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Immersed Boundary Surface Method foam-extend

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Dynamic mesh problems in modern Computational Fluid Dynamics (CFD) today are becoming increasingly complicated, both in terms of boundary-to-flow interaction and complex physics support. The adage of a choice between complex geometry with simple flow physics or simple geometry for complex physics is less and less acceptable in engineering practice. While the conventional methods of dynamic mesh deformation and preserved connectivity or topological mesh changes seem versatile and robust, they suffer from geometrical limitations in the freedom of boundary motion and boundary-to-boundary interaction. Further, traditional dynamic mesh setup demands significant user interaction and may fail without warning, due to limitations of user-defined motion / topological changes or unforeseen dynamic mesh states. Particularly problematic are cases of arbitrary solution-dependent motion and deformation, bodies in close vicinity and in particular the problems of boundary-to-boundary collision, which cannot be adequately treated within this framework.

Immersed Boundary Method (IBM) is a possible alternative to moving deforming meshes in CFD. It accounts for presence of boundaries within a computational domain without a body-fitted mesh structure. Instead, modifications in the discretised equations are performed at matrix level to account for presence of “internal boundaries”. Methods vary in the manner in which the presence of the boundary in the volume mesh is accounted for, as well as the spatial description of the discontinuous solution fields, either in the volume or at the boundary. Examples include continuous or discrete forcing methods, with indirect and direct imposition of boundary conditions (BC-s).

While conventional IBM has been in use for decades, close inspection shows significant drawbacks in each of its many variants, leaving scope for further improvement. Typically, they relate to the ability of the method to evaluate surface forces, preserve boundedness of bounded scalars, guarantee no flux through impermeable walls, support conventional turbulence modelling techniques such as wall damping and the manner of resolving non-polynomial solution functions, such as the bounded step-change in the Volume of Fluid (VoF) variable. The most promising of the IBM methods is the direct forcing approach with direct imposition of boundary conditions, which was previously implemented by the author. However, current experience with complex models and non-trivial physics shows it is still insufficiently robust for practical engineering use.

Based on the existing experience of direct-forcing direct-BC IBM, a new Immersed Boundary Surface (IBS) method is developed, implemented and validated in foam-extend-4.1 and will be the topic of this talk. The method combines the properties of body-fitted polyhedral background mesh and Immersed Boundary (IB) without computational overhead or geometrical simplification.

The IBS method avoids the problems of boundary fitting or equation forcing in other IBM techniques by mimicking the presence of additional immersed boundary faces in the mesh at the matrix level without the need for detailed geometrical description. It is stable and conservative, with compact computational stencil support and strict boundedness of variables. Possible geometrical problems in precise surface-to-cell intersections are handled by robust error-avoidance algorithms, capable of detecting and resolving common cutting errors such as direct point-on-point or edge-on-edge hit.
The basis of the algorithm is the adjustment of mesh metrics (cell volumes, face areas) and geometry (cell and face centres, weighting factors and delta coefficients) for the cells interacting with the IB surface, without the need to modify the mesh connectivity. Deactivated cells are treated within the same framework without the need for special practice. Boundary conditions in the IB surface are imposed in a “body-fitted” manner without simplification. Since the algorithm exactly mimics the presence of body-fitted faces next to the immersed boundary, conventional near-wall treatment such as law-of-the-wall or other forms of wall damping can be used without modification.

The IBS method is extended to moving deforming immersed boundary cases, which handle the space conservation law with robust error-avoidance equivalent to the static surface cutting cases. This is validated on moving deforming IBS cases which do not exhibit the Courant-Friedrichs-Levy (CFL) limitation in boundary motion.

The IBS algorithm operates in parallel without algorithmic degradation, since it is inherently local. It is also equipped with dynamic mesh refinement and coarsening for polyhedral cells in 2-D and 3-D, with optional load balancing.

Validation cases presented in this study range from simple Laplace and potential flow equation, laminar and turbulent flow in 2-D and 3-D. The focus of the study is the simulation of floating objects in free surface flow, where it is necessary to show the ability of the algorithm to preserve mass and boundedness of scalars, accurately evaluate forces on the IB surface and couple the precise evaluation of near-wall pressure and velocity with coupling to 6-Degree-of-Freedom (6-DoF) floating body simulations, which also serve as the ultimate test case.