The Journal of Open Source Software

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

Philip Cardiff [1¶], **Ivan Batistić** [2], **and Željko Tuković** [2]

1 School of Mechanical and Materials Engineering, University College Dublin, Dublin, Ireland **2** Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia ¶ Corresponding author

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Open Journals

Reviewers:

- @openjournals

Submitted: 01 January 1970
Published: unpublished

Summary

`solids4foam` is a toolbox designed for conducting solid mechanics and fluid-solid interaction simulations within the widely-used OpenFOAM software (ESI-OpenCFD, 2024; foam-extend, 2024; Foundation, 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.

Statement of Need

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

1. The need to perform fluid-solid interactions using 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.
4. **Code Quality:** Emphasis on code design and style, closely following the OpenFOAM coding style guide.

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 et al., 2014)), plasticity (J_2 (Cardiff, Tuković, De Jaeger, et al., 2016), Mohr-Coulomb (Tang et al., 2015)), viscoelasticity (Cardiff et al., 2018), thermo-elasticity (Cardiff et al., 2018), poroelasticity (Tang et al., 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 et al., 2012; Cardiff, Tuković, De Jaeger, et al., 2016), segment-to-segment (Batistić et al., 2022, 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

Acknowledgements

The `solids4foam` toolbox has not directly received funding from any source; nonetheless, many implementations within the toolbox have stemmed from research projects at University College Dublin, the University of Zagreb, and other institutes. With this in mind, Philip Cardiff gratefully acknowledges financial support from the Irish Research Council through the Laureate program, grant number IRCLA/2017/45, and the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation programme (Grant agreement No. 101088740), Science Foundation Ireland (SFI) through I-Form (SFI Grant Number 16/RC/3872), MaREI (SFI Grant Number RC2302 2), NexSys (SFI Grant Number 21/SPP/375), as well as the DJEI/DES/SFI/HEA Irish Centre for High-End Computing (ICHEC) for the provision of computational facilities and support (www.ichec.ie), and the UCD ResearchIT Sonic cluster funded by UCD IT Services and the UCD Research Office.

References

Batistić, I., Cardiff, P., Ivanković, A., & Tuković, Ž. (2023). A finite volume penalty-based implicit procedure for the treatment of the frictionless contact boundaries [Article]. *International Journal for Numerical Methods in Engineering*, *124*(18), 4171–4191. https://doi.org/10.1002/nme.7302

Batistić, I., Cardiff, P., & Tuković, Ž. (2022). A finite volume penalty based segment-to-segment method for frictional contact problems [Article]. *Applied Mathematical Modelling*, *101*, 673–693. https://doi.org/10.1016/j.apm.2021.09.009

Cardiff, P., Karač, A., & Ivanković, A. (2012). Development of a finite volume contact solver based on the penalty method. *Computational Materials Science*, *64*, 283–284.

Cardiff, P., Karač, A., & Ivanković, A. (2014). A large strain finite volume method for orthotropic bodies with general material orientations. *Computer Methods in Applied Mechanics and Engineering*, *268*, 318–335. https://doi.org/10.1016/j.cma.2013.09.008

Cardiff, P., Karač, A., Jaeger, P. D., Jasak, H., Nagy, J., Ivanković, A., & Tuković, Ž. (2018). Towards the development of an extendable solid mechanics and fluid-solid interactions toolbox for OpenFOAM. *Preprint*.

Cardiff, P., Tuković, De Jaeger, P., Clancy, M., & Ivanković, A. (2016). A Lagrangian cell-centred finite volume method for metal forming simulation. *International Journal for Numerical Methods in Engineering*, *109*(13), 1777–1803. https://doi.org/10.1002/nme.5345

Cardiff, P., Tuković, Jasak, H., & Ivanković, A. (2016). A block-coupled finite volume methodology for linear elasticity and unstructured meshes. *Computers & Structures*, *175*, 100–122. https://doi.org/10.1016/j.compstruc.2016.07.004

Degroote J, V. J., Bathe K-J. (2009). Performance of a new partitioned procedure versus a monolithic procedure in fluid-structure interaction. *Computers and Structures*, *87*(11-12), 793–801. https://doi.org/10.1016/j.compstruc.2008.11.013

ESI-OpenCFD. (2024). *OpenFOAM.com*. ESI Group. https://www.openfoam.com

foam-extend. (2024). *Foam-extend project*. https://sourceforge.net/projects/foam-extend/

Foundation, T. O. (2024). *OpenFOAM.org*. https://www.openfoam.org

Oliveira, I. L., Cardiff, P., Baccin, C. E., & Gasche, J. L. (2022). A numerical investigation of the mechanics of intracranial aneurysms walls: Assessing the influence of tissue hyperelastic laws and heterogeneous properties on the stress and stretch fields [Article]. *Journal of the Mechanical Behavior of Biomedical Materials*, *136*. https://doi.org/10.1016/j.jmbbm.2022.

105498

Oliveira, I. L., Cardiff, P., Baccin, C. E., Tatit, R. T., & Gasche, J. L. (2023). On the major role played by the lumen curvature of intracranial aneurysms walls in determining their mechanical response, local hemodynamics, and rupture likelihood [Article]. *Computers in Biology and Medicine*, *163*. https://doi.org/10.1016/j.compbiomed.2023.107178

Tang, T., Hededal, O., & Cardiff, P. (2015). On finite volume method implementation of poro-elasto-plasticity soil model. *International Journal for Numerical and Analytical Methods in Geomechanics*, *39*, 1410–1430. https://doi.org/10.1002/nag.2361

Tuković, Ž., Bukač, M., Cardiff, P., Jasak, H., & Ivanković, A. (2018). Added mass partitioned fluid-structure interaction solver based on a robin boundary condition for pressure. In *OpenFOAM selected papers of the 11th workshop* (pp. 1–23). Springer International.

Tuković, Ž., Karač, A., Cardiff, P., Jasak, H., & Ivanković, A. (2018). OpenFOAM finite volume solver for fluid-solid interaction. *Transactions of FAMENA*, *42*(3), 1–31. https://doi.org/10.21278/TOF.42301