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Comparative finite element and experimental analysis of a quasi-static inflation of a thin deployable membrane space structure

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ABSTRACT

The deployment of a thin, one-segment, large membrane space structure is examined by the means of a real time quasi-static inflation experiment with photogrammetry and finite element analysis with the explicit and implicit schemes applied to control volume, corpuscular and arbitrary Lagrangian-Eulerian inflation methods. The numerical solutions comparison is based on mesh size, energy ratio, number of particles, bleed-through leak coefficient, fluid pressure - surface depth stiffness coupling, accuracy and computational efficiency. An optimization of the number of particles and minimization of the bleed-through effects is effectively implemented in corpuscular and ALE approaches. The corpuscular and arbitrary Lagrangian-Eulerian are found to be most resembling the experimental results in the dynamic shape changes and the time history of the gas properties, but computationally expensive. The control volume, although computationally efficient, is lacking the adequate fluid-structure interaction, thus less accurately recreating the overall dynamics of the morphing surface. Only 0.2%–1.75% and 0.5%–2.5% difference is observed between the experimental, analytical and finite element inflation results respectively.

1. Introduction

Lightweight and thin membrane inflatable structures representing an emerging structural type in future space exploration endeavors have acquired popularity because they can fulfill structural requirements of a stationary space application and also provide fast deployment and inflation at a relatively low mass and cost. Inflatable space structures are complex assemblies of pressurized parts/segments made from flexible, durable and lightweight materials such as fabrics that behave like thin membranes during the deployment and inflation. The ability to control the deployment, inflation and an aerodynamic response of these assemblies requires not only the prediction of the material behavior in a complex and environmentally challenging setting, but also proper modeling of gas flow, fluid-structure interaction with the resulting final inflated shape. The deployment, inflation and stationary behaviors of relatively complex inflatable structures are typically predicted numerically using finite element analysis (*FEA*). As input, these numerical methods require fabric strength, constituent material coefficients, density, damping, potential for buckling-wrinkling deformation under continuously changing dynamic and thermal environments and a numerical scheme that can accommodate/discretize gas flow, fluid-membrane interaction and produces accurately inflated structure. The deployment and inflation testing of various inflatable prototypes in space can be extremely expensive and time consuming. In addition, the deployment and inflation in laboratory settings does not always accurately replicate all the physical phenomena that are present in space. Therefore, experimental data obtained from physical testing should be backed with numerical prediction of the interaction of the inflatable structure with the inflation gasses and the surrounding environment. Such a complex simulations of dynamically behaving thin membrane structures can be conducted with the utilization of several computational approaches like control volume (*CV*), corpuscular (*CP*) and the arbitrary Lagrangian-Eulerian (*ALE*) that are available in the Ls-DYNA® program.

While there has been a great effort in modeling of the deployment and impact kinematics of small inflatables such as airbags, the literature related to numerical modeling and experimental evaluation of larger inflatable structures is quite limited. Relatively, not much work has been devoted to the development of computational models and various

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inflation methods that can be used to predict the deployment and inflation behavior of large and highly complex space structures [1]. The simulations of deployment and inflation of small and large thin membrane structures are of interest to many researchers in automotive and aerospace industries [2]. The reproduction of the deployment of an airbag was first conducted with an explicit time-stepping *FEA* scheme to show the complex, non-linear behavior due to the continuously changing surface boundary and contact conditions. Wang and Nefske [3] first approximated the time-dependent pressure, temperature and density in the inflatable with the uniform pressure method. This method set the foundation for the development of the *CV* approach utilized in Ls-DYNA® [4] and Pam-Crash® [5]. Salama et al. [6] when researching foldable inflatable cylindrical tubes used the *CV* method. A simplified finite element model allowed for the discretization of gas flow, pressure variations and the resulting nonlinear deformation throughout the inflatable structure. Steele et al. [7] utilized approximate analysis to investigate the gradual unrolling process of the coiled tube. Haug et al. [8] used the *CV* approach while investigating a rigidizable, two chamber folded space antenna structures and validated the results with benchmark tests. An improvement to the gas flow simulation and its interaction with the membrane structure was introduced with the corpuscular method. Since its early development by Olovsson [9], it has gained popularity in the modeling of inflatables. Lian [10] conducted a comparative study of several types of inflatable structures and showed the functionality of the kinetic gas theory in the *CP* approach. Hirth et al. [11] conducted a comparative inflation study that investigated the *CP* method and its effectiveness dependent on the number of gas particles. An improvement in the simulation of the interaction between the moving gases and the membrane structure can be accomplished with the *ALE* approach [12]. This method allows for not only the inclusion of the gas inertia, but also the prediction of the transient fluid properties at any location inside the inflatable. A transient, finite element formulation were developed by Hughes et al. [13] for incompressible viscous flows in an arbitrarily mixed Lagrangian-Eulerian description that are appropriate for modeling the fluid sub-domain of many fluid-solid interactions present in inflatable structures. Similarly, Donea et al. [14] validated a finite element model for the prediction of a non-linear response of fluid-structure interactions due to dynamic loading. Marklund et al. [15] used the coupled fluid-structure interaction during the inflation of airbags. The coupling of the inflation gas and the surface of the inflated airbag was examined by Haufe et al. [16] who used the standard inflation procedures based on uniform pressure inside the inflatable. Breukels et al. [17] used a multi-body dynamics approach to simulate a complex tubular inflatable structure to determine a comparable dynamic response to the one from the numerical analysis. Although a very efficient approach, it did not account for the fluid-structure interaction and the results were simplified.

The purpose of this study is to present a cross-comparative summary of the finite element and experimental inflation methodologies applied to a large, thin, and light (*ss-c-ss*) semi-spherical/cylindrical/semi-spherical deployable space structure. The three (*CV*, *CP*, *ALE*) inflation approaches that utilize explicit and implicit solution schemes are examined based on the characteristics of the gas flow, the dynamics of the fluid-structure interaction and the computational efficiency. For an accurate, effective, efficient and experiment resembling simulation to occur several essential parameters must be set. The minimization of the energy ratio, optimization of the single mesh-inflatable area ratio, adjustment of the fluid-flow control and the reduction of the bleed through losses are the major improvements made to the *CV*, *CP* and *ALE* inflation models. The resulting internal gas properties, kinematics of the morphing surface's shape, stress-strain state as well as area and volume predicted by these methods are analyzed and compared with the experimental pressure, temperature and membrane's photogrammetry surface data. The advantages and drawbacks are followed by useful recommendations for future work involving modeling, simulation and analysis of light and large inflatable structures.

2. Numerical methodology of *CV*, *CP* and *ALE* inflation

The analysis of the deployable structure quasi-static inflation is conducted with the *FEA* based on either implicit scheme or explicit time-stepping approach that is suitable for geometrically complex, nonlinear models with various contact and boundary conditions of either flat or compactly folded inflatable structures. The theoretical and numerical background, advantages and disadvantages of the *CV*, *CP* and *ALE* approaches are discussed in this section.

2.1. Control volume method

The most direct approach for fluid discretization inside the inflatable structure would be to use expanding solid elements, expressing the real-time pressure-volume relationship within the structure by summing all of the contributions. However, in case of a large volume this approach is computationally prohibitive in real time inflation steps. The simpler and less computationally pressing method, which gives a good approximation of the state of the gases inside the continuously expanding inflatable structure, is the *CV* approach [18] with the gradual increase of the volume shown in Fig. 1a. Here, as the air flows at the rate $\dot{m}$ with the temperature T into the inflatable structure the $P_i \dots P_f$, $T_i \dots T_f$, $m_i \dots m_f$, $V_i \dots V_f$ and $A_i \dots A_f$ are pressure, temperature, accumulated mass, volume and surface area of the inflatable at gradually inflated states at times $t_i \dots t_f$. The P_a and T_a define the atmospheric air. If a leak is modeled (not a subject of this work), then the $\dot{m}_i^v$, $\dot{m}_i^p$ and $\dot{m}_i^d$ are the mass flow rates out of the inflatable due to venting, porosity or damage at each time step $t_i \dots t_f$. Depending on the equation of the state for the gas, the net mass flow rate and the dynamics of the membrane at each time step t_i, the volume V_i is calculated with the Gaussian integral which sums all the surface elements, relating the average coordinate $\overline{\psi}_e$, direction cosine n_{ψ_e} to the element surface area A_e.

Considering the ideal gas law, and the adiabatic inflation process the internal energy E_i at each time step t_i is determined by Eq. (1)

$$E(t_i) = E(t_i - \delta_{t_i}) + C_P \cdot \dot{m}(t_i) \cdot \delta_{t_i} T(t_i) \tag{1}$$

where the δ_{t_i} is the time increment, C_P is the specific heat of the gas at a constant pressure, $\dot{m}(t_i)$ and $T(t_i)$ are the mass flow rate and the temperature of the incoming gas. The density at each time step t_i is calculated with Eq. (2)

$$\rho(t_i) = \frac{[m(t_i - \delta_{t_i}) + \dot{m}(t_i) \cdot \delta_{t_i}]}{V(t_i - \delta_{t_i})} \tag{2}$$

with V being a volume at time $t_i - \delta_{t_i}$. Next, the pressure is calculated with the utilization of the ideal gas state with Eq. (3)

$$P(t_i) = \left(\frac{C_P}{C_V} - 1\right)\left[\frac{m(t_i - \delta_{t_i}) + \dot{m}(t_i)\delta_{t_i}}{V(t_i - \delta_{t_i})}\right]\left[\frac{E(t_i - \delta_{t_i}) + C_P \dot{m}(t_i)\delta_{t_i} T(t_i)}{m(t_i)}\right] \tag{3}$$

The pressures are then used in the set of equations of motion at each time step t_i specified by Eq. (4)

$$[M]_{t_i}\{\ddot{D}\}_{t_i} + [C]_{t_i}\{\dot{D}\}_{t_i} + [K]_{t_i}\{D\}_{t_i} = \{L^{EXT}\}_{t_i} \tag{4}$$

where $[M]$, $[C]$, $[K]$ are the global matrices for mass, damping and stiffness. The $\{\ddot{D}\}$, $\{\dot{D}\}$, $\{D\}$ are the vectors of acceleration, velocity and displacement. The $\{L^{EXT}\}$ is the external load vector that represents pressure, impulse or other force like gravity. This set of equations is solved explicitly utilizing the central difference scheme of Eq. (4) for vectors $\{\ddot{D}\}$, $\{\dot{D}\}$, $\{D\}$ producing the changes in the structure at each time t_i. Another solution scheme employed by the *CV* method is to use Eq. (5) supplemented by the internal load vector $\{L^{INT}\}$ and solve it implicitly in static or dynamic solver for the $\{\ddot{D}\}$, $\{\dot{D}\}$, $\{D\}$.