



A Computational Fluid-Structure Interaction Method for Simulating Supersonic Parachute Inflation

Jonathan Boustani

Department of Mechanical Engineering, University of Kentucky, Lexington, KY, 40506, USA

Computational Aerosciences Branch, NASA Ames Research Center, Moffett Field, CA, 94035, USA

Advanced Modeling & Simulation (AMS) Seminar Series

NASA Ames Research Center

Thursday, December 2nd, 2021

□ Introduction

- Background, motivation, problem statement, and research objectives

□ Methodology

- Computational fluid dynamics (CFD)
 - Immersed boundary method, porous media
- Computational structural dynamics (CSD)
 - Element selection, spatial and temporal discretization
- Loose fluid-structure coupling strategy

□ Validation of the Fluid-Structure Coupling Strategy

□ Application to Supersonic Parachutes

- Sub-scale Mars Science Laboratory
- Full-scale ASPIRE test flight

□ Conclusions

*“It has been said that parachute design is an art rather than a science, and there is very little published data to indicate otherwise. **This is particularly true about parachutes for use at supersonic speeds.**”*

- Julian Maynard

Aerodynamic Characteristics of Parachutes At Mach Numbers from 1.6 to 3 (NASA LARC, 1961)

- ❑ In the 1960's, NASA and the U.S. Air Force were looking for aerodynamic decelerators
 - A variety of parachute designs were considered for use in supersonic and hypersonic flows

- ❑ The disk-gap-band (DGB) design was eventually chosen for Martian missions
 - This was used to successfully land the Viking rovers on Mars

- ❑ Every Mars mission afterward used a geometrically-scaled version of this parachute
 - Using agreed-upon design margins, scaling laws, *etc.*

Background

- ❑ But these simple, analytical expressions make a few assumptions
 - Perhaps the most limiting assumption is that the parachute is already inflated



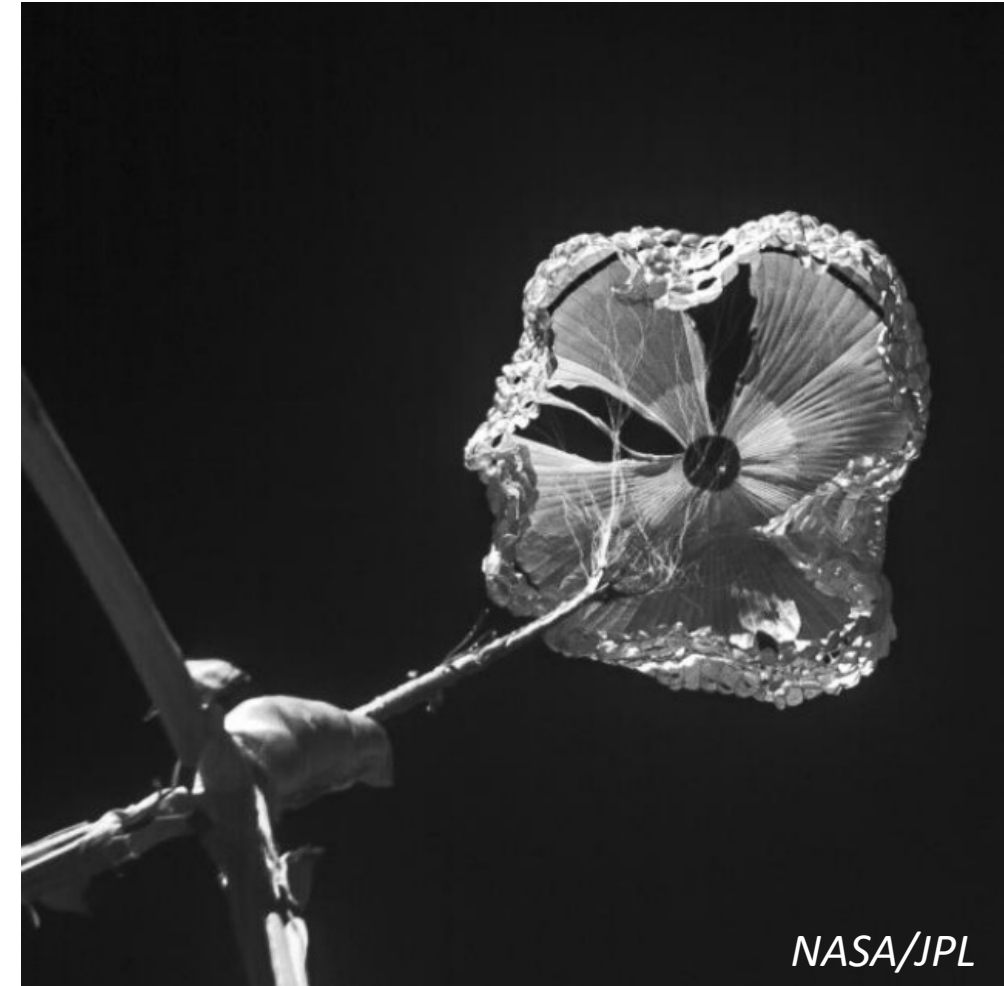
Video from the low-density supersonic decelerator (LDSD) missions (NASA/JPL)

- ❑ The LDSD parachute failed at a load 3-4x smaller than its design load

*“Although **static** analysis of the **fully inflated canopy** resulted in positive structural margins, it is postulated that the **asymmetries and dynamic loads** seen **during the inflation process** were greater than those assumed in the **pre-flight analysis**.”*

- Gallon *et al.* AIAA 2015

- ❑ The details of the inflation process cannot be ignored
- ❑ The ASPIRE missions were then conducted
 - Advanced Supersonic Parachute Inflation Research Exper.



NASA/JPL

Problem Statement



❑ The problems identified are as follows:

1. The ability to predict and model the stresses and loads occurring during supersonic inflation is lacking
 - As recently as 2015, supersonic parachutes have failed
2. There is a reliance on costly, time-consuming wind tunnel tests and drop tests
 - CFD and CSD have played primarily supporting roles since Mars Science Laboratory in 2012 (experiment design)
3. Supersonic parachute missions in general are approaching a concerning point
 - More mass → Larger area → Larger forces → Stresses are trending towards the strength of the broadcloth
 - Clark and Turner IEEE 2017 show the stresses are ~7x closer to the broadcloth strength since the Viking missions

There is a role for high-fidelity simulation capabilities that can predict parachute opening loads

Research Objectives

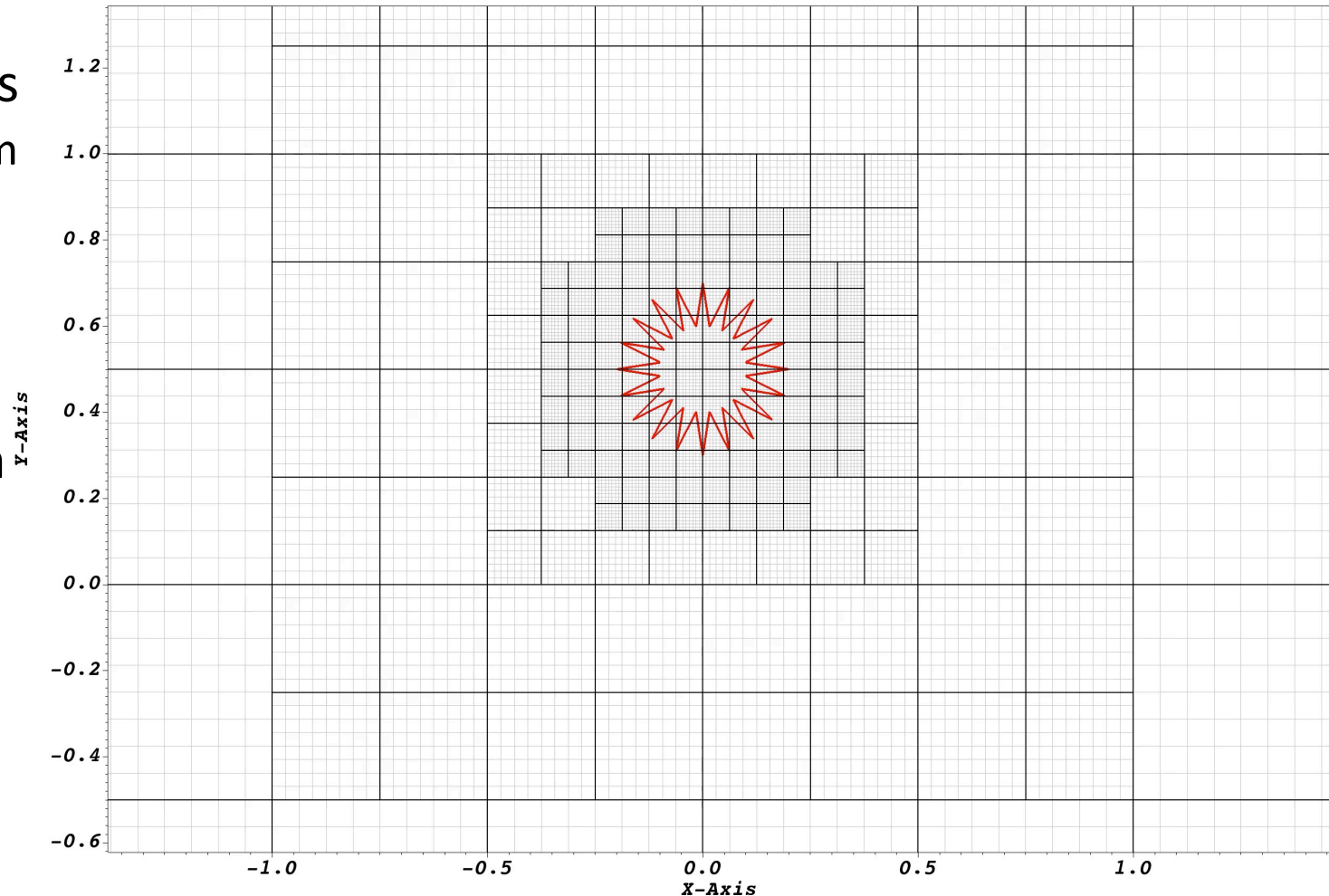


1. Enable an Immersed Boundary Method (IBM) to handle thin, complex, and moving geometries relevant for supersonic parachute inflation
 - Including an immersed boundary condition for modeling thin porous media
2. Develop a structural dynamics solver that utilizes the finite element method to simulate the unsteady response of thin shell and cable structures
3. Develop and validate a general loose coupling strategy for IBMs
 - Including an efficient (self-)contact identification and enforcement method
4. Validate the fluid-structure coupling strategy for use on supersonic parachutes
 - Use a sub-scale DGB parachute as a testbed to develop and validate the required methods
 - Final application and validation on the full-scale ASPIRE SR01 supersonic flight test

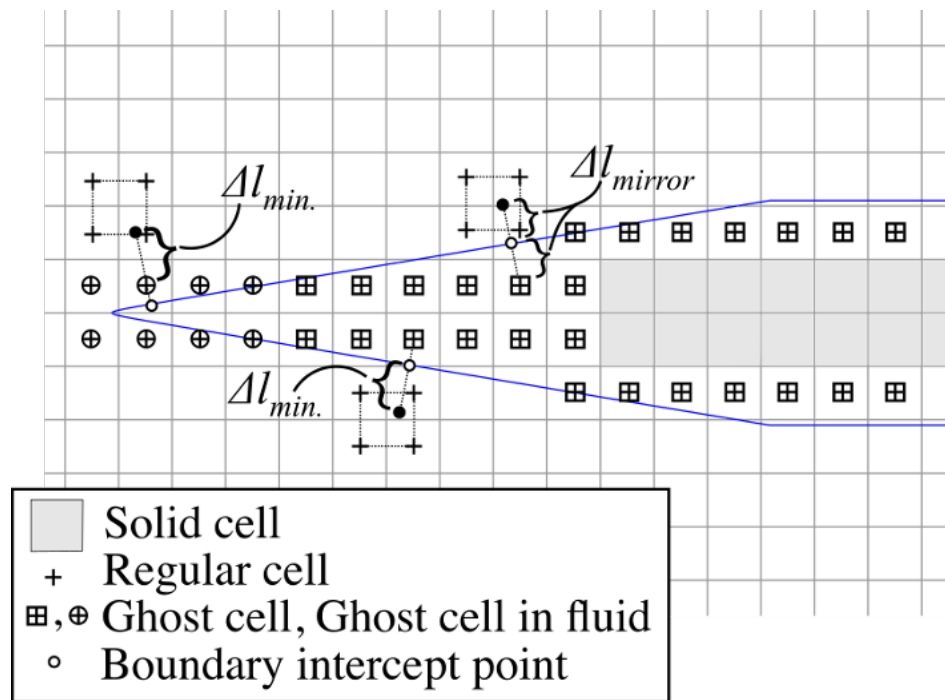
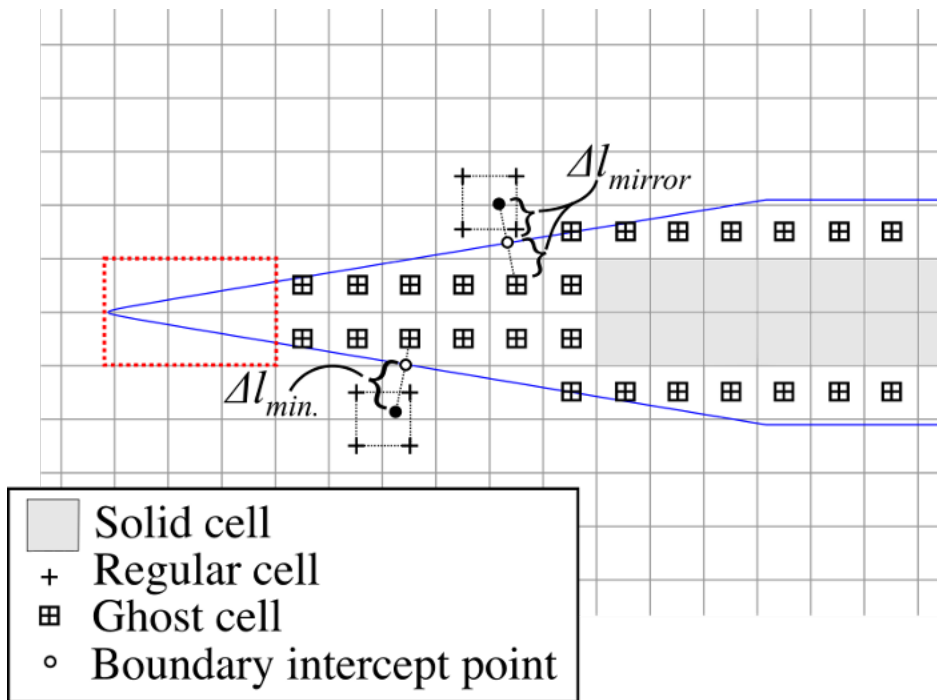
LAVA-Cartesian CFD: Immersed Boundary Method



- ❑ Efficient way to represent and track arbitrarily complex geometries
 - A Lagrangian geometry moves over a Eulerian background mesh
- ❑ No need for body-conforming grids
 - Very difficult and expensive to deform with arbitrary deformations
- ❑ Block-structured Cartesian grid facilitates higher-order finite difference (FD) stencil construction
- ❑ Octree block structure also makes adaption (refinement/coarsening) straightforward



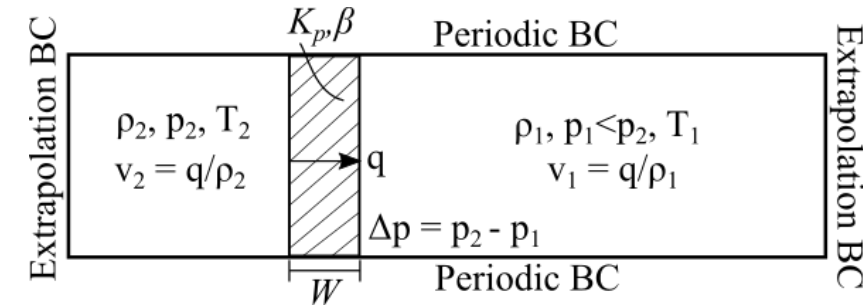
- ❑ Various ways to include the boundary in the numerical approach
- ❑ A “sharp” formulation enforces boundary conditions directly on the IB
 - Ghost cell method (GCM) within the LAVA-Cartesian Solver at NASA ARC



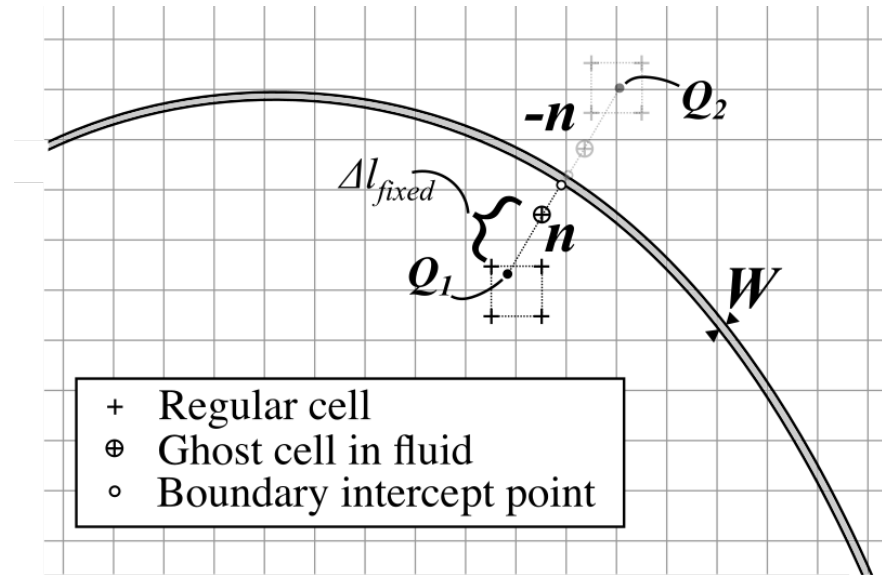
□ Darcy's law can be extended to high-Reynolds number flows

- A closed-form solution can be obtained with minor assumptions

$$q = \rho_1 v_{n,1} = \rho_2 v_{n,2} = -\frac{1}{2K_p\beta} \left(\mu(\bar{T}) - \sqrt{\frac{2K_p^2\beta(p_2^2 - p_1^2)}{WRT} + \mu(\bar{T})^2} \right)$$



□ Easily implemented into GCM framework

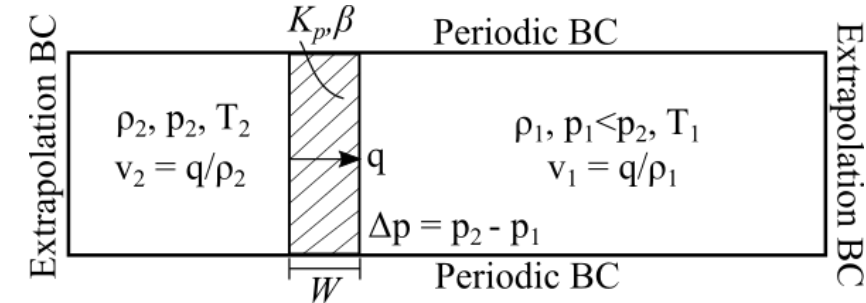


“An Immersed Interface Methodology for Simulating Supersonic Spacecraft Parachutes with Fluid-Structure Interaction”, Boustani et al., *Journal of Fluids and Structures*, 2021. Under review.

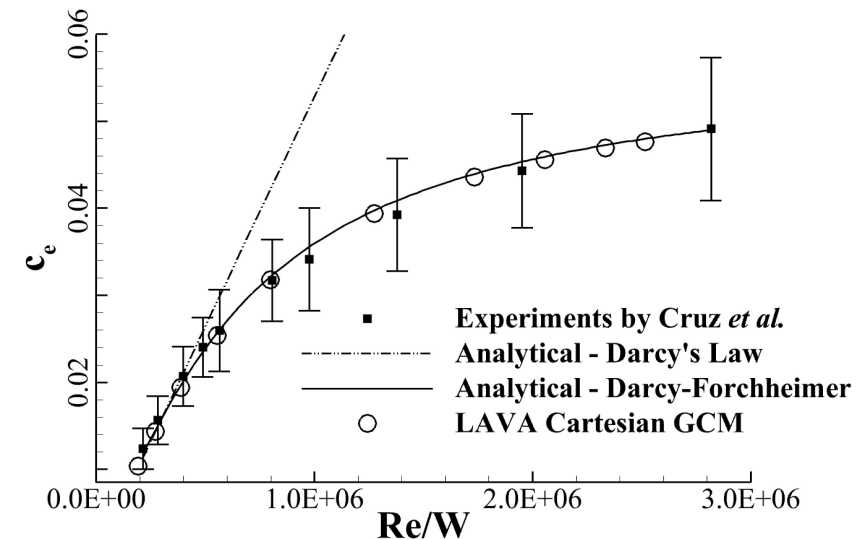
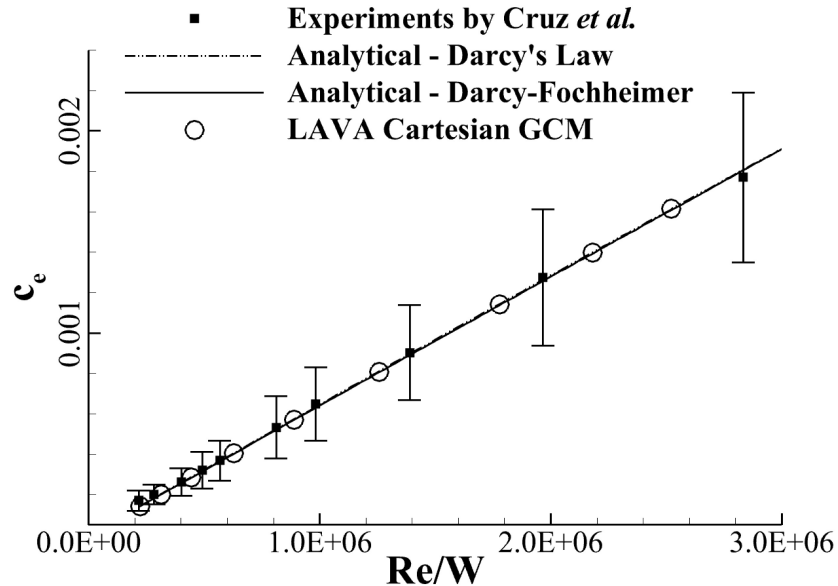
□ Darcy's law can be extended to high-Reynolds number flows

- A closed-form solution can be obtained with minor assumptions

$$q = \rho_1 v_{n,1} = \rho_2 v_{n,2} = -\frac{1}{2K_p\beta} \left(\mu(\bar{T}) - \sqrt{\frac{2K_p^2\beta(p_2^2 - p_1^2)}{WR\bar{T}} + \mu(\bar{T})^2} \right)$$



□ Easily implemented into GCM framework

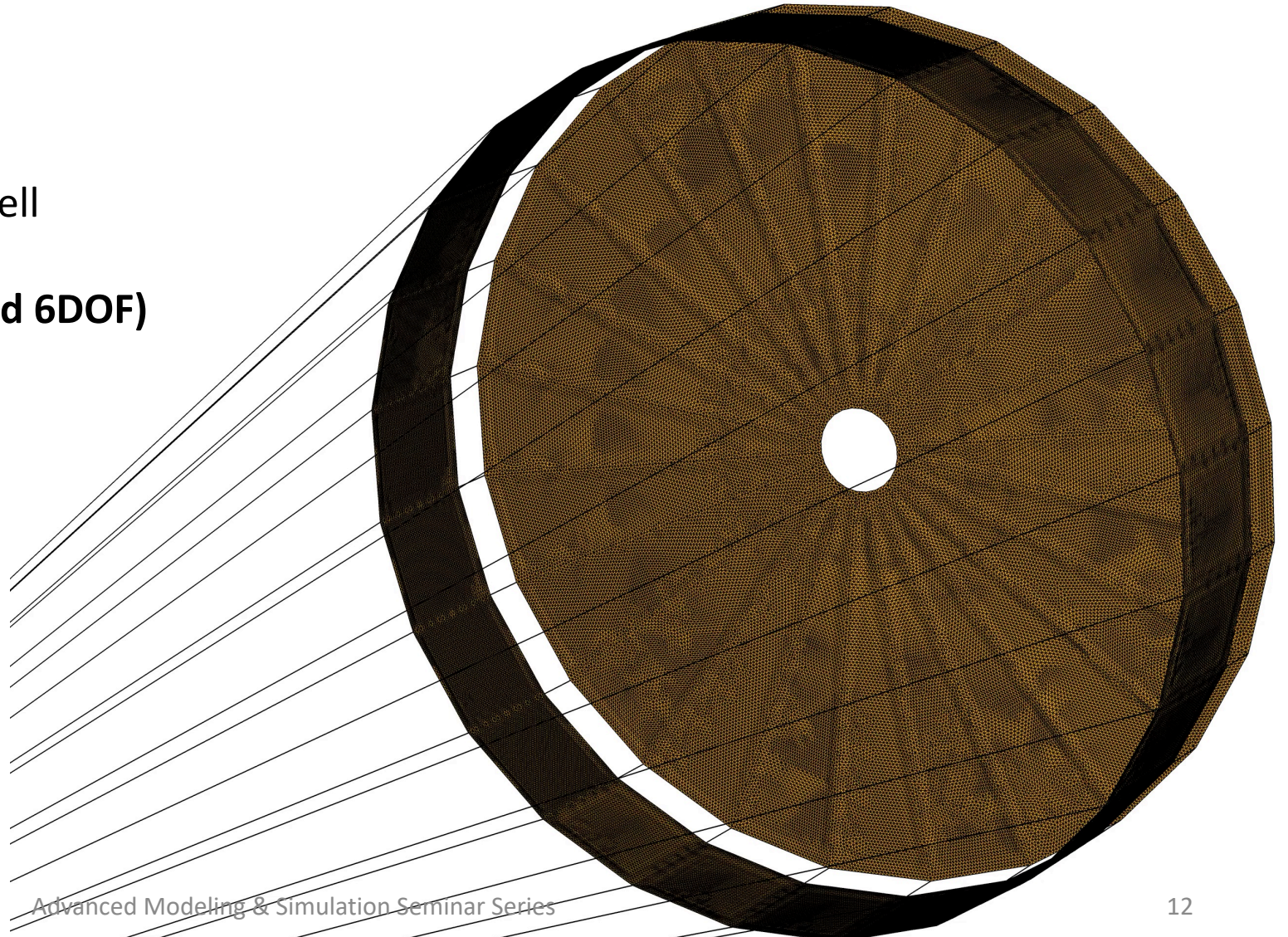
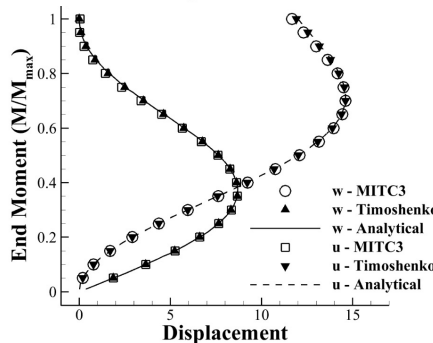
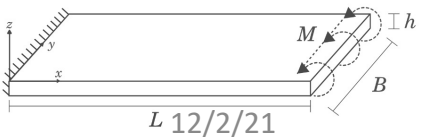
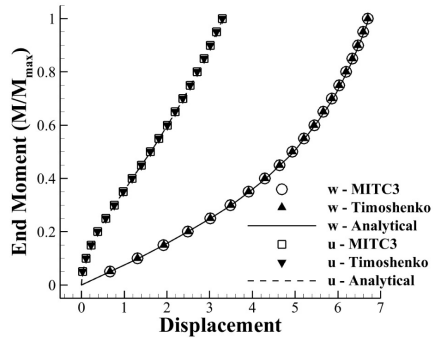
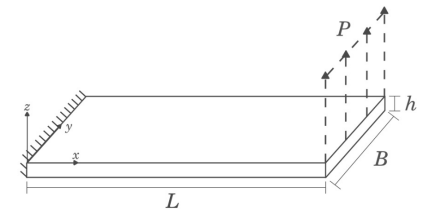


“An Immersed Interface Methodology for Simulating Supersonic Spacecraft Parachutes with Fluid-Structure Interaction”, Boustani et al., *Journal of Fluids and Structures*, 2021. Under review.

❑ The structural solver is capable of linear and nonlinear steady, unsteady, and modal analysis

❑ Elements available:

- Bernoulli-Euler beam
- Constant Strain Triangle (CST) shell
- **Cable**
- **MITC3 triangular shell (5DOF and 6DOF)**
- Timoshenko beam



□ Time integrators:

- **Implicit Newmark- β**
- Explicit central difference

$$\underline{\mathbf{M}}^{t+\Delta t} \ddot{\mathbf{u}}^{(k)} + {}^t \underline{\mathbf{K}}^{(k-1)} \Delta \mathbf{u}^{(k)} = {}^{t+\Delta t} \mathbf{r} - {}^{t+\Delta t} \mathbf{f}^{(k-1)}$$

Portable, Extensible Toolkit for Scientific Computation (PETSC)

- Krylov methods using GMRES, ILU, *etc.*
- Multifrontal Massively Parallel sparse direct Solver (MUMPs)
- MPI parallel only

□ Time integrators:

- Implicit Newmark- β
- **Explicit central difference**

Portable, Extensible Toolkit for Scientific Computation (PETSC)

- Krylov methods using GMRES, ILU, *etc.*
- Multifrontal Massively Parallel sparse direct Solver (MUMPs)
- MPI parallel only

In-house

- No global assembly (element-level)
- OpenMP-MPI parallelized
- Overlapping communication and computational strategy

$$\underline{\mathbf{M}}^t \ddot{\mathbf{u}} = {}^t\mathbf{r} - {}^t\mathbf{f}$$

$${}^t\underline{\mathbf{K}}^t u = \sum_{e=1}^{N_{elem.}} {}^t\underline{\mathbf{K}}_{local} {}^t\mathbf{u} = \sum_{e=1}^{N_{elem.}} {}^t\mathbf{f}$$

LAVA-Structural: Time Integration

Time integrators:

- Implicit Newmark- β
- **Explicit central difference**

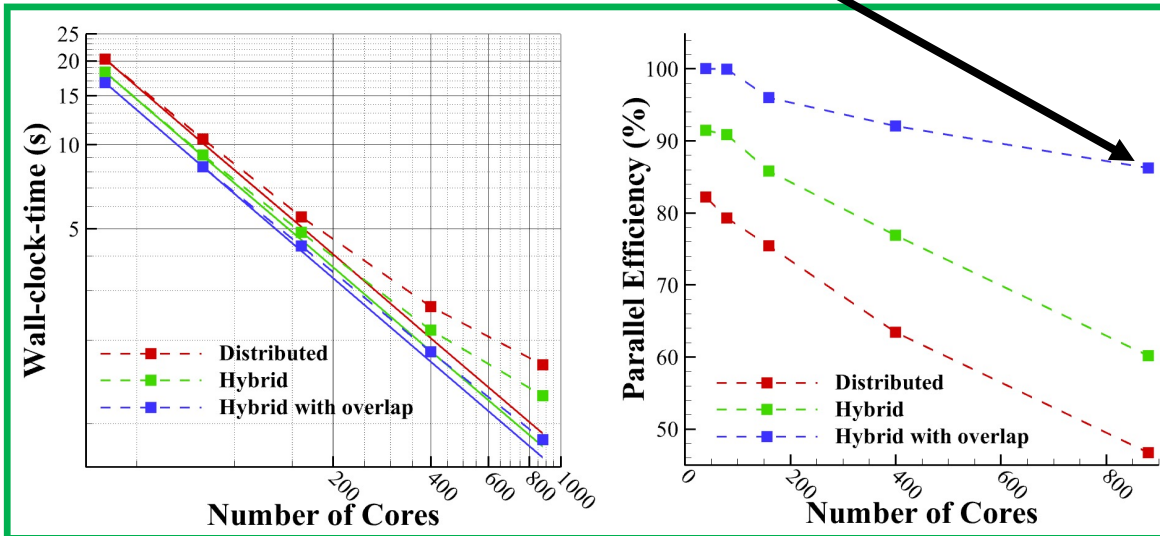
Hybrid+overlap
has 90% efficiency
at 3.2k DOF/core!

Portable, Extensible Toolkit for Scientific Computation (PETSC)

- Krylov methods using GMRES, ILU, etc.
- Multifrontal Massively Parallel sparse direct Solver (MUMPs)
- MPI parallel only

In-house

- No global assembly (element-level)
- OpenMP-MPI parallelized
- Overlapping communication and computational strategy



$$\underline{\mathbf{M}}^t \ddot{\mathbf{u}} = {}^t \mathbf{r} - {}^t \mathbf{f}$$

$${}^t \underline{\mathbf{K}}^t \mathbf{u} = \sum_{e=1}^{N_{elem.}} {}^t \underline{\mathbf{K}}_{local}^t \mathbf{u} = \sum_{e=1}^{N_{elem.}} {}^t \mathbf{f}$$

FSI

Monolithic

- Shared discretization
- Specialized framework
- Developed *a priori* for FSI

Partitioned

- Good for modularized solvers

Loose/weak/explicit

1. Step CFD
2. Load Transfer
3. Step CSD
4. Disp. Transfer
5. Advance time level

***Conditional stability**

Tight/strong/implicit

1. Step CFD
2. Load Transfer
3. Step CSD
4. Disp. Transfer
5. Check norms; back to 1.
6. Advance time level

FSI

Monolithic

- Shared discretization
- Specialized framework
- Developed *a priori* for FSI

Partitioned

- Good for modularized solvers

Loose/weak/explicit

1. Step CFD
2. Load Transfer
3. Step CSD
4. Disp. Transfer
5. Advance time level

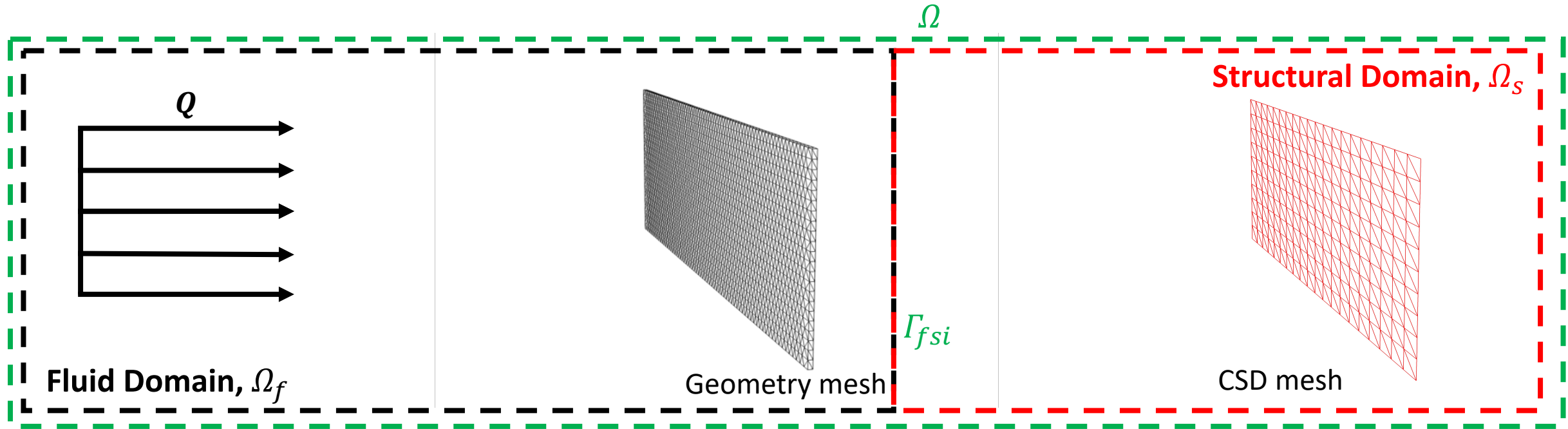
***Conditional stability**

Tight/strong/implicit

1. Step CFD
2. Load Transfer
3. Step CSD
4. Disp. Transfer
5. Check norms; back to 1.
6. Advance time level

Fluid-Structure Coupling Strategy

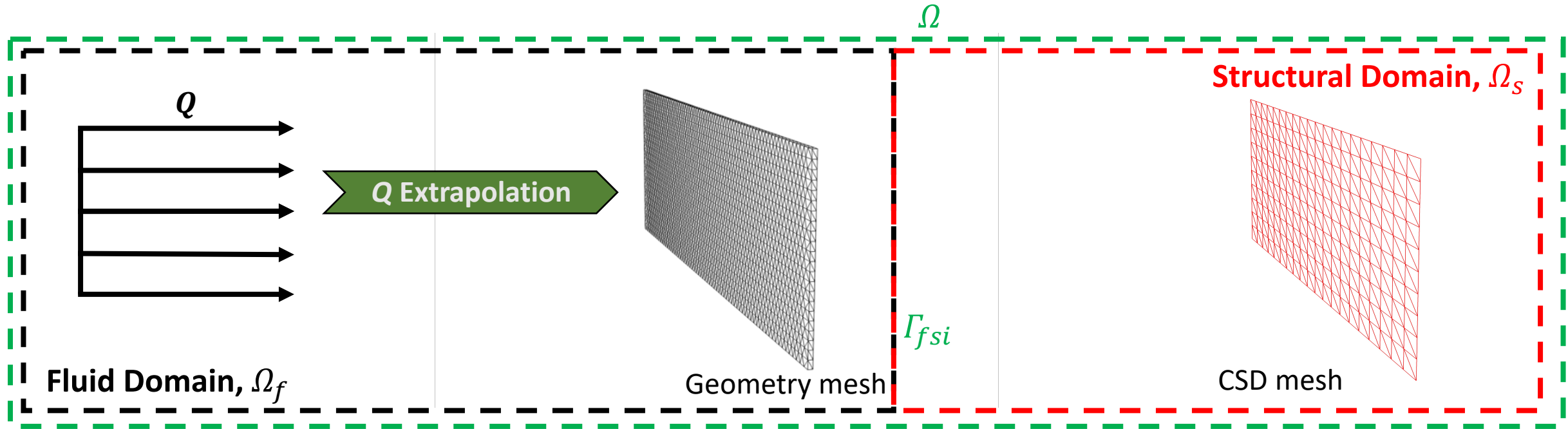
- ❑ The shared domain boundary is the surface triangulation representing the CFD geometry
 - Finite thickness (avoid over-specializing IBM framework)
 - Zero-mass, phantom representation



"An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures", Boustani et al., Journal of Computational Physics, 2021.

Fluid-Structure Coupling Strategy

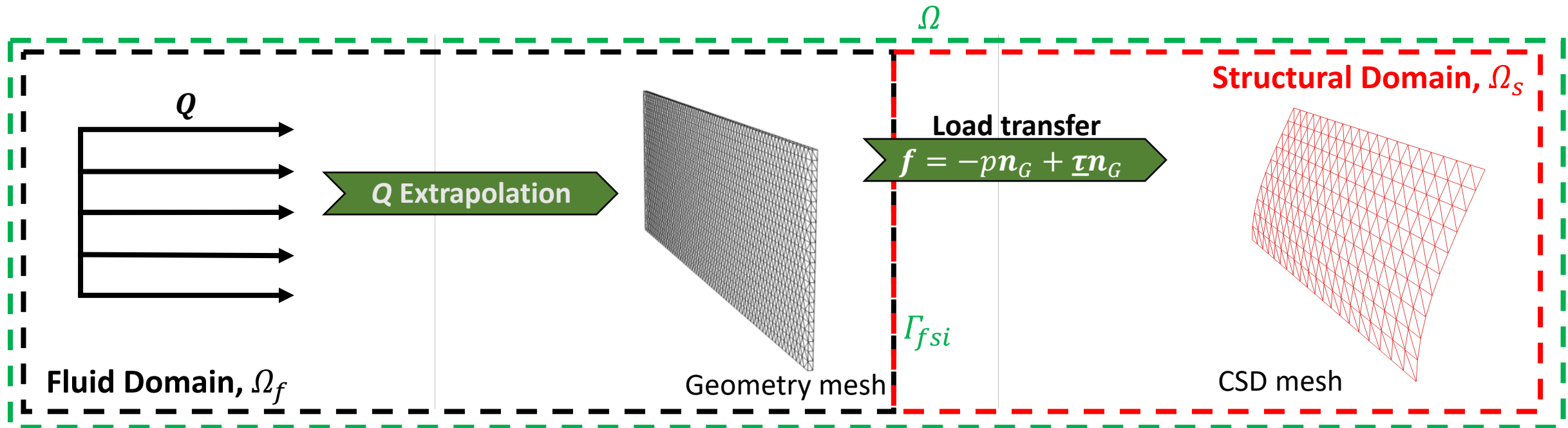
- ❑ The shared domain boundary is the surface triangulation representing the CFD geometry
 - Finite thickness (avoid over-specializing IBM framework)
 - Zero-mass, phantom representation



“An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures”, Boustani et al., Journal of Computational Physics, 2021.

Fluid-Structure Coupling Strategy

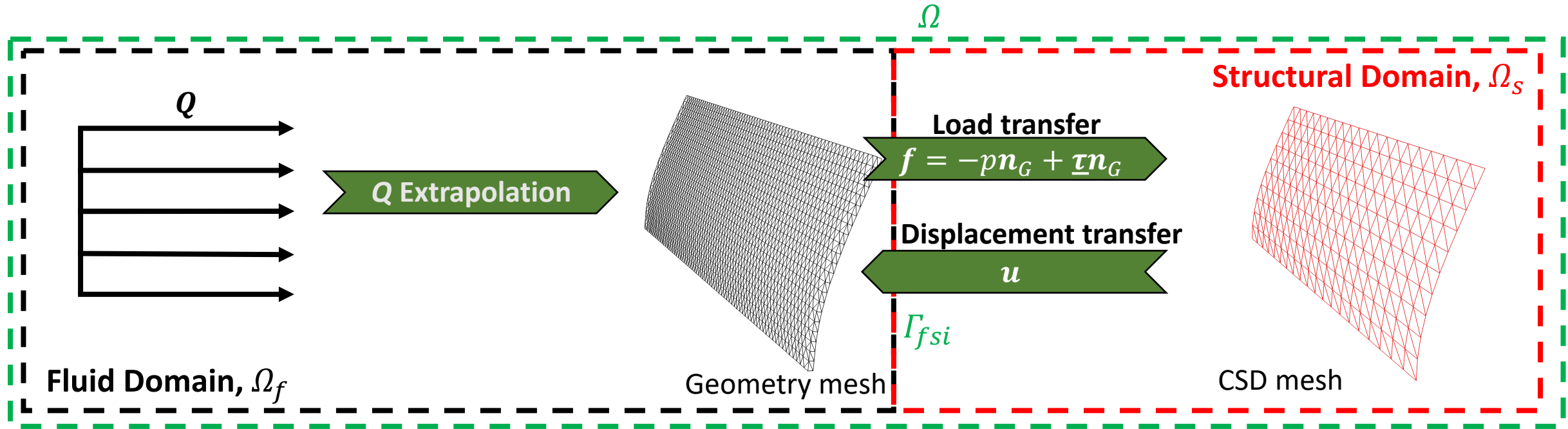
- ❑ The shared domain boundary is the surface triangulation representing the CFD geometry
 - Finite thickness (avoid over-specializing IBM framework)
 - Zero-mass, phantom representation



“An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures”, Boustani et al., *Journal of Computational Physics*, 2021.

Fluid-Structure Coupling Strategy

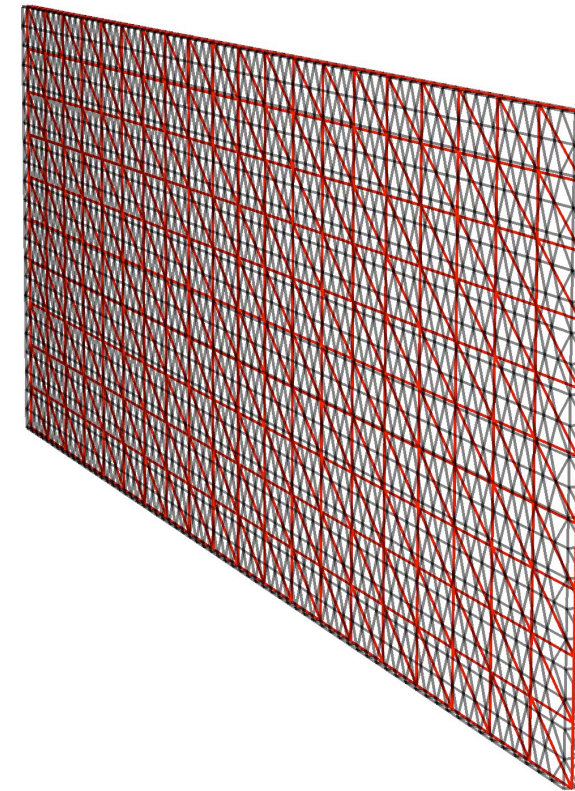
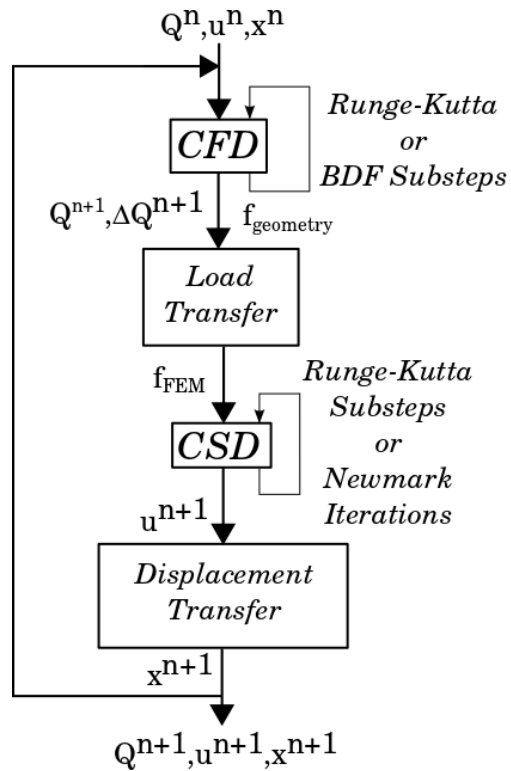
- ❑ The shared domain boundary is the surface triangulation representing the CFD geometry
 - Finite thickness (avoid over-specializing IBM framework)
 - Zero-mass, phantom representation



“An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures”, Boustani et al., *Journal of Computational Physics*, 2021.

Fluid-Structure Coupling Strategy

- ❑ The shared domain boundary is the surface triangulation representing the CFD geometry
 - Finite thickness (avoid over-specializing IBM framework)
 - Zero-mass, phantom representation

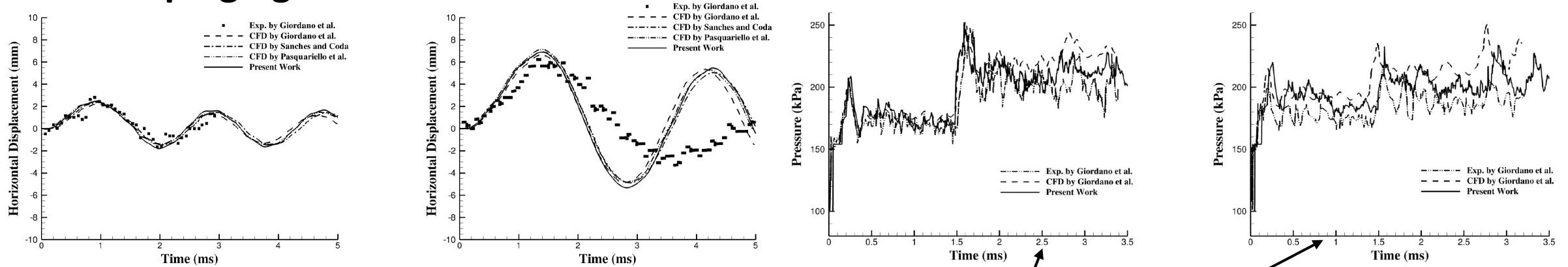


“An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures”, Boustani et al., *Journal of Computational Physics*, 2021.

Fluid-Structure Coupling - Validation



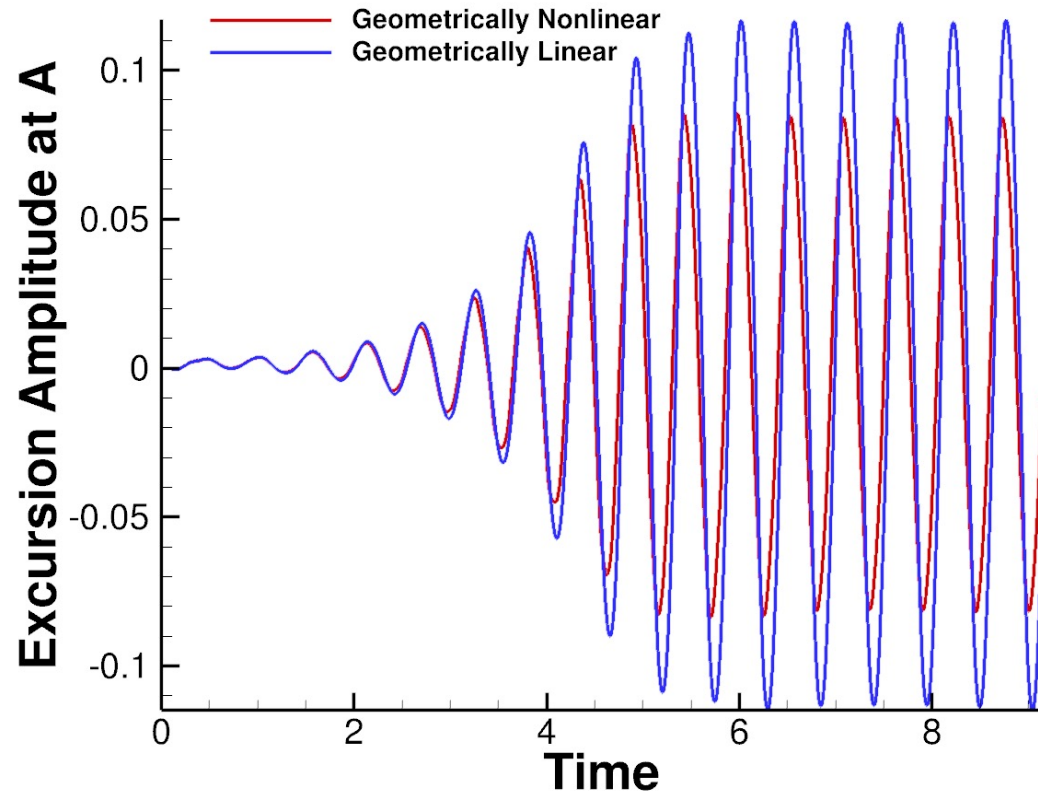
Shock Impinging on a 40mm and 50mm Cantilever Plate



"An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures", Boustani et al., *Journal of Computational Physics*, 2021.

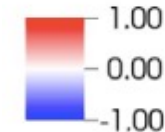
Fluid-Structure Coupling - Validation

Fixed Cylinder and Trailing Flexible Filament



Case 1	Reference	$\bar{A}$	St
Geometrically Nonlinear, $Re = 100$, $DR = 10$, $S_b = 1400$	Present Work	0.77	0.18
	Tian <i>et al.</i>	0.78	0.19
	Turek and Hron	0.83	0.19
	Bhardwaj and Mittal	0.92	0.19

Linear



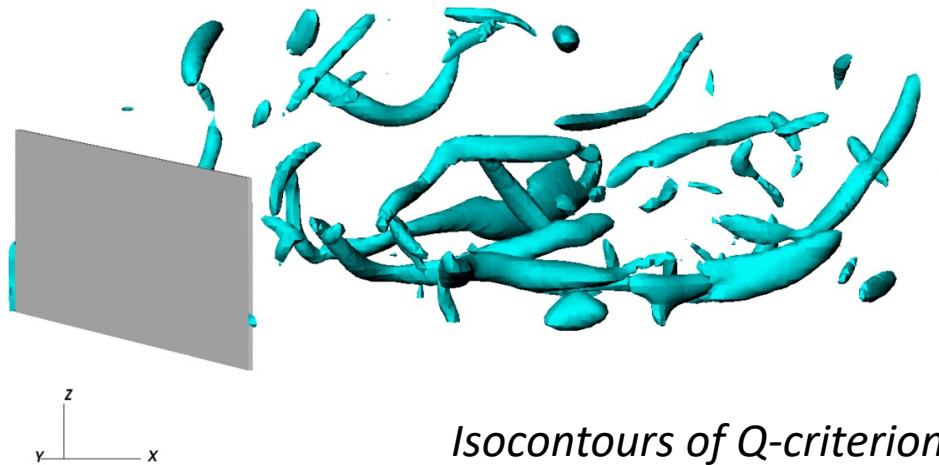
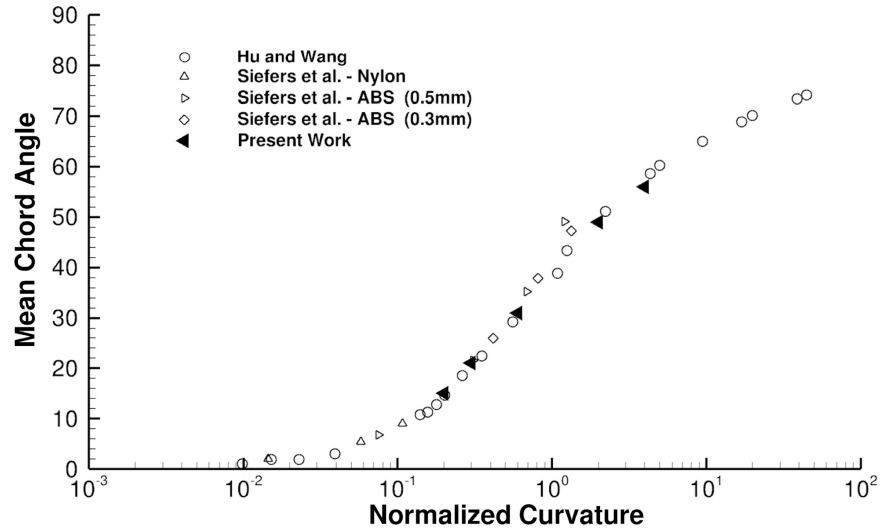
Pseudocolor contours of vertical velocity

Nonlinear

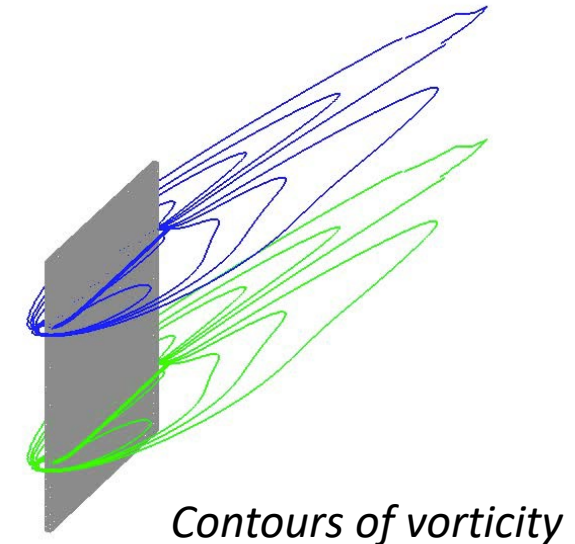
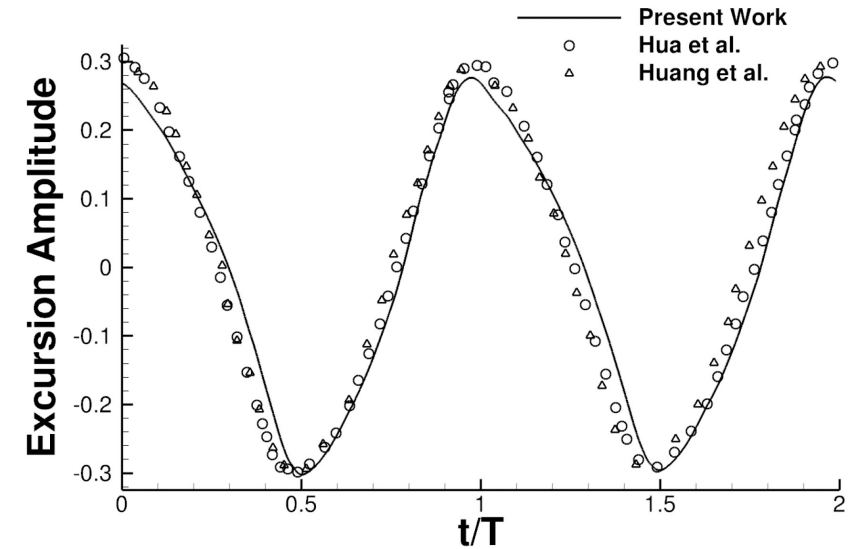


Fluid-Structure Coupling - Validation

Clamped Flexible Plate in Crossflow



Waving Flag

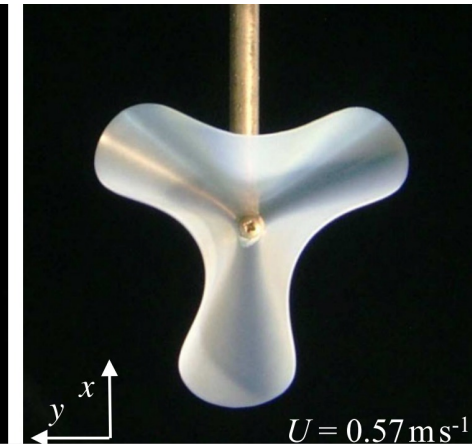
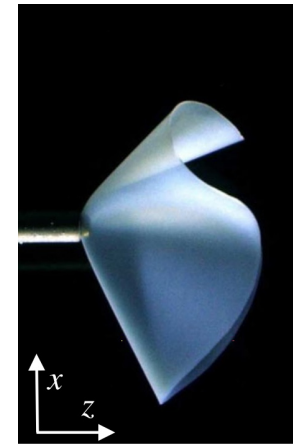
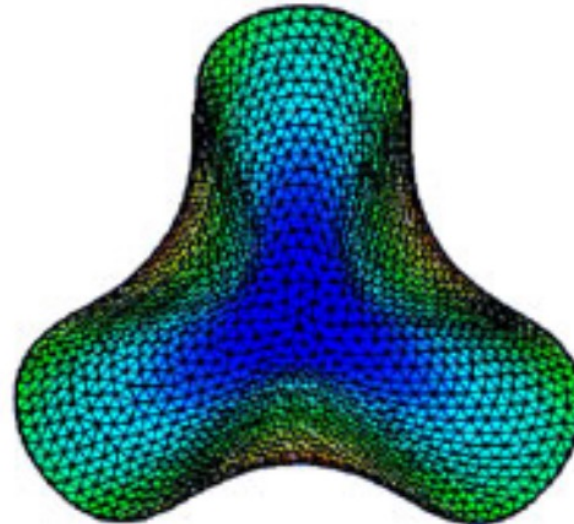
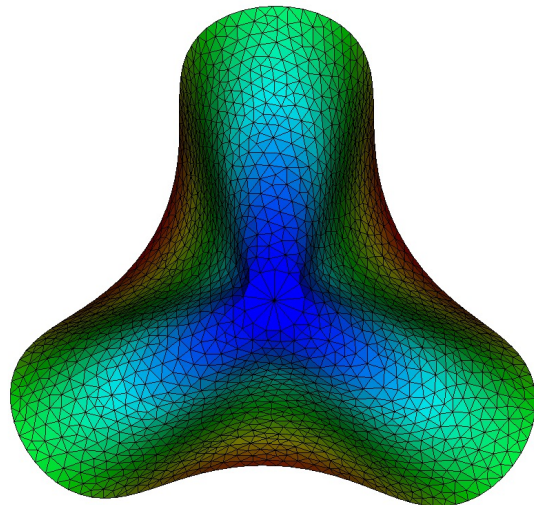
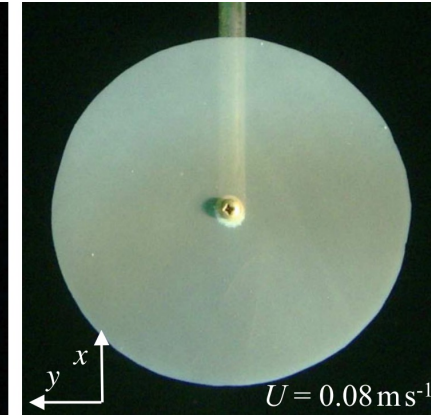
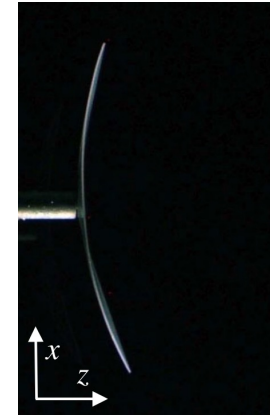
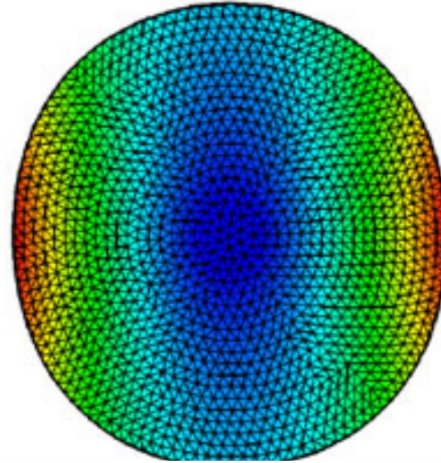
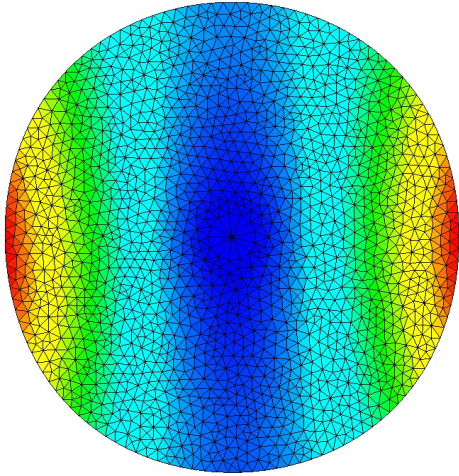


Fluid-Structure Coupling - Demonstration



Clamped Circular Disks in Crossflow

"An Immersed Boundary Fluid-Structure Interaction Method for Thin Shell Structures", Boustani et al., Journal of Computational Physics, 2021.



Present work

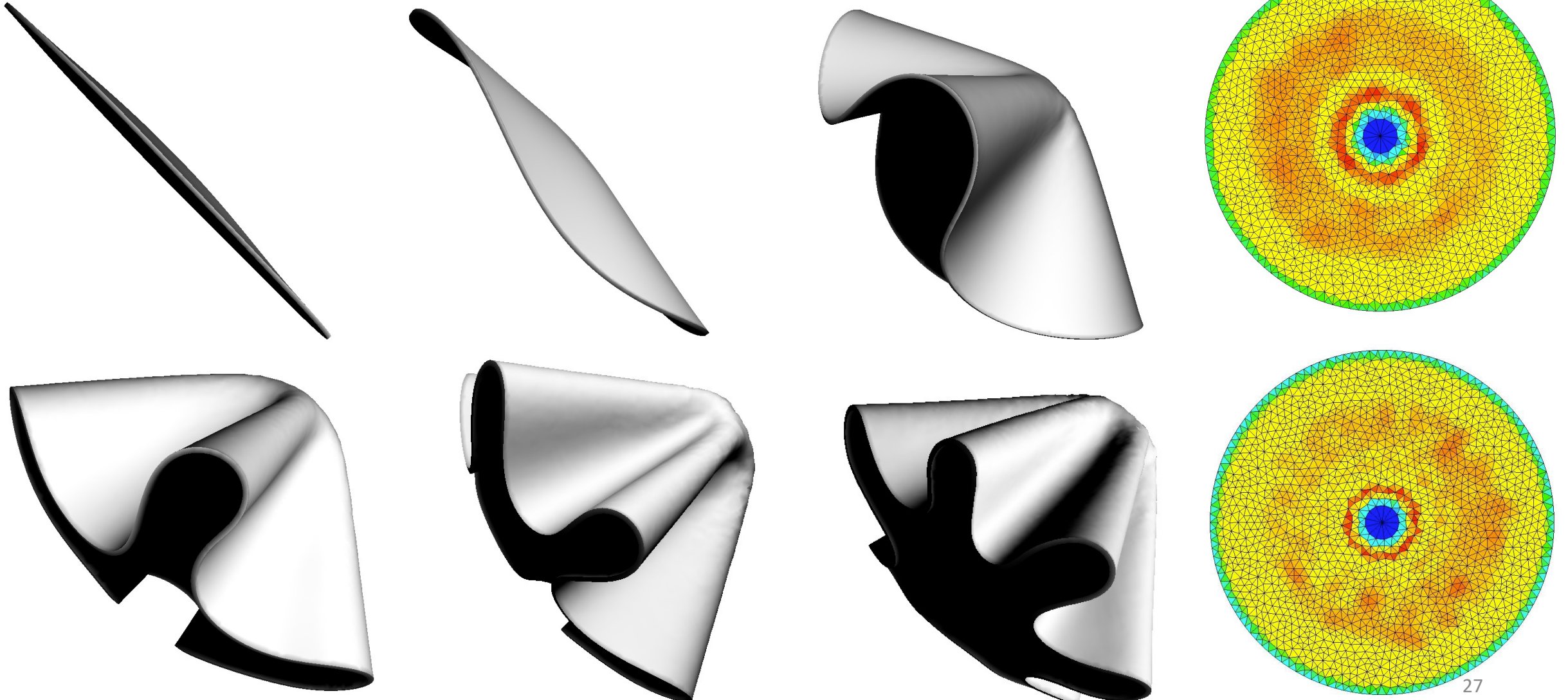
Simulations by Hua et al.
(Adjusted from JFM 2014)

Experiments by Schouveiler and Eloy
(Adjusted from Physical Review Letters 2013)

Fluid-Structure Coupling - Demonstration



Clamped Circular Disks in Crossflow





Contact Mechanics: Overview

- ❑ Massive (self-)contact occurs during the early stages of parachute inflation
- ❑ Very small gaps and geometry intersections are problematic for the CFD solver
- ❑ Difficult to address numerically:
 - No clear contactor-contacted relationship (no “one-way” seeking allowed)
 - Contact is possible across hundreds of thousands, even millions of triangles
 - “Soft goods” (parachute fabric) behave much differently than metals



- ❑ Contact identification in parallel is challenging
 - Must (1) partition the global problem then (2) identify contacting bodies across partition boundaries
- ❑ The global search step employs some bounding volume hierarchy (BVH) approach
 - In LAVA, this uses optimized commercial libraries
- ❑ The local search steps involves ray-triangle intersection tests

Contact Enforcement: Penalty Impulse

- ❑ “Virtual” contact is identified between two triangular elements of the geometry mesh
- ❑ A wall-normal impulse is derived from first principles
 - The “virtual mass” of the elements is obtained from the underlying structural mesh properties

$$p_{n,e} = \frac{m_e \cdot m_{pair}}{m_e + m_{pair}} (1 + \delta_{contact}) (v_{n,pair} - v_{n,e}) \quad \longrightarrow \quad \mathbf{F}_e = \frac{1}{\Delta t} p_{n,e} \mathbf{n}_{pair}$$

Impulse **Force**

“An Immersed Interface Methodology for Simulating Supersonic Spacecraft Parachutes with Fluid-Structure Interaction”, Boustani et al., *Journal of Fluids and Structures*, 2021. Under review.

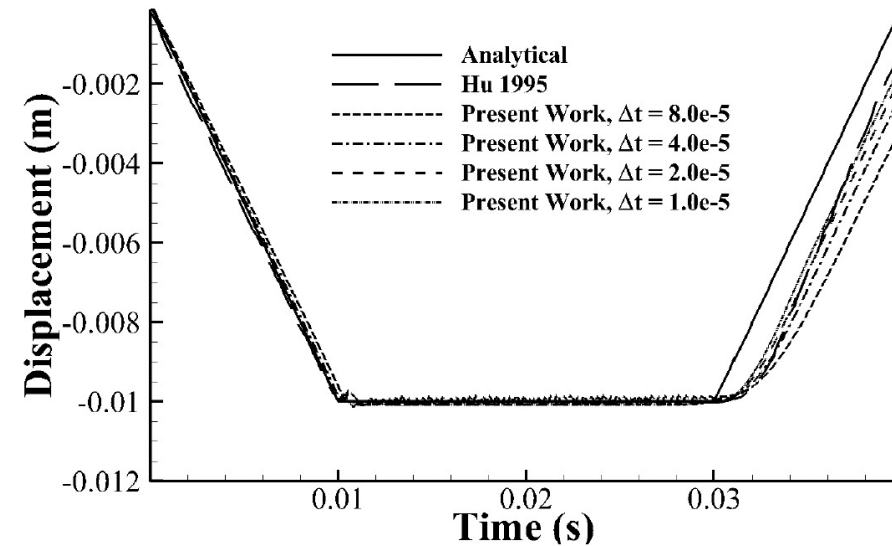
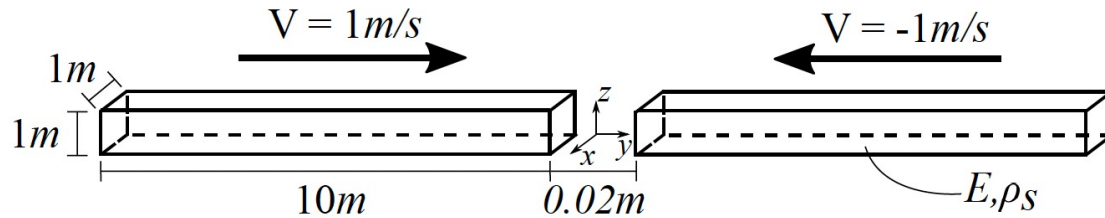
Contact Enforcement: Penalty Impulse

❑ “Virtual” contact is identified between two triangular elements of the geometry mesh

❑ A wall-normal impulse is derived from first principles

- The “virtual mass” of the elements is obtained from the underlying structural mesh properties

$$p_{n,e} = \frac{m_e \cdot m_{pair}}{m_e + m_{pair}} (1 + \delta_{contact}) (v_{n,pair} - v_{n,e}) \quad \longrightarrow \quad \mathbf{F}_e = \frac{1}{\Delta t} p_{n,e} \mathbf{n}_{pair}$$



“An Immersed Interface Methodology for Simulating Supersonic Spacecraft Parachutes with Fluid-Structure Interaction”, Boustani et al., *Journal of Fluids and Structures*, 2021. Under review.

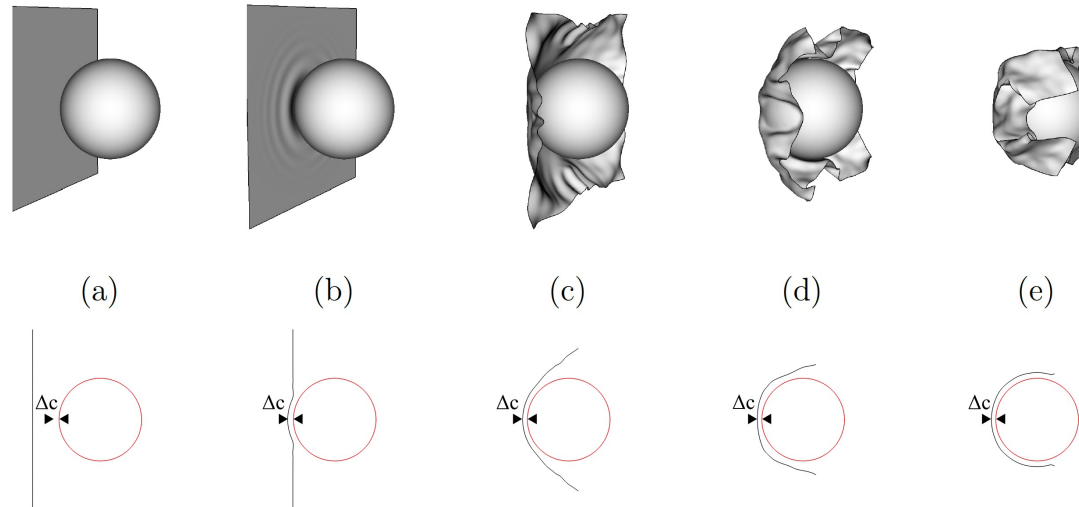
Contact Enforcement: Penalty Impulse

❑ “Virtual” contact is identified between two triangular elements of the geometry mesh

❑ A wall-normal impulse is derived from first principles

- The “virtual mass” of the elements is obtained from the underlying structural mesh properties

$$p_{n,e} = \frac{m_e \cdot m_{pair}}{m_e + m_{pair}} (1 + \delta_{contact}) (v_{n,pair} - v_{n,e}) \quad \longrightarrow \quad \mathbf{F}_e = \frac{1}{\Delta t} p_{n,e} \mathbf{n}_{pair}$$



“An Immersed Interface Methodology for Simulating Supersonic Spacecraft Parachutes with Fluid-Structure Interaction”, Boustani et al., *Journal of Fluids and Structures*, 2021. Under review.

Supersonic Parachute Inflation: Sub-scale MSL



❑ Wind tunnel experiments supporting MSL are reproduced

❑ Goals of this study:

- Demonstrate and evaluate all developments made for thin, complex geometries, porosity, and contact
- Further validate the FSI coupling strategy
- Begin to study the physical mechanisms dominating supersonic parachute inflation

Test Matrix

Case	M_∞	$q_\infty (kPa)$	$v_\infty (m/s)$	Upstream capsule	Porosity model
1	$M = 2.0$	17.4	692.2	Yes	PIA-C-44378C
2	$M = 2.5$	19.9	865.3	Yes	PIA-C-44378C
3	$M = 2.2$	18.6	761.5	Yes	PIA-C-44378C
4	$M = 2.2$	18.6	761.5	Yes	PIA-C-7020D
5	$M = 2.2$	18.6	761.5	No	PIA-C-44378C
6	$M = 2.2$	18.6	761.5	No	PIA-C-7020D

Study the effect of **Mach number** and **dynamic pressure** on parachute opening loads

“An Immersed Interface Methodology for Simulating Supersonic Spacecraft Parachutes with Fluid-Structure Interaction”, Boustani et al., *Journal of Fluids and Structures*, 2021. Under review.

Supersonic Parachute Inflation: Sub-scale MSL



❑ Wind tunnel experiments supporting MSL are reproduced

❑ Goals of this study:

- Demonstrate and evaluate all developments made for thin, complex geometries, porosity, and contact
- Further validate the FSI coupling strategy
- Begin to study the physical mechanisms dominating supersonic parachute inflation

Test Matrix

Case	M_∞	$q_\infty(kPa)$	$v_\infty(m/s)$	Upstream capsule	Porosity model
1	$M = 2.0$	17.4	692.2	Yes	PIA-C-44378C
2	$M = 2.5$	19.9	865.3	Yes	PIA-C-44378C
3	$M = 2.2$	18.6	761.5	Yes	PIA-C-44378C
4	$M = 2.2$	18.6	761.5	Yes	PIA-C-7020D
5	$M = 2.2$	18.6	761.5	No	PIA-C-44378C
6	$M = 2.2$	18.6	761.5	No	PIA-C-7020D

Study the effect of **porosity** on the aerodynamic drag performance

Supersonic Parachute Inflation: Sub-scale MSL



❑ Wind tunnel experiments supporting MSL are reproduced

❑ Goals of this study:

- Demonstrate and evaluate all developments made for thin, complex geometries, porosity, and contact
- Further validate the FSI coupling strategy
- Begin to study the physical mechanisms dominating supersonic parachute inflation

Test Matrix

Case	M_∞	$q_\infty(kPa)$	$v_\infty(m/s)$	Upstream capsule	Porosity model
1	$M = 2.0$	17.4	692.2	Yes	PIA-C-44378C
2	$M = 2.5$	19.9	865.3	Yes	PIA-C-44378C
3	$M = 2.2$	18.6	761.5	Yes	PIA-C-44378C
4	$M = 2.2$	18.6	761.5	Yes	PIA-C-7020D
5	$M = 2.2$	18.6	761.5	No	PIA-C-44378C
6	$M = 2.2$	18.6	761.5	No	PIA-C-7020D

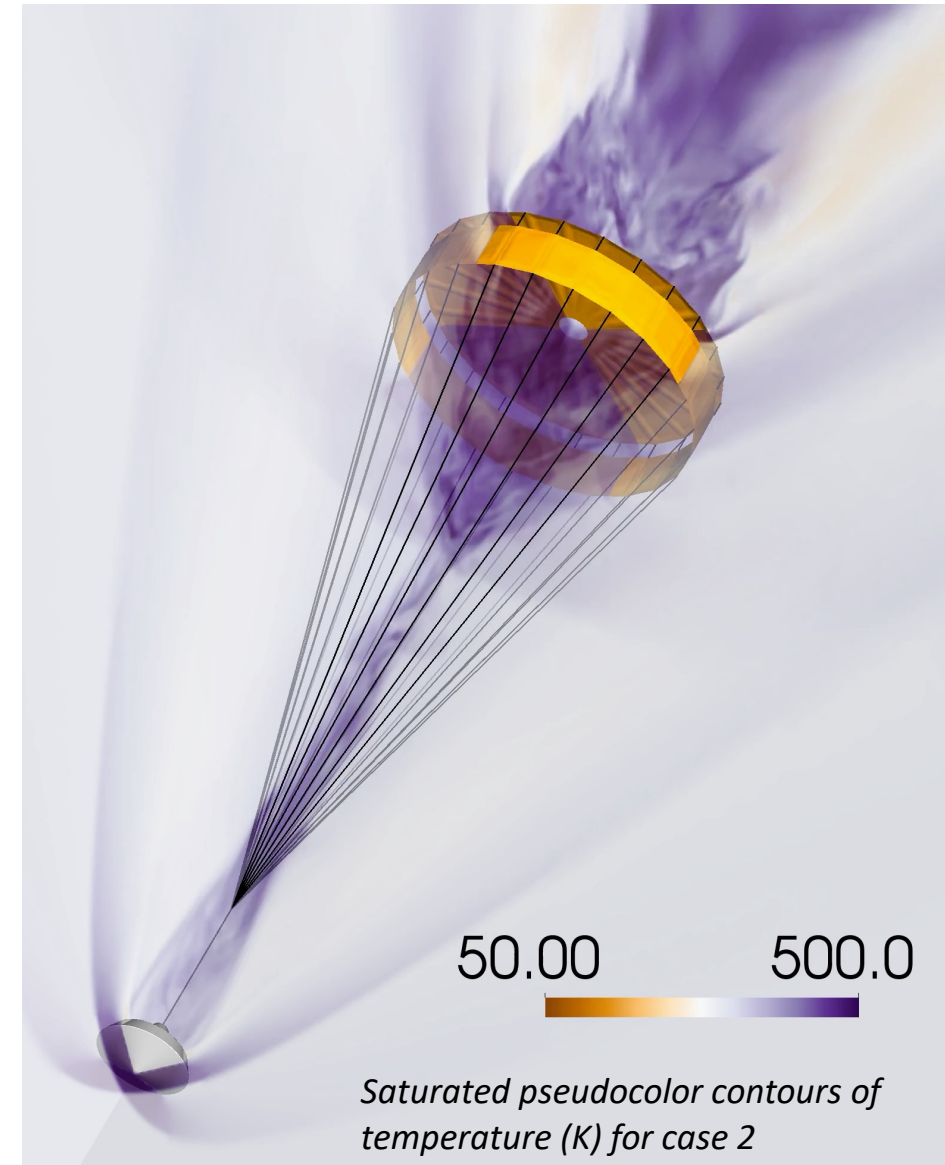
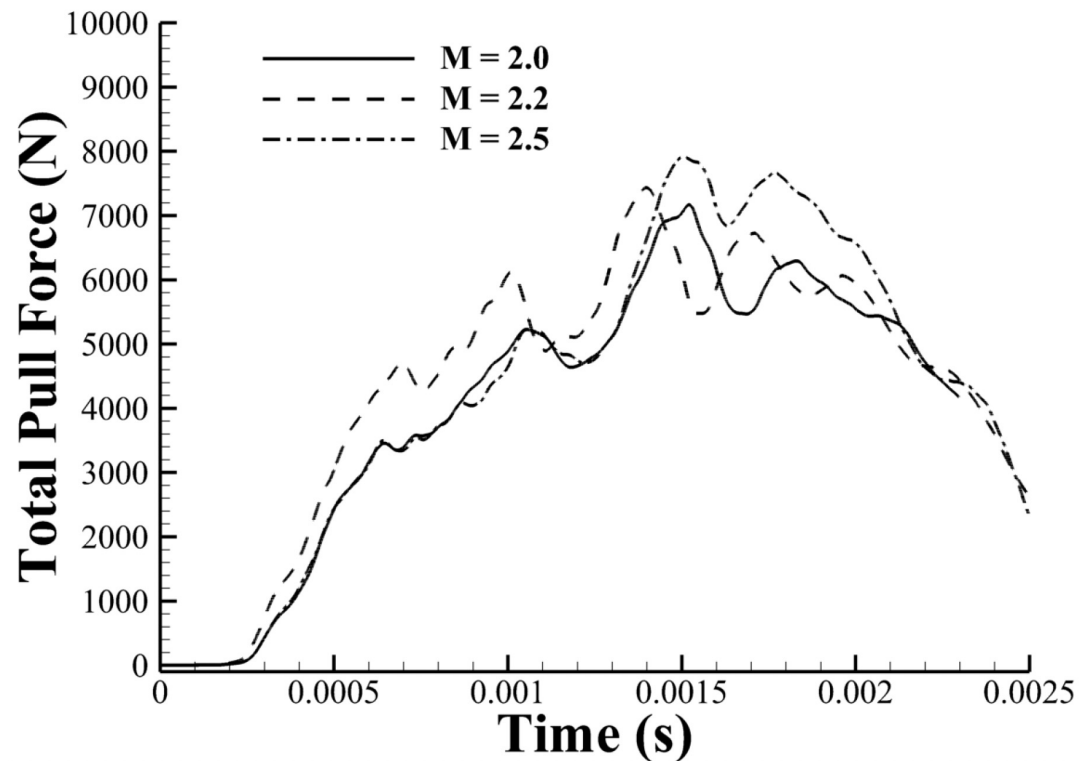
Study the effect of the
bluff upstream payload on
the opening loads and drag
performance

Sub-scale MSL: Opening Load Analysis



❑ Cases 1-3 are simulated with FSI

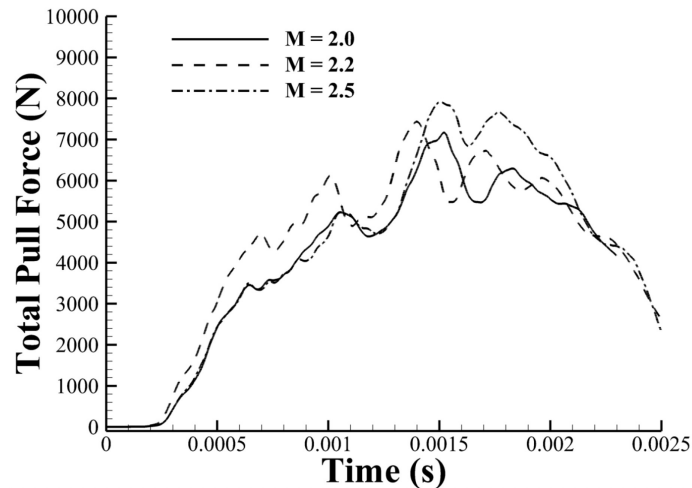
- The internal forces in the 24 suspension lines are summed
- Peak load is proportional to Mach number/dynamic pressure



Sub-scale MSL: Opening Load Analysis

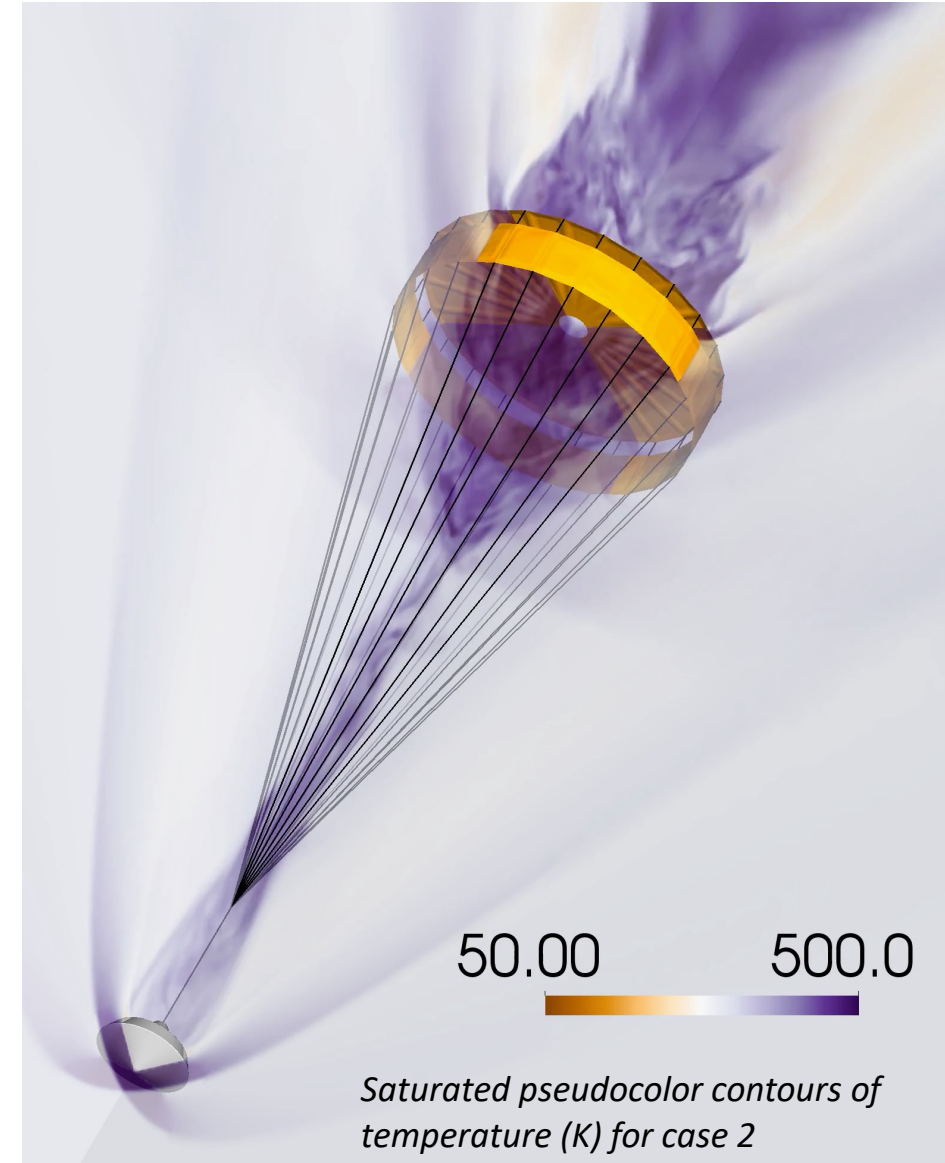
❑ Comparison with experimental data is fair

M/q	F_{peak} , Experiment	F_{peak} , FSI (%diff)
2.0/17.4kPa	6480.33N	7167.07N (10.59%)
2.2/18.6kPa	7402.05N	7403.83N (<1%)
2.5/19.9kPa	7322.68N	7910.73N (8.03%)



❑ Over prediction associated with modeling deficiencies:

- No attempt to model **thick** suspension lines in the flow
- No attempt to simulate wind tunnel/blockage (free flight)



Sub-scale MSL: Opening Load Analysis

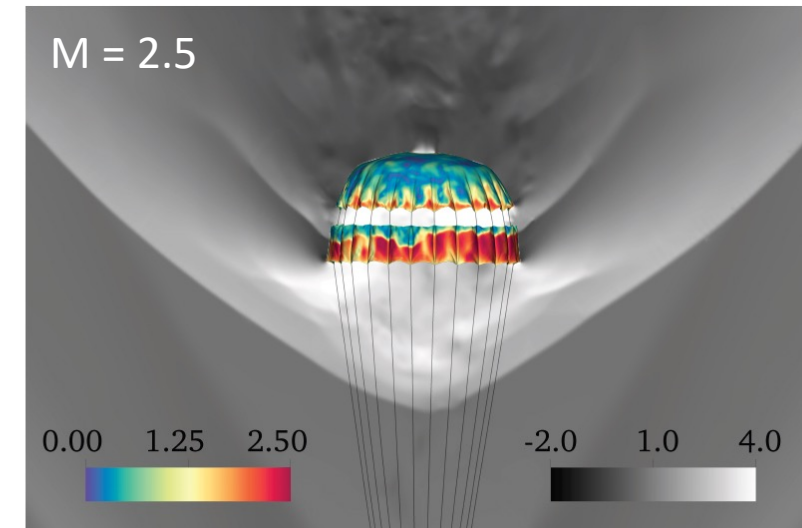
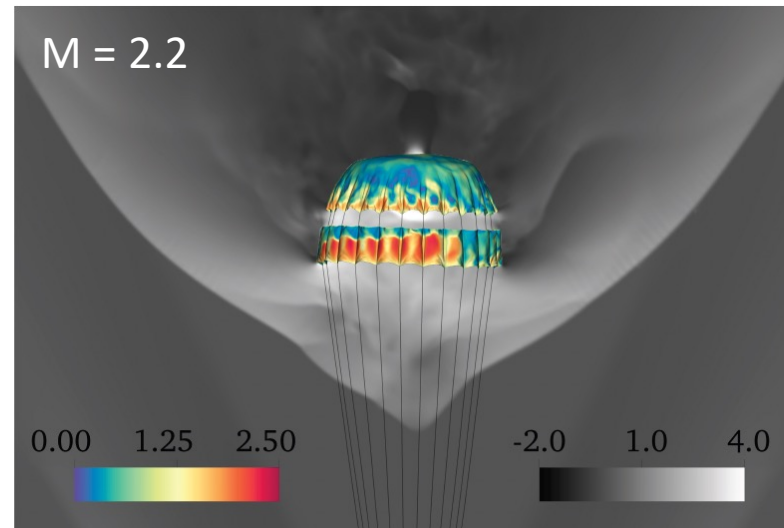
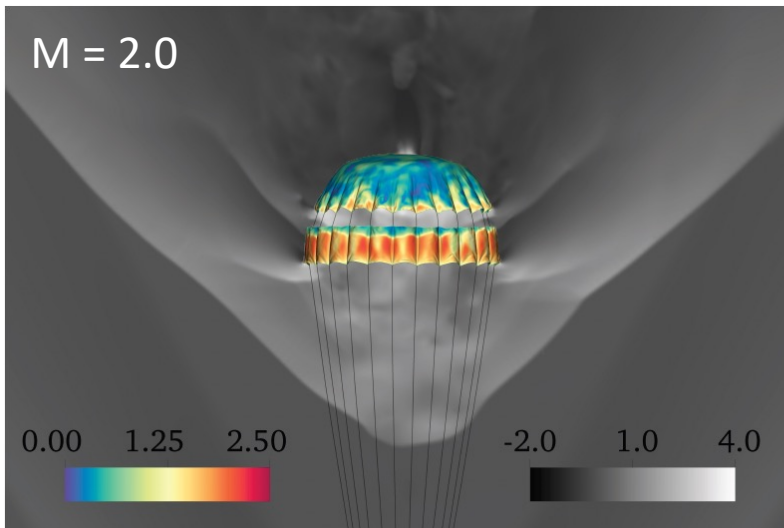
❑ An empirical formula was derived by Way (IEEE 2018)

- $k_p < 1$ represents freestream momentum deficit

$$F_{peak} = 2k_p q_{\infty} A_{proj.}$$

M/q	k_p	$F_{peak, Empirical}$	$F_{peak, FSI} (\%diff)$
2.0/17.4kPa	0.83027	6733.23N	7167.07N (6.44%)
2.2/18.6kPa	0.82817	7179.35N	7403.83N (3.13%)
2.5/19.9kPa	0.82406	7643.06N	7910.73N (3.50%)

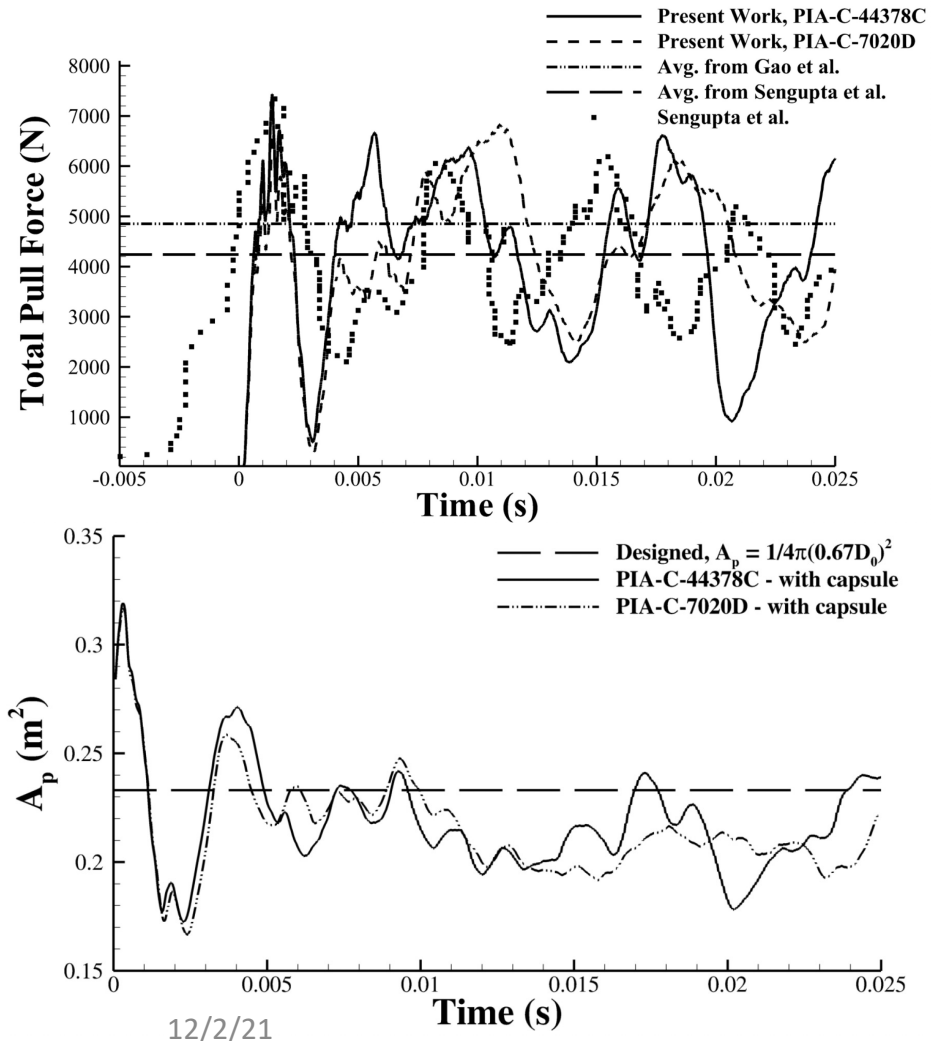
Saturated pseudocolor contours of the freestream-normalized gauge pressure shown in grey-scale on a cut-plane through the center of the domain and Mach number show on the surface of the parachute at the instance of peak loading.



Sub-scale MSL: Aerodynamic Drag Performance

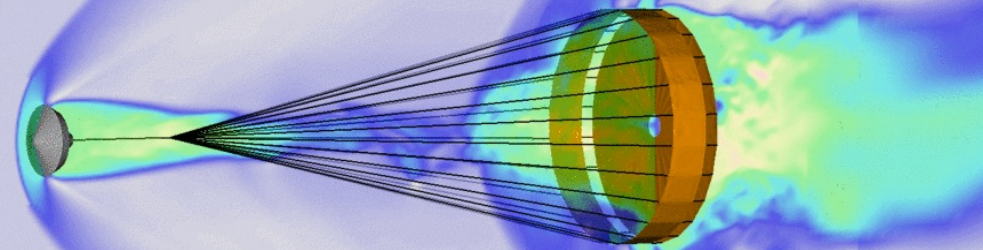
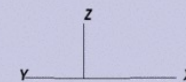
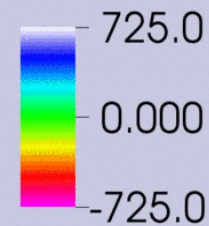


❑ High-cost and relatively long simulation times motivates only $M=2.2$ be studied here



Data set	$F_{avg.} (N)$	$C_d = F_{avg.}/(q_{\infty}A_0)$	% diff.
PIA-C-44378C	4580.81	0.474	-
PIA-C-7020D	4330.33	0.448	5.80%
FSI by Gao*	4850.05	0.502	5.58%
Exps. by Sengupta**	~4238.33	0.420-0.446	12.86-6.27%
Heritage Viking Exps.***	N/A	0.457	3.72%

Saturated pseudocolor contours of velocity (m/s) for case 2



*Gao *et al.* Advances in Space Research 2016

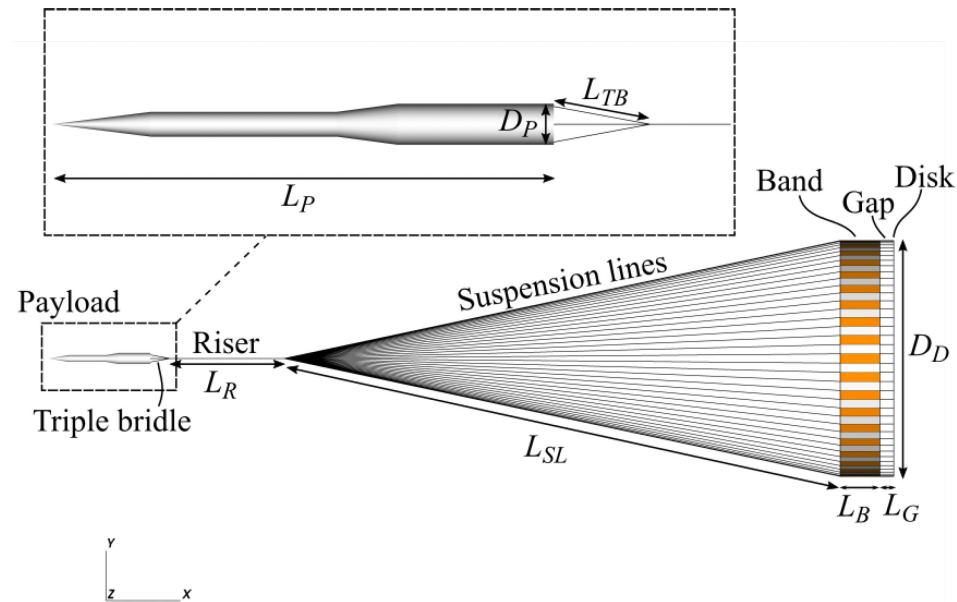
**Sengupta *et al.* Journal of Spacecraft and Rockets 2009

***Jaremenko *et al.* NASA Report 1971

Supersonic Parachute Inflation: Full-scale ASPIRE



- ❑ A build-to-print MSL parachute inflated in the wake of a slender payload at ~40km
- ❑ The goals of this study are to:
 - Validate the FSI coupling strategy for full-scale supersonic parachute inflation
 - Systematically study the grid resolution requirements in the fluid and structural domains

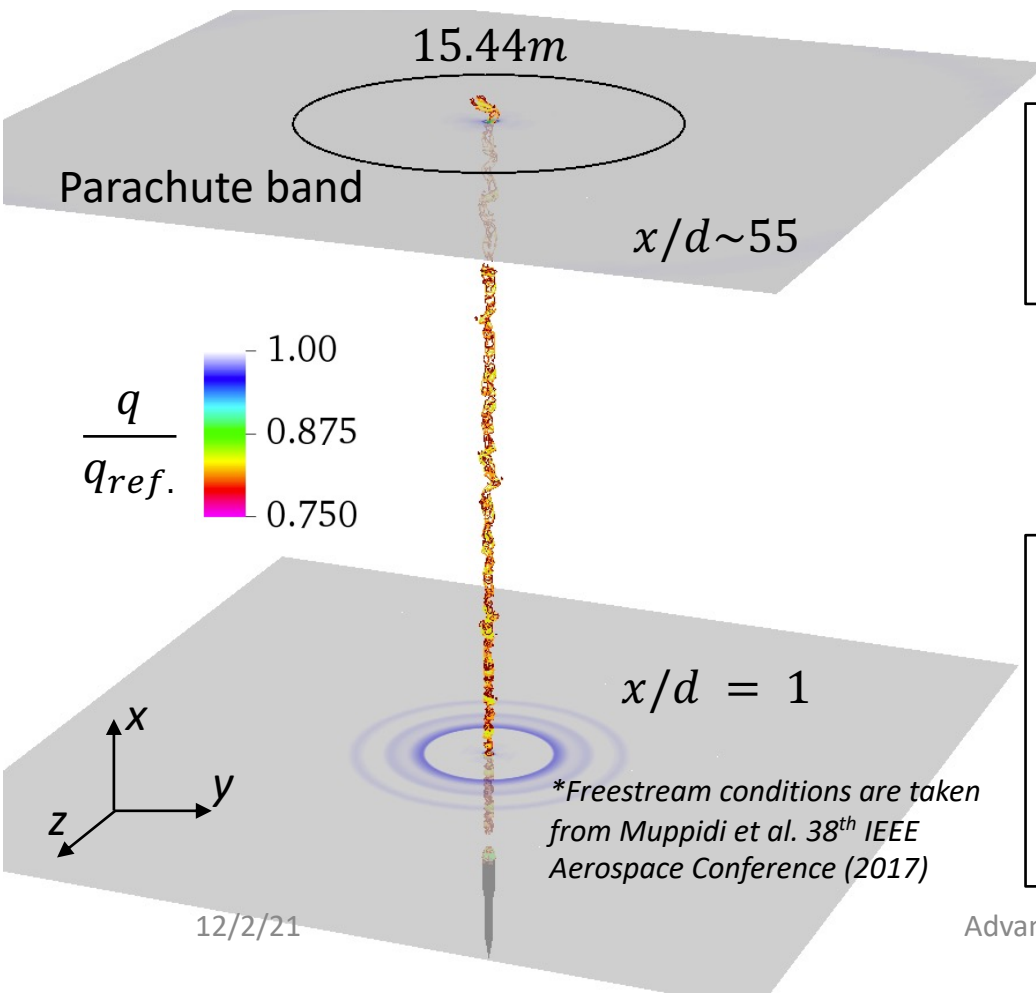


“Fluid-Structure Interaction Simulations of the ASPIRE SR01 Supersonic Parachute”, Boustani et al., AIAA SciTech 2022.

Grid Resolution Study: Slender Capsule Wake



- ❑ ASPIRE saw the use of a slender capsule as opposed to typical bluff-bodied entry capsules
 - This significantly affects the wake deficit and the level of capsule wake/canopy bow shock interaction



- ❖ Probes at: $y = 0.5d, y = d, y = 2d$
- ❖ Trailing distance of: $x = 40m$ behind the capsule nose
- ❖ Capsule diameter: $d \sim 0.72m$

Freestream conditions*

- $P = 251.45Pa$
- $U = 558.2 \frac{m}{s}$
- $T = 253.215K$
- $q_{ref} = 538Pa$
- $M = 1.75$

*Freestream conditions are taken from Muppidi et al. 38th IEEE Aerospace Conference (2017)

- A previous study by Muppidi *et al.* on the ASPIRE capsule found that the wake deficit quickly returns to unity as the probes move radially outward

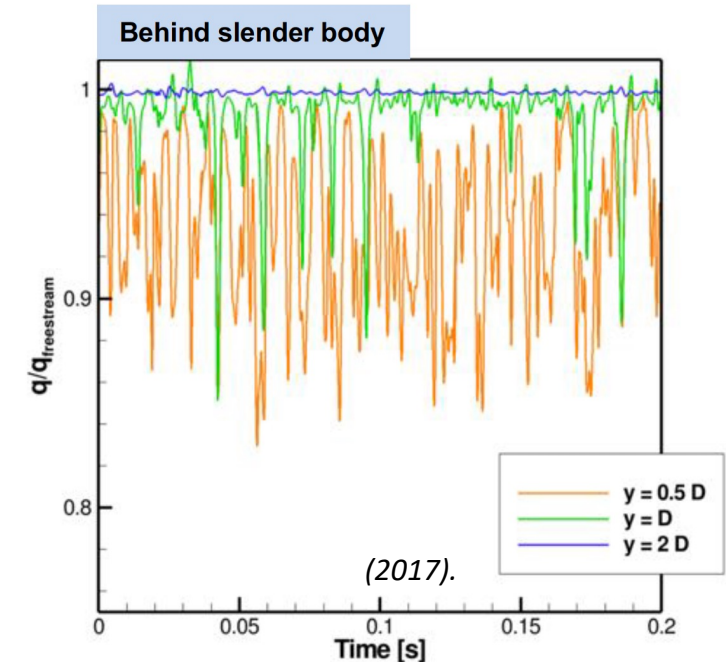
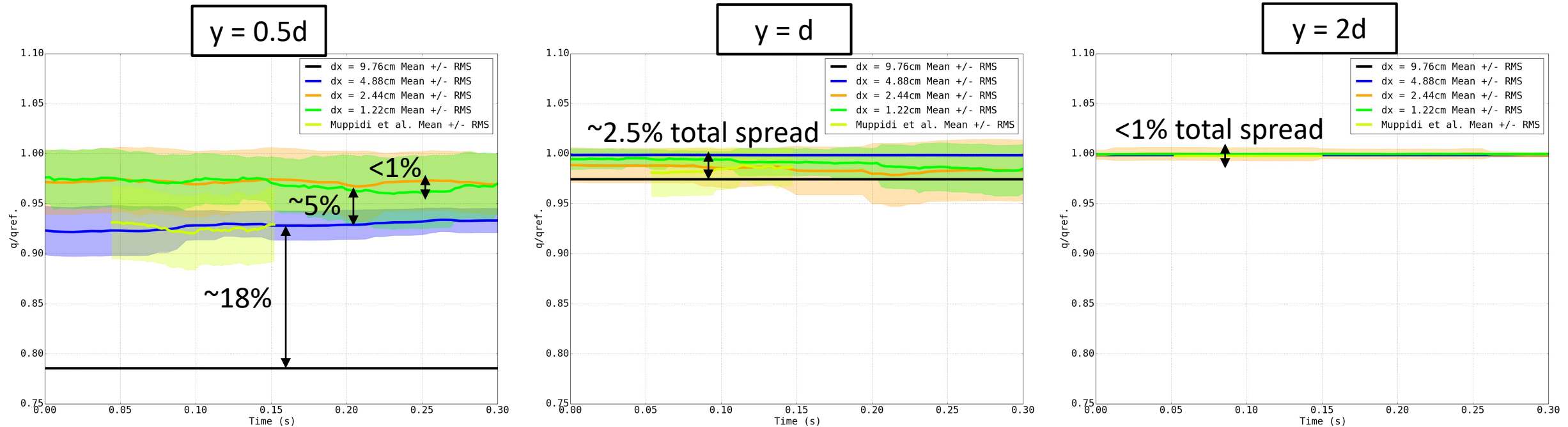


Image adjusted from Muppidi et al. 38th IEEE Aerospace Conference (2017).

Grid Resolution Study: Slender Capsule Wake



- ❑ In order to determine the level of grid resolution required to capture the slender wake, a grid resolution study is performed

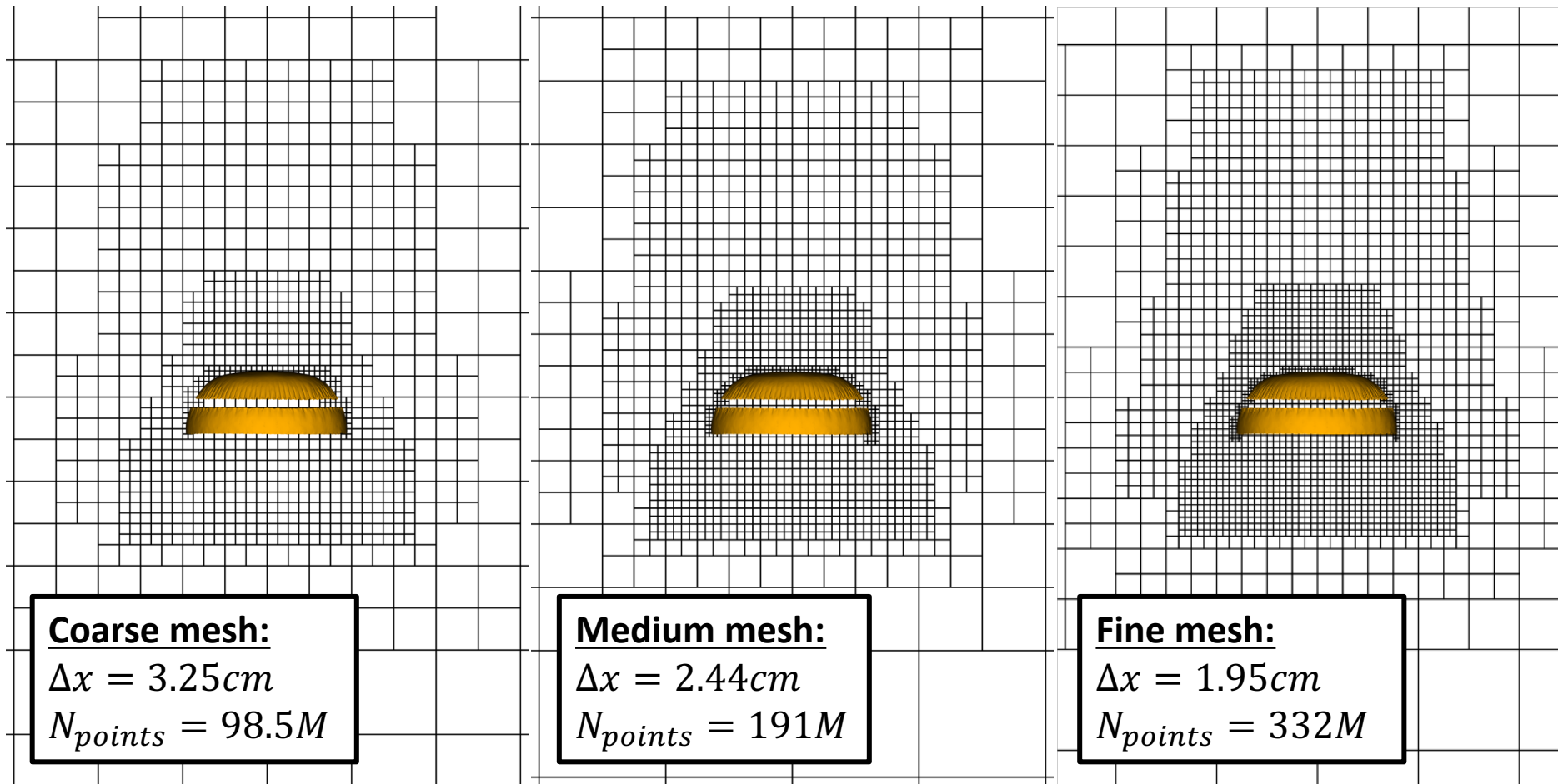


- ❑ The solutions converge quickly with successive halving of the volume grid spacing
 - Between the 2.44cm and 1.22cm resolutions, the dynamic pressure changes less than 1% at all 3 probes

Grid Resolution Study: Static Canopy

□ The same analysis is performed for the static, inflated canopy

- The 3 grids are scaled by factors of $2^{\frac{1}{3}}$ such that the number of grid points approximately doubles/halves



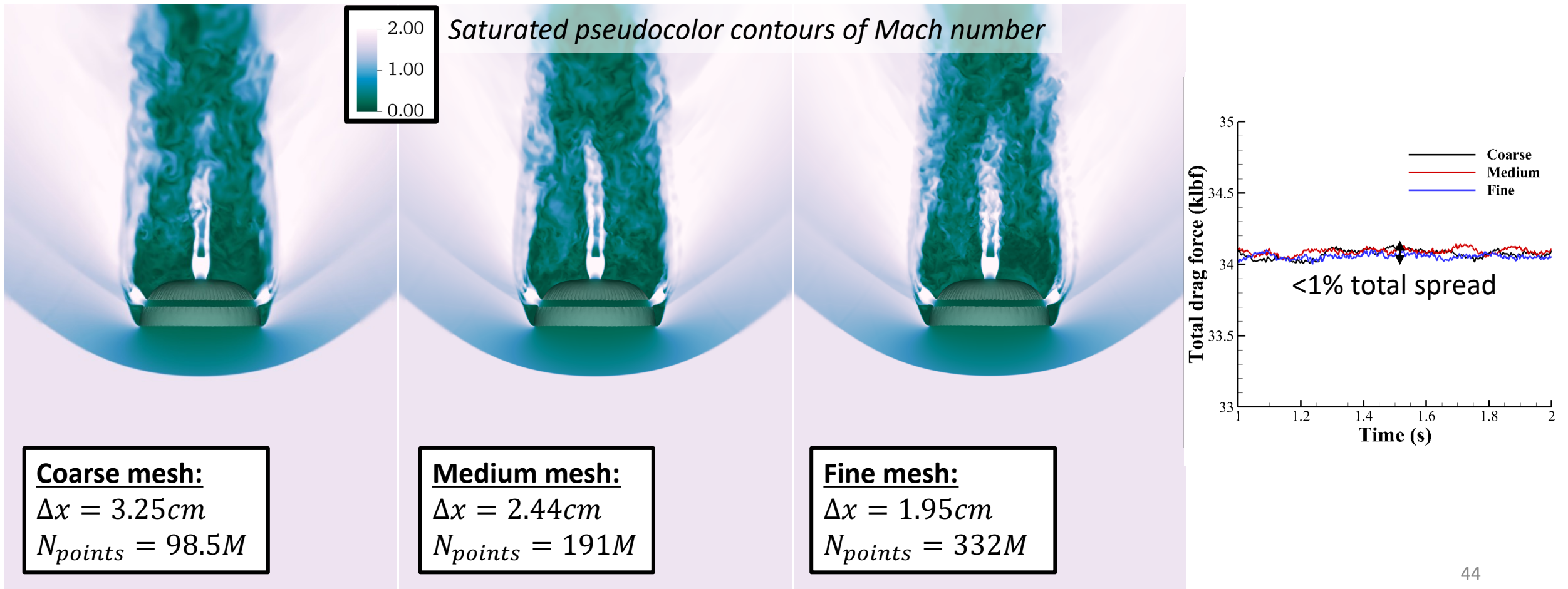
Freestream conditions*

- $P = 219.22Pa$
- $U = 567.74 \frac{m}{s}$
- $T = 249.339K$
- $q_{ref} = 491.68Pa$
- $M = 1.79$

**Freestream conditions are taken at the line stretch event described by the ASPIRE SR01 post-flight test report*

Grid Resolution Study: Static Canopy

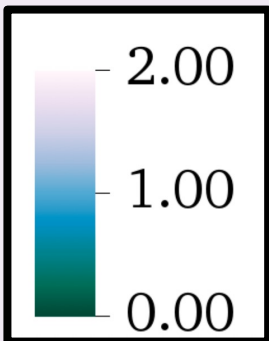
- ❑ Small sensitivity in the total drag force to the grid resolution is observed
 - Less than 1% difference between solutions in terms of aerodynamic drag
 - Qualitatively, the bow shock and wake structures are very similar between solutions



ASPIRE FSI Simulations



- ❑ Finally, the porosity and contact methods, and the results of the grid sensitivity study, are used in FSI simulations of the ASPIRE SR01 flight test
- ❑ Using the established best practices, the FSI simulation starts from a precursor CFD-only simulation

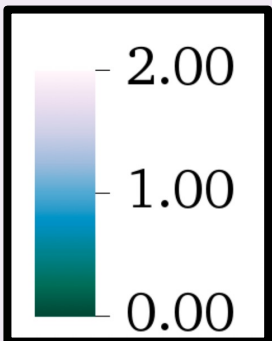
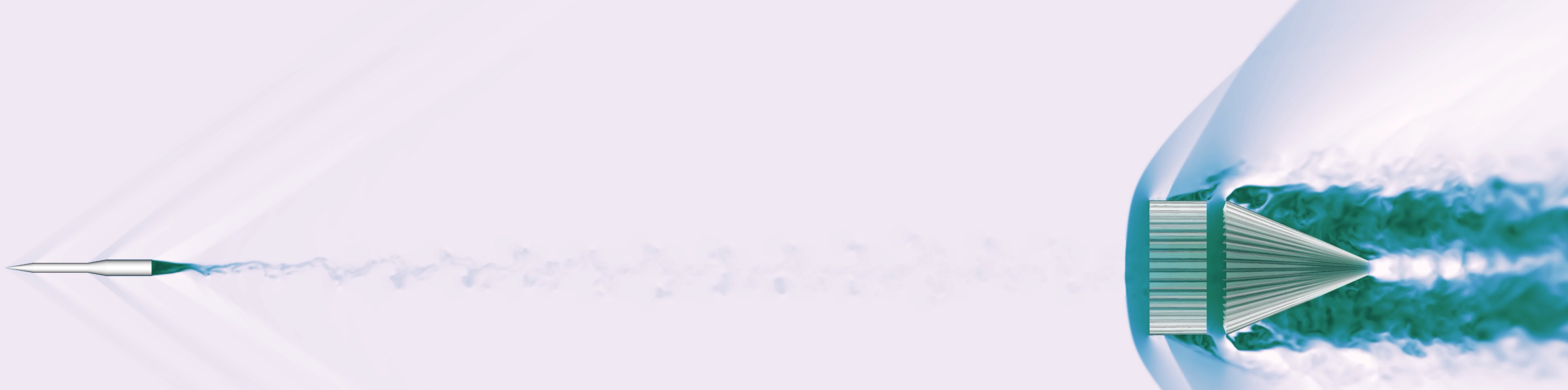


*Saturated pseudocolor
contours of Mach number*

ASPIRE FSI Simulations

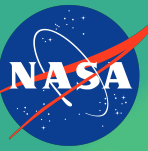


- ❑ Once the aerodynamic loads become statistically stationary, the FSI simulation is started
 - In other words, the CFD simulation is restarted, and the coupled CFD+CSD simulation begins



*Saturated pseudocolor
contours of Mach number*

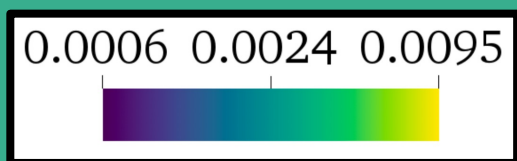
ASPIRE FSI Simulations



- ❑ Once the aerodynamic loads become statistically stationary, the FSI simulation is started
 - In other words, the CFD simulation is restarted, and the coupled CFD+CSD simulation begins



Saturated pseudocolor contours of the logarithm of density (kg/m^3)



Comparison of ASPIRE FSI Simulations with Flight Data

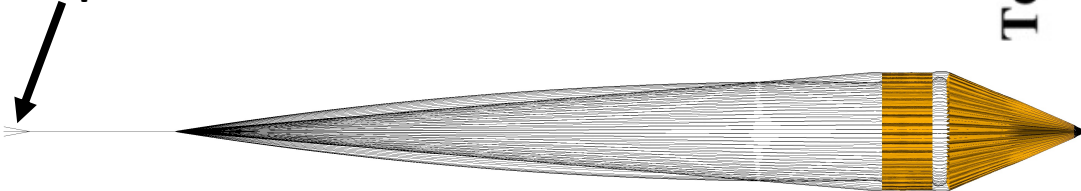


- ❑ The combined restoring force in the 3 beam elements at the leading edge of the triple bridle are used to measure the parachute forces

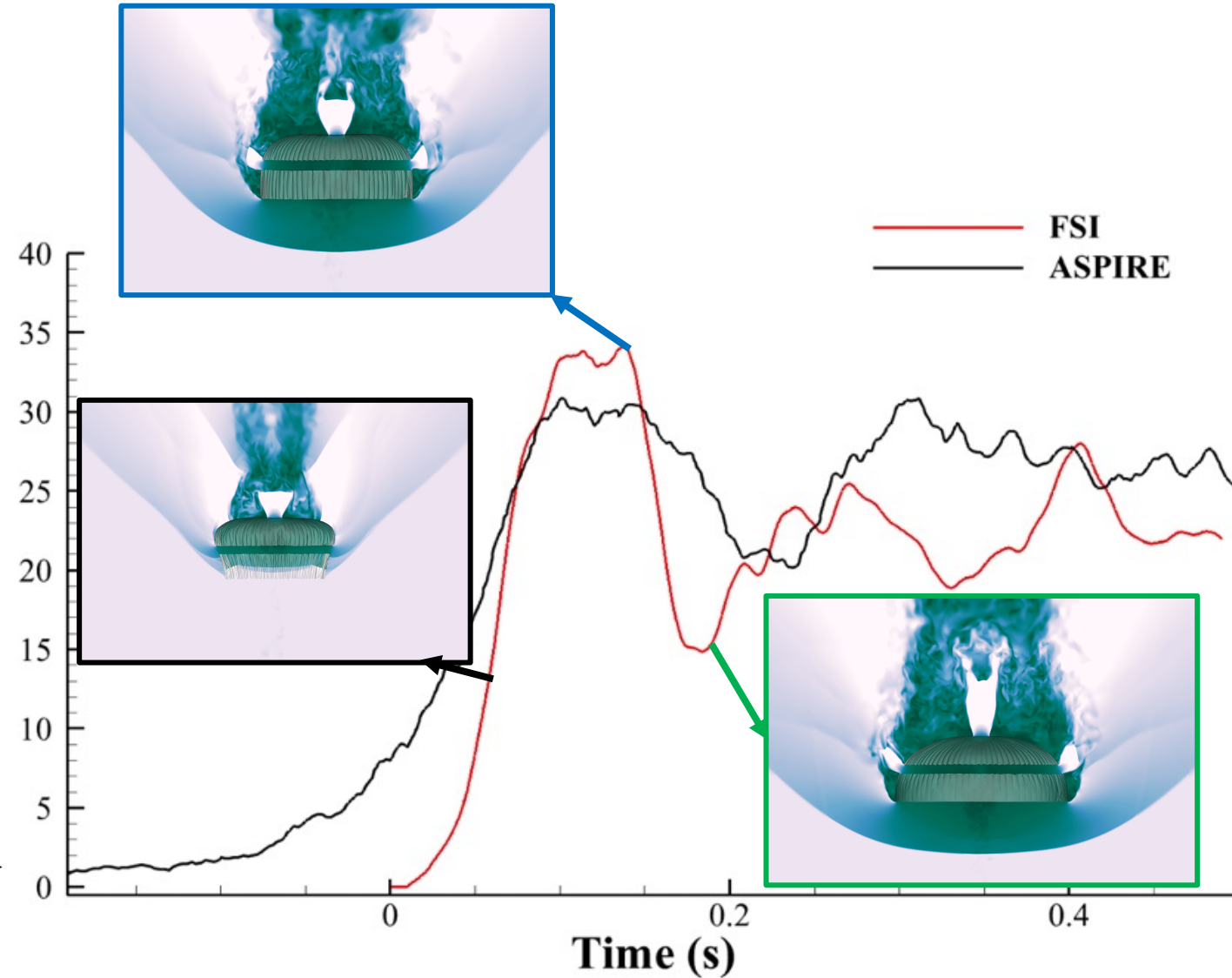
- Similar to load pins used in flight tests

- ❑ To determine if the overshoot is from discretization error, a grid sensitivity study is performed

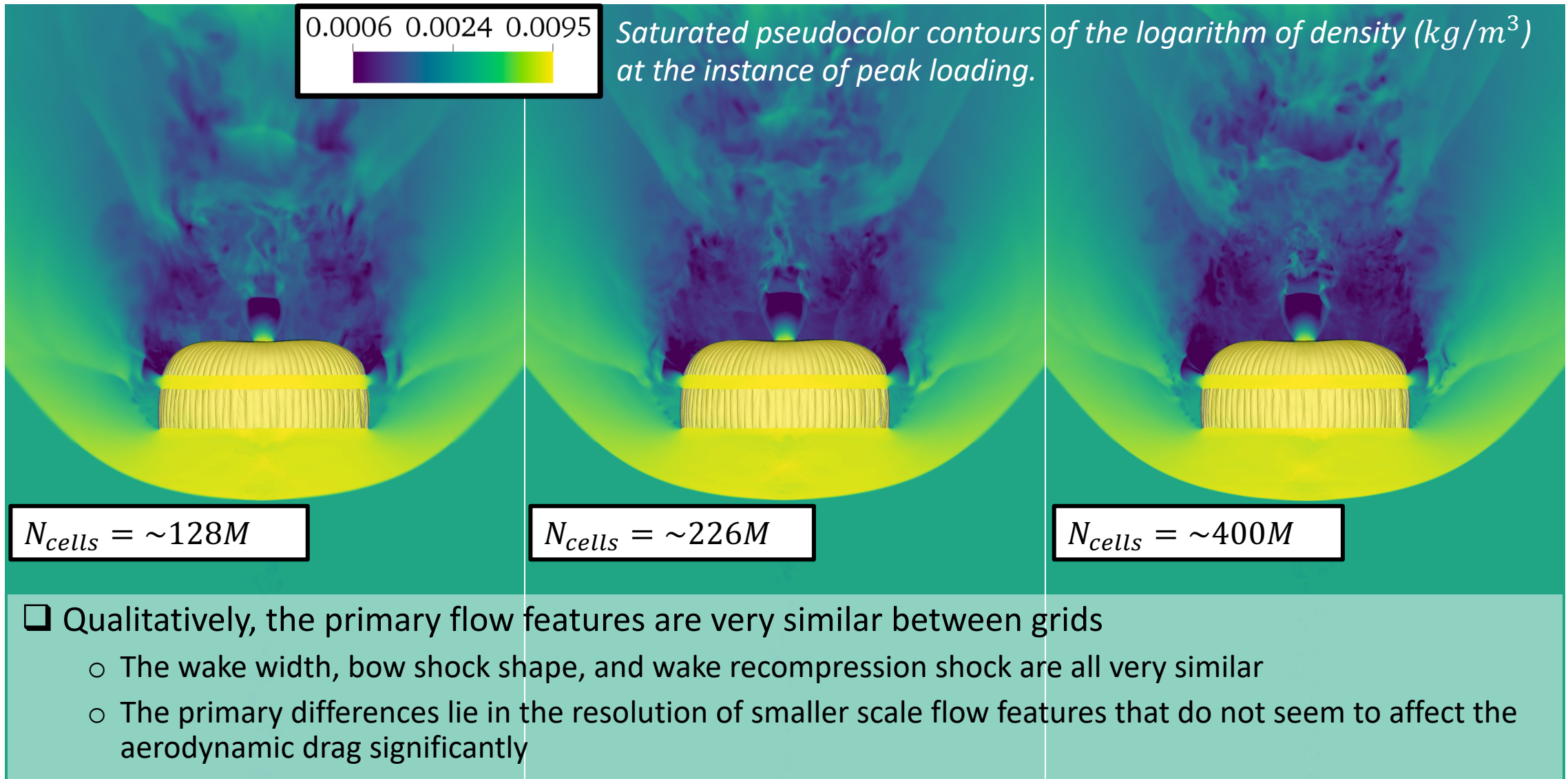
triple bridle



Total pull force (klbf)



Grid Resolution Study: ASPIRE FSI



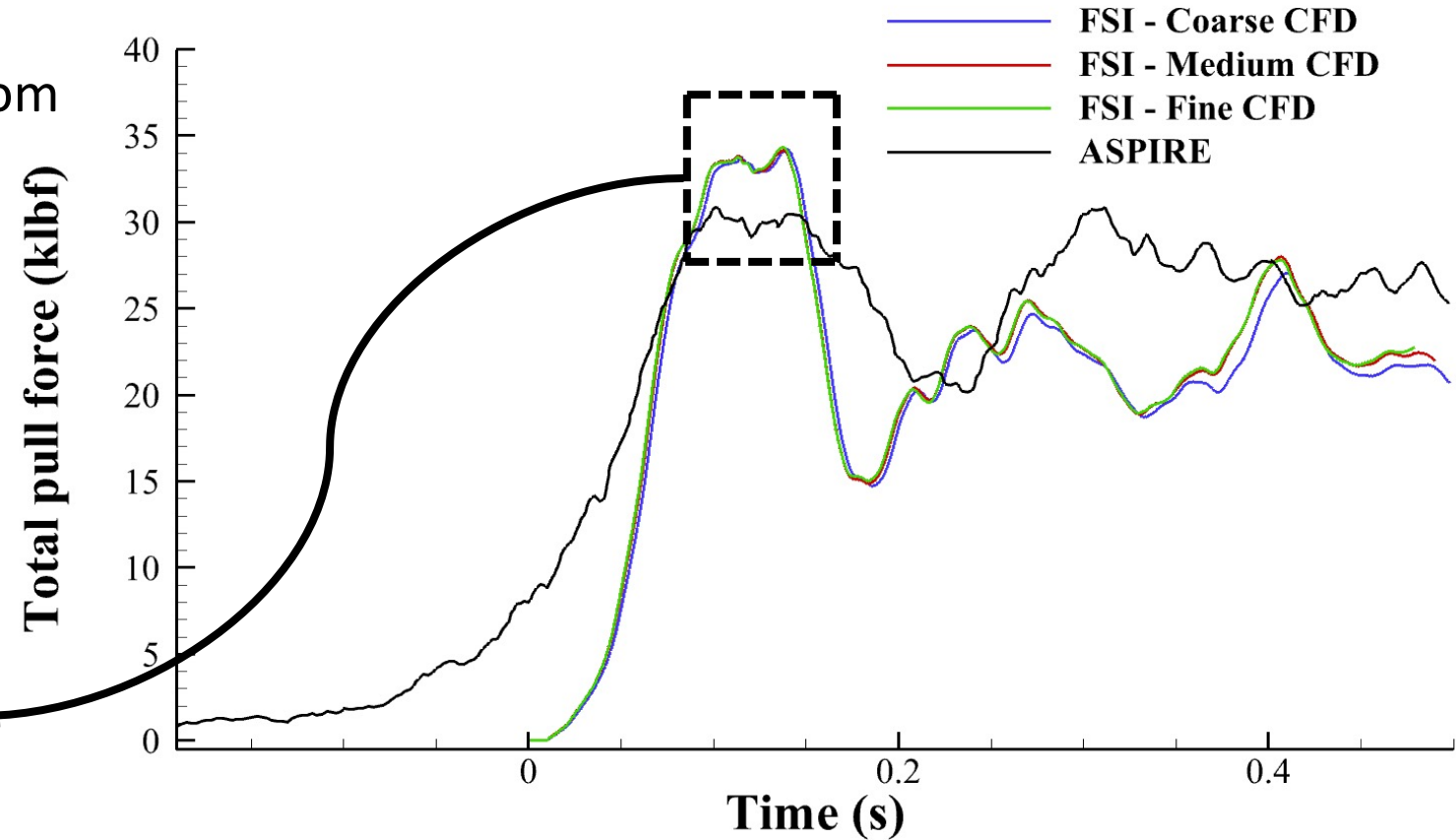
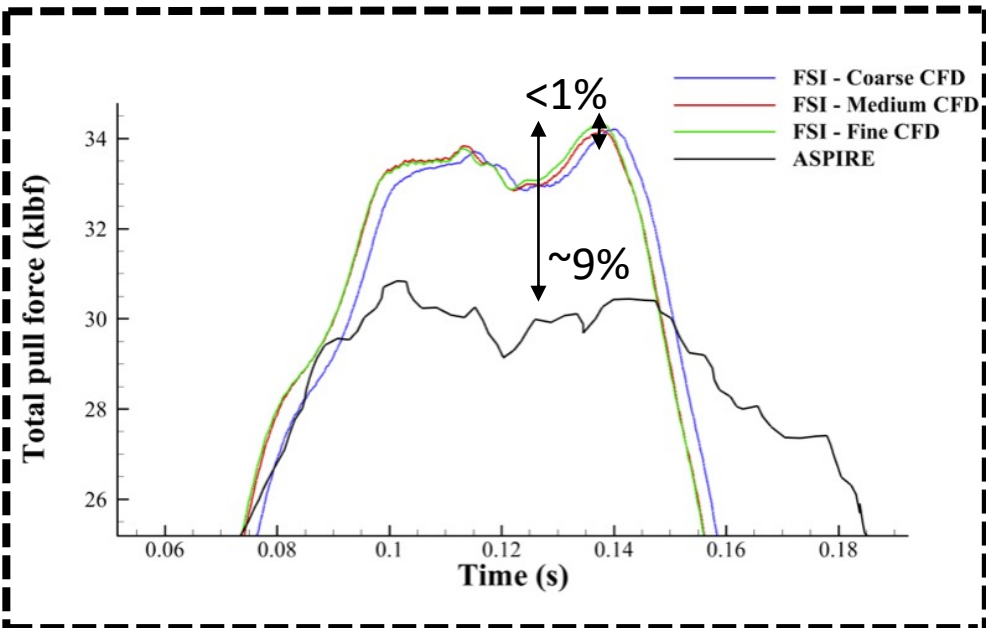
Grid Resolution Study: ASPIRE FSI



❑ All three volume resolutions predict peak loads within 1% of each other

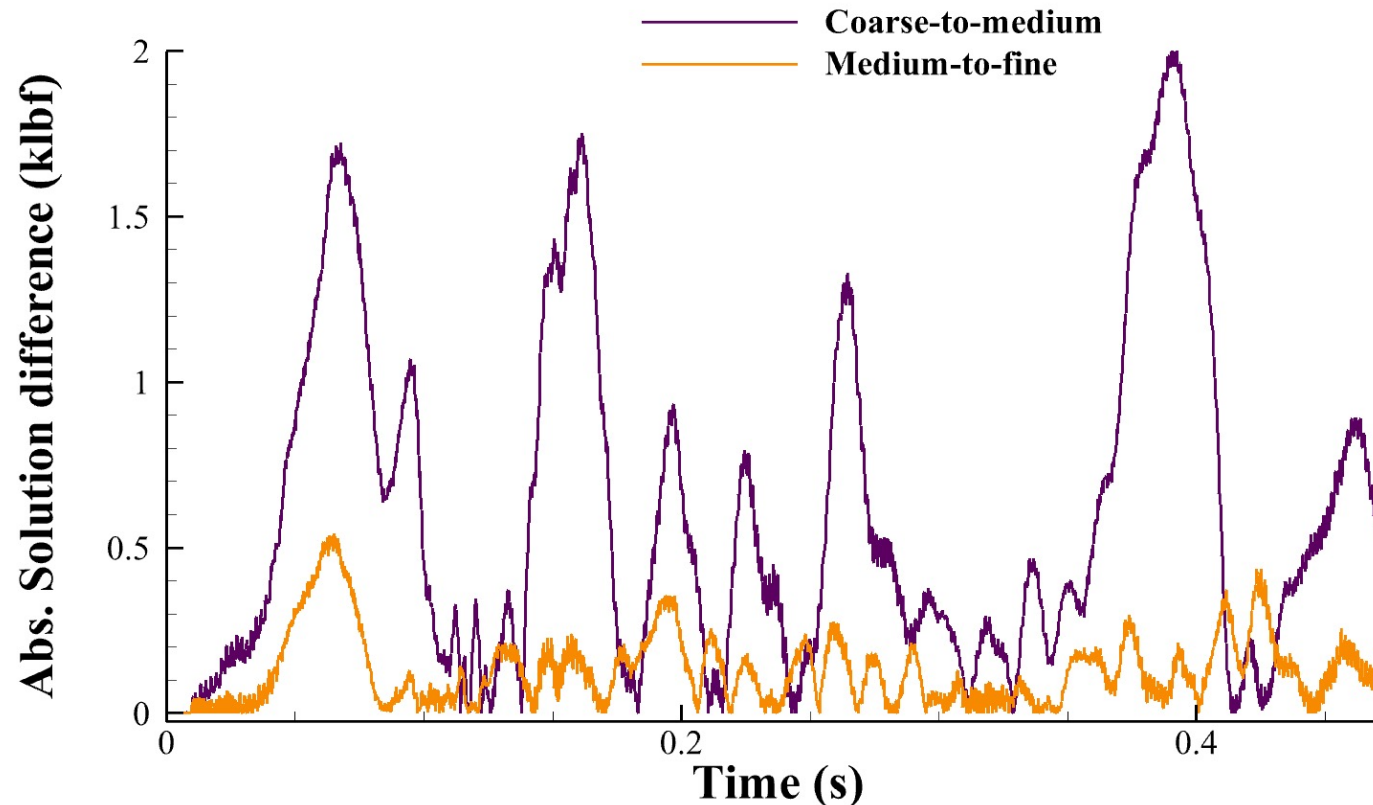
❑ ~9% difference in the peak load predicted by the simulation and that from flight test data

○ 3.3% uncertainty in flight data at peak load



Grid Resolution Study: ASPIRE FSI

- ❑ The coarse and medium grid solutions are projected onto the fine grid signal
 - Compute the absolute differences in the solutions
 - Convergent behavior is evident



Grid Resolution Study: ASPIRE FSI

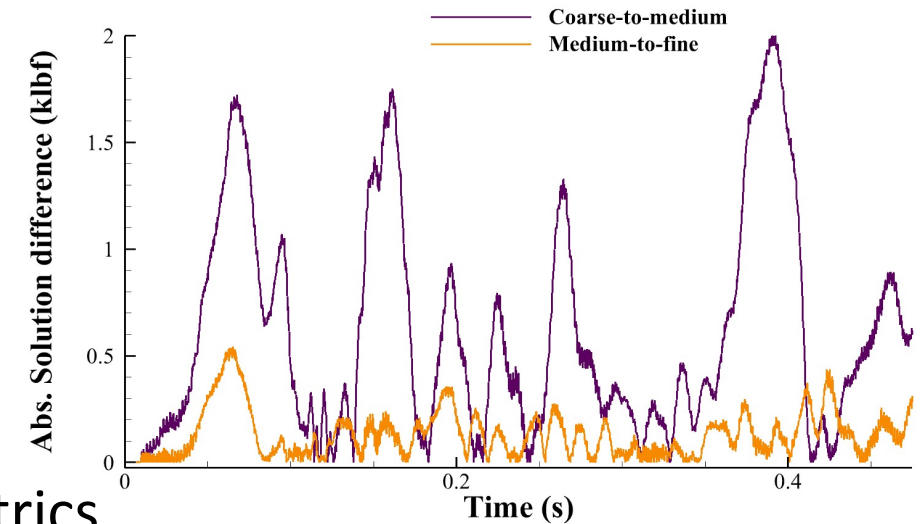


❑ The coarse and medium grid solutions are projected onto the fine grid signal

- Compute the absolute differences in the solutions
- Convergent behavior is evident

❑ An attempt is made to quantify the uncertainty

- The “inflation interval” of [0.095s, 0.145s] is considered



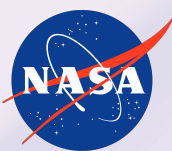
❑ Less than 0.15% grid-related uncertainty for both metrics

Metric	Coarse	Medium	Fine	GCI	Est. Converged Value	Est. Uncertainty
Peak Load (klbf)	33.2653	33.3620	33.3979	0.0014856	33.4255	± 0.047142
Peak Impulse (klbf·s)	1.6629	1.6679	1.6696	0.0013108	1.6707	± 0.002190

❑ Convergence rate of ~ 4 is computed, but likely does not reflect order of numerical method

- However, implies temporal discretization error is small compared to spatial discretization error

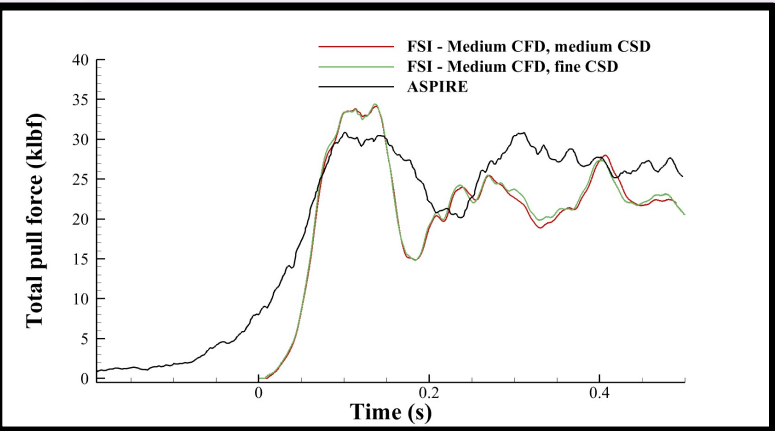
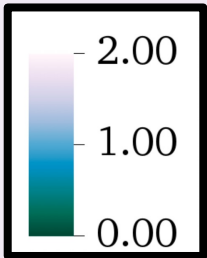
Structural Grid Refinement: ASPIRE FSI



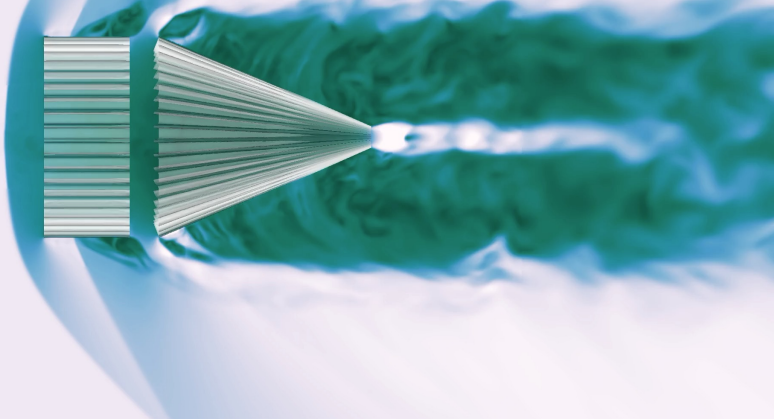
- ☐ The structural mesh is refined such that the average edge length is a factor $2^{\frac{1}{3}}$ smaller than the base mesh
- ☐ Again, the solution displays very little sensitivity to increasing resolution



Saturated pseudocolor contours of Mach number shown on a cut-plane through the center of the domain for a medium CFD - fine CSD simulation of ASPIRE SR01.



Simulation	N_{cores}	Duration (hours)	Resources (core-hours)
Coar. CFD - Med. CSD	1600	32	51,200
Med. CFD - Med. CSD	960	67	64,320
Fine CFD - Med. CSD	2400	70	168,000
Med. CFD - Fine CSD	2400	58	139,200



Conclusions



- ❑ A capability to simulate nonlinear FSI problems has been demonstrated
 - A wide range of flow conditions and structures were considered

- ❑ Methods to model broadcloth porosity and contact mechanics were developed and validated

- ❑ The LAVA-Cartesian/Structural FSI capability was validated using ASPIRE flight data
 - LAVA FSI simulations predict peak loading within ~9% of that measured during the flight test
 - Grid convergence with respect to the volume domain resolution was demonstrated for FSI simulations
 - The solution sensitivity with respect to the surface/structural resolution was studied
 - The remaining modeling error between the simulations and flight is attributed to other factors not yet considered

- ❑ Continue to investigate modeling challenges for supersonic parachute FSI simulations
 - The effect of the initial fold angle
 - Nonlinear and inelastic material modeling
 - Deceleration of the parachute system

- ❑ Investigate other requirements and challenges for subsonic applications (Orion/CPAS, etc.)
 - Geometry queries (multiple canopies)
 - Long time periods of interest and low Mach numbers
 - 6DOF required to capture relevant physics (pendulum)
 - Viscous effects, bluff capsule wake



Acknowledgements



- ❑ Drs. Cetin Kiris, Francois Cadieux, Gaetan Kenway, Mike Barad, and the entire LAVA team
- ❑ This work was partially supported by NASA's Entry Systems Modeling (ESM) project and NASA ARMD's Transformational Tools and Technologies (T³) project
- ❑ NASA Advanced Supercomputing (NAS) systems at NASA Ames Research Center
- ❑ My advisor, Dr. Christoph Brehm at the University of Maryland, College Park