Wrinkling Control of Inflatable Booms
Using Shape Memory Alloy Wires

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Abstract

Inflatable boom is a fundamental structural part of inflatable space structures maintaining the expected configuration of the whole system, supporting external loads and guaranteeing the efficiency of the membrane surface. The inflatable structure is a thin film structure compactly packaged and expanded to the desired configuration by the internal gas pressure. But, the structures can be easily distorted and even collapsed by wrinkling. In this study, the behavior of an inflatable boom structure is investigated numerically and experimentally. To achieve a better bending strength, the methodology to control the wrinkling growth and the deformed configuration of the inflatable boom structure with shape memory alloy (SMA) wire actuator is developed. For understanding of the nonlinear behaviors of an inflatable boom due to wrinkling, the structure is numerically modeled using ABAQUS finite element program with wrinkling algorithm developed based on the Miller-Hedgepeth membrane theory. To verify the present analysis method, the inflatable boom made of Kapton film is examined by the bending tests with various internal pressures. To delay the growth of wrinkling that rapidly deteriorates the bending strength of the inflatable boom, SMA wire actuator is applied. SMA wires are attached on the edge of inflatable boom and generate recovery force to remove wrinkling and restore the deformation of the boom.
1. Introduction

There have been a lot of attempts to achieve extremely large space structures such as antenna, telescope, and solar concentrator. Because the performance and applicable range of space structures are further extended as their surface areas are increased, the way to construct large surfaces has been investigated by many researchers. The inflatable structure is one of the most desirable solutions to construct large structure with light weight and small packing volume. The inflatable structure is a thin film structure compactly packaged and expanded to the desired configuration by the internal gas pressure. But, the structures can be easily distorted and even collapsed by wrinkling. Therefore, the prevention of wrinkling propagation is one of the important technologies to develop the inflatable structures.

During 1960s, the first inflatable satellite Echo1 demonstrated the potential development of inflatable structures. After failure of the Echo project, a more accurate theory was required to consider local deterioration of the structure [1]. Wagner [2] developed the Tension Field (TF) theory to predict the membrane state; whether wrinkling occurs or not. Stein and Hedgepeth [3] defined taut and wrinkled states of membrane by using the Stein-Hedgepeth theory based on the assumption that wrinkles are aligned with the major stress axis. Miller and Hedgepeth [4] developed Iterative Membrane Property (IMP) method by applying Stein-Hedgepeth theory to finite element implementation. It employed the wrinkling criteria by classifying elements into taut, wrinkled, and slack based on stress and strain states in each element. Lately, Adler [5] performed static and dynamic analysis of partially wrinkled membrane using ABAQUS with user defined material (UMAT) subroutine where the Stein-Hedgepeth theory was implemented.

To improve the performance of inflatable structure smart materials can be applied. In order to maintain the flexibility of membrane, film and wire type smart materials are preferred such as Macro Fiber Composites (MFC), Shape Memory Alloy (SMA) films or wires, and Electroactive Polymers (EAP). Sodano et al. [6] used multiple MFC devices for vibration control of inflatable torus, and Sakamoto et al. [7] controlled wrinkling of flat membrane by tensioning the distributed active cables using MFC as an out-of-plane actuator in finite element analysis. For the application of SMA strip
actuator to shape-adaptive structures, the thermomechanical responses of SMA and the interactions between host structure and the actuator are numerically investigated by considering 3-D effect of SMAs [8]. Roh et al. [9] proposed the numerical algorithm of the 2-D SMA thermomechanical constitutive equations for the thin film type actuators of SMAs and numerically demonstrated the new concept of membrane pump actuator with SMA thin film. Lee et al. [10] introduced a concept of the configuration control of inflated cylindrical beam by using SMA thin film actuators with appropriate heating and cooling cycles. Peng et al. [11] developed genetic algorithm based control system for active shape control of an inflatable structure using SMA wire actuator attached to the edge of the membrane surface structure.

In this paper, the methodology to control the wrinkling growth and deformed configuration of the inflatable boom structure with shape memory alloy (SMA) wire actuator is investigated. For understanding the nonlinear behaviors of an inflatable boom due to wrinkling, the structure is numerically modeled using ABAQUS finite element program with wrinkling algorithm. The numerical algorithm of wrinkling is developed based on the Miller-Hedgepeth membrane theory. To validate the numerical model, the bending test is performed for an inflatable boom made of Kapton film with various internal pressures. To delay the growth of wrinkling that rapidly deteriorates the bending strength of the inflatable boom, SMA wire actuator is applied. SMA wires are attached on the edge of inflatable boom and generate recovery force to remove wrinkling and restore the deformation of the boom.
2. Numerical modeling and verification

2.1 Model development

Modeling of an inflatable structure is performed based on finite element method using membrane element which can represent behavior of thin film structure well. Membrane element is defined as a surface element which transmits only in-plane forces with no bending rigidity. By this characteristic, membrane elements cannot display the three-dimensional wrinkling pattern or out-of-plane deformations; however membrane elements are appropriate for calculating exact value of stress and strain in membrane surface. In this paper, commercial finite element analysis program, ABAQUS is used with M3D4 membrane elements. The numerical model of inflatable boom structure is illustrated in Figure 1.

The constitutive behavior of membrane structure is difficult to predict because of the extreme nonlinearity of a specific local state such as wrinkling, which is the most harmful situation that could degrade the bending strength, stability, and surface accuracy. Therefore, an accurate numerical model considering wrinkling effect is required. To realize wrinkling phenomenon a specific numerical algorithm based on the Miller-Hedgepeth membrane theory is implemented using user defined material (UMAT) subroutine. User-defined subroutines including UMAT are supported by ABAQUS and very useful in applying new algorithms the previous numerical model. The IMP method used in UMAT subroutine is a recursive stiffness-modification procedure to predict the membrane states such as taut, wrinkled, and slack. The states of a membrane element are determined by combined stress-strain criteria [12] based on principal stress and strain described as,

\[ \sigma_2 > 0 \quad : \text{taut} \quad (1) \]

\[ \varepsilon_1 \leq 0 \quad : \text{slack} \quad (2) \]
\[ \varepsilon_1 > 0 \text{ and } \sigma_2 \leq 0 : \text{ wrinkled} \] (3)

where \( \sigma_1 \) is a principal maximum stress, \( \sigma_2 \) is a principal minimum stress, \( \varepsilon_1 \) is a principal maximum strain.

As decided by the criteria, each element should be adapted to modified stiffness given by

\[
K_{\text{naive}} = \frac{E}{1 - \nu^2} \begin{pmatrix} 1 & v & 0 \\ v & 1 & 0 \\ 0 & 0 & \frac{1 - \nu}{2} \end{pmatrix}
\] (4)

\[
K_{\text{wrinkled}} = \frac{E}{4} \begin{pmatrix} 2(1 + P) & 0 & Q \\ 0 & 2(1 + P) & Q \\ Q & Q & 1 \end{pmatrix}
\] (5)

\[
K_{\text{slack}} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\] (6)

where \( P = \cos(\alpha) \), \( Q = \sin(\alpha) \), and \( \alpha \) is a principal stress angle. The computing procedure of wrinkling algorithm is charted in Figure 2.

2.2 Results and parametric studies

There are several parameters which affect the behavior of inflatable boom such as material modulus, internal pressure, contribution of tip force, and material thickness. In this section, the tendency of boom response is demonstrated as each parameter is varied. The bending tests are numerically carried out on the inflatable boom of length 1m and of 0.190m diameter. The relations
between transverse loading at upper end and deflection at the same point are shown in this paper. Figure 3 represents the importance of considering wrinkling effect when the boom structure is pressurized by 5171Pa and its thickness is equal to $30 \mu m$. Without wrinkling algorithm the boom structure is linearly deflected, on the other hand with wrinkling algorithm the structure is rapidly distorted after some amount of loading. Comparing deflection curve with states of membrane element, it is obvious that the occurrence of wrinkle removes boom’s ability to support load as shown in Figure 4. Each element has four integration points and the states are determined at each integration point, therefore the number of wrinkled integration points represents the degree of wrinkling in each element.

The elastic modulus of material affects the stiffness of inflatable boom structure as illustrated in Figure 5. As the modulus of film increases, the slope of linear deformation region increases but the maximum load is hardly affected. Material thickness also contributes the stiffness of the boom by the similar way the material modulus does, as shown in Figure 6.

Internal pressure is the most decisive factor in determining the load carrying capacity of the inflatable boom structure. In Figure 7, the maximum load that the structure can sustain and the linear deflection limit are increased as the internal pressure is increased. However, it seems that the increase of the internal pressure has little effect on the initial linear region. The internal pressure is applied to the cylindrical surface and both ends of the boom. The former contributes to the hoop stress while the latter is related to the longitudinal stress. In case that the boom is not uniformly pressurized or is partly clogged, the resulting stretching force in the longitudinal direction, namely tip force, may not be the same as the pressure times the area of the boom end. To investigate the contribution of additional tip force, the deflection curve when the structure is pressurized by 5171Pa is illustrated in Figure 8 as the tip force is varied from 80% to 120% of the nominal value (the pressure times the area of the boom end). The thickness and Young’s modulus of this model are equal to $30 \mu m$ and $3.0 GPa$, respectively. The tip force plays important roles in the load carrying capacity of the boom.

It can be expected that the slope of linear deformation is affected by the change of the elastic modulus and thickness. It seems very natural that the incipient of collapse can be delayed by the internal pressure or tip force. However, it is somewhat unexpected results that the internal pressure
and tip force have hardly effect on the linear deformation. These bending behaviors of the inflatable boom can be also explained by using the previous analytical model [13]. From these results, it can be known that increasing the internal pressure and tip force or applying the external control force could be more efficient than improving the material properties to delay the collapse or wrinkling growth of the boom.

2.3 Experimental verification

In order to see the validity of the above numerical results, experiment studies were also performed. There were two purposes of experiment: to prove that the measured bending stiffness and the maximum load limit are consistent with the analysis result, and to observe wrinkle occurrence and its effect to the load carrying ability of the boom. The geometric dimension of the structure is the same as that of the numerical model; 1m in height, 0.190 m in diameter. It was made of Kapton FN film of 30㎛ thickness, and fixed at the bottom of the test frame. The test frame was designed to stand the inflatable boom up vertically and to measure the deflection of the end tip when it was loaded in a lateral direction. Load is applied at the tip point of the boom covered with acryl hoop by weighting. Deflection is measured by the laser sensor and recorded by a data acquisition system. Nitrogen gas was used as inflation gas, and the internal pressure is measured by pressure sensor attached bottom of the frame. Test frame and device set-up is shown in Figure 9. The experimental results with the comparison of analytic results are shown in Figure 10. Both the bending stiffness (the initial slope of the deflection curves) and the maximum load are agreed very well between the experiment and the numerical analysis. Wrinkled region can be also detected by photographs. Figure 11 shows photographs of the region near bottom end at each load step. The surface grid has 0.01 m intervals and the wrinkled range is counted by the number of wrinkled section. The degree of wrinkling defined by the ratio of wrinkled range to the total circumference of the boom is presented in Table 1. Since the experimental results correspond to the analysis result in the point of global deflection and local wrinkling, this numerical model proposed in this chapter is definitely effective to predict the behavior
of inflatable boom structure.

3. Performance improvement using SMA wires

3.1 Prerequisite tests for using SMA wires

Shape memory alloys (SMAs) are metals that remember their original shape due to a temperature-dependent martensitic phase transformation from a low-symmetry (martensite) to a highly symmetric crystallographic structure (austenite). When cooled, the austenite phase transforms to martensite in which SMA is soft and easily deformable, and when heated to its higher temperature phase (austenite) SMA returns into its original shape. This is called the one-way shape memory effect. The ability of shape memory alloys to recover a preset shape upon heating above the transformation temperatures and to return to a certain alternate shape upon cooling is known as the two-way shape memory effect [14].

In order to operate SMA wire actuator, the temperature increases to the transition temperature by the electric current. As the current through the wire rises, the strain shows stepwise increase [15]. The minimum current required for the strain to step up is named critical current in this paper. To use the contraction force of SMA wire as a control force, two prerequisite tests are needed: measuring the critical current and measuring the contraction force at critical current. Since the strain and critical current are irregular depending on the raw metal and training process, prerequisite tests should be performed to observe basic properties of SMA wire. Test specimen is $0.152 \times 10^{-3}$ m (0.006 inch) diameter Flexinol™ made by Dynalloy, Inc. In the test equipment shown in Figure 12, the laser sensor measures the deformation of SMA wire as the current increased. In order to develop the contraction force of wire actuator, 3 and 5 wires crimped together are used as bundled wire actuators. The deformation curve is stepwise as expected and the critical current of each bundled wire actuator is shown in Table 2. The portion of critical current assigned to a wire in a bundled wire actuator is less
than that of single wire because bundled case has small contact surface with surrounding air.

Using the critical current measured above as an input current, the contraction force of single wire and bundled wire actuators are measured. The test equipment specially designed for this purpose is shown in Figure 13. Ends of wire are fixed at upper and lower beam and tightened by moving the upper beam. As the current applied, the load cell located under the upper beam measures the contraction force. From the result, the contraction force is approximately 8N for each wire, and that of bundled wire actuator is directly proportional to the number of wires in the bundle.

3.2 Analysis result for performance improvement

The basic concept of performance improvement is eliminating wrinkles by tensioning the membrane when compressive force is applied to it. To tense the compressive area generally occurred in loading direction, SMA wire is attached at the opposite side of the loading and shrunk by pulling the tip and root points each other. Through this work, the deformation will be restored and wrinkles are removed.

To find the proper input force and observe the effect of control, numerical simulation using ABAQUS model is executed first. The control force produced by contraction of SMA wire is assumed to the point downward force. For the purpose of validating the downward control force is effective to improve performance of inflatable boom structures, wrinkled region, deflection, and the maximum load that boom can support are investigated. Figure 14 demonstrates the influence of control force on the deflection of boom structure. From the result, deflection recovery is proportional to the control force, and applying downward control force is definitely effective. The maximum load is also increased proportional to the control force. The states of membrane element determined by using wrinkling algorithm of UMAT subroutine are illustrated in Figure 15. Compared with Figure 4, wrinkling area is decreased by the function of SMA wire as can be expected.
3.3 Experimental result of performance improvement

The required contraction force of SMA wires to control the deflection and wrinkling of the boom is computed by numerical analysis. For instance, to restore deflection occurred by 500gf, contraction force of 44N is needed. To confirm the reasonability of numerical model, an inflatable boom with SMA wire actuator is constructed and tested. Six Flexinol™ SMA wires divided by 2 bundles are used, and 1.2A current is sent through them. Figure 16 illustrates the result of experiments with the comparison of numerical results. From this graph, it is shown that numerical model considering SMA wire effect is also accurate, and that the control mechanism is useful to restore deflection. Deflection is reduced about \(7.6 \times 10^{-3} m\) and wrinkling load, the maximum load the structure can support, is increased approximately 300gf, which is 30% of initial load limit. Wrinkled region can be observed by the photographs in Figure 17. Inflatable boom with SMA wire control is hardly wrinkled until 1150gf is loaded. Comparing with Figure 12, the control mechanism is also effective to hinder wrinkle generation.

As well as tip loading middle point loading is investigated. When transverse load is applied at the middle of the boom, downward control force is also applied to the middle point of the opposite side. Figure 18 shows the result of experiment and analysis at each internal pressure. The control using SMA wire is also efficient in mid load cases.
4. Conclusions

The behavior of inflatable boom structure is investigated numerically and experimentally. For understanding of the nonlinear behaviors of an inflatable boom due to wrinkling, the structure is numerically modeled using ABAQUS finite element program with wrinkling algorithm. The numerical algorithm of wrinkling is developed based on the Miller-Hedgepeth membrane theory. In order to investigate the contribution of each variable used in ABAQUS model to the response of the boom, parametric studies are performed. From the results of parametric studies some important conclusions are induced as follows: wrinkling modeling is essential to acquire accurate result, material modulus and thickness contributes the stiffness of the inflatable boom during linear deformation, and internal pressure and tip force strongly affect on the load carrying capacity. To verify the reasonability of numerical model, the inflatable boom made of Kapton film is examined by the bending tests with various internal pressures. The experimental results show that developed model is accurate to expect deflection and wrinkling. To achieve a better performance, the methodology to control the wrinkling growth and deformed configuration of the inflatable boom structure with shape memory alloy (SMA) wire actuator is developed. SMA wires are attached on the edge of inflatable boom and generate recovery force to remove wrinkling and restore the deformation of the boom. As can be observed from both results of analysis and experiment, the attempt to removing wrinkling region using SMA wire is successfully achieved. Through regulating control force of SMA wire, wrinkling region can be reduced, and wrinkle generation can be also delayed as much as expected. Finally, the structural performance, representatively maximum load that the structure can support, can be improved by this control mechanism.

Acknowledgements

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Table 1. Degree of wrinkling at each load step

<table>
<thead>
<tr>
<th>Load</th>
<th>0.00N</th>
<th>8.33N</th>
<th>9.31N</th>
<th>10.29N</th>
<th>11.27N</th>
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<td>0.50</td>
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<td>0.37</td>
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Table 2. Activating current and recovery strain of bundled SMA wire actuators

<table>
<thead>
<tr>
<th>Number of wires</th>
<th>Activating current</th>
<th>Strain</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3 A</td>
<td>4.0 %</td>
</tr>
<tr>
<td>3</td>
<td>0.6 A</td>
<td>3.7 %</td>
</tr>
<tr>
<td>6</td>
<td>1.0 A</td>
<td>3.9 %</td>
</tr>
</tbody>
</table>
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Figure 2. Flow chart of wrinkling algorithm
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(a) 0gf (=0N)  
(b) 850gf (=8.33N)  
(c) 950gf (=9.31N)  
(d) 1050gf (=10.29N)  
(e) 1150gf (=11.27N)
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(a) 850gf (=8.33N)  
(b) 950gf (=9.31N)  
(c) 1050gf (=10.29N)  
(d) 1150gf (=11.27N)  
(e) 1250gf (=12.25N)  
(f) 1300gf (=12.74N)
Figure 18. Load-deflection curves with and without SMA wire actuation when middle point load is applied.

(a) Internal pressure of 4309 Pa.

(b) Internal pressure of 5171 Pa.

(c) Internal pressure of 6033 Pa.