



Fully-Coupled Fluid-Structure Interaction Simulations of a Supersonic Parachute

Jonathan Boustani[+*], Michael F. Barad[+], Cetin C. Kiris[+]

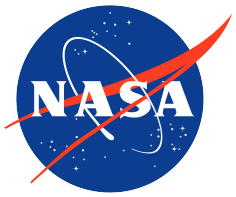
[+]*Computational Aerosciences Branch, NASA Ames Research Center, Moffett Field, CA, 94035, USA*

Christoph Brehm[*]

[*]*Department of Mechanical Engineering, University of Kentucky, Lexington, KY, 40506, USA*

Advanced Modeling & Simulation (AMS) Seminar Series

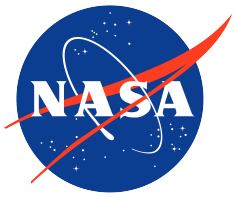
NASA Ames Research Center Thursday, September 19th 2019



Outline



- **Motivation/Introduction**
  - Mars, EDL system qualification, Simulation Capabilities
- **FSI Method**
  - Governing equations, Overview
  - Immersed Boundary Method for the Compressible Navier-Stokes Equations (CFD)
  - Geometrically Nonlinear Computational Structural Dynamics Solver (CSD)
  - Coupling procedure
- **Summary of FSI Method Validation**
- **Methods for Large-scale, Parallel CFD-CSD Coupling**
  - Disparate domain decomposition
- **Supersonic Parachute Inflation**
- **Summary and Outlook**



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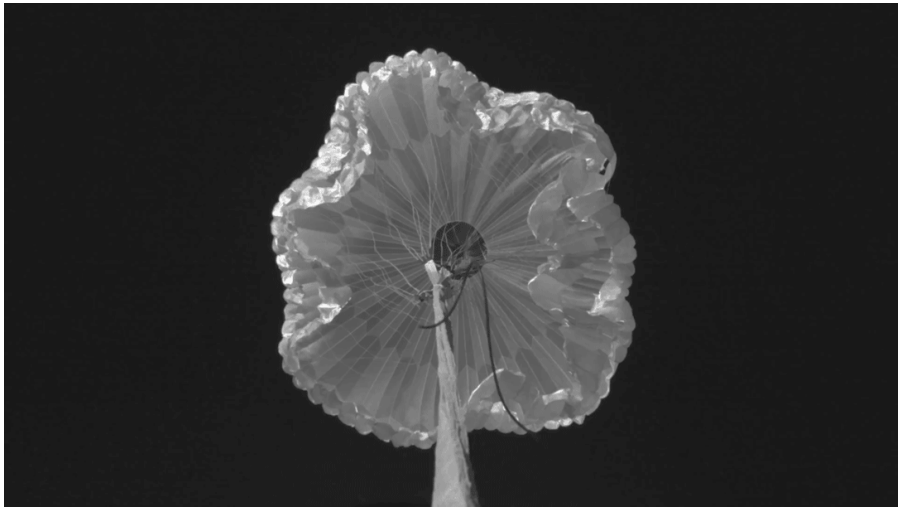
Motivation

- MSL EDL system was requalified
  - Payload weight, canopy size, and landing altitude exceeded those established by Viking mission

    (Sengupta *et al*. AIAA 2007,2009, Way *et al*. IEEE 2006)

- LDSD missions
  - Successful wind tunnel tests, parachute failure in real world tests

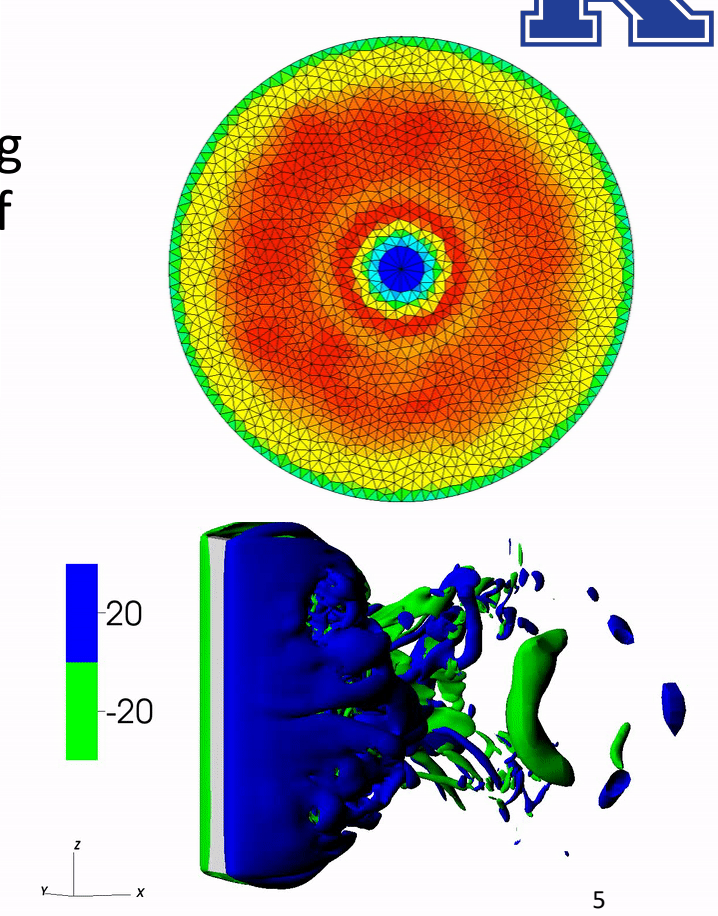
- NASA's mission to Mars will eventually require EDL re-qualification again
  - For hardware and humans required for sustained settlements, more demanding landing objectives



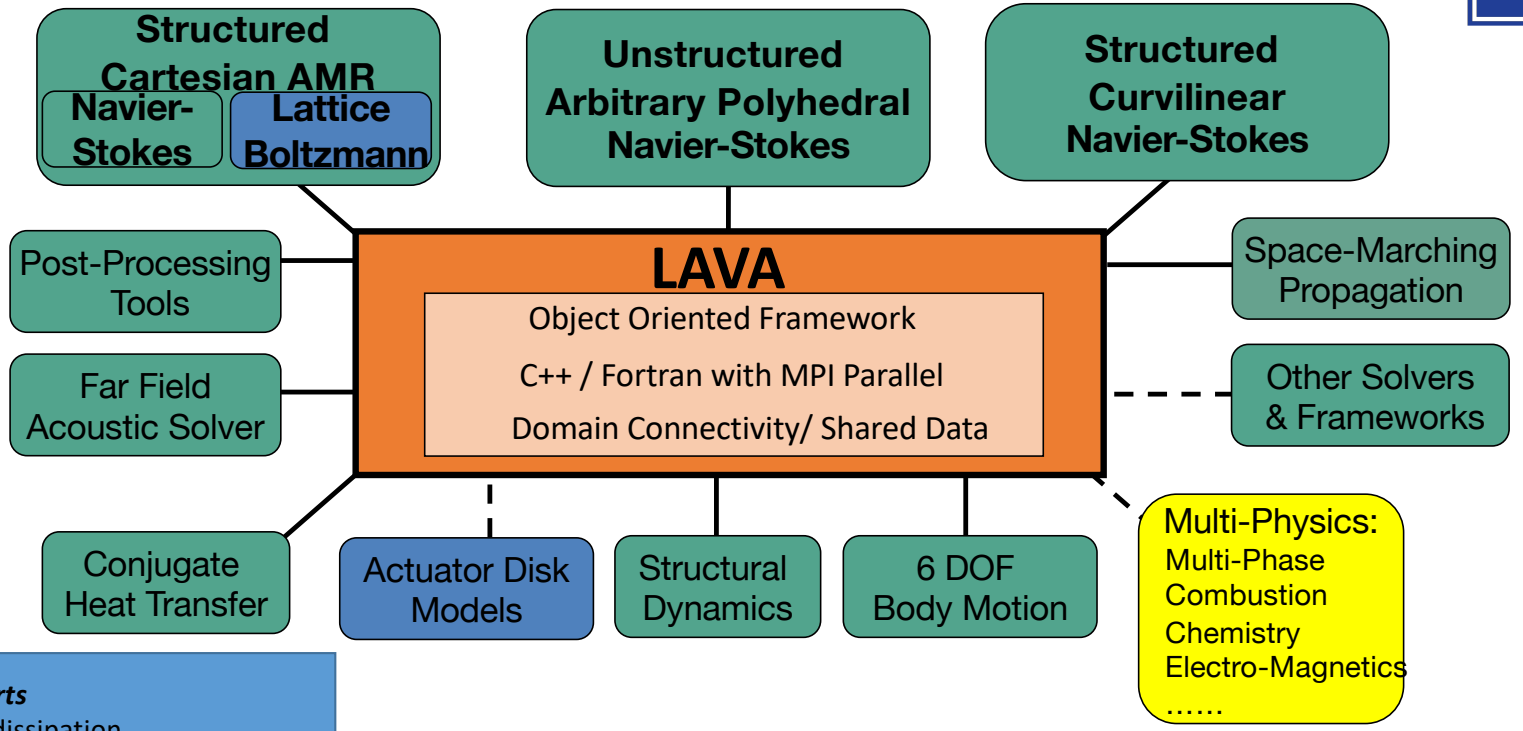
Deployment of parachute from ASPIRE test flight. (NASA/JPL)

Introduction

- Introduced and validated a method for simulating the large, geometrically nonlinear deformations of very thin shell structures (Boustani *et al*. SciTech 2019)
- Extended these capabilities to solving large-scale FSI problems in high-speed flows within a parallel computing environment
- End goal is high-fidelity supersonic parachute deployment simulations



LAVA Framework



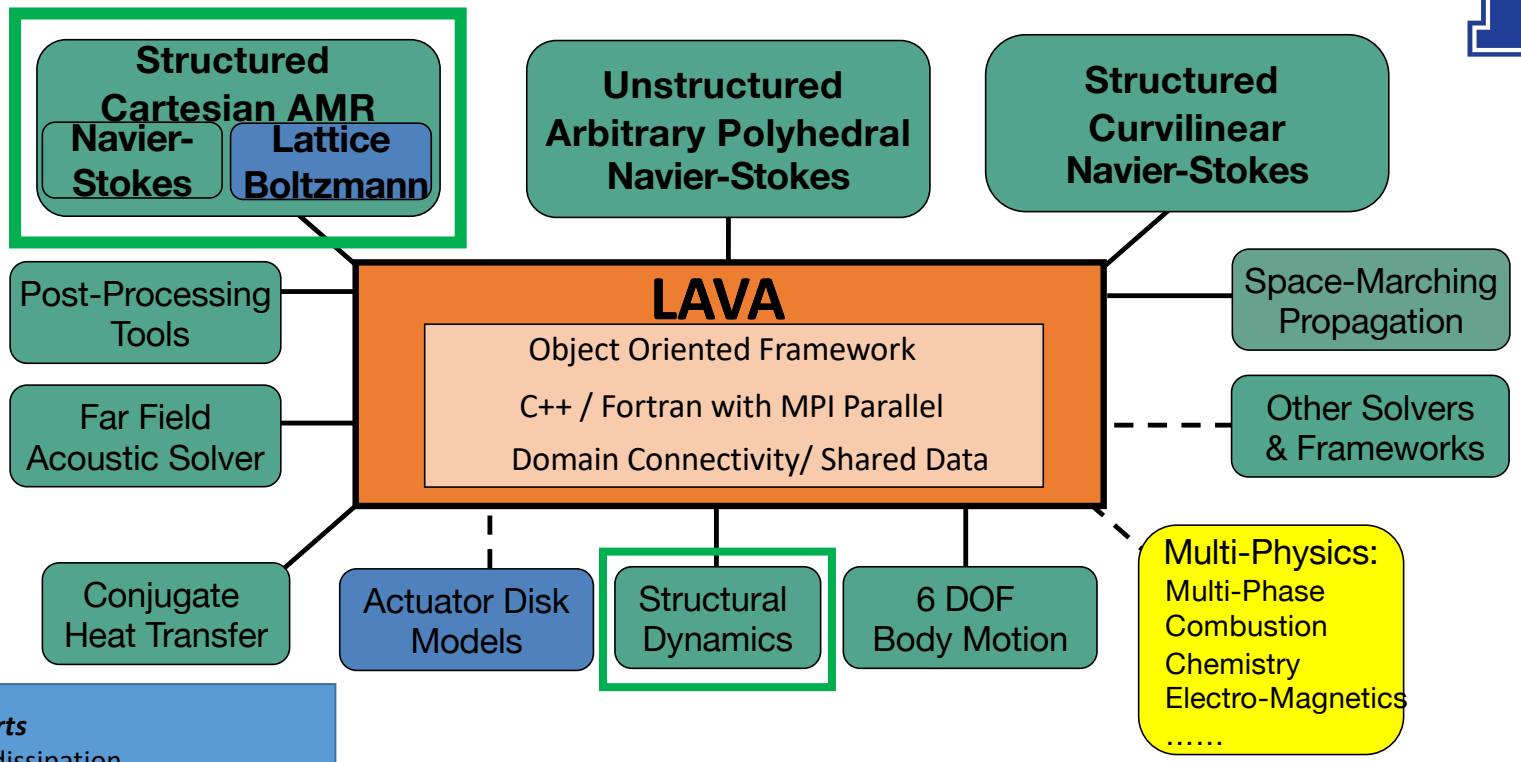
Other Development Efforts

- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)



Kiris at al. AIAA-2014-0070 & AST-2016

LAVA Framework



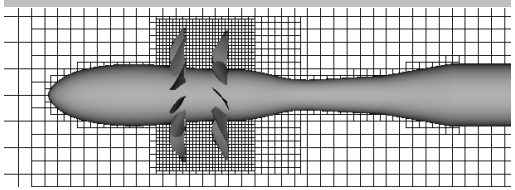
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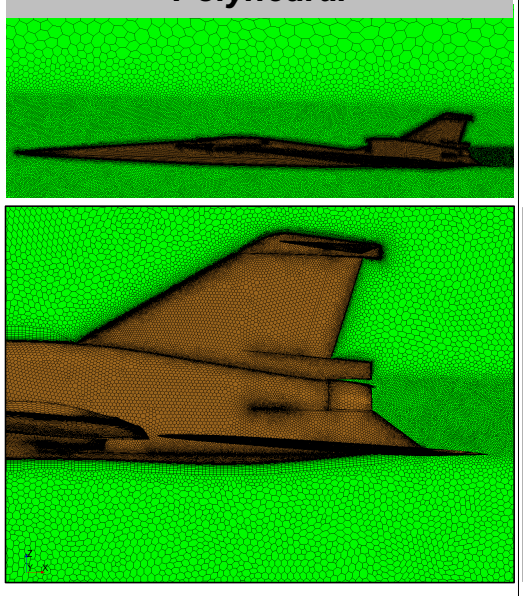
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Computational Grid Paradigms in LAVA



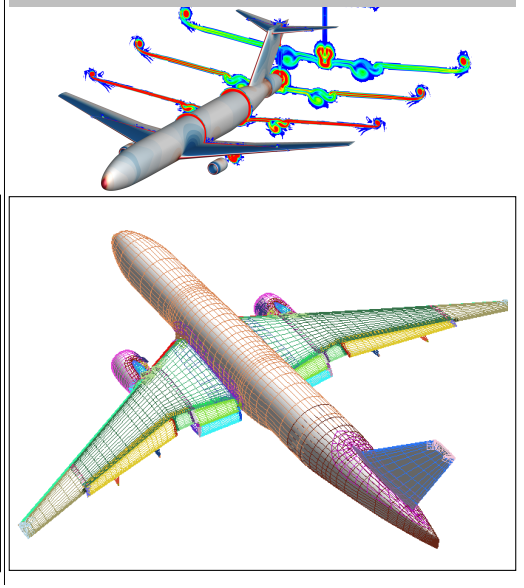
Structured Cartesian AMR

- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient



Unstructured Arbitrary Polyhedral

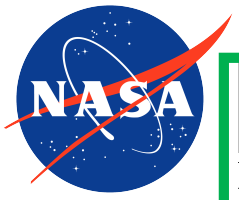
- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

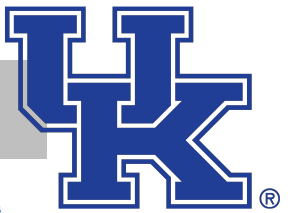


Structured Curvilinear

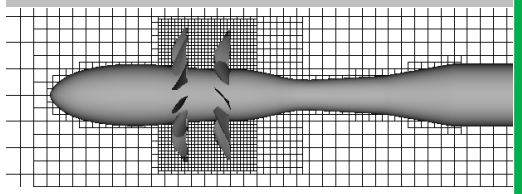
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- Reliable higher order methods
- Grid generation largely manual and time consuming

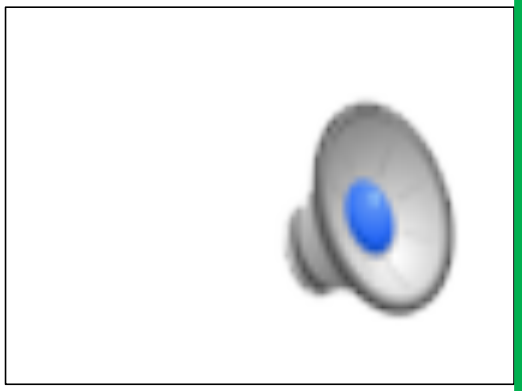
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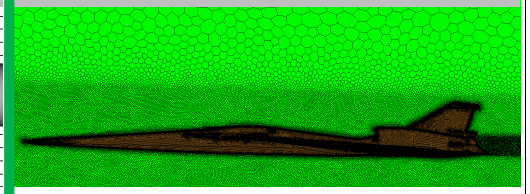
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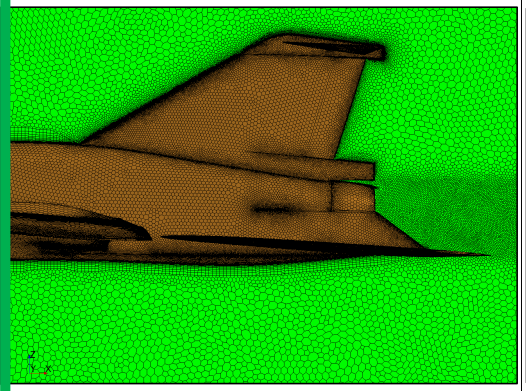




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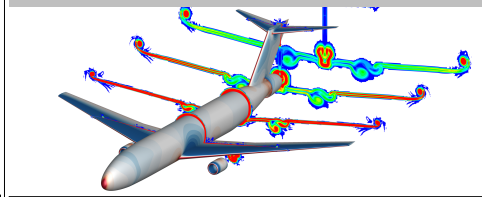
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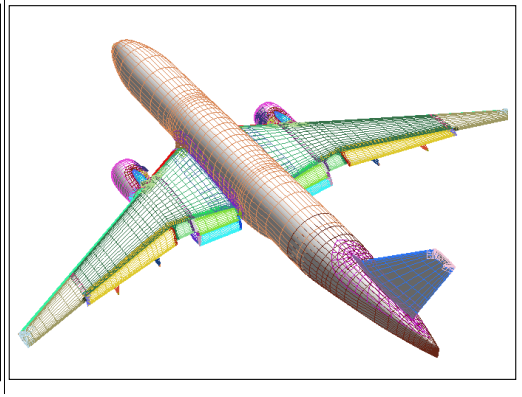




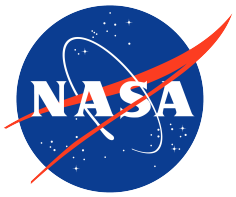
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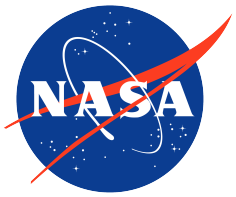
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Governing Equations



- The fluid regime considers the compressible Navier-Stokes equations, shown here in conservative form

$$\frac{\partial \mathbf{W}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \frac{\partial \mathbf{G}}{\partial z} = 0$$

$$\mathbf{W} = \left[\; \rho, \rho u, \rho v, \rho w, \rho e_t \; \right]^T$$

- The structural regime considers the Total Lagrangian equations of motion

$$\int_{{}_0V} {}_0\boldsymbol{S}_{ij}\delta_0\boldsymbol{\epsilon}_{ij}d^0V + \int_{{}_0V} {}^t_0\boldsymbol{S}_{ij}\delta_0\boldsymbol{\eta}_{ij}d^0V = {}^{t+\Delta t}\boldsymbol{\mathcal{R}} - \int_{{}_0V} {}^t_0\boldsymbol{S}_{ij}\delta_0\boldsymbol{e}_{ij}d^0V$$

- Partitioned solution involves solving strong and weak solutions together

FSI Method

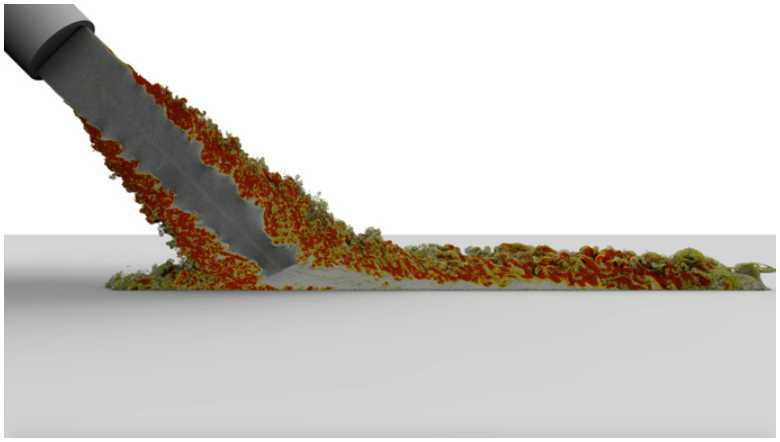
- The method used in this work couples together

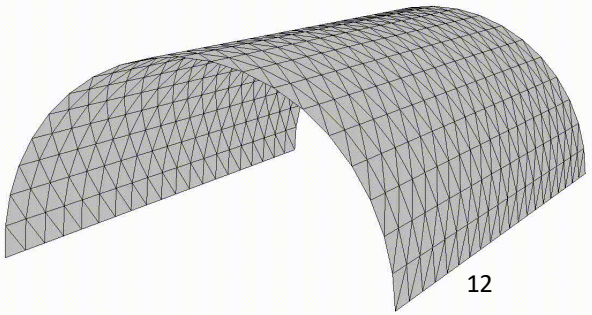
I. A block-structured Cartesian, higher-order, sharp, immersed boundary method for the compressible Navier-Stokes equations

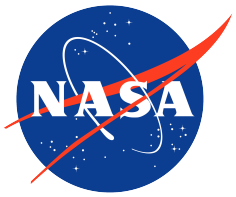
Brehm, C., Fasel, H., ***JCP 2013***
Brehm, C., Hader, C., Fasel, H., ***JCP 2015***
Kiris et al., ***Aerospace Sci. and Tech 2016***
Brehm, C., Barad, M. F., Kiris, C. C., ***JCP 2019***

II. A geometrically nonlinear structural finite element solver employing shell elements that utilize the Mixed Interpolation of Tensorial Components

Boustani et al., ***AIAA SciTech 2019***
Boustani et al., ***AIAA Aviation 2019***



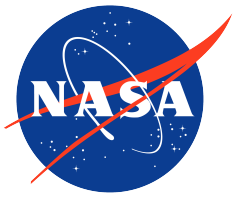




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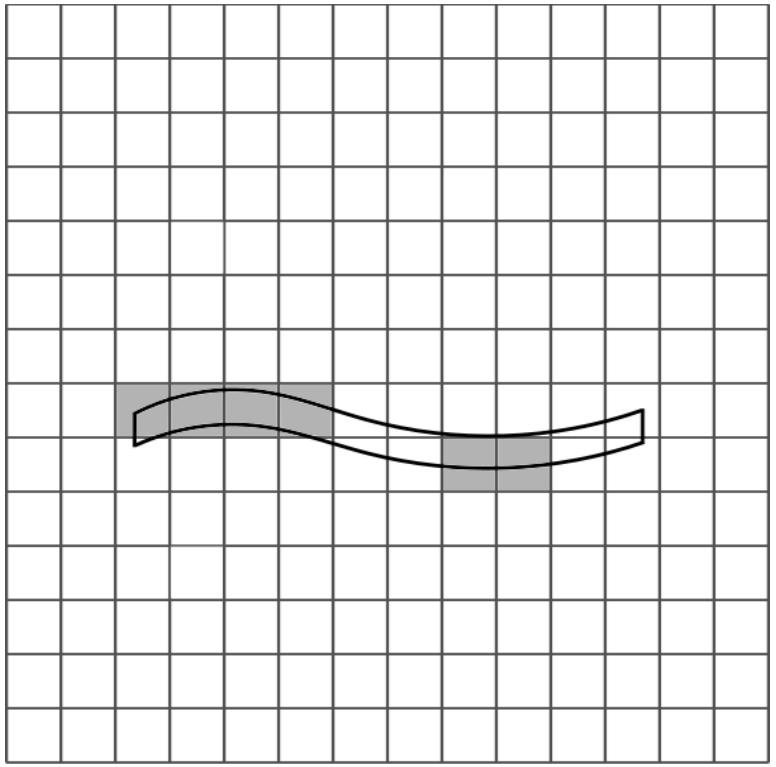
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Higher-Order IBM

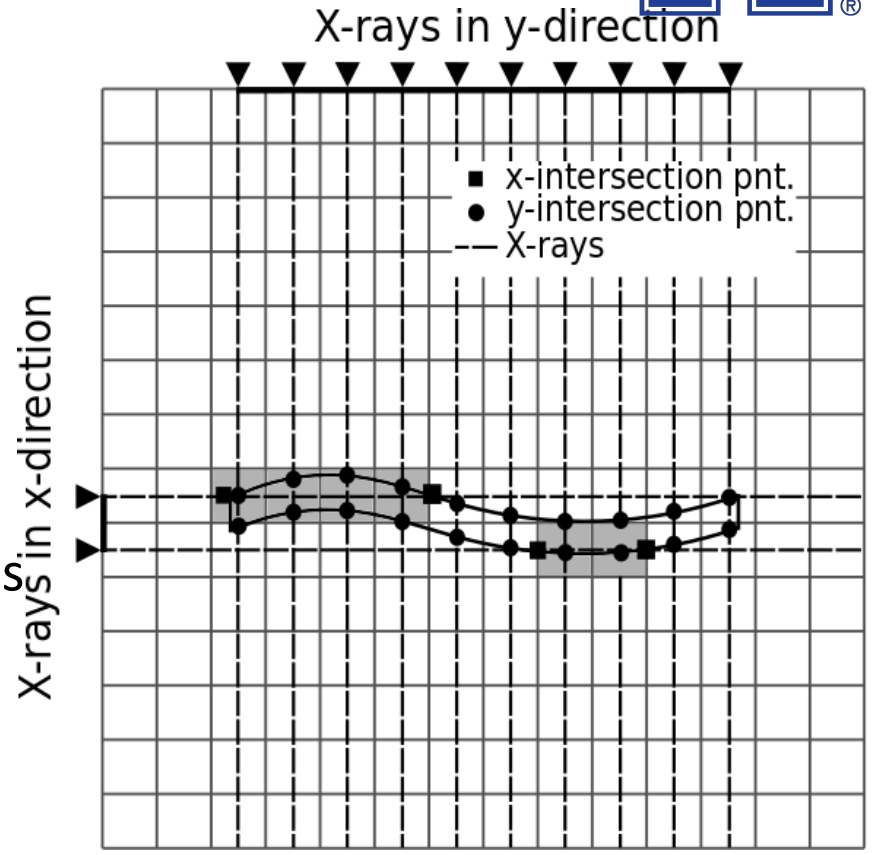


- **Stability is built into derivation**
  - In contrast to proving *a posteriori*
- Automatic volume mesh generation
  - For any arbitrarily complex geometry
- FD stencil coefficients at irregular grid points are locally optimized
  - Improved global stability



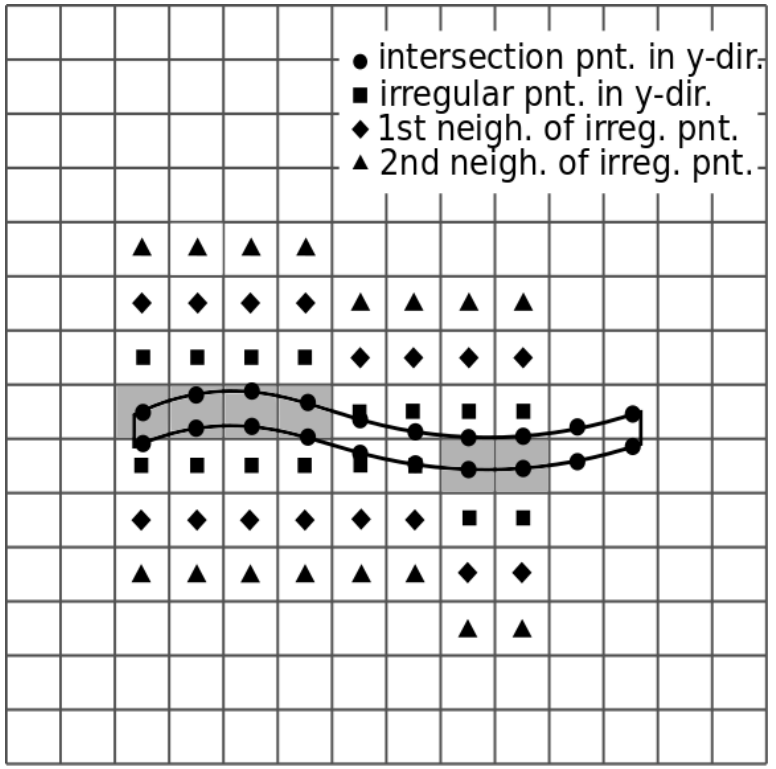
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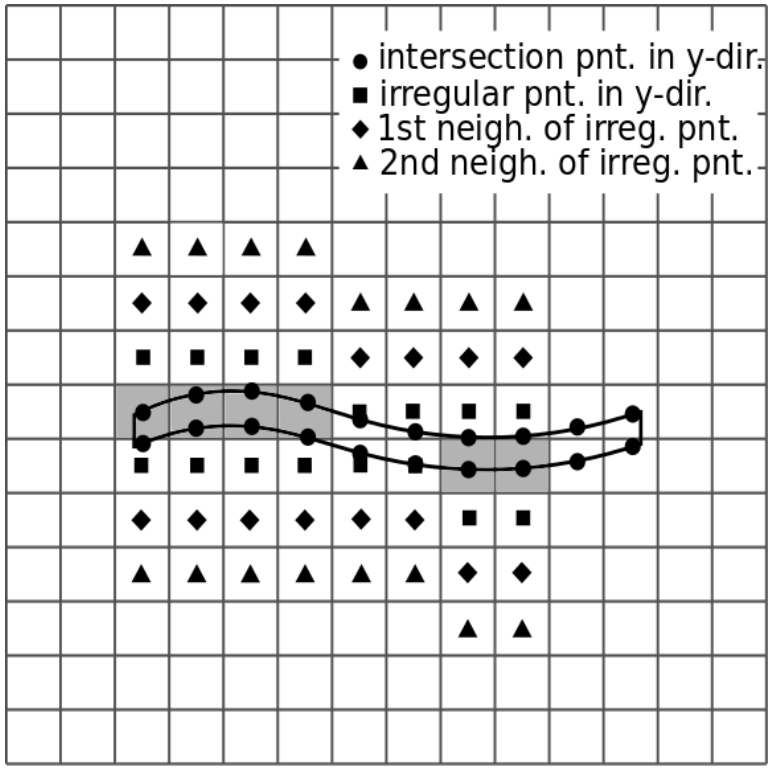
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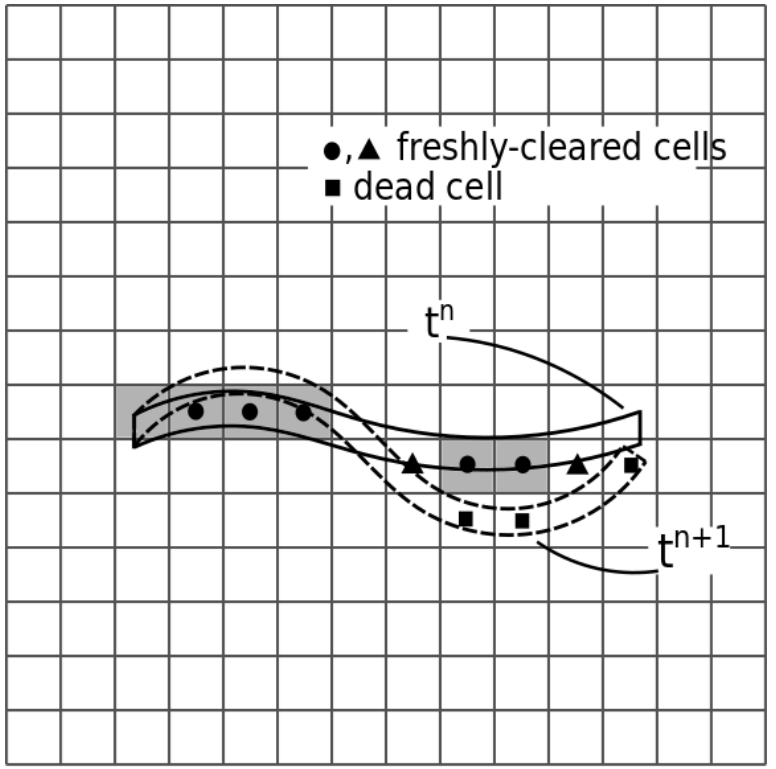
Higher-Order IBM

- Stability is built into derivation
  - In contrast to proving *a posteriori*
- Automatic volume mesh generation
  - For any arbitrarily complex geometry
- **'Sharp' classification → BCs applied at intersection points**
  - No valid data needed inside geometry
  - In other words, no cells needed inside geometry



Higher-Order IBM

- **Need to deal with freshly-cleared cells (FCCs)**
  - I. Inside/outside geometry (●)
  - II. Flipped boundary distance (▲)
- No valid time-history → extrapolate
- To reduce spurious oscillations in the pressure field, the stencil should be chosen to:
  - Extend into the direction with the maximum body velocity (low speed flows)
  - Utilize ENO (in supersonic flows)

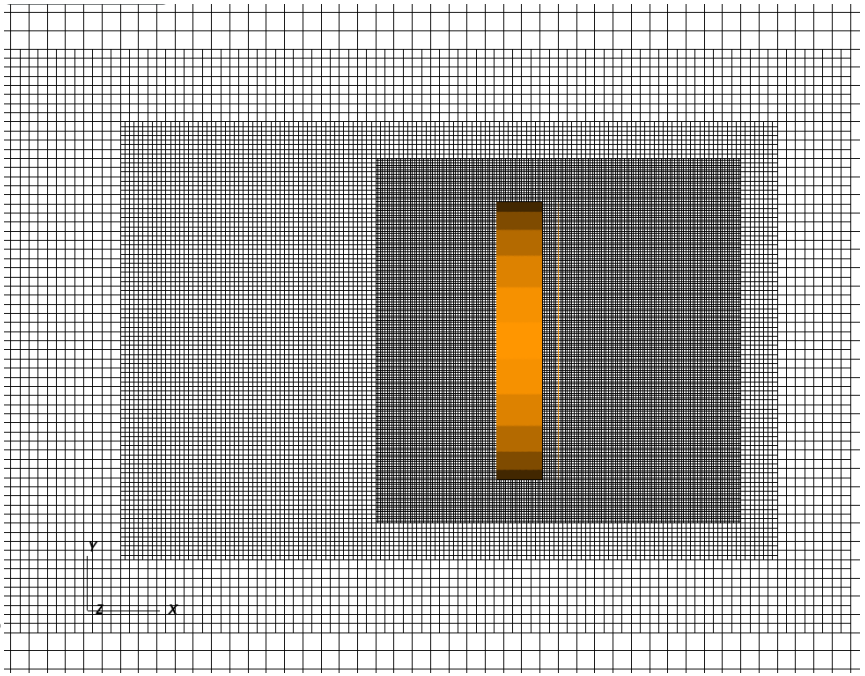


Higher-Order IBM

- Solution is obtained with:
  I. 2^{nd}-/4^{th}-order time integration (RK)
  II. 5^{th}-order spatial discretization (WENO)

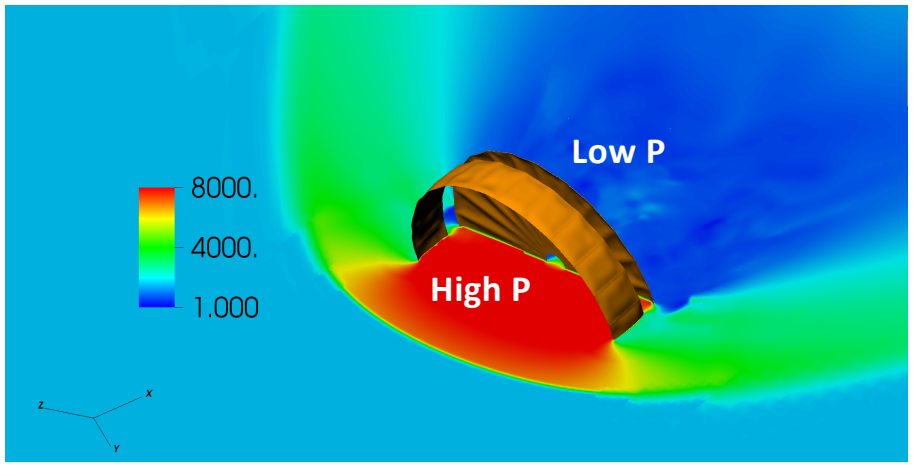
- Framework can handle geometries much smaller than the minimum grid spacing

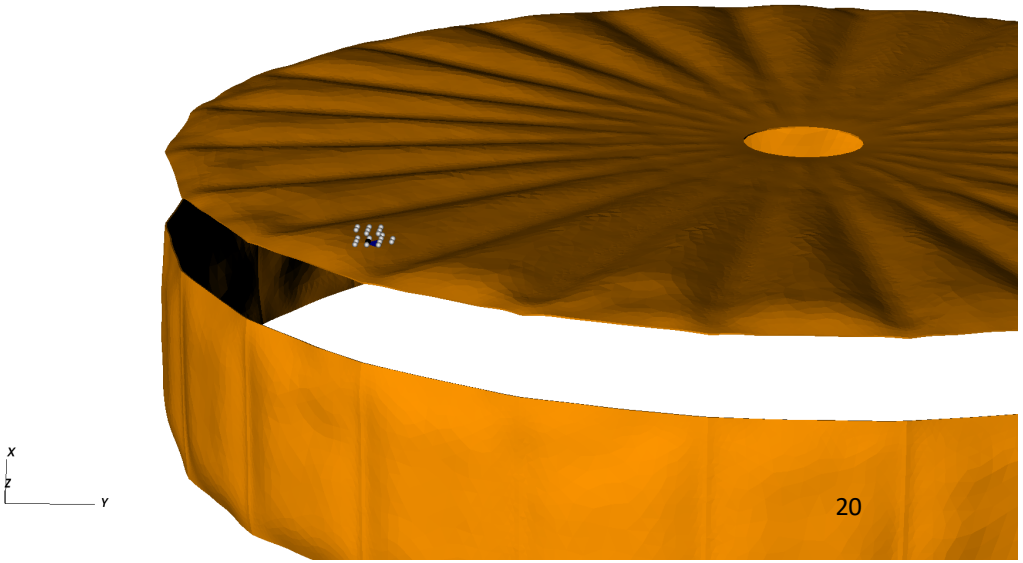
- Robust extrapolation of flow field quantities onto the surface



Higher-Order IBM

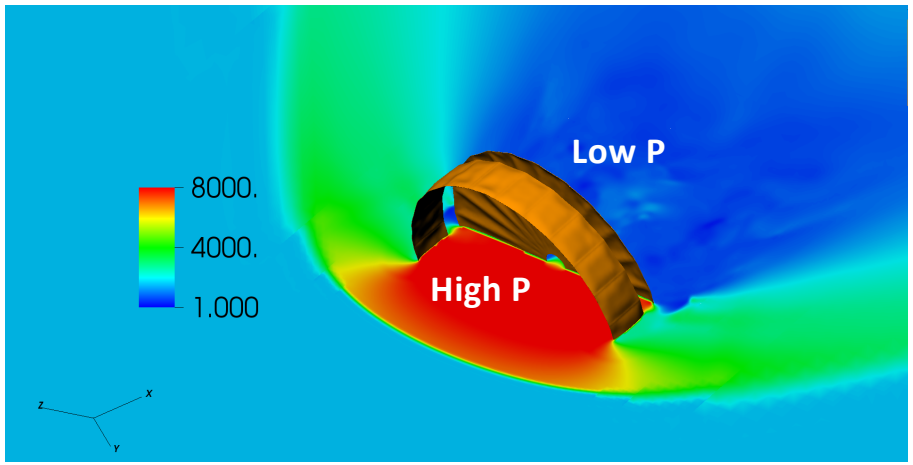
- Developing methods for robust extrapolating of flow quantities onto very thin and complex geometries

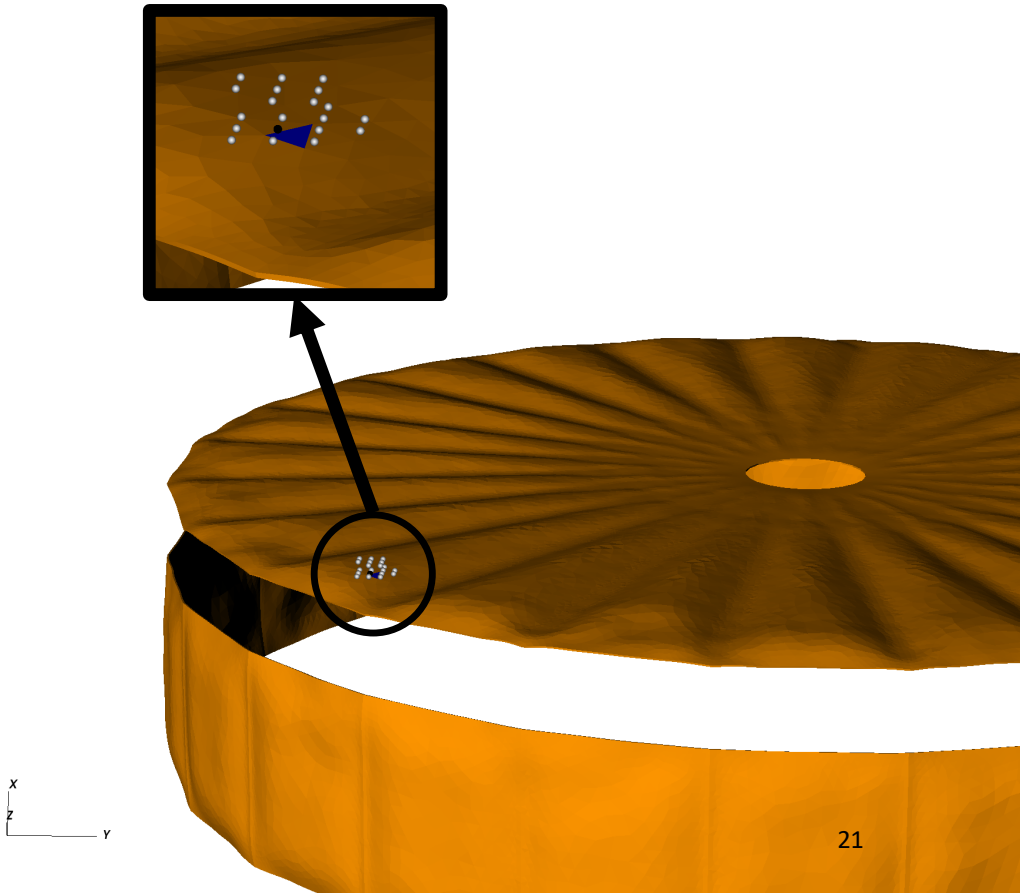




Higher-Order IBM

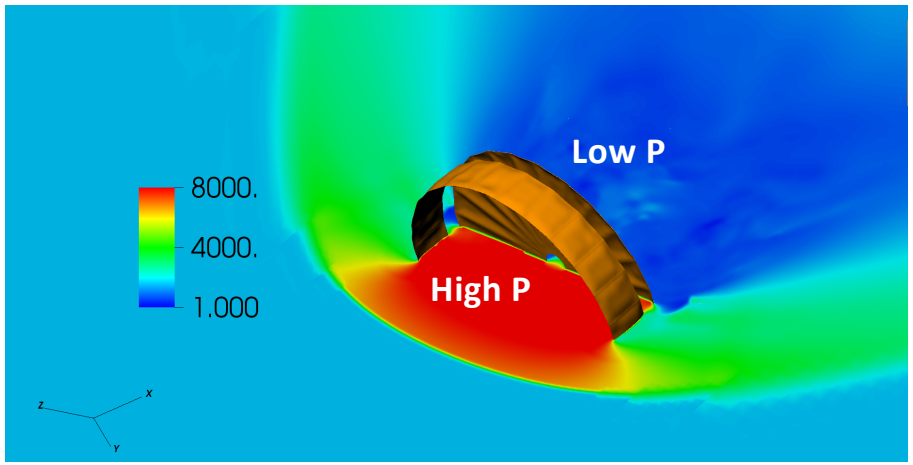
- This ensures smooth pressure and viscous loading for the CSD solver

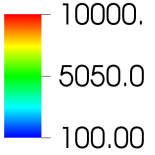




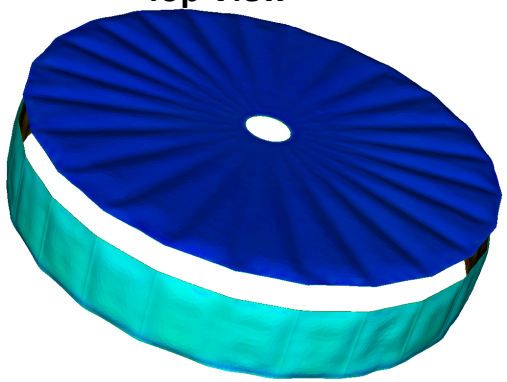
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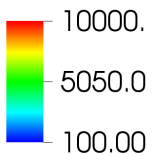
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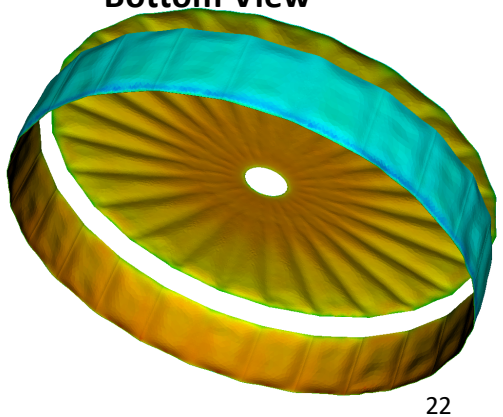


Top View



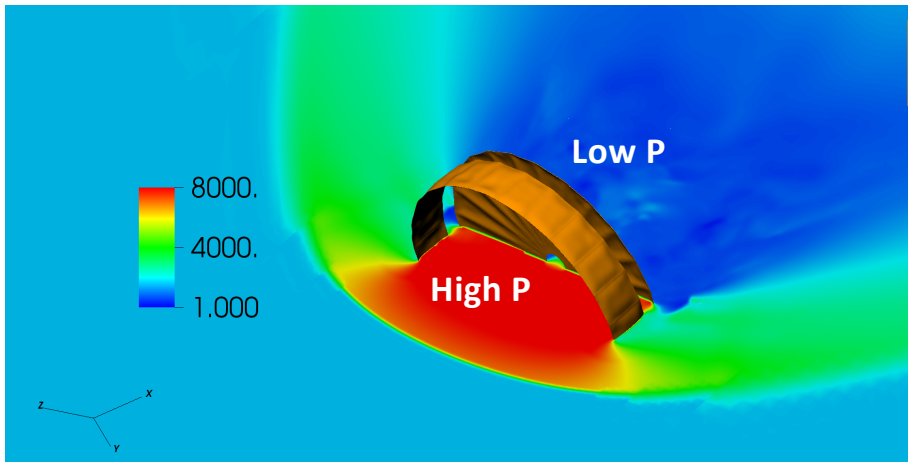


Bottom View

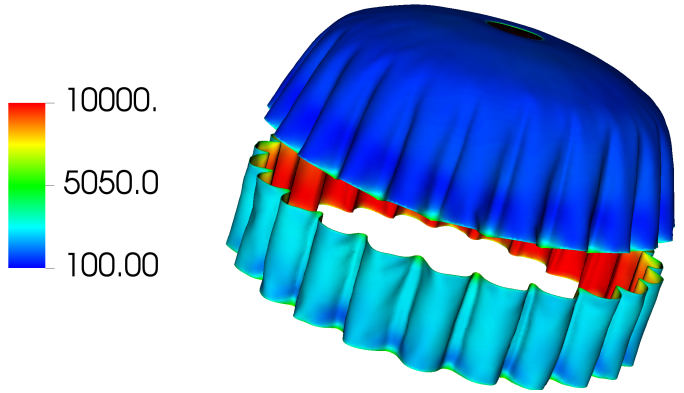


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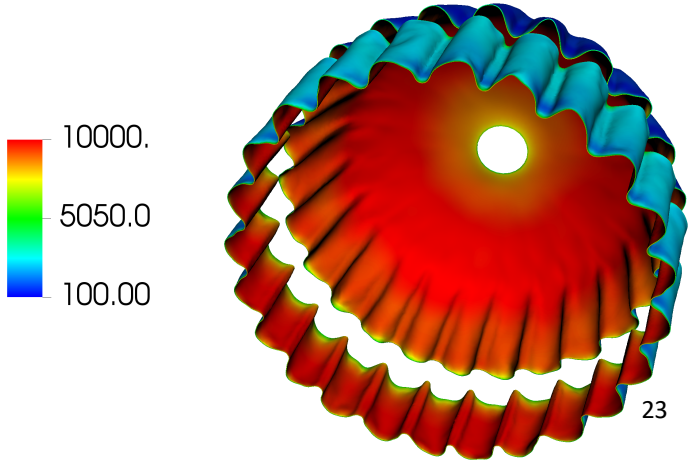
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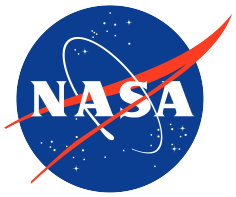


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  - Disparate domain decomposition
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- ❑ **Summary and Outlook**

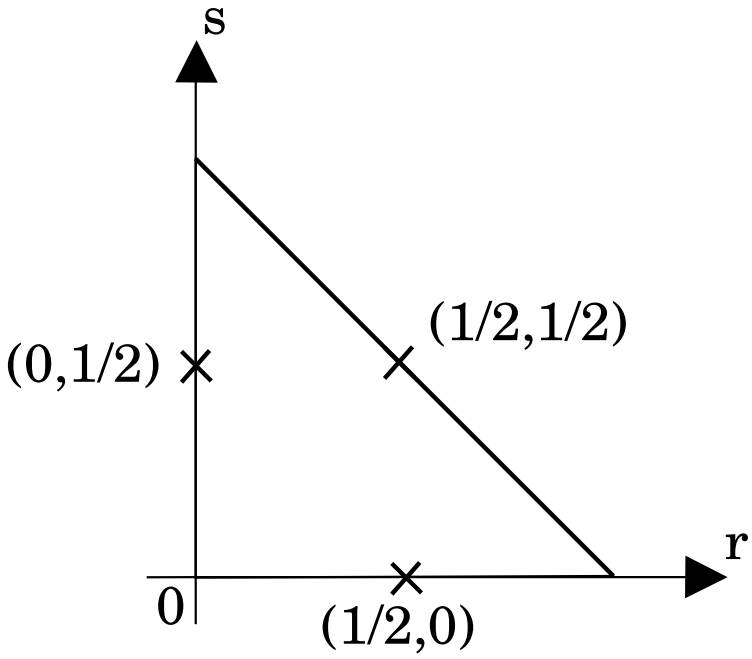
Structural Solver

- Element formulations used:
  - Geometrically nonlinear MITC3 triangular shell element (*Lee and Bathe, **Comp. and Struc. 2004***)
  - 2-node geometrically nonlinear cable element

- MITC3 shell element mitigates 'shear locking' via an assumed shear strain field:

$$\widetilde{e}_{rt} = e_{rt}^{(1)} + cs \qquad \widetilde{e}_{st} = e_{st}^{(2)} - cr$$

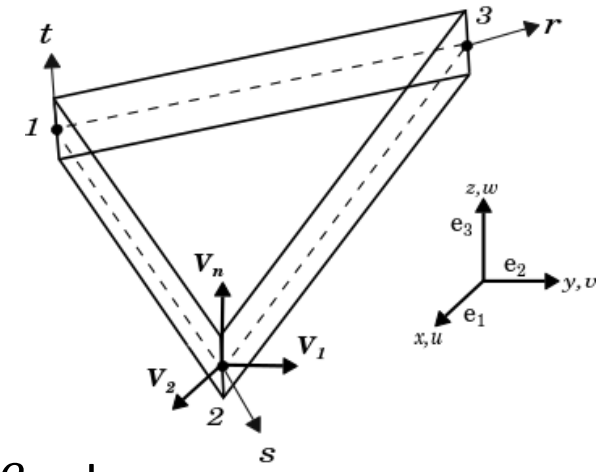
$$c = e_{st}^{(2)} - e_{rt}^{(1)} - e_{st}^{(3)} + e_{rt}^{(3)}$$



- Substitute displacement-based shear strain components for assumed shear strains

Structural Solver

- Element formulations used:
  - Geometrically nonlinear MITC3 triangular shell element (*Lee and Bathe, **Comp. and Struc. 2004***)
  - 2-node geometrically nonlinear cable element



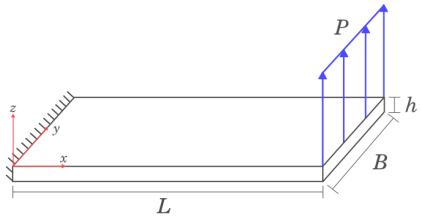
- St. Venant-Kirchoff hyperelastic strain-energy function

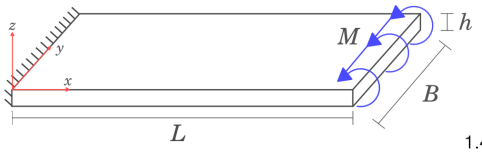
- Time integration is performed with the implicit Newmark-β scheme
  - Dynamic Newton-Raphson relaxation parameter optimizes convergence properties
  - Can converge very thin shell structures in steady and unsteady simulations
  - Robust to coarse CFD resolution loading and acoustic disturbances

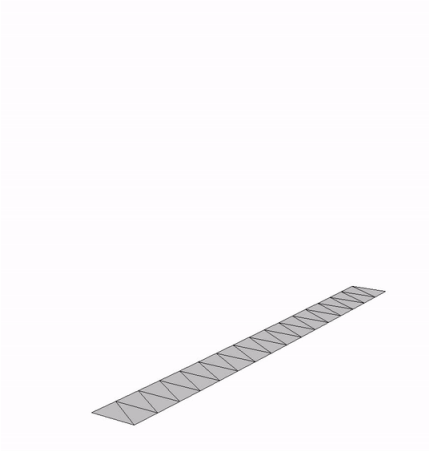
Structural Solver

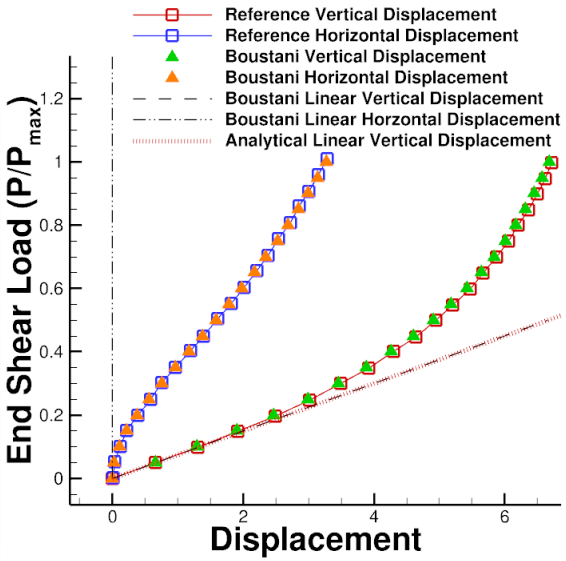
- CSD solver validated for canonical large deformation problems

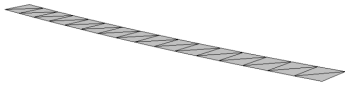
(Boustani *et al.*, **AIAA 2019)**

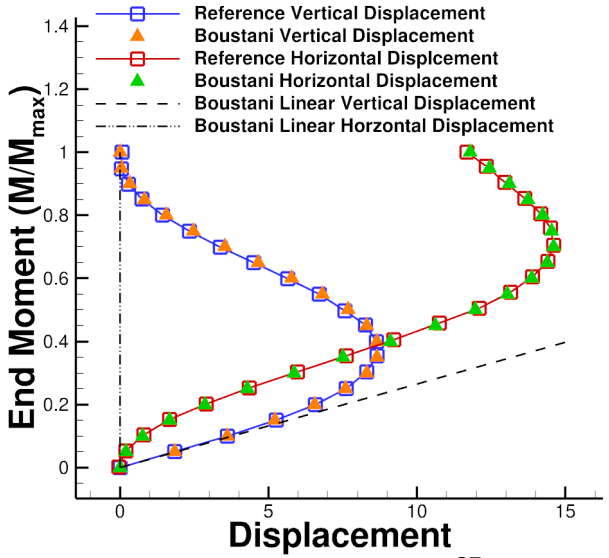








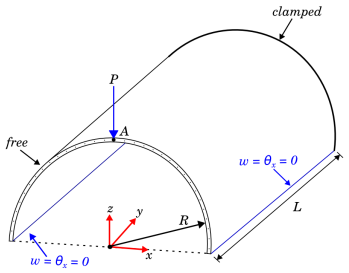


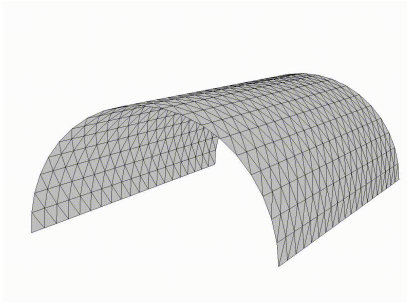


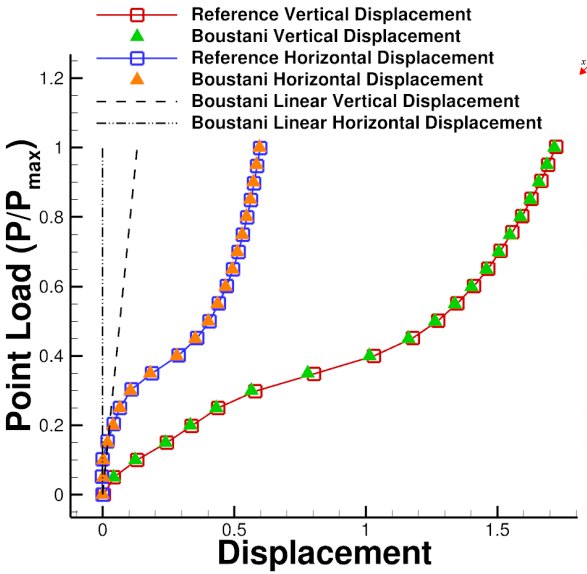
Structural Solver

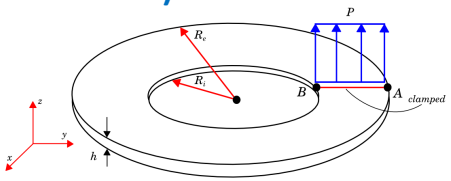
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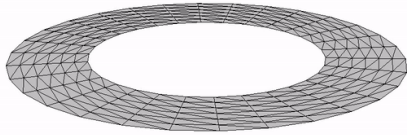
(Boustani *et al.*, **AIAA 2019)**

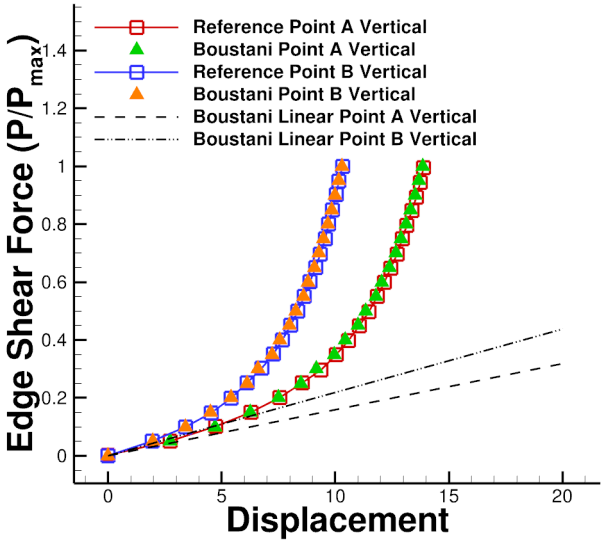


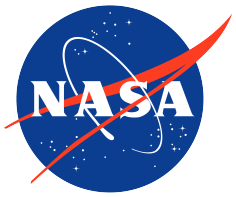








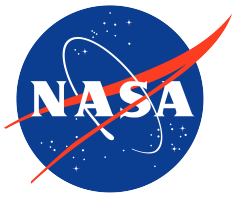




Outline



- ❑ **Motivation/Introduction**
  - Mars, EDL system qualification, Simulation Capabilities
- ❑ **FSI Method**
  - Governing equations, Overview
  - Immersed Boundary Method for the Compressible Navier-Stokes Equations (CFD)
  - Geometrically Nonlinear Computational Structural Dynamics Solver (CSD)
  - **Coupling procedure**
- ❑ **Summary of FSI Method Validation**
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Coupling Conditions



- The coupling conditions between the two regimes enforce the continuity of loads across the shared boundary

$$\mathbf{t}_{structure}(\overline{\mathbf{x}}_b(t), t) = \mathbf{t}_{fluid}(\overline{\mathbf{x}}_b(t), t)$$

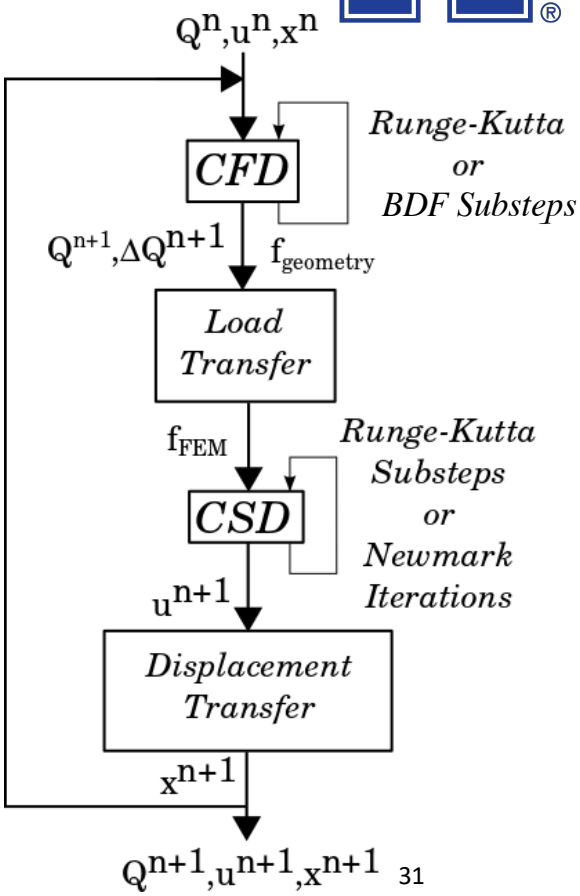
where the fluid traction vector considers pressure and viscous stresses

- The continuity of the position and velocity of the shared boundary itself is also enforced

$$\overline{\mathbf{x}}_b(t) = \mathbf{x}_{fluid}(t) = \mathbf{x}_{structure}(t), \text{ and}$$
$$\dot{\overline{\mathbf{x}}}_b(t) = \dot{\mathbf{x}}_{fluid}(t) = \dot{\mathbf{x}}_{structure}(t) \quad \forall t \geq 0$$

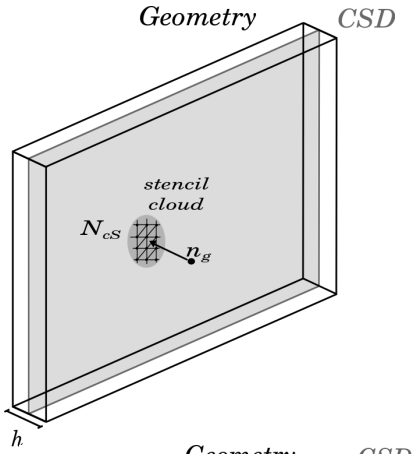
CFD-CSD Coupling

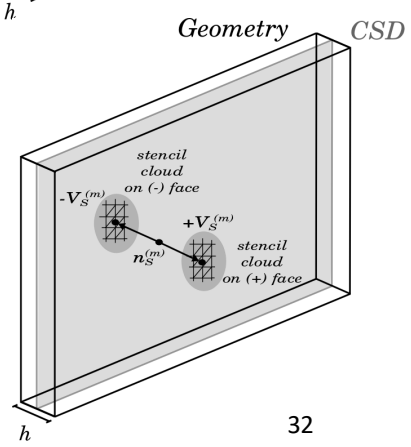
- The CFD and CSD solvers are weakly coupled
  - The solution procedure is **partitioned**
  - Parachute canopy is 33,000x more dense than upper Martian atmosphere
- An auxiliary and mass-less, or phantom, representation of the geometry with a finite thickness is used in the CFD solver
- The coupling conditions are enforced on the geometry representation

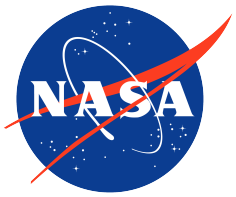


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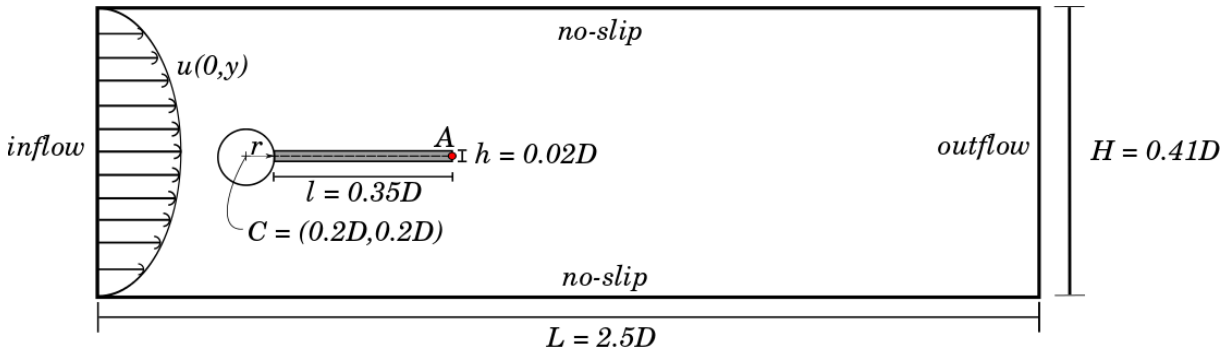
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Fixed Cylinder with Trailing Filament

- Benchmarked by Turek and Hron (*Fluid-Structure Interactions*, Springer, 2006)
- Parabolic velocity profile at the inlet

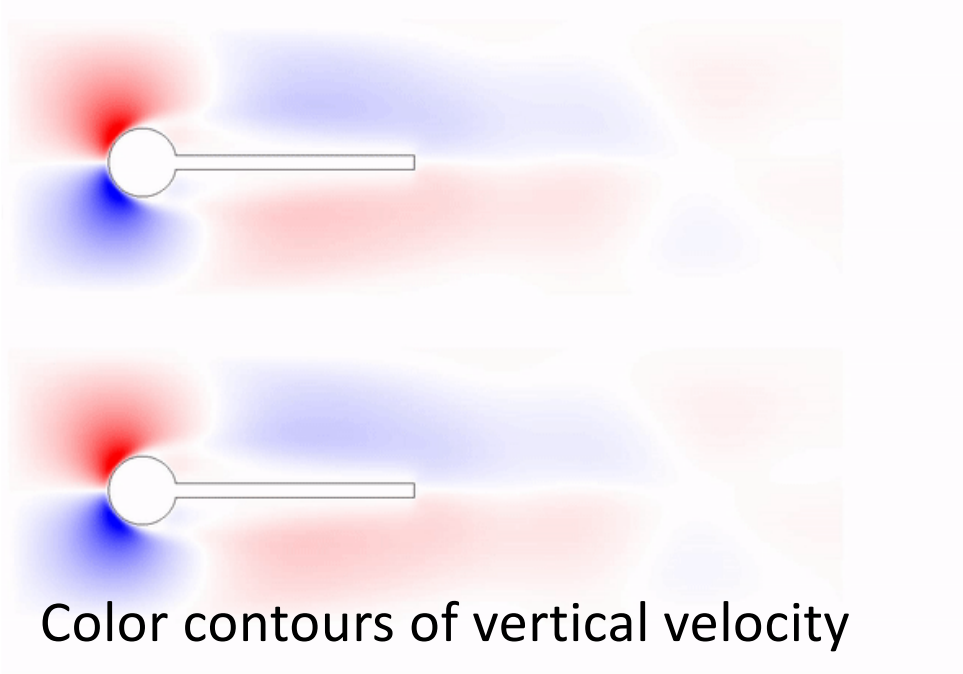
$$u(0,y) = 1.5\bar{U}\frac{y(H-y)}{\left(\frac{H}{2}\right)^2} = 1.5\bar{U}\frac{4.0}{0.1681}y(0.41-y)$$

- Normalized excursion amplitude and Strouhal number are compared



Fixed Cylinder with Trailing Filament

- **Case 1:**
  - $\boldsymbol{Re = 100}$
  - $\boldsymbol{DR = 10}$
  - $S_b = \frac{E_s}{\rho_f U^2} = 1{,}400$
  - $\Delta x_{min} = \Delta y_{min} = 0.16D$
  - 100 beam elements, 100 blocks of triangular elements



Color contours of vertical velocity

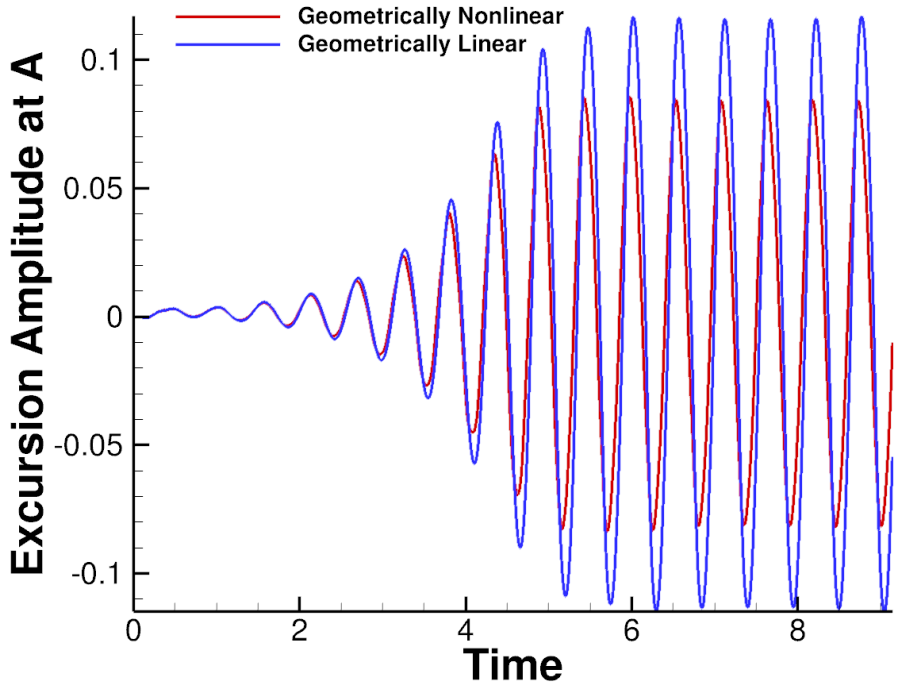
Fixed Cylinder with Trailing Filament

Results from Geometrically Nonlinear FSI Simulation

Reference	$\overline{A}$	St
Current Research	**0.84**	**0.18**
Turek and Hron *(2006)*	0.83	0.19
Tian *et al.* *(JCP 2013)*	0.78	0.19
Bhardwaj and Mittal *(AIAA Journal 2012)*	0.92	0.19

$$\overline{A} = \frac{1}{2}\frac{d_{y,max} - d_{y,min}}{D}$$

$$St = f\frac{D}{U}$$



Fixed Cylinder with Trailing Filament

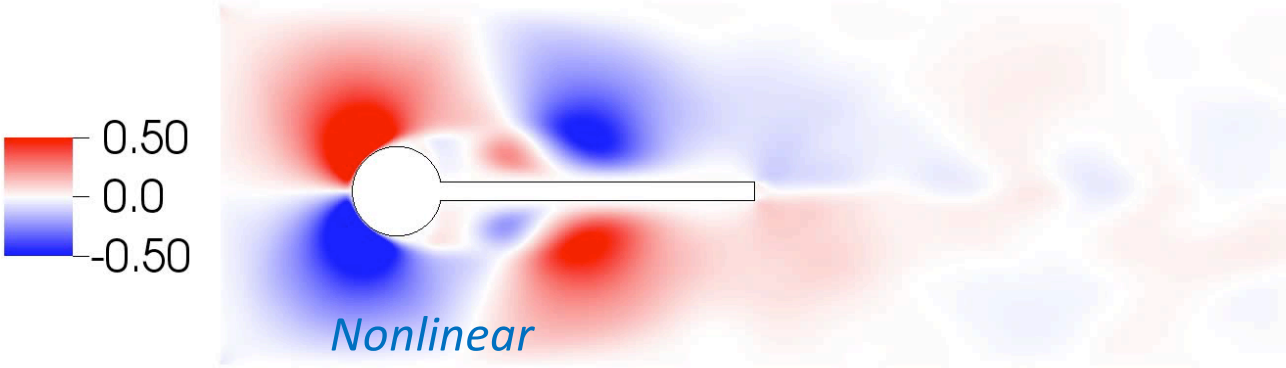
- **Case 2**:
  - $\boldsymbol{Re = 200}$
  - $\boldsymbol{DR = 1}$
  - $S_b = \frac{E_s}{\rho_f U^2} = 1{,}400$
  - $\Delta x_{min} = \Delta y_{min} = 0.16D$
  - 100 beam elements, 100 blocks of triangular elements

$$\overline{A} = \frac{1}{2}\frac{d_{y,max} - d_{y,min}}{D}$$

$$St = f\frac{D}{U}$$

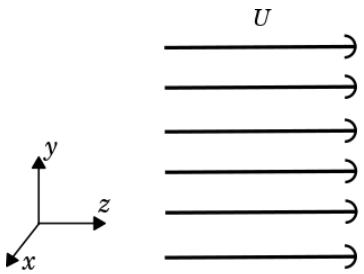
Results from Geometrically Nonlinear FSI Simulation

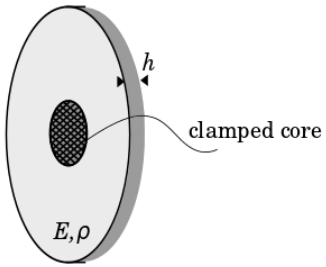
Reference	$\overline{A}$	St
Current Research	**0.29**	**0.26**
Turek and Hron *(2006)*	0.36	0.29
Tian *et al.* *(JCP 2013)*	0.32	0.26
Bhardwaj and Mittal *(AIAA Journal 2012)*	0.41	0.28

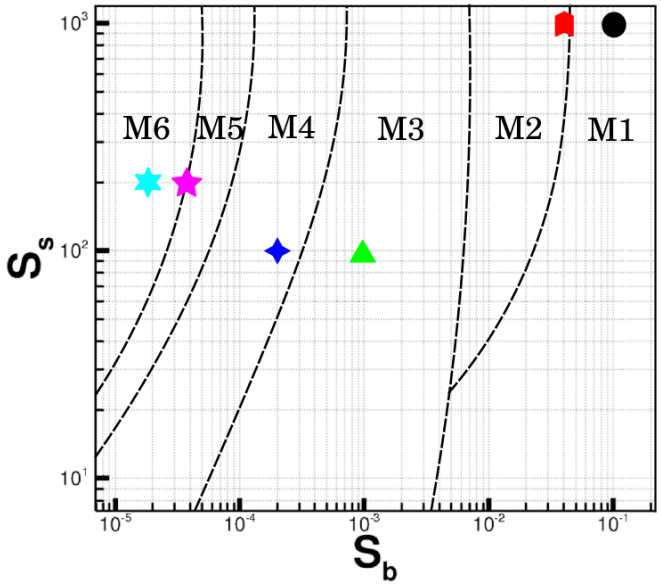


Compliant Disk in Viscous Flow

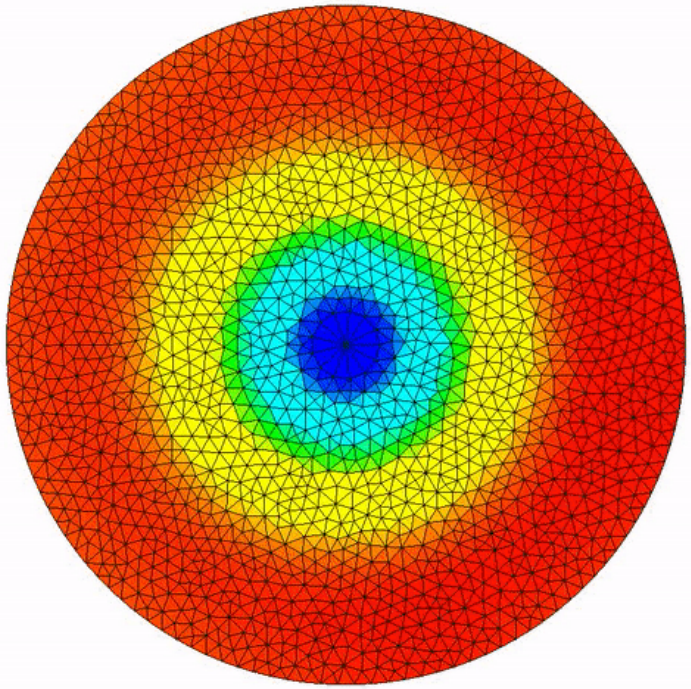
- Consider the crumpling and wrinkling of a thin, elastic sheet
  - $Re = 100$
  - $MR = 1$
  - S_b and S_s vary
  - $\Delta x_{min} = \Delta y_{min} = 0.015D$
  - 3,300 finite elements discretize the disk
  - Clamped core size $d_c = 0.1$







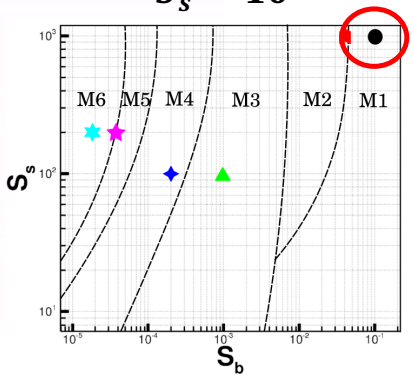
Compliant Disk in Viscous Flow

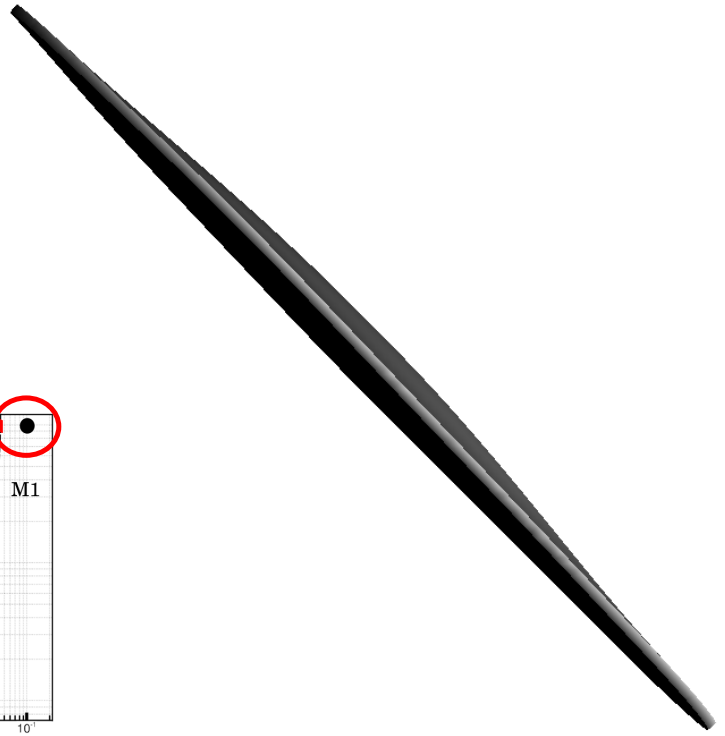


M1

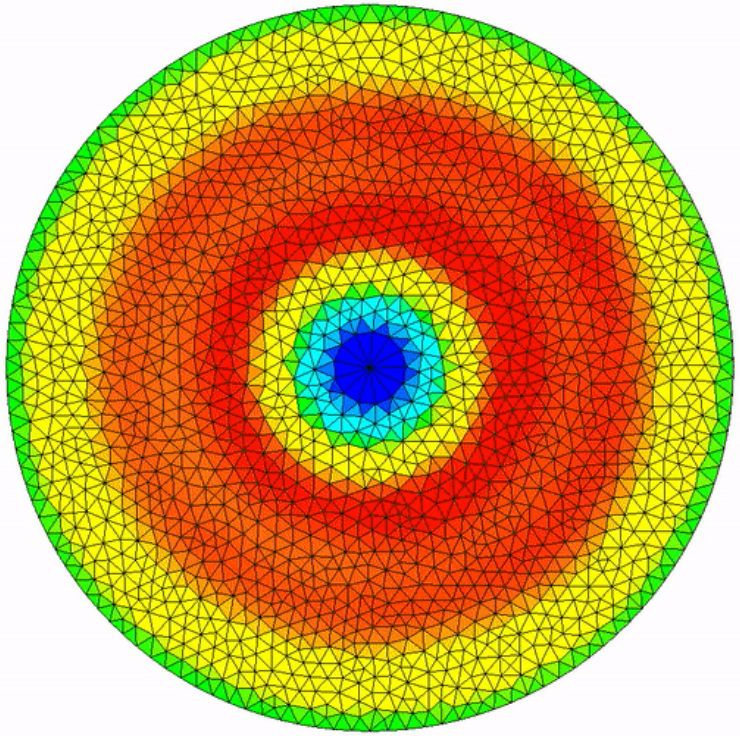
$S_b = 10^{-1}$

$S_s = 10^3$





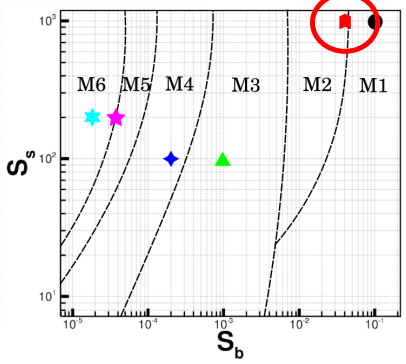
Compliant Disk in Viscous Flow

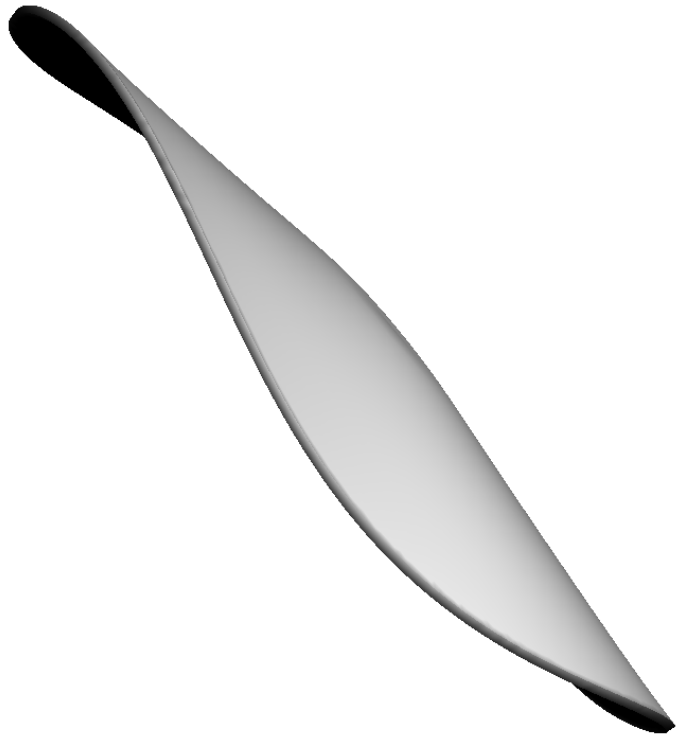


M2

$S_b = 4\times10^{-2}$

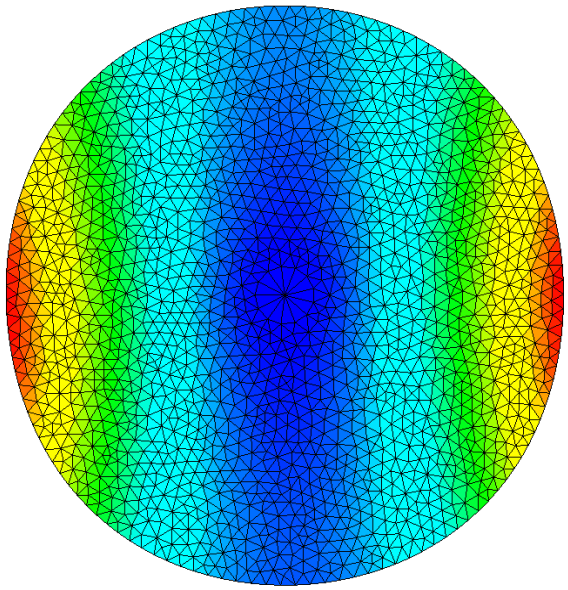
$S_s = 10^3$



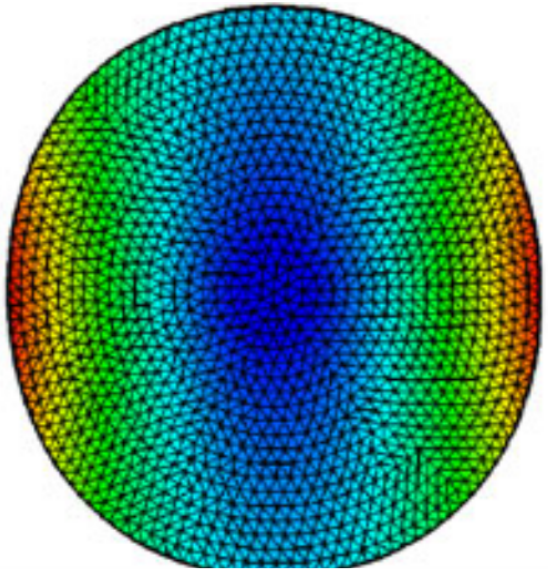


Compliant Disk in Viscous Flow

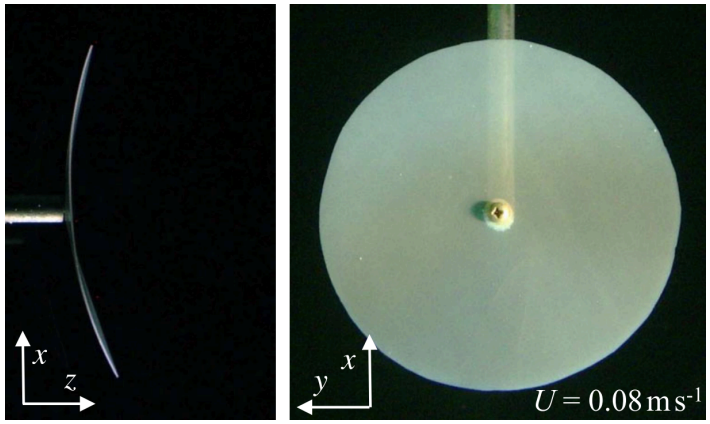
M2 Comparison



Current Research

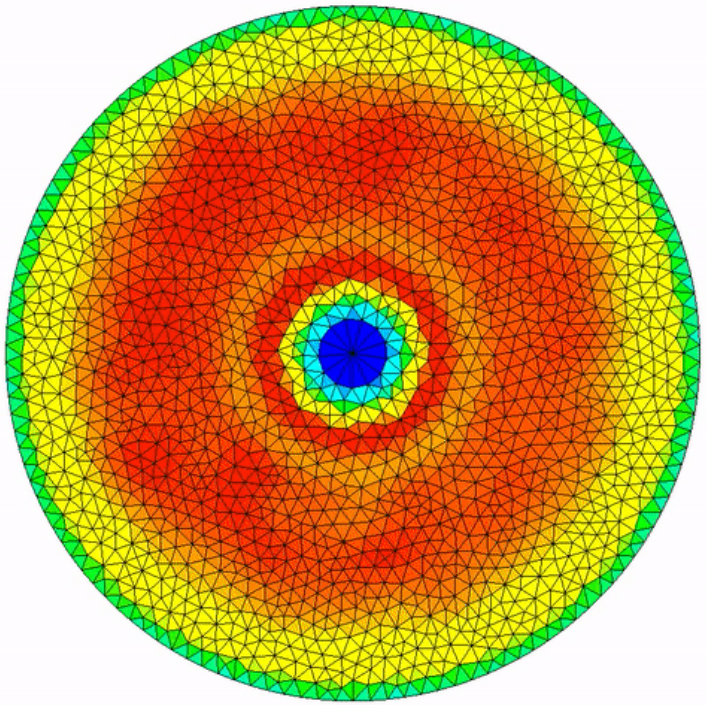


Simulations by Hua et al.
(Adjusted from JFM 2014)



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

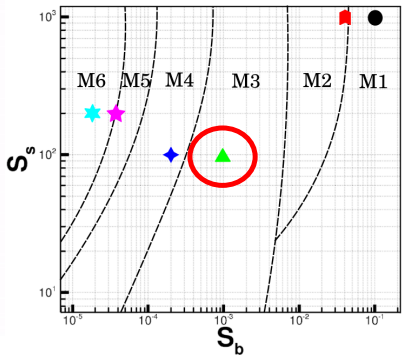
Compliant Disk in Viscous Flow



M3

$S_b = 10^{-3}$

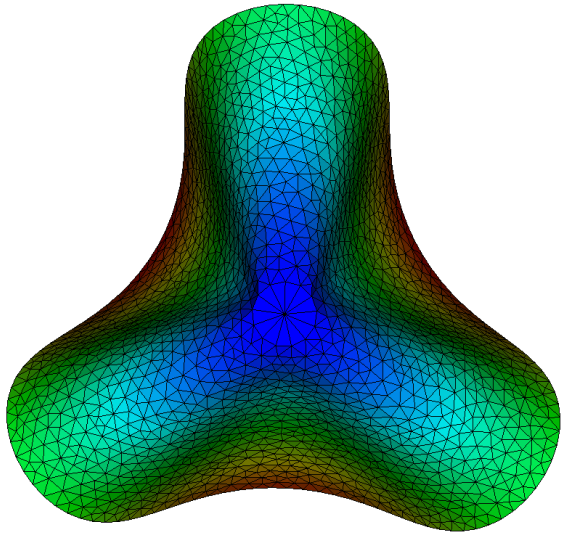
$S_s = 10^2$



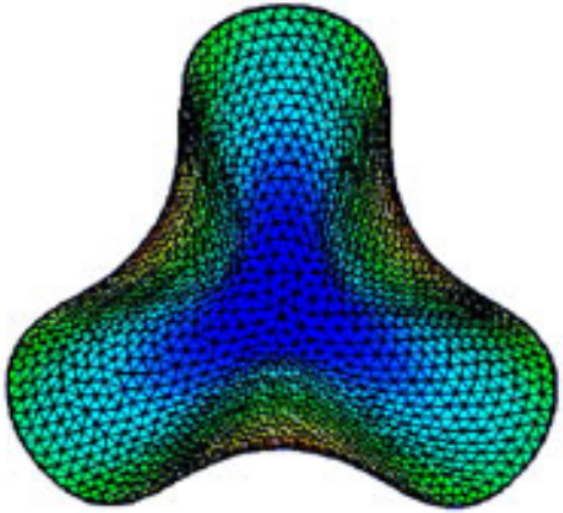


Compliant Disk in Viscous Flow

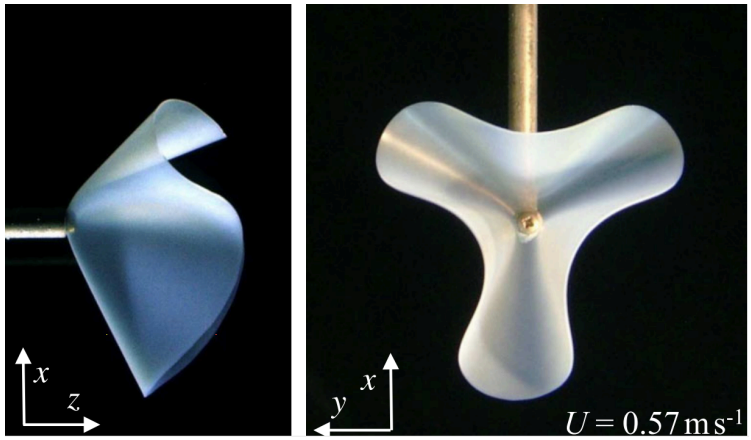
M3 Comparison



Current Research

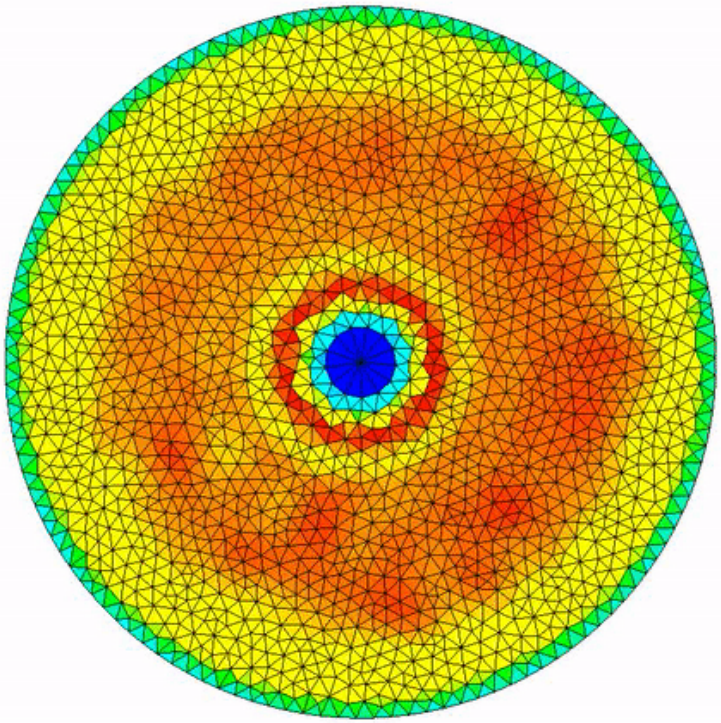


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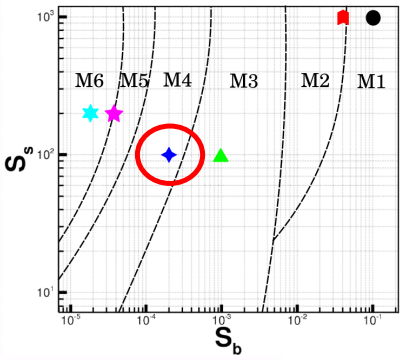
Compliant Disk in Viscous Flow

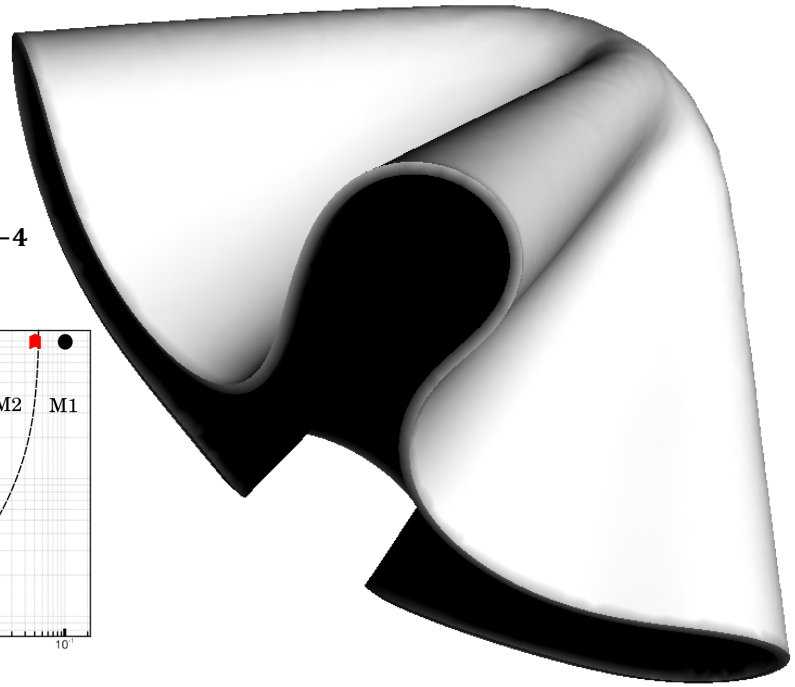


M4

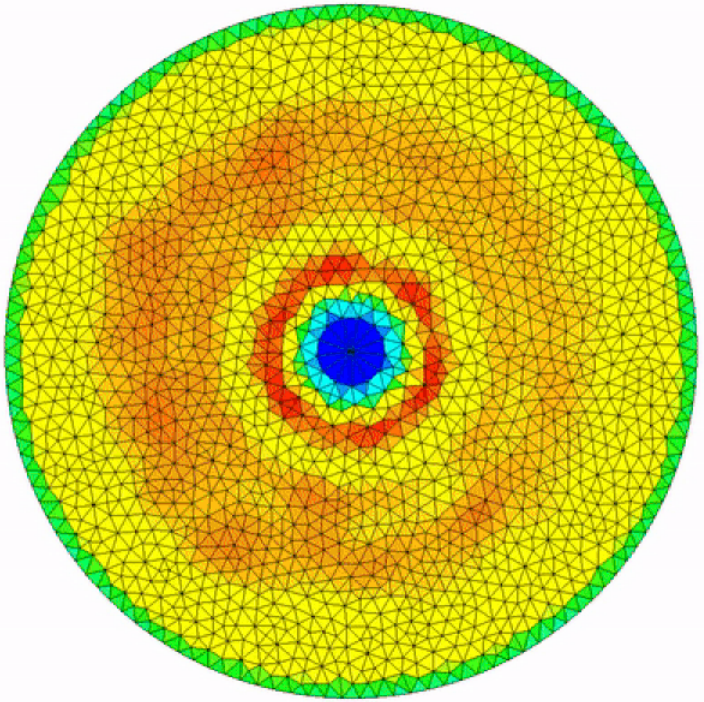
$S_b = 2\times10^{-4}$

$S_s = 10^3$





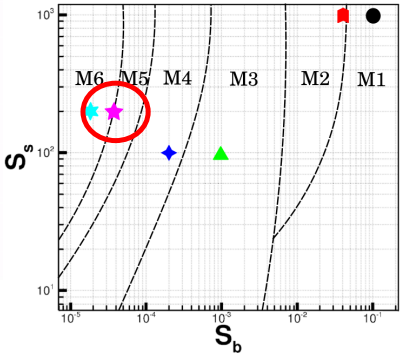
Compliant Disk in Viscous Flow



M5

$S_b = 3\times10^{-5}$

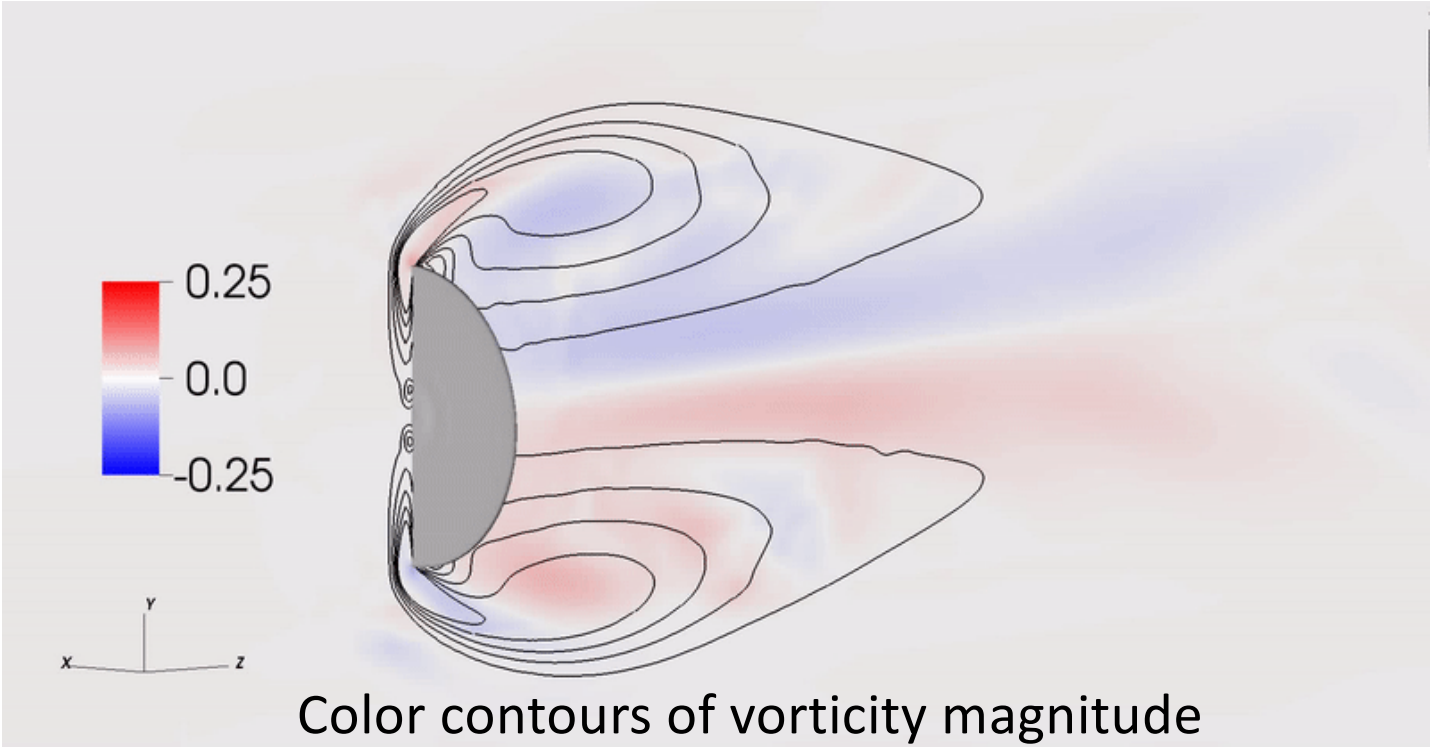
$S_s = 2\times10^{2}$





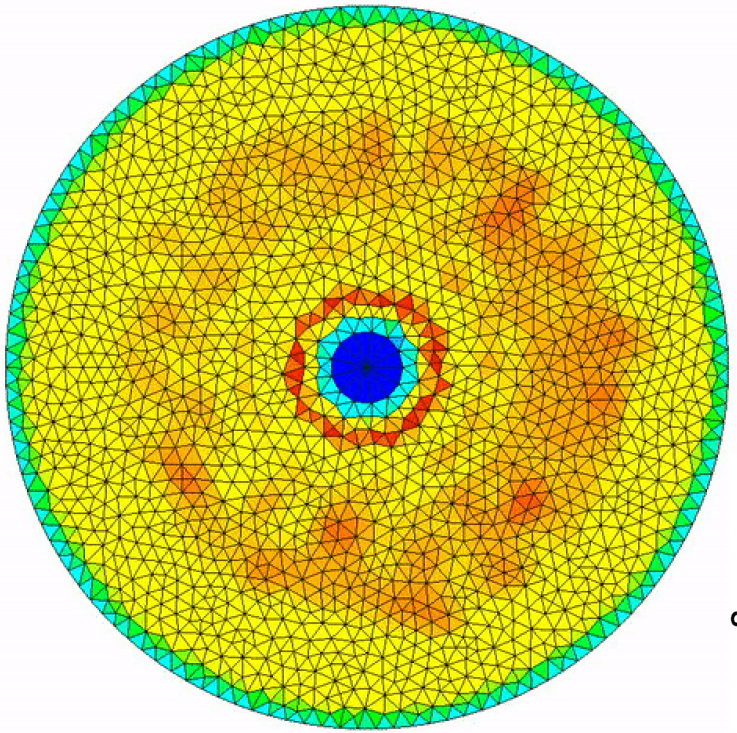
Compliant Disk in Viscous Flow

M5



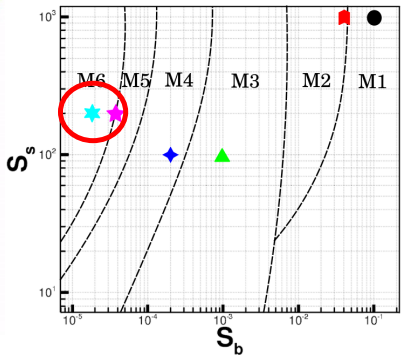
Color contours of vorticity magnitude

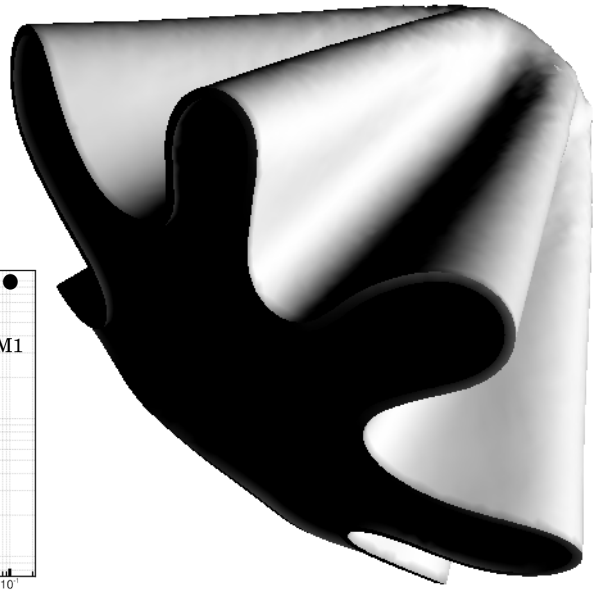
Compliant Disk in Viscous Flow



M6

$$S_b = 2\times10^{-5}$$
$$S_s = 2\times10^{2}$$





Bending of a Vertical Plate in Crossflow

- For comparison with Hu and Wang (JAFM 2016) and Womack and Seidel (AIAA 2014), Siefers *et al.* (AIAA 2018) introduced the

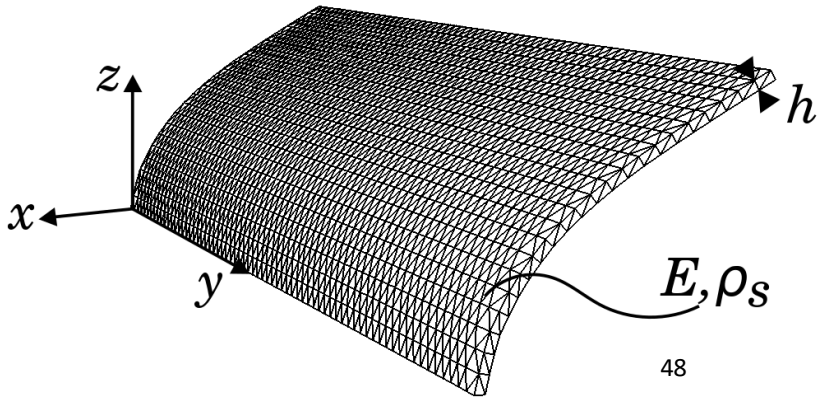
1. Mean chord angle

$$\emptyset = \tan^{-1}\left(\frac{\delta_x}{H - \delta_z}\right)$$

2. Normalized curvature

$$k = \frac{qH^3}{Eh^3}$$

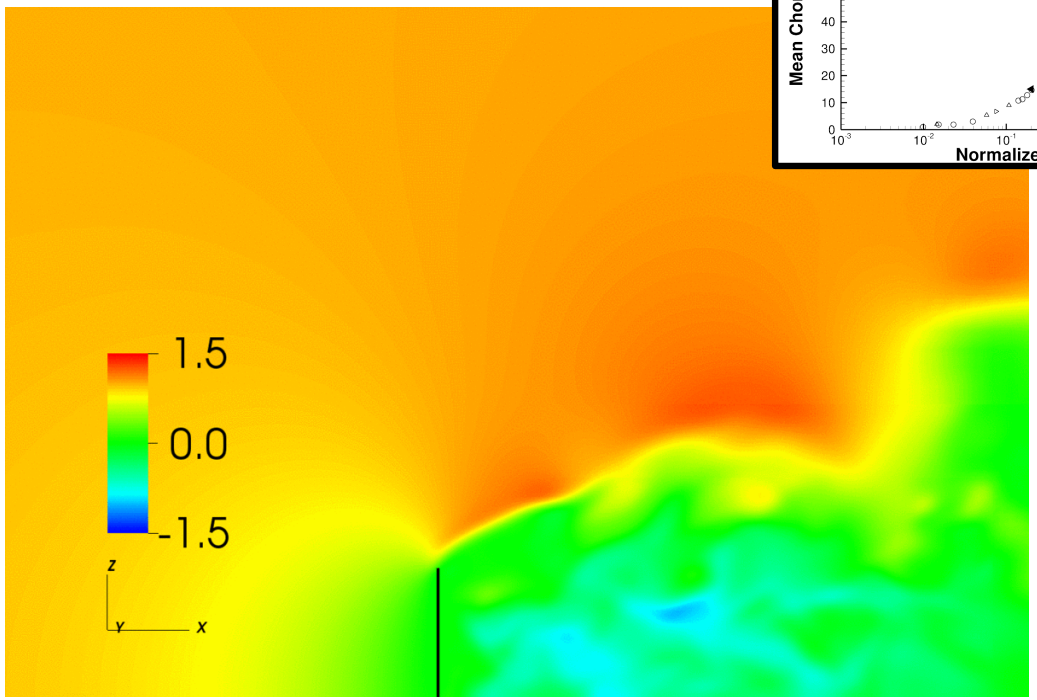
- These parameters reduce the solution to a single variable, $\emptyset$

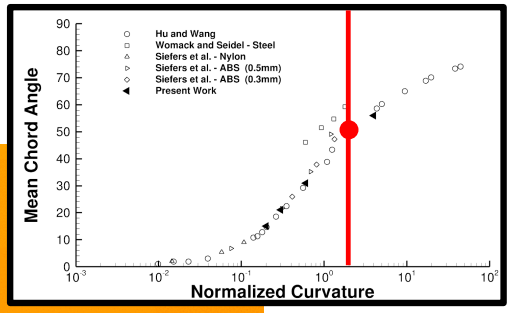


Bending of a Vertical Plate in Crossflow

Streamwise Velocity

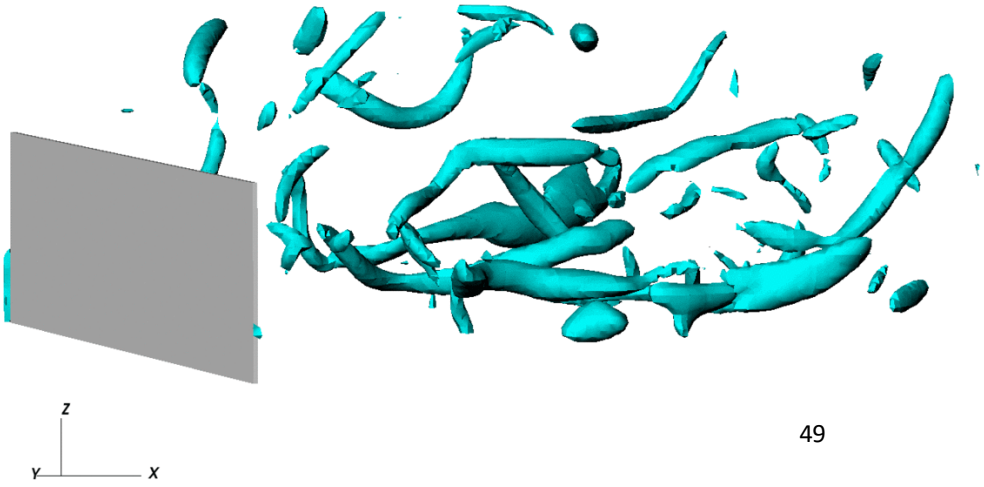
k = 2.0

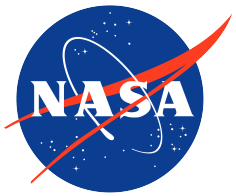




Q-Criterion (Q = 2,500)

k = 2.0

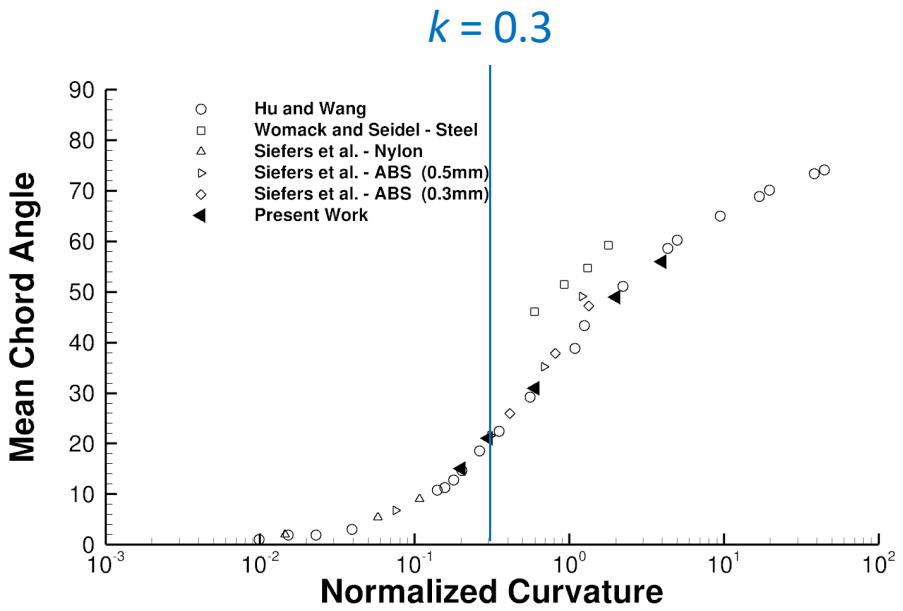




Bending of a Vertical Plate in Crossflow

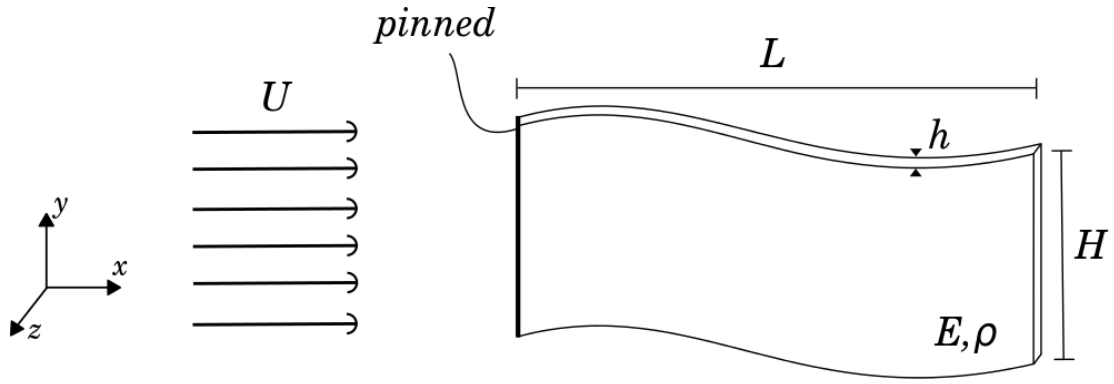


- Siefers *et al.* (AIAA 2018) notes that geometrically linear deformations become invalid after $k = 0.3$
- As shown, the current method shows good agreement with established experiments and simulations
- Plate response becomes unsteady for larger values of k

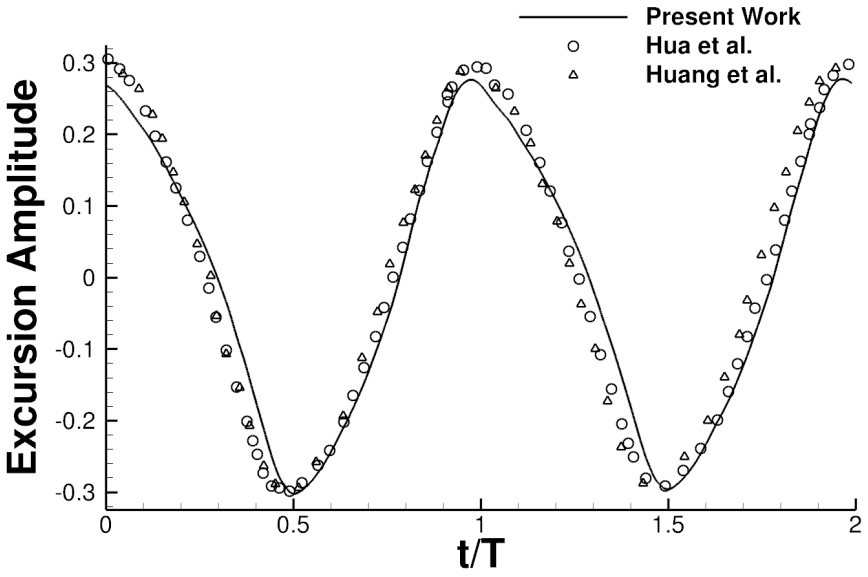


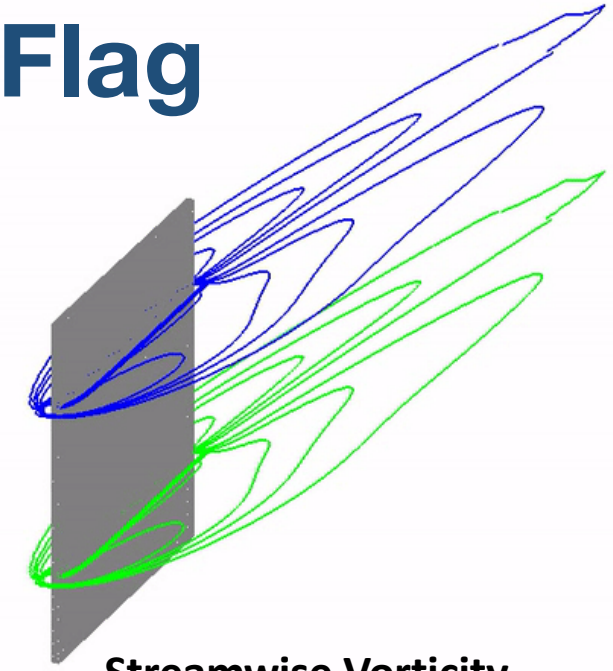
Waving Flag

- Consider the setup chosen by Huang *et al.* *(JFM 2010)* and Hua *et al.* *(JFM 2014)*
  - $Re = 100$
  - MR = $\frac{\rho_s h}{\rho_f L}$ =100
  - $\Delta x_{min} = \Delta y_{min} = 0.02L$
  - Discretized with 3,200 finite elements
  - FEM mesh is *pinned* at the leading edge
  - 18° crossflow to induced motion
  - Thickness, *h*, is 0.01
  - $\mathbf{S_s} = \frac{\boldsymbol{EI_s}}{\boldsymbol{\rho_f U^2 L^3}} = \mathbf{1{\times}10^3}$,
  - $\boldsymbol{S_b} = \frac{\boldsymbol{Eh}}{\boldsymbol{\rho_f U^2 L}} = \mathbf{1{\times}10^{-4}}$



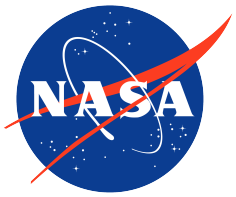
Waving Flag





Streamwise Vorticity

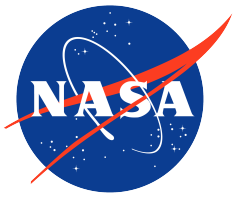
Reference	$\overline{A}$	St
Present Work	**0.57**	**0.22**
Huang *et al.* *(JFM 2010)*	0.58	0.24
Hua *et al.* *(JFM 2014)*	0.58	0.24



Outline



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- ❑ **Supersonic Parachute Inflation**
- ❑ **Summary and Outlook**



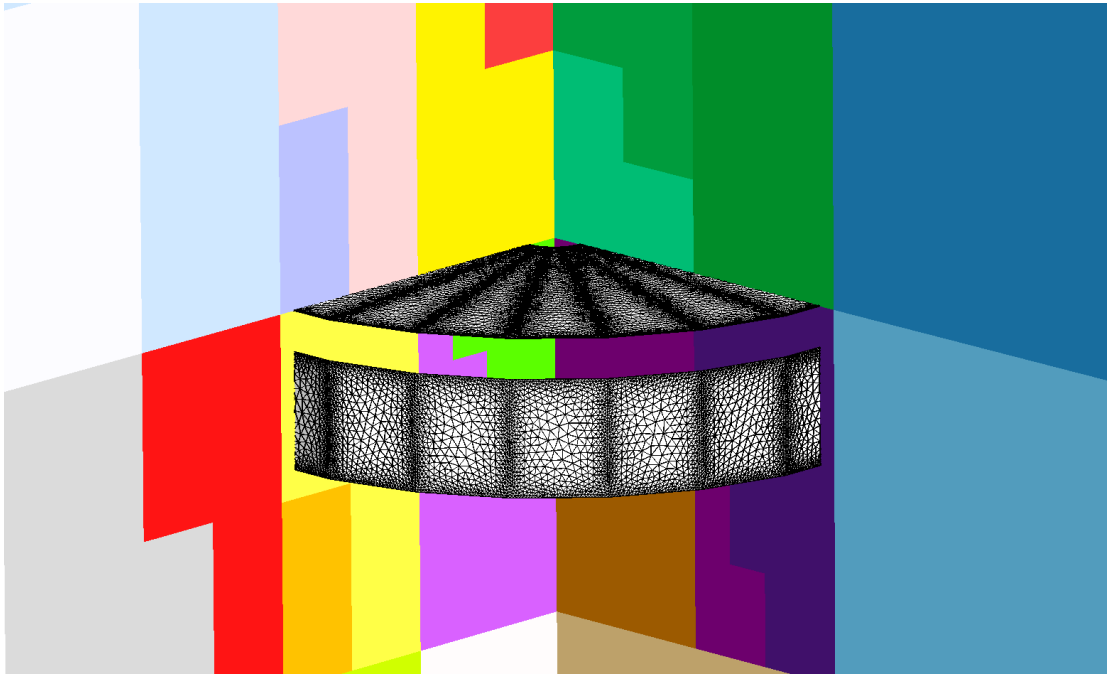
Large FSI Problems

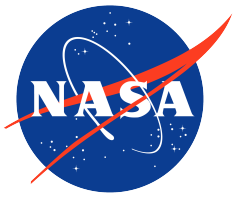


- The method was initially developed considering a parallel CFD – serial CSD coupling framework
  - The structures consisted of a few thousand shell elements
- When considering a parachute, the number of structural degrees of freedom became too large for a single processor
  - 100k and 200k+ elements in the structural domain
  - 6, 22, and 48+ million points in the fluid domain
  - 200k and 400k elements on the geometry representation *(CFD and CSD)*
- **Memory and speed optimization has been done for both solvers and the coupling framework**

Parallel FSI Approach

- The CFD solver uses an octree data structure to organize the volume data
  - **The geometry representation is partitioned accordingly**

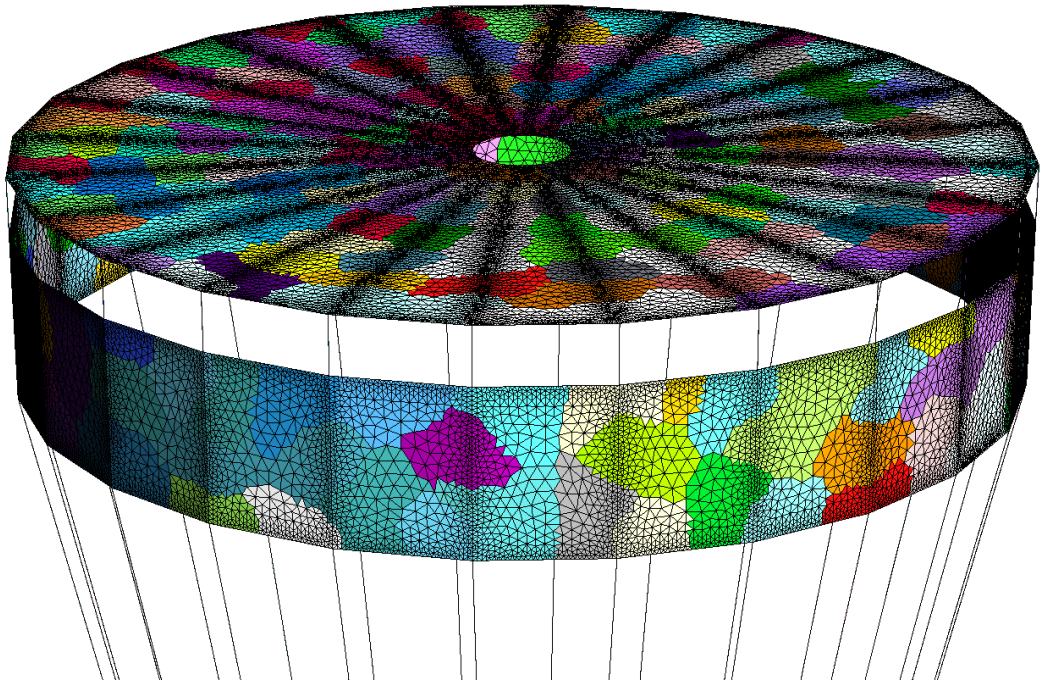


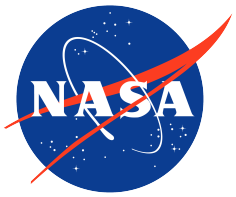


Parallel FSI Approach



- The CSD solver is partitioned on an unstructured mesh by ParMETIS

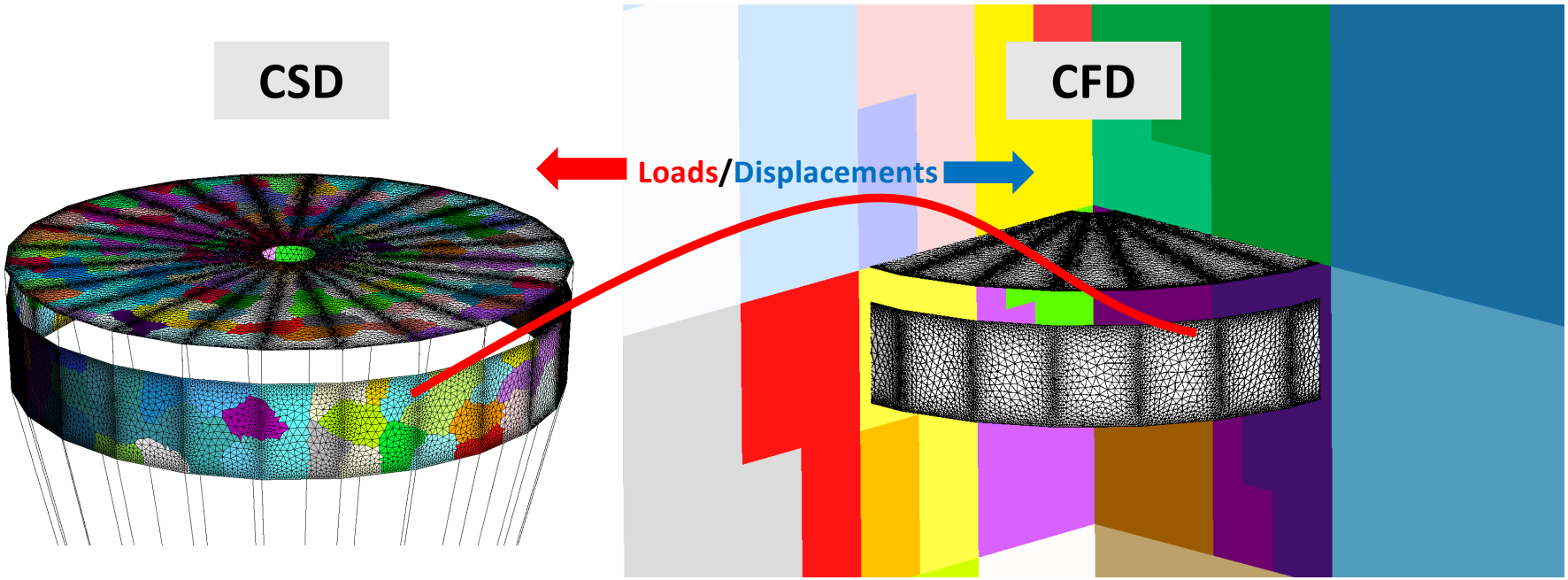




Parallel FSI Approach

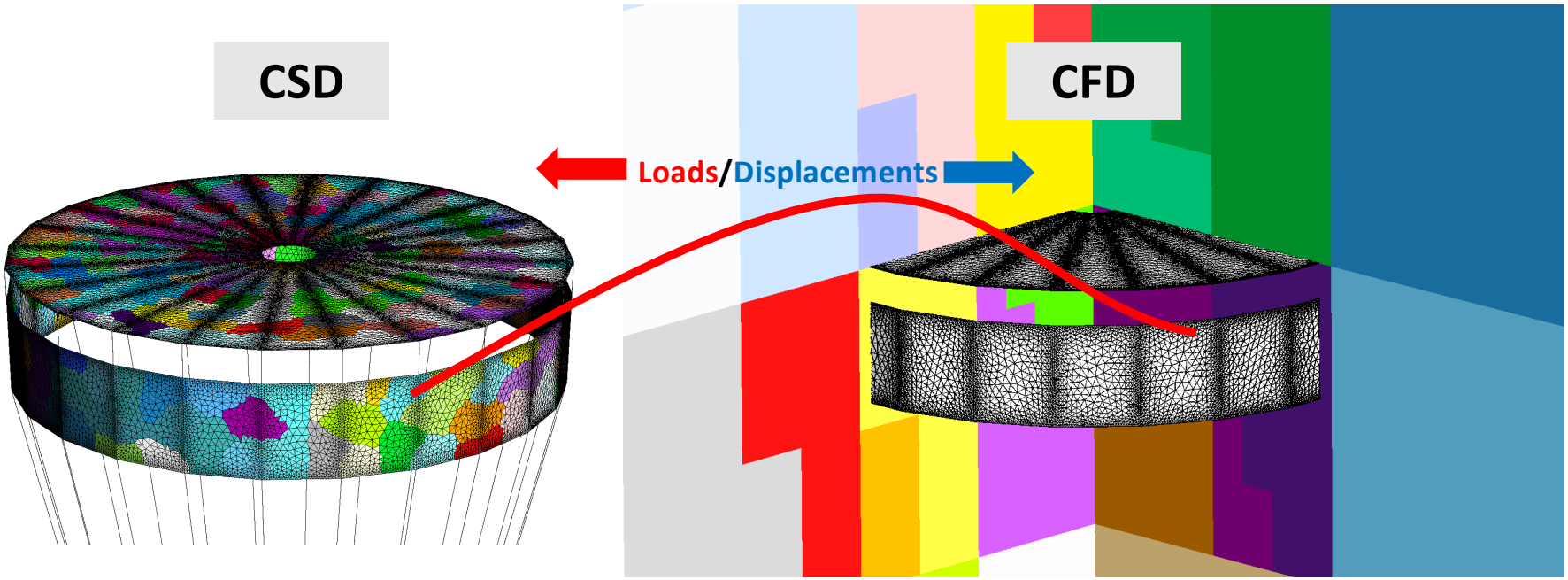


- The problem now is partitioned in both solvers
  - But the solvers must exchange information through the geometry representation



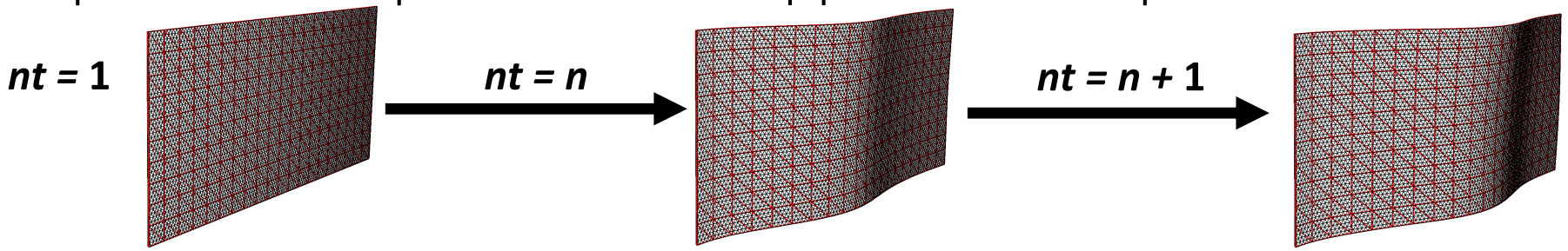
Parallel FSI Approach

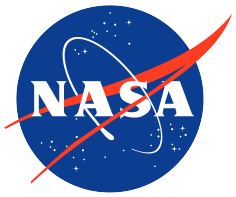
- To avoid large amounts of communication **throughout the simulation**, do a large amount of communication during ***initialization***



Parallel FSI Approach

- During initialization, pipelines between the CSD and CFD solvers are created
- These are stored for the duration of the simulation
  - Subsequently, information is simply passed through existing pipelines when necessary
- Able to avoid re-creating pipelines every timestep under **thin-shell assumption**
  - Pipelines at timestep *nt* = 1 are the same pipelines at timestep *nt* = *n*+1





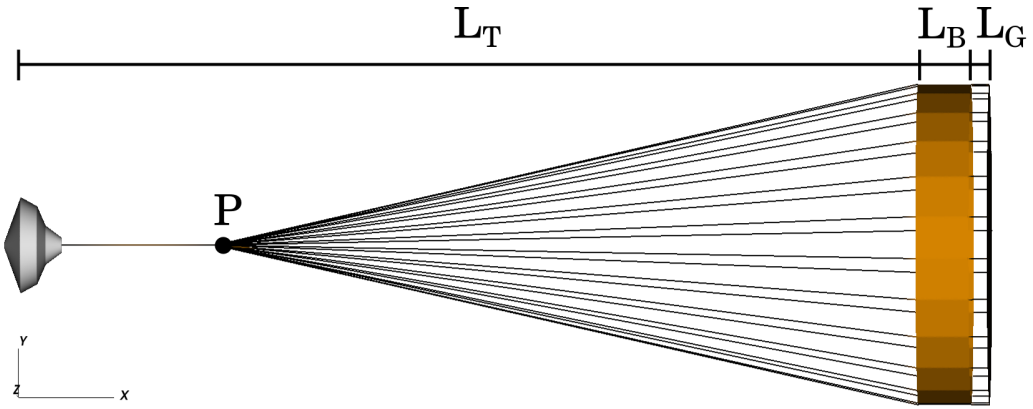
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Problem Setup

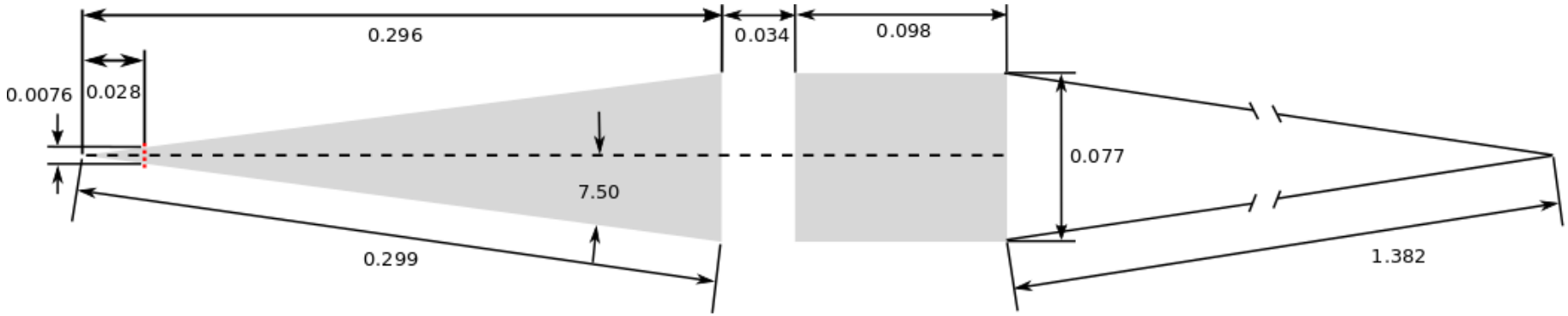
- Setup is chosen in accordance with
  - **Experiments:** Sengupta *et al.* (AIAA 2009)
  - **Simulations:** Karagiozis *et al*. (JFS 2011) and Yu *et al.* (AIAA 2019)
- 0.8m D_0 DGB Parachute design is based off Reuter *et al.* (AIAA 2009)
  - Sub-scale Viking parachute model ***with and without*** a sub-scale 70° Viking capsule

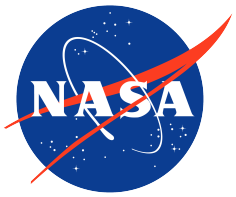


L_T	L_B	L_G
$\frac{x}{d} = 10.6$	$0.121D_0$	$0.042D_0$

Problem Setup

- Setup is chosen in accordance with
  - **Experiments:** Sengupta *et al.* (AIAA 2009)
  - **Simulations:** Karagiozis *et al*. (JFS 2011) and Yu *et al.* (AIAA 2019)
- 0.8m D_0 DGB Parachute design is based off Reuter *et al.* (AIAA 2009)
  - Sub-scale Viking parachute model ***with and without*** a sub-scale 70° Viking capsule





Problem Setup



- Problem resembles spacecraft entry into the upper Martian atmosphere:

Fluid Properties

- $Re = \frac{\rho_\infty u_\infty d}{\mu_\infty} = 10^5$
- μ_∞ via Sutherland's law at $T_\infty = 294.93K$
- $\rho_\infty = 0.0184527 \frac{kg}{m^3}$
- $u_\infty = 688.89 \frac{m}{s}$
- $M = \frac{u_\infty}{a_\infty} = 2.0$

Structural Properties

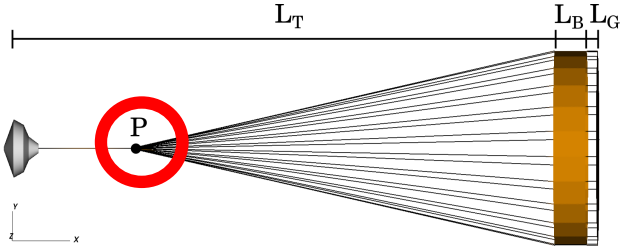
- $E_p = 878\ MPa$
- $\nu = 0.33$
- $h = 6.35\times10^{-5} m$
- $\rho_p = 614 \frac{kg}{m^3}$
- $d_c = 0.99\times10^{-3} m$
- $E_c = 43GPa$
- $\rho_c = 8.27\times10^{-4} \frac{kg}{m}$

- Setup time: virtually none after CSD mesh is created

Problem Setup

- Center of the vent hole is at (0,0,0)
- Domain: [-6.25D_0, 6.25D_0] × [-6.25D_0, 6.25D_0] × [-6.25D_0, 6.25D_0]
- Base case: $\Delta x_{min} = \Delta y_{min} = D_0/164$

- 600 geometrically nonlinear cables elements are used for the suspension lines
  - Fixed at point P

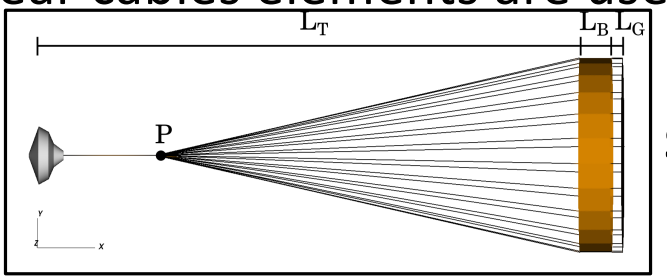


- 108,000 geometrically nonlinear shell elements resolve the disk and canopy

Problem Setup

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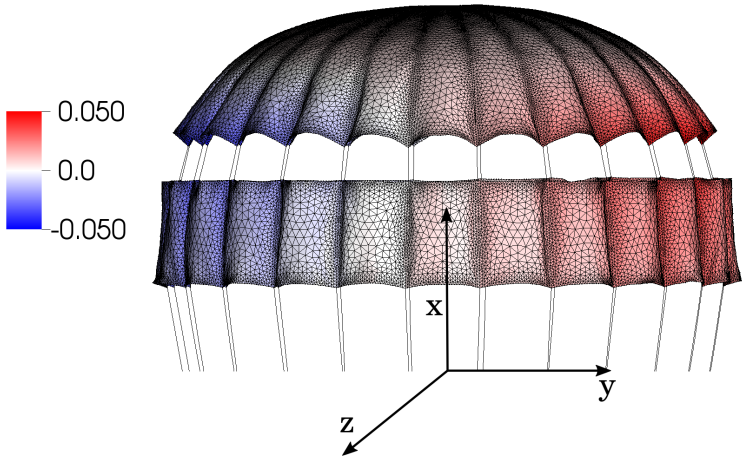


Simulation initial condition (unstressed)

- 108,000 geometrically nonlinear shell elements resolve the disk and canopy

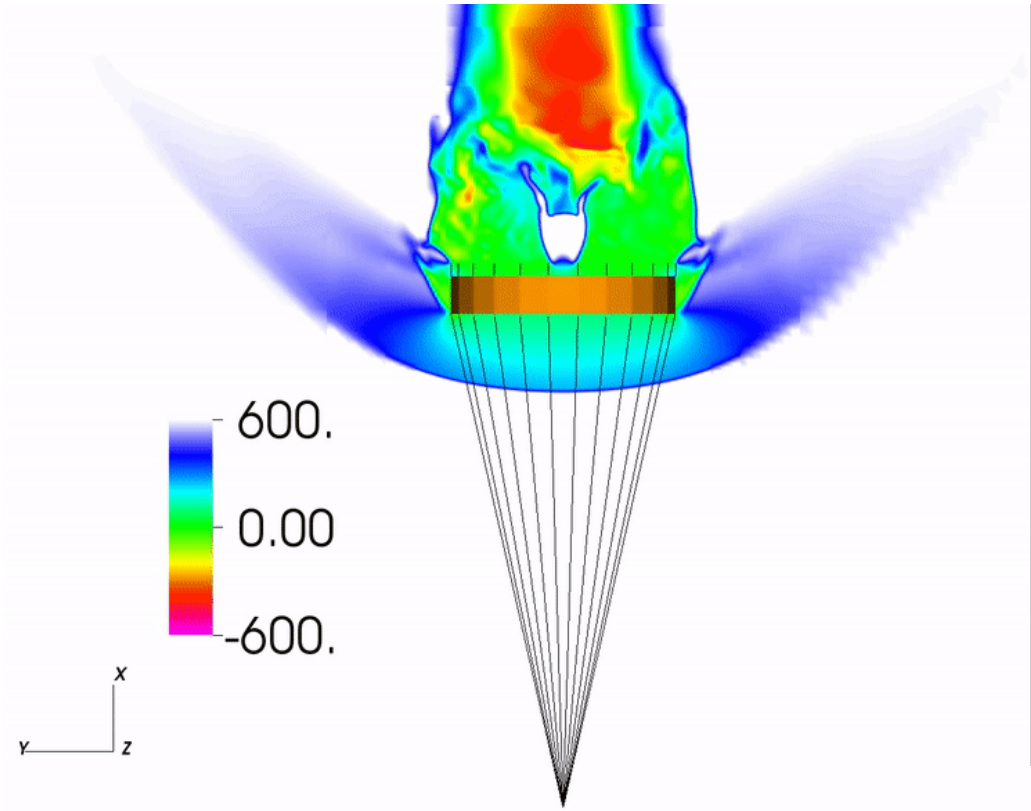
Problem Setup

- Structural mesh based off simulations by Derkevorkian *et al.* (AIAA 2019)
  - Elements along seams are thickened by a factor of 4 to represent the stitching pattern used in manufacturing of the canopy
  - Finely resolving these regions also helps capture the stress discontinuities across the seams

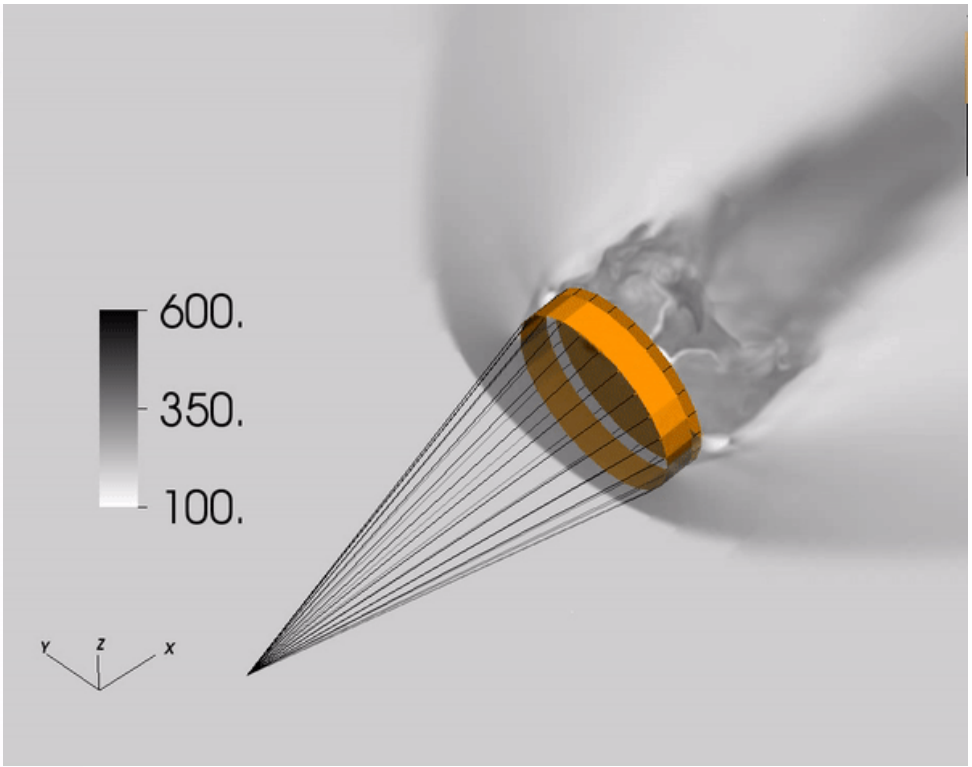


Case 1: Uniform Flow (no capsule)

Streamwise velocity

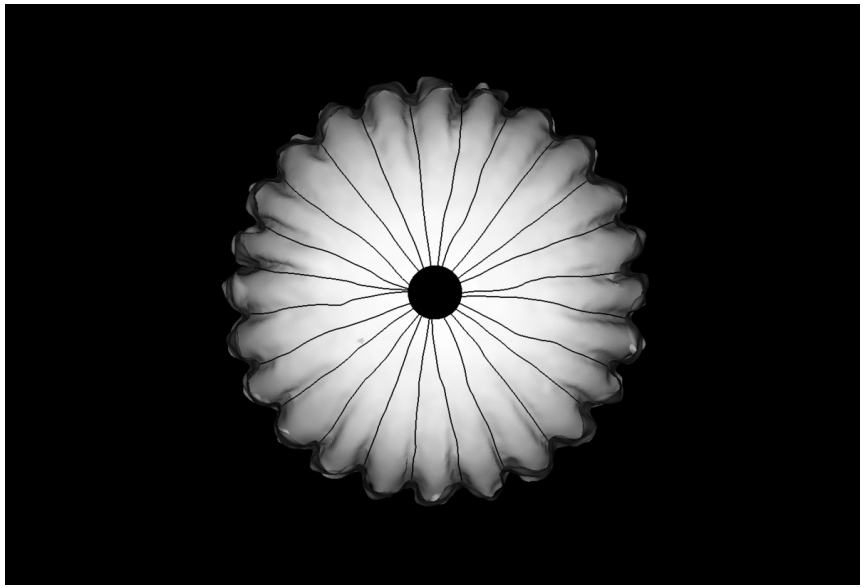


Temperature field

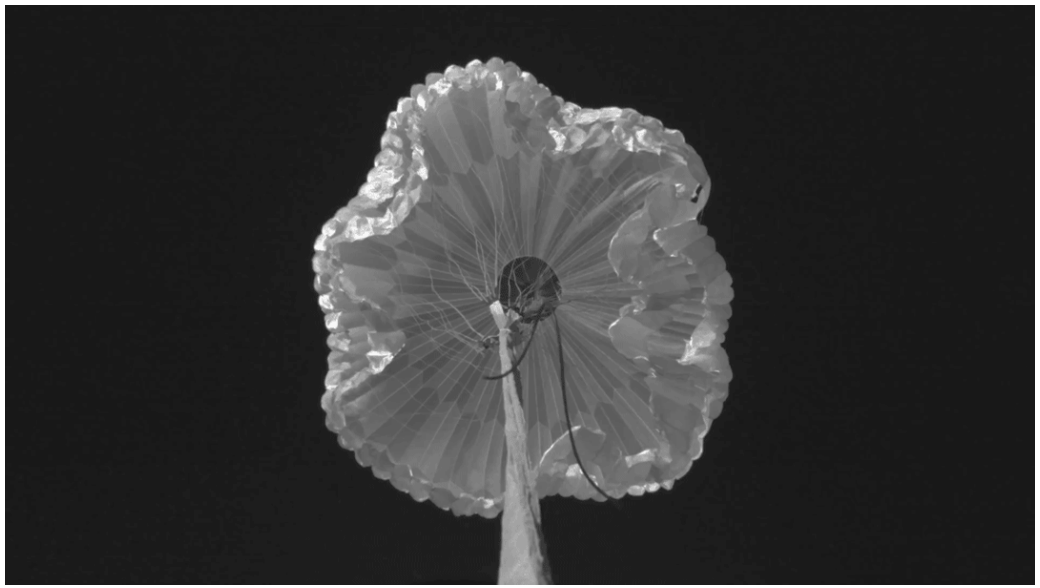


Case 1: Uniform Flow (no capsule)

Simulation of sub-scale DGB Parachute



Full-scale ASPIRE Test flight

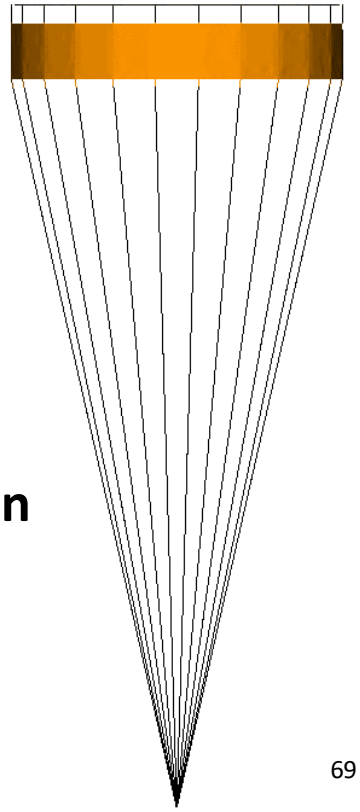


**Not a direct comparison*

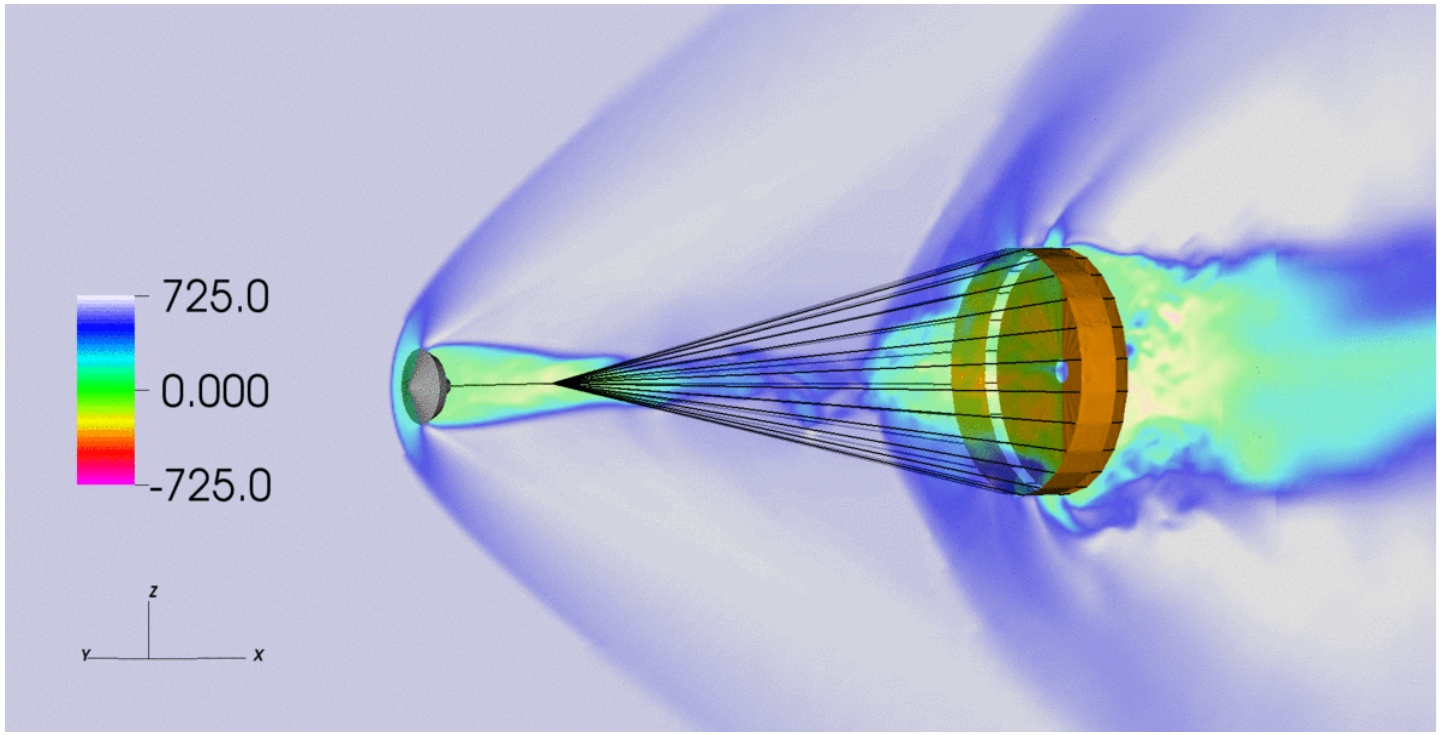
(NASA/JPL)

Case 1: Uniform Flow (no capsule)

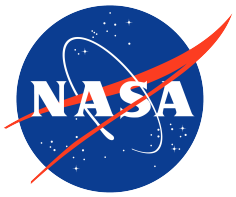
- The cables are not resolved in the CFD volume mesh
  - Nor do they experience any external loading
  - This may lead to large period, large amplitude swaying of the cables
- The cables, as well as the canopy, start the simulation in an unstressed/un-tensioned state
- **How much do the cable dynamics affect simulations of inflation versus reality?**



Case 2: Leading Viking-type Capsule



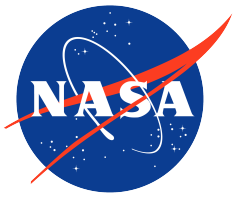
Streamwise velocity



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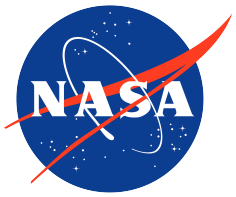


Summary and Outlook



❑ Summary:

- An overview of a validated numerical FSI method was presented
  - Cartesian IBM CFD
  - Nonlinear CSD
- The details of the weak, parallel coupling algorithm between the CFD and CSD solvers was outlined
- FSI validation cases were presented
- The FSI method was finally applied to the simulation of parachute inflation in the upper Martian atmosphere



Summary and Outlook



❑ **Outlook:**

- Apply porous material boundary conditions on the canopy
- Implement efficient contact algorithms for robustness and more interesting starting conditions
- Utilize adaptive mesh refinement (AMR) in the simulations
- Start to compare against ASPIRE missions

Questions?

