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Deployment Characteristics of Rotationally Skew Fold Membrane for Spinning Solar Sail

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A rotationally skew fold membrane for the spinning solar sail is discussed to examine the deployment characteristics. The membrane is characterized by double corrugation fold and is advantageous in the complete folding and compact storage. Spinning experiments with scaled models are performed to investigate the geometrical and deployment characteristics. As the result of the spinning experiments, it is indicated that the rotationally skew fold membrane is completely deployed and there is a minimum spin rate to complately deploy. The fact that the spin-direction wrapped membrane realizes quick deployment is also indicated. To investigate the dynamic characteristics, a non-dimensional similarity parameter derived with the theoretical analysis for one-dimensional Z-fold membrane is expressed by the geometrical parameters as the radius, folding pitch, material properties and spin rate. The theoretical similarity parameter is applied to the results of the spinning experiments and indicates the effect of the folding pitch of the rotationally skew fold membrane. Also the similarity parameter based on the experimental results is introduced.

I. Introduction

Solar sail is a spacecraft characterized by utilizing sunlight. It consists of highly reflective membrane that reflects photons to get momentum and propel the spacecraft forward without thrusters. The unique advantage of solar sail compared with conventional rocket is that it can get low acceleration constantly because photons keep hitting membrane as long as the solar sail is in space. Although this acceleration is very small, the speed of the solar sail increases day by day. Therefore, solar sails are suitable for a long flight such as an interstellar mission. It is also noted that the propellantless propulsion system and ultra-light weight structure can reduce both the manufacturing cost and launch one.

A basic concept of solar sails was first proposed by the Russian astronautical pioneers Friedrikh Tsander and Konstantin Tsiolkovsky in about 1920. Afterwards, the solar sails of various designs such as three axis stabilized square type, heliogyro type and spinning disk type were proposed according to the mission requirements. As the feasibility of the solar sail has improved greatly by the development of the thin film technology in recent years, some research groups have been starting the proof plan of their sails. NASA demonstrated the deployment experiments on the ground with the scaled square solar sail that uses the deployable masts and examined through the experimental results and analyses.[1–3] The Planetary Society has a plan of launching and deploying COSMOS-1 in space in spring of 2005.

In order to obtain the momentum from photons enough to propel a spacecraft forward, the surface of the sail membrane should be at least 50 meters diameter. Therefore, it is necessary that the membrane is stowed within the available size at the launch and is completely deployed in space. Also the solar sail should be designed while examining easiness of the manufacturing, stability of the deployment behavior and flatness after deployment. When the flight is a very long distance such as inquiry of Saturn, the diameter of the solar sail becomes about 100 meters. In

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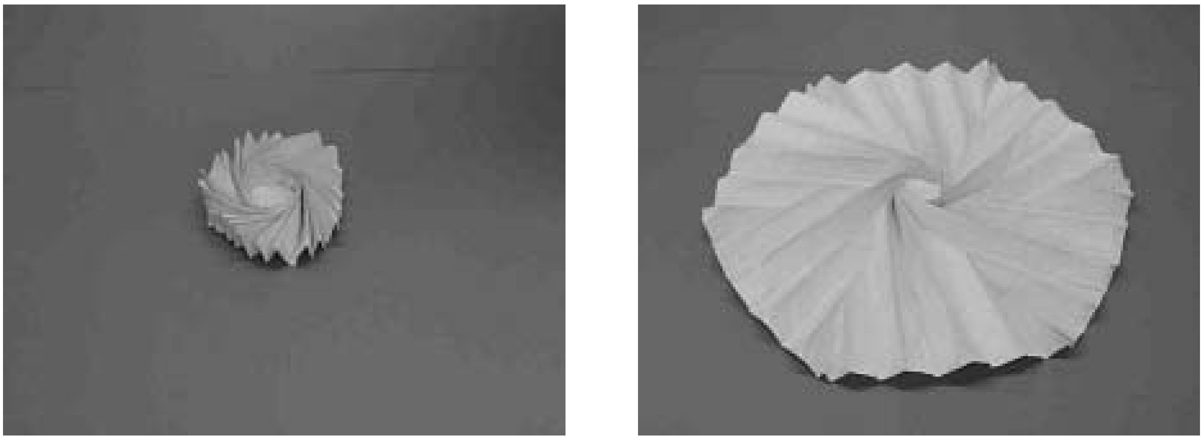
the case of using the deployable booms, substantial tension is needed for flatness of the sail membrane. Therefore, we have to improve the buckling load of the booms to support the sail membrane. As the weight of the sail increases with increasing the boom stiffness, it is inescapable that the propulsion efficiency decreases.

A spinning solar sail is one of the solutions to meet the requirements. The spinning solar sail is a structural system that generates a tension by the centrifugal force to deploy and stabilize the membrane. The spinning solar sail can achieve full deployment and flatness without deployable booms. Therefore, the minimum weight and huge scale solar sail membrane is realized for future space exploration missions. Onoda et al. investigated the effect of the creases and the radial tension in a spin-stabilized solar sail membrane.[4] ISAS/JAXA demonstrated the deployment experiment of two types of solar sail models in space using a S310 sounding rocket in August of 2004.[5,6] The diameter of the models is 10 meters. The experiment was performed successfully and proved that the spinning solar sail can work in practice. The two experimental models are called "fan type sail" and "clover type sail", respectively. The fan type sail consists of six triangular membranes called petal and some cables called bridge that connect with both side petals to deploy with utilizing circumferential tensions. On the other hand, the clover type sail is characterized by two stages deploying. Each petal is deployed like a cross in the first stage, and in the next stage the clover type sail is fully deployed. Both two types contain a little bit complex structural system.

Whereas we have proposed the two dimensional folding pattern called "rotationally skew fold" for spinning solar sail membrane (Fig. 1).[7] This design is characterized by double corrugation folding and is advantageous in the complete folding and compact storage. We have examined the basic geometrical characteristics of the rotationally skew fold membrane using small experimental model of 0.15 m in radius.

In this paper, we demonstrate spinning experiments with 0.15 m and 0.30 m radius models of the rotationally skew fold to investigate the deployment characteristics for various geometrical characteristics and spin rates. We consider similarity parameters through the theoretical analysis for a one-dimensional triangular Z-fold membrane and the experimental results, respectively. Also the similarity parameter based on the experimental results is introduced.



(a) Folding (b) Deployment

Figure 1. Folding and deployment configuration of rotationally skew fold

II. Rotationally Skew Fold

We have proposed a concept of the rotationally skew fold for spinning solar sail membrane in Ref. 7. In this section, the basic geometrical characteristics of the rotationally skew fold are briefly described.

Figure 2 indicates the plane view of the rotationally skew fold for spinning solar sail membrane. Solid and broken lines stand for mountain fold and valley fold, respectively. The fold is rotational symmetry and has the hexagonal center region. Six straight fold lines originate at the vertices of the center region and extend to the edge of the membrane. The mountain fold lines and valley fold lines are alternately drawn in parallel between the radial lines.

This fold membrane is wrapped around the center region and is completely foldable. As shown in Fig. 1, the packaging height is equal to the distance of the parallel fold line called “folding pitch”, and therefore, the height is independent to the membrane radius. In general, as the membrane thickness is less than 10 μm, the effects of thickness on the complete packaging are negligible. As the fold model consists of only membrane without any cables used in the fan type sail to transfer the radial force to the circumferential tension, deployment is realized without tension stresses in local areas. In addition, as the fold lines don’t concentrate near the vertices of the center region and the straight lines are parallel with each other, the rotationally skew fold membrane is easily stowed.

In the case of larger solar sail membranes, a method that some petals are connected with each other is considered as shown in Fig. 3. Two types of petal are indicated by thick lines in Fig. 2. Area A in Fig. 2 consists of Z-folds and area B consists of double corrugations (L-folds). Though the Z-folds are easily foldable, connecting with each petal is difficult due to the zigzag edges. On the other hand, the L-folds are difficult to fold but connecting with each petal is easier than the Z-folds due to the straight edges. Folding pitches are expected to be about 1 m to manufacture the real size solar sail and petals are made of the roll of membrane material as shown shaded portion in Fig. 2. Petals are connected with each other as rolled around the center region.

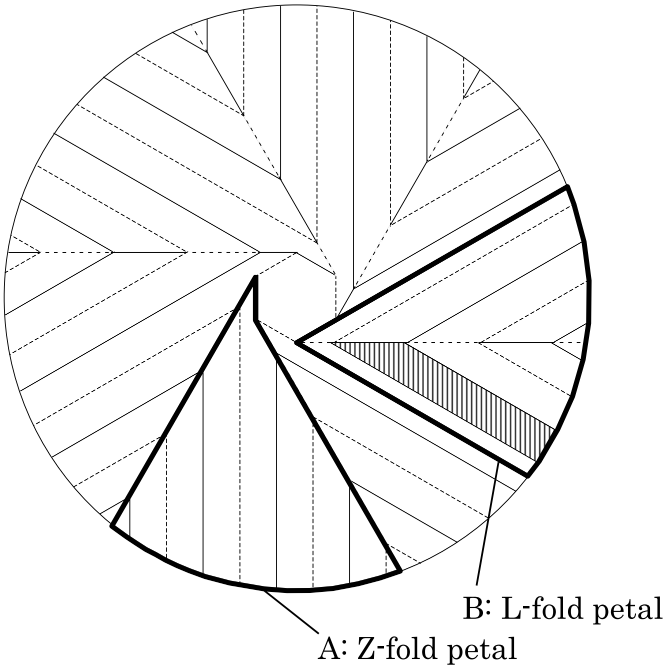
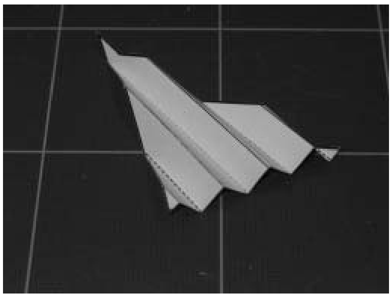


Figure 2. Plane view of rotationally skew fold



(a) Z-fold petal

(b) L-fold petal

Figure 3. Fold of petal element

III. Experiments

A. Experimental Setup

Spinning experiments of the rotationally skew fold membrane were performed to examine the deployment characteristics for various geometrical characteristics and spin rates. As shown in Table 1, we prepared three membrane models characterized by some radiuses and folding pitches. The models are made of 12.5 μm thickness polyimide film with aluminum coating (UPILEX-S, Ube Industries, ltd.) Table 2 shows the properties of the membranes used in the experiments.

A schematic diagram of the experimental setup is shown in Fig. 4. The membrane was fixed with and wrapped around the center hub, 35 mm diameter installed in the spinning table. In order to avoid the effect of the friction, the membrane was separated from the spinning table. This apparatus is covered in polypropylene case to reduce the effect of airflow. In addition, a digital camera was positioned over the spinning table.

In this experiment, the membrane was rotated by an AC power supply at the spin rates between 0 rpm and 350 rpm. The experiment starts from free condition and the spin rate increases step by step. At each step, deformations of the membrane on deploying were measured by the digital camera and spin rates were observed by a tachometer. The spinning direction of the spinning table was clockwise and membrane was set in such a way that wrapping directions are clockwise (cw) and counterclockwise (cc) from the view point of the digital camera.

Table 1. Notation of membranes

	R(m)	d(m)
model-1	0.15	0.02
model-2	0.30	0.02
model-3	0.30	0.04

Table 2. Properties of membranes

Thickness, h(m)	12.5×10^{-6}
Density, $\rho(\mathrm{g/cm^3})$	1.47
Young's modulus, $E(\mathrm{N/m^2})$	9.00×10^9

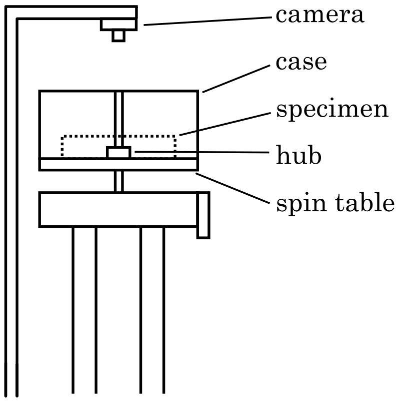
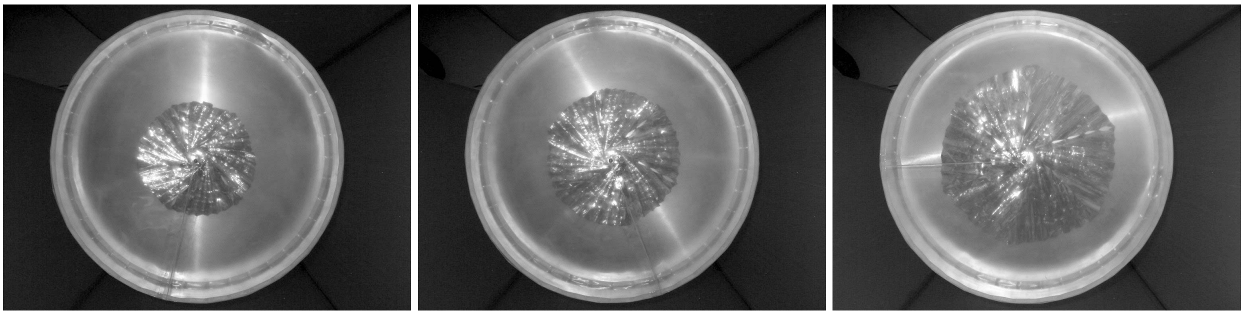


Figure 4. Experimental setup

B. Experimental Results

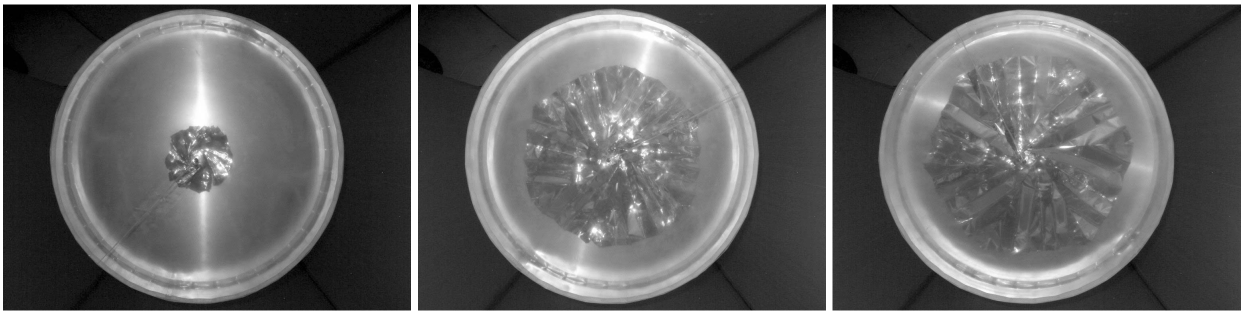
Figures 5-7 show the deploying configuration of model-2(cw), model-3(cw) and model-3(cc) and spin rates are expressed under each photograph. In each figure, (a) is the deformation of membrane at about 50 rpm, (b) is at about 100 rpm and (c) is at about 150 rpm, respectively.

As shown in Fig. 5, the model-2(cw) is deployed from the beginning to some degree and keep deploying monotonously as the spinning rate increases. The model-3(cw) is deployed rapidly between from 73 rpm (Fig. 6(a)) to 106 rpm (Fig. 6(b)). And the deployment area in Fig. 6(c) is larger than the model-2(cw) at 150 rpm in Fig. 5(c). As shown in Fig. 7(b) and 7(c), The model-3(cc), which is the same specimen as the model-3(cw) but an opposite wrapping direction, is deployed rapidly between from 97 rpm to 145 rpm. The deployment area in Fig. 7(c) is almost same as the model-3(cw) in Fig. 6(c).



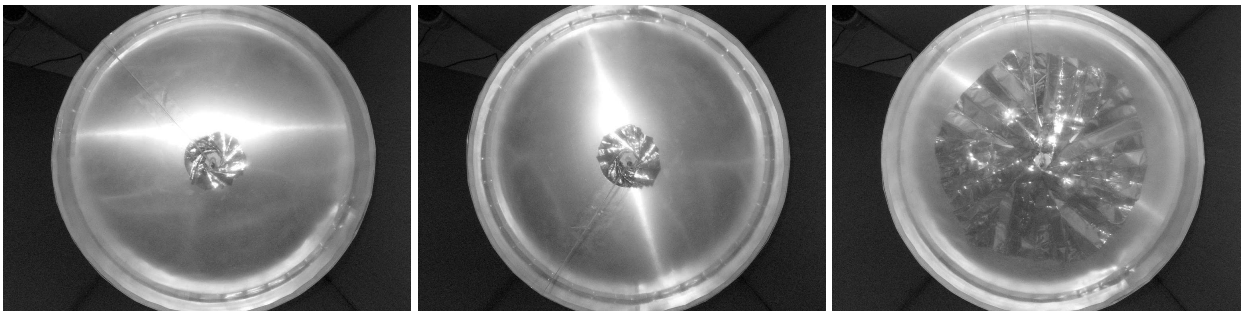
(a) ω=46 rpm (b) ω=105 rpm (c) ω=150 rpm

Figure 5. Deployment process of model-2 (cw)



(a) ω=73 rpm (b) ω=106 rpm (c) ω=152 rpm

Figure 6. Deployment process of model-3 (cw)



(a) ω=57 rpm (b) ω=97 rpm (c) ω=145 rpm

Figure 7. Deployment process of model-3 (cc)

Deploying radiuses were measured from each figure to investigate deployment behavior. The deployment ratio based on the deploying radius with respect to the spin rate is indicated in Fig. 8, where the deployment ratio is a ratio of the deploying radius to original radius. In Fig. 8, it seems the deployments doesn't proceed dramatically until about 150 rpm for the model-1(cw), 120 rpm for the model-2(cw), 90 rpm for the model-3(cw) and 130 rpm for the model-3(cc). For all models, as spin rate increases the deployment ratio increases gradually. The spin rate where the deployment ratio reaches 90% is 332 rpm for the model-1(cw), 284 rpm for the model-2(cw), 206 rpm for the model-3(cw) and 189 rpm for the model-3(cc).

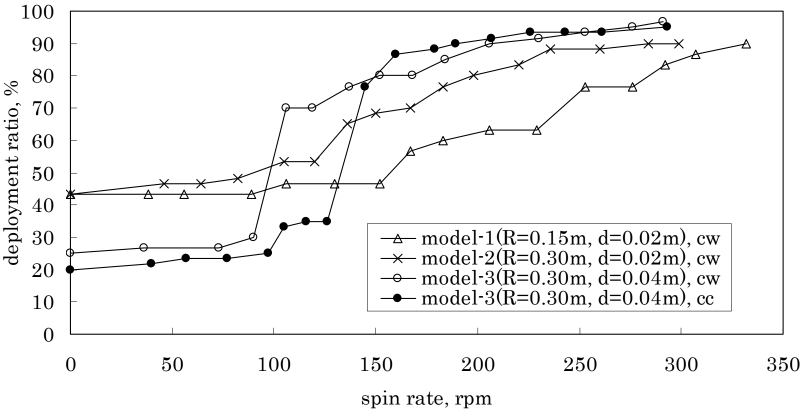


Figure 8. Spin rate vs deployment ratio

The model-1(cw) and the model-2(cw) begin to deploy at about 40% deployment ratio and the model-1(cw) seems to need faster spin rate to deploy compared with the model-2(cw). In addition, the model-1(cw) is drastically deployed at about 160 rpm and the same phenomena occurs at about 130 rpm for the model-2(cw). The different results indicate that the larger radius, the easier membrane deployed due to the increase of the centrifugal force by rotation. In the case of the model-3(cw), the deployment ratio at initial condition is about 25%. This shows the original configuration of spinning membrane depends on the folding pitch. This model is drastically deployed at about 90 rpm and the rise is much bigger than ones of the model-1(cw) and the model-2(cw). The difference is occurred by the restraint of adjoining folds of the two-dimensional folding pattern. Therefore, the results indicate that the large folding pitch enable membrane to be deployed with relatively small spin rate. The fact that the model-3(cw) is faster deployed than the model-3(cc) suggests that the spin-direction wrapped membrane realizes quick deployment.

IV. Non-dimensional Similarity Parameters

A. Similarity Parameters for One-dimensional Z-fold Membrane

1. Similarity Parameter for Rectangular Membrane

A similarity parameter is applied in order to examine the deployment behavior of the solar sail of flight model through the deployment characteristics of the experimental model. We have introduced the similarity parameter for the one-dimensional Z-fold membrane to investigate the deployment characteristics of a simpler folded membrane. The similarity parameter proposed in this section is derived with the deformation theorem of the membrane with assuming the membrane shape to be almost deployed. According to the spinning experiments, we analyzed the characteristics of the quasi-static deployment that intend for the behavior of membrane in steady state of constant spin rate.

It is shown in Ref. 8 that the deformation of the membrane is described by the following differential equation.

$$-EI\frac{\partial^3\Psi}{\partial s^3}+T\frac{\partial\Psi}{\partial s}=0 \tag{1}$$

where EI is the bending stiffness of the membrane, Ψ is the inclination angle of the neutral plane of membrane after deformation, s is the coordinate axis and T is the tension stress. Figure 9 shows an one-dimensional fold membrane model for the spinning solar sail.

The equilibrium equation for the gray portion in Fig. 9 is described as,

$$T = T + \delta T + mr\omega^2 \tag{2}$$

where m is the mass of the element and is described as the following.

$$m = \rho \delta rbh \tag{3}$$

where ρ is the density and h is the thickness. Assuming that the surface of the membrane is almost flat, the boundary condition is descried as,

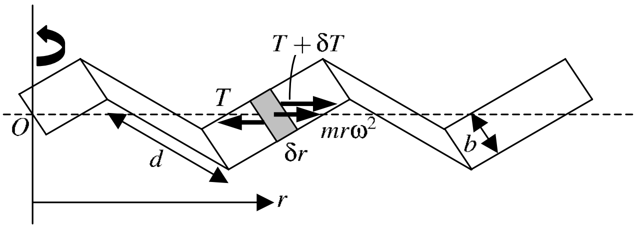


Figure 9. One-dimensional Z-fold membrane model

$$T|_{r=R} = 0 \tag{4}$$

where R is the radius. The tension stress T is obtained as the following.

$$T = \frac{1}{2}\rho bh\omega^2(R^2 - r^2) \tag{5}$$

The variable is introduced as,

$$s = ds^\star \tag{6}$$

Substituting Eq. (5) and Eq. (6) to Eq. (1), the non-dimensional equilibrium equation is expressed as,

$$-\frac{\partial^3\Psi}{\partial s^{\star 3}} + 6\alpha_{rec}(1 - \frac{r^2}{R^2})\frac{\partial\Psi}{\partial s^\star} = 0 \tag{7}$$

Finally, the following similarity non-dimensional parameter for rectangular one-dimensional Z-fold membrane is obtained.

$$\alpha_{rec} = \frac{\rho\omega^2 R^2 d^2}{Eh^2} \tag{8}$$

2. *Similarity Parameter for Triangular Membrane*

A petal of the solar sail membrane can be approximated to a triangular Z-fold membrane as shown in Fig. 10. Therefore, the similarity parameter for triangular Z-fold membrane is examined to be applied to experimental results of the rotationally skew fold membrane.

The mass m of the element of the triangular membrane is expressed instead of Eq. 3 as follows.

$$m = \rho r\delta rh\theta_0 \tag{9}$$

where θ_0 is the center angle of fan. Substituting Eq. (9) to Eq. (2), and therefore, the similarity parameter for triangular one-dimensional Z-fold membrane is obtained as,

$$\alpha_{tri} = \frac{\rho\omega^2 R^3 d}{Eh^2} \tag{10}$$

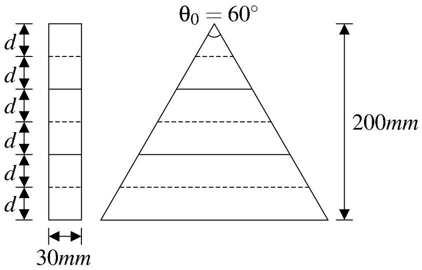
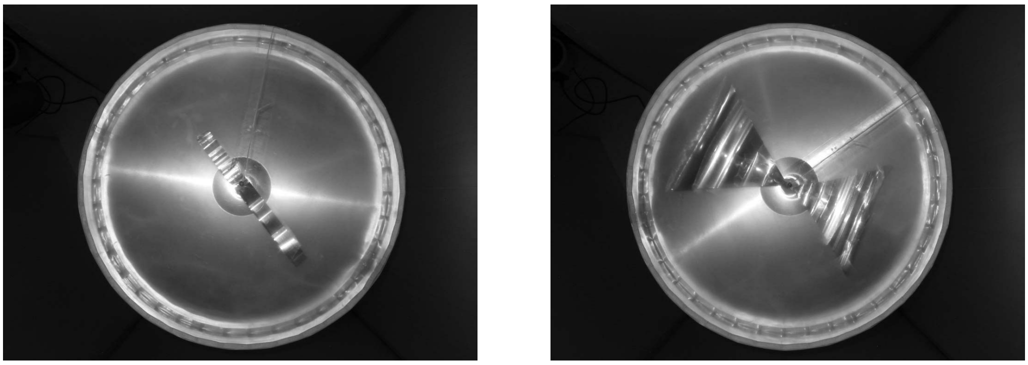


Figure 10. One-dimensional Z-fold membrane model

3. *Experiments and Results*

The rectangular membranes and the triangular membranes as shown Fig. 10 were examined in the spinning experiments to investigate the validity of the similarity parameters. The experiments were the same procedure as the case of the rotationally skew fold membrane.



(a) Rectangle

(b) Triangle

Figure 11. Configurations of deploying one-dimensional Z-fold membrane

Figure 11(a) shows the configuration of the rectangular Z-fold membrane at $\omega = 206$ rpm and Fig. 11(b) shows the configuration of the triangular Z-fold membrane at $\omega = 219$ rpm, respectively. In each experiment, two types of membrane for folding pitch were examined at the same time as shown Fig. 11. In Fig. 11(a), the folding pitch of an upper left membrane is 20 mm and the one of a lower right membrane is 40 mm. In Fig. 11(b), similarly, the folding pitch of a right membrane is 20 mm and the one of a left membrane is 40 mm. As shown in the figures, the membranes with smaller folding pitch seem to have less deployment performance due to the constraint of creases.

The similarity parameters of Z-fold membrane were applied to the experimental results as shown in Fig. 12 and Fig. 13. Both figures indicate good agreements between two types fold membranes from beginning to end of deploying. Therefore, the deployment ratios for the one-dimensional fold membranes model of other folding pitch are estimated by the similarity parameter and the experimental results.

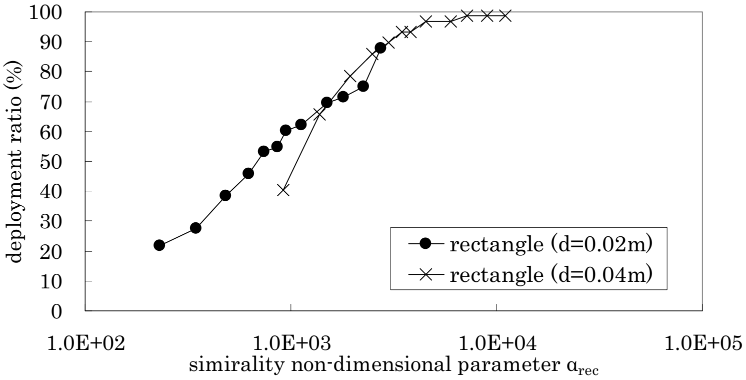


Figure 12. Similarity parameter α_{rec} vs deployment ratio

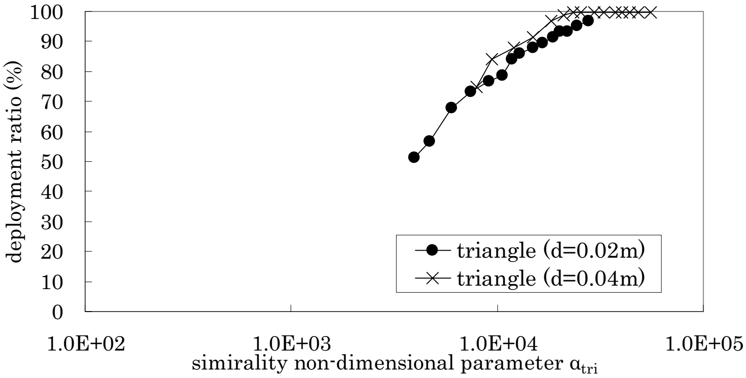


Figure 13. Similarity parameter α_{tri} vs deployment ratio

B. Similarity Parameter for Rotationally Skew Fold Membrane

1. *Theoretical Similarity Parameter*

To investigate the deployment characteristics of real size the rotationally skew fold membrane for the spinning solar sail, the similarity parameter α_{tri} for the triangular one-dimensional fold membrane is applied to the experimental results of the rotationally skew fold membrane.

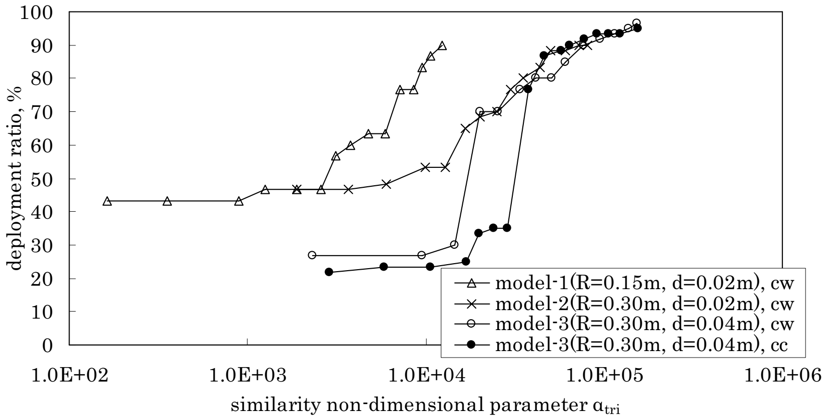


Figure 14. Similarity parameter α_{tri} vs deployment ratio

Shown in Fig. 14 is the deployment ratio with respect to the similarity parameter. Assuming this α_{tri} is appropriate to the similarity parameter for the rotationally skew fold membrane, the deployment performances are expected to be in agreement with each other at almost full deployment. The α_{tri} of the model-2(cw) is ten times compared with α_{tri} that give the same deployment ratio of the model-1(cw). The model-2(cw), the model-3(cw) and model-3(cc) are good agreements with each other at 80% or more of the deployment ratio because the theoretical similarity parameter is derived under the assumption of small deformation.

2. *Experimental Similarity Parameter*

We introduced an experimental similarity parameter including the effect of radius in consideration of the previous results. The similarity non-dimensional parameter based on the experiments is obtained as follows,

$$\alpha_{exp} = \frac{\rho \omega^2 L^2 R d}{E h^2} \tag{11}$$

where L is the constant that is introduced for non-dimensional. Figure 15 shows the results of the experiments by using Eq. (11). In the deployment ratio 80% or more, we can see a good agreement of the experimental results. Therefore, the effect of the radius is evaluated. Rapid deployments occur in the model-1(cw), the model-2(cw) at about $\alpha_{exp} = 1.0\text{E}+05$, the model-3(cw) and the model-3(cc) at about $\alpha_{exp} = 1.5\text{E}+05$. Therefore it is indicated that the models which have the same folding pitch occur quick deployment at the same α_{exp}.

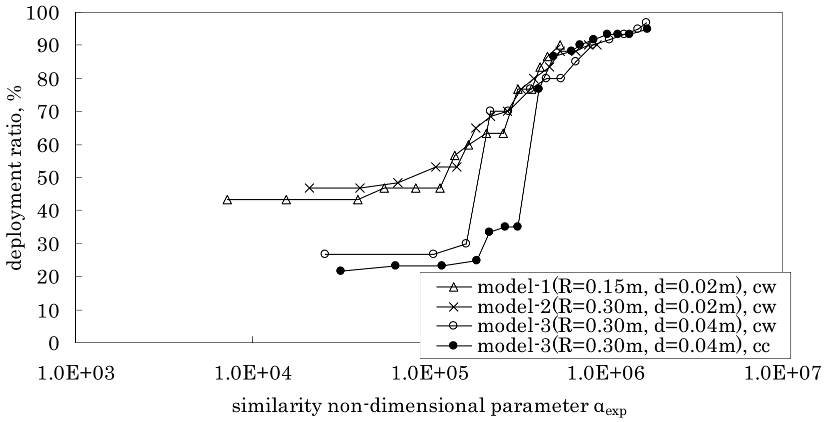


Figure 15. Similarity parameter α_{exp} vs deployment ratio

Requested spin rate for 95% deployment ratio with respect to the radius of the solar sail is investigated as shown in Table. 3. The properties of the membrane are the same as the experimental models. The folding pitches are assumed to be 4% of the radius. The solar sails, the radiuses of which are 1.0 m, 10.0 m and 25.0 m need 156 rpm, 15.6 rpm and 6.2 rpm, respectively for the deployment.

Table 3. Requested spin rate for 95% deployment ratio

	R(m)	d(m)	ω(rpm [Hz])
model-A	1.0	0.04	156 [2.60]
model-B	10.0	0.40	15.6 [0.26]
model-C	25.0	1.00	6.2 [0.10]

V. Conclusion

The deployment characteristics of the rotationally skew fold for spinning solar sail membrane were investigated through spinning experiments of small-scale models. The similarity parameters derived with one-dimensional triangular Z-fold membrane were introduced by theoretical analyses and had good agreement with the experimental results of the rectangular and triangular fold membrane. However, the similarity parameters were unable to apply to the skew fold membrane in terms of radius. To correct the effects of radius, the experimental similarity parameter was introduced. Finally, the similarity parameter based on the experiments could express the deployment characteristics for all the experimental models. By using the experimental similarity parameter, the requested spin rate of flight model was discussed.

VI. Acknowledgment

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