Fluid–Structure Interaction Modeling of Spacecraft Parachutes

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Computer modeling of parachutes involve all the numerical challenges of fluid–structure interaction (FSI) problems. The aerodynamics (fluid mechanics) of the parachute depends on the canopy shape and the deformation (structural mechanics) of the canopy depends on the aerodynamics forces, and the two systems need to be solved in a coupled fashion with proper interface conditions. Because the parachute FSI is in a category of problems where the structure is light (compared to the air masses involved in the parachute dynamics) and very sensitive to changes in the aerodynamics forces, the coupling technique, which determines how the coupling between the equation blocks representing the fluid mechanics, structural mechanics, and mesh moving equations is handled, requires extra care. Spacecraft parachutes are typically very large “ringsail” parachutes that are made of a large number of gores, where a gore is the slice of the canopy between two radial reinforcement cables running from the parachute vent to the skirt. Ringsail parachute gores are constructed from “rings” and “sails,” resulting in a parachute canopy with hundreds of “ring gaps” and “sail slits.” The complexity created by this “geometric porosity” makes FSI modeling inherently challenging.

The core technology used in the parachute FSI computations of the Team for Advanced Flow Simulation and Modeling (T\textsuperscript{★}AFSM) <tafsm.org> is the stabilized space–time FSI (SSTFSI) technique \cite{1}. This core technology is an outcome of the method-evolution process for the T\textsuperscript{★}AFSM parachute FSI computations, which started as early as 1997 with axisymmetric computations and goes as far back as 2000 for 3D computations.

In the early years of parachute modeling with the space–time FSI technique, the coupling between the equation blocks representing the fluid mechanics, structural mechanics, and mesh moving equations was handled with the block-iterative coupling technique (see \cite{1, 2} for the terminology). Later the computations moved to a more robust version of the block-iterative coupling technique that very much increased the coupling stability (see \cite{2}). In 2004 and later, the space–time FSI computations were based on the quasi-direct coupling and direct coupling techniques \cite{1, 2}, which yield more robust algorithms for FSI computations where the structure is light and therefore more sensitive to the variations in the fluid dynamics forces. These techniques are for the general case of nonmatching fluid and structure meshes at the interface, which is what we prefer in parachute computations, but reduce to monolithic techniques when the meshes are matching. Today, the quasi-direct coupling technique is the favored technique in the FSI computations of the T\textsuperscript{★}AFSM.

The Homogenized Modeling of Geometric Porosity (HMGP) was introduced in \cite{3}, and its new version, “HMGP-FG,” was introduced in \cite{4}. The HMGP helps us bypass the intractable complexities of the geometric
\[ u_n = - (k_F)_J \frac{A_E}{A_1} \Delta p - (k_G)_J \frac{A_G}{A_1} \text{sgn}(\Delta p) \frac{|\Delta p|}{p} \]

Figure 1. In the HMGPF-G, the normal velocity crossing the parachute canopy under a pressure differential \( \Delta p \) is modeled by using two homogenized porosity coefficients \((k_F)_J\) and \((k_G)_J\). The two coefficients are calculated from a one-time fluid mechanics only computation with an \( n \)-gore slice of the parachute canopy, where the flow through all the gaps and slits are accounted for. For details, see [3, 4].

Figure 2. The homogenized porosity coefficients \((k_F)_J\) and \((k_G)_J\) have good invariance properties with respect to the shape changes that the gaps and slits go through as the parachute canopy changes shape.

porosity by approximating it with an “equivalent,” locally-varying “homogenized” porosity, which is obtained from an HMGPF computation with an \( n \)-gore slice of the parachute canopy. Figure 1 summarizes the HMGPF-G model and how the two homogenized porosity coefficients of the model are calculated. For details, see [3, 4].

\( A_1 \): Fluid Surface Area  \( A_E \): Fabric Area  \( A_G \): Gap Area
Figure 2 shows that the coefficients have good invariance properties with respect to the shape changes that the gaps and slits go through as the parachute canopy changes shape.

Comparing our computed results to data from drop tests with a base parachute design helps us gain confidence in our parachute FSI model. Figure 3 shows the parachute shape and flow field at an instant during the computation and the comparison with the test data.

<table>
<thead>
<tr>
<th>Test Data</th>
<th>V_D (ft/s)</th>
<th>V_H (ft/s)</th>
<th>T_1 (s)</th>
<th>T_2 (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparable</td>
<td>&lt;10% Diff</td>
<td>&lt;10% Diff</td>
<td>6.7</td>
<td>16.4</td>
</tr>
</tbody>
</table>

* V_D: Descent Speed
* V_H: Relative Horizontal Speed
* T_1: Breathing Period
* T_2: Swinging Period

Figure 3. Parachute shape and flow field at an instant during the computation and comparison with the test data.

With that confidence, we can carry out simulation-based parachute design studies [5], such as evaluating the aerodynamic performance of the parachute as a function of the suspension line length (see Figure 4).

Figure 4. A simulation-based parachute design study, where the objective is to evaluate the aerodynamic performance of the parachute as a function of the suspension line length. See [5] for details of the study.

The contact between the canopies of a spacecraft parachute cluster is a computational challenge that we have addressed recently (see [6]) with a contact algorithm where the objective is to prevent the structural surfaces from coming closer than a minimum distance. The Surface-Edge-Node Contact Tracking (SENC) technique was introduced in [1] for this purpose, in [6] evolved into a conservative version that is more robust,
and is now an essential technology in the parachute cluster computations we carry out. Figure 5 shows a cluster of three parachutes at an instant during the FSI computation, with contact between two of the parachutes.

Figure 5. A cluster of three parachutes at an instant during the FSI computation, with contact between two.

References


