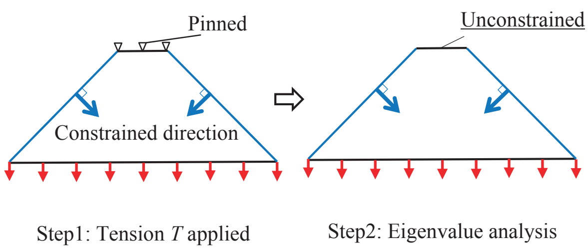

Fig. 9. Boundary conditions in each analysis step.

throughout the sail. In this study, uniform tension is applied along the edge of the solar sail model for simplification. This simplification enables to distinguish the effect of geometric stiffness due to tensions and the effect of second-moment area increase due to out-of-plane deformations.

For the reason mentioned in Section 2.2, the following new assumption is added to evaluate the membrane behavior under extremely low tension level. In the following, crease height is fixed at a constant value. In other words, the same size of beam section is added in the Simplified crease model, even though applied tension T [N/m] is changed. Crease heights are fixed to 0.5, 1.0, 2.0 and 3.0 mm.

For symmetry, only one trapezoidal sail membrane is modeled, as illustrated in Fig. 8. This model has the same size with IKAROS. Fig. 9 shows the boundary conditions. The equilibrium condition of the tensioned sail is calculated as follows in the geometrically nonlinear quasi-static analysis. In the first analysis step, upper edge is pinned, namely, all translational degrees of freedom (DOFs) are constrained, and the tension is applied along the bottom edge. In addition, the translational DOFs normal to both hypotenuses are constrained. In the second analysis step, all DOFs along the upper edge are unconstrained and linear vibration analysis is conducted using the tangent stiffness matrix in the equilibrium state.

Fig. 10 shows the FE model of the creased sail. IKAROS is folded 18 times in each trapezoidal membrane. Thus, there are 18 crease lines in the model. Table 2 shows other analysis conditions.

In order to estimate the relationship between the tension level in the sail and the spin rate of the sail, strain energies stored in the sail under uniform edge load and under the centrifugal force are compared. This analysis is described in Appendix A in detail.

3.2. Results of crease effect estimation

Figs. 11, 12 and 13 show the analysis results. Their abscissa is applied tension per unit length T [N/m], and the ordinate is

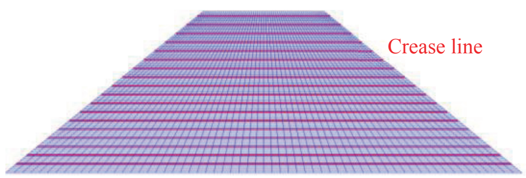

Fig. 10. FE model of solar sail membrane.

Table 2. Model properties of solar sail model.

	Membrane	Crease
Section	Shell (S4R)	Beam (B31)
Material properties	E = 3.0GPa ν = 0.3 ρ = 1420 kg/m^3 Thickness: 7.5μm	E = 3.0GPa ν = 0.3 ρ = 0 kg/m^3
Mesh size	0.1 m	
Number of element	6820 (for Creased membrane model) 5704 (for Flat membrane model)	

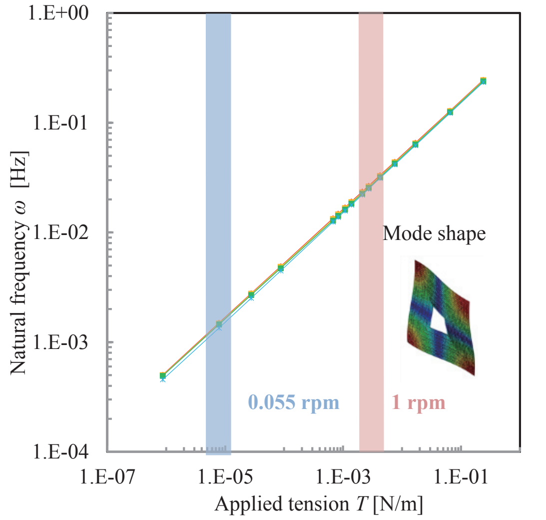

Fig. 11. Comparison of creased and flat membrane by natural frequency (mode1).

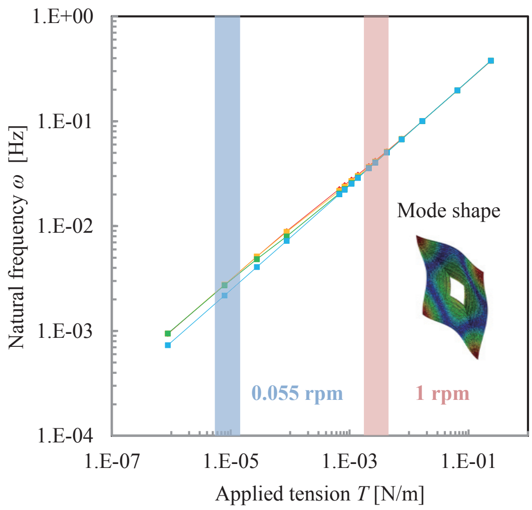

Fig. 12. Comparison of creased and flat membrane by natural frequency (mode 2).

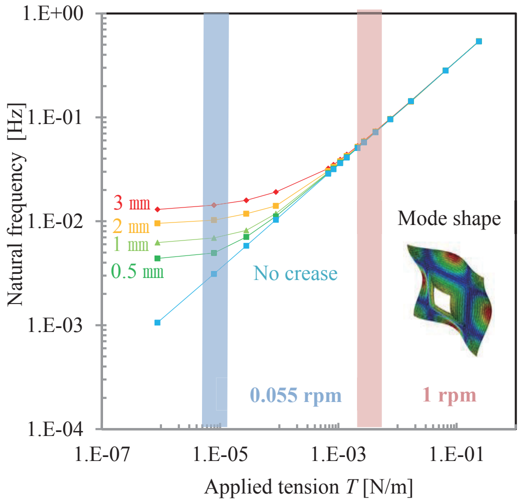

Fig. 13. Comparison of creased and flat membrane by natural frequency (similar mode shape is selected).

natural frequencies in Hz. There are four lines, which correspond to the variable crease heights: h = 0, 0.50, 1.0, 2.0, 3.0 mm. The first few lowest modes are used for evaluation. The corresponding mode shapes are shown in each figure. When the mode shapes are displayed, four of the FE models are combined using mirror symmetry.

Fig. 11 shows the results for "mode 1", which is the fundamental elastic mode in the vibration analysis. In this mode, crease effects on the natural frequency are rarely observed. At most, when $T = 8.75 \times 10^{-7}$N/m, natural frequency is 5.04×10^{-4}Hz at h = 3.0 mm. This natural frequency is 1.02 times higher than the non-creased model. In Fig. 12, "mode 2" is the second lowest mode appeared in the eigenvalue analysis. This mode is also only slightly affected by the creases. At most, when $T = 8.75 \times 10^{-7}$ N/m, natural frequency is 8.75×10^{-7}Hz at h = 3.0 mm, which is 1.30 times higher than non-creased model.

Unlike the previous two modes, the mode shape plotted in Fig. 13 is significantly affected by the creases. This mode shape appears as the forth to eleventh elastic mode. At most, when T $=8.75 \times 10^{-7}$N/m, natural frequency is 1.30×10^{-2}Hz at h =3.0mm, which is 12.3 times higher than non-creased model.

Comparing three modes, it is shown that the creases affect the natural frequencies only when the tension is small, and the crease effects are significantly depend on its mode shape. This is because the systematically creased membrane is highly anisotropic. To estimate the out-of-plane stiffness more adequately for the next solar sail, the methods to select the dominant modes for the sail deflection under solar radiation pressure should be constructed.

Figs. 11-13 also show that approximately what tension level in this sail model corresponds to the spin rate of IKAROS, using the estimation method described in Appendix A. As shown in Fig. 13, the effect of creases is minimal when the spin rate is 1 rpm. By contrast, the effect of creases is significant for this mode when the spin rate is 0.055rpm. This result suggests that the effect of creases of the sail should be properly taken into account during the low tension-level operation.

4. Conclusion

The effect of creases on the out-of-plane stiffness of a practical solar sail is estimated by using Simplified crease model. The simplified method uses beam elements attached along the crease lines. Creases affect the out-of-plane stiffness significantly to a certain vibration mode when the applied tension is small. The analysis in this paper suggests that the tension level in IKAROS during the low spin-rate operation was low enough that the effect of creases should be properly taken into account.

Acknowledgments

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Reference

1) Sawada, H., et al.: Mission Report on the Solar Power Sail Deployment Demonstration of IKAROS, AIAA Paper 2011-1887, April 2011.
2) Shirasawa, Y., et al.: A Study on Membrane Dynamics and Deformation of Solar Power Sail Demonstrator "IKAROS", AIAA Paper 2012-1747, April 2012.
3) Miyazaki, Y., et al.: Conserving Finite Element Dynamics of Gossamer Structure and Its Application to Spinning Solar Sail "IKAROS", AIAA 2011-2181, April 2011.
4) Miyazaki, K. Y., et al.: Effects Of Initial Configuration On Large Deformation Analysis For One-Dimensional Deployable Membrane, AIAA Paper 2005-2046, April 2005.
5) Papa, A., and Pellegrino, S.: Systematically Creased Thin-Film Membrane Structures, *Journal of Spacecraft and Rockets* **45** (2008), pp.10-18.
6) Woo, K., Nandukar, K., and Jenkins, C. H.: Dynamic Response of Systematically Creased Membranes, AIAA Paper 2007-1806, April 2007.

Appendix A. Estimation of equivalent uniform tension

As discussed in Section 3, this study replaced the centrifugal force applied to the IKAROS model by the uniform tension applied along the membrane edge. In this Appendix, an equivalent tension level that corresponds to a certain spin rate of IKAROS is estimated by comparing strain energies stored in the membrane. For this purpose, another sail model, on which centrifugal force is applied, is made. Estimation method is described as follows.

A.1. Trapezoidal sail model under centrifugal forces

First, the solar sail model applied uniform tension, which is the same model used in Section 3, is computed to obtain the stored strain energy in the equilibrium state. Fig. 15 shows the results by blue circles, and the results are fitted by a curve.

Second, another solar sail model is made, and applied centrifugal force. Fig. 14 shows the solar sail model applied centrifugal force. This model has tip masses (0.5 kg) and tethers that represent the actual IKAROS. These attached elements are removed when the strain energy is extracted from this model. Analysis conditions are shown in Table 3. The strain energy is again obtained in the equilibrium state using the geometrically nonlinear analysis.

A.2. Results

The relationship between strain energies and uniform tensions applied along the edge is shown in Fig. 15. A fitted curve is obtained as$T = 27.69\ S^{0.5}$. From this regression model, the equivalent uniform tension is estimated as T=2.60×10^{-3} [N/m] when the spin rate is 1 rpm, and estimated as T=7.87×10^{-6} [N/m] when the spin rate is 0.055rpm.

Table 3. Model properties of solar sail model (spin centrifugal force applied).

	Membrane	Crease	Tether
Section	Shell (S4R)	Beam (B31)	Beam(B31)
Material properties	E = 3.0Gpa ν = 0.3 ρ = 1420 kg/m^3 Thickness: 7.5μm	E = 3.0Gpa ν = 0.3 ρ = 0 kg/m^3	E = 11.0Gpa ν = 0.3 ρ = 1813 kg/m^3 Diameter : 1.46 mm
Mesh size	0.1 m		
Number of element	6178		
Spin rate	1 rpm, 0.055 rpm		

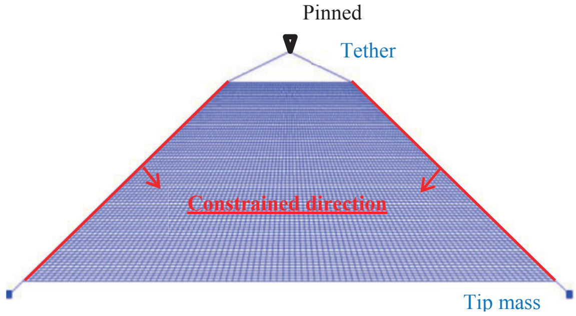

Fig. 14. FE model of sail membrane applied spin centrifugal force.

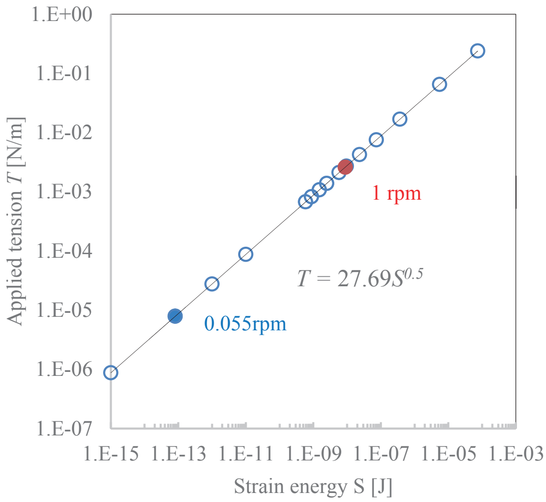

Fig. 15. Tension level versus strain energy for the estimation of equivalent tension.