A k-exact ENO-like least-square reconstruction for compressible flows applied to sharp immersed boundaries

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Numerical simulations of hypersonic flows have been used in lieu of, or as a supplement to wind-tunnel testing for many years. Such simulations require a high degree of skill in different domains, however in this discussion we really are interested in meshing strategy.
In the context of computer-aided vehicle development a large number of computations have to be made, iterating on successive designs, and the days taken to make the mesh for every iteration can amount to a major part of the allotted project time. The study presented here falls within this context and we suggest to use a sharp immersed boundary method (IBM) to cut the mesh generation time so as to allocate more time for the refining of the design - this discussion being the first of a series to gather all the ingredients to proceed to automatic design of hypersonic vehicles using computational fluid dynamics.
Sharp interface methods are usually preferred when there is a need to track precisely the interface and enforce the boundary condition at its exact location - flows with thin boundary layers like hypersonic flows are an example where the accuracy of a sharp interface method is favored. Among the sharp interface methods, cut-cell methods usually require numerous modifications when added to a pre-existing code, whereas the ghost-cell technique does not, and for that reason we shall focus in the present study on a ghost-cell immersed boundary method (GC-IBM).
A GC-IBM requires an as-accurate-as-possible computation of the values to assign to the ghost cells to correctly enforce the boundary condition at the immersed object's wall. Recent studies on the subject favor arbitrarily high-order weighted least-square (WLSQ) interpolations with a lessened impact on the whole computation spatial order of convergence. That is also the direction that we shall take for the new technique presented in this study. One of the most common assumption made in the development of an IBM based on WLSQ is however that the flow is smooth and devoid of any discontinuities inside the reconstruction stencil. This assumption does not hold anymore in the case of an hypersonic flow, wherein the shocks can get very close to the obstacle. In that regime, all the interpolation techniques involved in the IBM and based on a large enough stencil will eventually encounter a discontinuous field and fail to produce a physically relevant value for the ghost cell. The present study tackles this issue.
Our proposed k-exact weighted least-square interpolation is based on the work of Ollivier-Gooch *et al.* [2]. Its major feature is that the weights are automatically adapted to the presence of a discontinuity. In so doing, the reconstruction becomes ENO-like and mathematically consistent even in the presence of strong discontinuities [1]. The objective of this discussion is to demonstrate that it then becomes possible to use an IBM for the simulation of hypersonic flows and that it is robust, even for flows around complex geometries exhibiting discontinuities in contact with the body of interest.

[1] T. Bridel-Bertomeu. *Immersed boundary conditions for hypersonic flows using eno-like least-square reconstruction.* Computers & Fluids, **215**, 104794, 2021.

[2] C. F. Ollivier-Gooch. *Quasi-ENO schemes for unstructured meshes based on unlimited data-dependent least-squares reconstruction.* Journal of Computational Physics, **133(1)**, 6–17, 1997.

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