Simulation of parachute descent and maneuvers

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Abstract
In computational modeling of parachute descent and maneuvers we use the Deforming-Spatial-Domain/Stabilized Space–Time (DSD/SST) [1] formulation for our flow computations, a Lagrangian finite element formulation for the parachute cable-membrane structural computation [2], and advanced mesh update techniques. We describe our methods for simulation of parachute behavior and address some of the modeling challenges involved. These methods are demonstrated for a simulation involving maneuvers and descent of a round cargo parachute.

1 Introduction
The coupled behavior between a parachute and the surrounding flow field introduce a variety of challenges that must be properly addressed in computational modeling efforts. During operation, the light parachute structure interacts strongly with the surrounding flow field, responding with significant structural dynamics and large shape changes. In this paper we focus on the behavior of a steerable parachute during gliding maneuvers. In particular, we focus on glide performance that can be achieved with a traditional round parachute by deflecting a section of the canopy through riser control. In these operations, parachute fluid-structure interactions (FSI) are amplified due to the forced canopy deflections from the riser control. For example, retraction of a section of the canopy and subsequent response of the parachute causes the parachute to pitch towards the retracted section of the canopy. The pitching of the parachute leads to a gliding descent, which continues as long as the riser control is maintained.

For the parachute application in this paper, operation is at a low speed and, therefore, the aerodynamics is governed by the Navier–Stokes equations for incompressible flows. The parachute is treated as a cable–membrane structure. Parachute FSI during control line maneuvers involve severe canopy shape changes, which must be accounted for in numerical modeling. To accommodate the canopy shape changes and the parachute FSI during the control line maneuver, we use methods that are based on interface-tracking techniques. We use the Deforming-Spatial-Domain/Stabilized Space-Time (DSD/SST) [1] formulation for our flow computations, a Lagrangian finite element formulation for the parachute cable-membrane structural computation [2], along with advanced mesh update techniques. We use a six degree-of-freedom (6-dof) model to simulate the glide behavior of the parachute after the parachute has had time to respond to the riser control operation. In this paper we describe our methods for simulation of parachute FSI behavior and some of the modeling challenges involved. These methods are demonstrated
for a simulation of the maneuver and glide of a round cargo parachute resulting from a riser control operation.

2 Numerical model

2.1 Fluid Dynamics

Computations for the airflow surrounding the parachutes are governed by the Navier–Stokes equations of incompressible fluids. To obtain flow solutions for parachutes that undergo shape changes in time we use the DSD/SST finite element method. This method was introduced in the early 1990's for computations of flow problems with moving boundaries and interfaces and is based on stabilized finite element formulations, which are written over the space–time domains of the fluid mechanics problems considered. Thus, the formulation naturally handles deformations in the spatial domain over time and is well-suited for handling canopy shape changes encountered in parachute applications. As the canopy deforms, the changes in the shape of the spatial domain occupied by the fluid are handled with an automatic mesh update scheme based on the equations of linear elasticity, along with appropriate boundary conditions. Our mesh update consists of moving the mesh in a way that limits element distortion, with full or partial remeshing only when the element distortion becomes excessive.

2.2 Structural Dynamics

Computations for parachute structural dynamics are governed by the linear momentum balance equation for cable–membrane structures. The structure is assumed to experience large displacements and rotations, but small strains and no material damping. Hence, the membranes and cables are treated as Hookean materials with linear properties. Our numerical method is based on a total Lagrangian formulation of the problems, using semi-discrete finite element formulation based on the principle of virtual work.

2.3 Fluid–structure coupling

For FSI involving light structures, structural response can be very sensitive to small changes in the fluid dynamics. In these situations, achieving acceptable levels of convergence in the nonlinear equation systems for the FSI can be difficult. To improve convergence in iterative solution of the coupled, nonlinear equations of fluid and structural mechanics, we use the quasi-direct coupling method [3], which has been shown to be very effective for FSI involving light structures. This approach provides a much tighter fluid–structure coupling than the block-iterative coupling and, therefore, delivers significant improvement in convergence.

In certain situations it may be desirable to model a parachute as a rigid body with the dynamics governed by the force and moment balance equations. This 6-dof approach is more economical than a coupled FSI computation and can be used to simulate parachute glide after the canopy is deflected with a riser control. For the 6-dof simulations presented in the following section we use a block-iterative method for the fluid-object coupling. Here, the parachute is treated as a rigid “object” with the deformed parachute geometry resulting from a preceding FSI computation. The block-iterative coupling technique can be viewed as an approximate Newton–Raphson method, where the fluid–object coupling matrices are ignored in the solution of the linear equation system each Newton–Raphson iteration. Coupling is achieved through the transfer of interface data during the iterations.

3 Simulation of parachute glide with riser controls

FSI and 6-dof computations are carried out to study the glide performance of a G–12 cargo parachute that results from the retraction of two risers, deflecting one half of the canopy. The G–12 is a 64 ft diameter cargo parachute designed to deliver payloads of 2200 lb at descent speeds of 28 ft/s. The G–12 is constructed with 64 suspension lines each 51.2 ft that extend from the canopy to four risers each 10.24 ft. The risers are each connected to 16 suspension lines and merge to a single confluence point, which in turn is connected to four cables each 15.36 ft that hold the payload. The structural model is composed of membranes, cables, and concentrated masses. The canopy is modeled with triangular membrane elements. Linear cable elements are used to model the suspension lines, radial reinforcements along the
canopy, risers, and payload support cables. The payload is modeled with eight concentrated masses that are interconnected with a set of truss elements. Preliminary stand alone computations are carried out to determine the inflated (i.e., prestressed) shape of the G–12 and to obtain a developed flow about the inflated G–12. A preliminary FSI computation is carried out to eliminate any mismatch between the fluid forces and the parachute shape. This solution is used as the initial condition for the simulations presented in this paper, which are carried out in two stages. In the first stage, canopy shape changes and the onset of glide that results from riser retraction are simulated with a FSI computation. In the second stage, glide behavior is simulated with a 6-dof computation. We assume that glide performance is driven primarily by the canopy shape changes that result from the riser retraction, and less by FSI behavior.

The dynamic retraction of the two risers by 3.84 ft in 0.29 s is modeled during a first computation. A second computation continues the FSI with the retracted risers held at 3.84 ft for an additional 0.22 s, allowing the G–12 to respond to the retraction. The shape change for the parachute structure during the FSI of the two-riser retraction is shown in Figure 1. Although the riser retraction and FSI result in significant shape change in the parachute, the resulting pitch and glide of the parachute are just commencing at the end of the FSI computation. However, the pressure field from the FSI provides a horizontal component of aerodynamic force in the direction of anticipated glide (i.e., towards the retracted risers). Pitching and gliding of the parachute become more evident during the following 6-dof computation.

![Figure 1: G–12 geometry prior to (left) and after (right) the two-riser retraction.](image)

The solution at the end of the FSI computation is used as a starting condition for a 6-dof simulation of the gliding performance of the G–12 that results from the riser retraction. Here, motion of the rigid parachute structure is governed by the force and moment balance equation, with forces and moments calculated from the unsteady fluid pressure distribution on the canopy surface. The simulation is carried out for a physical time of approximately 12 s, during which the canopy pitches towards the deflected section of the canopy and transitions to glide. During transition, the canopy pitches forward due to a moment induced by the deflected canopy geometry, eventually pitches beyond equilibrium, and oscillates about the equilibrium (i.e., where the moment is zero). To handle the gliding parachute, mesh motion boundary conditions are imposed such that the outer boundaries of the mesh move with the center of mass of the parachute canopy, assuring that the parachute canopy interface remains centered in the fluid mesh. The trajectory of the payload and the velocity for the center of mass from the 6-dof simulation...
are shown in Figure 2. For our simulations, the two retracted risers are on the $+x$ side of the parachute and induce a preferred glide in the $x$–$z$ plane. Hence, the trajectory plot (left) is displayed in the $x$–$z$ plane, with the understanding that induced motion in the $y$-direction is initially minimal. The trajectory indicates a transition from vertical descent to glide in the $+x$-direction and is shown along with the anticipated trajectory without the maneuver. The components of velocity in the G–12 glide plane are shown (right) for the center of mass. As expected, induced glide is primarily in the $+x$-direction, with the glide speed initially building up as the simulation progresses. It is apparent from the figure that the glide speed and descent speed are of the same order of magnitude during glide performance.

![Figure 2: Trajectory of G–12 payload (left) and velocity of center of mass (right) during 6-dof simulation.](image)

### 4 Concluding remarks

A computational method was described for the simulation of parachute descent and maneuvers for round parachutes. The method uses the Deforming-Spatial-Domain/Stabilized Space–Time (DSD/SST) formulation for flow computations, a Lagrangian finite element formulation for structural computations, along with advanced mesh update methods. Results were presented from FSI and 6-dof computations of gliding behavior of a round cargo parachute. The results demonstrate the value of the methods we developed for this class of parachute applications.

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**References**

