A Higher-Order Position- and Orientation-Independent Embedded Boundary Method for High Reynolds Number Turbulent Flows

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ABSTRACT

Recently, there has been a renewed interest in non-boundary-conforming methods for Computational Fluid Dynamics (CFD), also known as Embedded Boundary Methods (EBMs) (for example, see [1, 2, 3]), particularly for flow problems involving complex geometries and Fluid-Structure Interaction (FSI). Indeed, EBMs are attractive because for CFD applications, they operate on fixed grids that do not have to align with the body surfaces and therefore are simpler to generate, in principle [4]. For FSI problems, EBMs offer an alternative to Arbitrary Lagrangian Eulerian methods that is far more robust with respect to large displacements and rotations, large deformations, and topological changes induced by cracks and other structural changes [5, 6]. However, operating on non body-fitted grids has its own difficulties. Chief among them is the accurate treatment of wall boundary and fluid-structure transmission conditions, which is typically performed on surrogates of the embedded discrete fluid-structure interfaces or some reshaped counterparts of these interfaces. Consequently, many EBMs tend to be at best first-order space-accurate at embedded discrete fluid-structure interfaces, and some are even inconsistent there [7]. For viscous flows, EBMs also tend to suffer from sensitivities with respect to the position and orientation of the embedded discrete interfaces relative to the embedding CFD mesh [8].

Originally developed for the solution of multiphase flow problems [9], the Finite Volume method with Exact two-phase Riemann solvers (FIVER) was transformed in [10, 11] into a genuine EBM for CFD and FSI problems. Its underlying approach constitutes a departure from the traditional EBMs in that it treats the velocity and pressure boundary conditions on the embedded discrete interfaces simultaneously rather than disjointly, enforces the appropriate value of the fluid velocity at a wall and recovers the corresponding value of the pressure at this wall via the exact solution of local, 1D, fluid-structure Riemann problems instead of relying for this purpose exclusively on interpolation or extrapolation, and in that it is applicable not only to Cartesian or structured grids, but also to unstructured meshes. However, the original FIVER method shares the same issues faced by traditional EBMs when it comes to the smoothness of some components of the solution near the embedded discrete interfaces, and to sensitivities with respect to the position and orientation of the embedded discrete interfaces relative to the embedding mesh. In particular, both the first- [10] and second-order accurate [12] implementations of the original FIVER method are not able to compute smooth values of the skin friction coefficient on embedded discrete surfaces, when the embedding mesh is not aligned with the outlines of these surfaces, although they are capable of predicting integral quantities such as lift and drag coefficients with a high level of accuracy [13, 14].

Hence, the main objectives of this talk are two-fold. First, to present a novel formulation of FIVER that enhances the accuracy of its original version near embedded discrete surfaces for high Reynolds number turbulent flows, enables its coupling with a wall function model to reduce the grid discretization requirements for such applications, removes its sensitivities to the position and orientation of the embedded discrete surfaces relative to the embedding CFD mesh,

while maintaining its provable second-order spatial accuracy for smooth problems. Second, to highlight the advantages and performance of this new FIVER method with the solution of high Reynolds number turbulent flows past complex geometries such as bird feathers and challenging FSI problems such as those associated with highly flexible flapping wings.

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