Evaluation of deployment method of Spin-Deployable Membrane

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Abstract

There have been proposed several deployment methods (fold patterns) of membrane for spinning solar sail in Japan. It is necessary to evaluate each proposed methods and compare them with each other. In this report, the criteria for the evaluation are presented, and numerical examples are shown for three deployment methods that have been proposed for spinning solar sail.

スピン展開膜面の展開方式の評価法

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概要

現在，日本では，ソーラーセイルの展開方法として，宇宙機自身がスピンし，それによる遠心力を利用してセイル膜面を展開する方法が検討されており，その際の折り畳み方がいくつか提案されている．しかし，それらの展開方式の比較・評価はほとんど行われていないのが現状である．今回は，異なる折り畳み法の特性をそれぞれ，定性的・定量的に評価することための評価指標を提案すること，および，異なる折り畳み法でいくつかの数値解析例を示し，その特性を比較することを目的とする．

1 Introduction

1.1 Spin-Deployable Membrane

A concept of extremely large space structures like solar sail doesn’t reach achievement, because there is no material that can endure space environment for a long term. But the technology of materials such as polyimide film is advanced in recent years. So, the research and development of membrane structures are actively carried out around the world.

A solar sail is a space craft which converts light from sun into thrust by reflecting the light. There are two ways for deploying membrane one method uses extendible beams, and another method uses the centrifugal force by spinning space craft. The spinning deployment method which is called spinning solar sail is considered in Japan.

1.2 Development of Solar Sail in Japan

Some deployment methods are proposed and their deploying experiments are conducted in Japan. But an experiment on ground is greatly influenced by gravity and air drag. Therefore, it is difficult that the experiment on ground simulates a behavior of deploying membrane in space. And there are some experiment including a deploying 20m class membrane by using the large scientific balloon, and deploying membrane in environment like high vacuum and micro gravity by using the sounding rockets. But these experiments are few as its cost and the launch chance. Therefore numerical analysis is necessary to understand the behavior of membrane in space.

1.3 Purpose

So, it is necessary to evaluate each proposed methods and compare them with each other for developing solar sail. The purpose is to propose the criteria for the evaluation, and to conduct some numerical examples with three deployment methods that have been proposed for spinning solar sail.

2 Numerical Analysis Model

In this section, three deployment methods that are used in numerical analysis are described.

2.1 Square Type

One of the features of Square type membrane is using two-staged deployment method. At 1st stage, the membrane is deploying gradually as 4 bands. And at next stage, wires that bind membrane into bands are released. Actual membrane model consists of 4 petals, but this report’s numerical model is made by 1 membrane.

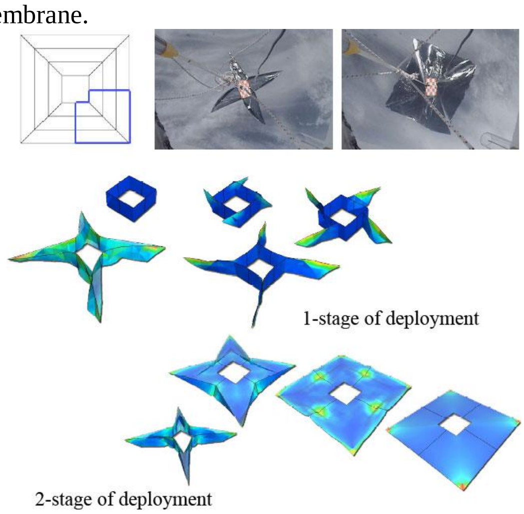

Figure 1 : Square Type

2.2 Fan Type

Fan type membrane consists of 6 petals, and each petal is linked to next petals by tethers that are called bridge. This model is one-staged deploying.

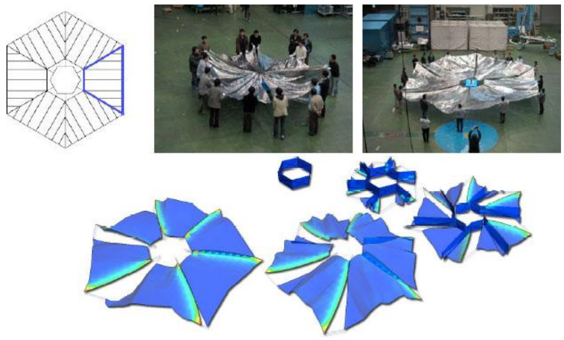

Figure 2 : Fan Type

2.3 Simple Wave Type

Simple wave type membrane made by 1 membrane. As this feature, it is difficult to produce and to fold real-size membrane.

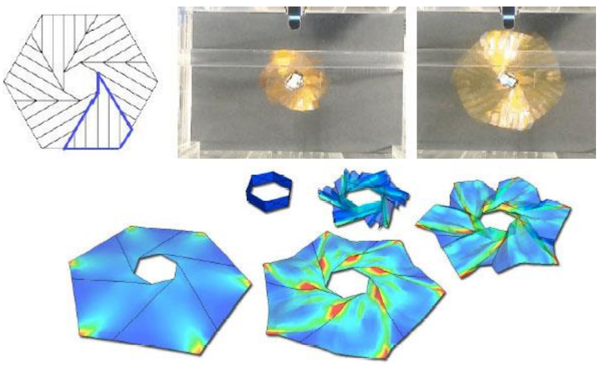

Figure 3 : Simple Wave Type

2.4 The Membrane Release Mechanism

Square type and Fan type have a membrane release system to control the release speed for quasi-static deploying. In numerical analysis models, the release mechanism is simulated by releasing node's displacement constraint, corresponds to membrane release speed.

Figure 4 : Membrane Releasing Mechanism

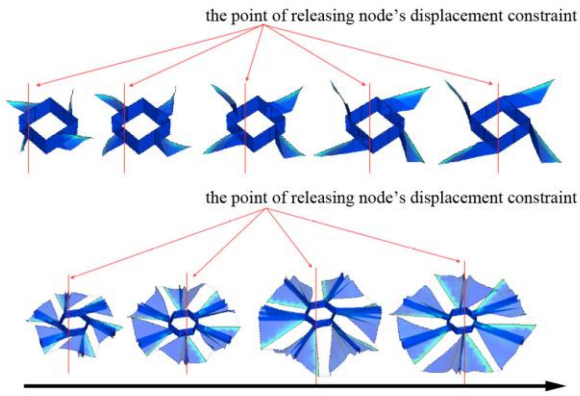

Figure 5 : The Numerical model of Membrane Releasing Mechanism

3 The Criteria for Evaluation

It is necessary to establish appropriate criteria to a quantitative evaluation of the deploying behavior from numerical analysis results. We use criteria as shown in table 1.

Table 1 : The criteria for evaluation

Evaluation Item	Evaluation Value
Deploying Characteristic	Tip mass deploying ratio, Maximum deplpoying ratio, Maximum deplying time, Projected area ratio
Residual Vibration Characterist	Tip mass deploying ratio, Tip mass shaped width ratio, Projected area ratio, Tip mass rotation angle ratio, Tip mass angular velocity ratio
Synchronous Characteristic	Tip mass rotation angle ratio, Tip mass angular velocity ratio
Energy Characteristic	Maximum strain energy density, Cumulative strain energy density
Deformation Characteristic	Deforamtion type occupied ratio

In this report, we focus Tip mass deploying ratio, Tip mass shaped width ratio, Tip mass rotation angle ratio, and Cumulative strain energy density. Equation 1 shows definitional equations for these evaluation values.

$$DR = \frac{r}{R},\ WR = \frac{h}{H};\ AR = \frac{\theta - \theta_0}{\Theta - \theta_0} \qquad (1)$$

$$AED_n = \int_0^t \pi_n dt$$

Where

- DR : Tip mass deploying ratio,
- WR : Tip mass shaped width ratio,
- AR : Tip mass rotation angle ratio,
- AED_n : Cumulative strain energy density of element "n",
- π_n : strain energy density of element "n".

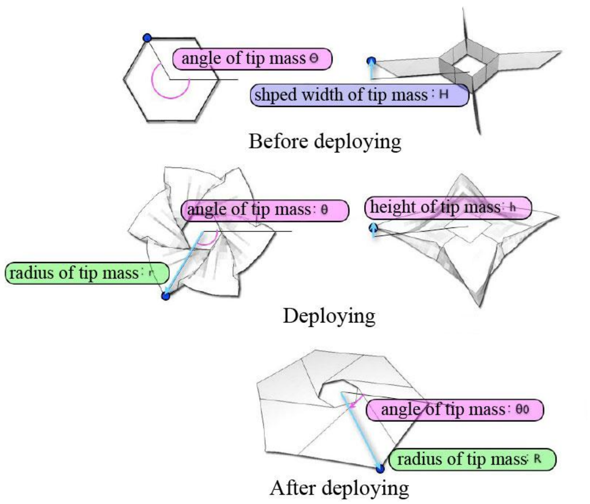

Figure 6 : Evaluation values

4 Numerical Analysis Results

We investigated the effect of some parameters for to evaluate the deploying characteristics of 3 deployment methods. Table 2 shows the parameters that are used, and its purpose. The analysis is conducted by changing these parameters, and table 3 shows the parameters that are material characteristics and basic values of these parameters.

Table 2 : Analysis parameters

Parameter	Purpose of changing parameter
Membrane Shape	There are square and hexagon type membrane. Hence we evaluate the effect of membrane shape in same deployment method.
Membrane Size	For saving computational cost, analysis model's membrane size is smaller than actual size. Hence we evaluate the effect of membrane size in same deployment method.
Spin Rate	To evaluate the effect of spin rate on residual vibration characterstics.
Membrane Release Speed	Square type and Fan type have membrane release mechanism. And we evaluate the effect of membrane release speed on residual vibration characterstics in these models.
Folding Stiffness	A membrane has folding stiffness that correspond to folding pattern. And we evaluate the effects of folding stiffness on deploying behavior.

Table 3 : Material characteristics and parameter's value

Name	Value	Unit
Radius of Center Hub	0.8	m
Spin Rate	2.2	rad/sec
Membrane Size	6	m class
Membrane Release Speed	0.63	rad/sec
Young's Modulus	2.5	GPa
Poisson's Ratio	0.3	−
Membrane's density	1420	kg/m^3
Membrane's thickness	10	μ m

4.1 The Effect of Membrane Shape

There are square and hexagon type membrane shapes. Hence, we evaluated the effect of membrane shape in same deployment methods, at first. Figure 7 shows analysis results of the effect of changing membrane shape (square and hexagon) in simple wave type membrane.

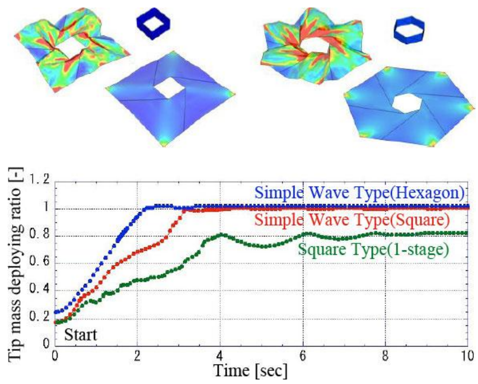

Figure 7 : Effect of membrane shape for tip mass deploying ratio

Figure 7 shows the deploying appearances of square and hexagon simple wave models respectively, and the tip mass deploying ratio of these models and square type 1-stage's one for comparison. There are some differences between square and hexagon models, but tendencies of deploying behavior, after-deploying behavior, and stress state coincide with each other (square and hexagon simple wave type).

4.2 The Effect of Membrane Size

An actual solar sail's membrane size will be tens of meters. Hence, the numerical model must be the same size. But in this report, analysis model's membrane size is smaller than actual one for saving computational costs. So we investigated the effect of membrane size on deploying behavior. Figure 8 shows the analysis results of the effect of membrane size on fan type membrane.

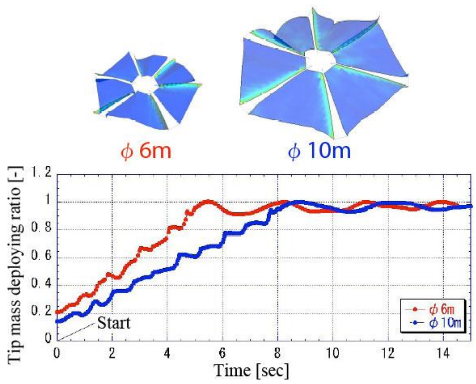

Figure 8 : Effect of membrane size for tip mass deploying ratio

Figure 8 shows the tip mass deploying ratio for diameter of 6m and 10m respectively. The tip mass deploying time is not equal because membrane release speed is constant. But the tendencies of deploying behavior and residual vibration characteristics are coincide with each other.

So, we concluded the deploying behavior doesn't depend on membrane shape or membrane size. It depends on folding pattern.

5 The Comparison of Each Deployment Methods

In this section, we show the numerical analysis result of residual vibration characteristic and synchronous characteristic for each deployment methods.

5.1 Residual Vibration Characteristic

Figure 9 shows the tip mass shaped width ratio of each deployment method. These graphs can evaluate the residual vibration characteristic in the direction of height. Square type's 1-stage is a phase which is deploying the membrane as 4 bands from the state of winded on the central hub. And, amplitudes of this phase's result is smaller than fan type's and simple wave type's one. So, we conclude that square type's 1-stage is a most stable deployment method. Fan type's amplitude of vibration is the largest, but the amplitude can be suppressed by decreasing membrane release speed.

5.2 Synchronous Characteristic

Figure 10 shows the tip mass rotation angle ratio of each deployment method. These graphs can evaluate the synchronous characteristic and the residual vibration in the direction of rotation during deploying.

The deployment methods that have most stable deploying and the finish of the deploying are fan type's 2-stage and simple wave type. Square type's 2-stage is a phase which is a deploying the membrane after the releasing 4 bands, and the membrane keep its position during the deploying. Fan type and square type's 1-stage have residual vibration in the direction of rotation, and fan type's residual vibration has small damping respect to square type's 1-stage's one. And also, fan type's amplitude can be suppressed by decreasing membrane release speed.

5.3 Cumulative Strain Energy Density

Figure 11 shows cumulative strain energy density of each deployment method. These figures can evaluate the distribution of strain energy to know the place which solar cells can put on.

In fan type's result, the strain energy is concentrated near the line from center hub to tip mass, and other area's strain energy is low level. And, the strain energy of square type and simple wave type are widely distributed respect to fan type. Hence, fan type is the most suitable for pasting the solar battery as large area which has low strain energy.

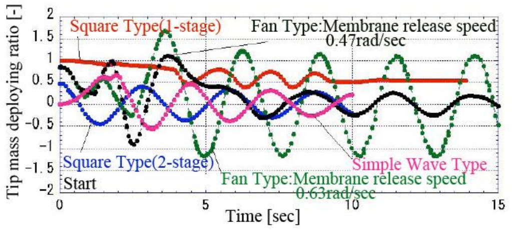

Figure 9 : Residual Vibration

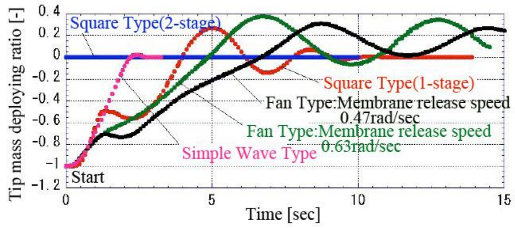

Figure 10 : Synchronous Characteristics

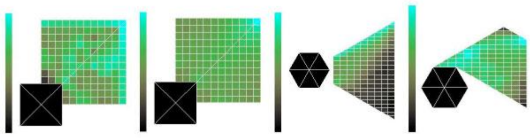

Figure 11 : Cumulative Strain Energy Density

6 Summary

The results of each comparison are summarized as table 4.

Table 4 : Summary of each result

Deployment Method	Residual Vibration Characteristic	Synchronous Characteristic	Cumulative Strain Energy Density
Square type's 1-stage	○	△	Distributed
Square type's 2-stage	△	○	Distributed
Fan type	×	×	Concentrated
Simple wave type	△	○	Distributed

It is confirmed that the difference went out to the development characteristics of whether composed of one membrane or composed of some membranes. In the deployment method composed on some membranes, each membrane and central hub is connected by tether, so it was supposed that the residual vibration characteristics is not good. And it is confirmed quantitatively by these evaluations. And, it is confirmed also that the distribution of strain energy is different from each other deployment method.

7 Conclusions

We proposed the criteria to evaluate deployment method each other, and conducted some numerical analysis for three deployment methods. And these results indicate the deployment method has its own characteristics.