

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

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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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Navier-stokes Equations In Planar Domains Matania Ben-artzi, Jean Pierre Croisille, Dalia Fishelov, 2013-03-07 This volume deals with the classical Navier Stokes system of equations governing the planar flow of incompressible viscous fluid It is a first of its kind book devoted to all aspects of the study of such flows ranging from theoretical to numerical including detailed accounts of classical test problems such as driven cavity and double driven cavity A comprehensive treatment of the mathematical theory developed in the last 15 years is elaborated heretofore never presented in other books It gives a detailed account of the modern compact schemes based on a pure streamfunction approach In particular a complete proof of convergence is given for the full nonlinear problem This volume aims to present a variety of numerical test problems It is therefore well positioned as a reference for both theoretical and applied mathematicians as well as a text that can be used by graduate students pursuing studies in pure or applied mathematics fluid dynamics and mathematical physics a

The Navier-Stokes Equations Rodolfo Salvi, 2001-09-27 Contains proceedings of Varenna 2000 the international conference on theory and numerical methods of the Navier Stokes equations held in Villa Monastero in Varenna Lecco Italy surveying a wide range of topics in fluid mechanics including compressible incompressible and non newtonian fluids the free boundary problem and hydrodynamic potential theory

Moving Interface Problems and Applications in Fluid Dynamics Boo Cheong Khoo, Zhilin Li, Ping Lin, 2008 This volume is a collection of research papers presented at the program on Moving Interface Problems and Applications in Fluid Dynamics which was held between January 8 and March 31 2007 at the Institute for Mathematical Sciences IMS of the National University of Singapore The topics discussed include modeling and simulations of biological flow coupled to deformable tissue elastic structure shock wave and bubble dynamics and various applications including biological treatments with experimental verification multi medium flow or multi phase flow and various applications including cavitation supercavitation detonation problems Newtonian and non Newtonian fluid and many other areas Readers can benefit from some recent research results in these areas

Spectral and High-Order Methods for Partial Differential Equations ICOSAHOM 2023

Sehun Chun, Jae-Hun Jung, Eun-Jae Park, Jie Shen, 2025-12-03 The book consists of contributions by plenary speakers and other speakers at the ICOSAHOM 2023 which was held at Yonsei University Korea during Aug 14 18 2023 The subjects of the

book focus on recent advances on the analysis and applications of spectral and high order methods In particular it includes several survey papers which provide reviews of recent progresses and descriptions of future directions in the related subjects The book will be of interest to scientists and engineers who are interested in numerical analysis and scientific computing particularly spectral and high order methods **Numerical Solution of Differential Equations** Zhilin Li,Zhonghua Qiao,Tao Tang,2017-11-30 A practical and concise guide to finite difference and finite element methods Well tested MATLAB codes are available online *Interface Problems and Methods in Biological and Physical Flows* Boo Cheong Khoo,Zhilin Li,Ping Lin,2009 This volume showcases lecture notes collected from tutorials presented at the Workshop on Moving Interface Problems and Applications in Fluid Dynamics that was held between January 8 and March 31 2007 at the Institute for Mathematical Sciences National University of Singapore As part of the program these tutorials were conducted by specialists within their respective areas such as Robert Dillon Zhilin Li John Lowengrub Frank Lu and Gretar Tryggvason The topics in the program encompass modeling and simulations of biological flow coupled to deformable tissue elastic structure shock wave and bubble dynamics and various applications like biological treatments with experimental verification multi medium flow or multiphase flow and various applications including cavitation supercavitation detonation problems Newtonian and non Newtonian fluid and many other areas This volume stand to benefit graduate students and researchers keen in the field of interfacial flows for application to physical and biological systems Even beginners will find this volume a very useful starting point with many relevant references applicable **Equations of Motion for Incompressible Viscous Fluids** Tujin Kim,Daomin Cao,2021-09-09 This monograph explores the motion of incompressible fluids by presenting and incorporating various boundary conditions possible for real phenomena The authors approach carefully walks readers through the development of fluid equations at the cutting edge of research and the applications of a variety of boundary conditions to real world problems Special attention is paid to the equivalence between partial differential equations with a mixture of various boundary conditions and their corresponding variational problems especially variational inequalities with one unknown A self contained approach is maintained throughout by first covering introductory topics and then moving on to mixtures of boundary conditions a thorough outline of the Navier Stokes equations an analysis of both the steady and non steady Boussinesq system and more Equations of Motion for Incompressible Viscous Fluids is ideal for postgraduate students and researchers in the fields of fluid equations numerical analysis and mathematical modelling *Pseudo-Monotone Operator Theory for Unsteady Problems with Variable Exponents* Alex Kaltenbach,2023-08-11 This book provides a comprehensive analysis of the existence of weak solutions of unsteady problems with variable exponents The central motivation is the weak solvability of the unsteady p Navier Stokes equations describing the motion of an incompressible electro rheological fluid Due to the variable dependence of the power law index p in this system the classical weak existence analysis based on the pseudo monotone operator theory in the framework of Bochner Lebesgue spaces is not applicable As a

substitute for Bochner Lebesgue spaces variable Bochner Lebesgue spaces are introduced and analyzed In the mathematical framework of this substitute the theory of pseudo monotone operators is extended to unsteady problems with variable exponents leading to the weak solvability of the unsteady p Navier Stokes equations under general assumptions Aimed primarily at graduate readers the book develops the material step by step starting with the basics of PDE theory and non linear functional analysis The concise introductions at the beginning of each chapter together with illustrative examples graphics detailed derivations of all results and a short summary of the functional analytic prerequisites will ease newcomers into the subject

Numerical Analysis of Compressible Fluid Flows Eduard Feireisl, Mária Lukáčová-Medvidová, Hana Mizerová, Bangwei She, 2022-01-01 This book is devoted to the numerical analysis of compressible fluids in the spirit of the celebrated Lax equivalence theorem The text is aimed at graduate students in mathematics and fluid dynamics researchers in applied mathematics numerical analysis and scientific computing and engineers and physicists The book contains original theoretical material based on a new approach to generalized solutions dissipative or measure valued solutions The concept of a weak strong uniqueness principle in the class of generalized solutions is used to prove the convergence of various numerical methods The problem of oscillatory solutions is solved by an original adaptation of the method of K convergence An effective method of computing the Young measures is presented Theoretical results are illustrated by a series of numerical experiments Applications of these concepts are to be expected in other problems of fluid mechanics and related fields

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