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OPTIMAL CONTROL OF LINEARIZED COMPRESSIBLE NAVIER–STOKES EQUATIONS

Shirshendu Chowdhury[1] and Mythily Ramaswamy[1]

Abstract. We study an optimal boundary control problem for the two dimensional unsteady linearized compressible Navier–Stokes equations in a rectangle. The control acts through the Dirichlet boundary condition. We first establish the existence and uniqueness of the solution for the two-dimensional unsteady linearized compressible Navier–Stokes equations in a rectangle with inhomogeneous Dirichlet boundary data, not necessarily smooth. Then, we prove the existence and uniqueness of the optimal solution over the control set. Finally we derive an optimality system from which the optimal solution can be determined.

Mathematics Subject Classification. 49J20, 49K20, 35Q30, 76N25.

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1. Introduction

The Navier–Stokes equations for a viscous compressible isentropic fluid in $\Omega \subset \mathbb{R}^N$ is

$$\left.\begin{aligned} \frac{\partial \rho}{\partial t}(t,x) + \operatorname{div}[\rho(t,x)\mathbf{v}(t,x)] &= 0, \\ \rho(t,x)\left[\frac{\partial \mathbf{v}}{\partial t}(t,x) + (\mathbf{v}(t,x)\cdot\nabla)\mathbf{v}(t,x)\right] &= -\nabla p(t,x) + \mu\triangle \mathbf{v}(t,x) + (\lambda+\mu)\nabla\left[\operatorname{div}\ \mathbf{v}(t,x)\right], \\ p(t,x) &= a\rho^{\gamma}(t,x), \quad t>0,\ x \in \Omega, \end{aligned}\right\} \tag{1.1}$$

where $\rho(t,x)$ is the density of the fluid, $\mathbf{v}(t,x) = (v_1(t,x),\ldots,v_N(t,x))$ denotes the velocity vector in $\mathbb{R}^N$ and $p(t,x)$ denotes the pressure. Note that the second equation of (1.1) componentwise is

$$\rho\left(\frac{\partial v_i}{\partial t} + \mathbf{v}\cdot\nabla v_i\right) = -\frac{\partial p}{\partial x_i} + \mu\triangle v_i + (\lambda+\mu)\frac{\partial}{\partial x_i}[\operatorname{div}\ \mathbf{v}], i = 1,2,\ldots,N.$$

Throughout this paper, we follow this same notational convention and use bold script to denote vectors and product spaces. The viscosity coefficients μ, λ are assumed to be constant satisfying the following thermodynamic restrictions: $\mu > 0$, $\lambda + \mu \geqslant 0$ and the constants $a > 0$, $\gamma > 1$.

Keywords and phrases. Optimal control, linearized compressible Navier–Stokes equations, boundary control, optimality system.

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Numerical Solution Of The Incomprebible Navierstokes Equations Vol 113

Mohamed M Hafez,Koichhi Oshima

Numerical Solution Of The Incomprebible Navierstokes Equations Vol 113:

Projection and Quasi-Compressibility Methods for Solving the Incompressible Navier-Stokes Equations ,2013-11-11 Projection methods had been introduced in the late sixties by A Chorin and R Teman to decouple the computation of velocity and pressure within the time stepping for solving the nonstationary Navier Stokes equations Despite the good performance of projection methods in practical computations their success remained somewhat mysterious as the operator splitting implicitly introduces a nonphysical boundary condition for the pressure The objectives of this monograph are twofold First a rigorous error analysis is presented for existing projection methods by means of relating them to so called quasi compressibility methods e g penalty method pressure stabilzation method etc This approach highlights the intrinsic error mechanisms of these schemes and explains the reasons for their limitations Then in the second part more sophisticated new schemes are constructed and analyzed which are exempted from most of the deficiencies of the classical projection and quasi compressibility methods this book should be mandatory reading for applied mathematicians specializing in computational fluid dynamics J L Guermond Mathematical Reviews Ann Arbor **Incompressible Flow** Ronald L. Panton,2024-01-31 Incompressible Flow The latest edition of the classic introduction to fluid dynamics This textbook offers a detailed study of fluid dynamics Equal emphasis is given to physical concepts mathematical methods and illustrative flow patterns The book begins with a precise and careful formulation of physical concepts followed by derivations of the laws governing the motion of an arbitrary fluid the Navier Stokes equations Throughout there is an emphasis on scaling variables and dimensional analysis Incompressible flow is presented as an asymptotic expansion of solutions to the Navier Stokes equations with low Mach numbers and arbitrary Reynolds numbers The different physical behaviors of flows with low medium and high Reynolds number are thoroughly investigated Additionally several special introductory chapters are provided on lubrication theory flow stability and turbulence In the Fifth Edition a chapter on gas dynamics has been added Gas dynamics is presented as Navier Stokes solutions for high Reynolds Number at arbitrary Mach number with a perfect gas as the fluid The existence of several excellent and free compressible flow calculators on the internet has been used in the presentation and the homework With this chapter the textbook becomes a survey of the entire field of fluid dynamics Readers of the Fifth Edition of Incompressible Flow will also find New content treating wind turbines Examples and end of chapter problems to reinforce learning MATLAB codes available for download Incompressible Flow is ideal for undergraduate and graduate students in advanced fluid mechanics classes and for any engineer or researcher studying fluid dynamics or related subjects **Computational Fluid Dynamics Review 1998 (In 2 Volumes)** Mohamed M Hafez,Koichhi Oshima,1998-11-20 The first volume of CFD Review was published in 1995 The purpose of this new publication is to present comprehensive surveys and review articles which provide up to date information about recent progress in computational fluid dynamics on a regular basis Because of the multidisciplinary nature of CFD it is difficult to cope with all the important

developments in related areas There are at least ten regular international conferences dealing with different aspects of CFD It is a real challenge to keep up with all these activities and to be aware of essential and fundamental contributions in these areas It is hoped that CFD Review will help in this regard by covering the state of the art in this field The present book contains sixty two articles written by authors from the US Europe Japan and China covering the main aspects of CFD There are five sections general topics numerical methods flow physics interdisciplinary applications parallel computation and flow visualization The section on numerical methods includes grids schemes and solvers while that on flow physics includes incompressible and compressible flows hypersonics and gas kinetics as well as transition and turbulence This book should be useful to all researchers in this fast developing field **Finite Element Methods for Flow Problems** Jean Donea,Antonio Huerta,2003-06-02 In recent years there have been significant developments in the development of stable and accurate finite element procedures for the numerical approximation of a wide range of fluid mechanics problems Taking an engineering rather than a mathematical bias this valuable reference resource details the fundamentals of stabilised finite element methods for the analysis of steady and time dependent fluid dynamics problems Organised into six chapters this text combines theoretical aspects and practical applications and offers coverage of the latest research in several areas of computational fluid dynamics Coverage includes new and advanced topics unavailable elsewhere in book form Collection in one volume of the widely dispersed literature reporting recent progress in this field Addresses the key problems and offers modern practical solutions Due to the balance between the concise explanation of the theory and the detailed description of modern practical applications this text is suitable for a wide audience including academics research centres and government agencies in aerospace automotive and environmental engineering Mathematical Aspects of Discontinuous Galerkin Methods Daniele Antonio Di Pietro,Alexandre Ern,2011-11-03 This book introduces the basic ideas to build discontinuous Galerkin methods and at the same time incorporates several recent mathematical developments The presentation is to a large extent self contained and is intended for graduate students and researchers in numerical analysis The material covers a wide range of model problems both steady and unsteady elaborating from advection reaction and diffusion problems up to the Navier Stokes equations and Friedrichs systems Both finite element and finite volume viewpoints are exploited to convey the main ideas underlying the design of the approximation The analysis is presented in a rigorous mathematical setting where discrete counterparts of the key properties of the continuous problem are identified The framework encompasses fairly general meshes regarding element shapes and hanging nodes Salient implementation issues are also addressed

High Performance Computing for Computational Science - VECPAR 2004 Michel Daydé,2005-04-28 This book constitutes the thoroughly refereed post proceedings of the 6th International Conference on High Performance Computing for Computational Science VECPAR 2004 held in Valencia Spain in June 2004 The 48 revised full papers presented together with 5 invited papers were carefully selected during two rounds of reviewing and improvement from initially 130 contributions

The papers are organized in topical sections on large scale computations data management and data mining GRID computing infrastructure cluster computing parallel and distributed computing and computational linear and non linear algebra

Thermal Convection Marcello Lappa,2009-11-05 Thermal Convection Patterns Stages of Evolution and Stability Behavior provides the reader with an ensemble picture of the subject illustrating the state of the art and providing the researchers from universities and industry with a basis on which they are able to estimate the possible impact of a variety of parameters Unlike earlier books on the subject the heavy mathematical background underlying and governing the behaviors illustrated in the text are kept to a minimum The text clarifies some still unresolved controversies pertaining to the physical nature of the dominating driving force responsible for asymmetric oscillatory convection in various natural phenomena and or technologically important processes and can help researchers in elaborating and validating new more complex models in accelerating the current trend towards predictable and reproducible natural phenomena and in establishing an adequate scientific foundation to industrial processes Thermal Convection Patterns Stages of Evolution and Stability Behavior is intended as a useful reference guide for specialists in disciplines such as the metallurgy and foundry field and researchers and scientists who are now coordinating their efforts to improve the quality of semiconductor or macromolecular crystals The text may also be of use to organic chemists and materials scientists atmosphere and planetary physicists as well as an advanced level text for students taking part in courses on the physics of fluids fluid mechanics the behavior and evolution of non linear systems environmental phenomena and materials engineering *Flow Simulation with High-Performance Computers II* Ernst Heinrich Hirschel,2013-04-17 Der Band enth lt den Abschlu bericht des DFG Schwerpunktprogramms Flu simulation mit H chstleistungsrechnern Es f hrt die Arbeiten fort die schon als Band 38 in der Reihe Notes on Numerical Fluid Mechanics erschienen sind Work is reported which was sponsored by the Deutsche Forschungsgemeinschaft from 1993 to 1995 Scientists from numerical mathematics fluid mechanics aerodynamics and turbomachinery present their work on flow simulation with massively parallel systems on the direct and large eddy simulation of turbulence and on mathematical foundations general solution techniques and applications Results are reported from benchmark computations of laminar flow around a cylinder in which seventeen groups participated Riemann Solvers and Numerical Methods for Fluid Dynamics Eleuterio F. Toro,2013-04-17 High resolution upwind and centered methods are today a mature generation of computational techniques applicable to a wide range of engineering and scientific disciplines Computational Fluid Dynamics CFD being the most prominent up to now This textbook gives a comprehensive coherent and practical presentation of this class of techniques The book is designed to provide readers with an understanding of the basic concepts some of the underlying theory the ability to critically use the current research papers on the subject and above all with the required information for the practical implementation of the methods Applications include compressible steady unsteady reactive viscous non viscous and free surface flows TILDA: Towards Industrial LES/DNS in Aeronautics Charles Hirsch,Koen Hillewaert,Ralf

Hartmann,Vincent Couaillier,Jean-Francois Boussuge,Frederic Chalot,Sergey Bosniakov,Werner Haase,2021-06-28 This book offers detailed insights into new methods for high fidelity CFD and their industrially relevant applications in aeronautics It reports on the H2020 TILDA project funded by the European Union in 2015 2018 The respective chapters demonstrate the potential of high order methods for enabling more accurate predictions of non linear unsteady flows ensuring enhanced reliability in CFD predictions The book highlights industrially relevant findings and representative test cases on the development of high order methods for unsteady turbulence simulations on unstructured grids on the development of the LES DNS methodology by means of multilevel adaptive fractal and similar approaches for applications on unstructured grids and on leveraging existent large scale HPC networks to facilitate the industrial applications of LES DNS in daily practice Furthermore the book discusses multidisciplinary applications of high order methods in the area of aero acoustics All in all it offers timely insights into the application and performance of high order methods for CFD and an extensive reference guide for researchers graduate students and industrial engineers whose work involves CFD and turbulence modeling Nonlinear Dynamics and Applications Santo Banerjee,Asit Saha,2022-10-06 This book covers recent trends and applications of nonlinear dynamics in various branches of society science and engineering The selected peer reviewed contributions were presented at the International Conference on Nonlinear Dynamics and Applications ICNDA 2022 at Sikkim Manipal Institute of Technology SMIT and cover a broad swath of topics ranging from chaos theory and fractals to quantum systems and the dynamics of the COVID 19 pandemic Organized by the SMIT Department of Mathematics this international conference offers an interdisciplinary stage for scientists researchers and inventors to present and discuss the latest innovations and trends in all possible areas of nonlinear dynamics *Recent Advances in Scientific Computing and Applications* Jichun Li,Hongtao Yang,Eric Alexander Machorro,2013-04-24 This volume contains the proceedings of the Eighth International Conference on Scientific Computing and Applications held April 1 4 2012 at the University of Nevada Las Vegas The papers in this volume cover topics such as finite element methods multiscale methods finite difference methods spectral methods collocation methods adaptive methods parallel computing linear solvers applications to fluid flow nano optics biofilms finance magnetohydrodynamics flow electromagnetic waves the fluid structure interaction problem and stochastic PDEs This book will serve as an excellent reference for graduate students and researchers interested in scientific computing and its applications Technology 2001 ,1991 **Applied Mechanics Reviews** ,1979 **New Sinc Methods of Numerical Analysis** Gerd Baumann,2021-04-23 This contributed volume honors the 80th birthday of Frank Stenger who established new Sinc methods in numerical analysis The contributions written independently from each other show the new developments in numerical analysis in connection with Sinc methods and approximations of solutions for differential equations boundary value problems integral equations integrals linear transforms eigenvalue problems polynomial approximations computations on polyhedra and many applications The approximation methods are exponentially converging

compared with standard methods and save resources in computation They are applicable in many fields of science including mathematics physics and engineering The ideas discussed serve as a starting point in many different directions in numerical analysis research and applications which will lead to new and unprecedented results This book will appeal to a wide readership from students to specialized experts **Scientific Computing and Applications** Peter Minev,Yanping Lin,2001 Scientific Computing Applications **A Structured-grid Adaptive Mesh Refinement Multigrid Algorithm for Steady-state Flows** Scott Andrew Dudek,1996 Handbook of Fluid Dynamics Richard W. Johnson,2016-04-06 Handbook of Fluid Dynamics offers balanced coverage of the three traditional areas of fluid dynamics theoretical computational and experimental complete with valuable appendices presenting the mathematics of fluid dynamics tables of dimensionless numbers and tables of the properties of gases and vapors Each chapter introduces a different fluid dynamics topic discusses the pertinent issues outlines proven techniques for addressing those issues and supplies useful references for further research Covering all major aspects of classical and modern fluid dynamics this fully updated Second Edition Reflects the latest fluid dynamics research and engineering applications Includes new sections on emerging fields most notably micro and nanofluidics Surveys the range of numerical and computational methods used in fluid dynamics analysis and design Expands the scope of a number of contemporary topics by incorporating new experimental methods more numerical approaches and additional areas for the application of fluid dynamics Handbook of Fluid Dynamics Second Edition provides an indispensable resource for professionals entering the field of fluid dynamics The book also enables experts specialized in areas outside fluid dynamics to become familiar with the field **Fundamental Directions in Mathematical Fluid Mechanics** Giovanni P. Galdi,John G. Heywood,Rolf Rannacher,2012-12-06 This volume consists of six articles each treating an important topic in the theory ofthe Navier Stokes equations at the research level Some of the articles are mainly expository putting together in a unified setting the results of recent research papers and conference lectures Several other articles are devoted mainly to new results but present them within a wider context and with a fuller exposition than is usual for journals The plan to publish these articles as a book began with the lecture notes for the short courses of G P Galdi and R Rannacher given at the beginning of the International Workshop on Theoretical and Numerical Fluid Dynamics held in Vancouver Canada July 27 to August 2 1996 A renewed energy for this project came with the founding of the Journal of Mathematical Fluid Mechanics by G P Galdi J Heywood and R Rannacher in 1998 At that time it was decided that this volume should be published in association with the journal and expanded to include articles by J Heywood and W Nagata J Heywood and M Padula and P Gervasio A Quarteroni and F Saleri The original lecture notes were also revised and updated **Viscous Flow Applications** Carlos A. Brebbia,2013-03-12 The Boundary Element Method has now become a powerful tool of engineering analysis and is routinely applied for the solution of elastostatics and potential problems More recently research has concentrated on solving a large variety of non linear and time dependent applications and in particular the method has been developed for viscous fluid flow

problems This book presents the state of the art on the solution of viscous flow using boundary elements and discusses different current approaches which have been validated by numerical experiments Chapter 1 of the book presents a brief review of previous work on viscous flow simulation and in particular gives an up to date list of the most important BEM references in the field Chapter 2 reviews the governing equations for general viscous flow including compressibility The authors present a compre hensive treatment of the different cases and their formulation in terms of boundary integral equations This work has been the result of collaboration between Computational Mechanics Institute of Southampton and Massa chusetts Institute of Technology researchers Chapter 3 describes the gen eralized formulation for unsteady viscous flow problems developed over many years at Georgia Institute of Technology This formulation has been extensively applied to solve aer09ynamic problems

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