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Simulation of parachute FSI using the front tracking method

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ABSTRACT

We use the front tracking method on a spring system to model the dynamic evolution of parachute canopy and risers. The canopy surface and the riser string chord of a parachute are represented by a triangulated surface mesh with preset equilibrium length on each side of the simplices. The stretching and wrinkling of the canopy and its supporting string chords (risers) are modeled by the spring system. The spring constants of the canopy and the risers are chosen based on the analysis of Young's surface modulus for the canopy fabric and Young's string modulus of the string chord. Damping is added to dissipate the excessive spring internal energy. The current model does not have radial reinforcement cables and has not taken into account the canopy porosity. This mechanical structure is coupled with the incompressible Navier–Stokes solver through the "Impulse Method". We analyzed the numerical stability of the spring system and used this computational module to simulate the flow pattern around a static parachute canopy and the dynamic evolution during the parachute inflation process. The numerical solutions have been compared with the available experimental data and there are good agreements in the terminal descent velocity and breathing frequency of the parachute.

1. Introduction

Simulation of parachute inflation *via* computational method has attracted attention of scientists at Laboratories of Department of Defense and academic alike. Some of the most successful studies include those reported in Stein et al. (1993, 1997, 2000), Stein et al. (2001a,b), and Stein et al. (2003), where the Deforming-Spatial-Domain/Stabilized Space–Time (DSD/SST) method (Tezduyar et al., 1992a,b) was used in Stein et al. (1997, 2000), Stein et al. (2011a,b), and Stein et al. (2003). The studies in Tezduyar et al. (2006, 2008), Takizawa et al. (2011a,b), and Tezduyar et al. (2010) also used the DSD/SST as the core numerical method, but involved new version and special techniques. These studies successfully address the computational challenges in handling the geometric complexities of the parachute canopy and the contact between parachute in a cluster. Kim and Peskin et al. used the immersed boundary method to study the semi-opened parachute in both two and three dimensions (Kim and Peskin, 2006, 2009), their simulations are on small Reynolds number (about 300) and applied payload with several grams. Yu and Ming (2007) studied the transient aerodynamic characteristics of the parachute opening process. Karagiozis used the large-eddie simulation to study the parachute in Mach 2 supersonic flow (Karagiozis et al., 2011). Purvis (1983, 1984) used springs to represent the structures of the forebody, the suspension lines, and the canopy, etc. In these papers, the author used cylindrical coordinate with the center line as the axis. In the paper by Strickland et al. (2003), the authors developed an algorithm called PURL to couple the

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structure dynamics (PRESTO) and fluid mechanics (CURL), in which mass is added to each of the structure node based on the diagonally added mass matrix and a pseudo is computed from the fluid code which is the sum of the actual pressure and the pressure associated with the diagonally added mass. Tutt and Taylor (2005) and Tutt et al. (2011) simulated the parachute through the LS-DYNA code. They used an Eulerian–Lagrangian penalty coupling algorithm and multi-material ALE capabilities with LS-DYNA to replicate the inflation of small round canopies in a water tunnel.

In this paper, we report a computational study of parachute inflation through application of the front tracking method, a method which has been successfully applied to many other problems in physics and engineering (Dutta et al., 2003; Glimm et al., 2005; Lim et al., 2008; Samulyak et al., 2008). The front tracking method has been coded in a software library named *FronTier*. We modify the data structure to allow the application of the *FronTier* library to the dynamic motion of fabric surface driven by the gravitational force of payload and the fluid pressure. We discretize the fabric surface in a homogeneously triangulated surface mesh. One of the most important properties of a fabric surface is that such a surface has finite stretchability. This property is mathematically realized by modeling the surface as a spring system using the vertices as mass points and the triangle sides as springs. A finite friction force is added to dissipate the spring internal energy and to prevent over-excitation of the system. The spring system is coupled with a finite difference solver for the incompressible Navier–Stokes equation. Our simulations extend to the field range of parachute dimensions and are compared with the realistic payload of certain types of parachutes.

In Section 3, we will introduce the numerical method in detail and discuss some of the major modifications we have made to both the *FronTier* functionalities and its coupling with the incompressible fluid solver. Section 3.7 discusses the numerical accuracy and stability in the computation of the spring system. In Section 4, we present several benchmark test cases on the modeling of fabric surface through the front tracking method and in Section 4.2, we report the simulation on dynamic motion of three types of parachutes: the T-10 personnel parachute, the G-11 cargo parachute, and the cross parachute. The mathematical model we used in this paper has certain simplifications. To make a more realistic simulation of the parachute system, some additional physical and numerical components must be added. Section 5 will discuss some of the on-going work and amendment to our current computational method for the parachute system.

2. Mathematical model for the parachute system

Since the focus of this paper is on subsonic parachute, the fluid equation we use to model the air flow as a continuum medium is the incompressible Navier–Stokes equation, which in vector form is

$$\rho \frac{D\mathbf{u}}{Dt} + \nabla p = \mu \nabla^2 \mathbf{u} + \mathbf{g}, \tag{1}$$

where $(D/Dt) = \partial/\partial t + \mathbf{u} \cdot \nabla$ is the partial derivative of the fluid. The incompressibility is described by the divergence-free condition

$$\nabla \cdot \mathbf{u} = 0. \tag{2}$$

For the parachute system, this equation is solved through the projection method (Brown et al., 2001) with special treatment at the canopy surface.

The non-fluid material in the parachute simulation is called the structure component whose motion is governed by the Newton's second law subject to certain internal constraints. Both the canopy surface and the string chords (or the risers) which connect the canopy and the payload are flexible structures and they too, are continuum systems. In many literatures, the motion of the structure is described by the quasi-ordinary equation

$$\rho_i \frac{d^2 \mathbf{x}_i}{dt^2} = \mathbf{f}_i - \nu \frac{d\mathbf{x}_i}{dt} + \nabla \cdot \boldsymbol{\sigma}_\mathbf{i}, \tag{3}$$

where at position $\mathbf{x}_i$, ρ_i is the density, $\mathbf{f}_i$ is the external force density (for example, due to gravity and fluid pressure), $\boldsymbol{\sigma}_\mathbf{i}$ is the stress tensor, and ν is the damping coefficient. In general, all derivatives in Eq. (3) should be considered as partial derivatives. However, very few have attempted to solve Eq. (3) exactly. Like the fluid, discretization of Eq. (3) is also needed.

In the model, we use for this paper, we seek to approximate Eq. (3) through physical intuition, that is, we approximate each discretized element as a mass point while the stress tensor $\boldsymbol{\sigma}_\mathbf{i}$ is approximated by a set of springs connecting to the neighboring points. The spring system has only the restoring force against stretching and compression, therefore it may not exactly describe the structure system, especially when the structure's stress tensor may include restoring force against bending and twisting. Since the structure involved in the parachute study contains only fabric surface and string chord, we believe such approximation is good enough and can capture the most important properties of the structure dynamics in the parachute system. The details of such system will be described in the following section.

To correctly model the parachute system, an accurate coupling between the Navier–Stokes equation and the structure dynamics must be carefully considered near the canopy surface. The method we designed for the simulations in this paper uses the superposition of impulse on every mass point. Each mass point in the spring system acts as an elastic boundary point and exerts an impulse to the fluid in its normal direction. Our algorithm ensures that the action and reaction