**Guided-Pin Mechanisms for Wrapping Folds of Large Space Membrane**

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Guided-pin mechanisms for large space membranes are developed for the purpose of folding a tapered pattern precisely and folding a larger membrane using a smaller apparatus. The guided-pin, which applies displacement to the fold line, is introduced to the fold apparatus. To realize folding with the guided-pin, guided-pin mechanisms are designed, where a mixed spiral fold is employed as the target fold pattern. The guided-pin mechanisms are manufactured to perform fold experiments using the guided-pin. The experimental results show that a 5,000 mm-sized membrane can be completely and precisely folded by 1,400 mm-sized guided-pin mechanisms, and thus, the feasibility of folding using the guided-pin mechanisms is verified.

**Key Words:** Solar Sail, Fold Line, Membrane Structure

1. Introduction

Space membranes, such as solar sails, large aperture antennas, sunshields, and space solar power systems, have been subject of continued interest and development over the past several decades. The required size for the space membrane has become larger and larger because of advanced missions. For example, JAXA plans to launch a solar power sail to Jupiter, where the diameter of the membrane of which is to be larger than 50 m. These large space membranes are folded and packed in a rocket, and are later deployed in space. The folded configuration and the deployment properties of the space membrane depend on the folding properties, and thus, folding is a key technical issue for the space membrane. For example, the membrane has to be folded to within an allotted size at the time of launch. The size of the folded membrane could be increased due to wrinkles. Additionally, simple manufacturing and folding processes are also requested. When ground testing is required, the repeatability of the folding must be improved.

Lanford has developed a wrapping apparatus to simplify folding of the membrane. In the wrapping apparatus, the fold lines are induced automatically on the non-creased membrane by applying tensile forces to the edge of the membrane and rotating a cylindrical center hub. The induced fold lines become spiral-shaped because the membrane thickness is not equal to zero. However, wrinkles are induced in the center area because the curved line, which is attached to the center hub, becomes straight by folding the membrane. As the membrane is not creased before wrapping, the repeatability of the fold line becomes lower. Additionally, the required apparatus size is larger than the membrane size because the tensile forces have to be applied to the edge of the membrane, and thus, the arbitrary sized membrane cannot be folded.

The authors have examined a fold pattern for the Lanford’s wrapping apparatus that reduces the wrinkles and realizes high repeatability. The wrinkles around the center area can be reduced by using a polygonal center hub. One of the fold patterns, which have the polygonal center hub, is the rotational skew fold, as shown in Fig.1 (a). Additionally, to realize high repeatability, hinge mechanisms, which are elements attached to the center area as shown in Fig.1 (b), have been proposed. In this case, the hinge mechanisms induce fold lines with high repeatability. The fold experiments for rotational skew fold with hinge mechanisms using the wrapping apparatus were performed, as shown in Fig. 2. It was found that the double corrugation area, which is indicated by the selected area in Fig.1 (a), was difficult to induce although reducing the wrinkles and high repeatability were realized. Thus, the mixed spiral fold shown in Fig. 3 has been proposed, where Lanford’s spiral fold is introduced for the double corrugation area of the rotational skew fold except for the hinge mechanisms. The target fold lines can be induced using the mixed spiral fold; however, the precision of the induced fold line is low because tensile force is used to induce the fold lines. Especially, the spiral fold is difficult to induce because the spiral fold is a tapered fold pattern; the interval of the fold line becomes large as the membrane radius becomes large.

In this paper, a fold mechanism for large space membranes is developed to precisely fold the tapered fold pattern and fold an arbitrary-sized membrane using
a smaller apparatus. At first, the conventional folding process is discussed to examine the fold mechanism capable of doing the tapered fold pattern. Then, a fold mechanism is designed based on the mixed spiral fold. Finally, fold experiments are performed to verify the feasibility of the proposed fold mechanism.

2. Concept of Guided-pin Mechanisms

This section examines the folding process of the conventional wrapping apparatus to propose a folding mechanism that can perform the tapered fold pattern precisely and fold an arbitrary-sized membrane.

Figure 4 (a) shows the conventional folding process discussed in other literature. As shown in the figure, the fold lines are induced by the tensile force applied to the edge of the membrane, and thus, the target fold line is difficult to induce because the induced fold line has to be controlled by the edge of the membrane. Especially, in the case of a tapered fold pattern, folding the target fold line becomes more difficult as the interval of the fold line changes. Additionally, as tensile force is applied to the edge of the membrane, the apparatus cannot fold an arbitrary-sized membrane.

Figure 4 (b) indicates the proposed folding process in this paper. In the folding process, guided-pins are introduced to induce the fold lines. The guided-pin applies displacement to the fold line of the membrane. The guided-pin does not move in the radial direction, and a fold line is induced when the membrane contacts the guided-pin. In this case, the fold line is induced near the center hub, and thus, the induced fold line can be controlled precisely. When the guided-pin is used, the vertical position of the guided-pin is easily changed. Therefore, the tapered fold pattern can be folded when the vertical position of the guided-pin is adjusted depending on the interval of the fold line. In addition, as the guided-pin applies displacement by sandwiching the membrane, an arbitrary-sized membrane can be folded using the smaller apparatus.
3. Design of Guided-pin Mechanisms

In this section, the design of the guided-pin mechanisms is discussed to realize the folding process proposed in Section 2. Figure 5 shows the overview of the guided-pin mechanisms, which can perform a mixed spiral fold using a square center hub. The maximum radius and height of the mechanisms are 1.4 m and 1.2 m, respectively. The square center hub, indicated by yellow color, can be rotated by turning wheel A.

The guided-pin mechanisms have 16 attachment frames for guided-pins because the mixed spiral fold with the square center hub consists of eight fold areas, which are four spiral folds and four z-folds, as shown in Fig. 3, and because two types of guided-pins are required to perform the hill folds and valley folds. The attachment frame indicated by red color and blue color are the guided-pin attachment frames for the z-fold and the spiral fold, respectively. Additionally, the upper attachment frame is for the guided-pin for the valley fold and the lower frame is for the hill fold.

The location of the attachment frame is determined by the fold line of the mixed spiral fold. The base of the non-wrapped membrane is in agreement with the corner of the center hub, and hence, the distance between the corner of the center hub and the guided-pin corresponds to the length of the non-wrapped membrane. The guided-pin location is determined to make the length of the non-wrapped membrane uniform, and thus, the attachment frame for the spiral fold is curved.

3.1. Attachment frame of guided-pin

As described in Section 3, guided-pin mechanisms have two types of attachment frame, which are for the z-fold and spiral fold. Figure 6 shows the folding process of the z-fold. As shown in Fig. 3, the fold lines of the z-fold are parallel to each other, and hence, the distance between the hill fold and valley fold does not change. Thus, as shown in Fig. 6, the location of the attachment frame for the z-fold does not move.

Figure 7 shows the folding process of the spiral fold. In the case of the spiral fold, as shown in Fig. 3, the distance between the hill fold and valley fold increases as the membrane radius becomes larger. Thus, the attachment frame for the spiral fold has to move up and down to make the spiral fold. Figure 7 (a) shows the initial conditions for the folding process. After the membrane is wrapped to some extent, as shown in Fig. 7 (b), the attachment frame for the hill fold of the spiral fold moves up. On the other hand, the attachment frame for the valley fold of the spiral fold moves down. These movements are realized by rotating wheel B, as indicated in Fig. 5.
3.2. Details of guided-pin

The guided-pin comes in contact with the membrane to apply displacement, and thus, the design of the guided-pin is important to avoid damaging to the membrane. The cross-section of the tip of the guided-pin is indicated in Fig. 8. Figure 8 (a) and 8 (b) show non-load condition and the loaded condition, respectively. As shown in the figure, the tip pin, which comes in contact with the membrane, can move up and down. The vertical location of the tip pin is determined by the equilibrium between the reaction force from the membrane and the restoring force of the spring. To determine the spring constant, the contact force is applied to the membrane by the tip pin, and then, the spring constant is determined so as not to induce plastic deformation in the membrane.

(b) After folding
Fig. 7. Folding process for spiral fold.

4. Fold Experiments with Guided-pin Mechanisms

This section discusses the wrapping fold experiments with the guided-pin mechanisms to verify the feasibility of the guided-pin mechanisms. In the following subsections, the details of the membrane specimen are described, and then, the experimental results are discussed.

4.1. Membrane specimen for fold experiments

Figure 9 shows the membrane specimen for the wrapping fold experiments using guided-pin mechanisms. The specimen is an octagonal membrane made from PET, whose diameter and membrane thickness are 5,000 mm and 6.0 µm. The Kapton tape is attached on the edge of the membrane not to tear from the edge.

The target fold pattern is a mixed spiral fold with a square center hub. The number of fold lines is 84. The hinge mechanisms, whose thickness is 300 µm, are attached to the center area of the membrane specimen. In the mixed spiral fold image shown in Fig. 9, the center of the spiral fold is in agreement with the neutral line of the folded height, and thus, the fold pattern has the half wavelength of the spiral fold and that of the z-fold between the spiral fold and the z-fold.

The target folded height of the mixed spiral fold is determined by the interval of the z-fold line when the interval of the z-fold is larger than that of the spiral fold. In the case of the membrane specimen in Fig. 9, the target folded height is 200 mm.

4.2. Results of fold experiments

Figure 10 indicates the folding process of a 5,000mm-sized membrane specimen using the
guiding-pin mechanisms. In the initial condition shown in Fig.10 (a), the membrane is attached to the center hub using Kapton tape. The guiding-pin for spiral folding does not come in contact with the membrane. On the other hand, the guiding-pin for z-folds comes in contact with the membrane because the attachment frame of the z-fold guiding-pin cannot move. Additionally, in the initial condition, the rotation angle of the center hub is $2\pi/8$ in order to induce the initial z-fold line. After setting the initial condition, the guiding-pin comes in contact with the membrane by rotating wheel B. Then, wheels A and B are simultaneously rotated, where the tensile forces in the circumferential direction are applied to the membrane in order to fold the membrane without wrinkles. The wheel rotation is manually operated and determined to maintain the tensile forces to some extent.

Figure 10 (b) shows a folding process with a rotation angle of $12\pi/8$. Detailed views of Fig.10 (b) are indicated in Fig.11 (a) and 11 (b), which show the z-fold line and spiral fold line, respectively. As shown in the figures, the z-fold and spiral fold are successfully and precisely induced by the guiding-pins. Finally, the membrane is completely folded as shown in Fig.10 (d). Thus, the feasibility of using guiding-pin mechanisms is verified.

In the course of folding, slipping between the membrane and the guiding-pin is observed, where the membrane in the z-fold area slips in the circumferential direction. When slip between the membrane and guiding-pin is induced, the fold line generated by the guiding-pin deviates from the target fold line. In this case, the folded height becomes large, and the packaged volume becomes larger. Additionally, as the fold line deviates from the target fold line, fold precision decreases. Thus, it is significant to reduce the slip between the membrane and guiding-pin. The slip is induced by the weight of the membrane because the weight of the membrane applies the tensile force to the folding membrane. To reduce slip, optimum locations for the guiding-pin and attachment frames were examined analytically and numerically in our previous research. The results indicate that slip can be reduced by increasing the distance between the center hub and the guiding-pin as well as the attachment frame.

Table 1 shows the folded configuration of the fold experiments using the guiding-pin mechanisms. In the table, the folded configuration obtained by the wrapping apparatus using the mixed spiral fold is also indicated. As shown in the table, the maximum folded height obtained by the guiding-pin mechanisms is 256 mm. As the target folded height is 200 mm, the deviation of the fold line is 56 mm. On the other hand, the deviation of the wrapping apparatus is 28 mm. The deviation obtained by the guiding-pin mechanisms is twice times larger than that of the wrapping apparatus because the target folded height of the guiding-pin mechanisms is also twice times larger than that of the wrapping apparatus. The folded thickness ratio, which indicates the ratio between the folded thickness per layer and the membrane thickness, becomes 2.6 times in the case of the guiding-pin mechanisms. On the other hand, the folded thickness ratio obtained by the wrapping apparatus is 4.2 times, and hence, the folded thickness ratio obtained by the guiding-pin mechanisms is smaller than that of the wrapping apparatus. This is because the guiding-pin applies displacement to the fold line although the wrapping apparatus applies tensile force to induce the fold line, and thus, the guiding-pin can induce the fold line more precisely.

5. Conclusion

This paper developed guiding-pin mechanisms that apply displacement to the fold lines of large space membranes. The guiding-pin mechanisms could perform tapered fold patterns and obtain an arbitrary-sized membrane using a smaller apparatus. The guiding-pin mechanisms were designed to realize a folding process using guided-pins. The fold experiments were demonstrated with guiding-pin mechanisms that used the mixed spiral fold pattern. As the result, a 5,000 mm-sized membrane was completely and precisely folded using 1,400 mm-sized guiding-pin mechanisms, and thus, the feasibility of the guiding-pin mechanisms was verified.

Acknowledgments

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References

Fig. 10. Folding process of experiments.

Fig. 11. Details of fold lines (rotation angle: 12π/8).

### Table 1. Folded configuration.

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<tr>
<th></th>
<th>Guided-pin mechanisms</th>
<th>Wrapping apparatus 4)</th>
</tr>
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<tbody>
<tr>
<td>Max. folded height [mm]</td>
<td>256</td>
<td>128</td>
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<td>Target folded height [mm]</td>
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<td>Deviation of fold line [mm]</td>
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<td>Folded thickness per layer [μm]</td>
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<td>Membrane thickness [μm]</td>
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<td>5.0</td>
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<tr>
<td>Folded thickness ratio (ratio between fold thickness per layer and membrane thickness)</td>
<td>2.6</td>
<td>4.2</td>
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