TOP-VPN

Towards Optimal Volume Penalization Methods for Incompressible Navier–Stokes Flows

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In Short

- Optimization of volume penalization (VPM) for incompressible Navier–Stokes
- Adjoint-based calibration of penalization parameters using canonical test cases (channel; cylinder) with systematic parameter studies.
- Efficient, fully explicit, MPI-parallel FDTD implementation targeting large-scale HPC.
- Checkpointing strategies to enable gradient evaluations under tight I/O and memory constraints.

The volume penalization method offers a particularly elegant and flexible approach for representing complex geometries and boundary conditions in fluid simulations. By embedding solid objects directly into a fixed Cartesian grid and introducing localized penalization terms, it avoids the need for complex body-fitted meshing and re-meshing during simulations with moving boundaries. This property makes the method especially attractive for large-scale high-performance computations and problems involving dynamic or deformable geometries. In this project, we focus specifically on the incompressible flow regime, where an optimized penalization formulation is crucial to accurately capture near-wall dynamics and ensure numerical stability.

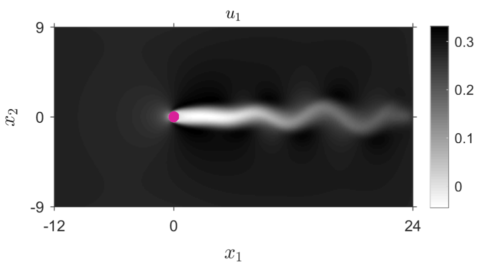

***Figure 1:** Exemplary flow past a circular cylinder, where the obstacle is modeled via volume penalization and highlighted in color. All length scales and the displayed streamwise velocity component u_1 are suitably normalized.*

We combine systematic parameter studies with adjoint-based optimization to identify near-optimal penalization parameters. The methodology is validated on canonical benchmarks (channel flow; cylinder) to assess accuracy, stability, and computational efficiency. The resulting insights pave the way for complex, time-dependent geometries relevant to bio-inspired flapping flight in turbulence, where coherent vortex dynamics and strong fluid–structure coupling dominate.

The computations demand large-scale HPC resources due to fine near-wall resolution, long integration horizons, and storage-intensive adjoint evaluations. We employ MPI-based domain/pencil decompositions, collective communications, and checkpointing/snapshotting to balance memory and I/O. The expected outcome is a set of optimized VPM schemes and reproducible workflows enabling scalable simulations of moving-body problems in turbulent flows.

WWW

http://cvsfit.cfd.tu-berlin.de/wordpress/

More Information

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