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Numerical simulations for gas-structure interaction in inflated deployment of folded membrane boom

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Abstract It is very important for gas-structure interaction between compressible ideal gas and elastic structure of space folded membrane booms during the inflatable deployment. In order to study this gas-structure interaction problem, Arbitrary Lagrangian-Eulerian (ALE) finite element method was employed. Gas-structure interaction equation was built based on equilibrium integration relationship, and solved by operator split method. In addition, numerical analysis of V-shape folded membrane booms inflated by gas was given, the variation of inner pressure as well as deployment velocities of inflatable boom at different stage were simulated. Moreover, these results are consistent with the experiment of the same boom, which shows that both ALE method and operator split method are feasible and reliable methods to study gas-structure interaction problem. © *2012 The Chinese Society of Theoretical and Applied Mechanics.* [doi:10.1063/2.1202204]

Keywords gas-structure interaction, membrane boom, ALE method, inflation

It is very important for gas-structure interaction between compressible ideal gas and elastic structure of space folded membrane booms during the inflatable deployment, in the past several decades, scholars all over the world investigated the theory and computational method on the gas-structure coupled dynamic problems, and obtained some achievements. However, gas-structure couple problems refer to multi-discipline, which should be considered on multiple aspects, it is more complicated than just solving problem in single fluid field or solid field. Gas-structure interaction problem is one of the challenging problems in numerical simulation, which is still on the initial stage. In recent years, with the new emerge of arbitrary Lagrangian-Eulerian (ALE) finite element method[1] and the development of high capacity parallel computing technology,[2] it is possible to solve gas-structure interaction problem numerically. During the deployment of membrane booms, the hole at the folded angle is a small gap to gradually expand the circular section, which will produce local resistance. When the hole becomes from small to large, the resistance will become from large to small. The flow rate will produce some changes, which will cause different pressure field, velocity field and energy changes. As the bending stiffness of the membrane boom wall is very low, this process will appear geometric non-linear problems, such as the large displacement, large rotation and small strain.

The inflatable deployment dynamic problem of space folded membrane booms under inflating gas can be summed up into the gas-structure interaction problem, which is between non-steady, ideal compressible fluid and nonlinear geometry elastic structures.[3] To this problem, there are three comparatively independent solution domains. The first domain is fluid domain, because the inflating gas is low velocity and compressible ideal gas, which belongs to computational fluid mechanical problems. The second domain is solid structure domain, because the drive force is induced by gas pressure, the deformation and movement of boom wall, as well as non-linearity in geometry, large displacement, large rotation and small strain problems and so on. All this problems belong to computational solid mechanical problems. The third one is the interaction at the interface between fluid and solid structure, the interaction between compressible ideal gas and elastic boom wall, which will influence the movement and deformation of two phase mediums. This paper is based on ALE fluid continuity equation and kinematic equation, adopt Lagrangian 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 booms for example, the configuration of deployment and the change of fluid domain during inflating deployment was investigated.

Figure 1 is the schematic of gas-structure interaction system of membrane boom, Ω_{s} and Ω_{f} stand for solid domain and fluid domain 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 outside 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, supposing the inflating gas is unsteady, compressible ideal fluid, and the wall of boom is isotropic elastic.

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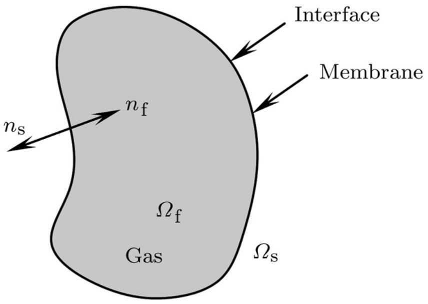


Fig. 1. Model of gas-solid interaction of the cross section at the folded line.

(1) In the fluid domain Ω_f, ALE equations are

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

where ρ, p are density and pressure, respectively, c_i is the relative velocity of gas.

(2) In the solid structure domain Ω_s, the Lagrange equation is

$$\sigma_{ij,j} + f_i = \rho_\mathrm{s} \ddot{u}_\mathrm{s}, \tag{2}$$

where 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, the volume force $f_i = 0$, assume the wall of boom is isotropic elasticity material, so the constitution equation can be written in the following form

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

where λ, μ are Lame constants, ε_{ij} is strain component, δ_{ij} is Kronecker symbol.

This solution includes the fluid domain, solid domain and the coupling interface. The ALE finite element method is one effective way to solve gas-structure coupling problem, numerical simulation helps in understanding inner gas pressure and velocity information which may be very hard to measure in experimental test. Numerical simulation has superiority of the low-cost, multiple simulations, and the less impact from experimental environment and test equipments. There are two main methods for solving ALE equation,[4,5] one is completely interaction solution for fluid mechanical equation, the weakness is that each element can only stands for one material. The other method is operator split method,[6] in which each time step was divided into two phases.[7,8] In the first phase, the mess grid was changed with Lagrange expression, which can calculate the velocity and work due to the change of stress and force. The second phase is advection phase, that the advection of mass, inner work and momentum across the mess grid, in this phase is re-map of the shaped mess in the first phase to initial position or any new position. The big advantage of this method is that each element is evolved in multiple materials.[9]

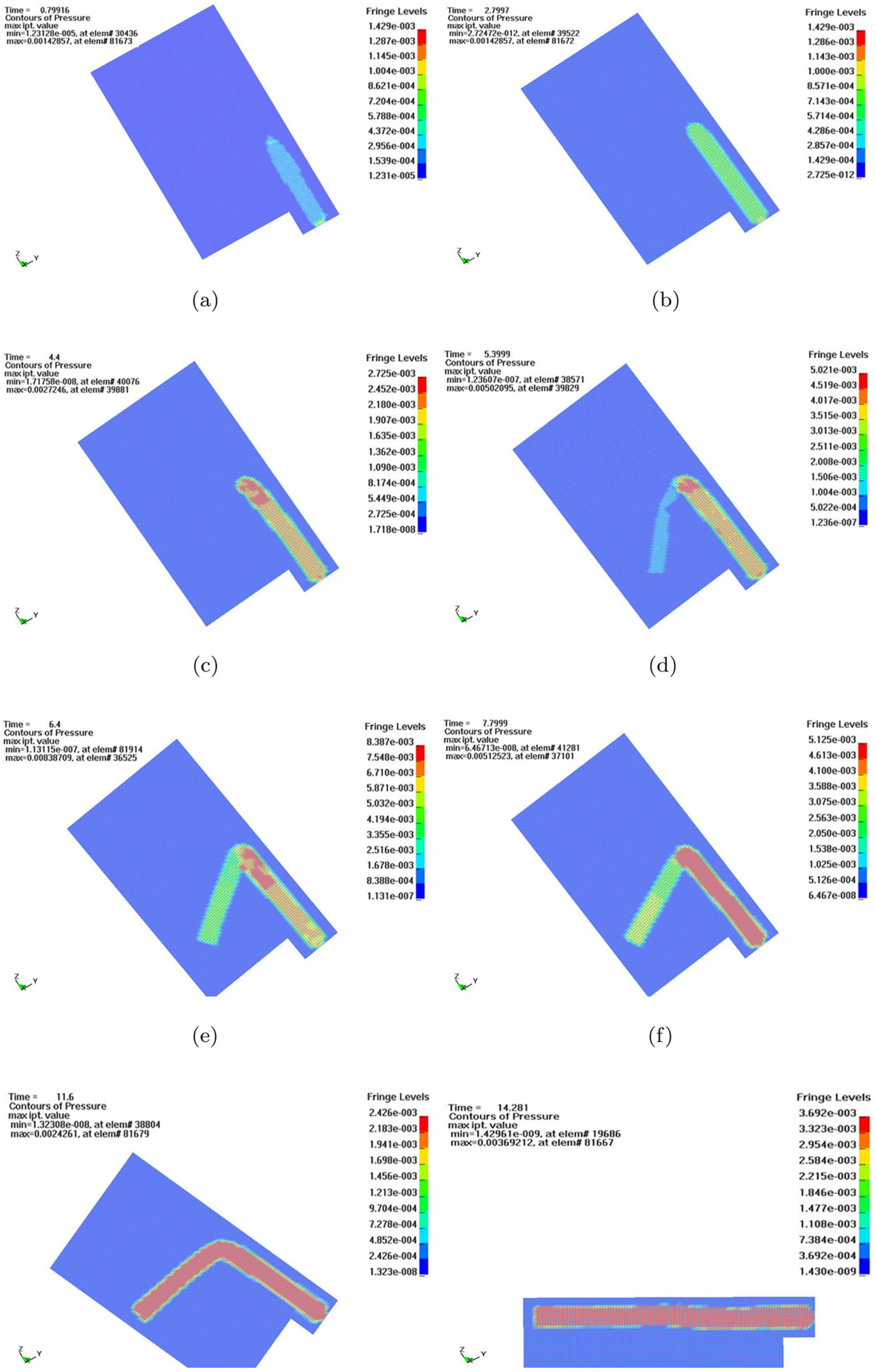
This paper focuses on ALE finite element equation for membrane inflated deployment process, used operator split method and centered difference algorithm for calculation. Firstly, ALE node, Lagrange node and their initial position are defined. Secondly, is integration point x_q within fluid domain? If it is, check each node $x_I(I$ is from 1 to $k)$, then calculate shape function $N_I(x_q)$, and its spatial derivative. End the loop of integration point x stress of each integration point, meanwhile, the internal force is calculated by $f_I^\mathrm{int} = \int_\Omega B_I^\mathrm{T} \sigma \, \mathrm{d}\,\Omega$. Interaction force f_I^ext is calculated using penalty function method. Finally, accelerations are calculated by $a_I^n = (M^L)^{-1}(f_I^\mathrm{ext} - f_I^\mathrm{int})$, and then update these velocities, displacement and coordinate. If ALE nodes change, update shape function and its difference function

$$x_I^{n+1} = x_I^\mathrm{LAG} + \Delta t(\hat{v}_I - v_I).$$

ALE explicit finite element method is used for studying the law of inflated deployment of space folded membrane boom. The length of membrane boom is 600 mm, each length of fold boom is 300 mm which can be easily verified by experimental data. ALE multiple material substance elements are employed in the process of space mess grid for single point integration, and also for the gas source inflated. Four-node shell element is used for boom wall and the end. Two-node bar element is used for the rotation shaft at the end of inflation point for finite element model.

In the finite element analysis, there are some assumptions. Suppose the membrane is isotropic linear elastic material, the end cap of boom and the box for the gas and the rotation axis are rigid materials. Assume the inflating gas is ideal gas, the gas density is 1.12 kg/m^3, the ideal gas heat capacity at constant volume and the ideal gas heat capacity at constant pressure are 717.7 J/(kg·K) and 1 004 J/(kg·K) respectively. In order to leave room for the movement of membrane boom, the ALE space mess is in box shape, and messed with rectangular shape element, the overall length, width, and height are 5 mm × 6 mm × 6 mm in respective. In this finite element model, the total number of nodes is 97 730, total number of elements is 89 182, the area for inflating gas at the initial position is 0.01 m × 0.01 m, the inflating gas velocity is 0.278 m/s, and the corresponding gas volume velocity is 0.1 m^3/h. Beside, assume there is no pre-stress at the initial phase of deployment, without accounting the damage at the folded line, the whole environment is of zero gravity, and there is no heat exchange between gas and boom wall.

The displacement boundary conditions are: the displacement of one end of the V-shape boom, which is for inflation, is zero, which can only rotate at its mass center. Another end can move within the plane. The V-shape folded membrane boom can be divided into two



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Fig. 2. The gas pressure variation inside the membrane boom during inflatable deployment.

parts, defining the boom from inflating hole to the fold line is part A, which is for gas inflation directly, and the left part from the fold line to the enclosed end is part B, which for deployment under gas inflation. The blue area in Fig. 2 is ALE mesh.

Figure 2 shows the gas pressure contour of space folded membrane boom at different deployment phase, which reflects the gas pressure change of the membrane boom at vertical section. According to these figures, in the initial phase, the inner pressure of the boom is equal to the environment pressure. With the inflation of gas at constant velocity, the inner gas pressure in the part A will increased, and the membrane boom will cause deformation and movement as well.

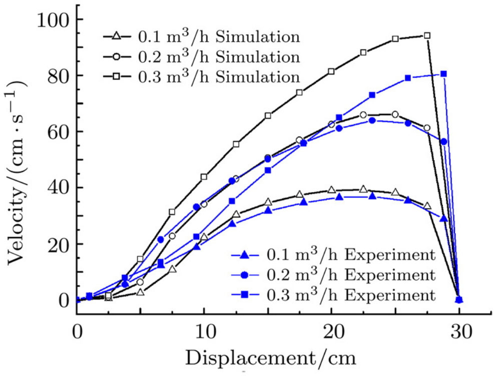


Fig. 3. Deployment velocities with different inflation gas velocities.

With the increase of gas, the cross section at fold line will enlarged, so more gas pass to part B of membrane boom, and increase the gas pressure in part B, as shown in Figs. 2(d)–2(f). Due to the resist of fold line, the pressure of part A will increase firstly, and the pressure in part B increased sequentially. With the increase of gas, the inner gas pressure will increase sharply, along with the movement and deformation of boom wall, Figs. 2(d)–2(f) show that the gas pressure in part A is much higher than in part B. Due to the increase of gas, the contact force of membrane boom wall around the fold line and the reaction force at the boundary will change, which drive the movement of membrane boom, as shown in Figs. 2(g) and 2(h). Because the whole membrane boom is enclosed and linked, the gas pressure in part A and part B equal to each other.

Based on the resistance theory of fluid motion, there is a local resistance in the folded angle. The partial loss is proportional to the gas flow rate, and the gas velocity through the folded hole is significantly less than the inlet gas velocity. Gas flow rate is connected with the geometric cross-sectional area of the hole, which is characterized by changes from the initial gap of 1 mm wide to circular cross section at the last.[11] For the gas pressure changes at the folded angle region, because there is a sudden change at the boom section of the folded angle, some gas molecules return to sport after the collision, the other part of the gas molecules pass through the gap into Part B. There are changes of the gas flow and the direction of speed, so the gas pressure near the folded angle increases in Part A, as shown in Fig. 2(d). This also shows that before the gas pressures in Part A and Part B are the same, pressure of Part A is greater than that of Part B. When the input flow rate is constant, the gas mass in Part A and Part B increase, and the pressure also increase. If the non-inflating end is enclosing, the internal pressure to increase makes the contact force at the folded angle to increase, and then the non-inflating end causes movement. The hole at the folded angle began to expand, and the partial loss also reduces. The mass of gas through the hole into part B increases in the unit time, the pressure in both parts tend fast to accordance. If the non-inflating end is not closed, when the laminar flow of the gas is fully developed, the cross-section of the hole basically remains unchanged.

In conclusion, the gas that inflated into the membrane boom can be divided into two phases: the free flow phase and the cumulative phase. In the first phase, that is at the initial position and when the fold line is open up, the gas can flow freely, so the gas pressure decreases rapidly. In the second phase, that is when gas reach the fold line and when gas reach the enclosed end of part B, the flow of gas was constrained, and the gas pressure will increase sharply, and due to the constraint of volume, the velocity slow down at the end.

In this paper, the deployment process of membrane boom was studied at different inflation gas velocity, the gas velocity were 0.1, 0.2 and 0.3 m^3/h respectively, all results were listed in Fig. 3. According to this figure, the larger inflating gas velocity, the higher motion velocity of membrane boom in the whole process of deployment. Under constant gas inflation velocity, the moving velocity of membrane boom ascend gradually, and reach its maximum point when the folding line fully unfolded, then decrease sharply to zero when membrane boom in straight state. Numerical simulation results show that, the inflation gas velocity affects the deploying velocity of v-shaped membrane boom. The higher moving velocity of membrane boom results in the bigger counter-back impact force.

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 boom 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.[10] The experimental data show that these deployment velocities of the folded booms are consistent with the simulation of the same model (in Fig. 3).

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 boom. 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. As the gap around the fold line enlarged, more gas from part A flow to part B, so the inner gas pressure of part A will reduce consequently. With the increase of gas, the pressure rebound back mildly at the end.

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1. Z. Li, X. L. Jin, and W. G. Qi, Computational Mechanics **24**, 727 (2007).
2. S. E. Ray, G. P wren, and T. E. Teaduyar, Parallel Computing **23**, 1279 (1998).
3. J. Z. Wei, H. F. Tan, and X. W. Du, Advances in Mechanics **38**, 177 (2008).
4. M. Souli, A. Ouchsine, and L. Lewin, Computer Methods in Applied Mechanics and Engineering **190**, 659 (2000).
5. F. Li, L. Y. Sun, and G. Y. Zhang, et al., Journal of Beijing University of Aeronautics and Astronautics **33**, 1117 (2007).
6. W. K. Liu, T. Belytschko, and H. Chang, Computer Methods in Applied Mechanics and Engineering **58**, 227 (1986).
7. Z. Li, X. L. Jin, and J. Shen, Journal of Shanghai Jiaotong University **41**, 19 (2007).
8. L. Olovsson, L. Nilsson, and K. Simonsson, Computers and Structures **72**, 497 (1999).
9. Z. Li, X. L. Jin, and X. D. Chen, Journal of Vibration and Shock **26**, 72 (2007).
10. J. Z. Wei, H. F. Tan, and C. Q. Miao, et al., Chinese Journal of Theoretical and Applied Mechanics **43**, 201 (2011).
11. X. F. Liu, X. W. Du, and Z. M. Wan, Engineering Mechanics **22**, 225 (2005).