Effect of Creases on the Stiffness of Spinning Circular Membrane

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In this study, the effect of creases on the out-of-plane stiffness of a spinning circular membrane was investigated. A circular polyimide membrane, 600 mm in diameter and 25 µm in thickness, was used. Fanfold and flat-creased circular membranes with 12 fanfold creases in the radial direction, as well as a flat circular membrane without creases, were considered. First, forced vibration experiments on the spinning membranes were conducted in a vacuum chamber and the relationships between the rotation speed and first resonant frequencies were measured to examine the variations in stiffness due to creases. Subsequently, large deformation analyses of the membranes under gravity and eigenvalue analyses of the equilibrium states were conducted using a commercial nonlinear finite element software (i.e., Abaqus), and the fundamental modal frequencies were obtained and compared with the experimental results. The fundamental frequencies without gravity were also numerically analyzed. The author found that the fundamental frequency of the fanfold membrane was almost independent of gravity. Finally, the cause of variation in the fundamental frequencies of the membranes is discussed by estimating the stiffness due to the three-dimensional equilibrium shapes.

Key Words: Membrane Structure, Spinning Circular Membrane, Crease, Out-of-plane Stiffness

1. Introduction

Deployable membrane structures are of great interest in the development of lightweight, large space structures. In recent years, a variety of de-orbit sails and solar sails have been studied, and some of them have been put into practical use. Most of them use extendible booms to deploy the stowed membranes. NanoSail-D2, LightSail, and many others are included in this type. The mechanical characteristics of the structures are primarily determined by the booms. This type of structure can be used for the appendages of spacecrafts, and various other applications will be possible although the sizes will be limited to prevent the booms from buckling.

Another typical method is spin deployment. In this case, the spacecraft or membrane structures need to rotate to deploy and maintain the membrane structure form. IKAROS and Heliogyro are representative examples. The out-of-plane stiffness of the structure is supposed to be generated by centrifugal force. This method is suitable for deploying larger membranes. However, the spin rates and the stiffness of the structure may be limited because attitude control becomes difficult when the angular momentum is too large. It would be effective if the stiffness can be increased independent of the spin rate. During the on-orbit experiments of the IKAROS, the membrane was observed to have maintained its shape even when the spin rate was extremely slow. This is considered to be caused by the out-of-plane deformation of the membrane owing to the curvatures of the thin-film devices on the membrane. This suggests that it may be possible for three-dimensionally folded membrane structures to be maintained by themselves.

To form three-dimensional membrane structures, using systematic creases may be effective. The properties of creases have been studied experimentally and analytically investigated. The non-linear stress-strain response of creased square membranes was studied through tensile testing. The effective moduli of creased square membranes were also studied using FEM. The load-displacement relationship of a square membrane with a Miura-ori folding pattern has been studied. The out-of-plane stiffness of the creased square membrane was investigated through vibration modes. Related to the IKAROS, the effects of creases on the out-of-plane stiffness of the spinning square solar sail were analyzed. Few studies have been done on the out-of-plane stiffness of creased circular membranes.

In this study, the effect of radial creases on the out-of-plane stiffness of a spinning circular membrane is investigated. Radial creases are essential to fold large circular membranes. A fanfold membrane, a flat membrane with creases, as well as a flat membrane without creases are considered. Forced vibration experiments of the spinning membranes are conducted and the relationship between the resonant frequencies and the rotation speeds are obtained. Nonlinear deformation analyses and eigenvalue analyses of the membranes under gravity are performed using a commercial nonlinear finite element software, Abaqus to compare with the experimental results. The analyses without gravity are also conducted. Finally, the cause of the variation in the fundamental frequencies of the membranes due to creases is discussed.
2. Experiments

2.1. Experimental model and setup

Figure 1 shows the experimental model of a circular polyimide membrane with 12 fanfold creases at intervals of 30°. The diameter and thickness of the membrane were 600 mm and 25 µm, respectively. To generate the creases, the membrane was folded 180° along the folding lines. The natural crease angles were difficult to maintain because the angles easily change due to elastoplastic deformations. The center of the membrane was clamped by washers with a 30-mm diameter. In this study, three types of membrane configurations were investigated: the fanfold membrane shown in Fig. 2(a), the flat creased membrane shown in Fig. 2(b), and a flat membrane without creases. The fanfold membrane was deployed downward. To maintain the fanfold shape, the center was clamped with a pair of corrugated washers. The schematic of the washers is shown in Fig. 3. In the cases of the flat creased membrane and flat membrane without creases, the center of the membrane was clamped using two flat washers.

The experimental setup is illustrated in Fig. 4. The center of the membrane was fixed to the shaft of a rotation and excitation mechanism placed in a vacuum chamber. A stepping motor rotates the membrane around its central axis with timing belt and a small shaker vibrates the spinning membrane in the vertical direction using a rotary ball spline. The out-of-plane displacement at the edge of the membrane was measured using a laser displacement sensor placed inside the chamber.

2.2. Experiment conditions

The rotation speed of the membranes was varied from 3 Hz to 12 Hz. When the rotation speed was lower than 3 Hz, the membrane deformed excessively because of gravity. The excitation was sinusoidal and the frequency was varied around the rotation speeds, as the first modal frequencies of the rotating circular membrane under gravity are near the rotation frequency. The air pressure in the chamber was less than 10 Pa. The resonant frequencies were determined by visual observation and using the output of the laser displacement sensor by slowly changing the excitation frequency at a constant rotation speed. An experiment involving a circular membrane without creases was also conducted for comparison.

Figure 5 shows the relationship between the rotation speed and lowest resonant frequency of the three membranes. The lowest vibration mode observed in the experiments is mode (0,0), which has no nodal diameter and no nodal circle. The resonant frequency of the circular membrane without creases is almost the same as the rotation frequency. We found that the resonant frequencies of the fanfold and flat creased membranes are higher than that of the flat circular membrane in the low rotation speed region where downward deformation of the membranes due to gravity is large. This indicates that the effect of creases appears when the geometric stiffness due to the centrifugal force is small.
However, the resonant frequencies of the creased membranes are lower than that of the flat membrane in the high rotation speed region where the membranes become almost flat. This is most likely because the creases change the geometric stiffness owing to the tension distribution. The resonant frequency of the flat creased membrane was also found to be almost always higher than that of the fanfold membrane within the range of this experiment.

3. Numerical Analysis

3.1. Introduction

In this section, the fundamental mode frequencies of the out-of-plane vibrations for the three membranes are estimated by using Abaqus commercial nonlinear finite element software and the results are compared with the experimental results. Following the analysis, the modal frequencies of the membranes without gravity are also studied and the cause of the variation in the frequencies is discussed.

3.2. Numerical models and analytical procedures

The analytical models of the fanfold, flat creased, and flat circular membranes are shown in Figs. 6, 7, and 8, respectively. The 3-node and 4-node general-purpose shell elements (S3 and S4R) are used for all of the models to account for the bending stiffness of the material, and the sizes of the elements were approximately 5 mm. The material properties are shown in Table 1. Static analysis with Abaqus/Standard was used and the numerical procedures are illustrated in Fig. 9.

For the fanfold membrane model shown in Fig. 6, two of the 12 fan-shaped parts surrounded by the red dashed lines are connected along the mountain folding line. The cyclic symmetry constraint is applied to the valley folding lines to enable large deformation analysis to perform efficiently. The boundary condition around the central hole is in accordance with the experiments. The initial angles between the fan-shaped parts are assumed to be their natural crease angles. The deformations around the creases are assumed to be elastic. The nodes on the central circular arc edges are completely fixed. In the numerical analysis, centrifugal force and gravity are applied to obtain the equilibrium state in the first step. Subsequently, eigenvalue analysis is performed to obtain the vibration modes around the equilibrium state in the second step. The fundamental modal frequency is estimated by referencing the effective mass in the out-of-plane...
direction. The rotation speed was varied from 0 to 12 Hz at intervals of 1 Hz.

For the flat creased membrane, the two parts surrounded by the red dashed lines are modeled and the cyclic symmetry constraint is applied as in the case of the fanfold membrane. In this case, the two parts are initially connected with a deep angle to create sharp creases, as shown in Fig. 7(a). In addition, the central hole is smaller than that of other models to fix the membrane as flat as possible over a wide area. In the first step, the membrane is stretched by adjusting the positions of the boundary nodes around the central hole and applying a moderate centrifugal force to obtain a flattened shape, as shown in Fig. 7(b). In the second step, the boundary nodes are completely fixed, and the centrifugal force of the specified rotation speed and gravity are applied to obtain the equilibrium state. In the third step, eigenvalue analysis is performed and the fundamental mode frequency is estimated.

For the flat circular membrane shown in Fig. 8, the whole circular membrane is modeled since no folding lines are present and the computation is easier than the other two models. The numerical procedure is the same as that of the fanfold membrane.

### 3.3 Numerical results under the effect of gravity

The equilibrium shapes of the fanfold and flat creased membranes under the effect of gravity when the rotation speed is 2, 6 and 12 Hz are shown in Figs. 10 and 11, respectively. The color contours display the Mises stress. The stress in the fanfold membrane is distributed in the fan-shaped regions when the rotation speed is low. The stress becomes localized around the center and mountain folding lines as the rotation speed increases. The shapes of the creases remain even when the speed is 12 Hz because of the boundary condition at the center. In the flat creased membrane, the stress is always localized around the center and both mountain and valley folding lines, and the equilibrium shape becomes almost flat as the rotation speed increases.

The equilibrium shapes of the flat circular membrane when the rotation speed is 4, 7 and 12 Hz are shown in Fig. 12. The shape of the circular membrane varies depending on the rotation speed. When the speed is less than 4 Hz, the deformation becomes too large and analysis could not be completed. When the rotation speed is less than 7 Hz, the deformation is neither axisymmetric nor cyclic symmetric. When the rotation speed is between 7 Hz and 10 Hz, the deformation is almost cyclic symmetric, and as the speed becomes higher, the membrane becomes almost flat.

The fundamental vibration modes of the three membrane models under the effect of gravity obtained by eigenvalue analysis are illustrated in Fig. 13. The variations in the modal frequencies are shown in Fig. 14. First, when the rotation speed is larger than 6 Hz, the lowest fundamental vibration mode of the flat circular membrane is the (1,0) mode, which has one nodal diameter and no nodal circle, as shown in Fig. 13(d), instead of the (0,0) mode shown in Fig. 13(c). In the experiments, however, the resonant frequency of the (0,0) mode was almost the same as that of the (1,0) mode because of finite amplitude vibrations. For the fanfold membrane, the regions around the mountain folding lines act as nodal diameters and the regions between them deform as shown in Fig. 13(a). The modal shape of the flat creased
membrane shown in Fig. 13(b) is similar to the shape of the (0,0) mode of the flat circular membrane.

Figure 14 shows that the fundamental mode frequency of the fanfold membrane is almost similar to that of the flat membrane in the analysis, although the frequency observed in the experiment was lower than that of the flat membrane when the rotation speed is higher than 6 Hz. However, the frequency of the fanfold membrane becomes higher when the rotation speed is low, as observed in the experiment. It is noteworthy that the solution of the fanfold membrane may not be accurate because the static dissipation energy, which should be smaller than the strain energy to obtain accurate solutions in Abaqus/Standard, becomes larger than the strain energy during this analysis. The frequency of the flat creased membrane is higher than that of the flat membrane under low rotation speeds and is lower under high rotation speeds. This behavior is qualitatively similar to the experiment. When the rotation speed is nearly zero, the natural frequencies of the fanfold and flat creased membranes are approximately 2 Hz. This is most likely because of the effect of creases and the cyclic symmetry constraint.

To examine the result of the fanfold membrane, a dynamic analysis using Abaqus/Explicit was conducted to perform the simulation of transient vibrations after applying a centrifugal force and gravity, and the vibration frequencies were calculated from the time histories. Figure 15 shows the comparison of the static and dynamic analyses of the fanfold membrane and the result of the flat membrane. The dynamic analysis when the rotation speed is 0 and 1 Hz under gravity cannot be completed owing to extremely large deformations. The amplitudes of the transient vibrations when the frequencies were estimated were approximately 40 mm. The vibration frequencies obtained by the dynamic analysis are found to be lower than those obtained by the static analysis and they are also lower than those of the flat membrane in the high rotation speed region as observed in the experiment.

A quantitative agreement between the numerical and experimental results could not be obtained in this study. One
possible reason is that the properties of the creases and the boundary conditions near the center are not accurate. The development of a simple elastoplastic crease model will be necessary. The other possible reason is that the large deformation analysis of thin shell elements with creases requires trial and error in analysis parameter setting in Abaqus and long computation time. The equilibrium states obtained by the analysis may include some quantitative errors.

3.4. Numerical results without the effect of gravity

The fundamental frequencies of the three spinning membranes without the effect of gravity are numerically investigated to study the basic properties in space. The numerical results are shown in Fig. 16. For the fanfold membrane, a static analysis, as well as a dynamic analysis, of the transient vibrations described in the previous section were performed without applying gravity.

By comparing Fig. 16 with Fig. 14, the (0,0) mode frequencies of the flat membrane show a remarkable decrease, while the (1,0) mode frequencies remain almost unchanged as a result of removing the effect of gravity. Furthermore, the modal frequencies of the fanfold membrane are found to remain almost unchanged, and that the frequencies of the flat creased membrane decrease in the high rotation speed region.

3.5. Discussion

The cause of the variation in the fundamental frequencies of the three membranes is discussed here.

The out-of-plane stiffness of a spinning membrane is considered to be generated by geometric stiffness due to the tension distribution and stiffness of the membrane itself owing to the three-dimensional shape. Hence, eigenvalue analyses of the membranes with three-dimensional shapes and no stress were conducted to estimate the contribution of the three-dimensional shapes. The numerical procedure is illustrated in Fig. 17. First, the coordinates of all of the nodes in an equilibrium state are set to the initial node coordinates of the membrane model. Subsequently, eigenvalue analysis of the three-dimensional membrane without tension is conducted to calculate the vibration modes. Table 2 shows the results for two rotation speeds.

When the rotation speed is 4 Hz, the eigenvalues of the fanfold and flat creased membranes without tension are approximately half of those of the tensioned membranes. However, the frequencies of the flat uncreased membrane without tensions are much smaller than those of the tensioned membrane. The tension distributions caused by gravity increase the frequencies of the three membranes. The stiffness of the flat membrane is mostly generated as the result of tension distribution.

When the rotation speed is 12 Hz, the fundamental eigenvalues of the membranes without tensions are small compared to those of tensioned membranes for all of the models. Hence, the difference in the eigenvalues is primarily caused by the difference in the tension distribution. Since the eigenvalue of the fanfold membrane is almost independent of gravity, the tension distribution is also almost independent of gravity. The reason for this is believed to be because the mountain foldings withstand the effect of gravity, as described in Section 3.3.

To examine the results for the flat creased membranes, an arrow plot of the principal components of stress when the rotation speed is 12 Hz is shown in Fig. 18. It is found that large stresses are generated around the creases. This is not clearly observed in the fanfold membrane. The eigenvalues of the flat creased membrane are the smallest, most likely because the centrifugal force and gravity generate stresses primarily in the circumferential direction, and the tension in the radial direction becomes smaller by relieving gravity.

In addition, it is expected that the fundamental frequencies under the effect of gravity asymptotically approach the frequencies under zero gravity as the rotation speed increases. The behaviors under such high rotation speeds are beyond the scope of this paper.

Table 2. Fundamental mode frequencies of the membranes with three-dimensional equilibrium shapes with/without stress.

| Rotation speed [Hz] | 4   | 12  |
|---------------------|-----|-----|
|                     | Yes | No  |
|                     | Yes | No  |
| Tension             |     |     |
| 4G                  |     |     |
| Fanfold [Hz]        | 4.84| 2.78|
| Flat creased [Hz]   | 5.09| 2.25|
| Flat [Hz]           | 4.20| 0.48|
| 12G                 |     |     |
| Fanfold [Hz]        | 4.03| 2.67|
| Flat creased [Hz]   | 4.25| 2.12|
| Flat [Hz]           | 2.38| 0.08|
| 0G                  |     |     |
| Fanfold [Hz]        | 4.03| 2.67|
| Flat creased [Hz]   | 4.25| 2.12|
| Flat [Hz]           | 2.38| 0.08|
4. Conclusion

The effects of creases on the out-of-plane stiffness of spinning fanfold, flat creased, and flat uncreased circular membranes were investigated by forced vibration experiments and nonlinear finite element analysis. The following results were obtained:

- The creases can decrease the out-of-plane stiffness of the spinning circular membrane because of the change in the tension distribution in the high rotation speed region.
- Three-dimensional shapes formed by the creases significantly contribute to the out-of-plane stiffness of the creased membranes in the low rotation speed region.
- The fundamental out-of-plane mode frequency of the flat circular membrane is decreased by relieving gravity as a result of the change in tension distribution.
- The stiffness of the fanfold membrane, the center of which is fixed to be fan-folded, is almost independent of gravity as the mountain folding lines act as nodal diameters.

To obtain better quantitative agreement between the experimental and numerical results, introducing an elastoplastic model for creases and improving the numerical procedures are necessary. The relationship between the creases and geometric stiffness, which cannot be observed in experiments, can be clarified through numerical analysis.

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