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

- 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](http://www.extend-project.de)
Advanced Capabilities of the Extend Project version 3.0 Jeju

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
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 have parallelization support

circleCylinder3D tutorial in foam-extend-3.0
Advanced Capabilities of Extend Project version 3.0 Jeju

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
Advanced Capabilities of Extend Project version 3.0 Jeju

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

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
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
- Viscoelastic nature of blood vessels
- Non-newtonian model for blood viscosity
Fluid-Structure Interaction

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

- 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

Maximum \( U_x = 0.1 \) m/s

Taken from page 16 of reference (2)
Fluid-Structure Interaction

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

ESTIMATE STRUCTURE DISPLACEMENT

\[ u^p \]

MOVE FLUID MESH

\[ \sigma_{TF/S} \]

SOLVE STRUCTURE

\[ u \]

\[ t = t + \delta t \]

\[ \text{STOP} \]

\[ t > t_{\text{end}} \]

\[ \text{NO} \]

\[ \text{YES} \]

\[ u^p = u \]

\[ \frac{\text{fluid density}}{\text{solid density}} \geq 1 \]

Figure 2: Loose-Coupling solver sequence
Fluid-Structure Interaction

Tight-Coupling

\[ u_i = \omega_i \hat{u}_i - (1 - \omega_i) u_{i-1} \]

\( \hat{u}_i \)

\( \sigma_{\Gamma_{F/S}} \)

\( t = t + \delta t \)

\( t > t_{\text{end}} \)

\( \sqrt{n} \)

\( \epsilon \)

- Aitken’s under-relaxation method
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

icoFoam

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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.
Q & A
References

1. Hrvoje Jasak, Henrik Rusche; *Dynamic Mesh Handling in OpenFOAM*; Advanced Training at the OpenFOAM Workshop, 21.6.2010, Gothenborg, Sweden


5. The OpenFOAM® Extend Project tutorials