Simulation for Gas-Structure Interaction in Inflatable Membrane Beams

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Summary It is very important for understanding gas-structure interaction between compressible ideal gas and elastic structure of space folded membrane beams during the inflatable deployment. In order to address this gas-structure interaction problem, Arbitrary Lagrange Euler finite element mess method was employed. Firstly, gas-structure interaction equation was built by equilibrium integration form, and then solved by operator split method and explicit centered difference method. In addition, an example was given on V-shape folded membrane beams inflated by gas, the inner pressure variations at different stage as well as deployment velocities of this beam end were got by numerically simulation. Finally, numerical results were validated through experimental investigation, which show that ALE method is a feasible and reliable method for studying gas-structure interaction problem.

INTRODUCTION

Up to the present, most of the large inflatable deform structures are made of flexibility thin film material, due to intrinsic strength of low mass, small compact volume during rock off, and can be deployed to super large aperture. It is more common to use this light inflatable deploy structures in forthcoming space tasks. However, the critical problem in applying thin film structures is mainly depending on the reliable control processing of deployment. In 1996, NASA conducted space deployment experiment of inflatable antenna experiment, found that uncontrolled inflation deploy process would induce chaos. So it was urgent for researchers to evaluate the deployment performance of inflatable deformable structures as well as the efficient control of its deploying behaviors.

The inflated deployment dynamic problem of Space folded membrane beams under inflating gas can be summed up into the gas-structure interaction problems, which are the interaction between non-steady, ideal compressible fluid and nonlinear geometry elastic structures. And there are three comparative independent solution fields respectively. The first part is fluid field, for the inflating gas is low velocity and compressible ideal gas, which belongs to computational fluid mechanical problems. The second part is solid structure field, for the drive force induced by gas pressure, and the deformation and movement of beam wall, as well as non-linearity in geometry, large displacement, large rotation and small strain problems, all this problems belong to computational solid mechanical problems. Lastly is the interaction at the interface between fluid and solid structure, the interaction between compressible ideal gas and elastic beam wall, which will influence the movement and deformation of two phase mediums. Gas-structure couple problems refer to multi-disciplines, which should be considered on multiple aspects, it is more complicated than just solve problem in single fluid field or solid field. This paper based on ALE fluid continuity equation and kinematic equation, adopt Lagrange description for solid wall, combined solid boundary and interaction boundary condition, used equilibrium integration form, built gas-structure interaction finite element equation, and finally solved the equation by operator split method and explicit centered difference method. In addition, taken V-shape folded membrane beams for example, investigated the configuration of deployment and the variation of fluid field during inflating deployment.

The model of Gas-structure interaction on the inflatable beam

Fig.1 is the schematic of gas-structure interaction system of membrane beam, which Ω_s and Ω_f stands for solid field and fluid field separately, S_o is the interface between gas and structure, S_u is structure displacement boundary, S_σ is the structure force boundary, n_f is the outer normal vector of gas boundary, n_s is normal vector of solid boundary. At any point of the interface of gas-structure, the direction of n_s and n_f are opposite, supposed the inflating gas is steady, compressible ideal fluid, and the wall of beam is isotropic elastic material. In the fluid field(Ω_f), the equation of ALE is

$$\left.\frac{\partial \rho}{\partial t}\right|_{\xi} + c_i \frac{\partial \rho}{\partial x_i} + \rho \frac{\partial v_i}{\partial x_i} = 0 \qquad \left.\frac{\partial v_i}{\partial t}\right|_{\xi} + c_j \frac{\partial v_i}{\partial x_j} + \frac{1}{\rho} \frac{\partial p}{\partial x_i} = 0 \tag{1}$$

where ρ 、 p are density and pressure of gas, and c_i is relative velocity. In the solid structure field (Ω_s), the Lagrange equation is

$$\sigma_{ij,j} + f_i = \rho_s \ddot{u}_s \tag{2}$$

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For σ_{ij} is stress component, u_s is displacement component, and ρ_s is mass density. As the folded membrane is supposed to be deployed in space micro gravity environment in this paper, the volume force $f_i = 0$, assume the wall of beam is isotropic elasticity, so the constitution equation can be written in the following form.

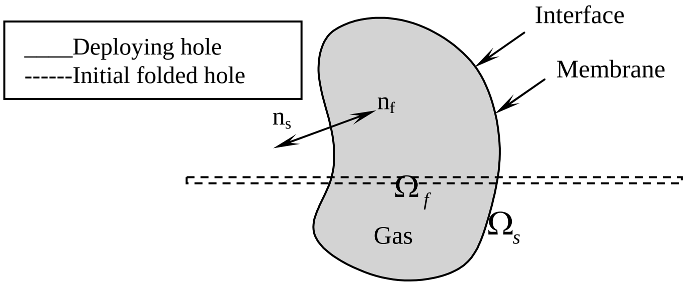

Fig.1 Model of gas-solid interaction system of inflatable membrane beam

$$\sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\mu \varepsilon_{ij} \tag{3}$$

The effect of dynamic property with different inflating gas velocity

In order to confirm this simulation, an inflation deployment experimental system in equivalent micro gravity environment was established based on air track. In the deployable experiment, based on the boundary conditions, both ends of the folded membrane beam are installed in two slides, and the sliders are suspended by the air-track. Non-contact photo-electricity measurement effectively could avoid the disturbance of contact sensor to the inflation deployment process. The dynamic properties of three kinds of inflation flows were tested 错误！未找到引用源。. The experimental results show that these deployment velocities of the folded beams are consistent with the simulation of the same model.

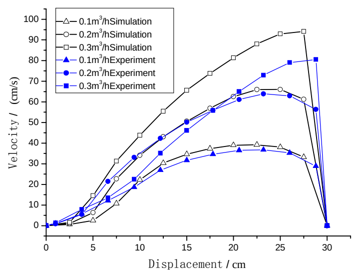

Fig.2 Deployment velocity with gas velocity

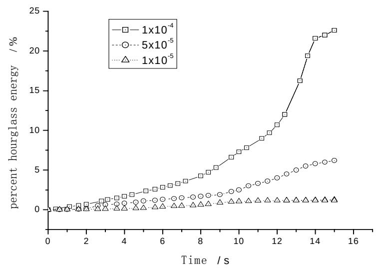

Fig 3 percent hourglass energy at different coefficient

The gas pressure analysis during inflating deployment

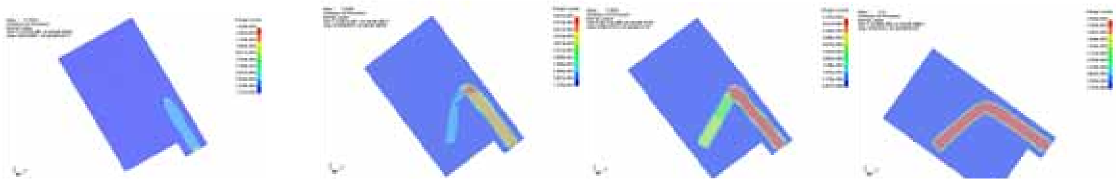

Fig 4 The gas pressure variation inside the membrane beam during inflatable deployment

CONCLUSIONS

These results indicate that both ALE explicit finite element method and operator split method are reasonable and feasible for calculating the process of inflating deployment of folded membrane beam. Gas pressure simulation shows that, with the constant inflation of gas, the inner gas pressure firstly increased until the counter force of gas overcome the constrain of fold line. The gap around the fold line was broken, so more gas at part A flow to part B, the inner gas pressure reduced quickly. With the increase of gas, the pressure rebound back mildly at the end. All above mentioned message indicate that using ALE explicit finite element method for calculating the process of inflating deployment of folded membrane beam is reasonable and feasible. Gas pressure analysis shows that, with the constant inflation of gas, the inner gas pressure increased firstly, until the counter force of gas overcome the constrain of fold line, then the gap around the fold line was broken, so more gas at part A can flow to part B, that the inner gas pressure reduced quickly. With the increase of gas, the pressure rebound back mildly at the end. Gas velocity analysis shows that, there are two phases in the process of deployment for V-shaped membrane beam, the free flow phase and the cumulative phase. At the initial position and when the fold line is open up, the gas flow freely, so the total velocity decreased rapidly. When gas reached the fold line and the enclosed end of part B, the gas velocity increased sharply, and due to the constraint of volume, the velocity slow down at the end.