Wrinkling control of inflatable booms using smart material patch

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Wrinkling control of inflatable booms using smart material patch

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ABSTRACT

The methodology to restrain the growth of wrinkling region in inflatable boom is numerically and experimentally investigated. The inflatable boom structure is numerically modeled by using ABAQUS finite element program with membrane elements. To consider the nonlinear deformations of inflatable boom due to wrinkling, the numerical algorithm of wrinkling based on Miller-Hedgepeth membrane theory is developed using user defined material (UMAT) subroutine supported by ABAQUS. The experimental model of inflatable boom is made of Kapton film. To characterize the nonlinear behaviors of inflatable boom, the bending tests for various internal pressures are performed. To delay the growth of wrinkled region and restore the deformed shape of inflatable boom, shape memory alloy (SMA) wire actuator attached on surface of the structure is applied.

Keywords : inflatable boom structure, wrinkling, finite element method, shape memory alloy, smart material

1. INTRODUCTION

The inflatable structures characterized as extremely low weight and on-orbit deployability are expected for one of principal instruments for space observations. Giant telescopes and antennas of which size has never been expected with conventional materials can be established using inflatable structure technology. Low cost and adaptability of packaging shape are additional advantages of inflatable structures. An emerging interest in inflatable structures has brought strong needs to analyze and control them effectively. Since 1960s, when the first inflatable satellite, Echo1, was launched, analysis of an inflatable structure has faced difficulties due to its nonlinear characteristics such as wrinkling. These nonlinear characteristics should be carefully considered in modeling inflatable structures [1]. However, in recent years, useful membrane theories and excellent commercial finite element softwares provide a possibility to precisely predict the nonlinear characteristics of an inflatable structure. 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 wrinkled criteria 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.

While investigating basic components of inflatable system such as inflatable torus, boom, and membrane surface analytically and experimentally, researchers have found that advanced material technologies required to control or improve inflatable structure without disturbing its flexibility. To achieve a better performance of inflatable structures, the film type smart materials have been used such as Macro Fiber Composite (MFC) produced by NASA Langley Center, and thin film Shape Memory Alloy (SMA). The basic concept to control the wrinkling and configuration of inflatable structure with smart films is attaching them on the surface of inflatable structures. Park [6] controlled vibrations of inflatable torus using multiple polyvinylindene fluoride (PVDF) patches as sensor and both MFC and bimorph PVDF as actuators. Sodano et al. [7] used multiple MFC devices for vibration control of inflatable torus. Meanwhile, Sakamoto et
al. [8] controlled wrinkling of flat membrane by tensioning the distributed cable activated using MFC as an out-of-plane actuator in finite element analysis, and Tung et al. [9] designed and fabricated a MEMS-based flexible sensor and actuator system to monitor and control the health of inflatable space structures. Because the SMA wire actuator has the same advantages of the smart film such as flexibility and adaptability to arbitrary shape, the smart wire is also effective to control shape and deformation of inflatable structures. Shey et al. [10] simulated a flexible beam actuated by externally-attached SMA wire considering thermo-mechanical characteristics of SMA. 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 numerically and experimentally investigated. 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. The experimental model of inflatable booms is made of Kapton film. To characterize the nonlinear behaviors of inflatable booms, the bending tests for various internal pressures are performed by experimentally and numerically. To delay the growth of wrinkling which rapidly deteriorates the structural performance of inflatable boom, SMA wire actuator is applied. SMA wires are attached on the surface of inflatable boom and generate recovery force to remove wrinkling region and restore the deformation of the boom.

2. NUMERICAL ANALYSIS

2.1. Modeling pressurized membrane circular cylinder

In modeling an inflatable boom using finite element method, membrane element is widely used because it 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. Although this characteristic makes membrane elements impossible to display the three dimensional wrinkling pattern or out-of-plane deformations, membrane element can be used to calculate exact value of stress and strain in the membrane surface. Inflatable boom is numerically modeled by membrane elements with pre-stress resulting from internal pressure of the boom. The geometric dimension of the boom studied in this paper is 0.19m in diameter, 1.0m in length, 30μm in thickness, and the mechanical material properties of the membrane, Kapton FN film, are as follows:

\[ E = 3.0 \text{GPa} \quad \nu = 0.34 \]  \hspace{1cm} (1)

2.2. Wrinkling algorithm

The structural wrinkling is the most harmful situation that could degrade the structural performance, maneuverability, stability, and surface accuracy. So, the wrinkling effect should be considered in the analysis procedures to accurately predict nonlinear behaviors of inflatable structures. In spite of its importance of predicting exact phenomena of wrinkling, the analysis of its amplitude and area still remains difficult. However, with the help of finite element implementations, we can observe wrinkled area and global behavior of membrane structure. Finite element model of inflatable boom structure is prepared with membrane element (M3D4) supported by ABAQUS. To simulate wrinkling phenomenon, the numerical algorithm of wrinkling based on the Miller-Hedgepeth membrane theory is developed using user defined material (UMAT) subroutine written by FORTRAN. The wrinkling algorithm provides not only information of the wrinkled region and direction but also modified stress and strain in the membrane. 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 state of a membrane element is determined by specific criteria based on principal stress or strain. The most common criteria, combined stress-strain criteria [12], are described as,

\[ \sigma_z > 0 \quad : \text{taut} \]  \hspace{1cm} (2)
\( \varepsilon_1 > 0 \) and \( \sigma_2 \leq 0 \) : wrinkled \hspace{1cm} (3) \\
\( \varepsilon_1 \leq 0 \) : slack \hspace{1cm} (4)

where \( \sigma_1 \) is a principal maximum stress, \( \sigma_2 \) is a principal minimum stress, and \( \varepsilon_1 \) is a principal maximum strain. After membrane states are decided by the criteria, the stiffness of each element should be modified as follows:

\[
K_{\text{taut}} = \frac{E}{1-v^2} \begin{pmatrix}
1 & v & 0 \\
v & 1 & 0 \\
0 & 0 & \frac{1-v}{2}
\end{pmatrix}
\] (5)

\[
K_{\text{wrinkled}} = \frac{E}{4} \begin{pmatrix}
2(1+P) & 0 & Q \\
0 & 2(1+P) & Q \\
Q & Q & 1
\end{pmatrix}
\] (6)

\[
K_{\text{slack}} = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
\] (7)

where \( P = \cos(\alpha) \), \( Q = \sin(\alpha) \), and \( \alpha \) is a principal stress angle.
2.3. Results and parametric study

The structural performance of an inflatable boom structure can be evaluated by the bending stiffness; therefore a deflection versus loading is mainly concerned. Considering wrinkled area of each load step from output data file, it is found that the growth of wrinkling deteriorates the performance of the inflatable boom. In other words, the deflection is rapidly increased under a small amount of additional load when wrinkling regions are generated. There are several factors which affect the behaviors of the inflatable boom in the numerical model, for example wrinkling, material properties, internal pressure, and thickness. In order to investigate the contribution of each factor to the response of the inflatable boom, parametric studies are performed. In this paper, the relations between the transverse loading and deflection at the boom end are demonstrated. Figure 3 shows the importance of considering a wrinkling effect. Without wrinkling algorithm, the inflatable boom is hardly folded or collapsed; therefore the numerical result seems much stiffer than the numerical model considering wrinkling effect. The elastic modulus of the membrane material also affects the behavior of the inflatable boom as shown in Figure 4. As the modulus increases, the structure becomes a little bit stiffer during linear deformation, but collapse loads are not significantly changed. The thickness of construction material, Kapton FN film, contributes stiffness of the boom as a material modulus does as shown in Figure 5. Internal pressure is the most decisive factor in determining the load carrying capability of the inflatable boom structure. Figure 6 illustrates how much load the inflatable boom can sustain when its internal pressure is changed. Although the slope of linear deformation area is slightly increased, the maximum load that can be supported by the inflatable boom is definitely increased.

![Figure 3: Load-deflection curve with and without wrinkling algorithm](image1)
![Figure 4: Load-deflection curves for various elastic moduli of material](image2)
![Figure 5: Load-deflection curve for various material thickness](image3)
![Figure 6: Load-deflection curve for various internal pressure](image4)
3. EXPERIMENTAL VERIFICATION

3.1. Experimental configuration

To verify the proposed numerical model of inflatable boom structure, experimental tests are performed. The structure is manufactured according to the geometric dimension of the numerical model; 1m in height, 190mm in diameter. It is made by Kapton FN film of 30 μm in thickness, and fixed at the bottom of the test frame. Load is applied at the tip point of the boom covered with acryl hoop by weighting. Deflection is recorded by laser sensor and DSP board. Nitrogen gas is used as an inflation gas, and the internal pressure is measured by pressure sensor attached bottom of the frame. Since membrane structures are extremely sensitive to the boundary conditions, manufacturing process should be carefully executed.

3.2. Results

An increment of load in experiment is 100g depending on scaled weights. The deflection curve of numerical analysis coincides with the experimental result as shown in Figure 8. In the experimental results, the boom seems to be less stiff and more easily distorted than numerical model because the boundary conditions in the experiment are not ideal.

![Figure 7: Experimental set-up for static bending test](image1)

![Figure 8: Analytical and experimental result for various internal pressure](image2)

![Figure 9: Time-deflection curve of SMA wire while the current is increased manually](image3)
4. WRINKLING CONTROL

4.1. SMA wire actuator for controlling inflatable boom

Shape memory alloy, one of the most popular smart materials, is a metal that remembers its original shape due to a temperature-dependent martensitic phase transformation from a low-symmetry (martensite) to a highly symmetric crystallographic structure (austenite). SMA indicates large strain, large force, and excellent damping characteristics before transition as its merits. Moreover it has good corrosion resistance, low density, and high fatigue strength [13]. From a point of view applying it to the inflatable structures, SMA wire is suitable to control inflatable structures for the reasons that it is flexible, compact, and light, produces large contraction force, and requires only small adhesion area. To control wrinkles in inflatable boom structure statically SMA wire is connected between two points expected to be pulled. Before applying SMA wire actuator to inflatable boom structure, characteristics of the actuator are measured. The test specimen is Flexinol, commercial SMA wire actuator produced by Dynalloy Inc.[14], with the dimensions of φ 0.152X240mm. When the electric current through the wire is increased gradually, the strain and contraction force shows increase stepwise as expected [15]. Strain and critical current at which strain of SMA wire steps up are observed by laser sensor. Recovery strain is approximately 4%, and measured critical current is 0.3A as a piece, 0.6A as a bundle of 3 wires, and 1.0A as a bundle of 6 wires. Contraction force of SMA wire actuator is measured by specially designed equipment as shown in Figure 10. After each ends of wire is tightened and fixed, current from power supply pass through the SMA wire. The contraction force is measured by the load cell located below the upper beam to which SMA wire is attached. As a result of this experiment, contraction force is approximately 8N for each wire, and independent of length. The total force of bundled wire actuator is directly proportional to the number of wires.

![Figure 10: Test configuration for measuring contraction force of SMA wire](image1)

![Figure 11: Analysis result of inflatable boom with different control force](image2)

4.2. Simulation results

In this section, control force produced by contraction of SMA wire is applied to the numerical model. The control force is modeled as a point downward force acting on the point that SMA wire is connected. To certify that the point downward force is efficient to demonstrate the contraction force of SMA wire, experiments should be performed. It will be covered later part of section 4. To validate that applying 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 11 shows the influence of control force on the deflection of boom structure. From this result, deflection recovery is proportional to the control force, and applying downward control force is definitely effective. With the assumption that
the wrinkling load is generally near to the transition area of deflection curve, wrinkling is delayed as much as the deflection is recovered. The states of each membrane such as taut, wrinkled, and slack can be quantitatively examined by using wrinkling algorithm of UMAT subroutine. Wrinkled region and its propagation are illustrated in Figure 12 at each load step of 8.4N, 10.3N, and 11.2N. Wrinkling area is decreased by the function of SMA wire as can be expected.

Figure 12 : Wrinkled region data from analysis

(a) without control force applied by SMA wire effect
(b) with control force applied by SMA wire effect

4.3. Experimental results

How much contraction force of SMA wires is required to control the deflection and wrinkling of the boom is concluded by numerical analysis. For example in the case of restoring deflection occurred by 500gf, contraction force of 44N is needed. To confirm the reasonability of numerical model, integrated system of SMA wire and inflatable boom, actual specimen is constructed and tested. SMA wires are tied by a terminal, and connected with the hoop at the height of 0.5m and 1.0m. Each hoop is made by Polyethylene Terephthalate (PET) film, and adhered to the surface of inflatable boom distributing control force to the entire circumference of the boom. To generate desired force, 44N as mentioned before, 6 SMA wires are used. Two bundles of Flexinol, the same specimen applied in the numerical analysis, are used, and 1.2A current is sent through them. Figure 13 illustrates the result of experiments compared to that of numerical analysis. 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 and to remove wrinkles. Deflection is reduced about 7.6mm and wrinkling load, the maximum load structure can support, is increased approximately 300gf, which is 30% of initial load limit.
5. CONCLUSION

The inflatable boom structure is numerically modeled by using ABAQUS finite element program with membrane elements. To consider the nonlinear deformations of inflatable boom due to wrinkling, the numerical algorithm of wrinkling based on Miller-Hedgepeth membrane theory is developed using user defined material (UMAT) subroutine supported by ABAQUS. The experimental model of inflatable boom is made of Kapton film. To characterize the nonlinear behaviors of inflatable boom, the bending tests for various internal pressures are performed by experimentally and numerically. The numerical model proposed in this research can effectively predict the nonlinear behavior of inflatable boom due to wrinkling. Also, the attempt to removing wrinkling region using shape memory alloy (SMA) wire is also 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 the structure can support can be improved by this control mechanism.

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