RICE UNIVERSITY

Fluid-Structure Interaction Modeling of the Reefed Stages of the Orion Spacecraft Main Parachutes

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Abstract

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Spacecraft parachutes are typically used in multiple stages, starting with a “reefed” stage where a cable along the parachute skirt constrains the diameter to be less than the diameter in the subsequent stage. After a certain period of time during the descent, the cable is cut and the parachute “disreef” (i.e. expands) to the next stage. Computing the parachute shape at the reefed stage and fluid–structure interaction (FSI) modeling during the disreefing involve computational challenges beyond those we have in FSI modeling of fully-open spacecraft parachutes. These additional challenges are created by the increased geometric complexities and by the rapid changes in the parachute geometry. The computational challenges are further increased because of the added geometric porosity of the latest design, where the “windows” created by the removal of panels and the wider gaps created by the removal of sails compound the geometric and flow complexity. Orion spacecraft main parachutes will have three stages, with computation of the Stage 1 shape and FSI modeling of disreefing from Stage 1 to Stage 2 being the most challenging. We present the special modeling techniques we devised to address the computational challenges and the results from the computations carried out. We also present the methods we devised to calculate for a parachute gore the radius of curvature in the circumferential direction. The
curvature values are intended for quick and simple engineering analysis in estimating the structural stresses.
Acknowledgments

Man has always looked to push his boundaries and conquer the next frontier. In 1903, the airplane changed everything by showing us that we had yet to explore the sky, let alone the stars. I think my curiosity drew me to this unknown and shaped my decision to do research and pursue a career in the last frontier.

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Chapter 1

Introduction

Spacecraft re-entry into the atmosphere poses many challenges. After the crew capsule experiences significant heating, a series of parachute deployments must be perfectly timed. This sequence attempts to reduce overall loading to improve crew and equipment survivability. When this complex task is finished, parachute flight characteristics must also be suitable for a soft landing of the crew vehicle. Some of the material in the rest of this introduction is from [59].

Fluid–structure interaction (FSI) modeling of ringsail spacecraft parachute clusters poses a number of computational challenges [57, 13]. These include the lightness of the parachute canopy compared to the air masses involved in the parachute dynamics, the geometric porosity created by the construction of the canopy from “rings” and “sails” with hundreds of “ring gaps” and “sail slits,” and the contact between the parachutes of the cluster. The Team for Advanced Flow Simulation and Modeling (T★AFSM) has been addressing these computational challenges with the Stabilized Space–Time FSI (SSTFSI) technique [78], which was developed and improved over the years by the T★AFSM and serves as the core numerical technology, and a number of special techniques developed in conjunction with the SSTFSI technique.

The SSTFSI technique originates from the Deforming-Spatial-Domain/Stabilized
ST (DSD/SST) method [66, 72, 74, 68] and its new versions [78, 55, 58]. The DSD/SST formulation is a general-purpose moving-mesh (interface-tracking) method for flows with moving interfaces. Its stabilization parts are the Streamline-Upwind/Petrov-Galerkin (SUPG) [16] and Pressure-Stabilizing/Petrov-Galerkin (PSPG) [66, 75] methods. The DSD/SST method is used with the advanced mesh update methods [73, 64, 28, 67, 78] developed by the T★AFSM. Mesh update includes moving the mesh for as long as possible and remeshing when needed. The ST approach, with higher-order functions in time, gives us more effective ways of mesh moving and remeshing (see [48, 46, 49, 50, 47]). While the Arbitrary Lagrangian–Eulerian (ALE) finite element formulation [27] is the most commonly used moving-mesh approach in FSI computations (see, for example, [33, 88, 4, 31, 15, 3, 23, 5, 7, 17, 11, 10, 6, 8, 25, 32, 9]), the DSD/SST formulation now also has a good record of being applied to some of the most challenging FSI computations (see [78, 85, 57, 42, 58, 56, 13, 12] and references therein).

Parachute FSI computations of the T★AFSM with the DSD/SST method precede the development of the SSTFSI technique and the associated special techniques. These computations started as early as 1997 (see [40]), with 3D computations going as far back as 2000 [29, 36], and with a good number of parachute FSI problems solved (see [65, 37, 41, 39, 38, 80, 83]) before reaching the SSTFSI technique. However, it was the SSTFSI technique, and the special techniques developed in conjunction with it, that brought the parachute FSI computations to a new era in addressing some of the most formidable computational challenges and truly supporting actual parachute design and testing (see [78, 81, 82, 87, 52, 63, 54, 53, 57, 44, 50, 56]).

In an FSI computation with a moving-mesh method, the FSI coupling technique determines how the coupling between the equation blocks representing the fluid mechanics, structural mechanics, and mesh moving equations is handled. The coupling techniques used in the T★AFSM parachute computations evolved from block-iterative
FSI coupling [69] (see [80, 78] for the terminology) used in the computations reported in [29, 36, 65, 37] to a more robust version of block-iterative coupling [69, 80, 83, 70] and to quasi-direct coupling [80, 83] and direct coupling [80, 83] techniques. The quasi-direct and direct coupling techniques, which are applicable to cases with non-matching fluid and structure meshes at the interface, yield more robust algorithms for FSI computations where the structure is light, such as parachute FSI computations. The SSTFSI technique is based on the new versions of the quasi-direct and direct coupling techniques with upgraded and additional interface projection methods [78, 81, 51, 87, 52], has a substantially increased robustness in FSI computations, and rendered the earlier ST FSI solvers obsolete. These new quasi-direct and direct coupling techniques automatically reduce to “monolithic” coupling when the interface has matching fluid and structure meshes. Allowing nonmatching meshes at the interface substantially increases the scope of the FSI solver, leading to success in FSI modeling of challenging problems, such as ringsail spacecraft parachutes (see [81, 82, 87, 52, 63, 54, 53, 57, 44, 50, 56]).

A good number of special FSI techniques were introduced in [78, 81, 51, 87, 52, 63, 54, 53, 44, 50] in conjunction with the SSTFSI technique. These special techniques are mostly in the category of interface projection techniques. They include the FSI Geometric Smoothing Technique (FSI-GST) [78], Separated Stress Projection (SSP) [81, 52], Homogenized Modeling of Geometric Porosity (HMGP) [81], adaptive HMGP [87], “symmetric FSI” method [87], accounting for fluid forces acting on structural components (e.g. parachute suspension lines) that are not expected to influence the flow [87], new versions of the HMGP that are called “HMGP-FG” [52] and “HMGP-FGR” [44], and other interface projection techniques [51]. The special FSI techniques in other categories include the Surface-Edge-Node Contact Tracking (SENCT) technique [78], which is a contact algorithm, multiscale sequentially-coupled FSI techniques [87, 63], rotational-periodicity techniques [52, 63], a new, conservative
version of the SENCT technique [54], computed-data reduction techniques [54, 53], intra-canopy versions of the contact algorithm [44], and using higher-order temporal functions in mesh moving [50].

The ringsail spacecraft parachutes the T★AFSM has been focusing on are very large, made of a large number of gores. A gore is the slice of the canopy between two radial reinforcement cables running from the parachute vent to the skirt. The construction of the canopy from rings and sails happens at the gore level. With the HMGP, we bypass the intractable complexities of the geometric porosity by approximating it at the fluid interface with an “equivalent,” locally-varying “homogenized” porosity. This is obtained from an HMGP computation with an n-gore slice of the parachute canopy where the flow through the ring gaps and sail slits is actually resolved (see [81, 82, 52, 63, 44] for details). In the earlier HMGP computations with a 4-gore slice, slip conditions were applied on the boundaries intersecting the canopy. With the rotational-periodicity techniques, less constraining conditions can be imposed on those boundaries [52, 63].

Spacecraft parachutes are typically used in clusters of two or three parachutes. The computational challenge associated with the contact between the parachutes of a cluster is addressed with the conservative version of the SENCT technique [54], which is also more robust than the original SENCT technique [78]. During the FSI computation, there might also be a contact within a canopy. This could be a contact between the gores of a parachute canopy, or even a contact between the nodes of a gore. These computational challenges are addressed with the intra-canopy versions of the contact algorithm [44].

As an additional computational challenge, the ringsail parachute canopy might, by design, have some of its panels and sails removed. The purpose is to increase the aerodynamic performance of the parachute. In FSI computation of parachutes with such “modified geometric porosity,” the flow through the “windows” created by the
removal of the panels and the wider gaps created by the removal of the sails cannot be accurately modeled with the HMGP and needs to be actually resolved. This and the other computational challenges described in the earlier paragraphs all need to be addressed simultaneously in FSI modeling of clusters of spacecraft parachutes with modified geometric porosity. This is what we have succeeded in doing to a large extent for the computations reported in this paper.

Parachutes are used to slow spacecraft upon re-entry into the atmosphere. They are deployed in multiple stages where a reefing line is used to constrict the parachute’s skirt. While transitioning from one stage to another, the line is cut instantly and the parachute begins to inflate. This process brings many computational challenges that we address with a new fluid-interface model. In addition, we calculate the average curvature for a parachute gore at each of its 13 sails. This computation is critical for NASA analysis because the data cannot be calculated from current drop tests. Finally, we conduct parachute stability tests for a single parachute and a 2-parachute cluster. We introduce a new method of symmetric FSI that enables us to perform this analysis and simulate parachute gliding at specified angles of attack. From this analysis, NASA will be able to better understand parachute behavior when experiencing adverse flight conditions.
Chapter 2

Governing Equations and Core FSI Methods

The material in this chapter is from [50].

2.1 Governing Equations of Fluid Mechanics

Let $\Omega_t \subset \mathbb{R}^{n_{ad}}$ be the spatial domain with boundary $\Gamma_t$ at time $t \in (0, T)$. The subscript $t$ indicates the time-dependence of the domain. The Navier–Stokes equations of incompressible flows are written on $\Omega_t$ and $\forall t \in (0, T)$ as

\begin{align*}
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - f \right) - \nabla \cdot \mathbf{\sigma} &= 0, \\
\nabla \cdot \mathbf{u} &= 0,
\end{align*}

where $\rho$, $\mathbf{u}$ and $f$ are the density, velocity and the external force, respectively. The stress tensor $\mathbf{\sigma}$ is defined as $\mathbf{\sigma} = -p\mathbf{I} + 2\mu\mathbf{\varepsilon}(\mathbf{u})$, with $\mathbf{\varepsilon}(\mathbf{u}) = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$. Here $p$ is the pressure, $\mathbf{I}$ is the identity tensor, $\mu = \rho \nu$ is the viscosity, $\nu$ is the kinematic viscosity, and $\mathbf{\varepsilon}(\mathbf{u})$ is the strain-rate tensor. The essential and natural boundary conditions for Eq. (2.1) are represented as $\mathbf{u} = \mathbf{g}$ on $(\Gamma_t)_g$ and $n \cdot \mathbf{\sigma} = \mathbf{h}$ on
(\Gamma_t)_h, where (\Gamma_t)_g and (\Gamma_t)_h are complementary subsets of the boundary \Gamma_t, n is the unit normal vector, and g and h are given functions. A divergence-free velocity field \( u_0(x) \) is specified as the initial condition.

### 2.2 Governing Equations of Structural Mechanics

Let \( \Omega^s_t \subset \mathbb{R}^{n_{xd}} \) be the spatial domain with boundary \( \Gamma^s_t \), where \( n_{xd} = 3 \) for the continuum element, \( n_{xd} = 2 \) for membranes, and \( n_{xd} = 1 \) for cables. The superscript “\( s \)” indicates the structure. The parts of \( \Gamma^s_t \) corresponding to the essential and natural boundary conditions are represented by \((\Gamma^s_t)_g\) and \((\Gamma^s_t)_h\). The equations of motion are written as

\[
\rho^s \left( \frac{d^2y}{dt^2} + \eta \frac{dy}{dt} - f^s \right) - \nabla \cdot \sigma^s = 0, \tag{2.3}
\]

where \( \rho^s, y, \eta, f^s \) and \( \sigma^s \) are the material density, structural displacement, damping coefficient, external force and the Cauchy stress tensor, respectively. The stresses are expressed in terms of the second Piola–Kirchoff stress tensor \( S \), which is related to the Cauchy stress tensor through a kinematic transformation. For the classes of FSI problems the T★AFSM has been focusing on, what makes one structural element model different from the other is the manner in which \( S \) is defined. These definitions can be found in earlier T★AFSM publications[78, 79, 57].
2.3 Core FSI Methods

2.3.1 DSD/SST Formulation of Fluid Mechanics

A space–time variational formulation of incompressible flows (see for example [66, 72, 74, 68, 78, 55]) is written over a sequence of \( N \) space–time slabs \( Q_n \), where \( Q_n \) is the slice of the space–time domain between the time levels \( t_n \) and \( t_{n+1} \), and \( P_n \) is the lateral boundary of \( Q_n \). We denote the trial and test functions spaces for the velocity and pressure as \( \mathbf{u} \in S_u \), \( p \in S_p \), \( \mathbf{w} \in \mathcal{V}_u \) and \( q \in \mathcal{V}_p \). The notation \((\cdot)_n^-\) and \((\cdot)_n^+\) denotes the function values at \( t_n \) as approached from below and above. At each time step, the integrations are performed over \( Q_n \). The essential and natural boundary conditions are enforced over \((P_n)_g\) and \((P_n)_h\), the complementary subsets of the lateral boundary of the space–time slab. In the DSD/SST method [66, 72, 74, 68, 78, 55], the space–time finite element interpolation functions are continuous within a space–time slab, but discontinuous from one space–time slab to another. Each \( Q_n \) is decomposed into elements \( Q_{n}^e \), where \( e = 1, 2, \ldots, (n_{el})_n \). The subscript \( n \) used with \( n_{el} \) is for the general case where the number of space–time elements may change from one space–time slab to another. The finite-dimensional trial and test functions spaces are denoted as \((S_u^h)_n \), \((S_p^h)_n \), \((\mathcal{V}_u^h)_n \) and \((\mathcal{V}_p^h)_n \).

The DSD/SST formulation (from [68]) is written as follows: given \((\mathbf{u}^h)_n^-\), find \( \mathbf{u}^h \in (S_u^h)_n \) and \( p^h \in (S_p^h)_n \), such that \( \forall \mathbf{w}^h \in (\mathcal{V}_u^h)_n \) and \( \forall q^h \in (\mathcal{V}_p^h)_n \):

\[
\begin{align*}
&\int_{Q_n} \mathbf{w}^h \cdot \rho \left( \frac{\partial \mathbf{u}^h}{\partial t} + \mathbf{u}^h \cdot \nabla \mathbf{u}^h - \mathbf{f}^h \right) dQ + \int_{Q_n} \varepsilon(\mathbf{w}^h) : \mathbf{\sigma}(p^h, \mathbf{u}^h) dQ \\
&- \int_{(P_n)_h} \mathbf{w}^h \cdot \mathbf{h}^h dP + \int_{Q_n} q^h \nabla \cdot \mathbf{u}^h dQ + \int_{\Omega_n} (\mathbf{w}^h)^+ \cdot \rho \left( (\mathbf{u}^h)^+ - (\mathbf{u}^h)_n^- \right) d\Omega \\
&+ \sum_{e=1}^{(n_{el})_n} \int_{Q_{n}^e} \frac{1}{\nu_{SUPG}} \left( \frac{\partial \mathbf{w}^h}{\partial t} + \mathbf{u}^h \cdot \nabla \mathbf{w}^h \right) + \tau_{PSPG} \nabla q^h \cdot \left[ \mathbf{L}(p^h, \mathbf{u}^h) - \rho \mathbf{f}^h \right] dQ \\
&+ \sum_{e=1}^{(n_{el})_n} \nu_{LSIC} \nabla \cdot \mathbf{w}^h \rho \nabla \cdot \mathbf{u}^h dQ = 0,
\end{align*}
\]
where
\[ L(q^h, w^h) = \rho \left( \frac{\partial w^h}{\partial t} + u^h \cdot \nabla w^h \right) - \nabla \cdot \sigma(q^h, w^h). \]  

(2.5)

This formulation is applied to all space–time slabs \( Q_0, Q_1, Q_2, \ldots, Q_{N-1} \), starting with \( (u^h)_0 = u_0 \). Here \( \tau_{\text{SUPG}}, \tau_{\text{PSPG}} \) and \( \nu_{\text{LSIC}} \) are the SUPG, PSPG and LSIC stabilization parameters. There are various ways of defining these parameters. Here we provide the definitions given in [68]:

\[ \tau_{\text{SUPG}} = \left( \frac{1}{\tau_{\text{SUGN12}}^2} + \frac{1}{\tau_{\text{SUGN3}}^2} \right)^{-\frac{1}{2}}, \]  

(2.6)

\[ \tau_{\text{SUGN12}} = \left( \sum_{a=1}^{n_{\text{en}}} \left| \frac{\partial N_a}{\partial t} + u^h \cdot \nabla N_a \right| \right)^{-1}, \]  

(2.7)

\[ \tau_{\text{SUGN3}} = \frac{h_{\text{RGN}}^2}{4\nu}, \]  

(2.8)

\[ h_{\text{RGN}} = 2 \left( \sum_{a=1}^{n_{\text{en}}} |r \cdot \nabla N_a| \right)^{-1}, \hspace{1cm} r = \frac{\nabla \| u^h \|}{\| \nabla \| u^h \| \|}, \]  

(2.9)

\[ \tau_{\text{PSPG}} = \tau_{\text{SUPG}}, \]  

(2.10)

and in [78]:

\[ \nu_{\text{LSIC}} = \tau_{\text{SUPG}} \| u^h - v^h \|^2, \]  

(2.11)

where \( n_{\text{en}} \) is the number of (space–time) element nodes and \( N_a \) is the space–time shape function associated with the space–time node \( a \). As an alternative to the construction of \( \tau_{\text{SUPG}} \) as given by Eqs. (2.6)–(2.7), another option was introduced in [78]. In that option, \( \tau_{\text{SUPG}} \) is constructed based on separate definitions for the
advection-dominated and transient-dominated limits:

\[ \tau_{\text{SUPG}} = \left( \frac{1}{\tau^2_{\text{SUGN1}}} + \frac{1}{\tau^2_{\text{SUGN2}}} + \frac{1}{\tau^2_{\text{SUGN3}}} \right)^{-\frac{1}{2}}, \tag{2.12} \]

\[ \tau_{\text{SUGN1}} = \left( \sum_{n=1}^{N_{\text{en}}} \left| (u^h - v^h) \cdot \nabla N_a \right| \right)^{-1}, \tag{2.13} \]

\[ \tau_{\text{SUGN2}} = \frac{\Delta t}{2}, \tag{2.14} \]

where \( v^h \) is the mesh velocity and \( \Delta t \) is the time-step size. It was noted in [78] that separating \( \tau_{\text{SUGN12}} \) into its advection- and transient-dominated components as given by Eqs. (2.13)–(2.14) is equivalent to excluding the \( \frac{\partial N_a}{\partial t} \bigg|_\xi \) part of \( \frac{\partial N_a}{\partial t} \) in Eq. (2.7), making that the definition for \( \tau_{\text{SUGN1}} \), and accounting for \( \frac{\partial N_a}{\partial t} \bigg|_\xi \) in the definition for \( \tau_{\text{SUGN2}} \) given by Eq. (2.14). Here \( \xi \) is the vector of element coordinates. For more ways of calculating \( \tau_{\text{SUPG}}, \tau_{\text{PSPG}} \) and \( \nu_{\text{LSIC}} \), see [76, 68, 1, 2, 84, 77, 20, 71, 34, 19, 26, 21, 22].

**Remark 1** As an alternative to how the SUPG test function is defined in Eq. (2.4), another option was proposed in [78], where the SUPG test function \( \left( \frac{\partial w^h}{\partial t} + u^h \cdot \nabla w^h \right) \) is replaced with \( (u^h - v^h) \cdot \nabla w^h \). This replacement is equivalent to excluding the \( \frac{\partial w^h}{\partial t} \bigg|_\xi \) part of \( \frac{\partial w^h}{\partial t} \). In [78], this option was called “WTSE,” and the option where the \( \frac{\partial w^h}{\partial t} \bigg|_\xi \) term is active, “WTSA.”

**Remark 2** With the function spaces defined in the paragraph preceding Eq. (2.4), for each space–time slab velocity and pressure assume double unknown values at each spatial node. One value corresponds to the lower end of the slab, and the other one the upper end. In [78], the option of using double unknown values at a spatial node is called “DV” for velocity and “DP” for pressure. In this case, as pointed out in [78], we use two integration points over the time interval of the space–time slab, and this time-integration option is called “TIP2.” This version of the DSD/SST formulation, with the options set DV, DP and TIP2, is called “DSD/SST-DP.”
Remark 3 In [78], the option of using, for each space–time slab, a single unknown pressure value at each spatial node was proposed with the option name “SP.” With this, another version of the DSD/SST formulation was proposed in [78], where the options set is DV, SP and TIP2. This version is called “DSD/SST-SP.” Because the number of pressure unknowns is halved, the computational cost is reduced.

Remark 4 To reduce the computational cost further, the option of using only one integration point over the time interval of the space–time slab was proposed in [78]. This time-integration option is called “TIP1.” With that, a third version of the DSD/SST formulation was proposed in [78], where the options set is DV, SP and TIP1. This version is called “DSD/SST-TIP1.”

Remark 5 As a third way of reducing the computational cost, the option of using, for each space–time slab, a single unknown velocity value at each spatial node was proposed in [78] with the option name “SV.” In the SV option, of the two parts of Eq. (2.4), the one generated by \((w^h)^+_n\) is removed, and we explicitly set \((u^h)^+_n = (u^h)^-n\), which makes the velocity field continuous in time. Based on the SV option, a fourth version of the DSD/SST formulation was proposed in [78], where the options set is SV, SP and TIP1. This version is called “DSD/SST-SV.” In this version of the DSD/SST formulation, as it was proposed in [78], one can use the SUPG test function option WTSE.

Remark 6 For DSD/SST-SP, DSD/SST-TIP1 and DSD/SST-SV, in integration of the incompressibility-constraint term over each space–time slab, as proposed in [43], we use only one integration point in time, shifted to the upper time level of the slab. All other terms in the space–time finite element formulation are integrated by using Gaussian quadrature points in time, with the number of points set to whatever we intended to have for the overall formulation. With this technique, as pointed in [43], the incompressibility constraint equation focuses on the velocity field \((u^h)^-_n+1\).
2.3.2 Semi-Discrete Formulation of Structural Mechanics

With $y^h$ and $w^h$ coming from appropriately defined trial and test function spaces, respectively, the semi-discrete finite element formulation of the structural mechanics equations (see [30, 14, 36]) is written as

$$
\int_{\Omega_0} w^h \cdot \rho^s \frac{d^2 y^h}{dt^2} d\Omega + \int_{\Omega_0} w^h \cdot \eta \rho^s \frac{dy^h}{dt} d\Omega + \int_{\Omega_0} \delta E^h : S d\Omega = \\
\int_{\Omega_f} w^h \cdot (t^h + \rho^s f^s) d\Omega. \tag{2.15}
$$

The fluid mechanics forces acting on the structure are represented by vector $t^h$. The above formulation is for structures represented by a membrane model. The left-hand-side terms of Eq. (2.15) are referred to in the original configuration and the right-hand-side terms in the deformed configuration at time $t$. Time discretization of Eq. (2.15) is based on the Hilber–Hughes–Taylor scheme [24].

**Remark 7** In the computations reported here and those reported earlier by the T*AFSM, the mass matrix associated with the first term of Eq. (2.15) is lumped.

2.3.3 Stabilized Space–Time Fluid–Structure Interaction technique

The SSTFSI technique was introduced in [78], where it was described based on the finite element formulations given by Eqs. (2.4) and (2.15), with a slight change of notation and with a clarification of how the fluid–structure interface conditions are handled. In that notation subscripts 1 and 2 refer to fluid and structure, respectively. Furthermore, while subscript $I$ refers to the fluid–structure interface, subscript $E$ refers to “elsewhere” in the fluid and structure domains or boundaries. Here we write
from [78] the equations representing the SSTFSI technique:

\[
\int_{Q_n} w_{1E}^h \cdot \rho \left( \frac{\partial u^h}{\partial t} + u^h \cdot \nabla u^h - f^h \right) dQ + \int_{Q_n} \varepsilon (w_{1E}^h) : \sigma (p^h, u^h) dQ \\
- \int_{(P_n)_h} w_{1E}^h \cdot h_{1E}^h dP + \int_{Q_n} q_{1E}^h \cdot u^h dQ + \int_{\Omega_n} (w_{1E}^h)_n \cdot \rho ((u^h)_n^+ - (u^h)_n^-) d\Omega \\
+ \sum_{e=1}^{(n_{el})_n} \int_{Q^n_e} \frac{1}{\rho} [\tau_{\text{SUPG}} \left( \frac{\partial w_{1E}^h}{\partial t} + u^h \cdot \nabla w_{1E}^h \right) + \tau_{\text{PSPG}} \nabla q_{1E}^h] \cdot [L(p^h, u^h) - \rho f^h] dQ \\
+ \sum_{e=1}^{(n_{el})_n} \int_{Q^n_e} \nu_{\text{LSIC}} \nabla \cdot w_{1E}^h \rho \nabla \cdot u^h dQ = 0,
\] (2.16)

\[
\int_{Q_n} q_{1I}^h \nabla \cdot u^h dQ + \sum_{e=1}^{(n_{el})_n} \int_{Q^n_e} \frac{1}{\rho} [\tau_{\text{PSPG}} \nabla q_{1I}^h] \cdot [L(p^h, u^h) - \rho f^h] dQ = 0,
\] (2.17)

\[
\int_{(\Gamma_{1I})_{\text{REF}}} (w_{1I}^h)_{n+1} \cdot ( (x_{1I}^h)_{n+1} - (x_{2I}^h)_{n+1}) d\Gamma = 0,
\] (2.18)

\[
\int_{(\Gamma_{1I})_{\text{REF}}} (w_{1I}^h)^- \cdot ( (u_{1I}^h)^- - u_{2I}^h) d\Gamma = 0,
\] (2.19)

\[
\int_{(P_n)_h} (w_{1I}^h)^-_{n+1} \cdot h_{1I}^h dP = - \int_{(P_n)_h} (w_{1I}^h)^-_{n+1} \cdot p^h n dP \\
+ \int_{Q_n} 2\mu \varepsilon ((w_{1I}^h)^-_{n+1}) : \varepsilon (u^h) dQ + \sum_{e=1}^{(n_{el})_n} \int_{Q^n_e} (w_{1I}^h)^-_{n+1} \cdot \nabla \cdot (2\mu \varepsilon (u^h)) dQ,
\] (2.20)

\[
\int_{(\Omega_{2I})_{\text{REF}}} w_{2I}^h \cdot (h_{2I}^h + (h_{1I}^h)_A + (h_{1I}^h)_B) d\Omega = 0,
\] (2.21)
\[
\int_{(\Omega_2)_0} \mathbf{w}_2^h \cdot \frac{\rho_2}{\Omega_2} \frac{d^2 \mathbf{y}^h}{dt^2} d\Omega + \int_{(\Omega_2)_0} \mathbf{w}_2^h \cdot \eta \rho_2 \frac{d\mathbf{y}^h}{dt} d\Omega + \int_{(\Omega_2)_0} \delta \mathbf{E}^h : \mathbf{S}^h d\Omega = \\
\int_{\Omega_2} \mathbf{w}_2^h \cdot \rho_2 \mathbf{f}_2^h d\Omega + \int_{\Omega_{2E}} \mathbf{w}_{2E}^h \cdot \mathbf{h}_{2E}^h d\Omega + \int_{\Omega_{2I}} \mathbf{w}_{2I}^h \cdot \mathbf{h}_{2I}^h d\Omega.
\] (2.22)

Here \((\Gamma_{1I})_{\text{REF}}\) and \((\Omega_{2I})_{\text{REF}}\) represent some reference configurations of \(\Gamma_{1I}\) and \(\Omega_{2I}\), and \(\mathbf{x}_{1I}^h\) and \(\mathbf{x}_{2I}^h\) are the fluid mechanics and structural mechanics nodal positions at the fluid–structure interface. In reconciling the slightly modified notation used here with the notation used in Eqs. (2.4) and (2.15), we note that \(\rho_2 = \rho^s\), \(\mathbf{f}_2^h = \mathbf{f}^s\), \((\Omega_2)_0 = \Omega_0^s\), \(\Omega_2 = \Omega_2^s\), and \(\Omega_{2I}\) and \(\Omega_{2E}\) denote the partitions of \(\Omega_2\) corresponding to the interface and elsewhere. We also note that \(\mathbf{h}_{2I}^h = \mathbf{t}^h\), and \(\mathbf{h}_{1I}^h\) and \(\mathbf{h}_{2I}^h\) represent the values of \(\mathbf{h}_{1I}^h\) associated with the fluid surfaces above and below the membrane structure. The symbol \(\mathbf{h}_{2E}^h\) denotes the prescribed external forces acting on the structure in \(\Omega_{2E}\), which is separate from \(\mathbf{f}_2^h\). In this formulation, \((\mathbf{u}_{II}^h)_{n+1} \) and \(\mathbf{h}_{1I}^h\) and \(\mathbf{h}_{2I}^h\) (the fluid velocity, fluid stress and structural stress at the fluid–structure interface) are treated as separate unknowns, and Eqs. (2.19), (2.20) and (2.21) can be seen as corresponding to these three unknowns, respectively. The structural displacement rate at the interface, \(\mathbf{u}_{2I}^h\), is derived from \(\mathbf{y}^h\).

**Remark 8** Equation (2.18) represents a projection at the fluid–structure interface that was not explicitly mentioned in [78] but was part of the original SSTFSI technique. It is the projection of the structure nodal positions to the fluid nodal positions. This projection equation is solved at every block-iteration between the fluid+structure block and mesh-moving block (see Section 5 of [78] for the terminology). It is solved with GMRES [35] iterations.

We note that Eq. (2.20) has been derived by assuming that the viscous-flux jump terms across inter-element borders are negligible. We also note that the last term of that equation, in its original form in [78], was written as a global integral \(\int_{Q_n}\) rather than a series of element-level integrals. Alternatively, one can leave that projection
equation in its form prior to the integration-by-parts:

\[
\int_{(P_n)_h} (w_{11}^h)_{n+1}^- : h_{11}^h \, dP = - \int_{(P_n)_h} (w_{11}^h)_{n+1}^- : p^h n \, dP \\
+ \int_{(P_n)_h} (w_{11}^h)_{n+1}^- : (n \cdot (2\mu \varepsilon(u^h))) \, dP. \tag{2.23}
\]

This requires also the projection of \( \varepsilon(u^h) \) from the element interiors to the nodes.

The formulation given by Eqs. (2.16)–(2.22) is based on allowing for cases when the fluid and structure interface meshes are not identical. If they are identical, as pointed out in [78], the same formulation can still be used.

It was noted in [78] that, for constant viscosity, the term \( \nabla \cdot (2\mu \varepsilon(u^h)) \) in Eq. (2.20) vanishes for tetrahedral elements and in most cases can be neglected for hexahedral elements. It was also noted in [78] that the same can be said about that term as part of \( L(p^h, u^h) \) in Eqs. (2.16) and (2.17).

**Remark 9** Although this detail was not discussed in [78], the two projection equations given by Eqs. (2.19) and (2.21) are solved by “numerical substitution,” which essentially consists of sub-level GMRES iterations.

**Remark 10** If the fluid and structure meshes at the fluid–structure interface are identical, then the projections given by Eqs. (2.18), (2.19) and (2.21) simplify to “direct substitution.”

**Remark 11** In [78], the versions of the SSTFSI technique corresponding to the DSD/SST-DP, DSD/SST-SP, DSD/SST-TIP1 and DSD/SST-SV formulations (see Remarks 2–5) were called “SSTFSI-DP,” “SSTFSI-SP,” “SSTFSI-TIP1” and “SSTFSI-SV,” respectively.
In computations where we account for the porosity of the membrane fabric, as formulated in [78], Eq. (2.19) is replaced with

$$\int_{\Gamma_{11}} (w_h^{h})_{n+1} \cdot ((u_h^{h})_{n+1} - u_2^h + k_{\text{PORO}} (n \cdot h_{11}^h) n) \, d\Gamma = 0, \quad (2.24)$$

where $k_{\text{PORO}}$ is the porosity coefficient. In our current implementation, in Eq. (2.24) we take into account only the pressure component of $h_{11}^h$.

Remark 12 In FSI computations with membranes and shells, the pressure at the interface has split nodal values corresponding to the fluid surfaces above and below the membrane or shell structure. It was proposed in [78] to use such split nodal values for pressure also at the boundaries (i.e. edges) of a membrane structure submerged in the fluid. As pointed out in [78], our computations show that this provides additional numerical stability for the edges of the membrane.
Chapter 3

Special Techniques

Here we describe the two methods we use for calculating the curvature, $\kappa$, from computed data. The techniques in this chapter are from [62].

3.1 Arc-Length Method

In this method we calculate the curvature from two points and the length $\ell$ between them (see Figure 3.1). The length and the arc angle, $\alpha$, are related as follows:

$$\ell = r\alpha,$$

(3.1)

Figure 3.1: Curvature calculation with the arc-length method.
and $\alpha$ satisfies the relationship

$$2r \sin \frac{\alpha}{2} = \|x_1 - x_2\|.$$ \hfill (3.2)

Thus, we solve for $\alpha$ the following nonlinear equation:

$$\sin \frac{\alpha}{2} = \frac{\alpha}{2} \frac{\|x_1 - x_2\|}{\ell}.$$ \hfill (3.3)

Then, we calculate the curvature from

$$\kappa = \frac{\alpha}{\ell}.$$ \hfill (3.4)

In solving Eq. (3.3), we use the Newton–Raphson method, with an initial guess of $\alpha^0 = \pi$.

**Remark 13** We note that Eq. (3.3) requires $\|x_1 - x_2\| \leq \ell$. To ensure that, we use $\ell$ based on the current configuration rather than the undeformed configuration.

### 3.2 $\beta$ Method

Here we calculate the curvature from three points. We define a plane from the three points. Then, we find on that plane the circle that passes through the three points (see Figure 3.2). From geometrical considerations, we can write an expression for the radius of the circle, $r$, as follows:

$$2r = \frac{\|x_1 - x_3\|}{\sin \beta},$$ \hfill (3.5)
and an expression for the angle $\beta$ as follows:

$$\cos \beta = \frac{(x_1 - x_2) \cdot (x_3 - x_2)}{\|x_1 - x_2\| \|x_3 - x_2\|}. \quad (3.6)$$

Then, the curvature is calculated from

$$\kappa = \frac{2 \sin \beta}{\|x_1 - x_3\|} \quad (3.7)$$

$$= \frac{2 \sqrt{1 - \cos^2 \beta}}{\|x_1 - x_3\|}. \quad (3.8)$$
Chapter 4

Parachute Examples

The material reported in this chapter is from [62, 60, 61]. We perform FSI analysis for ringsail parachutes in different configurations and flight conditions.

4.1 Single-MP Parachute Disreefing

Disreefing from one stage to another gradually reduces descent velocity and creates a smoother transition for later stages of flight. During disreefing, the parachute shape is highly dynamic and existing empirical models are not fully capable of obtaining data for the parachute. FSI modeling provides a good tool to predict parachute shapes and other performance variables such as peak loading.

4.1.1 Problem Setup

First, the disreefing of a single main parachute is investigated. The parachute has three stages: fully reefed (Stage 1), partially reefed (Stage 2), and fully open (Stage 3). The two reefed configurations (Stages 1 and 2) are characterized by a reefing ratio $\tau_{\text{REEF}} = D_{\text{REEF}}/D_o$, where $D_{\text{REEF}}$ is the reefed skirt diameter, and $D_o$ is the nominal diameter. For the main parachute, Stage 1 has a $\tau_{\text{REEF}}$ of 10% and Stage 2 has a
τ_{REEF} of 16%.

All computations are carried out using air properties at standard sea-level conditions. The density is $2.38 \times 10^{-3}$ slug/ft$^3$ and the kinematic viscosity is $1.57 \times 10^{-4}$ ft$^2$/s. The material properties of all cables and fabrics on the main parachute were obtained from NASA.

### 4.1.2 Description of the Parachute

The parachute model is the same as the modified porosity (MP) parachute in [44]. It is a 120-ft ringsail parachute with 4 rings and 9 sails. It is missing panels on every 5th gore on Sail 11 as well as the top 25% of Sail 6. It has a suspension-line to nominal diameter ratio of $L_s/D_o = 1.44$. The payload mass is about 6,900 lbs. Figure 4.1 shows the MP parachute.

![Figure 4.1: MP parachute.](image-url)
4.1.3 Fluid Interface

The fluid-interface model for the MP, shown in Figure 4.2, contains gaps where the top vent and missing panels are located. Fluid nodes are placed across these gaps so that flow can be resolved through them. Elsewhere, flow through the canopy due to geometric and fabric porosity is modeled using the HMGP-FGR technique (described in [44]). The fluid-interface model used in [44] differs from the current model in that it has a gap also where the top 25% of Sail 6 is missing. We model the flow through this gap with HMGP because it results in a more robust interface model for the highly dynamic conditions of disreefing.

Figure 4.2: Fluid-interface model for the MP parachute.

Remark 14 A Stage 2 MP parachute shape was found in [44]. However, we are not able to use that shape and fluid-interface mesh here because of the lack of robustness in the computations in trying to resolve the flow through the gap between Sails 5 and 6. Therefore, we use the fluid-interface mesh described in Section 4.1.3.
4.1.4 Computational Methods and Parameters

Meshes

The structure and fluid-interface meshes are shown in Figure 4.3. The number of nodes and elements for those meshes are given Table 4.1. The fluid mechanics volume mesh consists of four-node tetrahedral elements, and the membrane elements used in the parachute structure are quadrilateral. The computational domain is box-shaped, with dimensions $1,740 \text{ ft} \times 1,740 \text{ ft} \times 1,566 \text{ ft}$. In order to deal with contact more effectively, two layers of equal-thickness elements are generated in both directions from the fluid interface. The addition of these elements, from our computational experience, makes dealing with contact more robust. The data for the fluid mechanics volume meshes is in Table 4.7.

The reference frame is moved with a vertical velocity of $U_{\text{ref}}$, and the mesh translates horizontally and vertically with the average displacement rate of the structure beyond the reference velocity $U_{\text{ref}}$. Here $U_{\text{ref}}$ is set to a value suitable for the stage computed. We use the velocity form of the free-stream conditions at the lateral boundaries as well since the mesh translates horizontally.

Table 4.1: Number of nodes ($nn$) and elements ($ne$) in the structural mechanics and fluid-interface meshes for the single-MP parachute. The payload is modeled as a single point-mass element. The cable elements include 1 riser element and 20 elements per suspension line.

<table>
<thead>
<tr>
<th></th>
<th>$nn$</th>
<th>$ne$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface</td>
<td>$nn$</td>
<td>2,220</td>
</tr>
<tr>
<td></td>
<td>$ne$</td>
<td>4,276</td>
</tr>
</tbody>
</table>
Table 4.2: Number of nodes ($nn$) and elements ($ne$) in the fluid-volume meshes used in Stages 1 and 2.

<table>
<thead>
<tr>
<th></th>
<th>Mesh 1</th>
<th>Mesh 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$nn$</td>
<td>183,974</td>
<td>181,492</td>
</tr>
<tr>
<td>$ne$</td>
<td>1,070,764</td>
<td>1,055,401</td>
</tr>
<tr>
<td><strong>Stage 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$nn$</td>
<td>178,442</td>
<td>177,153</td>
</tr>
<tr>
<td>$ne$</td>
<td>1,037,214</td>
<td>1,029,197</td>
</tr>
</tbody>
</table>

**Structural Mechanics Computations**

In the stand-alone structural mechanics computations we have a time-step size of 0.0232 s, 4 nonlinear iterations per time step, and 120 GMRES iterations per nonlinear iteration. In the temporal discretization, we use the generalized-$\alpha$ method [18]. The parameters we use with the method, in the notation of [13], are $\alpha_m = 1$, $\alpha_f = 1$, $\gamma = 0.9$, and $\beta = 0.49$.

**Fluid Mechanics Computations**

The fluid mechanics computations with fixed shapes and positions are done in two parts. In the first part we use the semi-discrete formulation given in [68]. We compute 1,000 time steps with a time-step size of 0.232 s and 6 nonlinear iterations. The number of GMRES iterations per nonlinear iteration is 90. There is no porosity model in this part.

In the second part we use the DSD/SST-TIP1 technique [78], with the SUPG test function option WTSA (see Remark 2 in [78]). The stabilization parameters used are those given in [78] by Eqs. (9)–(12), (14)–(15) and (17), with the $\tau_{\text{SUPG}}$ term dropped from Eq. (14). We compute 300 time steps with a time-step size of 0.01 s, 6 nonlinear iterations per time step, and 90 GMRES iterations per nonlinear iteration. The porosity model is HMGP-FGR.
FSI Computations

The fully-discretized, coupled fluid and structural mechanics and mesh-moving equations are solved with the quasi-direct coupling technique (see Section 5.2 in [78]). We use the SSTFSI-TIP1 technique (see Remarks 5 and 10 in [78]), with the same SUPG test function option and stabilization parameters as those described in Section 4.1.4. The structural mechanics time integration method is the same as it is in Section 4.1.4.

The Surface-Edge-Node Contact Tracking (SENCT-FC) model and the edge-based contact algorithm described in [52] are used during the disreefing computations. The time-step size is 0.01 s, with 6 nonlinear iterations per time step. The number of GMRES iterations per nonlinear iteration is 120 for the fluid+structure block, and 30 for the mesh-moving block. We use selective scaling (see [78]), with the scale for the structure part set to 10 and for the other parts set to 1.

4.1.5 Disreef Computations

Stage 1 to 2

The Stage 1 reefed shape is obtained in an FSI computation by starting with a pad abort (PA) parachute shape at Stage 2, described in [44]. This parachute is then reefed to $\tau_{\text{REEF}} = 10\%$ in a symmetric FSI computation over 300 time steps. The displacements of the PA are then projected to an MP parachute model using a least-squares projection. With this MP shape, we generate a fluid-volume mesh (Mesh 1) that we describe in Table 4.7 and use that in computing the flow field, as we describe in Section 4.1.4. This solution is then used as our starting condition for a symmetric FSI computation, which is computed for 60 s to obtain a settled Stage 1 shape and flow field. Here, as part of the interface projection technique, we use the standard, vector stress projection method instead of the separated stress projection (SSP) [81]. The homogenization model is HMGP-FGR. The descent velocity settles at 137 ft/s
and the corresponding stagnation pressure is 22.3 lb/ft$^2$.

The Stage 1 to 2 disreef is simulated by changing the reefing line from $\tau_{\text{REEF}} = 10\%$ to 16% over 35 time steps. After that the reefing line is kept at $\tau_{\text{REEF}} = 16\%$. The interface projection method is switched to SSP after 150 time steps of disreefing and stays that way for the remaining computations. At this same instant we remesh, and the fluid volume mesh becomes Mesh 2.

**Stage 2 to 3**

A structural mechanics computation is first performed for the MP parachute to obtain a starting shape, using the parameters described in Section 4.1.4. A uniform stagnation pressure of 0.74 lb/ft$^2$, which corresponds to a descent velocity of 25 ft/s, is applied to the unstressed structure and the computation is carried out for 1,000 time steps, reaching a settled shape. Next, a fluid-volume mesh is generated to compute a developed flow field, using the procedures outlined in Section 4.1.4. Then, a symmetric FSI computation is performed, over 900 time steps, where the reefing-line elements are changed from their unstressed lengths to lengths that correspond to $\tau_{\text{REEF}} = 16\%$ to obtain the Stage 2 shape. During the reefing, we remesh after each 300 time steps. The final mesh is Mesh 1 in Table 4.7. We compute 45 s to reach a settled solution, at which time the descent speed is 65 ft/s and the corresponding stagnation pressure is 5.0 lb/ft$^2$.

In disreefing from Stage 2 to 3, the reefing line is instantly set to full length to simulate reefing-line cutting. We remesh 80 time steps after disreefing and use that mesh (Mesh 2) for the remaining 1,820 time steps. The homogenization model is HMGP for 1,000 time steps after disreefing, and HMGP-FGR for the remaining computation.
4.1.6 Results

Stage 1 to 2

Figure 4.4 shows the parachute at 6 instants during the Stage 1 to 2 disreef. The fabric stress is shown in Figure 4.5. The payload descent speed, shown in Figure 4.6, is a good qualitative match to experimental NASA drop test data. In Figure 4.6 and in the three subsequent plots (Figures 4.7–4.9), t=0 corresponds to 100 time steps prior to disreefing. Disreefing starts at t=1.0 s, ends at t=1.35 s, and remeshing takes place at t=2.5 s. The disreefing period is highlighted in blue. The payload deceleration, canopy skirt diameter and riser tension can be seen in Figures 4.7–4.9. The descent speed rapidly decreases, and then begins to steady out before it reaches its settled Stage 2 value. This is important for the disreef because it means the parachute does not over-inflate and smoothly transitions to its next stage of flight.

Stage 2 to 3

Figures 4.10 and 4.11 show the parachute and the fabric stress during the Stage 2 to 3 disreef. Figure 4.12 shows the payload descent speed. In that figure, and in the three subsequent plots (Figures 4.13–4.15), t=0 corresponds to 100 time steps prior to disreefing. Disreefing happens at t=1.0 s, and remeshing takes place at t=1.8 s. The blue vertical line marks the disreefing instant. The payload deceleration, canopy skirt diameter and riser tension can be seen in Figures 4.13–4.15. The Stage 2 to 3 disreef follows a similar qualitative trend as the Stage 1 to 2 disreef. The Stage 2 to 3 disreef exhibits greater peak loading on the riser, however the fabric stress is smaller on the canopy. After the parachute is fully inflated to Stage 3, it begins a breathing motion.
Figure 4.3: Structural mechanics mesh (top) and fluid-interface mesh (bottom) for the MP parachute. For the number of nodes and elements in these meshes, see Table 4.1.
Figure 4.4: Single-MP parachute during Stage 1 to 2 disreef at 0.5 s intervals.
Figure 4.5: Single-MP parachute maximum principal fabric stress (lb/in$^2$) during Stage 1 to 2 disreef at 0.5 s intervals.
Figure 4.6: Payload descent speed for the single-MP parachute during Stage 1 to 2 disreef.

Figure 4.7: Payload deceleration for the single-MP parachute during Stage 1 to 2 disreef.
Figure 4.8: Canopy skirt diameter for the single-MP parachute during Stage 1 to 2 disreef. The diameter is calculated from the area enveloped by the reefing line.

Figure 4.9: Riser tension for the single-MP parachute during Stage 1 to 2 disreef.
Figure 4.10: Single-MP parachute during Stage 2 to 3 disreef at 0.5 s intervals.
Figure 4.11: Single-MP parachute maximum principal fabric stress (lb/in$^2$) during Stage 2 to 3 disreef at 0.5 s intervals.
Figure 4.12: Payload descent speed for the single-MP parachute for Stage 2 during 3 disreef.

Figure 4.13: Payload deceleration for the single-MP parachute during Stage 2 to 3 disreef.
Figure 4.14: Canopy skirt diameter for the single-MP parachute during Stage 2 to 3 disreef.

Figure 4.15: Riser tension for the single-MP parachute for Stage 2 during 3 disreef.
4.2 2P Cluster Disreefing

4.2.1 Problem Setup

Here, a 2P cluster disreefing from Stage 2 to 3 is presented. Each parachute has \( \tau_{REEF} = 16\% \) at Stage 2, and the reefing line is cut instantly. The payload mass is about 20,000 lbs. The air properties are the same as those given in Section 4.1.1. The cluster of Stage 2 parachutes is assumed to be settled in a steady-state shape.

4.2.2 Computational Methods and Parameters

The structure and fluid-interface models are the same as those used for the single-MP parachute. The Stage 2 shape for each of the two parachutes is acquired by using the settled Stage 2 shape of the single-MP parachute from Section 4.1.

Meshes

The structural mechanics and fluid-interface meshes for the 2P cluster are generated by combining two single-MP meshes with an angle of 5° between the two parachute axes. See Table 4.3 for the number of nodes and elements for the structure and fluid-interface meshes.

The fluid-domain size is the same as in Section 4.1.4. In generating the fluid-volume mesh, again, two layers of equal-thickness elements are created in both directions from the interface. The data for the fluid mechanics volume mesh is in Table 4.4.

Fluid Mechanics and FSI Computation

The fluid mechanics and FSI computations are based on the same formulations, test functions, and stabilization parameters as those described in Sections 4.1.4 and 4.1.4. For the 2P cluster we use SSP as the interface projection technique.
Table 4.3: Number of nodes \((nn)\) and elements \((ne)\) in the structural mechanics and fluid-interface meshes for the 2P cluster. The payload is modeled as a single point-mass element. There are two risers consisting of one cable element each, and each suspension line has 20 elements.

<table>
<thead>
<tr>
<th>Structure</th>
<th>(nn)</th>
<th>59,427</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>(ne)</td>
<td>74,083</td>
</tr>
<tr>
<td>Cable</td>
<td>(ne)</td>
<td>24,322</td>
</tr>
<tr>
<td>Interface</td>
<td>(nn)</td>
<td>56,383</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fluid</th>
<th>(nn)</th>
<th>4,440</th>
</tr>
</thead>
</table>

Table 4.4: Number of nodes \((nn)\) and elements \((ne)\) in the fluid-volume meshes used in the 2P cluster computations.

<table>
<thead>
<tr>
<th>Mesh 1</th>
<th>Mesh 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(nn)</td>
<td>324,827</td>
</tr>
<tr>
<td>(ne)</td>
<td>1,900,291</td>
</tr>
</tbody>
</table>

The fluid mechanics computation is carried out with the mesh shown in Table 4.4 (Mesh 1), with the same procedure as described in Section 4.1.4. A time-step size of 0.01 s is used, with 6 nonlinear iterations per time step, and 120 GMRES iterations for the fluid+structure block and 30 for the mesh-moving block. The SENCT-FC and edge-based contact models are used.

### 4.2.3 Disreef Computations

After computing a developed flow field, which corresponds to a descent speed of 65 ft/s, a full FSI computation is performed. The full FSI computation continues for approximately 45 s to reach a settled descent velocity. The spin removal technique, described in [59], is utilized about every 300 time steps. The HMGP technique is used. The descent velocity settles at 75 ft/s, and the corresponding stagnation pressure is 6.7 lb/ft\(^2\).

Similar to Section 4.1.5, the reefing line is instantly set to full length to simulate
reefing-line cutting. We remesh 70 time steps after disreefing, and use that mesh (Mesh 2) for the remaining duration. The homogenization model is HMGP for 1,250 time steps after disreefing, and HMGP-FGR for the remaining computation.

### 4.2.4 Results

Figures 4.16–4.19 show the parachute during the disreef. The payload descent speed, as shown in Figure 4.20, is a good qualitative match to experimental NASA drop test data. In that figure, and in the three subsequent plots (Figures 4.21–4.23), t=0 corresponds to 100 time steps prior to disreefing. Disreefing happens instantly at t=1.0 s, and remeshing takes place at t=1.7 s. The blue vertical line marks the disreefing instant.

The payload deceleration, canopy skirt diameter, and riser tension can be seen in Figures 4.21–4.23. The riser tension and diameter are averaged between the two canopies since the data is very similar for each canopy.

Figure 4.16: 2P cluster at t=0 s and t=0.5 s.
Figure 4.17: 2P cluster at $t=1.0$ s and $t=1.5$ s.

Figure 4.18: 2P cluster at $t=2.0$ s and $t=2.5$ s.

Figure 4.19: 2P cluster at $t=3.0$ s and $t=3.5$ s.
Figure 4.20: Payload descent speed for the 2P cluster.

Figure 4.21: Payload deceleration for the 2P cluster.
Figure 4.22: Average canopy skirt diameter for the 2P cluster.

Figure 4.23: Average riser tension for the 2P cluster.
4.3 Single-MP Parachute Curvature

The main parachutes use a technique called skirt reefing as a way to incrementally open the parachute canopies. This is necessary for reducing opening forces on the parachutes. Each parachute undergoes three stages throughout the disreefing process. We will perform an analysis to determine the curvature for a parachute gore at these various stages. Each stage has different computational challenges, and we will address them in order to calculate the curvature for each stage. This section uses material from [62].

4.3.1 Flight Conditions

All computations are carried out using air properties at standard sea-level conditions. The density is $2.38 \times 10^{-3}$ slug/ft$^3$. The kinematic viscosity is $1.57 \times 10^{-4}$ ft$^2$/s. The material properties of all cables and fabrics on the main parachute were obtained from NASA. In this section we will calculate the curvature of a single-MP parachute at Stages 1–3. One curvature calculation will be given for Stages 1 and 2 because very little oscillation in skirt diameter occurs during this condition of flight. However, four individual curvatures calculations are performed for Stage 3. These four computations are for the points in the parachute breathing cycle shown in Figure 4.24.

4.3.2 Computational Methods and Parameters

Meshes

In Table 4.5 we give the number of nodes and elements for the single-MP structure and fluid-interface meshes. For the structure-only computation of the Stage 1 shape we use Mesh 1. For the Stage 2 and Stage 3 FSI computations, we use Meshes 2 and 3 respectively. The domain of the Stage 2 and Stage 3 computations is box-shaped with dimensions $1,740 \text{ ft} \times 1,740 \text{ ft} \times 1,566 \text{ ft}$. The fluid mechanics volume mesh
Figure 4.24: Four points in the breathing cycle where we calculate the curvatures.

consists of four-node tetrahedral elements, and the membrane elements used in the parachute structure are quadrilateral. We move the reference frame with a vertical velocity of $U_{ref}$, and the mesh translates horizontally and vertically with the average displacement rate of the structure beyond the reference velocity $U_{ref}$. Here $U_{ref}$ is set to a value suitable for the stage computed. We use the velocity form of the free-stream conditions at the lateral boundaries as well since the mesh translates horizontally.

Structural Mechanics Computation

To get the Stage 1 shape, we use a structure-only computation, which is described in Section 4.3.3. In the temporal discretization, we use the generalized-$\alpha$ method [18]. The parameters we use with the method, in the notation of [13], are $\alpha_m = 1$, $\alpha_t = 1$, $\gamma = 0.9$, and $\beta = 0.49$. The time-step size is 0.0232 s and we compute the structure for 1,000 time steps. We use 4 nonlinear iterations per time-step, with 120 GMRES iterations per nonlinear iteration.
Table 4.5: Number of nodes (nn) and elements (ne) for Meshes 1–3. Structure meshes have one riser, one payload, and 20 elements per suspension line.

<table>
<thead>
<tr>
<th></th>
<th>Mesh 1</th>
<th>Mesh 2</th>
<th>Mesh 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>nn</td>
<td>124,002</td>
<td>29,714</td>
<td>29,074</td>
</tr>
<tr>
<td>Membrane</td>
<td>114,048</td>
<td>24,880</td>
<td>24,240</td>
</tr>
<tr>
<td>Cable</td>
<td>22,041</td>
<td>12,161</td>
<td>12,321</td>
</tr>
<tr>
<td>Interface</td>
<td>28,192</td>
<td></td>
<td>27,552</td>
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<tr>
<td><strong>Fluid</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Interface</td>
<td>nn</td>
<td>2,220</td>
<td>2,236</td>
</tr>
<tr>
<td></td>
<td>ne</td>
<td>4,276</td>
<td>4,052</td>
</tr>
</tbody>
</table>

**FSI Computation**

The single-MP FSI computations are reported in [45] for Stage 3, and [60] for Stage 2. The methods for these computations along with the number of nodes and elements in the fluid mesh can be found in these publications.

**Curvature Calculation**

To calculate the curvature for the single-MP parachute we use the “β method” described in Section 3.2. We average the curvature in the circumferential direction of the gore for two locations per sail. The first location is the middle point of the sail and the second is at the leading edge. For a ringsail parachute, the leading edge is open at the bottom of each sail. We take these two curvature values and average them with 16 evenly spaced gores around the parachute (midway between two parachute windows).

**4.3.3 Computations**

**Stage 1 Shape for Curvature Calculation**

At the Stage 1 descent velocity the parachute is highly dynamic and getting a symmetric and settled shape for calculating curvature is essential. Therefore, we use a
structure-only computation to get this desired shape. To get this shape, we hold the reefing line constant at a value of \( \tau_{\text{REEF}} = 7\% \). We then apply a constant pressure profile to the structure that we show in Figure 4.25. For a fully open parachute, the pressure distribution is almost equally distributed. However, in the reefed configuration the upper sails are under much higher pressure. The pressure profile which is applied to the refined structure is determined iteratively to match the Stage 1 shape from NASA data. The result of this computation is shown in Figure 4.26.

Figure 4.25: Pressure profile (lb/ft\(^2\)) applied to the Stage 1 shape.
Figure 4.26: Structure shape for Stage 1.

Stage 2 Shape for Curvature Calculation

The Stage 2 shape is obtained by reefing the parachute in a symmetric FSI computation to a reefing ratio of $\tau_{\text{REEF}} = 16\%$. See [60] for the computations that we use to acquire the Stage 2 shape. The number of nodes and elements for the fluid volume can also be found in [60]. This computation yields a steady-state velocity of 65 ft/s after 45 s. The stagnation pressure that corresponds to this velocity is 5.0 lb/ft$^2$. The structure shape corresponding to this computation can be seen in Figure 4.27.
Stage 3 Shape for Curvature Calculation

The computations that we use to obtain the four Stage 3 shapes can be found in [45]. The computations provide a good characteristic breathing cycle for ringsail parachutes and four good shapes to calculate the curvature. Figure 4.28 shows the Stage 3 shape at Point 4. The number of nodes and elements for the fluid volume can also be found in [45].

4.3.4 Results

The four calculations for Stage 3 curvature can be seen in Figures 4.29–4.32. They show a trend of increasing curvature along a gore starting at the vent and ending at
the skirt. In addition, the curvature is higher at the leading edge compared to the middle point. The rings closer to the parachute vent, labeled Sails 1–4, are nearly flat as indicated by low curvature values. This is attributed to their lack of fullness when uninflated.

The curvature for the Stage 2 shape can be seen in Figure 4.33. Compared to the Stage 3 shapes, it is clear that the parachute has a higher curvature. Since the Stage 2 shape has a reefing ratio of $\tau_{\text{REEF}} = 16\%$, the sails must exhibit greater curvature as they are more tightly spaced. Only the curvatures for Sails 1–9 are plotted because the other sails are not inflated.

The Stage 1 curvature is shown in Figure 4.34. It has the highest curvature values
Figure 4.29: Curvature for the Stage 3 parachute at Point 1.

as can be expected with a reefing ratio of $\tau_{\text{REEF}} = 7\%$, and only Sails 1–6 are inflated.
Figure 4.30: Curvature for the Stage 3 parachute at Point 2.

Figure 4.31: Curvature for the Stage 3 parachute at Point 3.
Figure 4.32: Curvature for the Stage 3 parachute at Point 4.

Figure 4.33: Curvature for the Stage 2 parachute.
Figure 4.34: Curvature for the Stage 1 parachute.
4.4 MP Parachute Stability

We study the trend of the moment coefficient \((C_M)\) as a function of angle of attack \((\alpha)\) to assess the stability characteristics of a single modified-porosity (MP) parachute and a 2-parachute (2P) cluster.

4.4.1 Problem setup

We define \(C_M\) as

\[
C_M = \frac{M_P}{q_{\text{tot}} S_0 \bar{c}},
\]

(4.1)

where \(M_P\) is the moment about the payload and a negative value indicates that the parachute will rotate to decrease \(\alpha\). The nominal area, \(S_0\), is approximately 10,500 ft\(^2\) for each parachute, \(\bar{c}\) is approximately 120 ft, and \(q_{\text{tot}}\) is the stagnation pressure based on the instantaneous payload velocity. We conduct an angle of attack sweep to calculate the aerodynamic parameters. This knowledge can then be used in enhancing parachute stability and performance.

All computations are carried out using air properties at standard sea-level conditions. The density is \(2.38 \times 10^{-3}\) slug/ft\(^3\) and the kinematic viscosity is \(1.57 \times 10^{-4}\) ft\(^2\)/s. The material properties for all parachute cables and fabrics were obtained from NASA.

4.4.2 Computational Methods and Parameters

Meshes

The structure and fluid-interface meshes are shown in Figure 4.35. The structural mechanics and fluid-interface meshes for the 2P cluster are generated by combining two single-MP meshes with an angle of 15° between the two parachute axes. The ini-
tial displacement of the structure meshes comes from the inflated MP shape reported in [44]. The number of nodes and elements for those meshes are given in Table 4.6.

The fluid mechanics volume mesh consists of four-node tetrahedral elements, and the membrane elements used in the parachute structure are quadrilateral. The computational domain is box-shaped, with dimensions 1,740 ft × 1,740 ft × 1,566 ft. The data for the fluid mechanics volume meshes is in Table 4.7.

The reference frame is moved with a vertical velocity of $U_v$ and a horizontal velocity of $U_h$, and the mesh translates vertically with the average displacement rate of the structure beyond $U_v$. Here, $U_v$ is set to 25.7 ft/s for a single parachute, and 32.5 ft/s for the 2P. We set $U_h$ as $U_h = U_v \tan \alpha$ to achieve a specified angle of attack.

Figure 4.35: Structural mechanics mesh (top) and fluid-interface mesh (bottom) for the MP parachute. For the number of nodes and elements in these meshes, see Table 4.6.
Table 4.6: Number of nodes \((nn)\) and elements \((ne)\) in the structural mechanics and fluid-interface meshes for the MP parachutes. The payload is modeled as a single point-mass element. The cable elements include 1 riser element and 20 elements per suspension line.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Single-MP</th>
<th>2P Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane</td>
<td>(nn) 29,074</td>
<td>58,147</td>
</tr>
<tr>
<td>Cable</td>
<td>(ne) 24,240</td>
<td>48,480</td>
</tr>
<tr>
<td>Interface</td>
<td>(nn) 12,321</td>
<td>24,642</td>
</tr>
<tr>
<td>Interface</td>
<td>(ne) 27,552</td>
<td>55,104</td>
</tr>
<tr>
<td>Fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface</td>
<td>(nn) 2,236</td>
<td>4,280</td>
</tr>
<tr>
<td>Interface</td>
<td>(ne) 4,052</td>
<td>7,912</td>
</tr>
</tbody>
</table>

Table 4.7: Number of nodes \((nn)\) and elements \((ne)\) in the fluid-volume meshes used.

<table>
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<th>Single-MP</th>
<th></th>
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</thead>
<tbody>
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<td>(nn)</td>
<td>186,299</td>
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<tr>
<td>(ne)</td>
<td>1,150,150</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2P Cluster</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(nn)</td>
<td>314,896</td>
</tr>
<tr>
<td>(ne)</td>
<td>1,843,801</td>
</tr>
</tbody>
</table>

**Fluid mechanics computations**

The fluid mechanics computations with fixed shapes and positions are done in two parts. In the first part we use the semi-discrete formulation given in [68]. We compute 1,000 time steps with a time-step size of 0.232 s and 6 nonlinear iterations per time step. The number of GMRES iterations per nonlinear iteration is 90. There is no porosity model in this part.

In the second part we use the DSD/SST-TIP1 technique [78], with the SUPG test function option WTSA (see Remark 2 in [78]). The stabilization parameters used are those given in [78] by Eqs. (9)–(12), (14)–(15) and (17), with the \(\tau_{SUGN2}\) term dropped from Eq. (14). We compute 300 time steps with a time-step size of 0.0232 s, 6
nonlinear iterations per time step, and 90 GMRES iterations per nonlinear iteration. The porosity model is HMGP-FGR [44].

**FSI computations**

The fully-discretized, coupled fluid and structural mechanics and mesh-moving equations are solved with the quasi-direct coupling technique (see Section 5.2 in [78]). We use the SSTFSI-TIP1 technique (see Remarks 5 and 10 in [78]), with the same SUPG test function option and stabilization parameters as those described in Section 4.4.2. For the structural mechanics time integration we use the generalized-α method [18]. The parameters we use with the method, in the notation of [13], are $\alpha_m = 1$, $\alpha_t = 1$, $\gamma = 0.9$, and $\beta = 0.49$. We use the SSP method [81] as the interface projection technique.

The time-step size is 0.0232 s, with 6 nonlinear iterations per time step. The number of GMRES iterations per nonlinear iteration is 120 for the fluid+structure block, and 30 for the mesh-moving block. We use selective scaling (see [78]), with the scale for the structure part set to 10 and for the other parts set to 1.

**4.4.3 Symmetrization Methods**

To prevent the parachute from gliding and to achieve a settled solution, we use symmetric FSI techniques. By symmetrizing pressure difference, the parachute’s horizontal velocity is restricted when given an inflow velocity at a specified angle. This allows us to achieve settled solutions of $C_M$ at different angles of attack. For the single-MP, we use the axial-symmetric FSI method, which is the original symmetric FSI method [86]. In this method, we symmetrize the pressure difference on the fluid interface for each meridional ring of the parachute.

For the 2P cluster, we introduce a new method that we call planar-symmetric FSI. In this method, we symmetrize the pressure in two planes (see Figure 4.36).
The first plane is defined with three points: the centroid of each parachute canopy and the payload. The second plane is perpendicular to the line connecting the two parachute centroids and passes through the payload. The flow is parallel to the second plane. We define each 4-node set as the mirrored nodes across the two planes (see Figure 4.36) and average the pressure difference among the nodes. In addition, we symmetrize the structural displacement rate with these 4-node sets every 150 time steps. This method enables us to conduct the angle of attack sweep.

Figure 4.36: Node set for the planar-symmetric FSI method.

4.4.4 Computations

Single-MP

Using the starting shape for a single-MP found in [44], we develop the flow field in the fluid mechanics computations for 10 different angles of attack ranging from 0° to 30°.
The inflow velocity for each case is calculated using the technique in Section 4.4.2. With results from these computations as starting conditions, we compute the 10 cases with the axial-symmetric FSI method.

We compute each case to determine $C_M$ over a duration of about 80 s. In reporting the time-averaged values of $C_M$ at different angles of attack, we take only the last 60 s. Since the parachute descent speed is not constrained, the actual, instantaneous angle of attack changes a little. The instantaneous angle of attack is measured as the angle between the inflow velocity and the parachute riser. We use the same period of 60 s to calculate the time-averaged angle of attack. Figure 4.37 shows the flow field at $\alpha = 30^\circ$ during the axial-symmetric FSI computation.

Figure 4.37: MP at $\alpha = 30^\circ$. The velocity vectors are colored by their magnitude.
2P cluster

After calculating $U_h$ for the 7 angles of attack, we again develop the flow field in fluid mechanics computations. We then compute each case in planar-symmetric FSI as discussed in Section 4.4.3. The duration of each computation is about 30 s. To calculate the time-averaged values of $C_M$ and $\alpha$, we use the last 20 s. Figure 4.38 shows the flow field at $\alpha = 30^\circ$ during the planar-symmetric FSI computation.

Figure 4.38: 2P cluster at $\alpha = 30^\circ$. The velocity vectors are colored by their magnitude.
4.4.5 Results

We show the time history of $C_M$ for the single-MP in Figure 4.39. Figure 4.40 shows the time history of the instantaneous angles of attack for these cases. The highlighted regions are the ranges of time used in calculating the time-averaged values. The time-averaged $C_M$ as a function of $\alpha$ can be seen in Figure 4.41. We represent the standard deviation of our data with vertical bars at each data point. The curve shows that the parachute has a stable trim point at about $17.3^\circ$. By definition, where the curve has a negative slope at $C_M = 0$, it has positive static stability. The payload descent speed for these cases can be seen in Figure 4.42.

![Figure 4.39: Instantaneous $C_M$ for the single-MP parachute.](image)

We show the time history of $C_M$ for the 2P cluster in Figure 4.43. Figure 4.44 shows the time histories of the instantaneous angles of attack for these cases. For the
Figure 4.40: Instantaneous $\alpha$ for the single-MP parachute.

2P cluster, the time-averaged $C_M$ as a function of $\alpha$ can be seen in Figure 4.45. The payload descent speed corresponding to the data is shown in Figure 4.46.
Figure 4.41: Time-averaged $C_M$ for the single-MP parachute.
Figure 4.42: Payload descent speed for the single-MP parachute.
Figure 4.43: Instantaneous $C_M$ for the 2P cluster.
Figure 4.44: Instantaneous $\alpha$ for the 2P cluster.
Figure 4.45: Time-averaged $C_M$ for the 2P cluster.
Figure 4.46: Payload descent speed for the 2P cluster.
Chapter 5

Concluding Remarks

We focused in this thesis on modeling spacecraft parachutes for multiple stages and flight conditions. In addition, we calculated gore curvature and investigated the stability trends of the MP. We determined that the current reefing sequence reduces overall parachute loading and reduces the forces experienced by the spacecraft. Without this sequence, re-entry into the atmosphere would prove impossible for space travelers.

The geometric complexities of the MP proved challenging when modeling the hundreds of gaps and slits. In addition, we found modeling intra-canopy contact to be equally challenging when the parachute was under the highly dynamic reefing conditions. However, with the introduction of new techniques we were able to overcome the difficulties and develop a good model for disreefing. We also calculated the gore curvature for the MP. NASA engineers can use this data for simple engineering calculations of structural stresses. Finally, our new symmetric FSI techniques allowed us to conduct an angle of attack sweep of a single-MP and a 2P cluster. By restricting parachute gliding, we were able to calculate a curve for the moment coefficient with respect to angle of attack. This data is important for fully-open parachutes because it can help predict the flight characteristics of a spacecraft crew vehicle moments before it touches down. The methods developed by the T★AFSM, including those
presented in this thesis, continue to improve the accuracy of computational modeling of spacecraft parachutes and add to the value of computational methods in spacecraft parachute development.
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