The OpenFOAM® Extend Project & FSI Solvers

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Outline

- The OpenFOAM® Extend Project
- Capabilities of the Extend Project version 3.0 Jeju
- Fluid-Structure Interaction Applications
- Fluid-Structure Interaction (FSI) applications in The OpenFOAM® Extend Project
- icoFsiFoam
- icoFsiElasticNonLinULSolidFoam

The OpenFOAM® Extend Project

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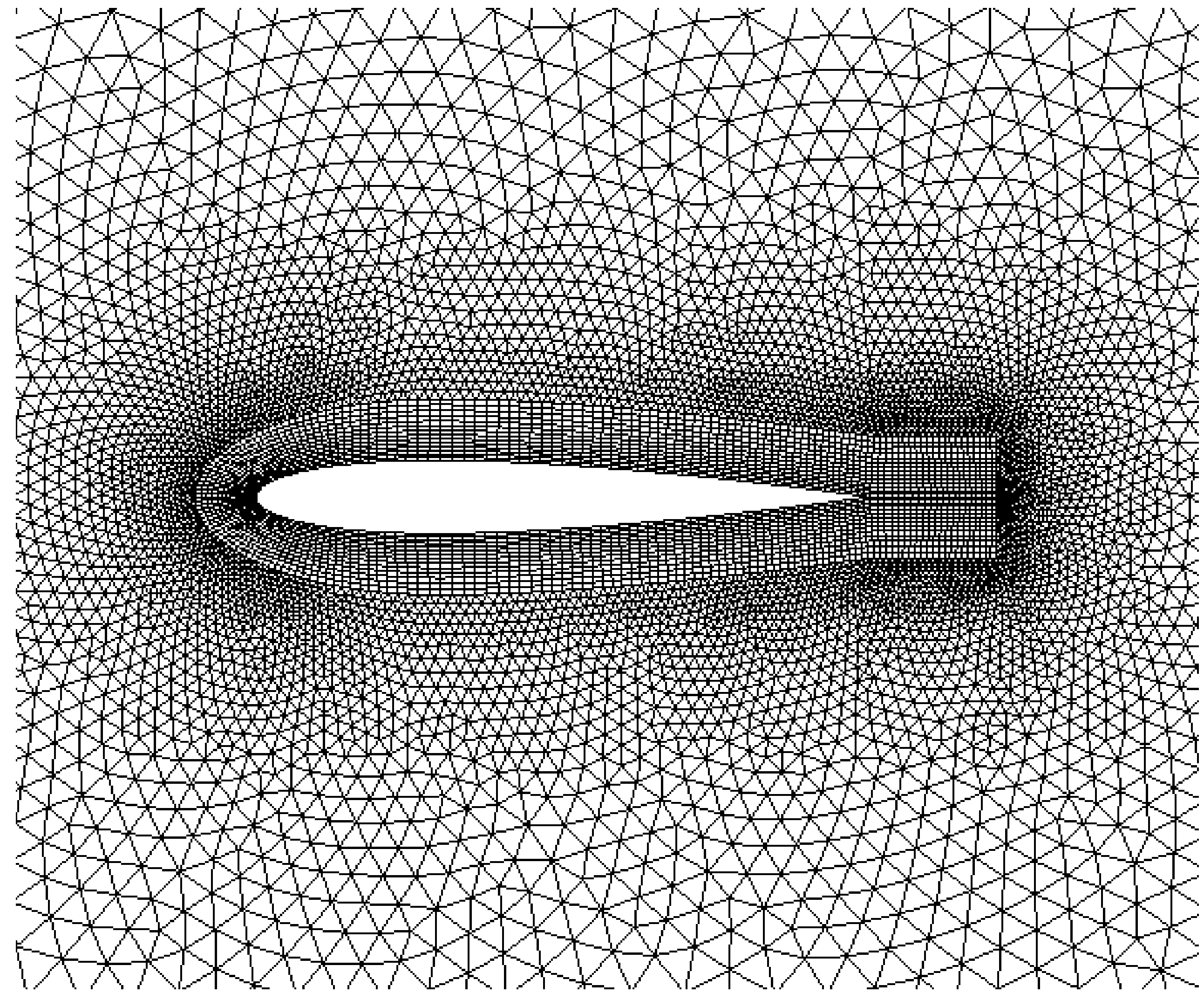
- Separate from Official OpenFOAM® project
- Supported by academics and community
- Recently published version named **foam-extend-3.0 Jeju**
- Further information can be found at http://www.extend-project.de

Dynamic Mesh

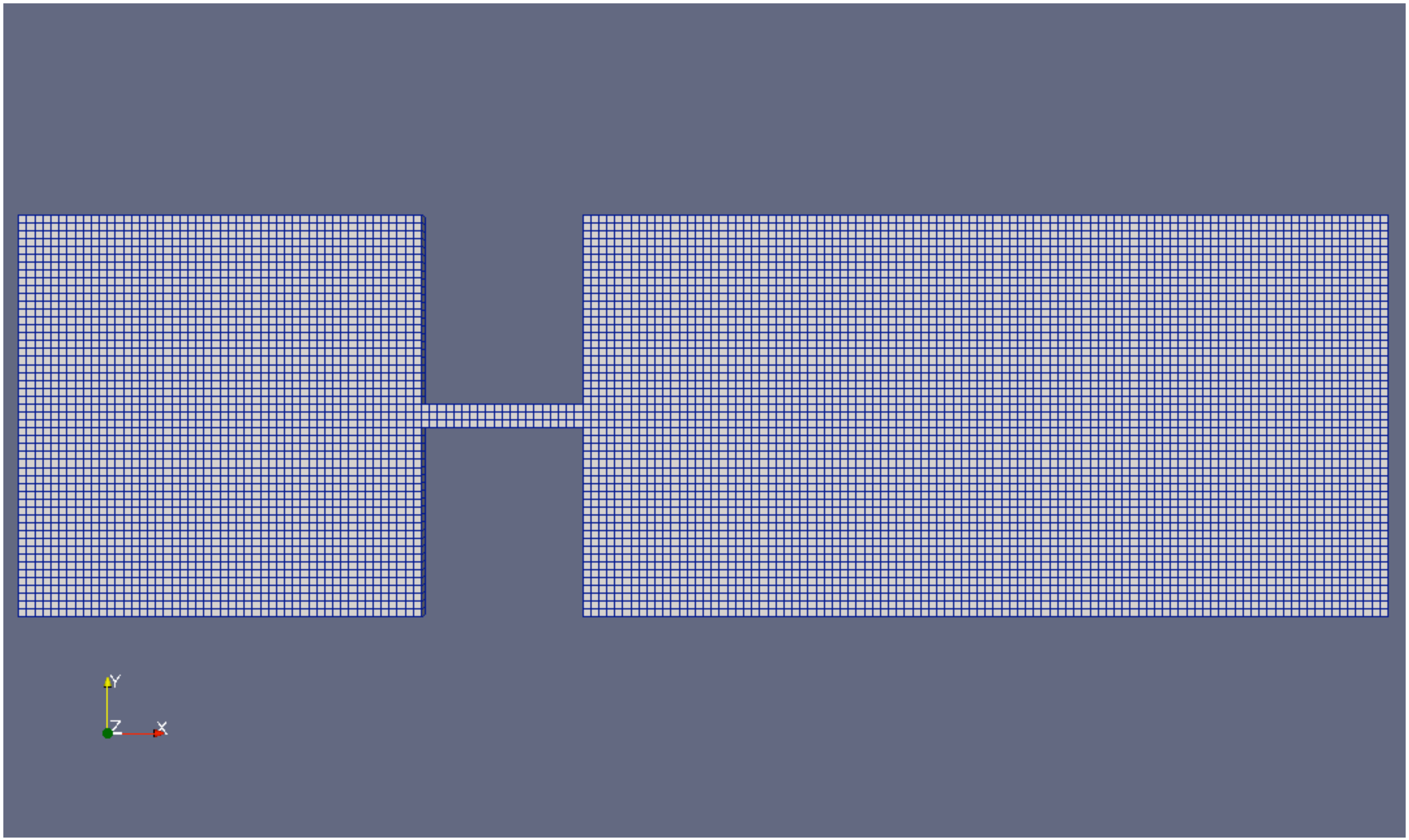
- Dynamic mesh with topological changes
- Sliding interfaces, mesh layering, attach-detach boundaries etc.
- Full second-order FVM discretization support on moving meshes with topological changes
- Finite Element Method with support for polyhedral meshes
- In foam-extend-3.0 **full parallel support** for topological changes



Taken from page 4 of reference (1)

Advanced Capabilities of Extend Project version 3.0 Jeju

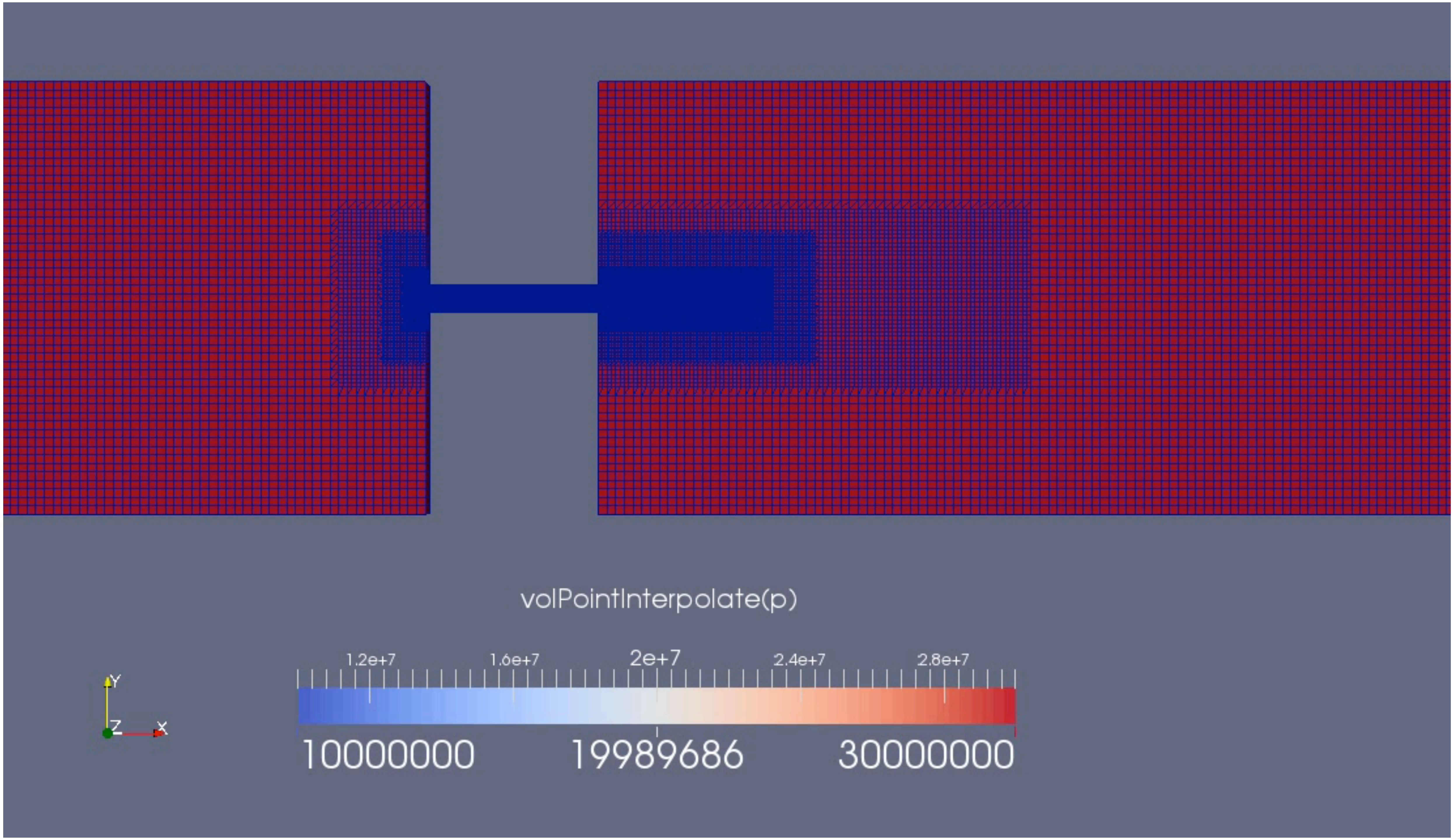
Refine Mesh



Initial Mesh view of “throttle” tutorial under tutorials/multiphase/cavitatingFoam/ras/throttle

Advanced Capabilities of Extend Project version 3.0 Jeju

Refine Mesh

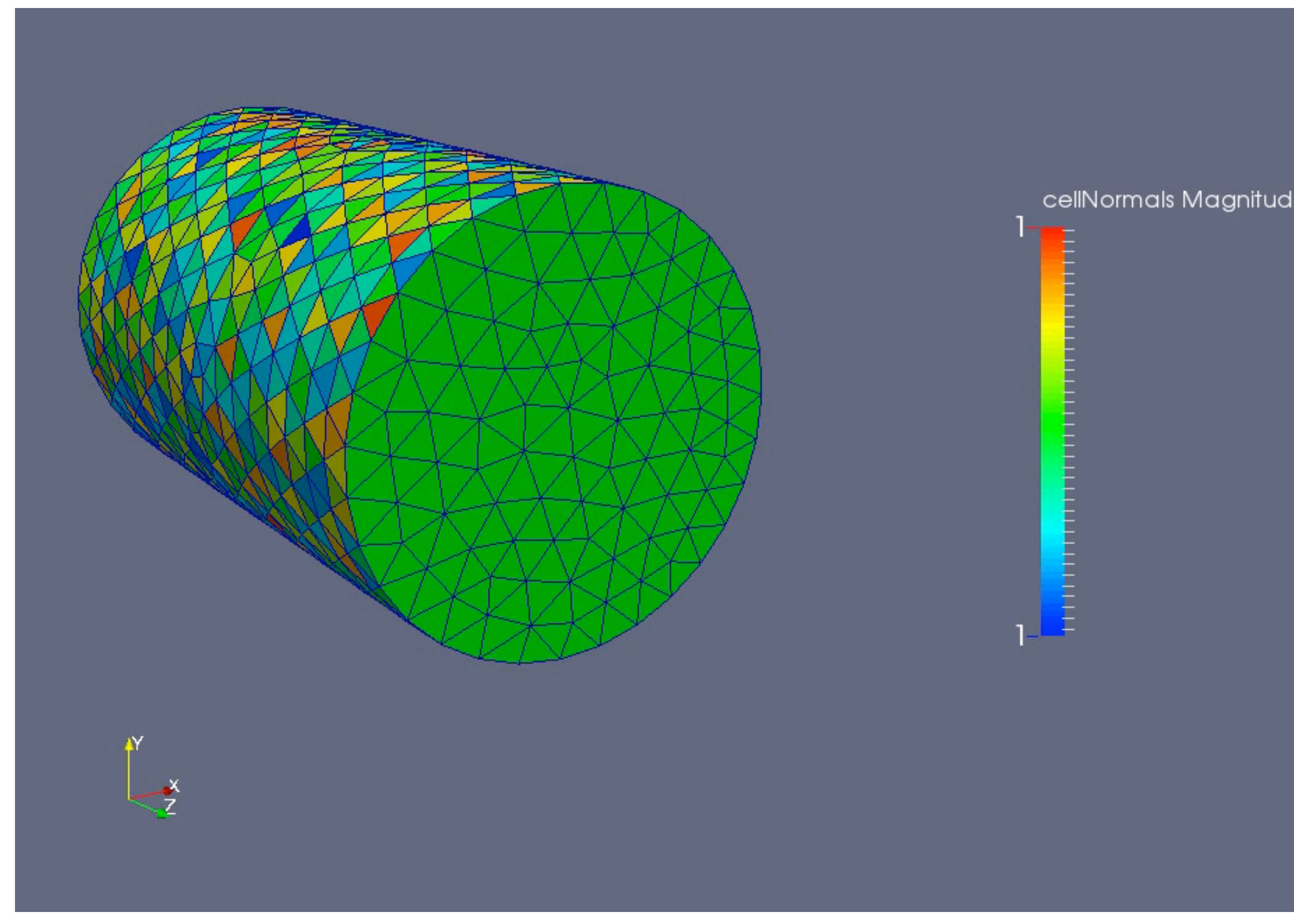


Final Mesh view of "throttle" tutorial under tutorials/multiphase/cavitatingFoam/ras/throttle

Advanced Capabilities of Extend Project version 3.0 Jeju

Advanced Mesh Deformation

- Tetrahedral FEM mesh deformation
- Radial Basis Function (RBF) mesh deformation
- Tetrahedral re-meshing dynamic mesh support
- Solid body motion functions
- All technologies has parallelization support



circleCylinder3D tutorial in foam-extend-3.0

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Solid Mechanics Modeling

- Linear and non-linear materials, contact, self-contact and friction, with updated Lagrangian or absolute Lagrangian formulation.

- Solution of damage models and crack propagation in complex materials via topological changes

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Advanced Solver Technologies

- Block-coupled matrix support, allowing fully implicit multi-equation solution of NxN equation sets, with full parallelization support. First release of a **block-AMG** linear equation solver
- Fully implicit conjugate-coupled solution framework, allowing implicit solution of multiple equations over multiple meshes, with parallelism
- Multi-solver solution framework, allowing multiple field models to be solved in a coupled manner
- Algebraic multi-grid solver framework
- CUDA® solver release, provided in full source

Advanced Capabilities of Extend Project version 3.0 Jeju

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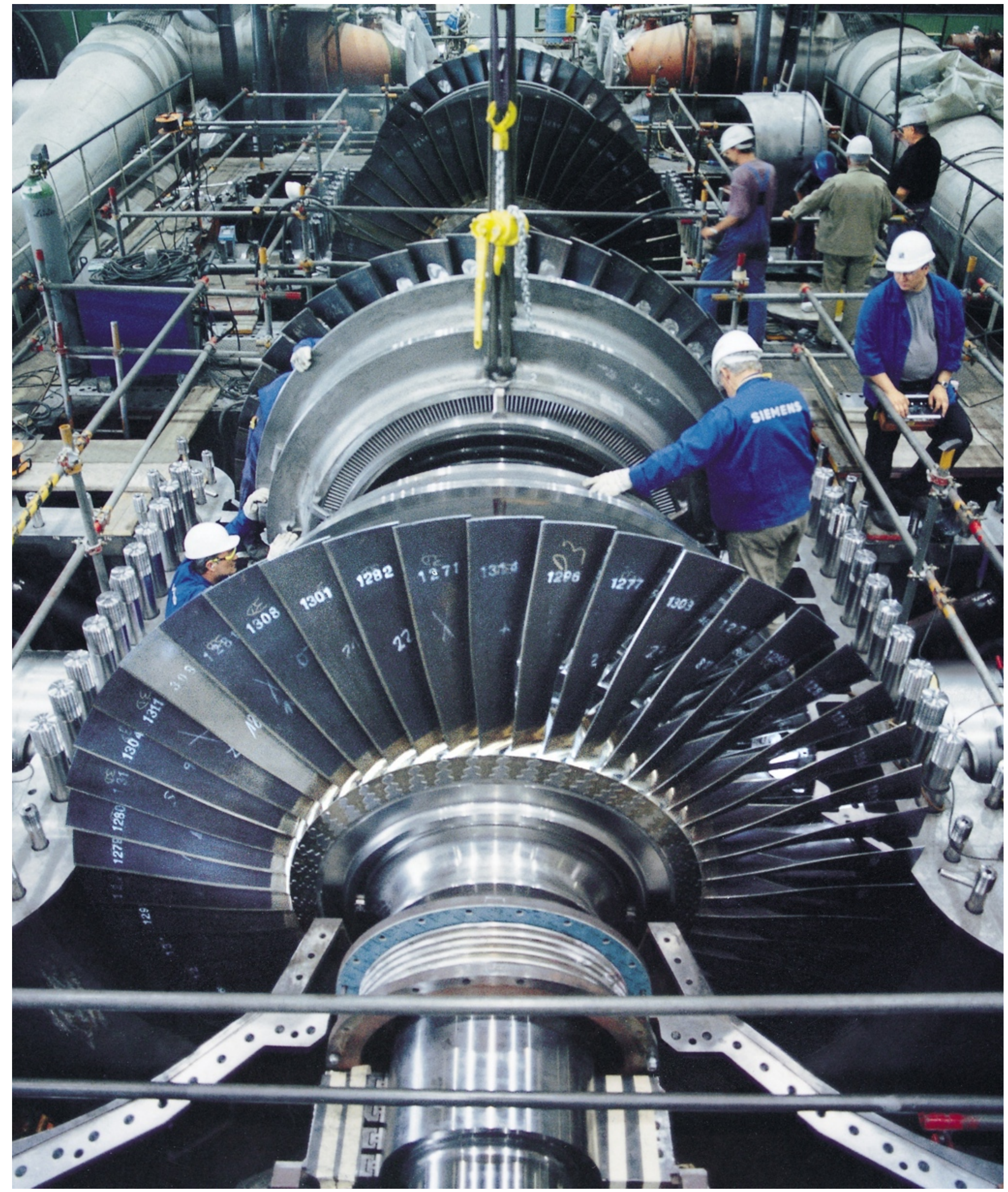
Applications

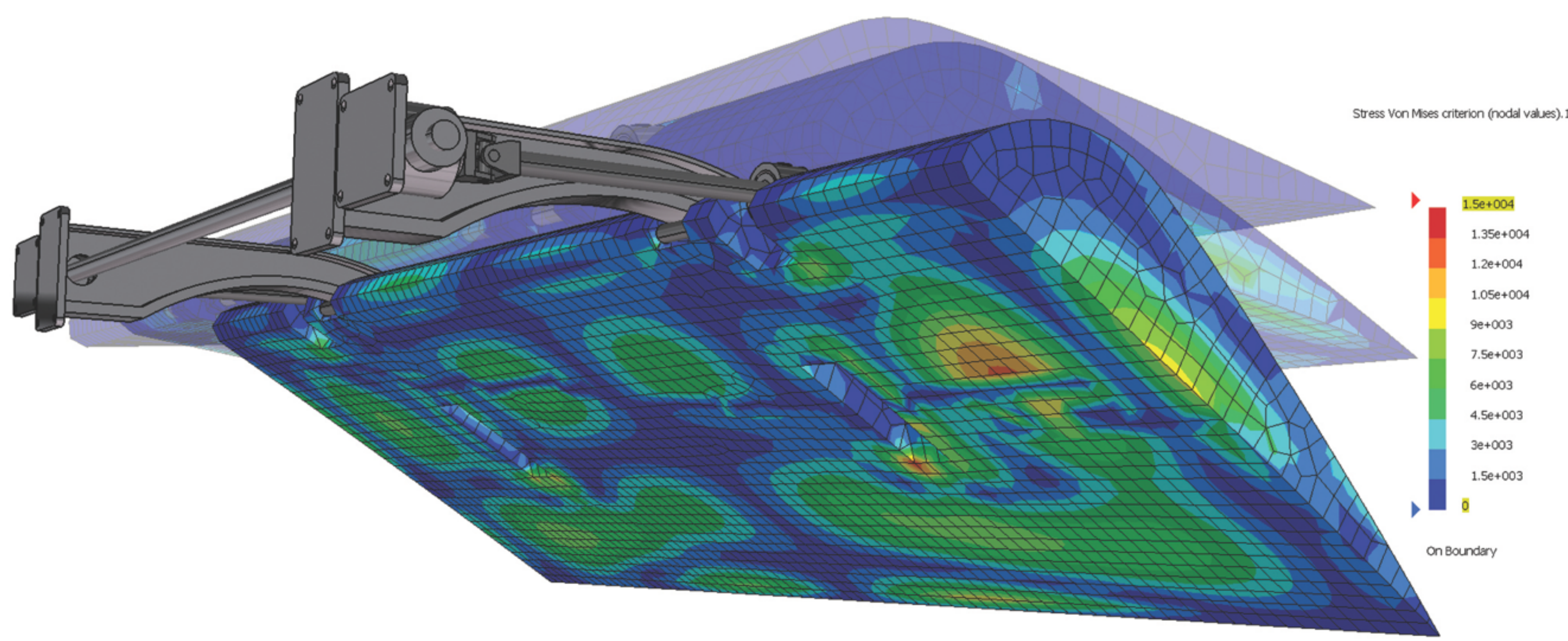
- Turbomachinery features
- Describes machines that transfer energy between a rotor and a fluid, including both turbines and compressors.
- Internal combustion engine-specific dynamic mesh classes
- Two-stroke engine, Various forms of 4-stroke, Multi-valve dynamic mesh classes
- Fluid-Structure Interaction



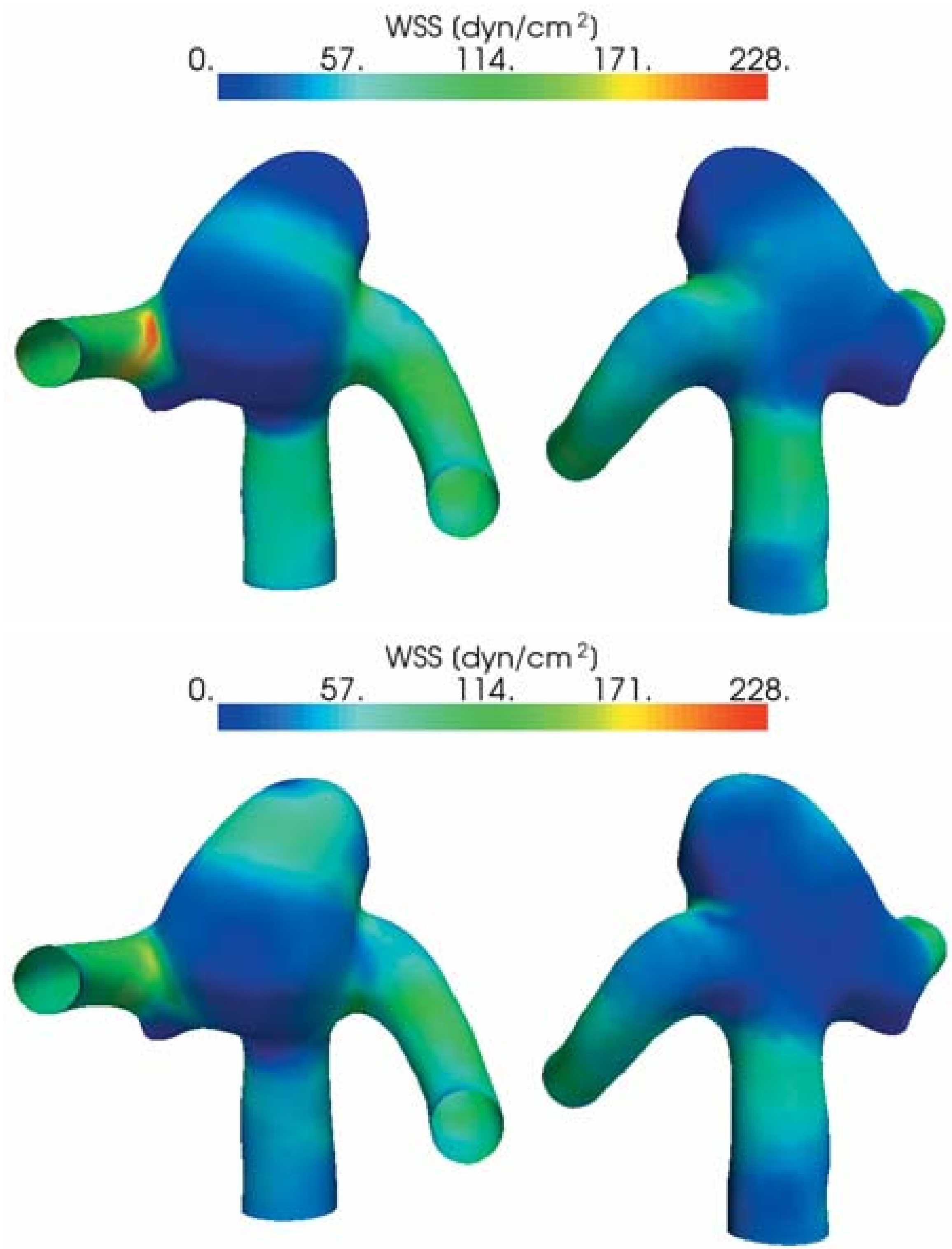
Mounting of a steam turbine produced by Siemens, Germany
Taken from Wikipedia

Fluid-Structure Interaction

- Significant mutual dependence between subdomains
- FSI gives more realistic approximations than CFD
- Examples : Car Aerodynamics, Blood Flow, Aircraft wings
- Problem Formulation, Numerical Discretization, Coupling



Why FSI?



- (Bazilevs, Hsu, Benson, Sankaran, & Marsden, 2009) showed almost 50% overestimation of Wall-Shear Stress on the vessel walls
- Viscoeleastic nature of blood vessels
- Non-newtonian model for blood viscosity

Fluid-Structure Interaction

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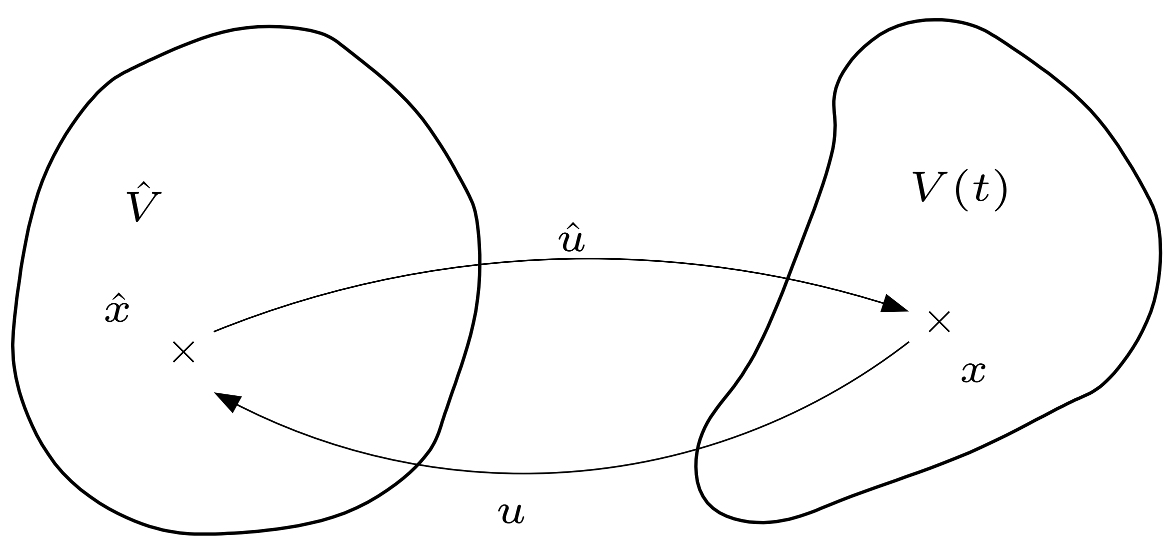
Problem Formulation in Continuum Mechanics



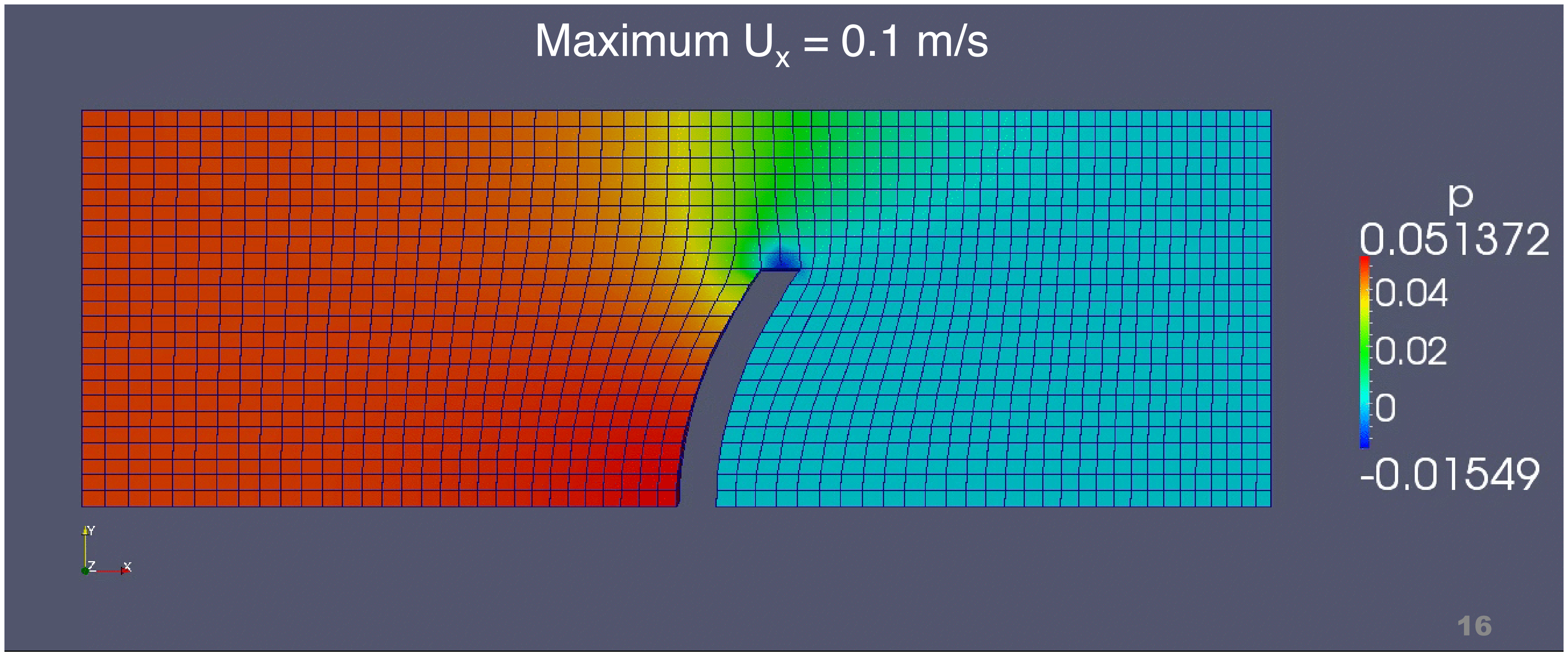
$$\hat{u} = x - \hat{x}$$

Figure 1: Deformation of a material particle $\hat{x}$ in a material body $\hat{V}$

- Material-centered - Lagrangian Framework
- Space-centered - Eulerian Framework

Fluid-Structure Interaction

Numerical Discretization



Taken from page 16 of reference (2)

- Accuracy, Stability, Robustness
- Discretization level is important for Coupling Interface
- Same level - easier and more robust
- Different level - need to be accurately implemented for traction and kinematics

Fluid-Structure Interaction

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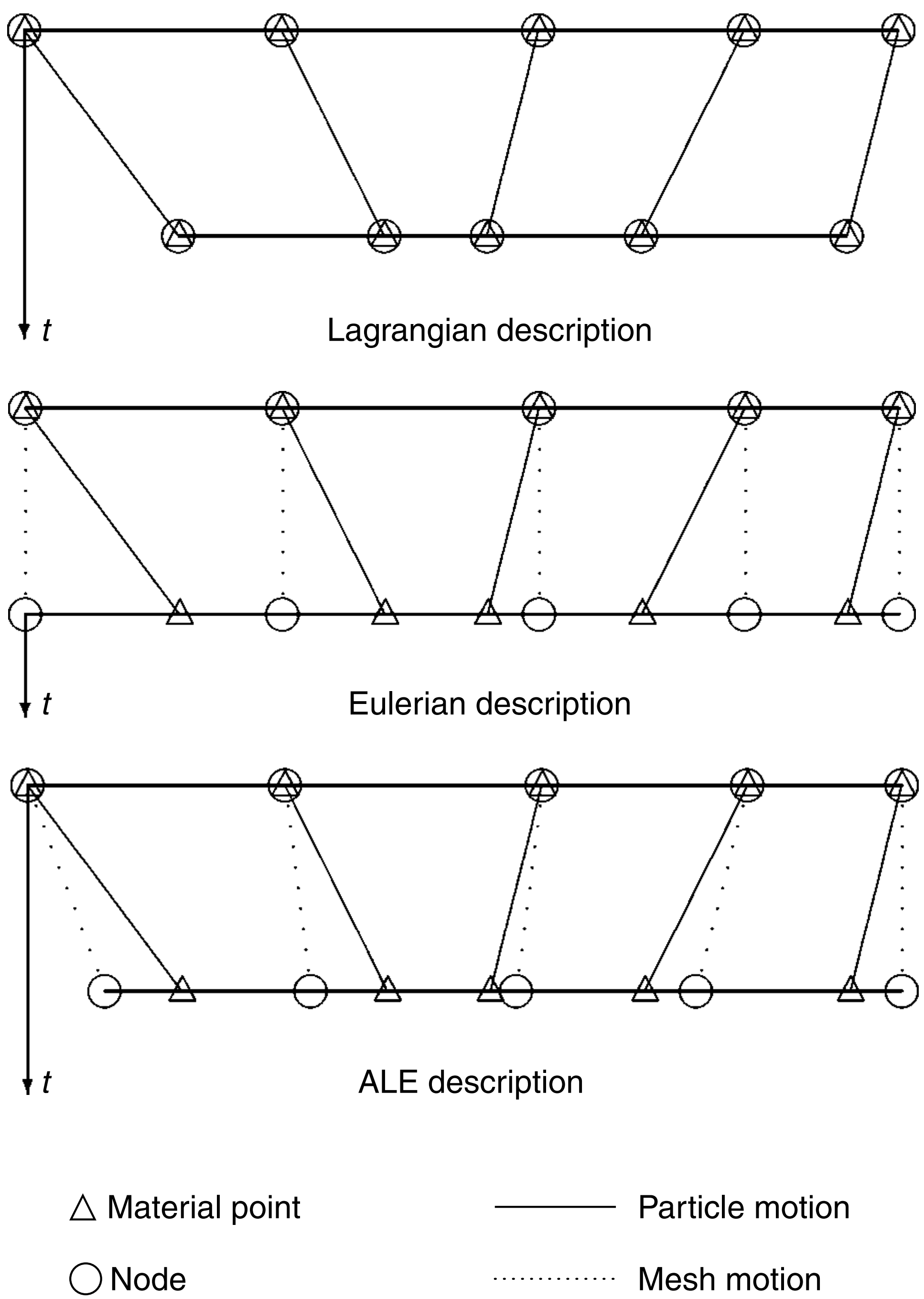
Fluid-Structure Coupling

- **Monolithic (Strongly-Coupled)**
- Governing equations are cast in terms of primitive variables
- Same level of discretization or different mesh sizes
- Fluid, Structure and Mesh Motion are solved simultaneously in a given time-step
- Fully-coupled - very robust
- Block-iterative, quasi-direct and direct-coupling

Fluid-Structure Interaction

Arbitrary Lagrangian-Eulerian



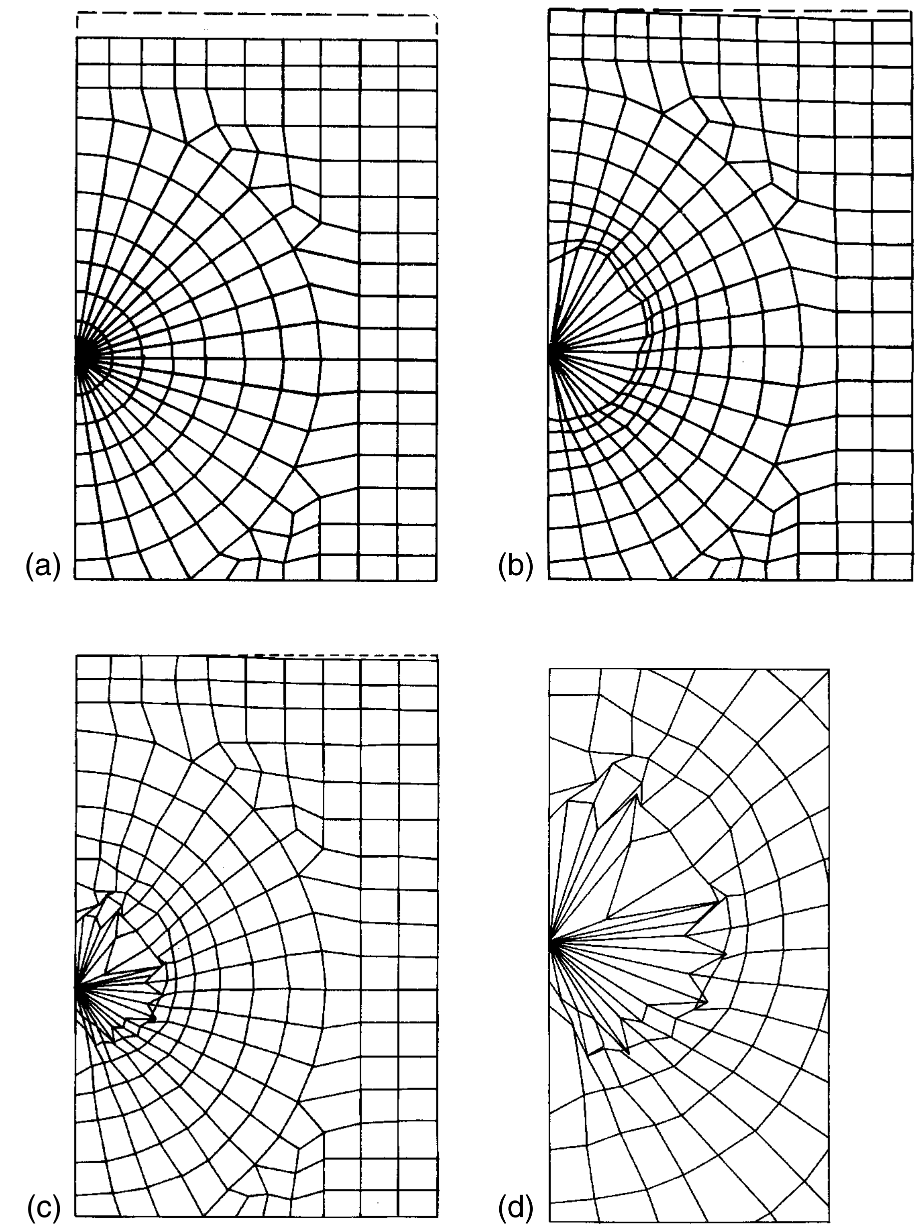


Figure 2. Lagrangian versus ALE descriptions: (a) initial FE mesh; (b) ALE mesh at $t = 1$ ms; (c) Lagrangian mesh at $t = 1$ ms; (d) details of interface in Lagrangian description.

Taken from page 2 of reference (4)

Fluid-Structure Interaction

Partitioned Coupling

- More flexible than Monolithic approach
- Existent fluid and structure solvers can be used
- Fluid-Structure interface coupling must be designed carefully
- **Loosely-coupled** and **Tightly-coupled**

Fluid-Structure Interaction

Loose-Coupling

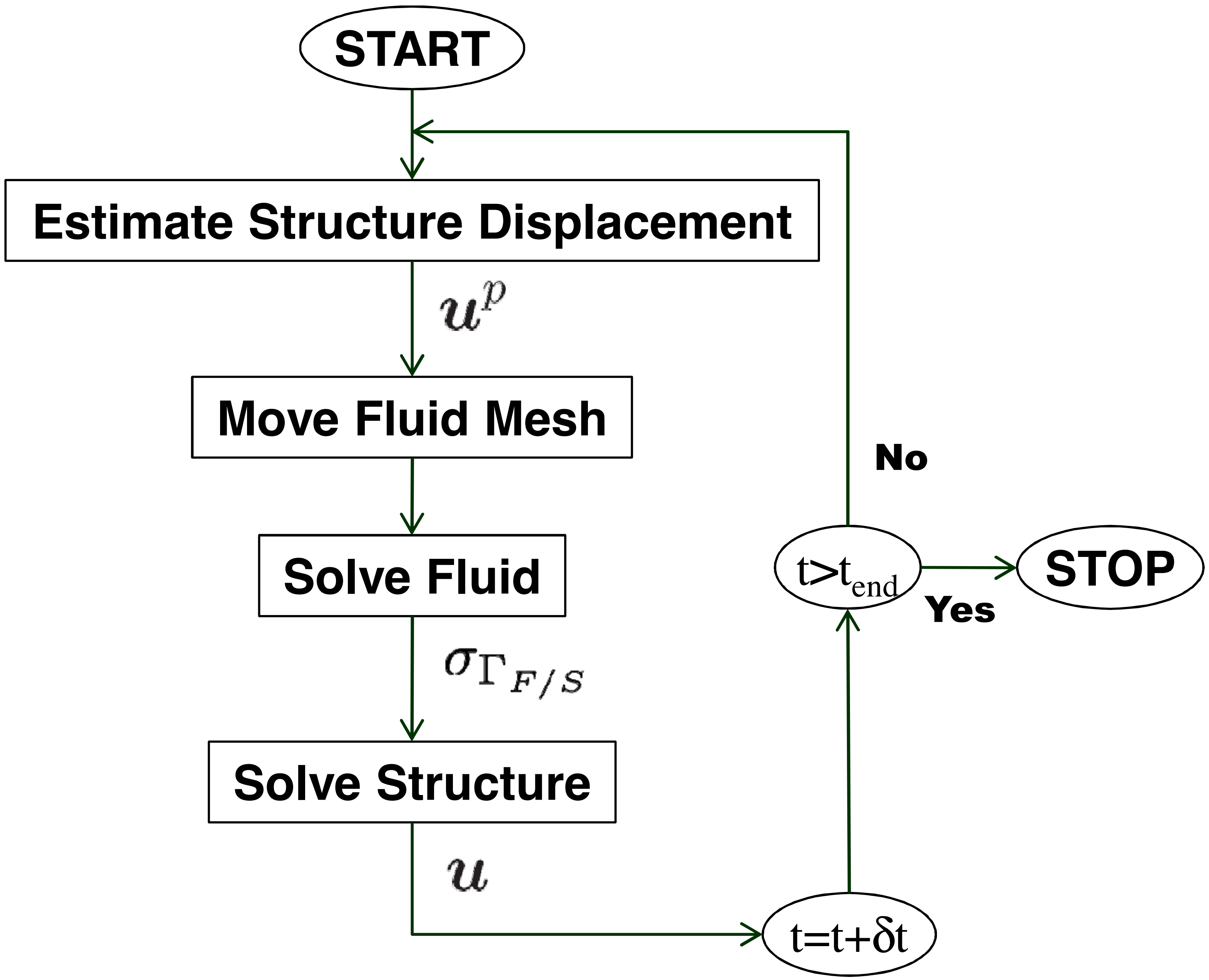


Figure 2: Loose-Coupling solver sequence

$$u^p \stackrel{?}{=} u$$

$$\frac{fluid\ density}{solid\ density} >= 1$$

Fluid-Structure Interaction

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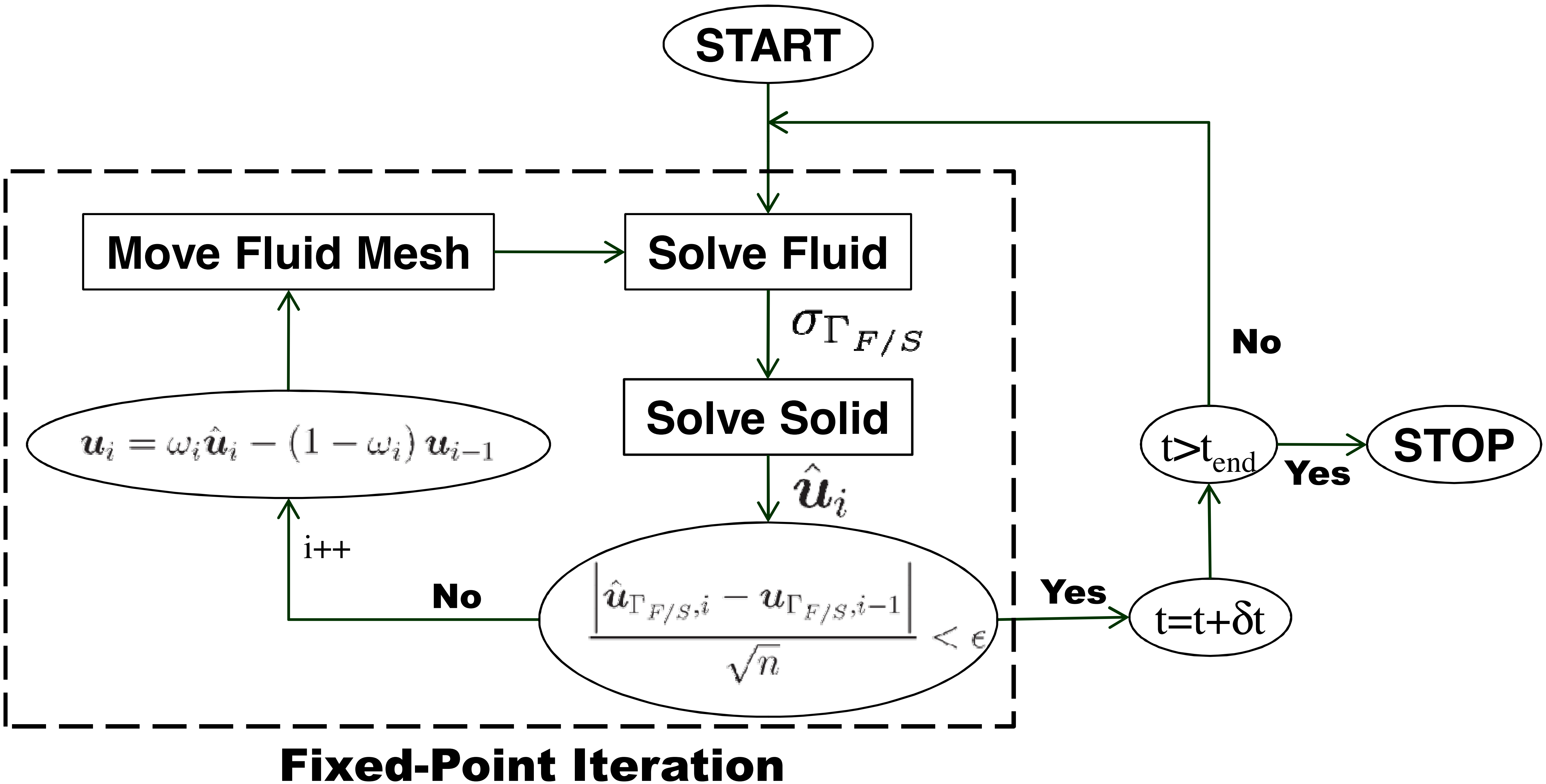
Tight-Coupling



- Aitken's under-relaxation method

FSI in The OpenFOAM® Extend

icoFsiFoam

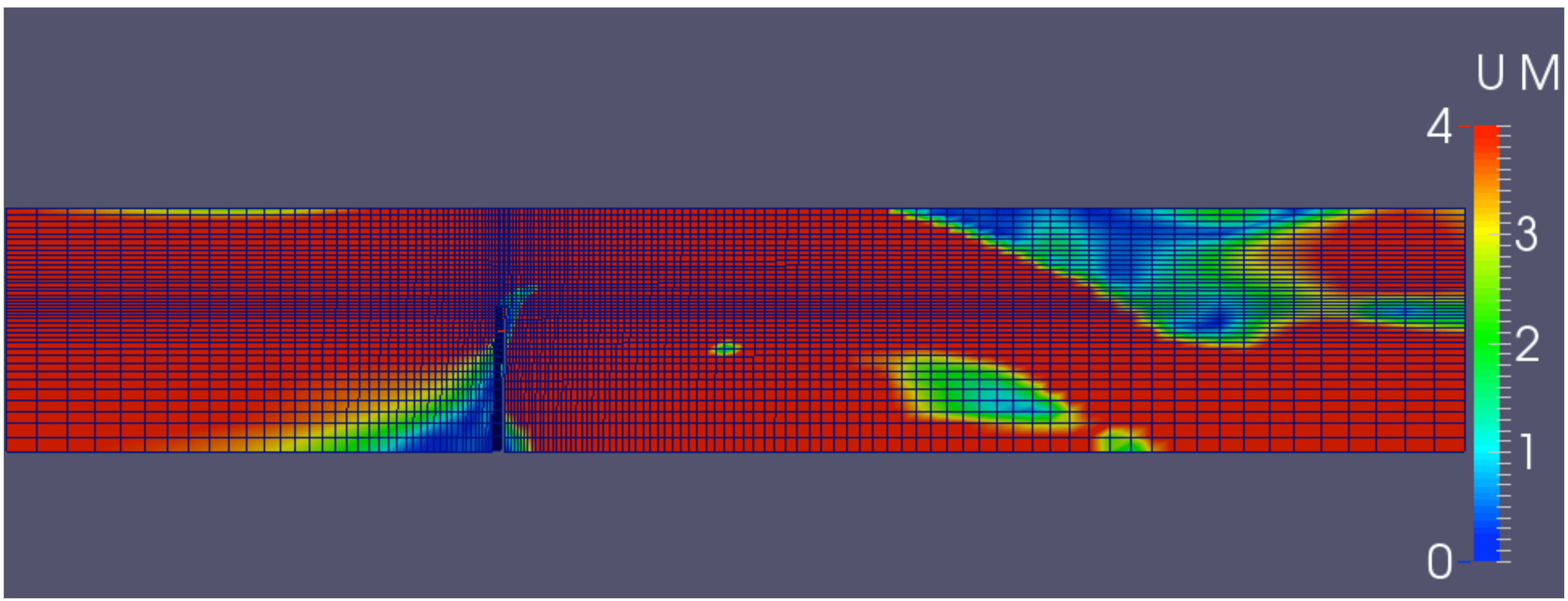
- Designed as a partitioned transient FSI solver for **incompressible flow** interacting with a **solid of linear elasticity**, causing **small deformations** in the solid. The algorithm performs the partitioned solver–loop:

1. Pressure is set on the FSI boundary
2. Traction on the solid boundary is updated
3. Solid deformation is solved using stressedFoam algorithm
4. Dynamic mesh is updated accordingly
5. Fluid domain is solved with a SIMPLE loop using additional pressure correction loops

FSI in OpenFOAM Extend

icoFsiFoam

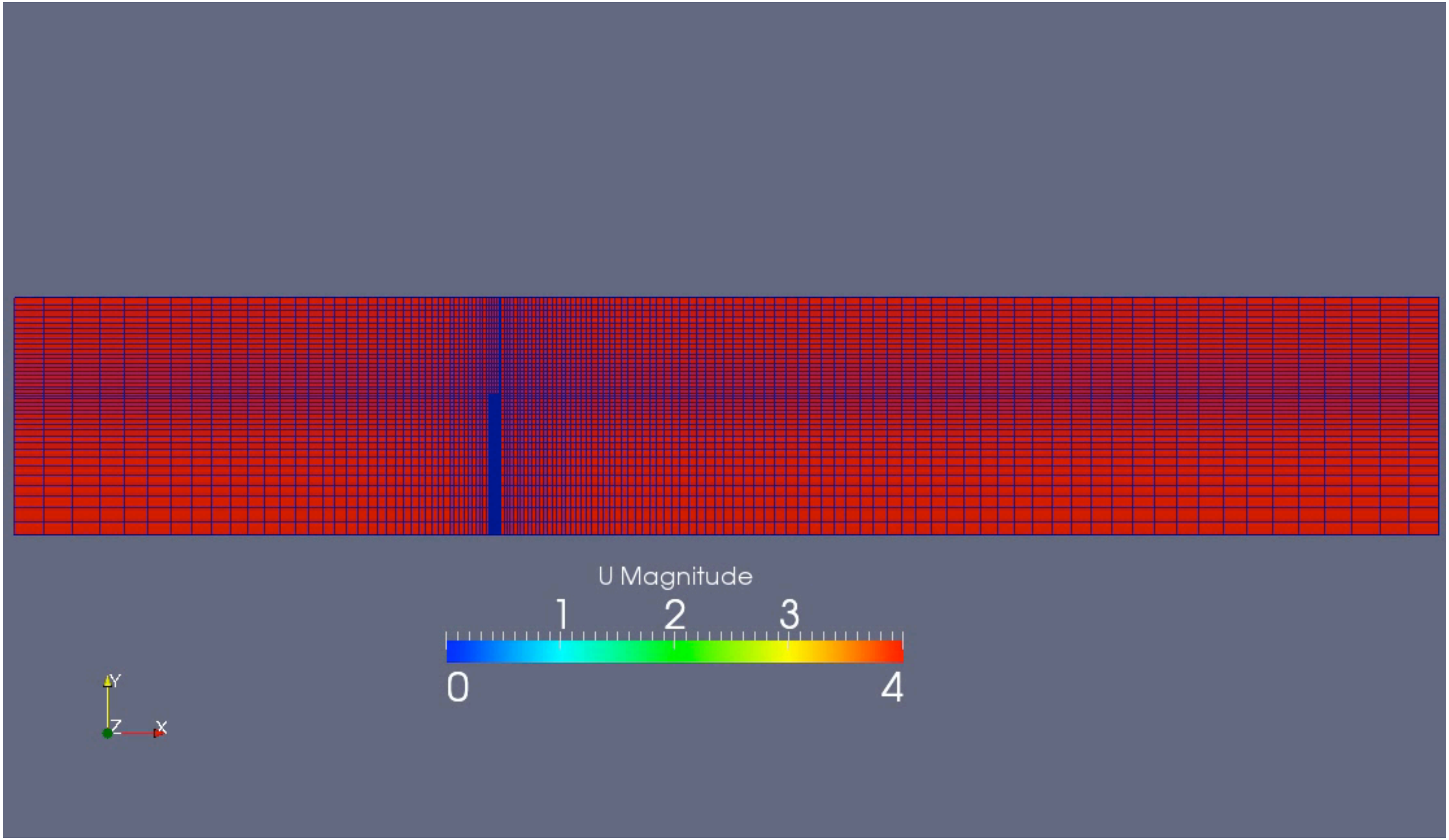
- Loosely-Coupled
- The most important part of the solver is setting motionU which determines how to solve mesh motion at given time-step.
- Dynamic Mesh takes care of everything automatically.



flappingConsoleSmall tutorial

FSI in OpenFOAM Extend

icoFsiFoam



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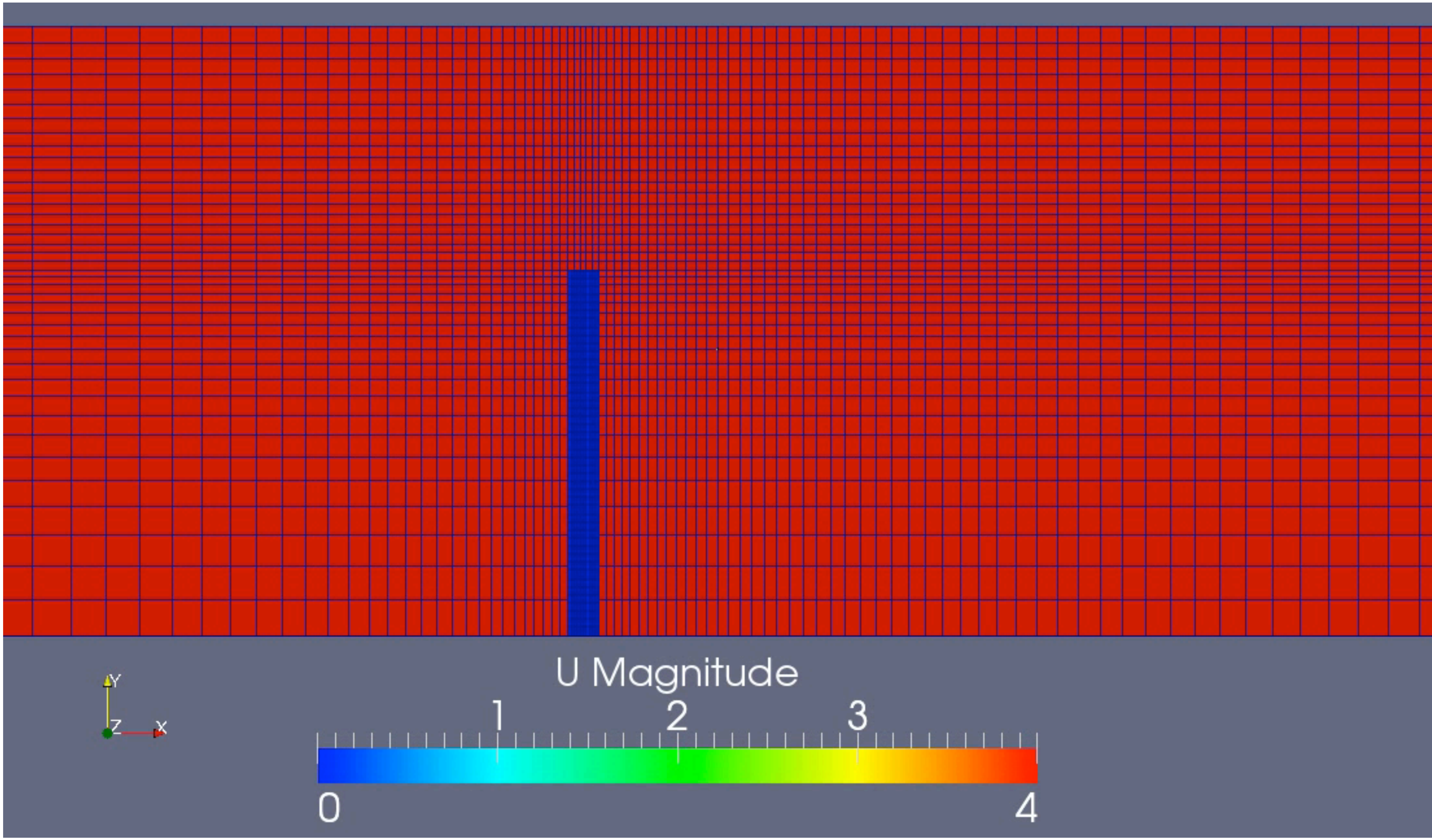

flappingConsoleSmall tutorial

FSI in OpenFOAM Extend

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Mesh Motion Equation

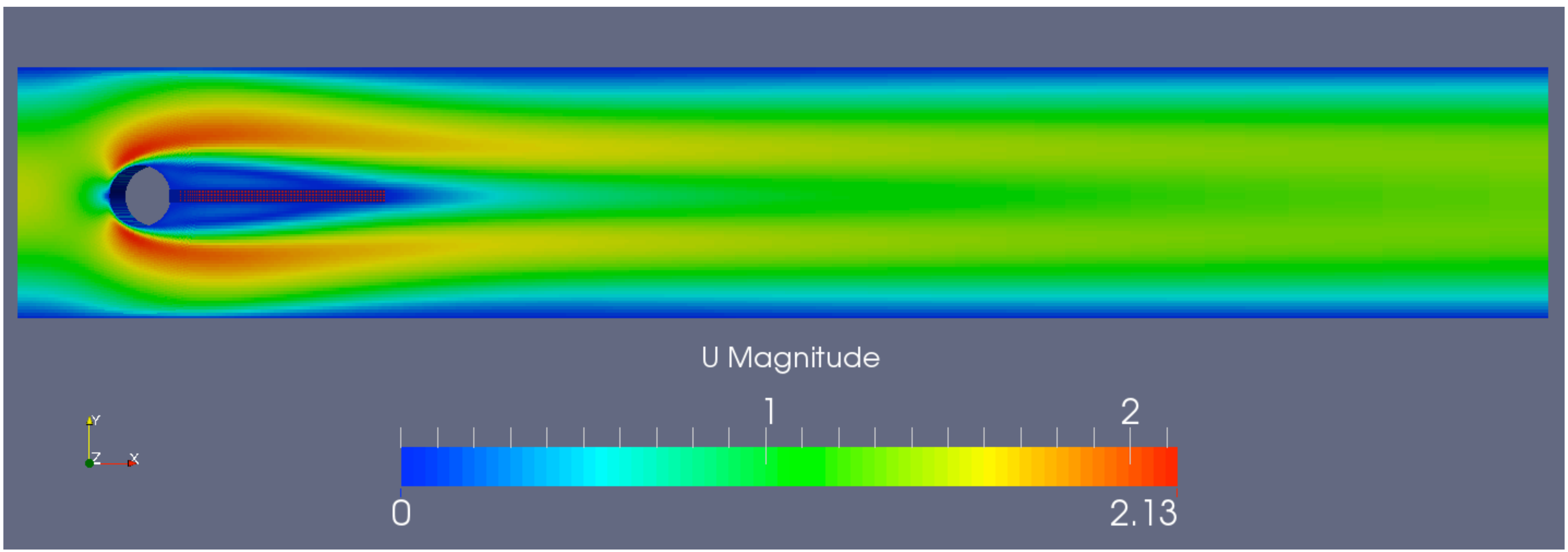
- Dynamic Mesh technique implemented in OpenFOAM is capable of refining mesh and updating the meshes on subdomains automatically. Since the mesh motion cannot be known priori, a mesh motion equation must be defined in order to solve moving mesh during the given time-step of FSI solver. There are 4 simple mesh motion equation present in OpenFOAM :

1. Spring analogy: insufficiently robust
2. Linear + torsional spring analogy: complex, expensive and non-linear
3. Laplace equation with constant and variable diffusivity
4. Linear pseudo-solid equation for small deformations

FSI in OpenFOAM Extend

icoFsiElasticNonLinULSolidFoam

- Tightly-Coupled
- Transient solver for fluid-solid interaction for an **incompressible fluid** and a **large strain solid**. Solid mesh is moved using **U interpolated using least squares method.**
- Aitken's under-relaxation method is used.



HronTurekFsi tutorial

Q & A

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References

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3. Bazilevs, Y., Hsu, M.-C., Benson, D., Sankaran, S., & Marsden, A. (2009). *Computational fluid–structure interaction: methods and application to a total cavopulmonary connection.* Computational Mechanics, 45(1), 77-89. Retrieved fromhttp://dx.doi.org/10.1007/s00466-009-0419-y doi: 10.1007/s00466-009-0419-y

4. J. Donea, Antonio Huerta, J.-Ph. Ponthot and A. Rodriguez-Ferran. *Arbitrary Lagrangian–Eulerian Methods*

5. The OpenFOAM® Extend Project tutorials

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