Treatment of discrete events in embedded boundary methods for CFD and fluid-structure interaction

Jonathan Ho\(^1\), Charbel Farhat\(^{1,2,3}\)

\(^1\)Department of Aeronautics & Astronautics, \(^2\)Department of Mechanical Engineering
\(^3\)and Institute for Computational and Mathematical Engineering
Stanford University, Stanford, CA 94305, USA

ABSTRACT

Embedded boundary methods (EBMs) are often preferred over body-fitted approaches for computational fluid dynamics (CFD) problems with complex geometries, and highly nonlinear fluid-structure interaction (FSI) problems with large deformations and/or topological changes.

When the boundary treatment characterizing an EBM attempts to sharply capture the material interface \(\Gamma\) and the fluid state at this interface, it tends to generate an oscillatory numerical solution for at least two different reasons. The first one is the ill-conditioning generated by extrapolation procedures in the vicinity of \(\Gamma\) which is a source of spatial oscillations. It is inherently a steady-state issue for EBMs, as it manifests itself even for CFD problems associated with fixed geometries, wherever a grid point on the fixed interface \(\Gamma\) is too close to a grid point of the embedding CFD grid. Of course, the likelihood of this ill-conditioning is even greater for steady and unsteady FSI problems, where, by definition \(\Gamma\) moves and possibly deforms. This first source of spurious oscillations in the solution has been previously addressed in the literature, in both contexts of incompressible and compressible flows (see [1], [2], and [3]). The second reason is the sudden status change of a grid point of the embedding CFD grid – from real (active) to ghost (inactive), or vice-versa – when this point is traversed by a moving interface \(\Gamma\). Because it introduces a discontinuity in the numerical solution process, such a discrete event is a source of spurious, temporal oscillations. It can occur in steady and unsteady FSI problems, as long as the position and/or shape of the embedded surface evolves in pseudo- or physical time. It has been previously discussed in the literature, but only in the context of incompressible flows [4, 5].

For some problems, the source of spatial oscillations tends to be the dominant one. For other problems – for example, for gradient-base shape optimization problems where the gradients of the flow solution with respect to \(\Gamma\) must be computed – the source of temporal oscillations becomes the most significant. Hence, both sources of spurious oscillations must be mitigated in general. Given that remedies for the second source were previously offered only for incompressible flows, and that none of them addressed the impact of discrete events on integrated quantities of interest such as flow-induced forces, this lecture will also present a novel approach for equipping EBMs with a treatment of discrete events that addresses all of these issues. The proposed approach evolves the concept of the status of a fluid grid point to that of the status of a fluid edge. It introduces two additional fluid edge types besides the conventional fluid-fluid and fluid-structure types and an interpolatory algorithm, in order to effectively enforce a smooth transition from the fluid-fluid type to the fluid-structure type, and vice-versa. Additionally, an enhanced moving least-squares scheme [6] that accounts for the degree of occlusion of a computational cell is introduced to address discrete events associated with the computation of quantities of interest. While the proposed approach is applicable to any EBM, it will be presented in the context of the FIVER EBM [7, 8, 9] for compressible flows.

References


