Immersed domain approach for fluid-structure-contact interaction problems

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The study of fluid-structure interaction (FSI) has gained significant traction in recent decades, with applications spanning various disciplines, including geophysics and biomedicine. In FSI, computational techniques are defined by the choice of discrete domain representation, falling into two main categories: "boundary-fitted" or "non-boundary-fitted" meshes. Boundary-fitted methods explicitly represent the fluid-solid interface and deform the fluid mesh in tandem with the solid mesh, typically within an arbitrary Eulerian-Lagrangian (ALE) framework. While these methods offer high accuracy, substantial solid deformations can severely distort the fluid mesh, leading to numerical problems and the need for remeshing. Non-boundary-fitted methods, on the other hand, maintain separate and non-matching fluid and structure meshes. The structure is described within a Lagrangian framework, while the fluid is typically described in a fully Eulerian framework. This flexibility demands higher mesh resolution to maintain comparable accuracy, necessitating the consideration of parallel computing.

We present an immersed domain approach for the numerical solution of fluid-structure-contact-interaction (FSCI) problems [1]. Within the overlapping volume, the fluid and structure are coupled, while mortar-based techniques are employed to couple different structures in contact on their surfaces. Specifically, we utilize dual Lagrange multipliers, which, within the nonlinear solution procedure, enable discrete field transfer using standard matrix-vector multiplication or storage of the linearized system of equations in a single matrix, thus facilitating algebraic multigrid strategies. We illustrate our general algorithmic framework and our primary parallel computing tools and discuss two studies conducted using variations of our approach.

The first study simulates the complete dynamics of a bio-prosthetic heart valve. We model the interactions between blood and the valve, blood and the aortic wall, and leaflets during valve closure. This solution strategy is specifically designed to address the contact problem using non-smooth methods, with solid and structure sub-problems solved in a segregated and iterative manner.

The second study simulates a diaphragm pump and the contact interaction between an elastic valve displaced by the fluid and the valve seats. This approach is monolithic, and penalty methods are employed to impose contact conditions.

References

[1] Nestola, M.G., Zulian, P., Gaedke-Merzhäuser, L. and Krause, R. Fully coupled dynamic simulations of bioprosthetic aortic valves based on an embedded strategy for fluid–structure interaction with contact. *EP Europace, 23 (Supplement 1), pp.i96-i104, 2021.*