Shape Control of Membrane Space Structures Using Shape Memory Alloy Wire Actuator

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Abstract

In the solar power sail demonstrator IKAROS launched by JAXA in 2010, an unexpected deformation of the sail membrane was observed, which was caused by the thermal deformation of thin-film solar cells. The influence of solar radiation pressure changes due to this deformation, resulting in unexpected attitude disturbance. In order to cancel the attitude disturbance, a large amount of fuel is required. This study proposes a shape control method for membrane space structures using Shape Memory Alloy Wire Actuator (SMA Actuator). SMA Actuator is one of artificial muscles that can be contracted and cured in response to thermal input. Various deformations can be effect by changing the locations and contraction directions of the actuators. Relationships between the control input and the effected deformations are investigated by numerical analysis and experiment.

形状記憶合金ワイヤーアクチュエータを用いた宇宙膜構造物の形状制御

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要旨

2010 年に JAXA によって打ち上げられたソーラー電力セイル実証機 IKAROS により，薄膜太陽電池の熱変形に伴う反りの影響で，予測不可能な変形状態を示すことがわかった．これにより太陽光圧の影響が変動し，姿勢外乱としてはたらく．IKAROS ではこの姿勢外乱を相殺するために，大量の燃料を消費する状況に陥った．そこで本研究では，形状記憶合金ワイヤーアクチュエータを用いて，特定の形状に制御する手法を提案する．このアクチュエータは，電圧印加による発熱によって収縮・硬化する人工筋肉の一種である．アクチュエータの搭載位置や収縮方向を変えることで，膜面形状を様々な形状に変形させることができる．本稿では数値解析と実験により，熱入力に対する形状の関係を明らかにする．

1. Introduction

In the solar power sail demonstrator IKAROS (Fig. 1) launched by JAXA in 2010, it is known that the membrane shape of the solar sail deformation due to the influence of the thermal deformation of the thin-film solar cell. The deformation of the entire membrane is thought to be caused by the change in the circumference of the four membrane materials called petals that configure the solar sail.

When the circumference after deformation is smaller than the circumference when deformation, the membrane shape is deformed into a saddle shape. On the other hand, it is known that When the circumference after deformation is bigger than the circumference when deformation, the membrane shape deformed into an umbrella shape (Fig. 2).

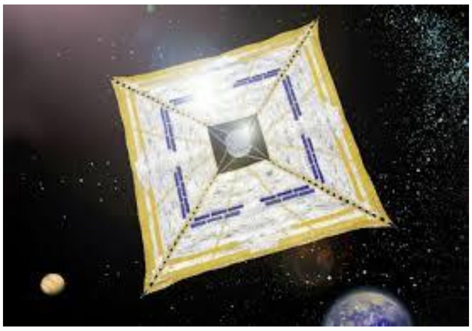


Fig. 1 IKAROS

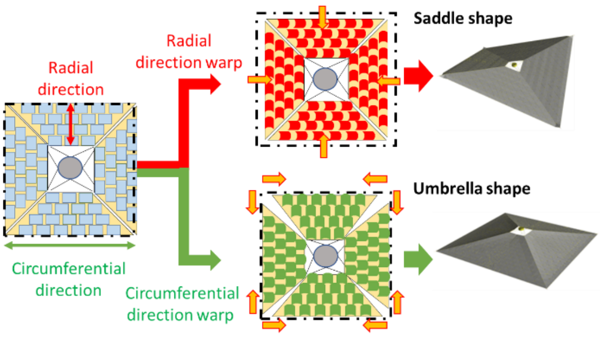


Fig. 2 Relationship between circumference margin and membrane shape (1)

When the membrane shape changes, disturbance torque is generated in the solar sail. It is thought to be caused by the change in the distance between the center of solar radiation pressure (SRP) and the mass of the solar sail. When deformed into a saddle shape, the SRP torque generated is small. Because the distance between the center of SRP and the mass is small. On the other hand, when deformed into an umbrella shape, the distance between the center of SRP and mass is large, so the torque is large (Fig. 3).

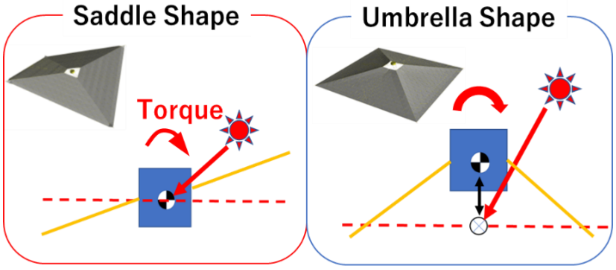


Fig. 3 Relationship of Membrane Shape and SRP Torque (1)

Deformation of membrane shape changes the SPR torque and acts as an attitude disturbance. In IKAROS, the “spiral motion” (Fig. 4) in which the rotation axis of the spacecraft tilts and the “windmill torque” (Fig. 5) in which the spin rate decreases due to deformation into the windmill shape were confirmed.

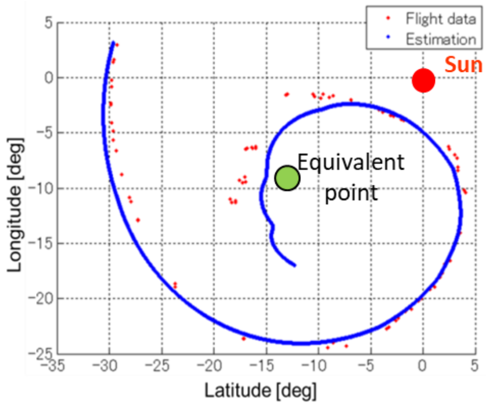


Fig. 4 Spiral Behavior (1)

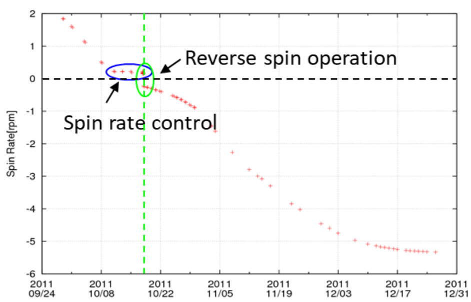


Fig. 5 Windmill Behavior (1)

In the previous research, the influence of the warp direction and location of the thin-film solar cell on the solar sail was confirmed using finite element method (FEM) analysis, and the shape deformation mechanism was clarified. In addition, the influence of the membrane shape on the spacecraft was clarified by calculating the SRP torque according to the membrane shape. (1)

In this study, we propose a shape control method for membrane structures assuming solar sail using Shape Memory Alloy Wire Actuator (SMA wire actuator). As a fundamental consideration, we show the utility of the shape control using the actuator from the finite element method analysis. In addition, the validity of the analysis result is confirmed from experiment.

2. Principle of control method

In this study, we used to propose a control method using SMA Wire Actuator (BMF150, TOKI corporation). SMA Wire Actuator is one of artificial muscles that can be contracted and cured in response to thermal input. This actuator is fixed at both ends and heat shrinks. The control method is considered to affect the deflection due to the contraction of actuator. The membrane shape is controlled using the deflection. Assume that multiple actuators are located to the membrane surface, as shown Figure 6. We considered the deformation control to various membrane shapes by the changing the contracting actuator.

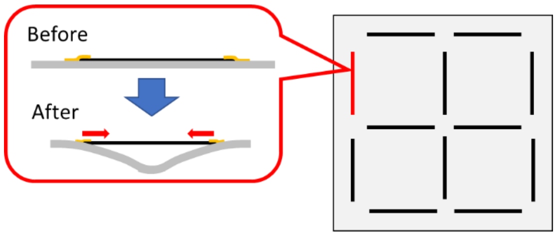


Fig. 6 Basic Membrane Model

3. Finite Element Model

3.1 Finite element model to confirm the usefulness of control methods

First, the utility of the control method is shown by numerical analysis using Finite Element Method (FEM). In this study, finite-element software Abaqus/Explicit 6.14-2 was used. The analysis model was set so that 12 actuators were fixed at both ends on the membrane surface. The analysis conditions were set that the actuator contracted by 4% when heat at 60 °C was applied (Fig. 7). Table 1 and Table 2 shows the set values and conditions for analysis. The boundary condition was set so that the displacement in the X, Y, and Z directions at the center of the membrane surface was zero in order to make it easier to see the effect on the membrane surface of the actuator.

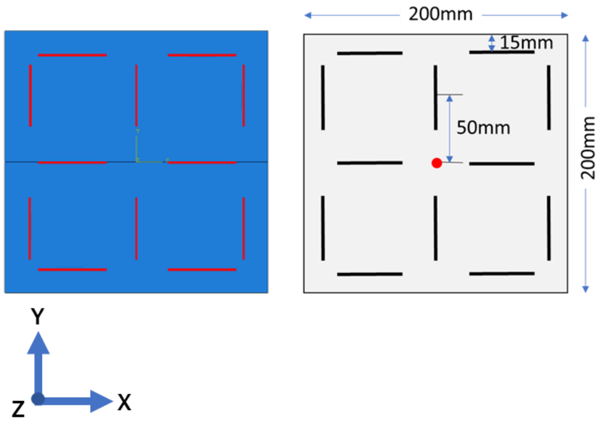


Fig. 7 Analysis Conditions of FEM Model

Table. 1 Properties of Membrane

Parameter	Value
Young's modulus [kPa]	4000000
Size [mm]	200 × 200
Thickness [μm]	50
Poisson's ratio [-]	0.33

Table. 2 Properties of SMA Wire Actuator

Parameter	Value
Young's modulus [kPa]	58840000
Length [mm]	50
Diameter [μm]	150
Thermal shrinkage [/℃]	-6.7×10^{-4}
Poisson's ratio [-]	0.3

3.2 Finite element model to confirm the validity of the membrane surface shape

The validity of the analysis model shown in 3.1 is examined by comparing the simple analysis model of the SMA wire actuator and the experiment. We consider a simple model with four actuators arranged in the circumferential and radial directions as shown in Figure 9. The properties of the membrane and actuator in the analysis are the same value as those shown in Table 1 and Table 2. In order to match the conditions of analysis and experiment, the boundary conditions of the model were set so that the displacement in the X, Y, and Z directions at the tip of the tether on the upper side of the membrane was zero.

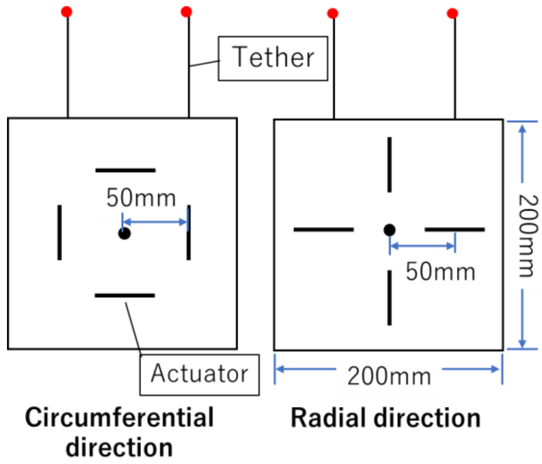


Fig. 9 Analysis condition of Finite Element Model of Membrane with SMA Wire Actuator

4. Experiment Method

4.1 Overview of experiment method

In the experiment, in order to confirm the validity of the finite element model, film surface shape data after deformation due to thermal contraction of the actuator is measured. In the experiment, the film surface shape was measured using a 3D scanner (SLS-3, DAVID).

4.2 3D Scanner

Figure 10 shows a schematic diagram of the experimental apparatus, and Figure 11 shows an overall view of the measurement. A 3D scanner can measure the shape of an object using a projector that projects light and a camera that captures the shape of the film surface. In this research, the film surface shape when the actuator is contracted is measured.

4.3 Configuration of membrane structure

Figure 12 shows the configuration of the actuator on the membrane surface. A matte polyethylene terephthalate (PET) membrane, Lumirror X42G was used in the experiment. Lumirror X42G is suitable for measurement using a 3D scanner because of its low transmittance and Young's modulus, which is similar to polyimide film. In addition, the SMA wire actuator can be contracted by using Joule heat generated when a voltage is applied. Copper wire was connected to the actuator, and both ends were fixed with polyimide tape. Further, a voltage of 1.5 V was applied so that the actuator contracted by 4%.

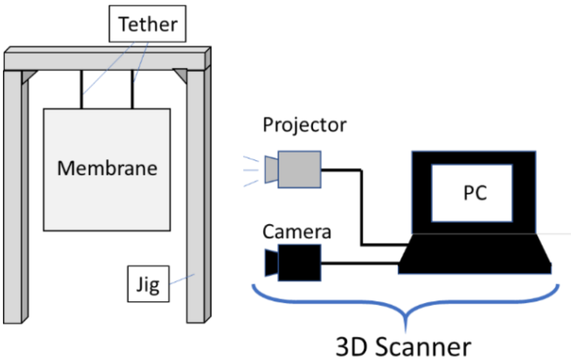


Fig. 10 Schematic diagram of experimental setup

Fig. 11 Outline of the Experiment

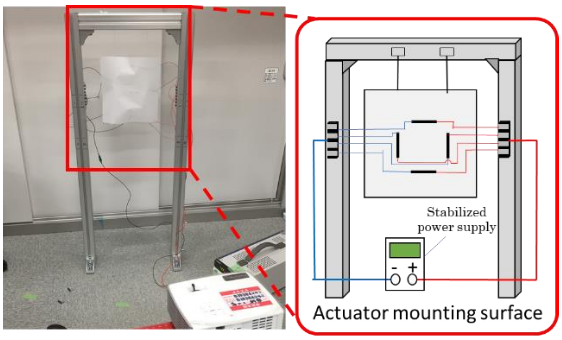
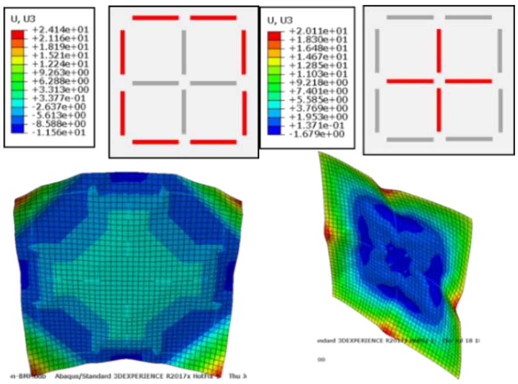


Fig. 12 Configuration of membrane structure

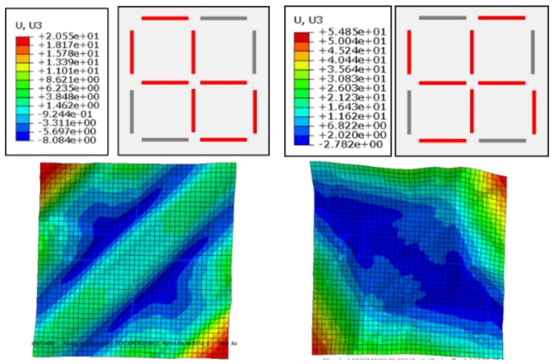
5. Results and Discussion

5.1 Results of the finite element Analysis to confirm the usefulness of control methods

Figure 13 shows the FEM analysis results. Figure 13 shows the case when it is transformed into an umbrella shape and a saddle shape. The position of the contracted actuator and the analysis result are shown.



Deformation of Umbrella Type



Deformation of Saddle Type

Fig. 13 Results of FEM Analysis

From the analysis results, it was confirmed that it can be deformed into a saddle shape or an umbrella shape by combining the positions of the contracting actuators. The membrane shape is considered to be generated by combining the membrane surface deflections caused by the contraction of the actuator (Fig. 14).

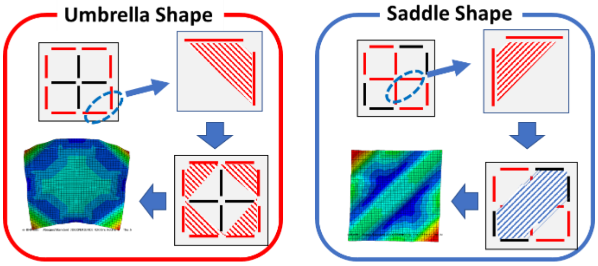


Fig. 14 Deformation of membrane shape

5.2 Results of Finite element model to confirm the validity of the membrane surface shape

Figure 15 shows the results of experiment and FEM analysis when four actuators are located on circumferential and radial directions.

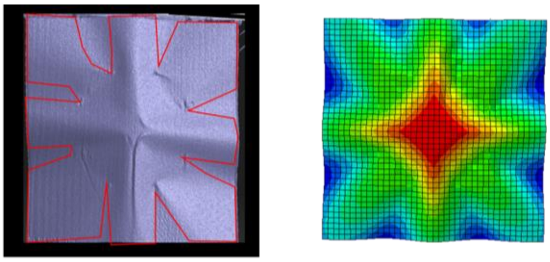


Image data of Experiment   Membrane displacement of FEM Analysis

Circumferential direction

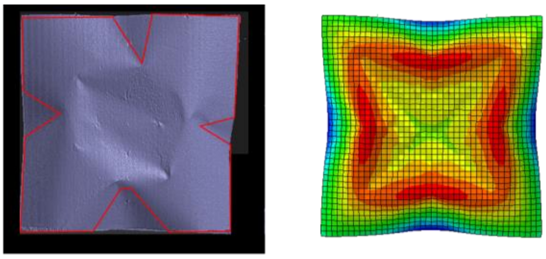


Image data of Experiment   Membrane displacement of FEM Analysis

Radial direction

Fig. 15 Result of Experiment and FEM Analysis

In addition, the membrane surface irregularities in the image data are expressed by red lines.

Comparing the result, it can be confirmed that the unevenness of the membrane surface shape is almost the same in the models with actuators located in the circumferential and radial directions.

Therefore, the validity of the FEM model could be shown from the results of experiments.

6. Conclusion

In this study, we proposed a control method for space membrane structures using Shape Memory Alloy Wire Actuators. As a fundamental consideration, the validity of the membrane surface control by the SMA Wire Actuator was shown by FEM analysis. As a result, the deformation of the membrane is thought to be generated by combining the deflection of the membrane surface caused by actuator contraction. In addition, the validity of FEM analysis results was clarified by comparing with experiments.

References

1) Rikushi KATO, Osamu MORI, Toshihiro CHUJO, Yasutaka SATOU, Nobukatsu OKUIZUMI, Hiroaki TSUNODA, "A Study of Shape and Stiffness of Membrane Structure Due to Warp of Membrane Device," 28th Workshop on Astrodynamics and Flight Mechanics, SA6000135019, A-19, Sagamihara, japan, 2018.