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On the verification and validation of a spring fabric for modeling parachute inflation

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ABSTRACT

A mesoscale spring–mass model is used to mimic fabric surface motion. Through coupling with an incompressible fluid solver, the spring–mass model is applied to the simulation of the dynamic phenomenon of parachute inflation. A presentation of a verification and validation efforts is included. The present model is shown to be numerically convergent under the constraints that the summation of point masses is constant and that both the tensile stiffness and the angular stiffness of the spring conform with the material's Young modulus and Poisson ratio. Complex validation simulations conclude the effort via drag force comparisons with experiments.

1. Introduction

The thinness and lack of bending stiffness of canopy-like structures, such as parachutes, introduces a separation in scales of local and global curvature, contact interactions, and two-sided fluid–structure interactions. Due to these complexities, parachute modeling and simulation has traditionally been empirical in nature. Realistic and accurate analysis requires sophisticated techniques in fluid–structure interaction (FSI) including computational fluid dynamics (CFD) and computational structure dynamics (CSD). Unfortunately these tools are not currently used to design aerodynamic deceleration systems due to the computational resources required and the lack of validation of physics-based modeling efforts. However, the computational platform based on the front tracking method (Glimm et al., 2000; Du et al., 2006) and the software library *FronTier* (Fix et al., 2005; Glimm et al., 2007), with intelligent data structures and functionalities for geometrical and topological evolution as well as the ability to handle the interaction between the moving interface and the fluid (both incompressible and compressible) lends itself to fill these voids.

The authors' previous studies of Kim et al. (2013) and Li et al. (2013) discuss the application of the mesoscale model in effects to mimic the dynamic motion of a fabric surface while coupled with an incompressible fluid solver for parachute inflating and descending. The numerical simulations demonstrated good agreement with the experimental results both qualitatively and quantitatively, but questions remain on the validity of the model and its relation to the continuum model of the fabric surface as an elastic membrane. Van Gelder (1998) argued that the simple spring–mass model cannot be related to the continuum model for the linear elastic membrane and therefore not suitable to represent the fabric surface. However, recently, Delingette (2008) proposed a revision of the spring–mass model that includes the angular deformation energy where the force at each triangle vertex includes spring forces through both its adjacent and opposite sides. This spring–mass model originates from the discretization of a St Venant

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Kirchhoff membrane on a linear triangle element. Delingette demonstrated that with this modification, the force in the spring model is indeed related to the strain and stress of the elastic membrane. For small displacements, as mentioned in Delingette (2008), the behavior of the membrane matches exactly with that of the linear elastic material, which is verified numerically in this paper. We will demonstrate that the difference between the spring–mass model used in our previous studies and Delingette model can be bridged by a re-interpretation of the spring constant and by adding additional forces contributed by the opposite sides of the vertex. We will show that the spring–mass model is numerically convergent under the constraints that the total mass is conserved and that both the tensile stiffness and the angular stiffness of the spring conform with the material's Young modulus and Poisson ratio. In addition, we will present an algorithm to compute the von-Mises stress of a fabric surface under strain.

The objective of this work is to employ the Delingette-modified spring–mass model in the simulation of parachute inflation, which was also studied in our previous work (Kim et al., 2013) focusing upon the steady drag and velocity during the terminal descent stage and the dependency of these variables on the parachute geometry, dimension, and payload. In contrast to terminal descent, parachute inflation has a relatively short time duration, typically a few seconds. However, this short period regime is paramount to the effectiveness of the deceleration system and modeling it accurately with physics-based tools is difficult. Any malfunction, such as inversion, barber's pole, or jumper-in-tow, happens in this short stage could have serious effect on the fate of the personnel and cargo delivery.

Parachute inflation is a complex aeroelastic phenomenon that involves complex aerodynamics and elastic structures. The fact that the flow field and the canopy's geometric shape are interactive makes the inflation process a very difficult event to model (Peterson, 1993). Researchers have studied parachute inflation with different methods including empirical analysis (Potvin, 1998), semi-numerical simulation (Potvin et al., 2011), and through experiments (Potvin et al., 2011; Potvin and McQuilling, 2011). During the inflation sequence, the canopy not only experiences extreme increase in internal volume and large loading, but also involves geometric and material nonlinearities which make it a highly challenging event to model from a dynamic structures perspective (Cochrane et al., 2010). Parachute inflation consists of a sequence of dynamically animated stages. These stages have been summarized in Yu and Ming (2007) and Hamid and Desabrais (2002). For example, during the inflation of a circular parachute, the canopy starts as a vertical tube with an open lower end. With very little drag, air quickly rushes into the canopy tube due to the fast descending velocity of the system. Due to the limited volume inside the canopy, the pressure at the apex point increases dramatically leading to a large pressure difference between the internal and the external sides of the canopy. Meanwhile, the continued accumulation of air inside the canopy (inflation) results in the expansion both vertically and horizontally. The duration of the inflation process depends on the orientation of the parachute to the oncoming flow, altitude, and flight speed and ends when a sufficient amount of high pressure air fills the canopy. The aerodynamic forces that act in opposite directions along the parachute determine its steady-state shape and the final shape of the recirculating region (air bubble) inside (Potvin, 1998). In addition, the presence of the intense flow separation outside the canopy, the strong turbulence near the edge of parachute canopy and the narrow space inside the canopy before it is fully inflated result in computational challenges from the CFD perspective (Yihua et al., 2010).

2. Improvement of mathematical model

The original spring model (Li et al., 2013) that serves as the basis for this effort is a simplified mesoscale model which assumes that the force required to bend the surface is negligible and the force to stretch the surface is proportional to the displacement from the equilibrium distance between adjacent mass points. In this model, the kinetic energy and the potential energy of the triangulated mesh are given by

$$T_i = \frac{1}{2} m_i |\dot{\mathbf{X}}_i|^2, \quad V = \frac{1}{4} \sum_{i=1}^{N} \sum_{j=1}^{N} \kappa (|\mathbf{X}_i - \mathbf{X}_j| - l_{ij}^0)^2 \eta_{ij}, \tag{1}$$

where $\mathbf{X}_i$ is the position of the vertex i, κ is the spring constant, l_{ij}^0 is the equilibrium length of the side shared by vertices $\mathbf{X}_i$ and $\mathbf{X}_j$, and η_{ij} is a Boolean variable for adjacency. Applying the Lagrangian equation to $L = T - V$, that is,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_j}\right) - \frac{\partial L}{\partial q_j} = 0, \tag{2}$$

here q_j refer to components of the coordinate, we can obtain the equation of motion for each vertex:

$$m_i \frac{d\dot{\mathbf{X}}_i}{dt} = \mathbf{F}_i, \quad i = 1, 2, \ldots, N, \tag{3}$$

where the force at each vertex point is

$$\mathbf{F}_i = \sum_{j=1}^{N} \eta_{ij} \kappa \left(|\mathbf{X}_i - \mathbf{X}_j| - l_{ij}^0 \right) \mathbf{e}_{ij} = \sum_{j=1}^{N} \eta_{ij} \kappa \, dl_{ij} \mathbf{e}_{ij}, \tag{4}$$

where $\mathbf{e}_{ij}$ is the unit vector from $\mathbf{X}_i$ to $\mathbf{X}_j$, and we have defined $dl_{ij} = |\mathbf{X}_i - \mathbf{X}_j| - l_{ij}^0$ as spring length elongation. Although this model can simulate the dynamic motion of a fabric surface and exert correct tension and wrinkling of the surface, there is a lack of proof on the relation between this model and the continuum model for an elastic membrane. Fig. 1 demonstrates the mesh structure of such mode.