Numerical Simulation for Damping-Controlled Deployment of Z-Folded Inflatable Tube

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Abstract: The damping-controlled deployment technology of flexible Z-folded inflatable tube is one of the key technologies of space inflatable structures. Constraint failure between couple nodes is proposed to simulate the damping-controlled deployment. And the equation of constraint failure is established. Inflation process of Z-folded tube is simulated with control volume method. Compared with uncontrolled method, it is indicated that the new method can effectively solve the disordered deployment problem of the slender Z-folded inflatable tube. By analyzing the displacement of the apical of the folded tube with different constraint forces during deployment process, the concept of effective constraint force is proposed. In the effective region of constraint force, the folded tube deploys with little retraction and fluctuation. Otherwise, The flexible folded tube would deploy disorderly or even cannot deploy. The simulation method and numerical results have a theoretical and instructive significance to the research on the space inflatable structures.

Key words: Z-folded tube; damping-controlled; inflation deployment; failure of constraints

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0 Introduction

Folded inflatable structures have the advantages of small package volume, light weight, low cost and large deployment area. Therefore, they have become a new form of space structure that is widely accepted in various space missions[1-2]. Inflatable tube is the basic building block and effectively simplified model of the space inflatable structures. Z-folded pattern is the basic packing method in many space missions such as solar sails and space antenna[3-4]. Stability and reliability of the deployment and inflation process of Z-folded tube guarantee the success of space missions. However, previous test results demonstrate that the deployment of long flexible tube with many folding layers is strongly random. If there is no control, the folded tube will be filled disorderly, thus causing mutual extrusion and tangle with each other. NASA once carried out the inflatable antenna experiment (IAE), and the deployment process was completely out of control[5] (Fig. 1). Therefore, the controlled deployment of Z-folded tube is one of the key technologies in space inflatable structures.

Controlled deployment research has been carried out since 1950s. Damping control is one of the most common methods at present. The principle is to load a certain damping device such as springs, velcro, and end brake, etc[6-7] on the inflatable structures, while all these methods are proposed for rolled type folded model. The folding direction's repeatability of Z-folded model results in rapid changes of air flow direction, which increases the difficulty of damping-controlled deployment. Velcro is easily adhered to the wall and packaged by Z-folding with flexible tubes because of its portability and flexibility. Unlike coil

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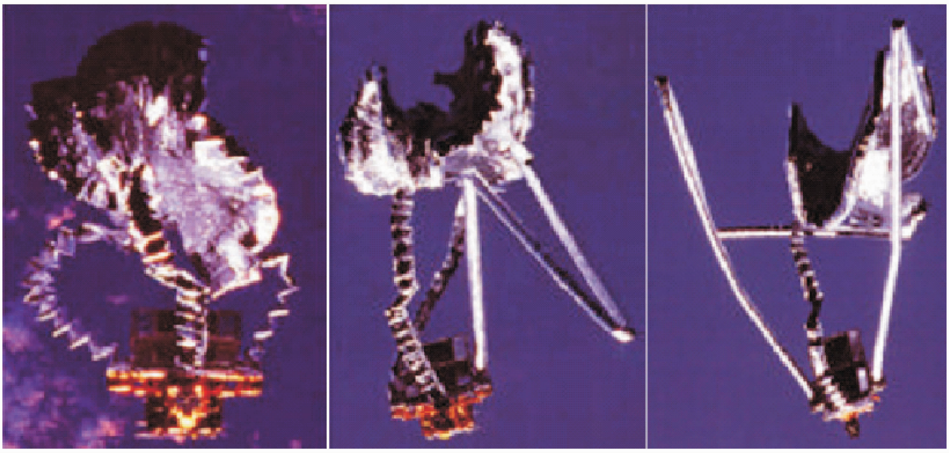

Fig. 1 Failure of inflatable antenna experiment

springs, there is no recovery force when the tube with velcro is inflated, which is advantageous to maintain the shape of inflatable structures[8]. So far it has been a unique control method for Z-folded tube. However, it is expensive and has great difficulty in data collection for space experiment. And it is difficult to forecast its deployment process in space for its vacuum micro gravity environment by ground test. Therefore, it is not easy to understand the deployment mechanics of space inflatable structures. However, with the rapid development of computer hardware, numerical simulation has become an important approach in the investigation of inflatable tube. The ductile fracture of one dimensional elastic-plastic rope unit is used to simulate the velcro-controlled deployment for rolled-folded tubes[9], while the brittle fracture of a virtual bar element is used to simulate the nylon fastening-controlled deployment process[10]. Though it can ensure the orderly deployment to some degree, it is usually applied to the rolled-folded tubes. So, papers about the numerical simulation of Z-folded tube′s inflation deployment have not been found.

Failure of constraint is proposed to simulate the damping-controlled inflation deployment of Z-folded tube and constraint failure equation is established. Numerical simulations of the controlled deployment of Z-folded tube are carried out with control volume method based on LS/DYNA finite element program. And the results demonstrate this new method can effectively solve the disorder problem of inflation deployment. Laws of the motion under different constraint forces are studied.

1 Theoretical Model

1.1 Model of control volume

The principle of control volume method is shown in Fig. 2. With changes of pressure in the controlled volume, the shape of control surface is changed[11-12]. The motion equation of inflatable structures is as follows[13]

$$\boldsymbol{M}\ddot{\boldsymbol{D}} + \boldsymbol{C}\dot{\boldsymbol{D}} + \boldsymbol{K}\boldsymbol{D} = \boldsymbol{R}^{\mathrm{ext}} \tag{1}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{K}$ are the mass matrix, damping matrix and stiffness matrix under the current configuration, respectively. $\boldsymbol{R}^{\mathrm{ext}}$ is the force vector including pressure. $\ddot{\boldsymbol{D}}$, $\dot{\boldsymbol{D}}$ and $\boldsymbol{D}$ denote the acceleration, velocity and displacement under the current configuration, respectively. With explicit solution method, the finite difference form of Eq. (1) is as follows

$$\left(\frac{1}{\Delta t^2}\boldsymbol{M} + \frac{1}{2\Delta t}\boldsymbol{C}\right)\boldsymbol{D}_t = \boldsymbol{R}^{\mathrm{ext}}_{t-\Delta t} -$$

$$\boldsymbol{K}\boldsymbol{D}_{t-\Delta t} + \frac{1}{\Delta t^2}\boldsymbol{M}\Big(2\boldsymbol{D}_{t-\Delta t} -$$

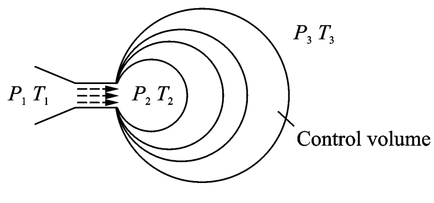

Fig. 2 Control volume theory

$$\boldsymbol{D}_{t-2\Delta t}+\frac{1}{2\Delta t}\boldsymbol{C}\boldsymbol{D}_{t-2\Delta t}\Big) \tag{2}$$

The increase of control volume depends on the gas mass flow rate, gas state equation and dynamic properties of membrane structure, etc. $\boldsymbol{D}_t$ can be obtained via Eq. (2). Then inflatable structure configuration is also obtained at t moment.

In Fig. 2, P and T are the pressure and temperature, respectively. And the subscripts 1, 2, 3 refer to inlet and interior of the control volume, and the ambient, respectively.

1.2 Constraint failure equation

The finite element idealization of the constrained nodes is shown in Fig. 3. f_n, f_s are the normal and shear constraint forces, respectively, both obtained by calculation[14].

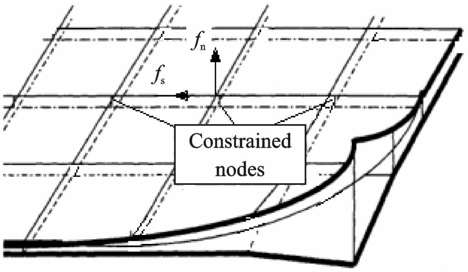

Fig. 3 Finite element idealization of the constrained nodes

These constrained nodes move at the same acceleration together before the failure of constraints. The acceleration expression is as follows[7]

$$a_{i_{\mathrm{common}}}=\frac{\sum_{j}^{n} M_j a_i^j}{\sum_{j}^{n} M_j} \tag{3}$$

where n is the number of constrained node, and a_i^j the acceleration of the i direction of the jth node constrained.

When the normal force f_n and shear force f_s meet the following condition, the constraints fail permanently[8].

$$\left(\frac{|f_\mathrm{n}|}{S_\mathrm{n}}\right)^{n_1}+\left(\frac{|f_\mathrm{s}|}{S_\mathrm{s}}\right)^{m}\geqslant 1 \tag{4}$$

where S_n, S_s are the normal and shear constraint failure forces, respectively, obtained experimentally. m, n_1 are the exponents of shear and normal constraint forces, respectively, defined by the ratio of tangential exponent and normal components.

Constraints fail in turn from the first degree of freedom. When the node displacements meet the following linear constraint equations, the first degree of freedom constraint fails[7].

$$u_1=C_0-\sum_{k=2}^{n}\frac{C_k}{C_1}u_k \tag{5}$$

where n is the number of nodes constrained, u_k the displacement of the constrained node, C_k the self-defined coefficient. Assuming that $C_0=0$, there exist the following relationships between degrees being constrained and unconstrained.

$$u_{\mathrm{unconstrained}}=[\boldsymbol{L}^t\boldsymbol{M}_1\boldsymbol{L}]^{-1}\boldsymbol{L}^t\boldsymbol{F} \tag{6}$$

where $\boldsymbol{M}_1$, $\boldsymbol{L}$ denote the mass diagonal matrix and the transformation matrix, respectively; and $\boldsymbol{F}$ the force in right direction.

2 Method Validation

The flexible Z-folded tube with a 22:1 ratio of length to diameter (2.2 m in length) is used as the research object here. And numerical simulations of controlled and uncontrolled inflation deployment are carried out. The model of numerical simulation is shown in Fig. 4. The constraint boundary conditions at the inlet and free end are shown at AB and CD. The spacings of wall layer and folding layer are 0.001 m and 0.003 m, respectively. The total number of elements is 28 586. To simulate the deployment process effectively, the flexible diaphragms are placed at the folding lines. The inflation tube is divided into 22 chambers. Basic parameters are shown in Table 1. The inlet mass flow is 0.002 2 kg/m^3.

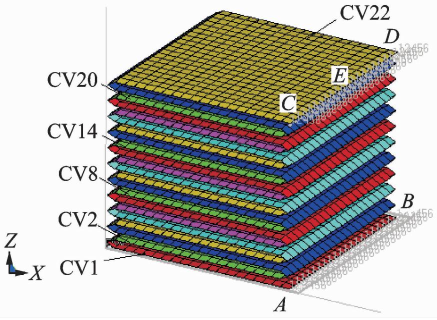

Fig. 4 Numerical model of uncontrolled deployment

Table 1 Basic parameters of numerical model

Model	Tube			
	Density/ ($kg \cdot m^{-3}$)	Elasticity modulus/Pa	Poisson's ratio	Thickness/ m
Tube	1 200	6.0e+7	0.35	0.000 1
Diaphragm	1.2	5 000	0.3	0.000 05

Constraints are added to the corresponding nodes between inter layers of the Z-folded tube (Fig. 5). The normal and shear forces are defined as $S_n = S_s = 5$ N.

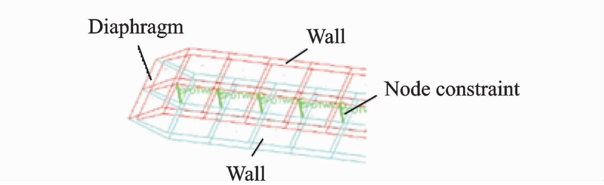

Fig. 5 Numerical model of node constraint

The numerical results of uncontrolled inflation deployment are shown in Fig. 6. The results shows that the folded tube deploys rapidly, and large deformations, displacements and rotations in all directions exist as well. The apical chamber moves in a reverse direction, and some chambers in the middle segment present a skewed state(see Fig. 6). The whole inflation process is chaotic and random. Numerical results agree with the uncontrolled deployment experiment of space antenna basically[5]. Therefore, numerical calculation can be well used to simulate the inflation deployment. Chaotic inflation would lead to failure of the whole space mission.

Fig. 6 Numerical results of uncontrolled inflation deployment

Numerical results of the damping-controlled deployment applying constraint force model in this paper are shown in Fig. 7. Before 2.5 s, gas flows into chambers through membrane in turn. Constraints between folding layers begin to fail, and tubes unfold gradually. Bulges emerge on each chamber, and inflation deployment presents a better order. Due to less aeration and lower pressure during 2.5—3.5 s, there exist a lot of wrinkles on the tube. During 3.5—6.0 s, pressure in the tube continues increasing, and the inflatable tube appears a smooth and naturally axial profile. Therefore, constraints failure between node couple can be well used to simulate damping-controlled deployment of Z-folded inflatable tube.

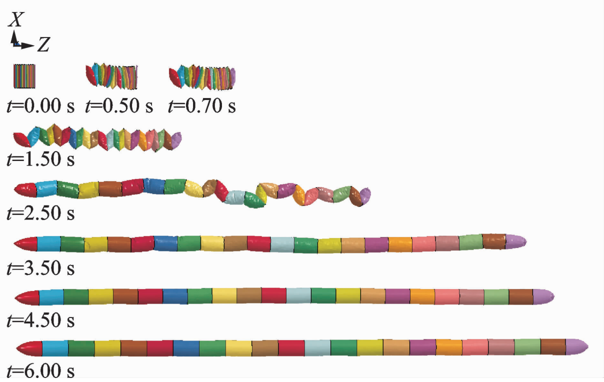

Fig. 7 Numerical results of damping controlled deployment

3 Impact of Constraint Force on Controlled Inflation Deployment

3.1 Impact on deployment progress

The shape of damping-controlled deployment of Z-folded tube under constraint force of 500 N is shown in Fig. 8. As the constraint force is too large, impact force cannot overcome the constraint force between folding layers, thus wrinkles cannot be opened. Numerical results agree with the ones that the rolled tube also cannot be opened as the constraint force is too big in Ref. [8]. A large number of numerical simulation experiments indicate that only when the constraint force is less than a critical value, the inflatable tube can deploy completely. Otherwise, nodes will be constrained with each other from the beginning to the end, and deployment cannot be accomplished.

To further explore the influence of constraint force on inflation deployment, Z-displacement of node *E* in Fig. 4 is measured in deployment

Fig. 8 Shape of inflatable tube under constraint force of 500 N

process, as shown in Fig. 9.

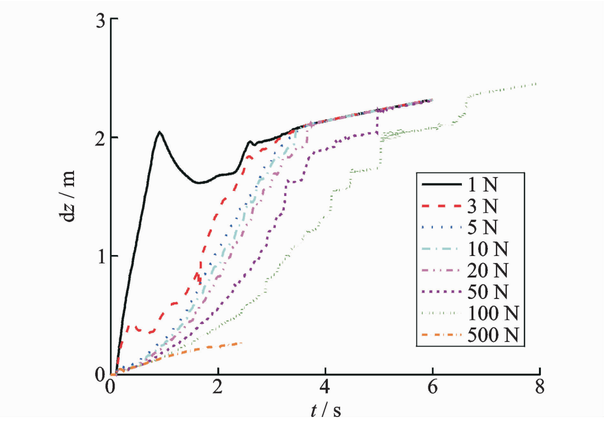

Fig. 9 Z-displacement of node E under different constraint forces

In general, when the constraint force is less than 100 N, the inter-layer confinement can fail completely. At the moment of failure, the displacement of the node E surges. The larger the constraint force, the more delayed and slower the movement of the top node E, and the longer time it will take to relieve the constraint of the inter-layer. When the constraint force is very small (such as 1—3 N in this case), relieving the constraint is very fast and the folded tube appears to be retraction because of the flexible material. The stability of the axial displacement of node E increases when the constraint force is up to 20 N. If the constraint force continues to increase to 100 N, the fluctuation in axial position of node E occurs. When the constraint force approaches to a large value 500 N, the maximum displacement of node E is only 0. 25 m, and relieving the constraint of the inter-layer failed. In short, there is an optimal effective constraint force for the flexible folded tube. In this region, the axial displacement of the folded tube increases in order with little retraction and fluctuation.

3. 2 Impact on volume and pressure of inflation tube

The changes of volume and pressure of some typical chambers are shown in Figs. 10, 11. The result shows that the volume of the chamber CV1 increases first, and then the other chambers volume increases orderly. The volumes at both ends are smaller than that of the middle chambers due to the structural constraints (see Fig. 10).

In Fig. 11, pressure changes at different chambers are coincident approximately. However, in the early stage of 0—1. 50 s, the pressure of each chamber increases in sequence. The pressure oscillation of each chamber occurs due to the deformation and motion of flexible material.

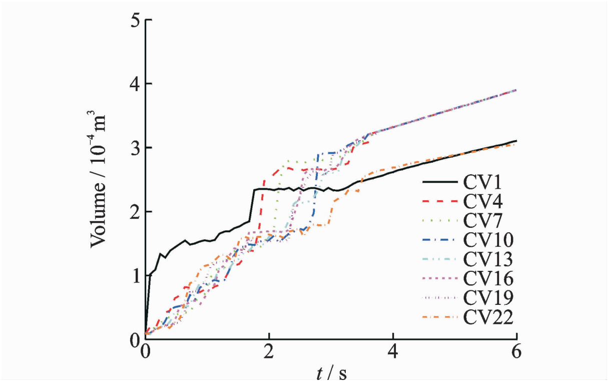

Fig. 10 Volume change of chambers in folded tube

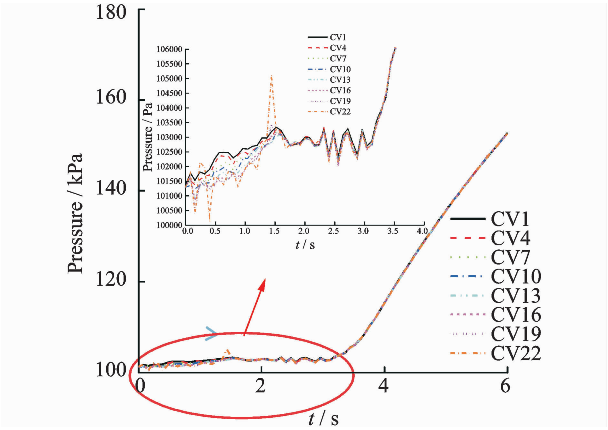

Fig. 11 Pressure change of chambers in folded tubes

4 Conclusions

Constraint failure equation is applied to simulate the damping-controlled deployment of Z-folded tube. After comparison between numerical results of uncontrolled and damping-controlled inflation deployment, conclusions can be summed up as follows:

(1) For uncontrolled Z-folded tube, the chamber volume experiences an oscillatory increase and a sudden decrease, and is in a disordered and unsteady state. The constraint failure model established in this paper can effectively solve the disorder inflation problem of numerical simulation.

(2) Damping control method makes each chamber of the folded tube inflate successively. Inflation progress is divided into two stages: initial development stage and full of pressurization stage. The volume and pressure of chambers increase nearly synchronized at pressurization stage.

(3) There is an effective constraint force to deploy in sequence for damping-controlled folded tube. If the constraint force is less than this constraint, the folded tube deploys disorderly. Otherwise, the folded tube cannot be deployed due to the excessive constraint force.

Acknowledgments

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