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Original Paper

Development of Repeatable Storage Method for a Large Solar Sail

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This paper proposes a method to store a large solar-sail membrane while ensuring repeatability of its stored configuration. Large membranes used as a solar sail should be stored compactly to save the launch volume; in addition, their stored configuration should be sufficiently predictable in order to guarantee reliable deployment in orbit. However, it is difficult to store a large membrane compactly because of the finite thickness of the membrane. This paper demonstrates the feasibility of the proposed "bulging roll-up" method experimentally using 10m-size membranes, and evaluates the repeatability of its stored configuration quantitatively.

Key Words: Membrane, Stowage, Packaging, Folding, Repeatability

1. Introduction

1.1. Background and objective

Analysis and development of solar sails have been widely carried out[1–5]. One of the very successful solar sail mission launched to date is IKAROS, as illustrated in Fig. 1, which was developed by Japan Aerospace Exploration Agency (JAXA)[6, 7]. Many studies have been conducted for IKAROS including deployment analyses through computational methods[8, 9] as well as through small-scale experiments[10]. In addition, on-orbit data are used to estimate the behavior of the sailcraft in space[7, 11]. For the next generation solar sail missions, such as JAXA's Trojan asteroid exploration mission using a larger sail than IKAROS[12], thorough understating of the IKAROS's experience is important. During the development of IKAROS, however, one problem became evident and has not been fully understood yet. The problem is on the repeatability of the stored configuration of a large membrane. In order to guarantee reliable deployment of the sail in orbit, the stored configuration of the sail should be sufficiently repeatable. However, the repeatable and compact storage of large membranes is challenging, because of membrane's finite thickness, as described in detail below. To this end, this paper aims at developing a repeatable and compact storage method for practical solar sails through analytical consideration (§2) and a series of sail-storage experiments using one of the proposed sail-storage methods (§3).

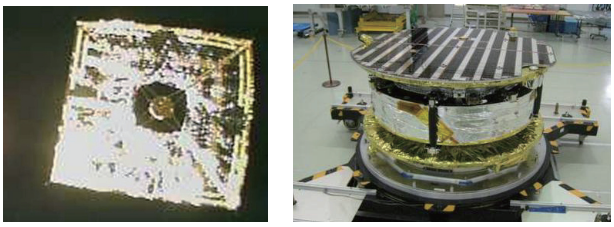
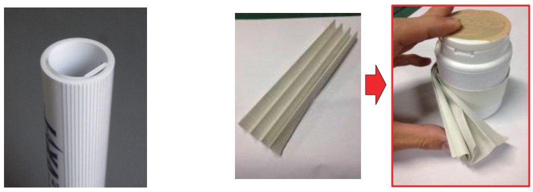

(a) Deployed configuration (b) Stored configuration

Fig. 1. Solar power sail demonstrator, IKAROS, which has been successfully operated since 2010 (© JAXA).

The simple examples shown in Fig. 2 illustrate the problem of how the finite thickness of membranes degrades the repeatability of their stored configuration. As shown in Fig. 2(a), when a calendar is rolled up, the tips of the papers do not align. This is due to the difference of circumferential length between the interior and exterior papers, caused by the finite thickness of the paper. When the Z-folded paper is rolled up around a hub, as depicted in Fig. 2(b), due to the circumferential length difference, the folded lines of the Z-fold cannot be kept and cannot be uniformly stored. If the originally designed crease lines cannot be used for the storage, as shown in Fig. 2(b), it is very difficult to guarantee the repeatability of the stored configuration. As discussed in the next section, for JAXA's next solar sail, more solar cells will be attached on its sail, and more number of Z-folds will be needed because of the larger sail size than IKAROS. As a result, the effect of the sail's thickness will be far from negligible.

If the finite thickness of membranes is not taken into account properly during the storage of a sail, there will be the following three problems. First, unexpected fold lines are created; thus, the stored configuration becomes less predictable and repeatable. Second, membranes cannot be stored uniformly and compactly; thus, more storage volume will be required. Third, too large tension/compression forces



(a) Rolling up a calendar (b) Wrapping a Z-folded paper

Fig. 2. Effect of thickness for wrapping fold.

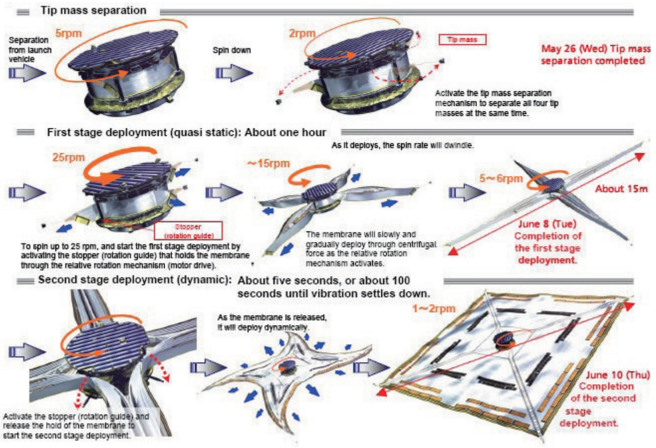


Fig. 3. Sail deployment sequence of IKAROS.

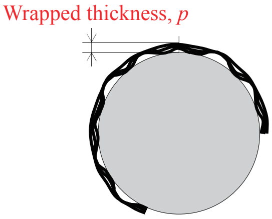


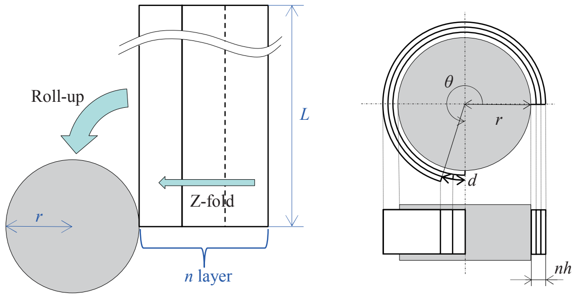
Fig. 4. Concept of "bulging roll up" employed by IKAROS.

may be applied in the membranes during and after the storage; thus, the membranes itself and devices attached on the membranes may be broken. Therefore, this study develops a method to control the stored configuration quantitatively by considering the membrane thickness, to enable a compact storage, and to avoid large forces applied in the stored membranes.

The stored configuration of a sail should be sufficiently repeatable, especially for the deployment method adopted by IKAROS. Figure 3 illustrates the deployment sequence of IKAROS$^{6)}$. As can be seen, IKAROS's sail is dynamically deployed using a centrifugal force, thus the deployment behavior is affected by the initial condition of the sail. Therefore, a repeatable storage is important for a reliable deployment. This study considers the folding pattern of IKAROS's sail as a base design. The folding pattern uses the Z-fold first, and then the Z-folded membranes are rolled-up around a cylindrical hub.

1.2. Past studies on folding non-negligible thickness membrane

There have been a few studies that provided a solution for wrapping a membrane with non-negligible thickness. Guest and Pellegrino$^{13)}$ proposed a folding pattern that considers the thickness of a membrane. The folding lines are not straight in their folding patterns to consider the thickness of a membrane. However, this folding pattern requires a high storage height unless a large number of folds is used. To solve this problem, Natori et al. proposed a spiral folding$^{14, 15)}$. Again, the folding lines are not straight in this folding pattern. It will be difficult to create non-straight crease lines for the storage of large membranes. Therefore, this study pursues a method to keep the crease lines straight.



(a) Z-fold and roll-up (b) The roll-up of completely stripped membrane

Fig. 5. A simple Z-fold and roll-up example.

Another approach that can avoid the effect of membrane thickness is to use the completely stripped architecture$^{1)}$. In this design, the sail is made of many membrane strips instead of a large membrane. Since this design does not require to roll up Z-folded membranes, the problems as shown in Fig. 2(b) will not happen. However, having numbers of long membrane strips will increase the complexity during production, storage, and deployment of a sail.

During the development of IKAROS, another method was adopted to countermeasure the effect of membrane thickness. The concept is shown in Fig. 4. When the Z-folded membrane bundle is rolled up around the hub, interior membranes of the bundle is intentionally slackened, whereas only the most exterior membrane is kept taut. This "bulging roll-up" method worked well enough for IKAROS. Now the method should be quantitatively evaluated to see whether this method is applicable to even larger membranes with more numbers of crease lines, where more solar cell devices are attached than IKAROS.

1.3. Organization of paper

The present paper is organized as follows. In §2, the effect of design parameters on the circumferential-length difference is clarified using a simple rectangular Z-folded membrane model. In §3, feasibility and repeatability of the bulging roll-up are demonstrated and evaluated through actually storing 10m-size membranes. From the results, the remaining problems to make the bulging roll-up more practical for solar-sail storage are identified.

2. Membrane Thickness Consideration in a Roll-up

This section analyzes the roll-up of the Z-folded membrane using a simple rectangular membrane model, aiming to clarify how the thickness effect appears depending on various design parameters. To observe the geometries in the roll-up of a

Table 1. Comparison of circumferential-length difference in IKAROS and JAXA's next solar power sail.

	IKAROS	*Next sail*
Layer thickness (average), h	10 μm	75 μm
Number of layers, n	18.5	60
Membrane length, L	7.0 m	30 m
Wrapping radius, r	0.75 m	1.5 m
Circumferential-length difference, d_m	1.62 mm	88.6 mm

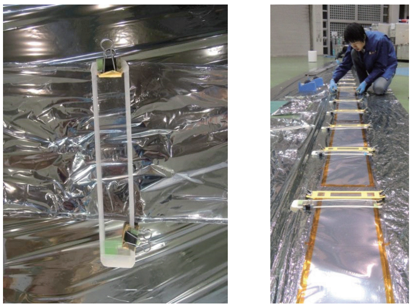


Fig. 6. A "binder" to hold membrane bundles.

Z-folded membrane, the simple model shown in Fig. 5(a) is considered. In this model, the rectangular membrane with a uniform thickness and a membrane length L is Z-folded along the straight crease lines in the tangential direction and rolled-up around a cylindrical hub with a radius r. This model is interpreted as a part of the solar sail having IKAROS's folding pattern.

First, assume that all the Z-fold crease lines in Fig. 5(a) are separated, which corresponds to the "completely stripped" architecture[1]. When the strips are wrapped around the cylindrical hub, as shown in Fig. 5(b), the strips' tips are not aligned because of the difference in the circumferential length caused by the membrane's finite thickness. The deviation d_m between the most interior and the most exterior strips are given by the following equation.

$$d_m = \left[\frac{(n-1)h}{r}\right]L \tag{1}$$

where n is the number of membrane strips (the number of Z-folded layers), h is the thickness of each membrane layer when rolled up. In addition, when the wrapped angle of the most interior strip is defined as θ , since $L = r\theta$,

$$d_m = (n-1)h\theta \tag{2}$$

In Eq. (1), the factor $[(n-1)h/r]$ is the effect of thickness per unit length of a membrane bundle, which should be properly absorbed by some methods for a compact storage if the Z-folded crease lines are not separated. This shows that the difficulty of the roll-up storage increases as the number of layers n and the layer thickness h get larger, and the radius of the hub r is smaller.

The amount of the deviation d_m that should be absorbed increases significantly for JAXA's next solar sail when compared to IKAROS. Table 1 shows the rough estimates of d_m for the two solar sails calculated by Eq. (1). In the next solar sail, the effect of thickness is more than 50 times larger than that of IKAROS. Thus, development of a method to absorb the deviation d_m is required.

To absorb this thickness effect, there are three methods as discussed in §1: (i) the use of non-straight Z-fold crease lines, (ii) completely stripped design, and (iii) bulging roll-up. This study pursues the method (iii). Consider the case that the rectangular membrane shown in Fig. 5 is Z-folded and rolled-up around the hub, and that the membrane tip is fixed so that the tips of the Z-folded layers do not deviate. One method to absorb the deviation d_m effect is that the interior layers form bulges as shown in Fig. 4, which we call as "bulging roll-up" herein. Only the most exterior layer becomes taut, and the other layers are slackened and deformed in the out-of- plane direction. As a result, the rolled-up thickness p becomes larger compared to the completely stripped case, shown in Fig. 5(b). In the following discussion, the thickness depicted in Fig. 4 is called p, and $p > nh$. It is difficult to predict the wrapped thickness, p, without rolling up an actual scale membrane. In addition, it is difficult to predict beforehand what value of p will be acceptable or unacceptable without actual testing. Hence, this study actually carries out the wrapping of a large membrane in the following section.

3. Experimental Quantification of Storage Repeatability

This section experimentally evaluates the feasibility and repeatability of the bulging roll up. This method enables to keep the Z-fold lines straight that will facilitates the storage procedure. However, the practical methods to realize the bulging roll-up of a large solar sail is not known yet. The problems addressed herein are the feasibility of the storage procedure of large membranes and the repeatability of their stored configuration.

3.1. Realization of bulging roll-up using binders and phase control

Two methods are introduced in order to make the bulging roll-up repeatable. They are the use of "binders", and the "phase control" of wrapped membranes. The binders hold the Z-folded membranes during the wrapping. They are made of two plastic plates with two paper clips, as shown in Fig. 6. The binders have two functions. First, they keep the originally formed crease lines during wrapping. Without any constraints, Z-fold crease lines naturally form curved lines[14, 15]. Second, the binders constrains the relative movement of each membranes in the Z-folded bundles, and help to form the bulges as uniformly as possible along the length.

To control the stored configuration of the membrane, this study employs the phase control along the entire membrane length. There can be three items to be controlled during wrapping the membrane, as illustrated in Fig. 7. They are wrapping tension, compression force, and wrapped phase of the membrane. To control the wrapped phase, the circumferential deviation, d, may be measured using the scale attached on the hub. The circumferential deviation, d, is defined as the distance of the maker on the membrane from the point where the zero-thickness membrane would be wrapped. When IKAROS's sail was stored, the sail wrapping mechanism was used[16]. This mechanism enabled to measure the wrapping tension, T, and the compression force, N, during the wrapping. However, regarding the wrapped

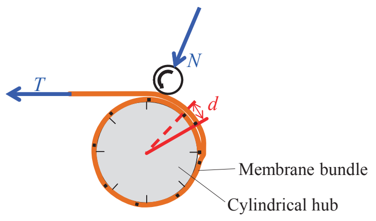


Fig. 7. Items that can be controlled during wrapping: wrapping tension, *T*, compression force, *N*, and circumferential deviation, *d*.

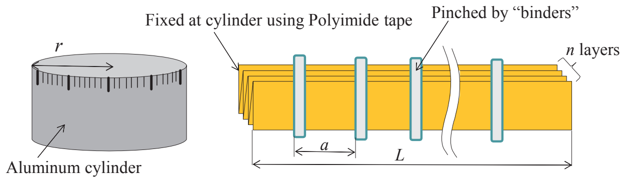


Fig. 8. Experimental configuration for wrapping a large Z-folded membrane.

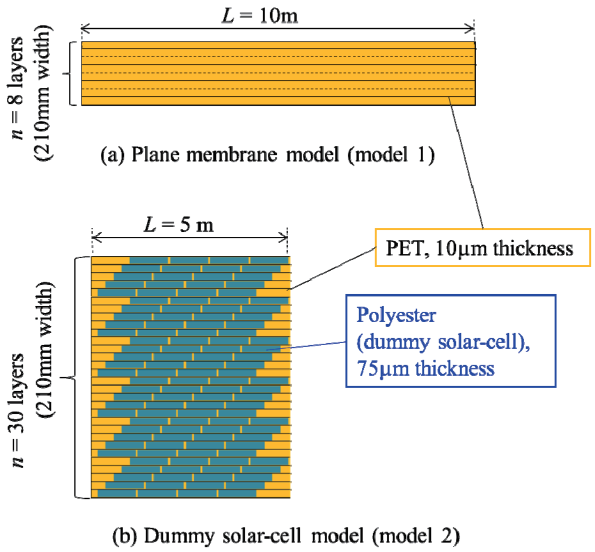


Fig. 9. Two sail models used for the wrapping experiments.

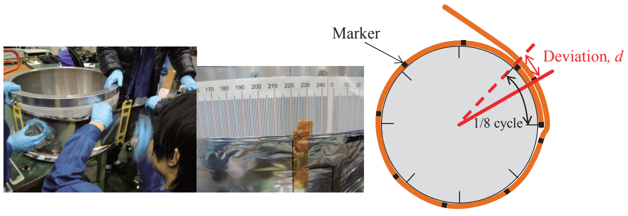


Fig. 10. Measurement of the circumferential deviation from zero-thickness membrane, *d*.

phase, only the locations of the sail tips are measured, thus the repeatability along the entire membranes was uncertain. In order to form uniform bulges with repeatability, the wrapped phase control along the entire membrane length is preferred. Therefore, this study measures the circumferential deviation, *d*, along the entire membrane length and quantifies the repeatability of the stored configuration.

3.2. Storage experiments using large membrane models

3.2.1. Objectives and procedure

In order to evaluate the feasibility and repeatability of the bulging roll-up, the sail storage experiments are conducted using large membranes. The experimental setup is illustrated in Fig. 8. As a hub, the aluminum cylinder with the radius r = 300 mm is used. Markers are attached on the large Z- folded membranes along their length at every intervals corresponding to one-eighth of the circumferential length of the cylinder. In addition, the Z-folded membranes are pinched by the binders at the positions of the markers. Namely, $a = 1/8\ (2\pi r)$ in Fig. 8. In order to evaluate the effect of the number of Z-fold layers, n, and the layer thickness, h, the following two membrane models, illustrated in Fig. 9, are used: (model 1) A 10 μ m-thick PET film, with the length L = 10 μ m, is Z-folded into n = 8 layers with the width of H = 210 mm. (model 2) A 10 m-thick PET film, with the length L = 5 m, is Z-folded into n = 30 layers with the width of H = 210 mm, additionally, on the almost entire PET film, 75 μ m-thick polyester films are attached as dummy solar cell devices.

Aiming at realizing a compact and repeatable storage, the membrane models are wrapped according to the following steps:

Step 1. The Z-folded membrane model is wrapped for one rotation preliminarily, and the positions of the markers attached at every one- eighth rotations on the membrane are measured using the scales on the cylinder. The circumferential deviations, *d*, from the fictitious zero- thickness membrane are recorded as illustrated in Fig. 10. For the first rotation, if the wrapped thickness of the membrane bundles, *p*, is assumed to be constant along the length, the circumferential deviation, *d*, will obey the following equation according to Eq. (2).

$$\textit{1st rotation}:\quad d = (r+p)\theta - r\theta = p\theta \tag{3}$$

Thus, the *p* for this membrane can be estimated by linear regression using the measured *d*.

Step 2. Now that the wrapped thickness *p*, estimated in Step 1, is assumed to be constant along the entire membrane length. Then, the target values of the circumferential deviation are calculated at every one-eighth rotations. For *the k-th rotation*,

$$d = \sum_{i=1}^{k}\left[2\pi(i-1)p\right] + (r+kp)\theta - r\theta = \sum_{i=1}^{k}\left[2\pi(i-1)p\right] + kp\theta \tag{4}$$

Figure 11 shows one set of the target values. It is the piecewise linear function whose gradient is increased at the transition of rotations.

Step 3. The membrane is wrapped around the cylinder to fit the marker positions at the target values. The membrane bundle is pinched by the binders until it is wrapped, and the binders are released when the marker at the position is adjusted to fit the scale. The circumferential deviation, *d*, measured herein is called *d during* the wrapping. Next, after the entire membrane is wrapped, the stored configuration is settled to an equilibrium condition. The circumferential deviation along the entire membrane length is then measured again. This is called *d after* the wrapping.

3.2.2. Wrapping the plane membrane model (model 1) using the constant wrapped-thickness target

First, the plane membrane model (model 1), shown in Fig.

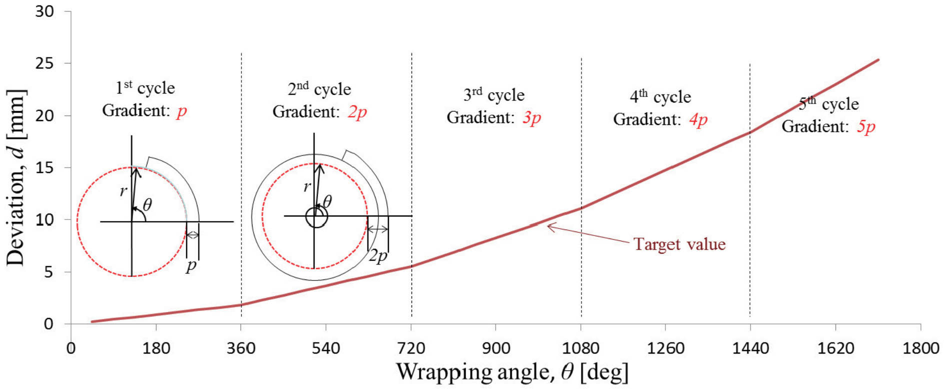
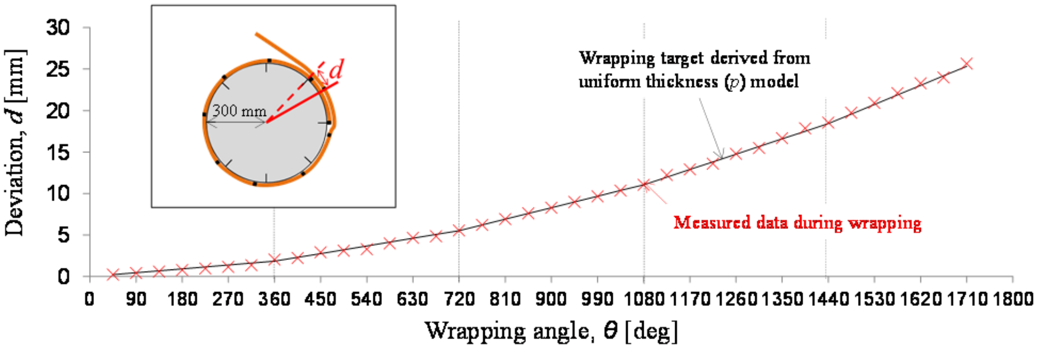
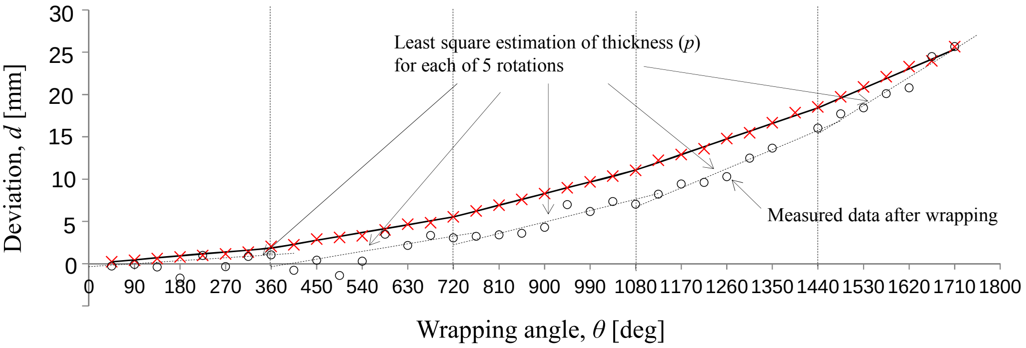


Fig. 11. Target value of the circumferential deviation with respect to the scale on the cylindrical hub.



(a) Deviation at 8 points on the cylinder during wrapping



(b) Deviation at 8 points on the cylinder after wrapping

Fig. 12. Measured deviation during and after the wrapping of the plane membrane model (model 1), assuming the constant wrapping thickness $p = 0.29$mm.

9(a), is Z-folded, and then wrapped around the cylinder. From the preliminary test, the constant wrapped thickness is estimated as p = 0.29 mm. Figure 12(a) shows the target values and the circumferential deviations, measured during the wrapping. The measured data show excellent agreements with the target values. However, the circumferential deviations measured after the wrapping are different from the ones during the wrapping, as depicted by the circles in Fig. 12(b).

The wrapped thicknesses, p, for each rotation after the wrapping are estimated by linear regression, as shown in Fig. 12(b). Figure 13 shows the results. Compared to the constant target value, p = 0.29 mm, the most interior bundle is thinner, and the exterior bundles are thicker. This phenomenon is understood as the interior bundles are compressed to the rigid cylinder to become thinner, whereas the exterior bundles are not compressed from outside at all. Therefore, the assumption of the constant wrapped thickness was not appropriate. If the wrapped configuration changes during and after the wrapping, the reliability of the deployment will be degraded. Thus, in the next section, the target values are modified so that the wrapped configuration changes less during the wrapping.

3.2.3. Wrapping of the plane membrane model (model 1) using the variable wrapped-thickness target

In order to develop a method to reduce the movement of the membrane bundles during/after the wrapping, the target value is modified as follows. When the target values at every one-eighth rotations are calculated, the wrapped thickness p = 0.2 mm is assumed for the most interior bundles, p = 0.36 mm is assumed for the most exterior bundles, and p = 0.29 mm is assumed for other intermediate bundles. The reasons for choosing these thicknesses are explained in Appendix A. Figure 14 shows the wrapped results using the modified target values. The difference between circumferential deviations during and after the wrapping is significantly less than the previous result. Thus, the wrapped configuration is controlled better and more repeatable with the modified target value.

However, the results in Fig. 14 show another problem. The circumferential deviations during the wrapping have larger values than the target values especially at the first two rotations. This means that the bundles are too thick during the wrapping to fit the target circumferential deviation. In other words, the deformation modes of wrapped membrane bundles due to the tension T and due to the compression force N are different; thus, only applying tension during wrapping is not sufficient to follow the thinner target wrapped-thickness. If more precise fitting is required, the compression force N should be applied on the already wrapped bundles during the wrapping.

3.2.4 Wrapping of the dummy solar-cell model (model 2) using the constant wrapped-thickness target

Next, in order to evaluate the feasibility and repeatability of the membrane storage with more numbers of layers, n, and a larger layer thickness, h, the dummy solar-cell model (model 2), as shown in Fig. 9(b), is used for the storage experiment. In this model, 75 μ mm-thick polyester films are attached on the 10mm-thick PET film. This polyester films imitate the solar cell devices that will be attached on JAXA's next solar sail. In this experiment, the wrapped thickness is assumed to be constant along the membrane length when the target values are calculated. This is because the appropriate setting of variable wrapped thicknesses for each rotation is not known yet. The constant wrapped thickness is estimated as p = 5.0 mm according to Step 1. It should be noted that the wrapping of this (model 2) is found to be more difficult than (model 1). The experimenters are required to form the uniform bulges more carefully, otherwise the membrane bundles easily form undesired, non-straight crease lines. In addition, relatively large "bulges", as the example is shown in Fig. 15, are observed even after the successful wrapping.

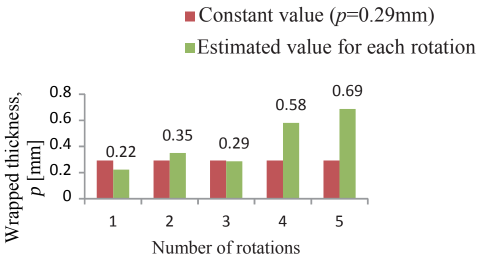


Fig. 13. Comparison of the constant wrapped thickness, p, used as a target value and the estimated wrapped thickness from measured data for each rotation.

Figure 16 shows the results. The experiments are conducted twice, and the two sets of results show good repeatability. Even though this (model 2) has the larger number of Z-fold layers, n, and the larger layer thickness, h, than (model 1), the trend of the results is similar to (model 1) in the following aspect. The circumferential deviations, d, are precisely adjusted at the target values during the wrapping, although these d values during the wrapping of (model 2) are not shown in Fig. 16. However, as can be seen in the figure, the d value after the wrapping reduces after the wrapping especially at the most interior rotation. Again, the authors believe that this reduction is caused by the fact that the bundles are compressed by the exterior bundles after wrapping, except for the most exterior bundle. This effect is not included in the constant wrapped-thickness target.

Next, the use of the smaller target values at the most interior rotation is tried, but the markers on the membrane bundles cannot be aligned to the target values because of the same reason with the previous experiments: the deformed shape of the interior bundles caused by the exterior compression force cannot be made only by applying the tension during wrapping. Hence, the compression force should be applied along the wrapped bundles when thinner storages are required.

3.3. Discussion on the bulging roll-up method

The series of storage experiments demonstrated that the repeatable "bulging rollup" of large membranes is feasible if the "binders" and the "phase control" are properly used. It also showed that in order to realize more compact and more repeatable stored configuration, the compression force, N, should be applied during the wrapping. For the appropriate

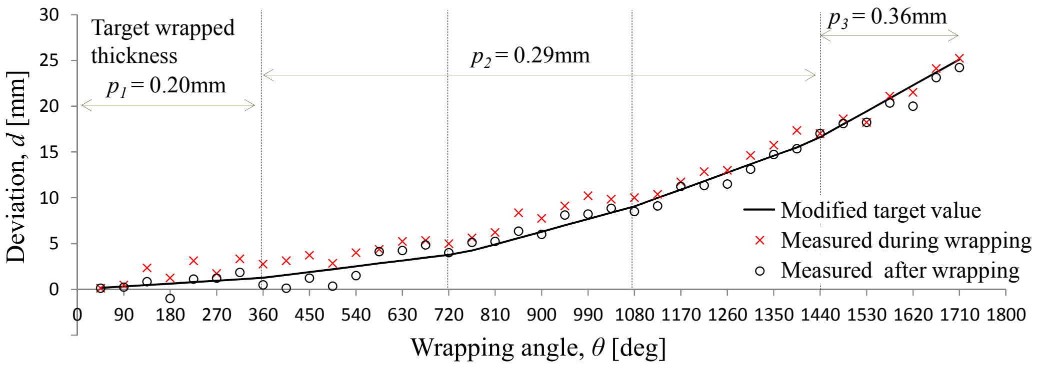


Fig. 14. Measured deviation during and after the wrapping of the plane membrane model (model 1), using the variable wrapped-thickness target.

selection of the compactness, the tightness, or the repeatability of the stored configuration, the following three kinds of additional information will be required. First, the sensitivity of the stored configuration of the membrane to the deployment reliability should be more clarified through deployment simulations. Such analysis will clarify the requirements about the repeatability of the stored configuration. Second, the stability of the stored configuration during the rocket's launch should be evaluated through vibration tests of the stored membrane. The method to keep the stored configuration during the launch should be designed together with the storage method. Third, the effect of bulging deformations on the performance of solar cells attached on the membrane needs to be evaluated. The result will provide the minimum acceptable radius of curvature of the sail during the bulging roll-up. By clarifying the requirements for the stored configuration, an appropriate storage method will be determined based on the knowledge found in this study.

4. Concluding Remarks

This study has made the following three contributions. First, how the effect of membrane's finite thickness appears depending on various design parameters is clarified. Second, the feasibility and repeatability of the proposed method for making "bulging roll-up" are demonstrated through storage experiments of 10m-size membranes. Third, the remaining problems to make the storage method more practical are clarified.

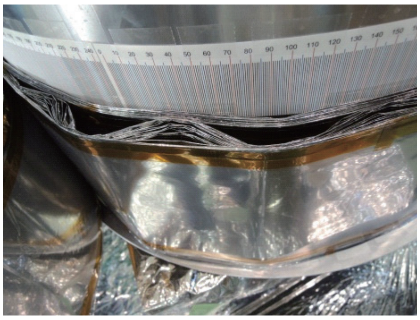


Fig. 15. The deformation of dummy solar cells after the wrapping.

Appendix A: Determination of Variable Wrapped-thickness Target

In the experiment described in §3.2.3, the present authors choose the trial variable wrapped-thickness target as follows, in order to assess the feasibility of this modified target concept. First, it is assumed that there are three wrapped-thicknesses (p_1, p_2, p_3), as illustrated in Fig. 14, based on the conditions of the bundles in the wrapped configuration. The most interior bundle (p_1) is compressed to the solid cylinder, the intermediate bundles (p_2) are surrounded by sail bundles from both interior and exterior, and the most exterior bundle (p_3) is not compressed from its exterior. Second, the wrapped-thickness target for the intermediate bundles is chosen as p_2 = 0.29 mm, which is the value used as the constant wrapped-thickness target in §3.2.2. Finally, (p_1, p_3) are chosen so that the new target fits the best to the circumferential deviation result after wrapping in the constant wrapped-thickness experiment, shown in Fig. 12(b), in a least square sense.

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References

1) Greschik, G. and Mikulas, M. M.: "Design Study of a Square Solar Sail Architecture," *Journal of Spacecraft and Rockets*, **39** No. 5, Sept.-Oct. (2002), pp. 653–661.

2) Murphy, D. M.: "Validation of Scalable Solar Sailcraft System," *Journal of Spacecraft and Rockets*, **44** No. 4, July-Aug. (2007), pp. 797–808.

3) Lappas, V., Wie, B., McInnes, C., Tarabini, L., Gomes, L. and Wallace, K.: "Microsolar Sails for Earth Magnetotail Monitoring," *Journal of Spacecraft and Rockets*, **44** No. 4, July-Aug. (2007), pp. 840–848.

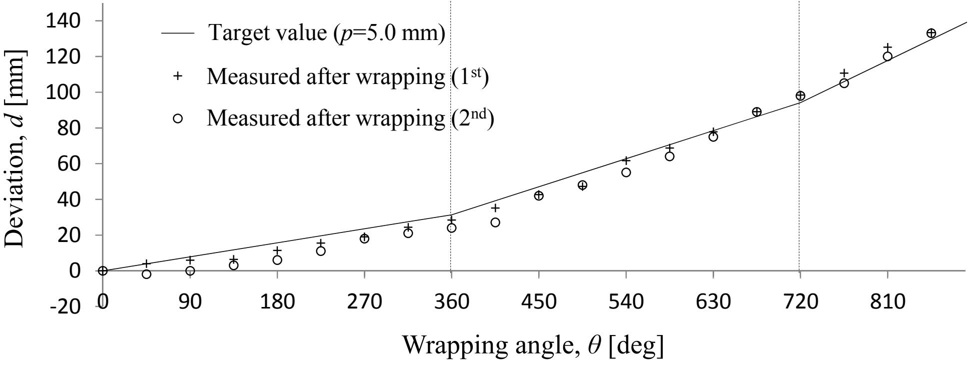

Fig. 16. Measured deviation during and after the wrapping of the dummy solar-cell model (model 2), assuming the constant wrapped thickness p = 5.0mm.

4) Banik, J. A. and Ardelean, E. V.: “Verification of a Retractable Solar Sail in a Thermal Vaccum Environment,” AIAA Paper 2010-2585, 2010.

5) Guerrant, D. V., Lawrence, D. A. and Wilkie, W. K.: “Performance of a Heliogyro Blade Twist Controller with Finite Bandwidth,” AIAA Paper 2012-4661, 2012.

6) Sawada, H., Mori, O., Okuizumi, N., Shirasawa, Y., Miyazaki, Y., Natori, M. C., Matunaga, S., Furuya, H. and Sakamoto, H.: “Mission Report on The Solar Power Sail Deployment Demonstration of IKAROS,” AIAA Paper 2011-1887, 2011.

7) Tsuda, Y., Saiki, T., Funase, R., Shirasawa, Y. and Mimasu, Y.: “Shape Parameter Estimation of IKAROS Solar Sail Using In-Flight Attitude Determination Data,” AIAA Paper 2011-1889, 2011.

8) Shirasawa, Y., Mori, O., Miyazaki, Y., Sakamoto, H., Hasome, M., Okuizumi, N., Sawada, H., Furuya, H., Matsunaga, S. and Natori, M. C.: “Analysis of Membrane Dynamics Using Multi-Particle Model for Solar Sail Demonstrator “IKAROS”,” AIAA Paper 2011-1890, 2011.

9) Miyazaki, Y., Shirasawa, Y., Mori, O., Sawada, H., Okuizumi, N., Sakamoto, H., Matunaga, S., Furuya, H.: and Natori, M. C.: “Conserving Finite Element Dynamics of Gossamer Structure and Its Application to Spinning Solar Sail “IKAROS”,” AIAA Paper 2011-2181, 2011.

10) Okuizumi, N., Muta, A., Matsunaga, S., Sakamoto, H., Shirasawa, Y. and Mori, O.: “Small-scale Experiments and Simulations of Centrifugal Membrane Deployment of Solar Sailcraft “IKAROS”,” AIAA Paper 2011-1888, 2011.

11) Shirasawa, Y., Mori, O., Sawada, H., Chishiki, Y., Kitamura, K. and Kawaguchi, J.: “A Study on Membrane Dynamics and Deformation of Solar Power Sail Demonstrator “IKAROS”,” AIAA Paper 2012-1747, 2012.

12) Funase, R., Kawaguchi, J., Mori, O., Sawada, H. and Tsuda, Y.: “IKAROS, A Solar Sail Demonstrator and Its Application to Trojan Asteroid Exploration,” AIAA Paper 2012-1748, 2012.

13) Guest, S. D. and Pellegrino, S.: “Inextensional Wrapping of Flat Membranes,” *First International Conference on Structural Morphology*, edited by R. M. Montpellier and T. Wester, Sept. 1992, pp. 203–215.

14) Natori, M. C., Kishimoto, K., Watanabe, H. and Higuchi, K.: “Morphological Concept on Efficient Space Structures with Deployable and/or Adaptive Functions,” AIAA Paper 2008–2211, 2008.

15) Natori, M. C., Watanabe, H., Kishimoto, N. and Higuchi, K.: “Folding Patterns of Deployable Membrane Space Structures Considering Their Thickness Effects,” *18th International Conference of Adaptive Structures and Technologies*, Ottawa, Ontario, Canada, Oct. 2007.

16) Furuya, H., Mori, O., Sawada, H., Okuizumi, N., Shirasawa, Y., Natori, M. C., Miyazaki, Y. and Matunaga, S.: “Manufacturing and Folding of Solar Sail IKAROS,” AIAA Paper 2011-1967, 2011.