

A Fast Chebyshev Spectral Method for Nonlinear Fourier Transform

Vishal Vaibhav

Abstract—In this letter, we present a fast and well-conditioned spectral method based on the Chebyshev polynomials for computing the continuous part of the nonlinear Fourier spectrum. The algorithm achieves a complexity of $\mathcal{O}(N_{\text{iter}} N \log N)$ per spectral node for N samples of the signal at the Chebyshev nodes where N_{iter} is the number of iterations of the biconjugate gradient stabilized method.

I. INTRODUCTION

This paper considers the Zakharov and Shabat (ZS) [1] scattering problem which forms the basis for defining a nonlinear generalization of the conventional Fourier transform dubbed as the *nonlinear Fourier transform* (NFT). In an optical fiber communication system the nonlinear Fourier (NF) spectrum offers a novel way of encoding information in optical pulses where the nonlinear effects are adequately taken into account as opposed to being treated as a source of signal distortion [2], [3]. One of the challenges that has emerged in realizing these ideas is the development of a fast and well-conditioned NFT algorithm that can offer spectral accuracy at low complexity. Such an algorithm would prove extremely useful for system design and benchmarking. Currently, there are primarily two successful approaches proposed in the literature for computing the continuous NF spectrum which are capable of achieving algebraic orders convergence at quasilinear complexity: (a) the integrating factor (IF) based exponential integrators [4]–[7] (b) exponential time differencing (ETD) method based exponential integrators [8]. Note that while the IF schemes uses fast polynomial arithmetic in the monomial basis, the ETD schemes use fast polynomial arithmetic in the Chebyshev basis. For the inverse transforms, a sampling series based approach for computing the “radiative” part has been proposed in [9] which achieves spectral accuracy at quasilinear complexity per sample of the signal. In this paper, we propose a spectral method for direct NFT that achieves quasilinear complexity per sample of the continuous spectrum. The signal in this case must be sampled at the so-called Chebyshev–Gauss–Lobatto nodes.

Introducing the “local” scattering coefficients $a(r; \xi)$ and $b(r; \xi)$ such that $\Phi(r; \xi) = (a(r; \xi)e^{-iG\xi}, b(r; \xi)e^{iG\xi})^T$, the ZS scattering problem can be written as $\partial_r a(r; \xi) = q(r)b(r; \xi)e^{2iG\xi}$ and $\partial_r b(r; \xi) = r(r)a(r; \xi)e^{-2iG\xi}$. Let the scattering potential $q(r)$ (with $r(r) = \alpha q^*(r)$ where $\alpha \in \{+1, -1\}$) be supported in $I = [-1, 1]$. Specializing to the real line $\xi = \xi \in \mathbb{R}$, the initial conditions for the *lost* solution Φ are: $a(-1; \xi) = 1$ and $b(-1; \xi) = 0$. The scattering coefficients a and b are given by $a(\xi) = a(+1; \xi)$ and $b(\xi) = b(+1; \xi)$ so that the

reflection coefficients is $\rho = b/a$. Let $g(r; \xi) = q(r)e^{-2iG\xi}$ and $h(r; \xi) = \alpha g^*(r; \xi)$. In the following, we describe a numerical scheme based on the Chebyshev polynomials to solve the coupled Volterra integral equations given by

$$a(r) = 1 + \int_{-1}^r g(s)b(s)ds, \quad b(r) = \int_{-1}^r h(s)a(s)ds, \quad (1)$$

derived from the ZS problem using the aforementioned initial conditions where the dependence on ξ is suppressed for the sake of brevity of presentation. We refer the reader to [10] for the nonlinear Fourier analysis of time-limited signals.

II. THE NUMERICAL SCHEME

In this section, we describe the numerical scheme and carry out the theoretical analysis of its convergence and stability. Let us set the following notations: $\mathbb{N} = \{1, 2, \dots\}$ and $\mathbb{N}_0 = \{0\} \cup \mathbb{N}$ (the set of whole numbers), ℓ^p ($1 \leq p \leq \infty$) denotes the discrete Lebesgue spaces with norm $\|\mathbf{C}\|_p = (\sum_{n=0}^{\infty} |C_n|^p)^{1/p}$, $1 \leq p < \infty$, and $\|\mathbf{C}\|_{\infty} = \sup\{C_0, C_1, \dots\}$.

The first step is to obtain a discrete representation of an integral operator in the Chebyshev basis using the relations

$$\begin{aligned} \int_{-1}^r T_0(s)ds &= T_1(r) + T_0(r), & \int_{-1}^r T_1(s)ds &= \frac{T_2(r)}{4} - \frac{T_0(r)}{4}, \\ \int_{-1}^r T_n(s)ds &= \frac{T_{n+1}(r)}{2(n+1)} - \frac{T_{n-1}(r)}{2(n-1)} - \frac{(-1)^n T_0(r)}{n^2 - 1}, & n > 1. \end{aligned}$$

Let $c(r) = \sum_{n=0}^{\infty} C_n T_n(r)$ and $d(r) = \mathcal{K}[c](r)$ where $\mathcal{K}[c](r) = \int_{-1}^r c(s)ds$, we have

$$\begin{aligned} d(r) &= \left[C_0 - \frac{1}{4}C_1 - \sum_{n=2}^{\infty} \frac{(-1)^n C_n}{n^2 - 1} \right] T_0(r) \\ &\quad + \left[C_0 - \frac{1}{2}C_2 \right] T_1(r) + \sum_{n=2}^{\infty} \frac{1}{2n} [C_{n-1} - C_{n+1}] T_n(r). \end{aligned} \quad (2)$$

Now setting $d(r) = \sum_{n=0}^{\infty} D_n T_n(r)$, and, introducing the infinite dimensional vectors $\mathbf{C} = (C_0, C_1, \dots)^T$ and $\mathbf{D} = (D_0, D_1, \dots)^T$, we have

$$\mathbf{D} = \begin{pmatrix} 1 & -\frac{1}{4} & -\frac{1}{12} & +\frac{1}{8} & -\frac{1}{15} & \dots \\ 1 & 0 & -\frac{1}{4} & -\frac{1}{8} & \dots \\ & \frac{1}{2} & 0 & -\frac{1}{4} & -\frac{1}{8} & \dots \\ & & \frac{1}{8} & 0 & -\frac{1}{8} & \dots \\ & & & \ddots & \ddots & \ddots \end{pmatrix} \mathbf{C} = \mathcal{K}\mathbf{C}. \quad (3)$$

The next step in the discretization of (1) involves expanding the scattering potentials in the Chebyshev basis. Let $g(r) = \sum_{n=0}^{\infty} G_n T_n(r)$ and $h(r) = \sum_{n=0}^{\infty} H_n T_n(r)$ where $H_n = \alpha G_n^*$. A truncated expansion upto N terms can be accomplished

Chebyshev And Fourier Spectral Methods Chebyshev And Fourier Spectral Methods

David Gottlieb, Steven A. Orszag



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Partial Differential Equations with Numerical Methods Stig Larsson, Vidar Thomee, 2008-12-05 The main theme is the integration of the theory of linear PDE and the theory of finite difference and finite element methods For each type of PDE elliptic parabolic and hyperbolic the text contains one chapter on the mathematical theory of the differential equation followed by one chapter on finite difference methods and one on finite element methods The chapters on elliptic equations are preceded by a chapter on the two point boundary value problem for ordinary differential equations Similarly the chapters on time dependent problems are preceded by a chapter on the initial value problem for ordinary differential equations There is also one chapter on the elliptic eigenvalue problem and eigenfunction expansion The presentation does not presume a deep knowledge of mathematical and functional analysis The required background on linear functional analysis and Sobolev spaces is reviewed in an appendix The book is suitable for advanced undergraduate and beginning graduate students of applied mathematics and engineering

Spectral Methods for Incompressible Viscous Flow Roger Peyret, 2013-03-09 The objective of this book is to provide a comprehensive discussion of Fourier and Chebyshev spectral methods for the computation of incompressible viscous flows based on the Navier Stokes equations and confidence in the numerical results the re For reasons of efficiency searchers and practitioners involved in computational fluid dynamics must be able to master

the numerical methods they use Therefore in writing this book beyond the description of the algorithms I have also tried to provide information on the mathematical and computational as well as implementational characteristics of the methods The book contains three parts The first is intended to present the fundamentals of the Fourier and Chebyshev methods for the solution of differential problems The second part is entirely devoted to the solution of the Navier Stokes equations considered in vorticity streamfunction and velocity pressure formulations The third part is concerned with the solution of stiff and singular problems and with the domain decomposition method In writing this book I owe a great debt to the joint contribution of several people to whom I wish to express my deep gratitude First I express my friendly thanks to L Sirovich editor of the series Applied Mathematical Sciences who suggested that I write the book Many thanks are also addressed to my colleagues and former students who contributed to the completion of the book in various ways I am happy to thank P Bontoux O Botella J A Desideri U Ehrenstein M Y Forestier J Frohlich S

Spectral Methods Using Multivariate Polynomials On The Unit Ball Kendall Atkinson, David Chien, Olaf Hansen, 2019-11-11 Spectral Methods Using Multivariate Polynomials on the Unit Ball is a research level text on a numerical method for the solution of partial differential equations The authors introduce illustrate with examples and analyze spectral methods that are based on multivariate polynomial approximations The method presented is an alternative to finite element and difference methods for regions that are diffeomorphic to the unit disk in two dimensions and the unit ball in three dimensions The speed of convergence of spectral methods is usually much higher than that of finite element or finite difference methods Features Introduces the use of multivariate polynomials for the construction and analysis of spectral methods for linear and nonlinear boundary value problems Suitable for researchers and students in numerical analysis of PDEs along with anyone interested in applying this method to a particular physical problem One of the few texts to address this area using multivariate orthogonal polynomials rather than tensor products of univariate polynomials

Spectral Methods for Time-Dependent Problems Jan S. Hesthaven, Sigal Gottlieb, David Gottlieb, 2007-01-11 Spectral methods are well suited to solve problems modeled by time dependent partial differential equations they are fast efficient and accurate and widely used by mathematicians and practitioners This class tested 2007 introduction the first on the subject is ideal for graduate courses or self study The authors describe the basic theory of spectral methods allowing the reader to understand the techniques through numerous examples as well as more rigorous developments They provide a detailed treatment of methods based on Fourier expansions and orthogonal polynomials including discussions of stability boundary conditions filtering and the extension from the linear to the nonlinear situation Computational solution techniques for integration in time are dealt with by Runge Kutta type methods Several chapters are devoted to material not previously covered in book form including stability theory for polynomial methods techniques for problems with discontinuous solutions round off errors and the formulation of spectral methods on general grids These will be especially helpful for practitioners

A Practical Guide to Pseudospectral

Methods Bengt Fornberg,1998-10-28 This book explains how when and why the pseudospectral approach works

Spectral Methods Jie Shen,Tao Tang,Li-Lian Wang,2011-08-25 Along with finite differences and finite elements spectral methods are one of the three main methodologies for solving partial differential equations on computers This book provides a detailed presentation of basic spectral algorithms as well as a systematical presentation of basic convergence theory and error analysis for spectral methods Readers of this book will be exposed to a unified framework for designing and analyzing spectral algorithms for a variety of problems including in particular high order differential equations and problems in unbounded domains The book contains a large number of figures which are designed to illustrate various concepts stressed in the book A set of basic matlab codes has been made available online to help the readers to develop their own spectral codes for their specific applications

Numerical Analysis of Spectral Methods David Gottlieb,Steven A. Orszag,1977-01-01 A unified discussion of the formulation and analysis of special methods of mixed initial boundary value problems The focus is on the development of a new mathematical theory that explains why and how well spectral methods work Included are interesting extensions of the classical numerical analysis

Spectral Methods in MATLAB Lloyd N. Trefethen,2000-01-01 This is the only book on spectral methods built around MATLAB programs Along with finite differences and finite elements spectral methods are one of the three main technologies for solving partial differential equations on computers Since spectral methods involve significant linear algebra and graphics they are very suitable for the high level programming of MATLAB This hands on introduction is built around forty short and powerful MATLAB programs which the reader can download from the World Wide Web

Spectral and High Order Methods for Partial Differential Equations ICOSAHOM 2016

Marco L. Bittencourt,Ney A. Dumont,Jan S. Hesthaven,2017-11-07 This book features a selection of high quality papers chosen from the best presentations at the International Conference on Spectral and High Order Methods 2016 offering an overview of the depth and breadth of the activities within this important research area The carefully reviewed papers provide a snapshot of the state of the art while the extensive bibliography helps initiate new research directions

A Primer on Radial Basis Functions with Applications to the Geosciences Bengt Fornberg,Natasha Flyer,2015-09-30 Adapted from a series of lectures given by the authors this monograph focuses on radial basis functions RBFs a powerful numerical methodology for solving PDEs to high accuracy in any number of dimensions This method applies to problems across a wide range of PDEs arising in fluid mechanics wave motions astro and geosciences mathematical biology and other areas and has lately been shown to compete successfully against the very best previous approaches on some large benchmark problems Using examples and heuristic explanations to create a practical and intuitive perspective the authors address how when and why RBF based methods work The authors trace the algorithmic evolution of RBFs starting with brief introductions to finite difference FD and pseudospectral PS methods and following a logical progression to global RBFs and then to RBF generated FD RBF FD methods The RBF FD method conceived in 2000 has proven to be a leading candidate for numerical simulations

in an increasingly wide range of applications including seismic exploration for oil and gas weather and climate modeling and electromagnetics among others This is the first survey in book format of the RBF FD methodology and is suitable as the text for a one semester first year graduate class

Spectral Methods in Chemistry and Physics Bernard Shizgal, 2015-01-07

This book is a pedagogical presentation of the application of spectral and pseudospectral methods to kinetic theory and quantum mechanics There are additional applications to astrophysics engineering biology and many other fields The main objective of this book is to provide the basic concepts to enable the use of spectral and pseudospectral methods to solve problems in diverse fields of interest and to a wide audience While spectral methods are generally based on Fourier Series or Chebychev polynomials non classical polynomials and associated quadratures are used for many of the applications presented in the book Fourier series methods are summarized with a discussion of the resolution of the Gibbs phenomenon Classical and non classical quadratures are used for the evaluation of integrals in reaction dynamics including nuclear fusion radial integrals in density functional theory in elastic scattering theory and other applications The subject matter includes the calculation of transport coefficients in gases and other gas dynamical problems based on spectral and pseudospectral solutions of the Boltzmann equation Radiative transfer in astrophysics and atmospheric science and applications to space physics are discussed The relaxation of initial non equilibrium distributions to equilibrium for several different systems is studied with the Boltzmann and Fokker Planck equations The eigenvalue spectra of the linear operators in the Boltzmann Fokker Planck and Schrödinger equations are studied with spectral and pseudospectral methods based on non classical orthogonal polynomials The numerical methods referred to as the Discrete Ordinate Method Differential Quadrature the Quadrature Discretization Method the Discrete Variable Representation the Lagrange Mesh Method and others are discussed and compared MATLAB codes are provided for most of the numerical results reported in the book see [Link](#) under Additional Information on the the right hand column

Spectral Methods for Non-Standard Eigenvalue Problems Călin-Ioan Gheorghiu, 2014-04-22

This book focuses on the constructive and practical aspects of spectral methods It rigorously examines the most important qualities as well as drawbacks of spectral methods in the context of numerical methods devoted to solve non standard eigenvalue problems In addition the book also considers some nonlinear singularly perturbed boundary value problems along with eigenproblems obtained by their linearization around constant solutions The book is mathematical posing problems in their proper function spaces but its emphasis is on algorithms and practical difficulties The range of applications is quite large High order eigenvalue problems are frequently beset with numerical ill conditioning problems The book describes a wide variety of successful modifications to standard algorithms that greatly mitigate these problems In addition the book makes heavy use of the concept of pseudospectrum which is highly relevant to understanding when disaster is imminent in solving eigenvalue problems It also envisions two classes of applications the stability of some elastic structures and the hydrodynamic stability of some parallel shear flows This book is an ideal reference text for professionals

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