DEPLOYMENT ANALYSIS OF SPACE INFLATABLE TUBE

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Abstract

There has been a lot of attention recently on space inflatable structures. Some programs taking the advantages of inflatable structures have been suggested already. Experiments on the deployment of inflatable tube were performed under micro-gravity environment. It has been reported that the peculiar vibration of tube was observed. Researches about material, strength and shape accuracy after deployment have been progressing fairly. But, deployment analysis of inflatable structures has not been researched adequately. In this study, we propose an analysis method in consideration of the interaction between the highly nonlinear deformation of tubes and gas flow. And we analyzed the deployment motion of the tube initially folded in half under the deployment.

1. Introduction

There has been a lot of attention recently on space inflatable structures. Inflatable structure consists of flexible tubes, membranes and so on. They are made of flexible thin films (e.g. Polymer, Kapton, Teflon). Inflatable structures are deployed by injection of the gas, and their shapes are maintained by injected gas pressure. Researches about material and, strength and accuracy after deployment have been progressing fairly. But, the deployment analysis of inflatable structures has not been researched enough.

Some of the most important characteristics of inflatable structures are following[1]
* Their weight is about half of the best mechanical system's, as inflatable structures are made of thin films.
* Inflatable structures can be folded in a small volume, and extraordinary variety of shapes.
* Inflatable structures can be produced for less money than mechanical structures.

* It is possible to produce inflatable structures to symmetric shapes and curved surfaces.
* Deployment mechanism of inflatable structure is very simple.

These properties above mentioned are suitable for the tendency of the recent space development, “faster, better, and cheaper”. Some programs taking these advantages of inflatable structures have been suggested already. Inflatable structures are useful for various areas of space structures, e.g. sunshades for space telescopes, deployment and support of solar arrays, pressurized habitats in space or on planetary surfaces, antenna reflectors, solar concentrators.

In the STS-77 mission in May 1996, the Inflatable Antenna Experiment (IAE) was performed. The IAE antenna reflector was made of very lightweight thin aluminized Mylar (0.0064 millimeters thickness). The inflatable support struts were made of a thin rubberized material called Neoprene-coated Kevlar. The 14-meter diameter antenna was dish-shaped and was supported by three 28-meter inflatable tubes. These tubes were folded in zigzag form before the deployment. The maintenance of the deployed shape of the antenna was completed insufficiently because of the leakage of the gas and the vibration. But this experiment showed the potential of inflatable structure as large space structure.

The dynamics of inflatable tube is formulated by finite element method. It is necessary to consider the interaction between highly nonlinear deformation of tubes and the flow of injected gas to analyze the deployment of inflatable tubes. As the cross-sectional form of tube changes by the time, the flow of injected gas is unsteady.

In this study, we propose an analysis method in consideration of the interaction between deformation of tubes and gas flow.
Experiments on the deployment of inflatable tube were performed under micro-gravity environment. These experiments were performed in JAMIC (JApan Micr-o-gravity Center) by Hokkaido university [2][3]. The tube was folded in half initially. The rigid body was put on one end of the tube to deploy the tube smoothly by its inertia. Another end of the tube was connected with the gas tank. It has been reported that the peculiar vibration of tube like pendulum was observed, and such phenomenon would depend on injected gas pressure and the stiffness of tube. This vibration was observed on the experiment with chloroethylene tube, but not observed on the experiment with polyethylene tube.

The process of the vibration was as following.
(a) The gas was injected into the tube from gas tank, and the angle of the tube’s fold increased as tube was inflated.
(b) A little while later, the angle of the tube’s fold started to decrease.
Figure 1 shows these processes of the vibration. The deployment of the tube was accomplished after repeating these processes.

This vibration has influence on the deployment of inflatable tube. The mechanism of this phenomenon has not been clarified.

2. Formulation

We formulate the dynamics of the tube with finite element method, and consider the iteration between the highly nonlinear deformation of the tube and the flow of injected gas. In this section, we propose a simple model of the injected gas flow, and describe the iteration analysis scheme of the tube’s deformation and the gas flow[4].

It is very difficult to analyze the unsteady flow of the gas injected into the tube, because the cross section of the tube changes by time, the change affects the gas flow. We assumed that the gas flow have one dimension along the longitudinal direction. The tube is divided into some cylindrical element. We assume that the gas instantaneously became in steady state in each element, at each time step.

\begin{align*}
L & : \text{Length} \\
d & : \text{Diameter} \\
t & : \text{Thickness} \\
r_i^k & : \text{Nodal position vector} \\
A_i & : \text{Cross-section} \\
V_i & : \text{Volume} \\
\rho_i & : \text{Density} \\
m_i & : \text{Mass} \\
P_i & : \text{Pressure} \\
u_i & : \text{Velocity}
\end{align*}

Figure 2 illustrates the cylindrical division of the tube and the symbols with their descriptions. The subscript \(i\) represents the number of the cylindrical element, and the subscript \(k\) represents the nodal number along the circumference of the tube in each cross-section. We represent \(P_i\) as the internal pressure of gas in element \(i\), \(\rho_i\) as density, \(u_i\) as velocity, \(m_i\) as mass, \(V_i\) as volume, and \(A_i\) as the cross section between element \(i\) and \(i-1\). \(V_i\) is approximated follows.
\[ V_i = \frac{A_i + A_{i+1}}{2} \cdot h_i \]  
\[ A_i = \frac{1}{2} \left( \sum_{k=1}^{N} k^{r_k} \times h_i \right) \]  
\[ h_i = \left( \sum_{k=1}^{N} r_{i+k}^k \right) / N \]  
\[ r_i^k \] expresses the position vector of the \( k \)-th node on perimeter of the \( i \)-th cross section. \( A_i \) is defined as equation (3).

\[ A_i = \max \{ \min (A_i^-, A_i^+) - 0 \} \]  
\[ A_i^- = A_i \cdot \frac{h_{i+1}}{h_i}, \quad A_i^+ = A_i \cdot \frac{h_i}{h_{i+1}} \]

\( A_i \) represents the effective area of the gas flow.

\( \dot{m}_i \) expresses mass flow of the gas \( w_i \) is approximated as the following.

\[ w_i = (p_i - p_i) A_i - (p_i - p_{i+1}) A_{i+1} + \dot{m}_i | u_i | \]  
\[ (\text{case 1}: w_i > 0) \]

\[ u_{i+1} = \sqrt{w_i / p_i A_{i+1}}, \quad \dot{m}_{i+1} = \rho_i A_{i+1} u_{i+1} \]  
\[ (\text{case 2}: w_i \leq 0) \]

\[ u_{i+1} = \sqrt{-w_i / p_{i+1} A_{i+1}}, \quad \dot{m}_{i+1} = \rho_{i+1} A_{i+1} u_{i+1} \]  

The gas pressure has influence on generalized external force \( \bar{F} \). The contribution of the gas pressure to \( \bar{F} \) is calculated as equation (7).

\[ \Delta q^T \bar{F} = \bar{p}_i \Delta V_i \]  
\( q \) represents the nodal position vector. The bar on the symbol expresses the mean value between time \( t = t \) and \( t = t + \Delta t \), that is \( [ ] = (\int k_{ij} + \int k_{i+1j})/2 \) The delta \( \Delta \) expresses the value of the increase from time \( t = t \) to \( t = t + \Delta t \), that is \( \Delta [ ] = (\int k_{i+1j} - \int k_{ij}) \).

We calculated the pressure in element \( i \) with equation (1) \( \sim (6) \) using the following algorithm.

1. Set time \( t = 0 \). Give the value of the variable.

2. Calculate equations (1)-(6) using node position vector \( \vec{r}_i^k(t) \).

3. Calculate the mass of each cylindrical element at time \( t = t + \Delta t \) by the following equation.

\[ m_i(t + \Delta t) = m_i(t) + \left( \dot{m}_i(t) - \dot{m}_{i+1}(t) \right) \Delta t \]

The value of the mass flow \( \dot{m}_i \) from the gas tank has been given beforehand.

4. Calculate the nodal position vector \( \vec{r}_i(t + \Delta t) \) at time \( t = t + \Delta t \) by Newton-Raphson method. The pressure is calculated as the following. In these equations, \( \kappa \) expresses the ratio of specific heat, and the volume \( V_i(t + \Delta t) \) is calculated from the unknown variable \( p_i(t + \Delta t) \)

\[ p_i(t + \Delta t) = \frac{m_i(t + \Delta t)}{V_i(t + \Delta t)} \]  
\[ p_i(t + \Delta t) = p_i(t) \left( \frac{p_i(t + \Delta t)}{p_i(t)} \right)^{\kappa} \]

5. Set time \( t = t + \Delta t \), and get back to 2.

3. Numerical Result

In this section, the tube's model and the results of the deployment analysis are described. We analyzed the deployment of the tube which was folded in half to compare numerical analysis with experiments as mentioned in introduction. The deployment of the tube were simulated in three cases that the tube was made of chloroethylene, polyethylene and more stiff material. And we considered the influence that the stiffness of the tube has on the vibration.
Figure 3 illustrates the numerical model. One end of the tube is clamped and connected with the gas tank. Another end is closed with circular rigid body. The angle of the tube's fold is represented by $\theta$.

![Diagram of the numerical model](image)

Table 1 shows the geometry of the tube and the properties of the injected gas. The injected gas was carbon dioxide.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter $d$ [m]</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>Length $L$ [m]</td>
<td>$2.5 \times 10^{-1}$</td>
</tr>
<tr>
<td>Thickness $t$ [m]</td>
<td>$4.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>Initial fold angle $\theta$ [deg]</td>
<td>45.0</td>
</tr>
<tr>
<td>Specific heat $\kappa$</td>
<td>1.3</td>
</tr>
<tr>
<td>Gas constant $R$ [J/kg·K]</td>
<td>$1.89 \times 10^{-2}$</td>
</tr>
<tr>
<td>Initial temperature $T$ [K]</td>
<td>$2.88 \times 10^{2}$</td>
</tr>
<tr>
<td>Mass flow [kg/s]</td>
<td>$5.99 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

3.1 Simulation Result (case 1)

In this simulation, we supposed that the tube was made of chloroethylene film, and Young's modulus $E$ was $3.0 \times 10^5$ Pa. Figure 4 shows the configuration under the above-mentioned condition. Figure 5 shows the path of the center of the rigid body set on the tube's end and the time-history of its coordinates.

![Deployment of the tube (case 1)](image)

![Motion of the rigid body (case 2)](image)
Figure 5 shows that the x-coordinate decreases and y-coordinate increases at t=0.18sec and 0.42sec. In the case that the tube is deployed smoothly, x-coordinate should increase monotonously and y-coordinate should decrease monotonously till $\theta=90\,\text{deg}$. The vibration observed on the experiments under micro-gravity appeared in this simulation.

### 3.2 Simulation Result (case 2)

In this simulation, we supposed that the tube was made of polyethylene film, and Young's modulus $E$ was $1.1 \times 10^8$ Pa. Figure 6 shows the configuration under this condition Figure 7 shows the path of the center of the rigid body set on the tube's end and the time-history of its coordinates.

![Figure 6: Motion of the tube (case 2)](image)

![Figure 7: Motion of the rigid body (case 2)](image)

Figure 7 shows that the tube is deployed smoothly. After the deployment, the tube vibrated extremely in comparison with the simulation result of chloroethylene (Figure 5). It took more time to deploy straightly than that in the case1. The vibration observed on the experiments under micro-gravity didn't appear in this simulation.

### 3.3 Simulation Result (case 3)

In this simulation, we supposed that the tube was made of more stiff material than chloroethylene and polyethylene, and its Young's modulus $E$ was $7.8 \times 10^9$ Pa. Figure 6 shows the path of the center of the rigid body set on the tube's end and the time-history of its coordinates.

Figure 8 shows that the x-coordinate decreases and the y-coordinate increases at t=0.20sec, 0.42sec, 0.60sec and 0.81sec. The vibration observed on the experiments under micro-gravity appeared in this simulation.
The vibration appeared in these simulations. But there was the case that the vibration was not simulated [4][5]. We have not distinctly clarified parameters that have influence on the vibration except the stiffness of the tube, but guess that some of those parameters are the mass and the shape of the rigid body, the length and the radius of the tube, initial shape, and the mass flow of the injected gas.

4. Conclusion

In this study, we proposed an analysis method of the inflatable tube’s deployment, and simulated some models. These simulation results agreed with the experiment results. The Young’s modulus of the tube’s material is larger, the frequency of the vibration is larger. We found that the stiffness of the tube was one of the parameters that influence the vibration. In the future, we are going to try to simulate many cases, and clarify all parameters that cause the vibration.

References