Immersed boundary methods for numerical simulation of confined fluid and plasma turbulence in complex geometries

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Immersed boundary techniques, including penalization approaches, are nowadays commonly employed to solve boundary or initial-boundary value problems in complex geometries. They consist in embedding the original, possibly complex spatial domain inside a bigger domain having a simpler geometry, for example a Cartesian geometry, while keeping the boundary conditions approximately enforced thanks to new terms that are added to the equations.

One particular example is the volume penalization method [Angot et al., 1999] which, inspired by the physical intuition that a solid wall is similar to a vanishingly porous medium, uses the Brinkman-Darcy drag force as penalization term. The main advantage of such penalized equations is that they can be discretized independently of the geometry of the original problem, since the latter has been encoded into the penalization terms. Such a simplifcation permits a massive reduction in solver development time, since it avoids the issues associated to the design and management of the grid, allowing for example the use of simple FFT based spectral solvers in Cartesian geometries. The gain becomes even more substantial when the geometry is time-dependent, as in the case of moving obstacles, or when fluid-structure interaction is taken into account.

Typically Dirichlet boundary conditions are considered corresponding to impose the value of the solution at the boundary. Extensions how to deal with Neumann boundary conditions [Kolomenskiy et al., 2014] will also be presented. Considering simple examples in one space dimension allows to understand and analyze the convergence behavior of the penalization techniques when the penalization parameter tends to zero. We show that, for a given numerical discretization of the penalized equations, there exists a value of the penalization parameter, corresponding to a balance between penalization and discretization errors, below which no further gain in precision is achieved. These results shed light on the behavior of volume penalization schemes when solving the penalized equations, outline the limitations of the method, and gives indications on how to choose the penalization parameter in practical cases. Finally, different illustrations will be given for hydro and magnetohydrodynamic problems in the turbulent regime including a study of the spatiotemporal self-organization of viscoresistive magnetohydrodynamics in toroidal geometries with different cross sections while imposing curl-free toroidal magnetic and electric fields.