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Dynamic deployment simulations of inflatable space structures

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Abstract

The feasibility of using Control Volume (CV) method and the Arbitrary Lagrangian Eulerian (ALE) method in LS-DYNA to simulate the dynamic deployment of inflatable space structures is investigated. The CV and ALE methods were used to predict the inflation deployments of three folded tube configurations. The CV method was found to be a simple and computationally efficient method that may be adequate for modeling slow inflation deployment sine the inertia of the inflation gas can be neglected. The ALE method was found to be very computationally intensive since it involves the solving of three conservative equations of fluid as well as dealing with complex fluid structure interactions.

1 Introduction

Inflatable space structures have become very attractive because they are suitable for many space applications at low cost. An inflatable structure can be folded to fit into the shroud of a small launch vehicle and can be deployed in space by a small amount of inflation gas. Recently NASA and DoD have sponsored many inflatable space structure programs to develop large solar panels, solar sails, aerocapture and aeroentry structures, antennas, and living quarters for astronauts.

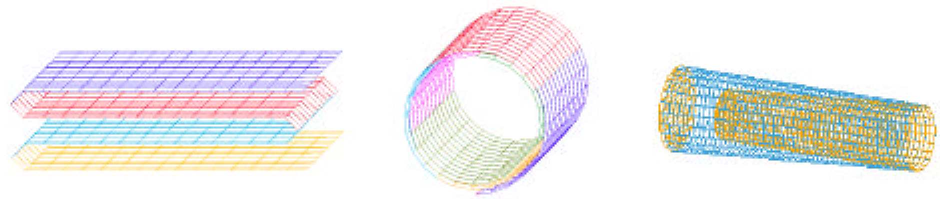
During an inflation deployment, components within a folded large space structure can become tangled, or parts of the inflatable structure can be overstressed due to excessive inflation pressure. Unfortunately, testing prototypes in space is prohibitively expensive. Testing on the ground may not be representative of the space environment because the deployment dynamics and the final deployed shape can be affected by the presence of gravity, temperature, or air. Thus, it is highly desirable to have robust computational methods that can simulate accurately the deployment of inflatable structures.

The objective of this study is to investigate the feasibility of using the Control Volume (CV) method and the Arbitrary Lagrangian and Eulerian (ALE) method in LS-DYNA for simulating the deployment of inflatable space structures. Inflation deployment simulations of thin wall tubes representing the folded solar-sail booms are performed. The CV method is used to simulate the deployment of three folded tube models shown in Figure 1, including Z-folded, coiled, and telescopically-folded configurations. The ALE method is used to simulate the telescopically-folded configuration. Deployment characteristics predicted by both methods are presented, and the computational issues related to each method for future research efforts are discussed.

2 Two inflation deployment simulation methods

The two dynamic inflation deployment simulation methods are presented in this section. Equations pertinent to both methods obtained from published literature are given herein, such as Salama et al. [1], Hallquist [2], Wang [3], Belytschko et al. [4], and Donea et al. [5].

2.1 The CV method: This method assumes that a folded inflatable structure can be divided into many connected



(a) Z-folded model (b) Coiled model (c) Telescopically-folded model

Figure 1: Three folded tube models

control volumes, and that pressure is uniformly distributed within each control volume, Hallquist [2]. The inflation gas can flow among connected control volumes. During inflation deployment, the incremental volume change for a CV depends on the net inflow-mass rate, the equation of state for the gas, and the dynamics of the membrane structure bounding the CV. Assuming all variables are known at time $t-\Delta t$, an approximation of the internal energy $E(t)$, in the CV at time t is given by

$$E(t) = E(t-\Delta t) + c_p \dot{m}(t)\Delta t T_{in} \tag{1}$$

where c_p is the specific heat at constant pressure, Δt is the time step, T_{in} is the inflation gas temperature, and $\dot{m}(t)$ is the mass flow rate of the inflation gas.

According to the equation of state for an ideal gas, the pressure $p(t)$, is calculated as,

$$p(t) = (k-1)\,r(t)\frac{E(t)}{m(t)} \tag{2}$$

where k is the ratio of the specific heat at constant pressure to the specific heat at constant volume. The pressure is used as input to the finite element analysis to determine the structural onfiguration at time t. The equations of motion of the inflatable structure can be solved by the explicit method to determine the deformed shape of the inflatable structure at time t.

The work performed by the volume expansion reduces the internal energy. Therefore, a modified internal energy, $E(t)*$, for next time increment can be obtained according to the internal energy evolution equation,

$$E(t)^* = E(t)\left[\frac{V(t)}{V(t-\Delta t)}\right]^{1-k} \tag{3}$$

where $V(t)$ is the volume at time t.

2.2 The ALE method: The Arbitrary Lagrangian Eulerian [ALE] finite element method is suitable for solving transient, nonlinear fluid-structure interaction problems, see Belytschko et al. [4] and Donea et al. [5]. The ALE method possesses both Eulerian and Lagrangian features to generalize the kinematical descriptions of the fluid domain. Hence, the ALE method can address the shortcomings of purely Lagrangian and purely Eulerian descriptions. These shortcomings include mesh distortion problems if the Lagrangian description is used to model the fluid, and complexity in handling fluid-structure coupling for the Eulerian description. As shown in Figure 2, the ALE method contains three domains, namely the material domain, the spatial domain, and the ALE domain.

In the ALE method, both the motions of the mesh and the material must be described, as in Belytschko et al. [4]. The function, $x = f(X,t)$, maps the body from the initial configuration to the current or spatial configuration. The function, $x = \hat{f}(c,t)$, maps the point at c in the ALE domain to the location x in the spatial domain. Here, c is used to define the ALE coordinates. In most cases, the initial spatial, ALE, and material domains are collocated, $f(X,0) = c(X,0) = X$. The ALE domain is used to describe the motion of the mesh and is independent of the motion of the material. The ALE domain is also used to construct the initial mesh. It remains coincident with the mesh throughout the computation, so it is also considered as the computational domain.

In the ALE method, the inflation gas is considered as an inviscid compressible fluid. Three conservation equations and an equation of state are solved. The three conservation equations are expressed in the ALE frame as

$$\frac{\partial r}{\partial t}\Big|_c = -r\frac{\partial v_i}{\partial x_i} - c_i\frac{\partial r}{\partial x_i},$$

$$r\frac{\partial v_i}{\partial t}\Big|_c = \left(\frac{\partial p}{\partial x_i} + rb_i\right) - rc_j\frac{\partial v_i}{\partial x_j}, \qquad (4)$$

$$r\frac{\partial e}{\partial t}\Big|_c = \left(p\frac{\partial v_i}{\partial x_i} + rb_iv_i\right) - rc_j\frac{\partial e}{\partial x_j}$$

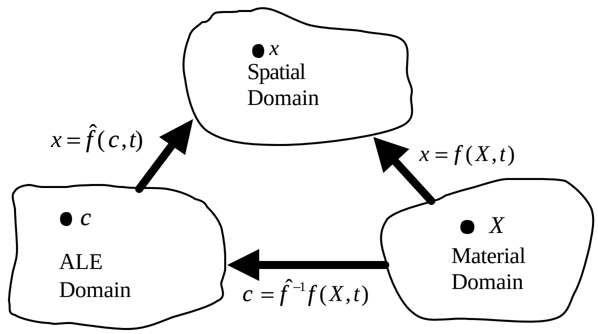


Figure 2: ALE Method containing three domains

where $c_i = v_i - w_i$. In this expression, r is the fluid density, v_i is the fluid velocity, w_i is the mesh velocity, b_i is the body force in the i-direction, e is the total specific energy, and p is the pressure defined by an equation of state. If w_i is set to zero, Equation 4 becomes a pure Eulerian formulation. On the other hand, if c_i is set to be zero, it becomes a pure Lagrangian formulation.

These partial differential equations given above, as well as the equations of motion of the inflatable tube, are then discretized using finite element modeling methods and solved by the explicit method. The fluid and structure interactions are achieved by coupling the Lagrangian shell elements (Slave) to Eulerian or ALE fluid elements (Master) using constraint-based or penalty-based methods.

3 Inflation deployment examples

3.1 Deployment simulations by the CV method: The CV method was used to simulate the deployment of the three folded tube models shown in Figure 1. The ambient pressure outside each tube model is set near zero to represent the space environment. Each inflatable structure was divided into many separated volumes, namely control volumes (CVs), and the pressure within each CV was assumed to be uniformly distributed. The incremental volume change during a time step for a CV depends on the net inflow-mass rate, the equation of state for the gas, and the dynamics of the membrane structure bounding the CV. The exchange of gas among CVs is based on either an artificial orifice model or on a pressure differential model, Hallquist [2]. Deployment simulations, using the CV method, for a coiled tube and a Z-folded tube are shown in Figures 3 and 4, respectively. The deployment simulations of the telescopically-folded tube are very similar to those predicted by the ALE method shown in Figure 5.

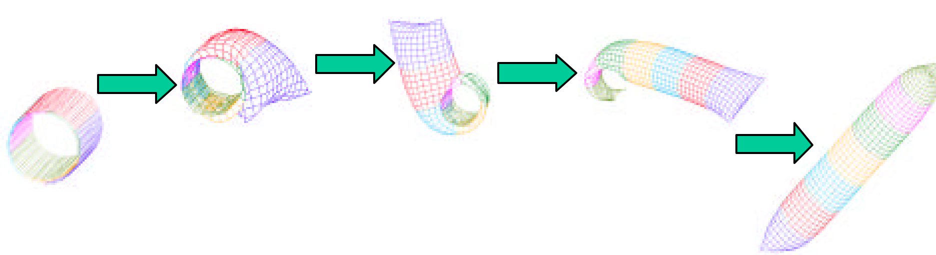


Figure 3: CV deployment simulations of coiled tube

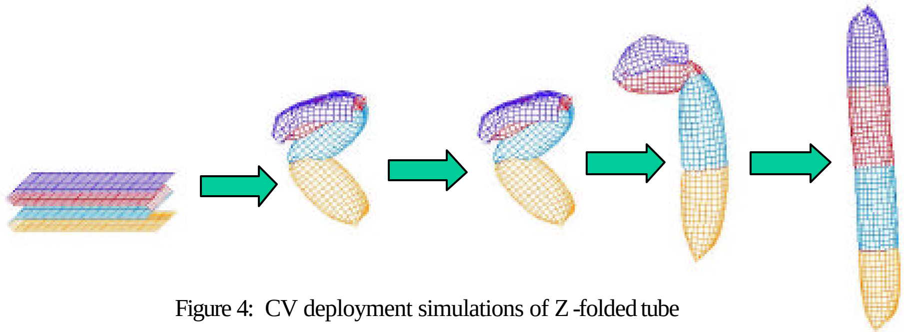


Figure 4: CV deployment simulations of Z-folded tube

3.2 Deployment simulations by the ALE method: A rapid inflation deployment can be more accurately represented as a fluid structure interaction in which the momentum of the fluid is also considered. An ALE model for simulating the inflation deployment of the telescopically-folded tube is shown in Figure 5. This model contains an ALE mesh for modeling the fluid propagation and a Lagrangian mesh for modeling the folded tube structure. Note that the gas injector is modeled as part of the ALE mesh. The initial pressure of the ALE elements, not including the injector, is set to near zero for representing the space environment. The deployment simulations of the telescopically-folded tube are shown in the lower part of Figure 5. Unlike the CV method, the pressure distribution within the tube can be predicted and any excessive high pressure locations can be identified.

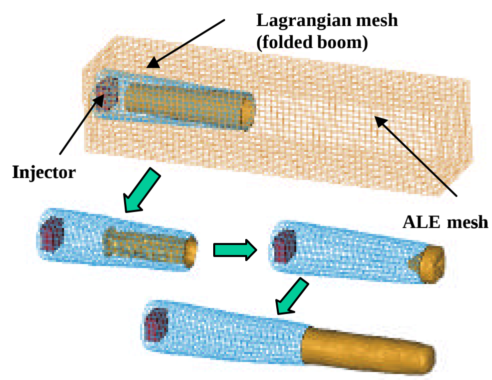


Figure 5: ALE deployment simulations of telescopically folded tube

4 Concluding remarks

The CV and ALE methods were found to be suitable tools for dynamic inflation deployment simulations of space structures. The CV method is a simple and computationally efficient method that may be adequate for modeling slow inflation deployment since the inertia of the inflation gas can be neglected. The ALE method is very computationally intensive since it involves the solving of three conservative equations of fluid as well as the dealing with complex fluid structure interactions. More robust fluid structure interaction methods are needed for addressing this computational intensive issue.

5 References

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