ANALYSIS OF FULLY DISCRETE FINITE ELEMENT METHODS FOR 2D NAVIER–STOKES EQUATIONS WITH CRITICAL INITIAL DATA

BUYANG LI, SHU MA, AND YUKI UEDA

ABSTRACT. First-order convergence in time and space is proved for a fully discrete semi-implicit finite element method for the two-dimensional Navier–Stokes equations with L^2 initial data in convex polygonal domains, without extra regularity assumptions or grid-ratio conditions. The proof utilises the smoothing properties of the Navier–Stokes equations in the analysis of the consistency errors, an appropriate duality argument, and the smallness of the numerical solution in the discrete $L^2(0, t_m; H^1)$ norm when t_m is smaller than some constant. Numerical examples are provided to support the theoretical analysis.

1. Introduction

We consider the initial and boundary value problem of the incompressible Navier–Stokes (NS) equations

$$\begin{cases} \partial_t u + u \cdot \nabla u - \Delta u + \nabla p = 0 & \text{in } \Omega \times (0, T], \\ \nabla \cdot u = 0 & \text{in } \Omega \times (0, T], \\ u = 0 & \text{on } \partial\Omega \times (0, T], \\ u = u^0 & \text{at } \Omega \times \{0\}, \end{cases} \qquad (1.1)$$

in a convex polygon $\Omega \subset \mathbb{R}^2$ with boundary $\partial\Omega$, up to a given time $T > 0$. It is known that for any given initial value

$$u^0 \in \mathring{L}^2 = \{v \in L^2(\Omega)^2 : \nabla \cdot v = 0 \text{ and } v \cdot \nu = 0 \text{ on } \partial\Omega\}$$

(where ν denotes the unit normal vector on $\partial\Omega$), problem (1.1) has a unique weak solution $u \in L^2(0, T; \mathring{H}^1_0) \cap H^1(0, T; \mathring{H}^{-1}) \hookrightarrow C([0, T]; \mathring{L}^2)$, where

$$\mathring{H}^1_0 = \{v \in H^1_0(\Omega)^2 : \nabla \cdot v = 0\} \quad \text{and} \quad \mathring{H}^{-1} \text{ denotes the dual space of } \mathring{H}^1_0;$$

see [45, Theorem 3.2 of Chapter 3].

Stability and convergence of the numerical solution to the NS equations (1.1) were studied based on different regularity assumptions on the solution and initial data. In particular, if the initial data are sufficiently smooth, i.e. $u^0 \in \mathring{H}^1_0 \cap H^2(\Omega)^2$ or above, then the numerical solution was proved to be convergent with optimal order for finite element and spectral Galerkin methods with different time-stepping schemes, including the Crank–Nicolson method [24], the implicit-explicit Crank–Nicolson/Adams–Bashforth method [21, 34, 47], the semi-implicit Crank-Nicolson extrapolation method [5, 15, 27, 44], the stabilization methods based on the Crank–Nicolson method [12], the Crank–Nicolson extrapolation method [31], the backward Euler method [10] and the BDF2 method [32], the projection methods [1, 41, 42], the projection-based variational multiscale methods based on the Crank-Nicolson method [40], the fractional-step methods [4], the three-step implicit-explicit backward extrapolating scheme [6, 48], the backward differentiation formulae [3, 7, 9], a second order energy- and helicity-preserving method [36], the implicit-explicit Euler method [34], and the implicit Euler methods with different spatial discretizations [8, 9, 14, 28]. The error estimates in the above-mentioned articles do not apply to nonsmooth initial data.

Finite Element Methods And Navierstokes Equations

François Thomasset

Finite Element Methods And Navierstokes Equations:

Finite Element Methods for Navier-Stokes Equations Vivette Girault,Pierre-Arnaud Raviart,2012-12-06 The material covered by this book has been taught by one of the authors in a post graduate course on Numerical Analysis at the University Pierre et Marie Curie of Paris It is an extended version of a previous text cf Girault Raviart 32J published in 1979 by Springer Verlag in its series Lecture Notes in Mathematics In the last decade many engineers and mathematicians have concentrated their efforts on the finite element solution of the Navier Stokes equations for incompressible flows The purpose of this book is to provide a fairly comprehen sive treatment of the most recent developments in that field To stay within reasonable bounds we have restricted ourselves to the case of stationary prob lems although the time dependent problems are of fundamental importance This topic is currently evolving rapidly and we feel that it deserves to be covered by another specialized monograph We have tried to the best of our ability to present a fairly exhaustive treatment of the finite element methods for inner flows On the other hand however we have entirely left out the subject of exterior problems which involve radically different techniques both from a theoretical and from a practical point of view Also we have neither discussed the implemen tation of the finite element methods presented by this book nor given any explicit numerical result This field is extensively covered by Peyret Taylor 64J and Thomasset 82   **Finite Element Methods and Navier-Stokes Equations** C. Cuvelier,A. Segal,A.A. van Steenhoven,2001-12-14 In present day technology the engineer is faced with complicated problems which can be solved only by advanced numerical methods using digital computers He should have mathematical models at his disposal in order to simulate the behavior of physical systems In many cases including problems in physics mechanics chemistry biology civil engineering electrodynamics solid mechanics space engineering petroleum engineering weather forecasting mass transport multiphase flow and last but not least hydrodynamics such a physical system can be described mathematically by one or more partial differential equations Some of these problems require extreme accuracy while for other problems only the qualitative behavior of the solution need to be studied The finite element method FEM is one of the most commonly used methods for solving partial differential equations PDEs It makes use of the computer and is very general in the sense that it can be applied to both steady state and transient linear and nonlinear problems in geometries of arbitrary space dimension The FEM is in fact a method which transforms a PDE into a system of linear algebraic equations The following aspects may be identified in the study of a physical phenomenon i engineering mathematical sciences to formulate the problem correctly in terms of PDEs ii numerical methods to construct and to solve the system of algebraic equations applied numerical functional analysis to give error estimates and convergence proofs iii informatics and programming to perform the calculations efficiently on the computer   **Finite Element Methods and Navier-Stokes Equations** Cornelis Cuvelier,August Segal,Anton A. Steenhoven,1986   *Implementation of Finite Element Methods for Navier-Stokes Equations* F. Thomasset,2012-12-06 In structure mechanics analysis finite element methods are now well estab lished and well

documented techniques their advantage lies in a higher flexibility in particular for i The representation of arbitrary complicated boundaries ii Systematic rules for the developments of stable numerical schemes ap proximating mathematically wellposed problems with various types of boundary conditions On the other hand compared to finite difference methods this flexibility is paid by an increased programming complexity additional storage require ment The application of finite element methods to fluid mechanics has been lagging behind and is relatively recent for several types of reasons i Historical reasons the early methods were invented by engineers for the analysis of torsion flexion deformation of bearns plates shells etc see the historics in Strang and Fix 1972 or Zienckiewicz 1977 ii Technical reasons fluid flow problems present specific difficulties strong gradients l of the velocity or temperature for instance may occur which a finite mesh is unable to properly represent a remedy lies in the various upwind finite element schemes which recently turned up and which are reviewed in chapter 2 yet their effect is just as controversial as in finite differences Next waves can propagate e g in ocean dynamics with shallowwaters equations which will be falsely distorted by a finite non regular mesh as Kreiss 1979 pointed out We are concerned in this course with the approximation of incompressible viscous Newtonian fluids i e governed by N avier Stokes equations   Implementation of Finite Element Methods for Navier-Stokes Equations François Thomasset,1981   **Finite Element Methods for Navier-Stokes Equations** Vivette Girault,Pierre-Arnaud Raviart,1986-05-01   **Finite Element Methods and Navier-Stokes Equations** C. Cuvelier,A. Segal,A.A. van Steenhoven,1986-03-31   *Finite Element Methods for Incompressible Flow Problems* Volker John,2016-10-27 This book explores finite element methods for incompressible flow problems Stokes equations stationary Navier Stokes equations and time dependent Navier Stokes equations It focuses on numerical analysis but also discusses the practical use of these methods and includes numerical illustrations It also provides a comprehensive overview of analytical results for turbulence models The proofs are presented step by step allowing readers to more easily understand the analytical techniques   **Finite Element Approximation of the Navier-Stokes Equations** Vivette Girault,P. A. Raviart,2014-09-01   **Finite Volume Methods for the Incompressible Navier–Stokes Equations** Jian Li,Xiaolin Lin,Zhangxing Chen,2022-01-20 The book aims to provide a comprehensive understanding of the most recent developments in finite volume methods Its focus is on the development and analysis of these methods for the two and three dimensional Navier Stokes equations supported by extensive numerical results It covers the most used lower order finite element pairs with well posedness and optimal analysis for these finite volume methods The authors have attempted to make this book self contained by offering complete proofs and theoretical results While most of the material presented has been taught by the authors in a number of institutions over the past several years they also include several updated theoretical results for the finite volume methods for the incompressible Navier Stokes equations This book is primarily developed to address research needs for students and academic and industrial researchers It is particularly valuable as a research reference in the fields of engineering mathematics physics and computer sciences   **A Control-volume Finite-element**

Method for Navier-Stokes Equations Hsiao-Wen Lin,1989   Mathematics and Finite Element Discretizations of Incompressible Navier–Stokes Flows Christine Bernardi ,Vivette Girault,Pierre-Arnaud Raviart ,Beatrice Riviere,2024-12-26 Navier Stokes equations are one of the most impactful techniques for modeling physical flow phenomena The coupling of velocity and pressure along with the nonlinearity is a challenge for the mathematical and numerical analysis of these equations This self contained book provides a thorough theoretical study of finite element methods for solving incompressible Navier Stokes equations which model ow of incompressible Newtonian uids and are used in many practical applications It focuses on efficient and widely used finite element methods that are well adapted to large scale simulations In this revised and expanded edition of Girault and Raviart s 1986 textbook Finite Element Methods for Navier Stokes Equations Springer Verlag readers will find rigorous proof of stability and convergence analysis of practical algorithms and a stand alone chapter on finite element methods that is applicable to a large range of PDEs In addition to the basic theoretical analysis this book covers up to date finite element discretizations of incompressible Navier Stokes equations a variety of numerical algorithms used in the computer implementation of Navier Stokes equations and numerical experiments standard and nonstandard boundary conditions and their numerical discretizations via the finite element methods and conforming and nonconforming finite elements as well as their stability and instability This book is intended for applied mathematicians and graduate students interested in learning about the theory of various finite element methods for solving the Navier Stokes equations Engineers seeking reliable algorithms for computational fluid dynamics will also find the book of interest   **Advances In Numerical Heat Transfer** W. Minkowycz,1996-11-01 This is the first volume in the series It analyzes several fundamental methodology issues in numerical heat transfer and fluid flow and identifies certain areas of active application The finite volume approach is presented with the finite element methods as well as with energy balance analysis Applications include the latest development in turbulence modeling and current approaches to inverse problems   Finite Element Approximation of the Navier-Stokes Equations Vivette Girault,P.-A. Raviart,2006-11-15 Principles of Airway Management is the leading text on the essentials of airway management First published in 1988 and now in its Fourth Edition it remains the text of choice for clinicians and trainees across a range of specialties anesthesiology emergency medicine critical care medicine surgery and acute care medicine who confront the issue of airway management Highlights Step by step guidance on airway management More than 400 illustrations tables and boxes many now in color New chapter on innovations in airway equipment New chapter on extubation strategies Major update on the pediatric airway The latest on equipment techniques surgical approaches and the Laryngeal Mask Airway Comprehensive coverage of complications Well referenced with suggestions for additional reading Thorough coverage of applied anatomy From the reviews of the Third Edition Airway texts tend to fall into one of two extremes the oversimplified handbook or the comprehensive text that can be overburdening to read Principles of Airway Management is a superb bridge of these two worlds Anesthesia Analgesia Covers well the basic

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