solids4foam-v2.1: A toolbox for performing solid mechanics and fluid-solid interaction simulations in OpenFOAM

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Summary

`solids4foam` is a toolbox designed for conducting solid mechanics and fluid-solid interaction simulations within the widely-used OpenFOAM software (ESI-OpenCFD 2024; Foundation 2024; foam-extend 2024). The toolbox has a comprehensive set of features, including advanced algorithms for fluid-solid and thermo-fluid-solid coupling, a variety of solid material models, non-trivial solid boundary conditions, and numerous discretisation and solution methods for solid mechanics.

The solids4foam toolbox is one of the most comprehensive solid mechanics and fluid-solid interaction toolboxes available within OpenFOAM, having evolved from the `solidMechanics` and `extend-bazaar/FluidSolidInteraction` toolboxes of the foam-extend community (foam-extend 2024). Several other OpenFOAM-based toolboxes provide capabilities for solid mechanics and fluid-solid interaction, including `FOAM-FSI` (Mehl et al. 2016), `miniGeotechFoam` (Tang, Hededal, and Cardiff 2015), `explicitSolidDynamics` Haider et al. (2018), as well as more specialised solvers such as the membrane fluid-solid interaction solver (Wagner, Münsch, and Delgado 2022), a coupled actuator line and finite element analysis tool (Schmitt and Robinson 2022), and a modular multiphysics framework (St-Onge and Olivier 2023). However, many of these toolboxes are no longer actively maintained and lack the broad range of solid mechanics and fluid-solid interaction features required for general-purpose simulations. Beyond OpenFOAM-based solutions, preCICE (Chourdakis, Schneider, and Uekermann 2023) provides an alternative approach by coupling OpenFOAM with widely-used finite element solvers such as deal.II (Arndt et al. 2021), CalculiX (Dhondt 2004), FEniCS (Logg et al. 2012), and Code_Aster (France 1989--2017), enabling flexible multiphysics simulations. While solids4foam is among the first general finite volume-based toolboxes for solid mechanics and fluid-solid interaction, established finite element-based codes such as FEniCS (Logg et al. 2012) and deal.II (Arndt et al. 2021)

offer comparable functionality but differ in their numerical methodology. Furthermore, domain-specific fluid-solid interaction solvers, such as SimVascular (Zhu et al. 2022) and Ambit (Hirschvogel 2024) for cardiovascular simulations or turtlefluid-solid interaction (Bergersen et al. 2020) for general monolithic fluid-solid interaction problems, provide specialised solutions for particular applications. Despite these alternatives, `solids4foam` remains a uniquely positioned toolbox within OpenFOAM, offering a well-maintained and feature-rich platform for solid mechanics and fluid-solid interaction simulations based on the finite volume method.

Statement of Need

The `solids4foam` toolbox addresses four primary needs within the OpenFOAM community:

1. The need to perform fluid-solid interactions within OpenFOAM.
2. The need to solve complex solid mechanics problems directly within OpenFOAM.
3. The necessity for a modular approach to coupling various solid and fluid processes in OpenFOAM.
4. The demand for an extendable framework to facilitate research into innovative finite volume methods for solid mechanics.

The design of `solids4foam` adheres to four guiding principles:

1. **Usability:** If you can use OpenFOAM, you can use `solids4foam`.
2. **Compatibility:** Supports the three main OpenFOAM forks: OpenFOAM.com, OpenFOAM.org, and foam-extend.
3. **Ease of Installation:** The toolbox is easy to install and requires minimal additional dependencies beyond OpenFOAM.

Features

`solids4foam` employs a modular design, offering generic class interfaces for solid mechanics, fluid dynamics, fluid-solid coupling methods, and solid material models. It also supports all native OpenFOAM modularity, including boundary conditions and function objects.

The `solids4foam-v2.1` release includes the following features:

Partitioned Fluid-Solid Interaction Coupling Methods

- Fixed under-relaxation (Tuković, Karač, et al. 2018)
- Aitkens accelerated under-relaxation (Tuković, Karač, et al. 2018)
- Interface-quasi-Newton coupling (Degroote J 2009)
- Robin-Neumann coupling (Tuković, Bukač, et al. 2018)
- Thermo-fluid-solid interaction coupling

Finite Volume Solid Model Discretizations and Solution Algorithms

- Segregated (Cardiff et al. 2018), coupled (Cardiff, Tuković, Jasak, et al. 2016), and explicit solution algorithms
- Linear geometry (small strain) and nonlinear geometry (finite strain) formulations, including total and updated Lagrangian
- Cell-centered and vertex-centered formulations
- Continuum and plate formulations

Solid Material Models

- Linear elasticity (isotropic, orthotropic (Cardiff, Karač, and Ivanković 2014)), plasticity (J_2 (Cardiff, Tuković, De Jaeger, et al. 2016), Mohr-Coulomb (Tang, Hededal, and Cardiff 2015)), viscoelasticity (Cardiff et al. 2018), thermo-elasticity (Cardiff et al. 2018), poroelasticity (Tang, Hededal, and Cardiff 2015)
- Hyperelasticity (neo-Hookean, Ogden, Mooney-Rivlin (Oliveira et al. 2022, 2023), Fung (Oliveira et al. 2022, 2023), Yeoh (Oliveira et al. 2022, 2023)), hyperelastoplasticity (Cardiff, Tuković, De Jaeger, et al. 2016)
- Interface to Abaqus material model subroutines (UMATs)

Solid Boundary Conditions

- Frictional contact (node-to-segment (Cardiff, Karač, and Ivanković 2012; Cardiff, Tuković, De Jaeger, et al. 2016), segment-to-segment (Batistić, Cardiff, and Tuković 2022; Batistić et al. 2023))
- Cohesive zone models
- Traction, displacement, rotation

Fluid Models

- Incompressible (PIMPLE, PIMPLE-overset)
- Multiphase (volume-of-fluid)
- Weakly compressible (Oliveira et al. 2022)

Function Objects

- Energies, displacements, forces, stresses, principal stresses, torques

Utilities and Scripts

- Scripts for ensuring compatibility with the main OpenFOAM forks
- Mesh conversion utilities: OpenFOAM to/from Abaqus

Tutorials

- A suite of example cases and benchmark problems to demonstrate functionality and verify performance

Software compares to other commonly-used packages

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