Jet Propulsion Laboratory
California Institute of Technology

Advanced Modeling of Fluid-Structure Interaction for Softgoods in Supersonic Flow

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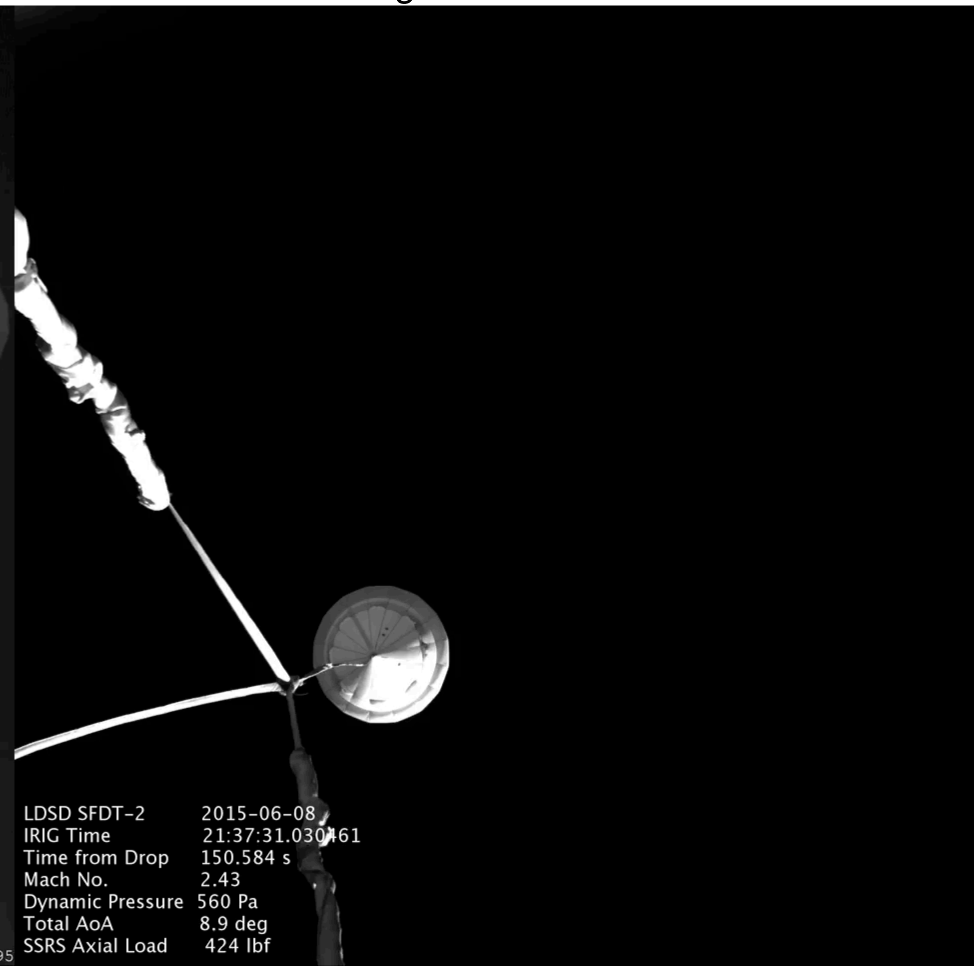
Director’s Review and Discussion
October 15, 2018

We are developing new computational tools for supersonic parachute inflation.

Disksail Parachute

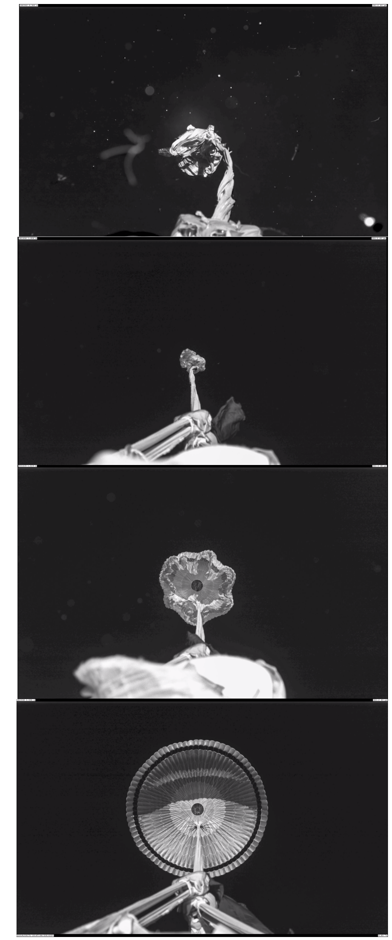
Ringsail Parachute



Low Density Supersonic Decelerator (LDSD) project's Supersonic Flight Dynamics Tests (SFDT)
June 28, 2014 (SFDT 1), and June 8, 2015 (SFDT 2)

Exploratory study in FY16 revealed no current code had the needed capability.

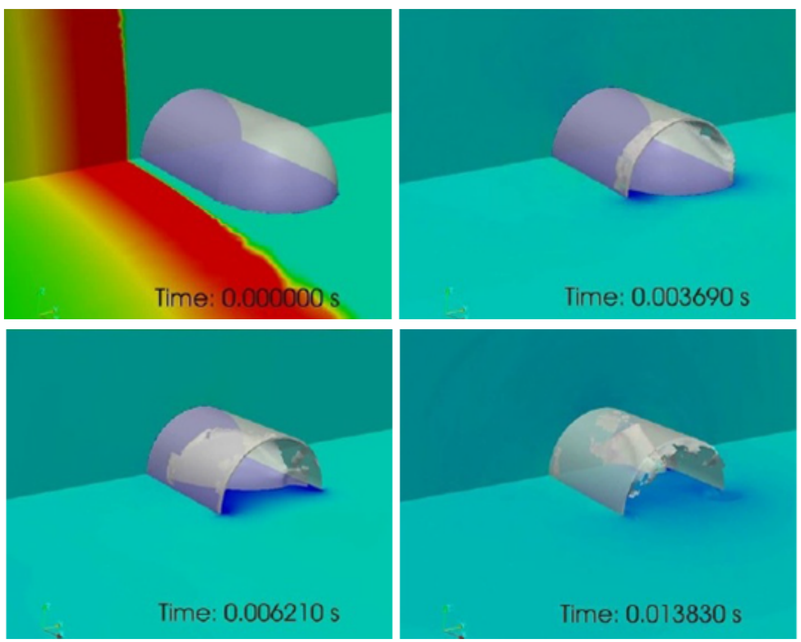
- Strategic R&TD
  - Greg Davis (Original Initiative Lead), Chris Tanner (Current Initiative Lead)
  - Visits/consultations with Sandia, NASA ARC, Academia
- Challenging Fluid-Structure Interaction (FSI) Problem:
  - Couple a moving structure with large relative motion to a fluid
    - Moving (Lagrangian) structural mesh and stationary (Eulerian) fluid mesh
  - Supersonic compressible flow
    - Turbulent wakes (entry vehicle, suspension lines, canopy)
    - Geometric and material porosity
  - Changing structural topology with
    - Massive self-contact
    - Nonlinear material (fabric) stress-strain



ASPIRE Supersonic Parachute Flight Test, Oct. 4, 2017
https://www.jpl.nasa.gov/video/details.php?id=1507

JPL-Stanford team formed in FY17 to leverage prior DOD investment in new FSI technology.

- Stanford numerical framework is embodied in AEROF and AEROS open source codes (https://bitbucket.org.frg)
- New approach for fluid-structure interaction (FSI) validated on DOD applications



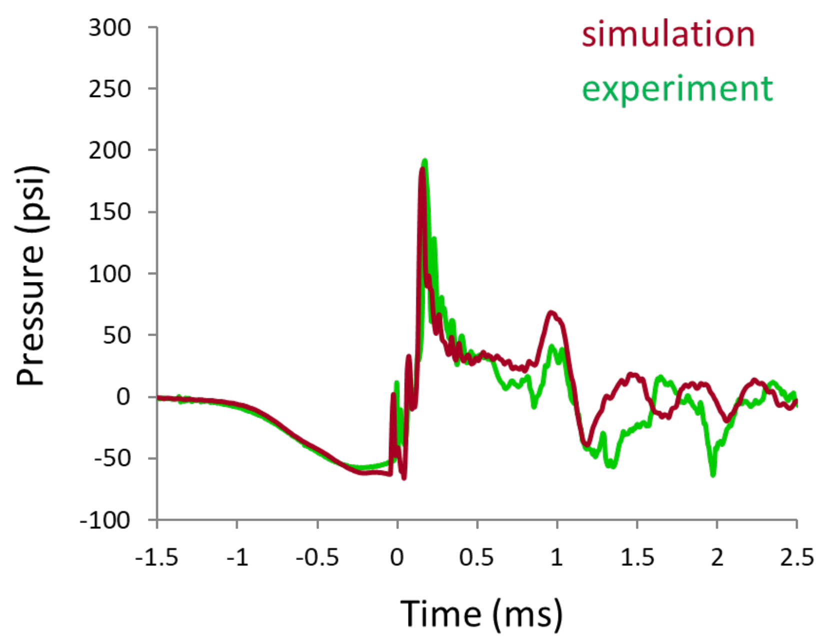


Image Credit: Charbel Farhat

Our project adds capabilities required for specific application to supersonic parachutes.

- JPL: Leads V&V and implementation
  - Armen: Structural Modeling (AEROS)
  - Jason: CFD (AEROF)
  - Lee: Uncertainty Quantification (UQ)
- Stanford: Leads code development
  - Farhat Research Group (FRG)
  - Numerical method development
  - Software development
- Frequent interactions between JPL and Stanford
  - Excellent interactions with a highly responsive Stanford team (especially with code development and debugging)
- Cross-agency interactions with ARC, JSC, Universities, Industry
  - Annual TIM's

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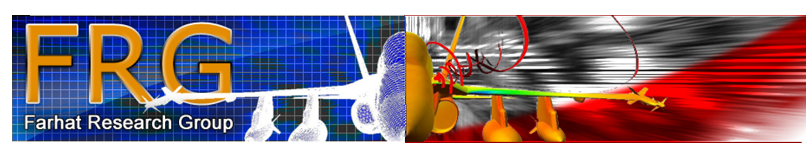
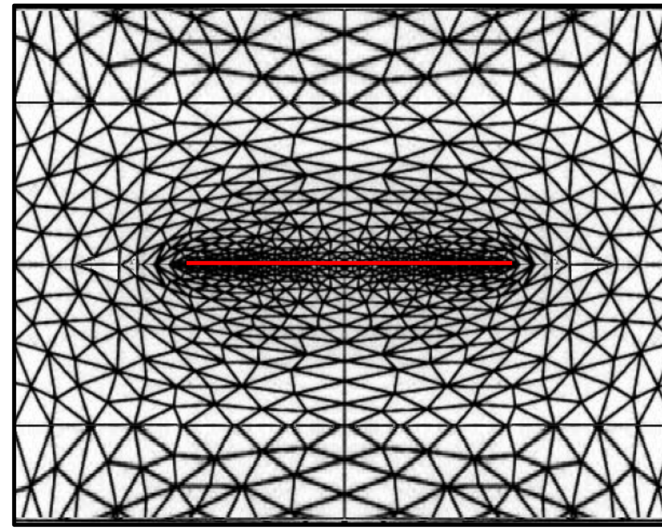
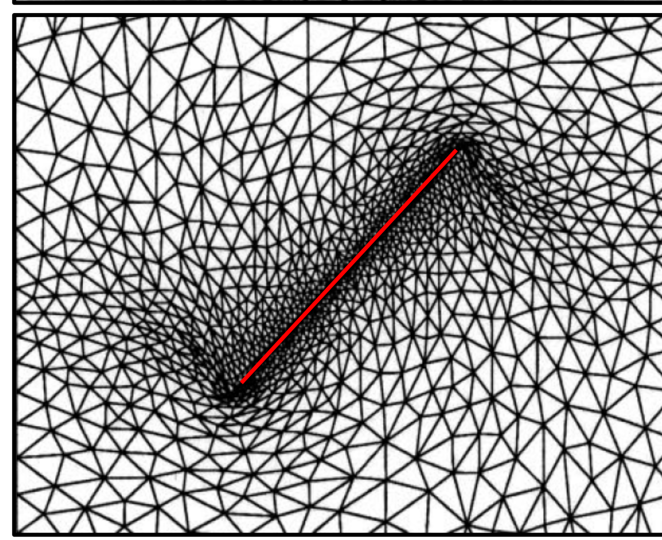


Traditional FSI Method: Arbitrary Lagrangian-Eulerian (ALE)

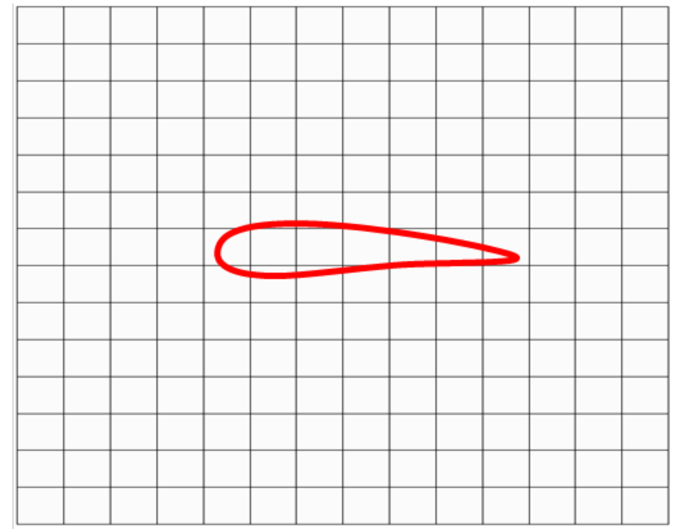
- Eulerian (stationary) Fluid Mesh
- Lagrangian (moving) Structural Mesh
- Coupled by distorting the fluid mesh to follow the structure
- Pros:
  - Direct mapping of flow to structure boundary condition
- Cons
  - Complex mesh generation
  - Severe ill-conditioning of distorted mesh for large motions
- Implemented in existing commercial codes (LS-Dyna)





New FSI Technology: Embedded Boundary Method

- Finite Volume Exact Riemann (FIVER) Method
  - Fluid mesh remains stationary
  - Flow mapped to moving structural mesh
- Pros:
  - Allows large structural motion and topological changes
  - Simplifies mesh generation procedure
- Cons
  - Complex numerical treatment for the fluid-structure interface
  - Difficult to track boundary layer and shocks without adaptive mesh refinement (AMR)



A family of position- and orientation-independent embedded boundary methods for viscous flow and fluid–structure interaction problems, https://doi.org/10.1016/j.jcp.2018.03.028
Image Credit: Raunak Borker

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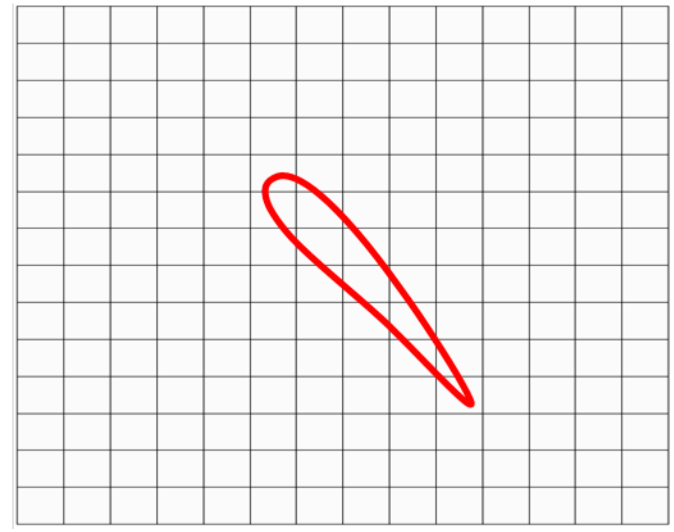

A family of position- and orientation-independent embedded boundary methods for viscous flow and fluid–structure interaction problems, https://doi.org/10.1016/j.jcp.2018.03.028
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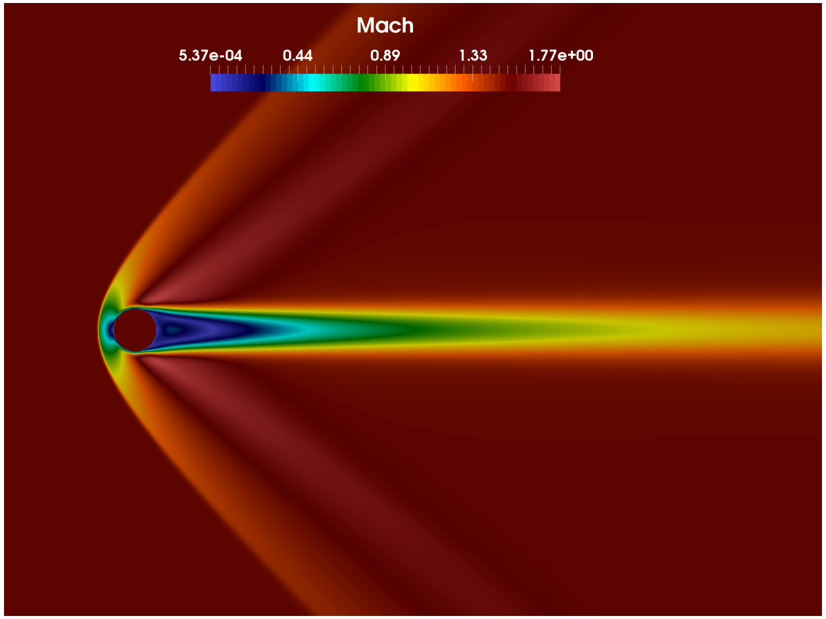
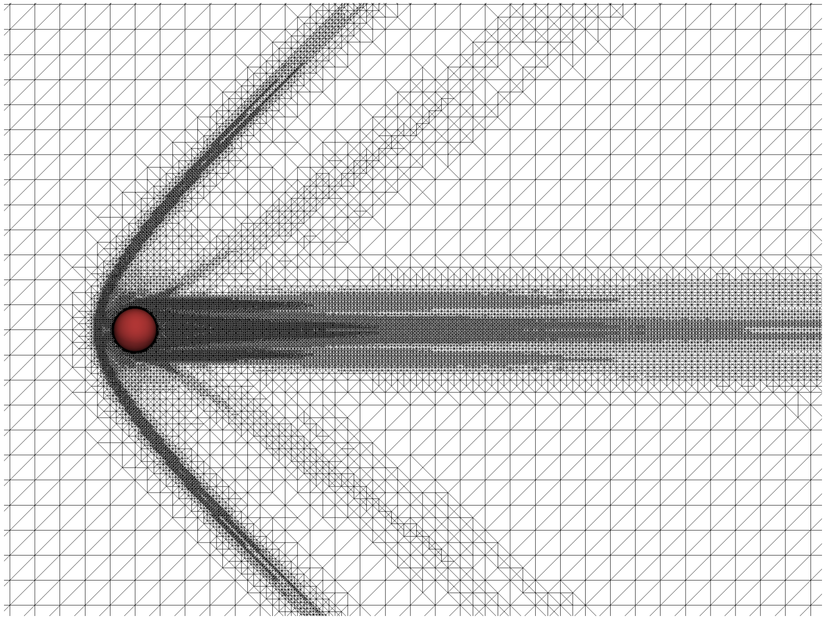
FIVER relies on Adaptive Mesh Refinement (AMR) to resolve boundary layers and shocks

Supersonic Flow Past a Sphere
using FIVER and AMR



Automatically Adapted
Fluid Mesh Based on Error Bound



Figures taken from: R. Borker, D. Z. Huang, S. Grimberg, C. Farhat, P. Avery, J. Rabinovitch, "An Adaptive Mesh Refinement Approach for Viscous Fluid-Structure Computations Using Eulerian Vertex-Based Finite Volume Methods," *in process.*

$$\underbrace{|W^m - W_h^m|_{\infty,k} \leq c|W^m - \Pi_h W^m|_{\infty,k}}_{\text{Cea's lemma (elliptic)}} \leq \underbrace{c_d \max_e |e^T H e|}_{\text{Taylor series; scheme-independent (curvature)}} \quad m = 1, \ldots, n$$

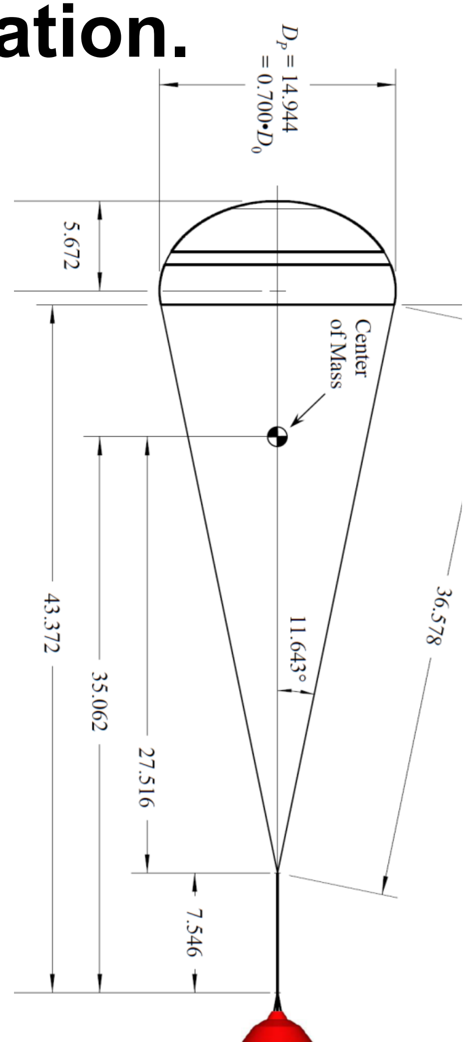
Cea's lemma
(elliptic)

Taylor series

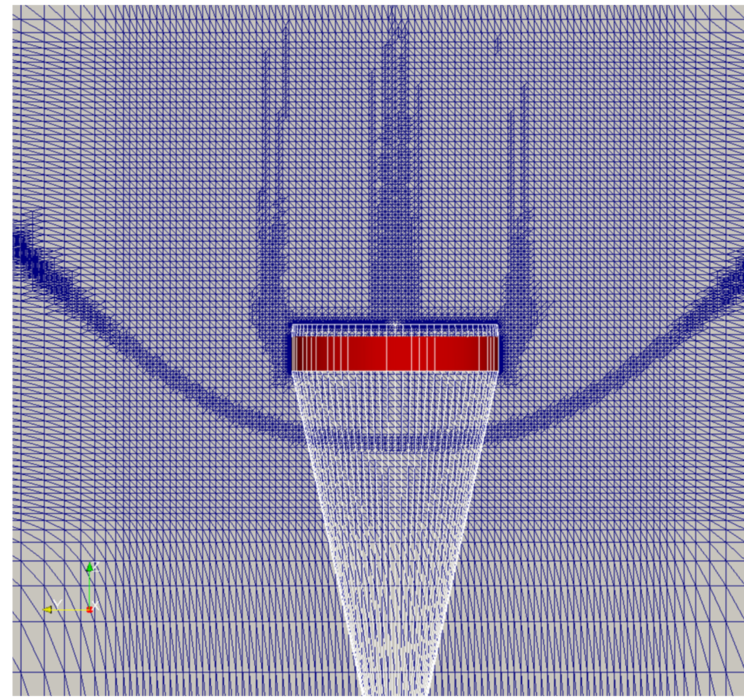
scheme-independent
(curvature)

FY 17's DGB "Gen-I" begins simulation in "as-built" configuration.

- Includes
  - Supersonic flow
  - Viscosity
  - Linear fabric model
- Excludes
  - Entry body
  - Suspension line flow

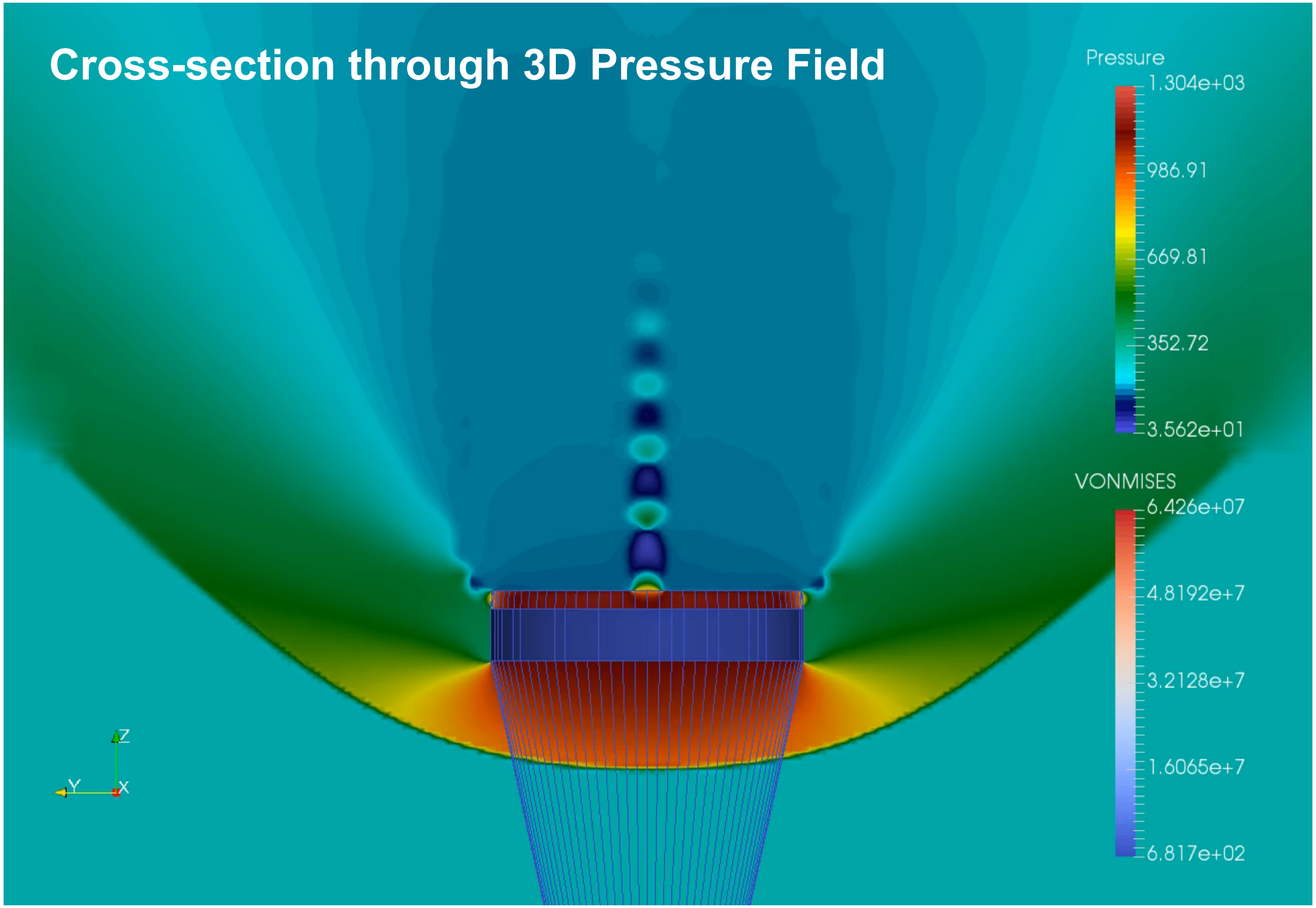


MSL Parachute Schematic
(Cruz et al., AIAA 2013-1250)

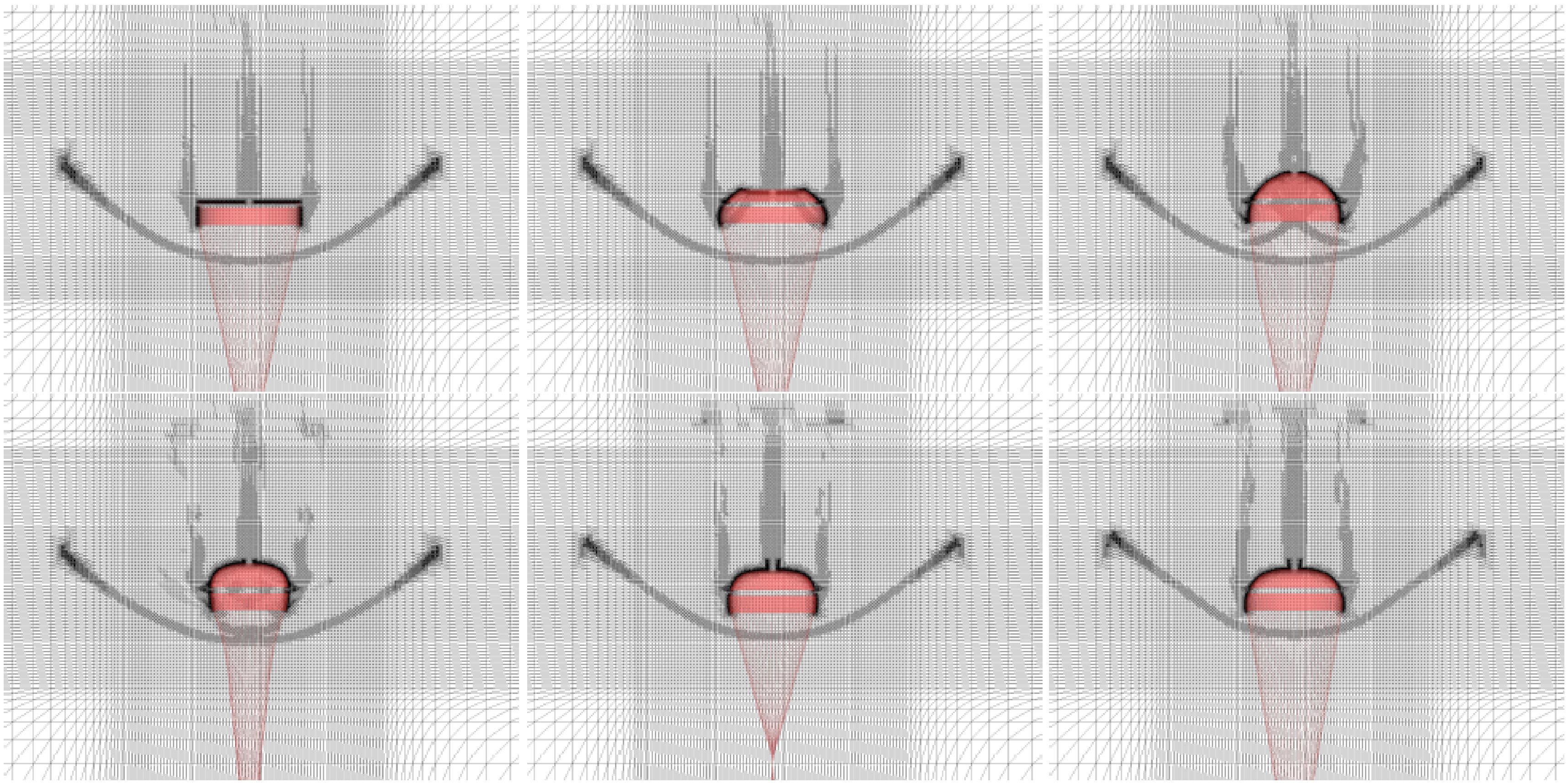


Initial Condition Showing AMR Mesh Around Flow Feature

3D DGB "Gen-I" Inflation Simulation Results



DGB Gen-I illustrates the AMR refinement with reversible coarsening capability.



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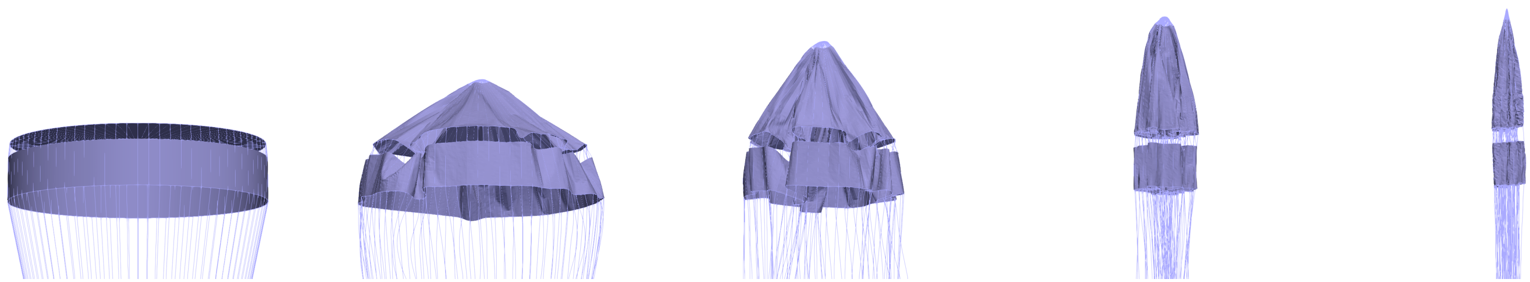
DGB Gen-II (underway) will start with a "stretched" initial condition

- Massive "self-contact" in the canopy structure was a computational challenge



- DGB Gen-II also includes
  - Material fabric nonlinearity
  - Entry vehicle, riser and triple bridle
- First simulations expected Q1/FY19

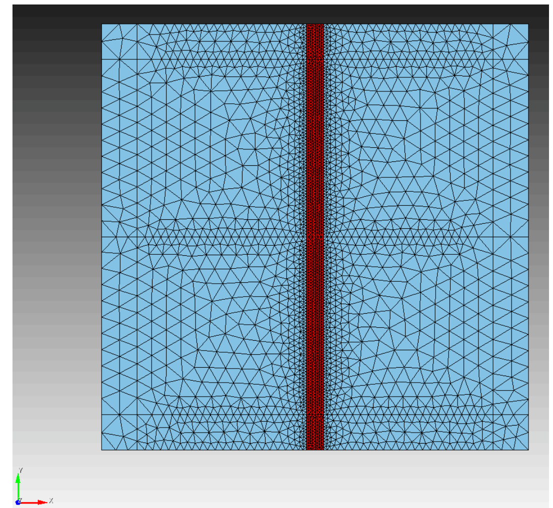
JPL Model V&V and UQ Efforts

- Using practices from Sandia "Quantification of Margins and Uncertainties" (QMU)
- Development of Phenomena Identification and Ranking Table (PIRT) identified modeling gaps
  - Verification Test Suite (VERTS)
  - Validation Test Suite (VALTS)
- JPL VERTS supplemental to the existing Stanford test regression suite

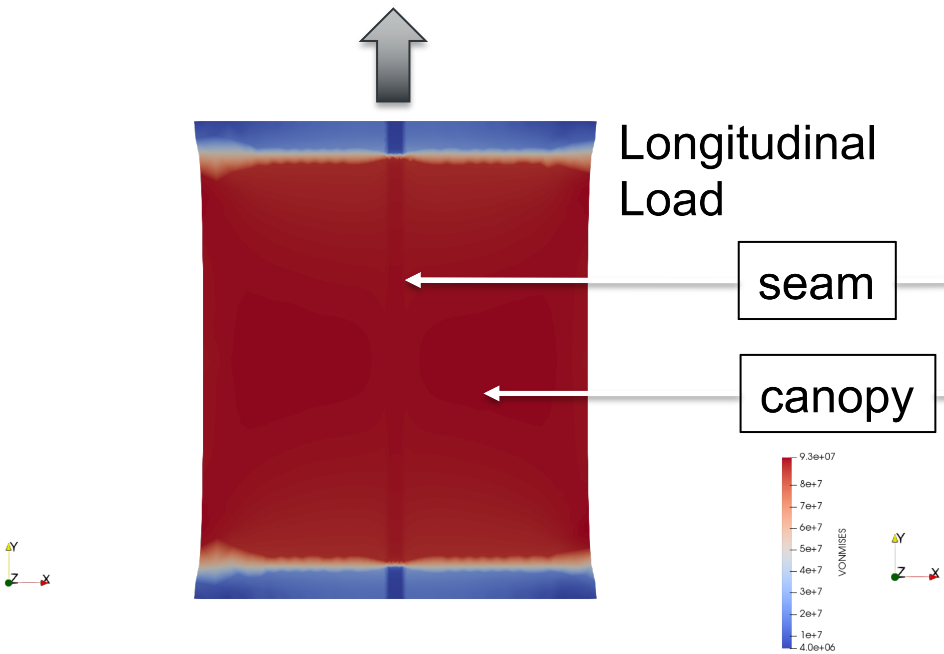
PIRT for QOI Peak Strain		Importance	Adequacy for Intended Use			
ID	Phenomena	QoI	Math Model	Code	Validation	Parameters
A	Parachute Packed on Vehicle					
A1	Packing patterns	U	M	L	U	U
A2	Pre-load & and Pre-Stress due to packing pressure	U	H	H	H	H
A3	Type of parachute (parachute configuration)	H	L	L	L	L
A4	Thermal and atmospheric environment inside the bag	L	L	L	L	L
B	Bag Deployment					
B1	Initial deployment physics	U	H	H	L	U
B2	Transmission of dynamic loads into parachute bag due to deployment					
B2.1	High-frequency shock wave (elastic) propagation into the lines+parachute bag due to deployment mechanism (mortar, drogue, etc.)	L	H	H	U	U
B2.2	Low-freqeuency dynamic loads due to deployment	H	H	H	U	U
B3	Tangling of the lines (i.e., bridles, risers, suspension lines)	H	H	L	U	U
B4	Inertial loads due to vehicle	L	H	H	M	U

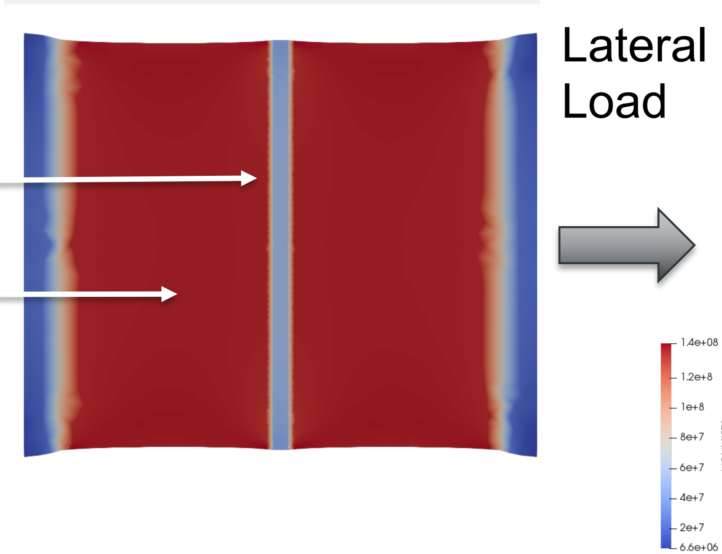
Example Structural Verification Test: Seam Modeling Benchmark

- Informs seam modeling choices
  - Topology
  - Element type
  - Mesh density
  - Nonlinear fabric model



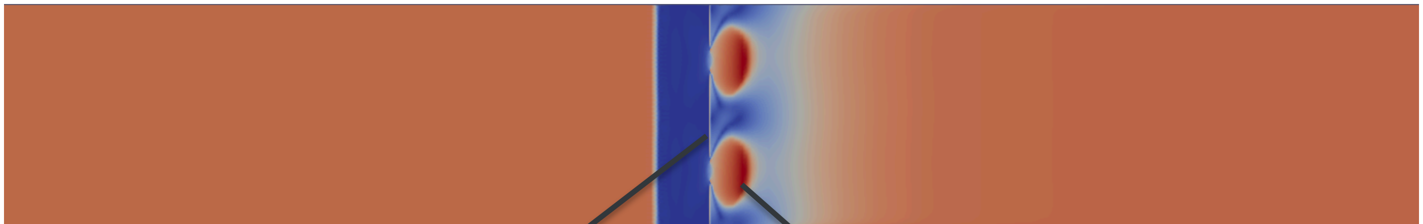
Mesh





Example Fluid Verification Tests

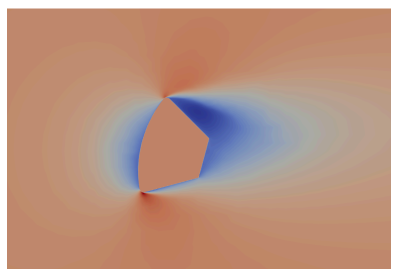
- Shock Tube Porous Flow



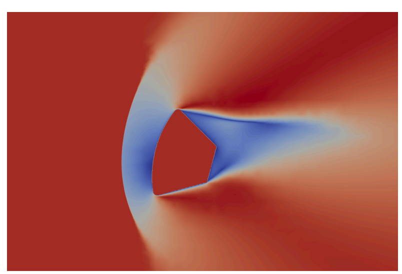
Fabric Pore   Barrel Shock

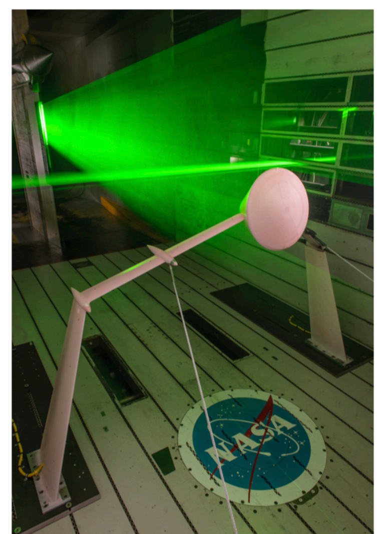
- Orion Capsule (includes validation test data)

Subsonic



Supersonic



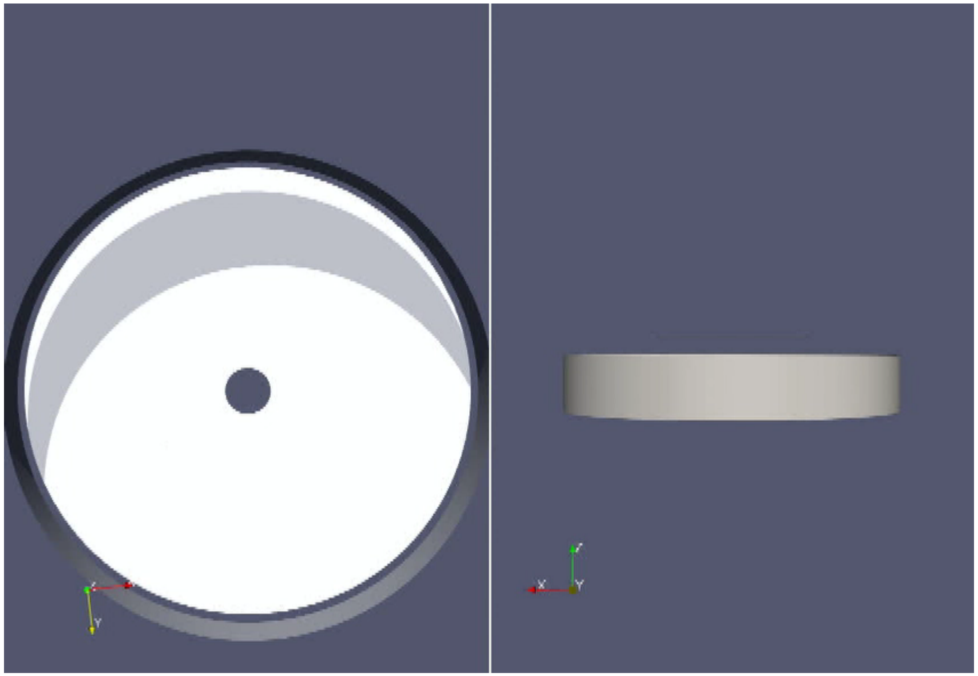


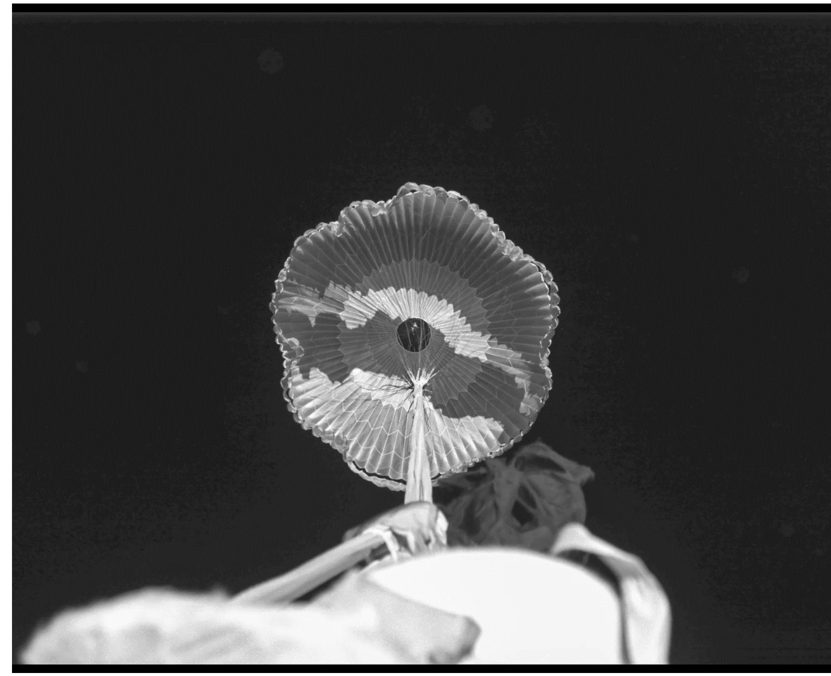
Wind Tunnel Test

End of FY 19 Goal: Simulation Comparison with Test

- DGB Gen II and III
  - Sharable configuration with Stanford
  - Expected New Model Features
    - Stretched initial condition
    - Nonlinear fabric model
    - Entry vehicle, triple bridle and riser
    - Suspension line flow
    - Seam details
- JPL-Only Models (Flight configurations)
  - ASPIRE
  - LDSD

Qualitative Comparison DGB Gen-I with ASPIRE





- Quantitative comparison with Gen-II and Gen-III models FY19
- Exploring follow-on infusion in support of ASPIRE and SRL

Publications

Rabinovitch J., Huang Z., Avery P., Farhat C., Derkevorkian A., Peterson L. D., “Preliminary Verification and Validation Test Suite for the CFD Component of Supersonic Parachute Deployment FSI Simulations,” 2018 AIAA Aerospace Sciences Meeting, 8-12 January, Kissimmee, Florida (AIAA 2018-1542).

Borker R., Grimberg S., Avery P., Farhat C., Rabinovitch J., “An Adaptive Mesh Refinement Concept for Viscous Fluid-Structure Computations Using Eulerian Vertex-Based Finite Volume Methods,” 2018 AIAA Aerospace Sciences Meeting, 8-12 January, Kissimmee, Florida (AIAA 2018-1072).

Derkevorkian A., Rabinovitch J., Peterson L. D., Avery P., Farhat C., “Evaluation of an Advanced Suite of Numerical Codes for Structural Simulation of Parachute Fabric,” 2018 AIAA Aerospace Sciences Meeting, 8-12 January, Kissimmee, Florida (AIAA 2018-1541).

Peterson L. D., Derkevorkian A., Rabinovitch J., Farhat C., Avery P., “Model Verification and Validation Assessment for a Simulation of Supersonic Parachute Inflation during Martian Entry,” 2018 AIAA Aerospace Sciences Meeting, 8-12 January, Kissimmee, Florida (AIAA 2018-1539).

Huang Z., Avery P., Farhat C., Rabinovitch J., Derkevorkian A., Peterson L. D., “Simulation of Parachute Inflation Dynamics Using an Eulerian Computational Framework for Fluid-Structure Interfaces Evolving in High-Speed Turbulent Flows,” 2018 AIAA Aerospace Sciences Meeting, 8-12 January, Kissimmee, Florida (AIAA 2018-1540).

Derkevorkian A., Avery P., Peterson L. D., Farhat C., Rabinovitch J., “Studies into Computational Modeling of Seams in a Parachute Canopy,” 2019 AIAA Aerospace Sciences Meeting, 7-11 January, San Diego, California (to be published).

Rabinovitch, J., Griffin, G. S., Seto, W., O’Farrell, C., Tanner, C. L., Clark, I. G., Derkevorkian A., and Peterson L. D., “ASPIRE Supersonic Parachute Shape Reconstruction: Experimental Results and Comparisons to Simulations, 2019 AIAA Aerospace Sciences Meeting, 7-11 January, San Diego, California (to be published).

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