

An Immersed Interface Method for the Incompressible Navier-Stokes Equations in Irregular Domains

Duc-Vinh Le*, Boo Cheong Khoo^{*†}, Jaime Peraire^{*‡}

^{*}Singapore-MIT Alliance

[†]Department of Mechanical Engineering, National University of Singapore

[‡]Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

Abstract—We present an immersed interface method for the incompressible Navier-Stokes equations capable of handling rigid immersed boundaries. The immersed boundary is represented by a set of Lagrangian control points. In order to guarantee that the no-slip condition on the boundary is satisfied, singular forces are applied on the fluid at the immersed boundary. The forces are related to the jumps in pressure and the jumps in the derivatives of both pressure and velocity, and are interpolated using cubic splines. The strength of singular forces is determined by solving a small system of equations at each time step. The Navier-Stokes equations are discretized on a staggered Cartesian grid by a second order accurate projection method for pressure and velocity.

Keywords: Immersed interface method, Navier-Stokes equations, Cartesian grid method, finite difference, fast Poisson solvers, irregular domains.

1. INTRODUCTION

This paper considers the immersed interface method (IIM) for the incompressible Navier-Stokes equations in general domains involving rigid boundaries. In a 2-dimensional bounded domain Ω that contains a rigid interface Γ , we consider the incompressible Navier-Stokes equations, written as

$$\mathbf{u}_t + (\mathbf{u} \cdot \nabla)\mathbf{u} + \nabla p = \mu \Delta \mathbf{u} + \mathbf{F} \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

with boundary and initial conditions

$$\mathbf{u}|_{\partial\Omega} = \mathbf{u}_b \quad (3)$$

$$\mathbf{u}(\mathbf{x}, 0) = \mathbf{u}_0 \quad (4)$$

where \mathbf{u} is the fluid velocity, p the pressure, and μ the viscosity of the fluid. Here, we simply assume that the density, $\rho = 1$, and the viscosity, μ , are constant. The singular force \mathbf{F} has the form

$$\mathbf{F}(\mathbf{x}, t) = \int_{\Gamma} \mathbf{f}(s, t) \delta(\mathbf{x} - \mathbf{X}(s, t)) ds \quad (5)$$

where $\mathbf{X}(s, t)$ is the arc-length parameterization of Γ , s is the arc-length, $\mathbf{x} = (x, y)$ is spatial position, and $\mathbf{f}(s, t)$ is the force density. The Navier-Stokes equations are discretized using finite differences on a staggered Cartesian grid. The main features of our method are:

- It is a Cartesian grid method; the method does not require complex mesh generation.
- It is second order accurate for velocities.
- The Poisson-like equations resulting at each time step are solved using a cyclic reduction algorithm which has a complexity $O(N \log N)$, where N is the number of degrees of freedom.

Methods utilizing a Cartesian grid for solving interface problems or problems with complex geometry have become popular in recent years. One of the most successful Cartesian grid methods is Peskin's immersed boundary (IB) method ([10], [11], [15]). In order to deal with rigid boundaries, Lai and Peskin [11] propose to evaluate the force density using an expression of the form,

$$\mathbf{f}(s, t) = \kappa(\mathbf{X}''(s) - \mathbf{X}(s, t)), \quad (6)$$

where κ is a constant, $\kappa \gg 1$, and \mathbf{X}'' is the arc-length parameterization of the required boundary position. The forcing term in Eq (6) is a particular case of the feedback forcing formulation proposed by Goldstein et al. [12] with $\beta = 0$. In [12], the force is expressed as

$$\mathbf{f}(s, t) = \alpha \int_0^s \mathbf{U}(s, t') dt' + \beta \mathbf{U}(s, t) \quad (7)$$

where \mathbf{U} is the velocity at the control points, and α and β are chosen to be negative and large enough so that \mathbf{U} will stay close to zero. Lima E Silva et al. [15] proposed an alternative model to compute the force density \mathbf{f} based upon the evaluation of the various terms in the momentum equation (1) at the control points. The force density \mathbf{f} is calculated by computing all the Navier-Stokes terms at the control points.

Once the force density is obtained at the boundary, the immersed boundary method uses a discrete delta function to spread the force density to the nearby Cartesian grid points. Since the IB method uses the discrete delta function approach, it smears out sharp interface to a thickness of order of the meshwidth and it is only first-order accurate for problems with non-smooth but continuous solutions.

In contrast, the immersed interface method (IIM) can avoid this smearing and maintains a second-order accuracy by incorporating the known jumps into the finite difference

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