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Original Paper

Wrapping Experiments of Piecewise Straight Fold Membrane for Large Solar Sail

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Piecewise Straight Fold is proposed for large solar sail membranes to simultaneously realize the high packaging efficiency and the simple folding. The fold pattern is based on Spiral Fold to reduce the deviation of the fold line, which improve the packaging efficiency. In addition, the fold pattern consists of piecewise straight fold lines, which approximate the Spiral Fold line, in order to simplify the folding. A simple manufacturing process of Piecewise Straight Fold is developed based on the Z-fold membrane. The preliminary experimental results show the feasibility of the Piecewise Straight Fold and its simple manufacturing process, where the high packaging efficiency is also verified. The wrapping fold experiments for the solar power sail membrane is demonstrated by using the Piecewise Straight Fold. In the wrapping fold experiments, the applicability of the Piecewise Straight Fold to the solar power sail membrane is verified.

Key Words: Wrapping Fold, Solar Power Sail, Thickness Effect, Spiral Fold

1. Introduction

The solar sail is one of the efficient propulsion systems for long duration exploration, which is accelerated continuously by sun's photons without propellant. Currently, JAXA plans to launch a solar power sail to Jupiter, where many solar cells are attached to a large membrane[1)]. The solar sail membrane is folded and packed in a rocket and are later deployed in space. The folded configuration and the deployment properties of the solar sail membrane depend on the folding properties, and thus, the folding is a key technical issue for the solar sail membrane. For example, the high packaging efficiency has to be realized to fold the membrane within the available size at launch. The simple manufacturing and folding process are also requested. In addition, residual deformation of the solar cells must be reduced so as not to decrease the power generation efficiency of the solar cells.

One of the folds for the solar sail membrane is a wrapping fold[2)], which includes the wrapping process in the course of the folding. The wrapping fold process of Square Fold, which is an example of the wrapping fold and was employed in the solar power sail demonstrator IKAROS[3)], is indicated in Fig.1. As shown in Fig.1, the membrane is folded into z-fold at first. The fold lines of the z-fold are straight and are parallel with each other. Then, the membrane is wrapped around the center hub. Figure 2 shows a folded configuration of the square fold. In Fig.2, new fold lines, which deviates from the target straight fold lines, are induced. The deviation of fold line affects the structural properties of the solar sail membrane. For example, the folded width, which is shown in Fig.2, is increased, and thus, the folded size becomes large. In addition, residual deformation would be induced on the solar cells because the new fold line is induced. The deviation of fold line is caused by the thickness effects of the folded membrane because the folded thickness is not equal to zero. In that case, the difference of circumferential length between the inner wrapped membrane and the outer wrapped membrane of the folded membrane is induced. Therefore, it is significant to consider the thickness effects to realize the large solar sail.

Several fold patterns, which consider the thickness effects, have been proposed. Natori et al. proposed Spiral Folding[4)], which is consists of the spiral lines to consider the thickness effects of the wrapping fold. However, as the fold lines are not straight, it is difficult to fold the membrane when the membrane size becomes large.

In this paper, fold techniques are proposed for large solar sail membranes to simultaneously realize the high packaging efficiency and the simple folding. At first, a fold pattern, Piecewise Straight Fold, is proposed by approximating the fold line of the Spiral Fold with piecewise straight line as shown in Fig.3. Then, simple manufacturing technique for the Piecewise Straight Fold is developed. These two fold techniques enable the simple folding with high packaging efficiency. We focus on the selected area by red line in Fig.1 because of the rotation symmetry and the line A-A is the start position of the wrapping. The feasibility and the effectiveness of the proposed fold techniques are verified experimentally with solar power sail membrane.

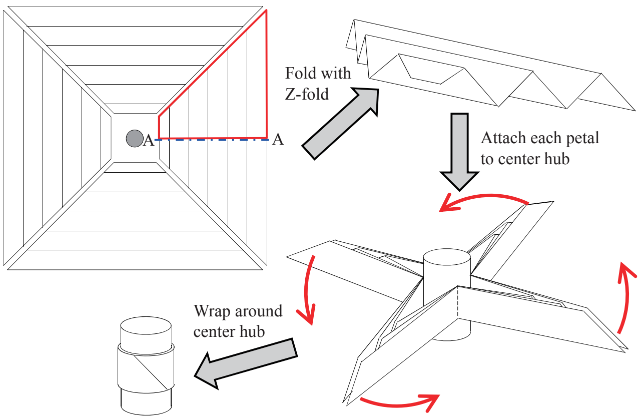


Fig. 1. Wrapping fold process of Square Fold.

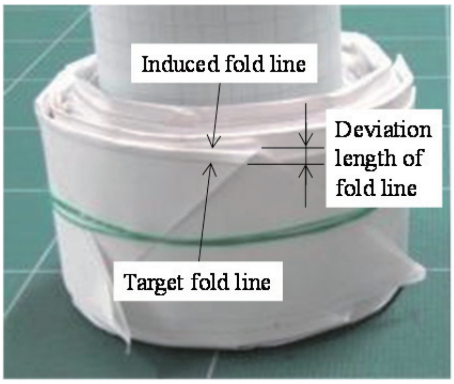


Fig. 2. Folded configuration of Square Fold.

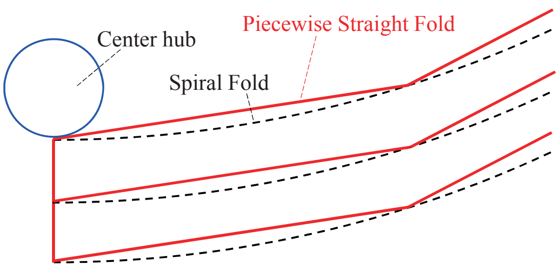


Fig. 3. Overview of Piecewise Straight Fold.

2. Details of Piecewise Straight Fold

This section presents how to design the Piecewise Straight Fold. As the Piecewise Straight Fold approximates Spiral Folding, there are two steps to design the fold pattern, which are (1) Design of Spiral Fold line, and (2) Approximation of Spiral Folding. These parameters are described in the following subsections.

2.1. Design of spiral folding

Fold line of Spiral Folding has curvature so as not to induce the difference of circumferential length between the inner wrapped membrane and the outer wrapped membrane. The idea of the Spiral Folding is extended to the selected area in Fig.1.

The folded and deployed configurations of the n-th fold line are shown in Fig.4a and b. In the figure, r_0 is the radius of the center hub, r_n is the radius of the wrapping of the fold line L_n, x_n is the wrapped length of the n-th fold line, R_n is the radius of curvature of the n-th fold line, l_0 is the interval of the fold line, and h^* is layer thickness, which is the folded thickness per layer. Also, the element of $d\varphi$ in the folded configuration corresponds to the element of $d\theta$ after the deployment. When we assume that the membrane is wrapped with no elongation, the length of the element in folded configuration is equal to the length of the element in deployed configuration. Thus, the following relationships are obtained.

$$R_n d\theta = r_n d\varphi, \quad R_{n-1} d\theta = r_{n-1} d\varphi \tag{1}$$

where, R_n and r_n can be calculated as,

$$R_n = R_1 + (n-1) l_0, \quad r_n = r_0 + (n-1) h^* \tag{2}$$

Using Eqs.(1) and (2), R_n is calculated as,

$$R_n = \frac{l_0 r_0}{h^*}\left\{1 + \frac{h^*(n-1)}{r_0}\right\} \tag{3}$$

When we assume the equivalent layer thickness is sufficiently smaller than the radius of the center hub, the radius of curvature of the fold line can be approximated as,

$$R_n \cong \frac{l_0 r_0}{h^*} \tag{4}$$

As shown in Eq.(4), the radius of curvature of fold line is proportional to the interval of fold line and the center hub radius, and is inversely proportional to the layer thickness.

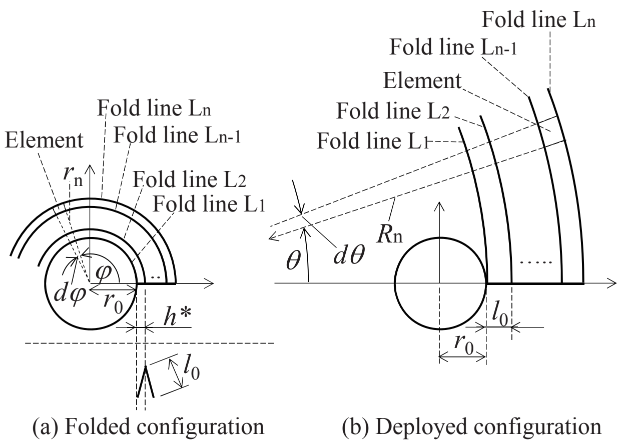


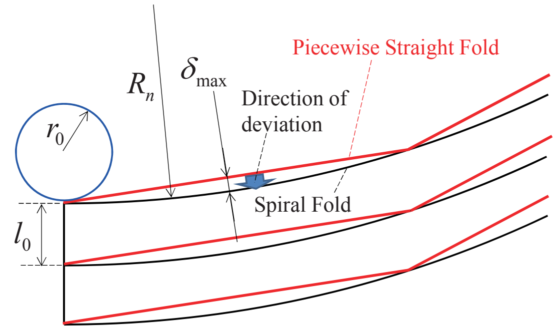
Fig. 4. Configuration of Spiral Fold line.

2.2. Approximation of Spiral Folding

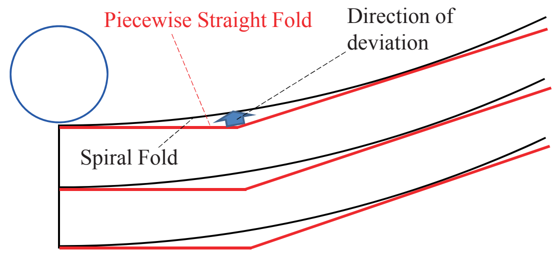
There are two design parameters to approximate the Spiral Folding by piecewise straight line.

As shown in Fig.5, there are two types of approximation, the inscribed type and the circumscribed type, which are indicated in Fig.5a and b, respectively. In the case of inscribed type, the length of fold line becomes shorter than the Spiral Fold line. On the other hand, the length of the fold line of the circumscribed type is longer than the Spiral Fold line. When the fold line is not Spiral Fold, the fold line approaches to the Spiral Fold line in the course of the wrapping fold, because the Spiral Fold is the ideal fold line. Hence, the fold line of the inscribed type deviates in the outer direction, and that of the circumscribed type deviates in the inner direction, as shown in Fig.5a and b. Thus, it is requested to locate the devises on the membrane in consideration of the direction of the deviation.

The second design parameter is the approximation error δ_{max} in Fig.5. Although the difference of the circumferential length and the deviation can be reduced when the δ_{max} decreases because the fold line approaches the Spiral Fold, the manufacturing and the folding becomes difficult. On the other hand, when the δ_{max} increases, the membrane is folded simply, and the difference of the circumferential length becomes large.



(a) Inscribed type



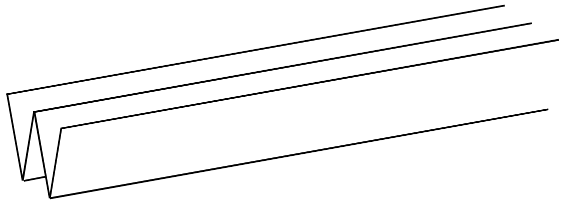
(b) Circumscribed type

Fig. 5. Fold line of Piecewise Straight Fold.

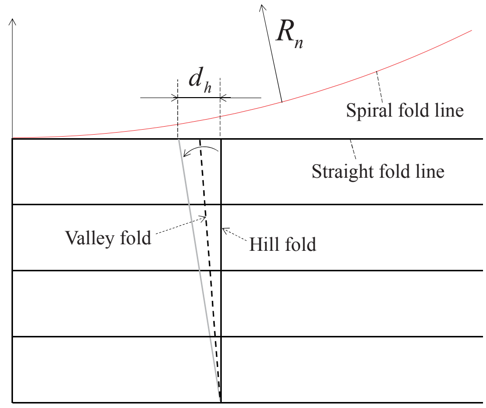
3. Piecewise Straight Fold Based on Z-fold

This section proposes a simple manufacturing technique for the Piecewise Straight Fold. The manufacturing process of the Piecewise Straight Fold is not sufficiently simple because the fold line has turning points. An example of the simple manufacturing fold pattern is the fold pattern consisted of Z-fold such as the Square Fold. The manufacturing technique for the Piecewise Straight Fold based on the Z-fold membrane is proposed as follows.

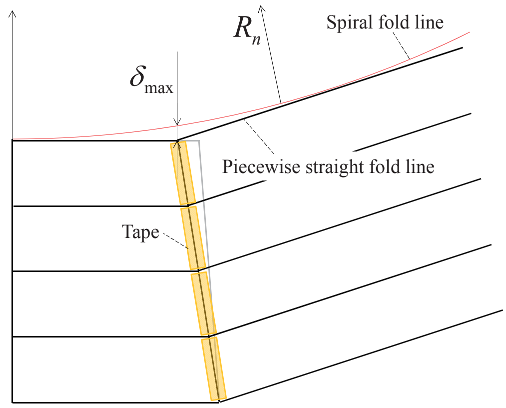
Figure 6 shows the proposed simple manufacturing process of the Piecewise Straight Fold. At first, the Z-fold is induced as shown in Fig.6a. Then, the membrane is once deployed in Fig.6b. Next, a hill fold and a valley fold are induced on the deployed configuration, and fold as shown in Fig.6c. In these processes, the fold lines of the circumscribed type of the Piecewise Straight Fold are induced. Then, the membrane is folded with the crease, which is induced in Fig.6a as shown in Fig.6d. Finally, the membrane is wrapped in Fig.6e.



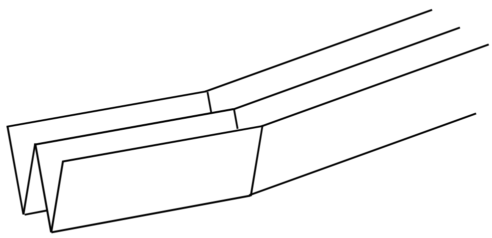
(a) Fold with Z-fold



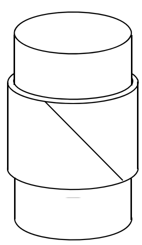
(b) Deploy of folded membrane



(c) Induce Piecewise Straight Fold



(d) Fold with creased fold line



(e) Wrap around center hub

Fig. 6. Simple manufacturing process for Piecewise Straight Fold.

4. Preliminary Experiments for Piecewise Straight Fold

Preliminary experiments are performed for a paper specimen to examine the feasibility of the Piecewise Straight Fold. Figure 7 shows the initial configuration of the paper specimen. The size is 800mm*1091mm, and the thickness is 75µm. The interval of the fold line is 100mm.

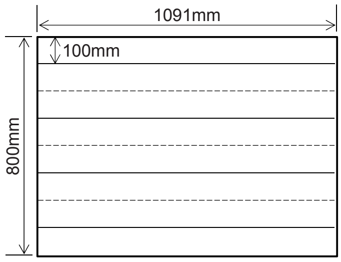
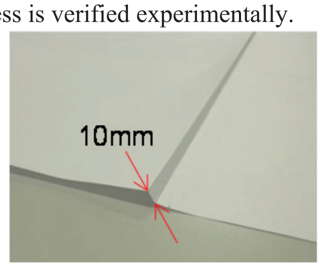


Fig. 7. 800mm*1091mm paper specimen.

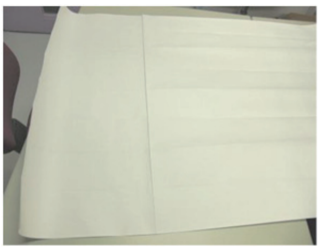
4.1. Manufacturing experiment

The paper specimen is folded based on the proposed simple manufacturing process. The manufacturing process is indicated in Fig.8. At first, the fold lines of Z-fold are generated in Fig.8a. As the paper is thick, the residual deformation of the crease is sufficiently induced. Figure 8b shows the folding process of the hill fold and the valley fold for the Piecewise Straight Fold to the Z-fold membrane. As the layer thickness h^*, which is required to design the Piecewise Straight Fold, is unknown parameter, we measure the layer thickness, where the specimen is wrapped a few centimeters. As the results of the measurement, the layer thickness is h^*=0.15mm, and the radius of curvature of the fold line is calculated to be R_n=5.1e+4mm. In addition, the approximation error is δ_{max}=5mm. Using these parameters, the fold line is designed. Next, the Piecewise Straight Fold is generated by folding the fold line induced in Fig.8b, as shown in Fig.8c. Finally, the specimen is wrapped around the center hub in Fig.8d. As shown in the figure, the simple manufacturing process is realized, and hence, the feasibility of the simple manufacturing process is verified experimentally.

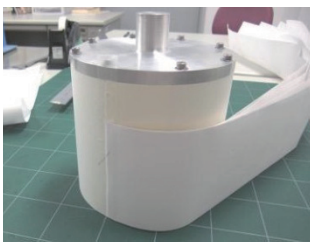
(a) Fold with Z-fold line



(b) Induce Piecewise Straight Fold



(c) Fold with creased fold line



(d) Wrap around center hub

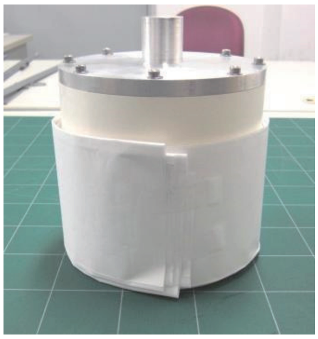
Fig. 8. Simple manufacturing process for paper specimen.

4.2. Wrapping fold experiments

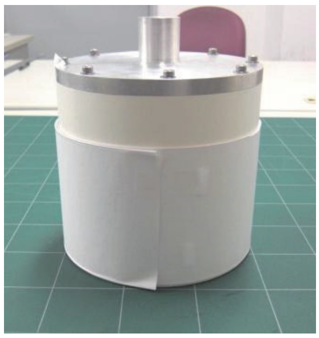
Wrapping fold experiments are performed for the Z-fold and the Piecewise Straight Fold to examine the effectiveness of the Piecewise Straight Fold. Figure 9a and b show the folded configuration of the Z-fold and the Piecewise Straight Fold, respectively. The wrapping fold for the Z-fold is carried out because of the contrast experiment. As shown in the folded configuration of the Z-fold in Fig.9a, the difference of the circumferential length and the deviation of the fold line are observed. On the other hand, the circumferential difference and the deviation are reduced in the case of Piecewise Straight compared with the Z-fold, as shown in Fig.9b, and the paper specimen is uniformly folded.

Table.1 shows the details of the folded configuration. The folded height of the Z-fold and the Piecewise Straight Fold are 108mm and 102mm, respectively. As the target folded height is 100mm, which is equal to the interval of the fold lines, the deviation of the fold line of the Z-fold and the Piecewise Straight Fold are 8mm and 2mm, respectively. Thus, the deviation becomes 1/4 times by using the Piecewise Straight Fold. The folded thickness of the Z-fold and the Piecewise Straight Fold are 7.0mm and 2.6mm, respectively. The folded thickness of Z-fold is larger than that of Piecewise Straight Fold because the paper specimen is not sufficiently creased in the case of Z-fold since the new fold line is generated by the deviation. The ratio between the folded thickness and the paper thickness of Z-fold and the Piecewise Straight Fold are 3.8 and 1.4. Hence, the packaging efficiency of the Piecewise Straight Fold becomes 2.7 times higher than that of the Z-fold.

Based on the above discussion, the high packaging efficiency is realized by using the Piecewise Straight Fold. Thus, the effectiveness of the Piecewise Straight Fold is verified.



(a) Z-fold



(b) Piecewise Straight Fold

Fig. 9. Folded configuration of preliminary experiments.

Table 1. Folded configuration.

	Z-fold	Piecewise Straight Fold
Folded height	108mm	102mm
Deviation of fold line	8mm	2mm
Folded thickness	7.0mm	2.6mm
Folded thickness/Paper thickness	3.8	1.4

5. Fold Experiments for Solar Power Sail Membrane

In this section, the applicability of the Piecewise Straight Fold to the solar power sail membrane is examined. To realize the objective, the large membrane with dummy solar cells is used for the specimen. Although the solar power sail membrane is square shape, the folded membrane is the repeat structure of Z-fold, and thus, an element of the Z-fold is used for the membrane specimen. The overview of the membrane specimen is indicated in Fig.10. The size of the membrane specimen is 1050mm*5008mm, the material is Polyimide, and the membrane thickness is 10μm. In addition, the dummy solar cells, whose material is PET and thickness is 75μm, are attached to the membrane specimen. The interval of the fold line is 210mm, the number of the layer of the folded configuration is 5, and the radius of the center hub is 316mm.

In the membrane specimen, the dummy solar cells are located stepwise. To avoid the crease on the solar cells, the fold area for the Piecewise Straight Fold is generated between the solar cells as indicated by the red line in Fig.10. The detail process is indicated in the lower side in Fig.10. The selected area by red line is slit, and the fold area for the Piecewise Straight Fold is generated as shown in the right figure. To reinforce the slit line, Kapton tape is attached on the membrane. Practically, this process is undesirable for the actual solar power sail membrane because the membrane would be torn from the slit line. In the practical manufacturing process, there are two ideas to realize the Piecewise Straight Fold. The one is to widen the gap of the solar cells, and generate the fold area of the Piecewise Straight Fold on the base film. The other is to locate the solar cells on the fold line of the Piecewise Straight Fold.

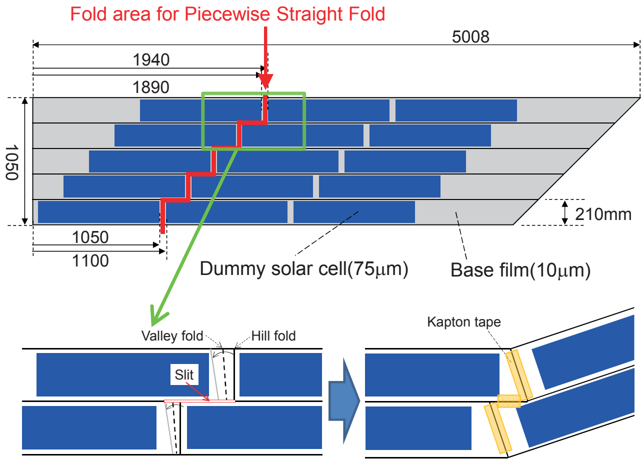
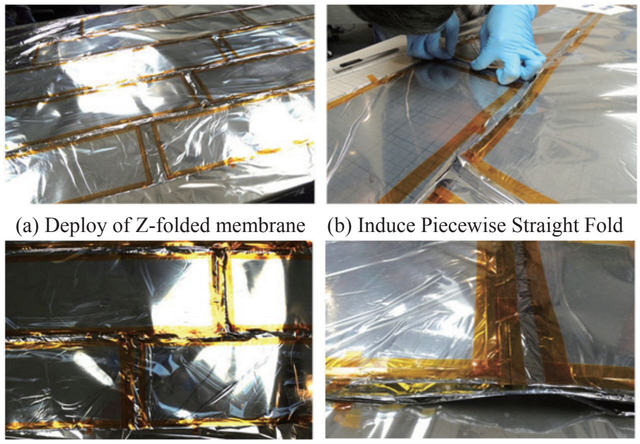


Fig. 10. Membrane specimen for solar power sail.

5.1. Manufacturing experiment

Figure 11 shows the overview of the manufacturing process of the Piecewise Straight Fold for the solar power sail membrane. The deployed configuration after folding the Z-fold is indicated in Fig.11a. The fold area for the Piecewise Straight Fold is generated on the deployed configuration in Fig.11b, and the membrane is reinforced as shown in Fig.11c. Figure 11d shows the folded configuration before the wrapping. As shown in the figure, in the fold area for the Piecewise Straight Fold, the folded membrane rises because the circumferential length of the outer membrane is longer than that of the inner membrane. The results of the manufacturing experiments indicate that the feasibility of the manufacturing of the Piecewise Straight Fold for the solar power sail membrane is verified.



(a) Deploy of Z-folded membrane (b) Induce Piecewise Straight Fold

(c) Reinforce by Kapton tape (d) Fold membrane

Fig. 11. Manufacturing process for solar power sail membrane.

5.2. Wrapping fold experiments

The wrapping fold experiments are performed to examine the effectiveness of the Piecewise Straight Fold for the solar power sail membrane. The effects of the Piecewise Straight Fold are examined by measuring two parameters, which are the difference of the circumferential length and the deviation of the fold line. The experimental results are discussed in terms of these parameters, where the experimental results are compared with the results of the contrast experiments with the Z-fold membrane.

Figure 12 shows the difference of the circumferential length of the innermost membrane and the outermost membrane. The horizontal axis is the rotation number of the center hub. As shown in the left figures, when the innermost membrane is longer than the outermost membrane, the sign is positive, and in the opposite case, the sign is negative. In addition, the horizontal axis, rotation number of center hub corresponds to the length of the membrane specimen indicated in the lower side. As shown in the figure, in the case of the Z-fold membrane, the circumferential difference is monotonously increased as the membrane is wrapped. In the case of the Piecewise Straight Fold, the circumferential difference is increased monotonously in the initial wrapping. However, when the rotation number becomes about 0.95, the sign of the circumferential difference becomes negative. This location is in agreement with the fold area for the Piecewise Straight Fold in the innermost membrane. Additionally, the fold area for the Piecewise Straight Fold and the reduction of the circumferential difference are 11mm and 10mm, respectively. Thus, the target reduction of the circumferential difference is in agreement with the experimental result. Therefore, the effectiveness of the Piecewise Straight Fold is verified.

Figure 13a and b show the deviation of the fold line of Z-fold membrane and Piecewise Straight Fold membrane, respectively. As shown in Fig.13a, the deviation is induced on all fold lines of Z-fold membrane, and these directions are same. On the other hand, in the case of Piecewise Straight Fold, the deviation is not induced in three fold lines, however, the deviation is observed in one fold line, and the direction is opposite side of the Z-fold case. This result is discussed in terms of the layer thickness. The layer thickness, which is designed before wrapping, is 0.2mm, and the layer thickness, which is measured in the experiment, is 0.18mm. Hence, the larger layer thickness is used in the design of the Piecewise Straight Fold. In that case, the deviation can be induced. Thus, the deviation is induced by the overestimation of the layer thickness. To confirm the discussion, the layer thickness is changed to 0.18mm, and the wrapping experiments are performed. As the results, the deviation is not induced. Therefore, it is found that the deviation can be reduced by using the precise layer thickness in the design of Piecewise Straight Fold.

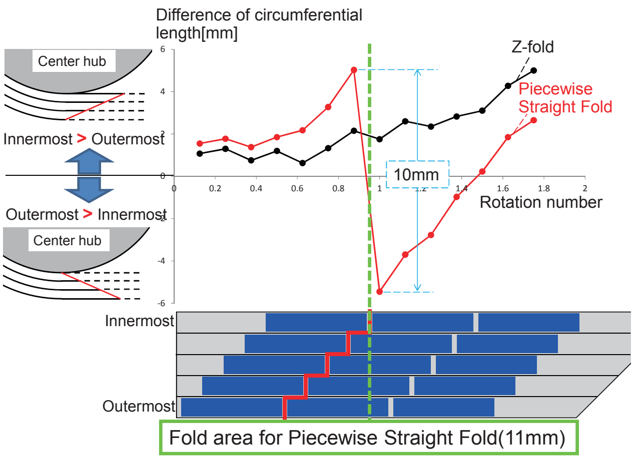
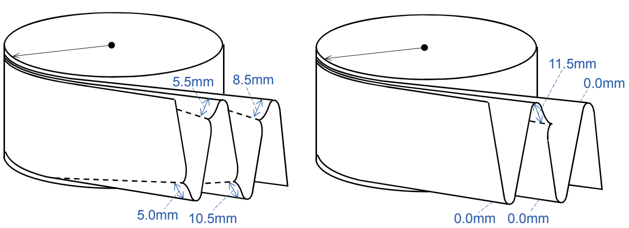


Fig. 12. Difference in circumferential length.



(a) Z-fold (b) Piecewise Straight Fold

Fig. 13. Deviation of fold line.

6. Conclusions

This paper proposed Piecewise Straight Fold to fold a large solar sail membrane simply with high packaging efficiency. A simple manufacturing process based on the Z-fold membrane was developed, and the feasibility was verified experimentally. Then, the wrapping fold experiments with a paper specimen and a solar power sail membrane were carried out. The experimental results showed that the difference in circumferential length and the deviation of the fold line, which were induced by the thickness effects, were reduced by using the Piecewise Straight Fold, and thus, the high packaging efficiency was realized.

Acknowledgments

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