

# Adaptive boundary element methods with convergence rates

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## Abstract

This paper presents adaptive boundary element methods for positive, negative, as well as zero-order operator equations, together with proofs that they converge at certain rates. The convergence rates are quasi-optimal in a certain sense under mild assumptions that are analogous to what is typically assumed in the theory of adaptive finite element methods. In particular, no saturation-type assumption is used. The main ingredients of the proof that constitute new findings are some results on *a posteriori* error estimates for boundary element methods, and an inverse-type inequality involving boundary integral operators on locally refined finite element spaces.

## 1 Introduction

Let  $\Gamma$  be a (closed or open) polyhedral surface in  $\mathbb{R}^3$ . We consider equations of the form

$$Au = f, \quad (1)$$

where  $f \in H^{-t}(\Gamma)$ , and  $A : H^s(\Gamma) \rightarrow H^{-t}(\Gamma)$  is an invertible linear operator. Strictly speaking, the function spaces should be slightly modified if  $\Gamma$  is an open surface or  $t > 0$ , but for the sake of this introduction we will gloss over this point. The operators of interest are the *boundary integral operators* that arise from reformulations of boundary value problems as integral equations on the domain boundary, cf. McLean (2000). Then the problem (1) corresponds to a *boundary integral equation*, and a very popular class of methods for its numerical solution is *boundary element methods* (BEM), which can crudely be described as finite element methods (FEM) applied to boundary integral equations, cf. Sauter and Schwab (2011). As with finite elements, there is the adaptive version of BEM, whose main feature is to automatically distribute mesh points hopefully in an optimal way so as to obtain an accurate numerical solution. Even though these methods perform very well in practice, their mathematical theory is not in a very satisfactory state, especially if one compares it with the corresponding theory of adaptive FEM. In the latter context, the sequence of papers Dürfler (1996), Morin, Nochetto, and Siebert (2002), Einev, Dahmen, and DeVore (2004), Stevenson (2007), and Cascon, Kreuzer, Nochetto, and Siebert (2008)

# Adaptive Finite And Boundary Element Methods

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## **Adaptive Finite And Boundary Element Methods:**

**Adaptive Finite and Boundary Element Methods** C. A. Brebbia, M. H. Aliabadi, 1993 *Adaptive Finite Element Methods for Differential Equations* Wolfgang Bangerth, Rolf Rannacher, 2003-01-23 The key issues are a posteriori error estimation and its automatic mesh adaptation. Besides the traditional approach of energy norm error control, a new duality based technique, the Dual Weighted Residual method for goal oriented error estimation, is discussed in detail. This method aims at economical computation of arbitrary quantities of physical interest by properly adapting the computational mesh. This is typically required in the design cycles of technical applications. For example, the drag coefficient of a body immersed in a viscous flow is computed, then it is minimized by varying certain control parameters, and finally the stability of the resulting flow is investigated by solving an eigenvalue problem. Goal oriented adaptivity is designed to achieve these tasks with minimal cost. At the end of each chapter, some exercises are posed in order to assist the interested reader in better understanding the concepts presented. Solutions and accompanying remarks are given in the Appendix. *Error-controlled Adaptive Finite Elements in Solid Mechanics* Ekkehard Ramm, E. Rank, R. Rannacher, K. Schweizerhof, E. Stein, W. Wendland, G. Wittum, Peter Wriggers, Walter Wunderlich, 2003-08-01 Finite Element Methods are used for numerous engineering applications where numerical solutions of partial differential equations are needed. As computers can now deal with the millions of parameters used in these methods, automatic error estimation and automatic adaptation of the utilised method according to this error estimation has become a hot research topic. This text offers comprehensive coverage of this new field of automatic adaptation and error estimation, bringing together the work of eight outstanding researchers in this field who have completed a six year national research project within the German Science Foundation. The result is a state of the art work in true reference style. Each chapter is self contained and covers theoretical, algorithmic and software presentations as well as solved problems. A main feature consists of several carefully elaborated benchmarks of 2D and 3D applications. First book to go beyond the Finite Element Method in itself. Covers material from a new research area. Presents benchmarks of 2D and 3D applications. Fits with the new trend for genetic strategies in engineering. *Error-controlled Adaptive Finite Elements in Solid Mechanics* Ekkehard Ramm, E. Rank, R. Rannacher, K. Schweizerhof, E. Stein, W. Wendland, G. Wittum, Peter Wriggers, Walter Wunderlich, 2002-12-30 Finite Element Methods are used for numerous engineering applications where numerical solutions of partial differential equations are needed. As computers can now deal with the millions of parameters used in these methods, automatic error estimation and automatic adaptation of the utilised method according to this error estimation has become a hot research topic. This text offers comprehensive coverage of this new field of automatic adaptation and error estimation, bringing together the work of eight outstanding researchers in this field who have completed a six year national research project within the German Science Foundation. The result is a state of the art work in true reference style. Each chapter is self contained and covers theoretical, algorithmic and software

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**Advanced Finite Element Methods with Applications** Thomas Apel,Ulrich Langer,Arnd Meyer,Olaf Steinbach,2019-06-28 Finite element methods are the most popular methods for solving partial differential equations numerically and despite having a history of more than 50 years there is still active research on their analysis application and extension This book features overview papers and original research articles from participants of the 30th Chemnitz Finite Element Symposium which itself has a 40 year history Covering topics including numerical methods for equations with fractional partial derivatives isogeometric analysis and other novel discretization methods like space time finite elements and boundary elements analysis of a posteriori error estimates and adaptive methods enhancement of efficient solvers of the resulting systems of equations discretization methods for partial differential equations on surfaces and methods adapted to applications in solid and fluid mechanics it offers readers insights into the latest results

*Adaptive Finite Elements in Linear and Nonlinear Solid and Structural Mechanics* Erwin Stein,2007-04-02 This course with 6 lecturers intends to present a systematic survey of recent research results of well known scientists on error controlled adaptive finite element methods in solid and structural mechanics with emphasis to problem dependent concepts for adaptivity error analysis as well as h and p adaptive refinement techniques including meshing and remeshing Challenging applications are of equal importance including elastic and elastoplastic deformations of solids contact problems and thin walled structures Some major topics should be pointed out namely i The growing importance of goal oriented and local error estimates for quantities of interest in comparison with global error estimates based on dual finite element solutions a The importance of the p version of the finite element method in conjunction with parameter dependent hierarchical approximations of the mathematical model for example in boundary layers of elastic plates Hi The choice of problem oriented error measures in suitable norms considering residual averaging and hierarchical error estimates in conjunction with the efficiency of the associated adaptive computations iv The importance of implicit local postprocessing with enhanced test spaces in order to get constant free i e absolute not only relative discretization error estimates v The coupling of error controlled adaptive discretizations and the mathematical modeling in related subdomains such as boundary layers The main goals of adaptivity are reliability and efficiency combined with insight and access to controls which are independent of the applied discretization methods By these efforts new paradigms in Computational Mechanics should be realized namely verifications and even validations of engineering models

BEM-based Finite Element Approaches on Polytopal Meshes Steffen Weißer,2019-07-18 This book introduces readers to one of the first methods developed for the numerical treatment of boundary value problems on polygonal and polyhedral meshes which it subsequently analyzes and applies in various scenarios The BEM based finite element approaches employs implicitly defined

trial functions which are treated locally by means of boundary integral equations A detailed construction of high order approximation spaces is discussed and applied to uniform adaptive and anisotropic polytopal meshes The main benefits of these general discretizations are the flexible handling they offer for meshes and their natural incorporation of hanging nodes This can especially be seen in adaptive finite element strategies and when anisotropic meshes are used Moreover this approach allows for problem adapted approximation spaces as presented for convection dominated diffusion equations All theoretical results and considerations discussed in the book are verified and illustrated by several numerical examples and experiments Given its scope the book will be of interest to mathematicians in the field of boundary value problems engineers with a mathematical background in finite element methods and advanced graduate students

*An Adaptive Finite Element Method for Initial-Boundary Value Problems for Partial Differential Equations* Stephen F. Davis, Joseph E.

Flaherty, RENSSELAER POLYTECHNIC INST TROY NY DEPT OF MATHEMATICAL SCIENCES., 1981 A finite element method is developed to solve initial boundary value problems for vector systems of partial differential equations in one space dimension and time The method automatically adapts the computational mesh as the solution progresses in time and is thus able to follow and resolve relatively sharp transitions such as mild boundary layers shock layers or wave fronts This permits an accurate solution to be calculated with fewer mesh points than would be necessary with a uniform mesh The overall method contains two parts a solution algorithm and a mesh selection algorithm The solution algorithm is a finite element Galerkin method on trapezoidal space time elements using either piecewise linear or cubic polynomial approximations and the mesh selection algorithm builds upon similar work for variable knot spline interpolation A computer code implementing these algorithms has been written and applied to a number of problems These computations confirm that the theoretical error estimates are attained and demonstrate the utility of variable mesh methods for partial differential equations Author

**Advanced Boundary Element Methods** Joachim Gwinner, Ernst Peter Stephan, 2018-07-28 This book is devoted to the mathematical analysis of the numerical solution of boundary integral equations treating boundary value transmission and contact problems arising in elasticity acoustic and electromagnetic scattering It serves as the mathematical foundation of the boundary element methods BEM both for static and dynamic problems The book presents a systematic approach to the variational methods for boundary integral equations including the treatment with variational inequalities for contact problems It also features adaptive BEM hp version BEM coupling of finite and boundary element methods efficient computational tools that have become extremely popular in applications Familiarizing readers with tools like Mellin transformation and pseudodifferential operators as well as convex and nonsmooth analysis for variational inequalities it concisely presents efficient state of the art boundary element approximations and points to up to date research The authors are well known for their fundamental work on boundary elements and related topics and this book is a major contribution to the modern theory of the BEM especially for error controlled adaptive methods and for unilateral contact and dynamic

problems and is a valuable resource for applied mathematicians engineers scientists and graduate students **Adaptive Boundary Element Methods in Elastostatics** Shin-Ichi Umetani,1988 Numerical Treatment of Coupled Systems Wolfgang Hackbusch,2013-04-17 The GAMM Committee for Efficient Numerical Methods for Partial Differential Equations organizes seminars and workshops on subjects concerning the algorithmic treatment of partial differential equations The topics are discretisation methods like the finite element and the boundary element method for various type of applications in structural and fluid mechanics Particular attention is devoted to the advanced solution methods The series of such seminars was continued in 1995 January 20 22 with the 11th Kiel Seminar on the special topic Numerical Treatment of Coupled Systems at the Christian Albrechts University of Kiel The seminar was attended by 100 scientist from 9 countries 23 lectures were given including two survey lectures Different kinds of couplings are considered in this volume The coupling of different components may occur in the physical model On the other hand a coupling of subsystems can be generated by the numerical solution technique General examples of the latter kind are the domain decomposition see p 128 or subspace decomposition p 117 The local defect correction method couples different discretizations of the same problem in order to improve the results although the basic linear system to be solved remains unchanged p 47 In general the aim of the numerical coupling is to make use of efficient subsystem solvers p 1 The combination of different discretization techniques is mentioned on page 59

**Applied Mechanics Reviews** ,1997 **Encyclopedia of Computational Mechanics, 6 Volume Set** Erwin Stein,René de Borst,Thomas J. R. Hughes,2018-03-12 An extensively expanded and revised edition of the leading major reference work in computational engineering The completely updated and extended second edition of Encyclopedia of Computational Mechanics Second Edition has once again been prepared under the guidance of three of the world s foremost experts in the field It follows the same structure as the first edition yet has been expanded from three to six full volumes to give readers a more in depth and complete understanding of the topic Volumes 1 Isogeometric analysis as well as various direct and iterative solvers time dependent parabolic problems and FEMs for the Maxwell equation further new chapters on uncertainty quantification and related stochastic solution methods are included Volumes 3 constitutive theories and their implementation materials and processing interaction problems and identification stochastics and optimization Volumes 5 cover the various aspects of incompressible viscous flows focus on compressible fluid dynamics and address problems involving moving domains and free surfaces and application areas The single most comprehensive reference on computational mechanics 18 new chapters added representing a more than 20% increase over current edition Extensive revision plan with major updates to the majority of existing articles Covers solid and fluid mechanics with extensive treatment of FEA and CFD techniques With contributions from leading experts around the globe this is an essential and comprehensive reference for any university engineering department or corporation and contains invaluable up to date content for researchers students and practitioners alike *Mathematical and Computational Aspects* Carlos A.

Brebbia, Wolfgang L. Wendland, G. Kuhn, 2013-11-21 This book contains the edited versions of most of the papers presented at the 9th International Conference on Boundary Elements held at the University of Stuttgart Germany from August 31st to September 4th 1987 which was organized in co operation with the Computational Mechanics Institute and GAMM Society for Applied Mathematics and Mechanics This Conference as the previous ones aimed to review the latest developments in technique and theory and point out new advanced future trends The emphasis of the meeting was on the engineering advances versus mathematical formulations in an effort to consolidate the basis of many new applications Recently engineers have proposed different techniques to solve non linear and time dependent problems and many of these formulations needed a better mathematical understanding Furthermore new approximate formulations have been proposed for boundary elements which appeared to work in engineering practice but did not have a proper theoretical background The Conference also discussed the engineering applications of the method and concentrated on a link between BEM practitioners industrial users and researchers working on the latest development of the method The editors would like to express their appreciation and thanks to Ms Liz Newman and Mr H Schmitz for their unstinting work in the preparation of the Conference

**Large-Scale Structures in Acoustics and Electromagnetics** National Research Council, Division on Engineering and Physical Sciences, Commission on Physical Sciences, Mathematics, and Applications, Board on Mathematical Sciences, 1996-05-05 This book focuses on computational methods to determine the dynamics of large scale electromagnetic acoustic and mechanical systems including those with many substructures and characterized by an extended range of scales Examples include large naval and maritime vessels aerospace vehicles and densely packed microelectronic and optical integrated circuits VLSI The interplay of time and frequency domain computational and experimental procedures was addressed emphasizing their relationship and synergy and indicating mathematics research opportunities

**Adaptive Finite Element Methods for Control Constrained Distributed and Boundary Optimal Control Problems** Michael Hintermüller, Ronald H. W. Hoppe, 2008

**The Mathematics of Finite Elements and Applications** J. R. Whiteman, 1994 World leaders in diverse disciplines whose common interest is finite element methods address the latest developments in the field Mathematical theory engineering and scientific applications computational techniques large scale analysis and implementation of related methods are among the subjects discussed

*Acta Numerica 1995: Volume 4* Arieh Iserles, 1995-07-13 *Acta Numerica* has established itself as the prime forum for the presentation of definitive reviews of numerical analysis topics The invited review papers by leaders in their respective fields allow researchers and graduate students alike quickly to grasp trends and developments Highlights of the 1995 issue include articles on sequential quadratic programming mesh adaption free boundary problems and particle methods in continuum computations

**Contributions to Partial Differential Equations and Applications** B. N. Chetverushkin, W. Fitzgibbon, Y.A. Kuznetsov, P. Neittaanmäki, J. Periaux, O. Pironneau, 2018-07-19 This book treats Modelling of CFD problems Numerical tools for PDE and Scientific Computing and Systems of ODE for

Epidemiology topics that are closely related to the scientific activities and interests of Prof William Fitzgibbon Prof Yuri Kuznetsov and Prof O Pironneau whose outstanding achievements are recognised in this volume It contains 20 contributions from leading scientists in applied mathematics dealing with partial differential equations and their applications to engineering ab initio chemistry and life sciences It includes the mathematical and numerical contributions to PDE for applications presented at the ECCOMAS thematic conference Contributions to PDE for Applications held at Laboratoire Jacques Louis Lions in Paris France August 31 September 1 2015 and at the Department of Mathematics University of Houston Texas USA February 26 27 2016 This event brought together specialists from universities and research institutions who are developing or applying numerical PDE or ODE methods with an emphasis on industrial and societal applications This volume is of interest to researchers and practitioners as well as advanced students or engineers in applied and computational mathematics All contributions are written at an advanced scientific level with no effort made by the editors to make this volume self contained It is assumed that the reader is a specialist already who knows the basis of this field of research and has the capability of understanding and appreciating the latest developments in this field

**Adaptive Finite Element Methods for Parabolic Partial Differential Equations** J. E. Flaherty, J. M. Coyle, R. Ludwig, S. F. Davis, 1983 The authors discuss a finite element method for solving initial boundary value problems for vector systems of partial differential equations in one space dimension and time The method automatically adjusts the computational mesh as the solution evolves in time so as to approximately minimize the local discretization error They are thus able to calculate accurate solutions with fewer elements than would be necessary with a uniform mesh This overall method contains two distinct steps a solution step and a mesh selection step They solve the partial differential equations using a finite element Galerkin method on trapezoidal space time elements with either piecewise linear or cubic Hermite polynomial approximations A variety of mesh selection strategies are discussed and analyzed Results are presented for several computational examples

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