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.

I. 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

$$\mathbf{u}_t + (\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla p = \mu\triangle\mathbf{u} + \boldsymbol{F} \tag{1}$$

$$\nabla\cdot\mathbf{u} = 0 \tag{2}$$

with boundary and initial conditions

$$\mathbf{u}|_{\partial\Omega} = \mathbf{u}_b \tag{3}$$

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

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

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

where $\boldsymbol{X}(s,t)$ is the arc-length parameterization of Γ, s is the arc-length, $\boldsymbol{x} = (x,y)$ is spatial position, and $\boldsymbol{f}(s,t)$ 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,

$$\boldsymbol{f}(s,t) = \kappa(\boldsymbol{X}^*(s) - \boldsymbol{X}(s,t)), \tag{6}$$

where κ is a constant, $\kappa \gg 1$, and $\boldsymbol{X}^*$ 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

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

where $\boldsymbol{U}$ is the velocity at the control points, and α and β are chosen to be negative and large enough so that $\boldsymbol{U}$ will stay close to zero. Lima E Silva et al. [15] proposed an alternative model to compute the force density $\boldsymbol{f}$ based upon the evaluation of the various terms in the momentum equation (1) at the control points. The force density $\boldsymbol{f}$ 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 Irregular Domains L. Stupelis,2013-03-14 The analytical basis of Navier Stokes Equations in Irregular Domains is formed by coercive estimates which enable proofs to be given of the solvability of the boundary value problems for Stokes and Navier Stokes equations in weighted Sobolev and H lder spaces and the investigation of the smoothness of their solutions This allows one to deal with the special problems that arise in the presence of edges or angular points in the plane case at the boundary or noncompact boundaries Such problems cannot be dealt with in any of the usual ways Audience Graduate students research mathematicians and hydromechanicians whose work involves functional analysis and its applications to Navier Stokes equations *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 viscid 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 *Numerical Solution of Differential Equations* Zhilin Li,Zhonghua Qiao,Tao Tang,2017-11-30 This introduction to finite difference and finite element methods is aimed at graduate students who need to solve differential equations The prerequisites are few basic calculus linear algebra and ODEs and so the book will be accessible and useful to readers from a range of disciplines across science and engineering Part I begins with finite difference methods Finite element methods are then introduced in Part II In each part the authors begin with a comprehensive discussion of one dimensional problems before proceeding to consider two or higher dimensions An emphasis is placed on numerical algorithms related mathematical theory and essential details in the implementation while some useful packages are also introduced The authors also provide well tested MATLAB codes all available online 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 **Interface Problems And Methods In Biological And Physical Flows** Boo Cheong Khoo,Zhilin Li,Ping Lin,Frank K Lu,2009-05-05 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 benefits 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 Domain-based Parallelism and Problem Decomposition Methods in Computational Science and Engineering David E. Keyes,Yousef Saad,Donald G. Truhlar,1995-01-01 This refereed volume arose from the editors recognition that physical scientists engineers and applied mathematicians are developing in parallel solutions to problems of parallelization The cross disciplinary field of scientific computation is bringing about better communication between heterogeneous computational groups as they face this common challenge This volume is one attempt to provide cross disciplinary communication Problem decomposition and the use of domain based parallelism in computational science and engineering was the subject addressed at a workshop held at the University of Minnesota Supercomputer Institute in April 1994 The authors were subsequently able to address the relationships between their individual applications and independently developed approaches This book is written for an interdisciplinary audience and concentrates on transferable algorithmic techniques rather than the scientific results

themselves Cross disciplinary editing was employed to identify jargon that needed further explanation and to ensure provision of a brief scientific background for each chapter at a tutorial level so that the physical significance of the variables is clear and correspondences between fields are visible **Numerical Analysis of Compressible Fluid Flows** Eduard Feireisl,Mária Lukáčová-Medviďová,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 **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 andnon 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 **Meshfree Methods for Partial Differential Equations VII** Michael Griebel,Marc Alexander Schweitzer,2014-12-02 Meshfree methods particle methods and generalized finite element methods have witnessed substantial development since the mid 1990s The growing interest in these methods is due in part to the fact that they are extremely flexible numerical tools and can be interpreted in a number of ways For instance meshfree methods can be viewed as a natural extension of classical finite element and finite difference methods to scattered node configurations with no fixed connectivity Furthermore meshfree methods offer a number of advantageous features which are especially attractive when dealing with multiscale phenomena a priori knowledge about particular local behavior of the solution can easily be introduced in the meshfree approximation space and coarse scale

approximations can be seamlessly refined with fine scale information This volume collects selected papers presented at the Seventh International Workshop on Meshfree Methods held in Bonn Germany in September 2013 They address various aspects of this highly dynamic research field and cover topics from applied mathematics physics and engineering Parallel Computational Fluid Dynamics '95 A. Ecer,N. Satofuka,Jacques Periaux,S. Taylor,1996-01-25 Parallel Computational Fluid Dynamics CFD is an internationally recognised fast growing field Since 1989 the number of participants attending Parallel CFD Conferences has doubled In order to keep track of current global developments the Parallel CFD Conference annually brings scientists together to discuss and report results on the utilization of parallel computing as a practical computational tool for solving complex fluid dynamic problems This volume contains the results of research conducted during the past year Subject areas covered include novel parallel algorithms parallel Euler and Navier Stokes solvers parallel Direct Simulation Monte Carlo method and parallel multigrid techniques The content of the book also demonstrates that considerable effort is being made to utilize parallel computing to solve a variety of fluid dynamics problems in topics such as climate modeling consultation aerodynamics and in many other areas Readers of this book will gain a valid insight into the exciting recent developments in Parallel CFD research *Singular Limits in Thermodynamics of Viscous Fluids* Eduard Feireisl,Antonín Novotný,2009-03-28 Many interesting problems in mathematical fluid dynamics involve the behavior of solutions of nonlinear systems of partial differential equations as certain parameters vanish or become infinite Frequently the limiting solution provided the limit exists satisfies a qualitatively different system of differential equations This book is designed as an introduction to the problems involving singular limits based on the concept of weak or variational solutions The primitive system consists of a complete system of partial differential equations describing the time evolution of the three basic state variables the density the velocity and the absolute temperature associated to a fluid which is supposed to be compressible viscous and heat conducting It can be represented by the Navier Stokes Fourier system that combines Newton s rheological law for the viscous stress and Fourier s law of heat conduction for the internal energy flux As a summary this book studies singular limits of weak solutions to the system governing the flow of thermally conducting compressible viscous fluids Computational and Information Technologies in Science, Engineering and Education Yuri Shokin,Zhassulan Shaimardanov,2019-02-20 This book constitutes the refereed proceedings of the 9th International Conference on Computational and Information Technologies in Science Engineering and Education CITech 2018 held in Ust Kamenogorsk Kazakhstan in September 2018 The 25 revised full papers presented were carefully reviewed and selected from 64 submissions The papers address issues such as mathematical and computer modeling fundamental problems of mathematics technological aspects of the applications of parallel computer systems high level parallel programming languages and systems **Domain Decomposition Methods in Science and Engineering** Alfio Quarteroni,1994 This book contains the proceedings of the Sixth International Conference on Domain Decomposition held in June 1992 in Como Italy Much of the

work in this field focuses on developing numerical methods for large algebraic systems **Numerical Analysis and Its Applications** Zhilin Li,Lubin Vulkov,Jerzy Wásniewski,2005-02-07 This book constitutes the thoroughly refereed post proceedings of the Third International Conference on Numerical Analysis and Its Applications NAA 2004 held in Rousse Bulgaria in June July 2004 The 68 revised full papers presented together with 8 invited papers were carefully selected during two rounds of reviewing and improvement All current aspects of numerical analysis are addressed Among the application fields covered are computational sciences and engineering chemistry physics economics simulation fluid dynamics visualization etc **Fifth International Symposium on Domain Decomposition Methods for Partial Differential Equations** David E. Keyes,1992-01-01 Papers presented at the May 1991 symposium reflect continuing interest in the role of domain decomposition in the effective utilization of parallel systems applications in fluid mechanics structures biology and design optimization and maturation of analysis of elliptic equations with theoretic *Many-Particle Dynamics and Kinetic Equations* C. Cercignani,U.I. Gerasimenko,D.Y. Petrina,2012-12-06 As our title suggests there are two aspects in the subject of this book The first is the mathematical investigation of the dynamics of infinite systems of in teracting particles and the description of the time evolution of their states The second is the rigorous derivation of kinetic equations starting from the results of the aforementioned investigation As is well known statistical mechanics started in the last century with some papers written by Maxwell and Boltzmann Although some of their statements seemed statistically obvious we must prove that they do not contradict what me chanics predicts In some cases in particular for equilibrium states it turns out that mechanics easily provides the required justification However things are not so easy if we take a step forward and consider a gas is not in equilibrium as is e g the case for air around a flying vehicle Questions of this kind have been asked since the dawn of the kinetic theory of gases especially when certain results appeared to lead to paradoxical conclu sions Today this matter is rather well understood and a rigorous kinetic theory is emerging The importance of these developments stems not only from the need of providing a careful foundation of such a basic physical theory but also to exhibit a prototype of a mathematical construct central to the theory of non equilibrium phenomena of macroscopic size **Advanced Computational Infrastructures for Parallel and Distributed Adaptive Applications** Manish Parashar,Xiaolin Li,Sumir Chandra,2010-01-05 A unique investigation of the state of the art in design architectures and implementations of advanced computational infrastructures and the applications they support Emerging large scale adaptive scientific and engineering applications are requiring an increasing amount of computing and storage resources to provide new insights into complex systems Due to their runtime adaptivity these applications exhibit complicated behaviors that are highly dynamic heterogeneous and unpredictable and therefore require full fledged computational infrastructure support for problem solving runtime management and dynamic partitioning balancing This book presents a comprehensive study of the design architecture and implementation of advanced computational infrastructures as well as the adaptive applications developed

and deployed using these infrastructures from different perspectives including system architects software engineers computational scientists and application scientists Providing insights into recent research efforts and projects the authors include descriptions and experiences pertaining to the realistic modeling of adaptive applications on parallel and distributed systems The first part of the book focuses on high performance adaptive scientific applications and includes chapters that describe high impact real world application scenarios in order to motivate the need for advanced computational engines as well as to outline their requirements The second part identifies popular and widely used adaptive computational infrastructures The third part focuses on the more specific partitioning and runtime management schemes underlying these computational toolkits Presents representative problem solving environments and infrastructures runtime management strategies partitioning and decomposition methods and adaptive and dynamic applications Provides a unique collection of selected solutions and infrastructures that have significant impact with sufficient introductory materials Includes descriptions and experiences pertaining to the realistic modeling of adaptive applications on parallel and distributed systems The cross disciplinary approach of this reference delivers a comprehensive discussion of the requirements design challenges underlying design philosophies architectures and implementation deployment details of advanced computational infrastructures It makes it a valuable resource for advanced courses in computational science and software systems engineering for senior undergraduate and graduate students as well as for computational and computer scientists software developers and other industry professionals *Differential Quadrature and Its Application in Engineering* Chang Shu,2012-12-06 In the past few years the differential quadrature method has been applied extensively in engineering This book aimed primarily at practising engineers scientists and graduate students gives a systematic description of the mathematical fundamentals of differential quadrature and its detailed implementation in solving Helmholtz problems and problems of flow structure and vibration Differential quadrature provides a global approach to numerical discretization which approximates the derivatives by a linear weighted sum of all the functional values in the whole domain Following the analysis of function approximation and the analysis of a linear vector space it is shown in the book that the weighting coefficients of the polynomial based Fourier expansion based and exponential based differential quadrature methods can be computed explicitly It is also demonstrated that the polynomial based differential quadrature method is equivalent to the highest order finite difference scheme Furthermore the relationship between differential quadrature and conventional spectral collocation is analysed The book contains material on Linear Vector Space Analysis and the Approximation of a Function Polynomial Fourier Expansion and Exponential based Differential Quadrature Differential Quadrature Weighting Coefficient Matrices Solution of Differential Quadrature resultant Equations The Solution of Incompressible Navier Stokes and Helmholtz Equations Structural and Vibrational Analysis Applications Generalized Integral Quadrature and its Application in the Solution of Boundary Layer Equations Three FORTRAN programs for simulation of driven cavity flow

vibration analysis of plate and Helmholtz eigenvalue problems respectively are appended These sample programs should give the reader a better understanding of differential quadrature and can easily be modified to solve the readers own engineering problems **Elliptic Marching Methods and Domain Decomposition** Patrick J. Roache,1995-06-29 One of the first things a student of partial differential equations learns is that it is impossible to solve elliptic equations by spatial marching This new book describes how to do exactly that providing a powerful tool for solving problems in fluid dynamics heat transfer electrostatics and other fields characterized by discretized partial differential equations Elliptic Marching Methods and Domain Decomposition demonstrates how to handle numerical instabilities i e limitations on the size of the problem that appear when one tries to solve these discretized equations with marching methods The book also shows how marching methods can be superior to multigrid and pre conditioned conjugate gradient PCG methods particularly when used in the context of multiprocessor parallel computers Techniques for using domain decomposition together with marching methods are detailed clearly illustrating the benefits of these techniques for applications in engineering applied mathematics and the physical sciences

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