Location of Guided-Pin in Retraction Mechanisms for Large Deployable Space Membrane

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Abstract
Guided-pin location of retraction mechanisms is examined to improve the fold precision of a large deployable space membrane. The guided-pin, which is introduced to the retraction mechanisms, generates the fold lines on the membrane. The retraction experiments with the guided-pins are performed to investigate the fold precision. In the course of the retraction, the fold precision is interfered by the slips between the guided-pin and the membrane. To investigate the non-slip condition, the mechanics of the slip is examined introducing a one-dimensional slip model for the guided-pin location. Finally, the non-slip condition, which is derived with the slip model, is evaluated by the results of the retraction experiments.

1. Introduction
There is currently much interested in the use of large deployable space membranes for several lightweight space structures: solar sails, large aperture antennas, sunshields, and solar power satellites. Since these structures are consists of thin and large membranes, the membrane is retracted into the rocket on the ground. There are several technical issues for the retraction of the thin and large membrane. The membrane requested to be folded simply with high packaging density. The fold precision is also required to realize the deployment.

Several retraction techniques for solar sails have been proposed. 'Flog-leg folding', which folds the membrane in two directions, is developed by ESA to minimize the storage volume\(^1\). In NASA, the sail is folded stripe by stripe, segmented like the boom packaging\(^2\). JAXA/ISAS introduced wrapping fold in IKAROS\(^3\). The membrane with solar cells is folded zigzag pattern and wrapped around the center hub.

Retraction mechanisms for the wrapping fold have been proposed to retract the membrane simply, automatically, and repeatedly on the ground by the authors\(^4\). The membrane is folded and wrapped around a polygonal center hub using the tensile forces in the retraction mechanisms. Extending the retraction mechanisms, guided-pin mechanisms have been also proposed to fold an arbitrary-sized membrane with guided-pins\(^5\). Retraction experiments with the guided-pin mechanisms indicated that the fold precision is interfered by the slip between the guided-pins and the membrane, and the slip depends on the location of the guided-pin.

In this paper, the location of the guided-pin is examined to improve the fold precision. First, a one-dimensional slip model is introduced to examine the mechanics of the slip. Then, the non-slip condition for the guided-pin location is derived numerically with the slip model. Finally, the non-slip condition is discussed by the results of the retraction experiments.

2. Guided-pin retraction mechanisms

The guided-pin mechanisms are consists of tensile forces and a center hub to wrap and fold the membrane. To fold an arbitrary-sized membrane, guided-pins (upper hand of Fig.1) were introduced. The retraction experiments showed that the
guided-pin generates the fold line with the out-of-plane enforced displacement and with the tensile forces by the friction between membrane and the guided-pin. The mixed spiral fold (lower hand of Fig.1) was obtained in the experiments, and it performs the uniform folding and high packaging density.

Figure 2 indicates the retraction configuration with the guided-pin mechanisms. The diameter of the membrane specimen is 5 meters, and the membrane thickness is 6µm. In the retraction experiments, the precise folding is realized by tuning the location of the guided-pin. However, the slip between the guided-pin and the membrane are observed in the course of the retraction without tuning of the location of the guided-pin. The direction of the slip is the wrapping direction as shown in the Fig.3. The slip is observed in the Z-fold region mainly.

Fig. 1: Overview of guided-pin retraction mechanisms

Fig. 2: Retraction configuration

Fig. 3: Direction of slip

3. One-dimensional slip model

The mechanics of the slip between the guided-pin and the membrane is examined to derive the non-slip condition.

A one-dimensional slip model is introduced to examine the mechanics of the slip. As the slip is mainly observed in the Z-fold region(Fig.4), the membrane in the Z-fold region is modeled. Figure 5 indicates the one-dimensional slip model of the Z-fold region. $R_1$ and $R_2$ is frictional force in A and B each other. Non-slip conditions in A and B are

$$-\mu(T_3\cos\theta + T_4\cos\theta) \leq R_2 \leq \mu(T_3\cos\theta + T_4\cos\theta) \quad (1)$$
$$-\mu(T_5\cos\theta + T_6\cos\theta) \leq R_1 \leq \mu(T_5\cos\theta + T_6\cos\theta) \quad (2)$$

Where, $\mu$ indicates the frictional coefficient, and $T_3$, $T_4$, $T_5$, and $T_6$ are tensile forces of the membrane. These tensile forces are described as,

$$T_3 = T_1 + (f\sin\theta - w\cos\theta)a \quad (3)$$
$$T_4 = T_2 + (-w\cos\theta - 3f\sin\theta)a + R_1 \quad (4)$$
$$T_5 = T_2 + (w\cos\theta - f\sin\theta)a + R_1 \quad (5)$$
$$T_6 = T_2 + (w\cos\theta - f\sin\theta)a \quad (6)$$

Where, $w$ is the self-weight of the membrane, and $f$ is the horizontal component of the tensile forces, and $a$ is the length of the membrane(Fig.5). In this model, we assume the tensile forces of the membrane are positive, and following relationships are considered.

$$T_3, T_4, T_5, T_6 \geq 0 \quad (7)$$
The relationships between $R_1$ and $R_2$ is also described with $w$ and $f$ as,

$$R_1 + R_2 = T_1 - T_2 + 4f \sin \theta$$  \hspace{1cm} (8)

The horizontal component of the tensile forces $f$ in the Eq.(3)\textendash (6) and (8) is derived geometrically using Fig.5 as,

$$f = w' \tan \alpha$$ \hspace{1cm} (9)

Where, $\alpha$ is the wrapping angle as shown in the Fig.5, and $w'$ is the self-weight of the membrane which is in the outside of the guided-pin as shown in the Fig.6. In the figure, $h$ is length of the outside membrane, and $l$ is the length of the fold line. Using Eq.(3)\textendash (6) and (9), the non-slip conditions (1) and (2) is described as following four equations.

$$\begin{align*} 
2(1 - \mu \cos \theta)R_1 - (1 + \mu \cos \theta)\gamma_3 l - 2 \gamma_1 htan\alpha(4 - 2 \mu \cos \theta)\sin \theta + 2 \gamma_1 \mu \cos^2 \theta & \leq 0 \quad (10) \\
-2(1 + \mu \cos \theta)R_1 + (1 - \mu \cos \theta)\gamma_3 l - (1 - \mu \cos \theta)\gamma_2 l + 2 \gamma_1 htan\alpha(4 + 2 \mu \cos \theta)\sin \theta + 2 \gamma_1 \mu \cos^2 \theta & \leq 0 \quad (11) \\
-(1 + \mu \cos \theta)R_1 - \mu \cos \theta \gamma_3 l - \mu \cos^2 \theta \gamma_1 l + 2 \mu \cos \sin \theta \gamma_1 htan\alpha & \leq 0 \quad (12) \\
(1 - \mu \cos \theta)R_1 - \mu \cos \theta \gamma_3 l - \mu \cos^2 \theta \gamma_1 l + 2 \mu \cos \sin \theta \gamma_1 htan\alpha & \leq 0 \quad (13) 
\end{align*}$$

Where, $\gamma_1, \gamma_2,$ and $\gamma_3$ are described with the density of the membrane $\rho$, gravitational acceleration $g$, the membrane thickness $t$, and the membrane length $b_1$ and $b_2$ which generate $T_1$ and $T_2$ each other, as,

$$\gamma_1 = \rho g t a, \gamma_2 = \rho g t b_1, \gamma_3 = \rho g t b_2$$ \hspace{1cm} (14)

Equation (7) is also described with $\gamma_1, \gamma_2, \gamma_3, \alpha$, and $l$ as,

$$\begin{align*} 
-\gamma_2 l - 2 \gamma \sin \theta htan \alpha + \gamma_1 \cos \theta l & \leq 0 \quad (15) \\
-\gamma_3 l + \gamma_1 \cos \theta l + 6 \gamma \sin \theta htan \alpha - 2 R_1 & \leq 0 \quad (16) \\
-\gamma_3 l - \gamma_1 \cos \theta l + 2 \gamma \sin \theta htan \alpha - 2 R_1 & \leq 0 \quad (17) \\
-\gamma_3 l - \gamma_1 \cos \theta l + 2 \gamma \sin \theta htan \alpha & \leq 0 \quad (18) 
\end{align*}$$

We derive the non-slip condition for the guided-pin location numerically applying Eq.(10) \textendash (13) considering Eq.(15) \textendash (18).
4. Retraction experiments with guided-pin

Retraction experiments are performed to evaluate the non-slip condition.

4.1 Experimental setup

As the slips are occurred in the Z-fold region, the membrane of the Z-fold region is used for the membrane specimen as shown in the Fig. 7. O indicates the center point of the center hub. Four guided-pins are used to generate the Z-fold. The fold pitch of the Z-fold is 200 mm, which is the widest fold pitch the retraction mechanisms can fold. The membrane is 6 µm thick, whose compressive force is negligible.

Figure 8 indicates the detailed view of guided-pin and the membrane. On the assumption of the repeating structure of the Z-fold, the membrane length \(a_1\) and \(a_3\) are 100 mm, and \(a_2\) is 200 mm. The distance between the guided-pin 2 and 3 (= 40 mm) is twice as long as that of 1-2 and 3-4 (= 20 mm) in consideration of the ratio of the membrane length.

Figure 9 shows the location of guided-pin 3 for the experiments. The \(x_1-x_2\) coordinate system is space fixed system. To examine the effects of the distance from the center hub on the slip, the guided-pin is located either of three kinds of locations; \(L_1(x_2 = 521 \text{ mm})\), \(L_2(x_2 = 586 \text{ mm})\), \(L_3(x_2 = 651 \text{ mm})\). The \(x_1\) coordinate of the guided-pin location is changed for each of \(L_1\), \(L_2\), and \(L_3\).

In the experiments, we measure the slipped length at each guided-pin location to evaluate the slip quantitatively. As the slipped length depends on the length of the outside membrane (Fig. 6) \(h\), the experiments are performed for a fixed amount of \(h\); 409 mm.

\[\begin{align*}
&\text{Fig. 7: Overview of retraction experiments} \\
&\text{Fig. 8: Detailed view of guided-pin} \\
&\text{Fig. 9: Guided-pin location for experiments}
\end{align*}\]

4.2 Experimental results

The slipped length is measured for each guided-pin location to examine the mechanics of the slip experimentally. The slipped length on the guided-pin 3 is measured because the slip is observed on that guided-pin. We define the direction of the slip indicated by the arrow in the Fig. 8 as the positive. On the guided-pin 2, the slip is not definable because the membrane dose not contact with that guided-pin.

Figure 10 indicates the relationships between the slipped length and the value of \(x_1\) of the guided-pin location. The experimental results of \(L_1\), \(L_2\), and \(L_3\) are shown in the Fig. 10a, b, and c, respectively. The slipped length is measured three times for each guided-pin location (Fig. 9). The black dots indicate the average values of the experimental results. The error bar is the range of the maximum value to the minimum one. As shown in these figures, the slipped length becomes negative value as the value of \(x_1\) is increased. In the case of the guided-pin location \(L_1\), the slip occurs at \(x_1 = 120 \text{ mm}\) because the slipped length is within \(-6 \text{ mm}\) when the value of \(x_1\) is less than 100 mm. As shown in the Fig. 10b, in the guided-pin location \(L_2\), the maximum value of the slipped length is the smallest of three kinds of guided-pin locations. In the case of the guided-pin location \(L_3\), the slipped length gradually increases as the value of \(x_1\) is increased. Focusing on the error bar, the slipped length varies 20 mm at the maximum.
5. Guided-pin location for non-slip condition

The non-slip condition for the guided-pin location derived by the one-dimensional slip model is examined numerically compared with the experimental results. In the numerical simulation, the experimental data shown in the Table 1 is used for Eq.(10) - (13) and Eq.(15) - (18) to calculate the non-slip condition. As the membrane does not contact with the guided-pin, the value of $R_2$ of Eq.(8) is assumed to be 0. We also assume three kind of frictional coefficients; 0.2, 0.1, 0.05.

Figure 11 indicates the results of numerical simulation for the one-dimensional slip model and the guided-pin location for the retraction experiments. The results of the numerical simulation for each frictional coefficient are indicated, which determine the bounds of the guided-pin location for the non-slip condition and the slip one. The bounds are expressed with curves $C_{i,j}$, and $i$ and $j$ are the equation number and the frictional coefficient, respectively. In the case of positive value of $x_1$, the slip occurs when the value of $x_1$ becomes larger and the value of $x_2$ becomes smaller. In that case, the non-slip condition is determined by the Eq.(13). When the non-slip condition by the Eq.(13) is satisfied, the condition by Eq.(18) is also satisfied. In the case of negative value of $x_1$, the Eq.(12) determines the non-slip condition, which indicates the slip occurs when the value of $x_1$ and $x_2$ become smaller.

Applying the non-slip condition obtained by $C_{13}^{0.05}$ to the guided-pin location L1, the slip occurs when the value of $x_1$ is greater than 0.14m. In the experiments, the slipped length is larger than any other slipped length when the value of $x_1$ is greater than 0.14m. Hence, the experimental results are expressed qualitatively by the non-slip condition derived by the slip model. The direction of the slip is then discussed. When the guided-pin location is right-hand-side of the curve $C_{13}^{0.05}$, $R_1$ is positive value. The direction of the slip due to the positive value of $R_1$ is negative, as shown in the Fig.5. In the experimental results, the slip direction is almost negative as shown in the Fig.10. Thus, the slip direction derived by the numerical simulation coincides with that of the experimental results.

6. Conclusions

Guided-pin location of the retraction mechanisms was examined numerically and experimentally to improve the fold precision of a large deployable space membrane. The mechanics of the slip between the guided-pin and the membrane was investigated introducing a one-dimensional slip model. The non-slip condition was derived numerically applying the experimental data to the equation of the slip model. The guided-pin location for the slip condition was qualitatively agreement between the numerical simulation and the retraction experiments.

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Fig. 11: Guided-pin location for non-slip condition

Table 1 Parameters for numerical simulation

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<th>Parameter</th>
<th>Value</th>
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<td>Membrane density, ( \rho )</td>
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<td>Membrane thickness, ( t )</td>
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<td>Frictional coefficient, ( \mu )</td>
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<td>Length, ( a )</td>
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<td>Height, ( b_1, b_2 )</td>
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<tr>
<td>Height, ( h )</td>
<td>409 mm</td>
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References


