

Least-Squares Minimising Finite-element Formulation for Static and Stationary Electric and Magnetic Fields

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Abstract—The present paper describes a finite-element formulation for static and stationary electric and magnetic fields in terms of the electric and of the magnetic field strength. The formulation is based on a simultaneous minimisation in the least-squares sense of the error in modelling the curl and the divergence equations. For consistently modelling the field equations and the interface and boundary conditions, use is made of generalised Cartesian expansion functions.

Index terms—finite-element formulation, static and stationary fields, least-squares minimisation.

I. INTRODUCTION

A numerical formulation for computing static and stationary electric and magnetic fields directly in terms of the relevant field strength was examined in [1]. It was based on a finite-element formulation described in [2] that used a combination of nodal and edge elements for the field strength expansion. The mathematical properties of this formulation were extensively analysed in [1]. It turned out that when the solution of the field equations is square-integrable up to and including its second derivatives, it is possible to derive a finite-element formulation that uses linear expansion functions and that minimises the error in modelling the field equations, in the least-squares sense, inside all interface free, open sub-domains of the domain of computation. The expansions used for the least-squares minimisation must satisfy the following conditions:

- C1. Their curl and divergence is square-integrable over all interface free, open sub-domains of the domain of computation.
- C2. They satisfy explicit zero boundary conditions and ensure the continuity of the relevant components of the field strength and of the flux density across source free interfaces.

In the cases when

- non-zero boundary conditions are prescribed

and/or

- interfaces with non-zero surface sources are present inside the domain of computation,

additional expansion functions that satisfy the condition C1 and that model these features of the field in an acceptable manner must be made available. The finite-element formulation described in [2] was shown to represent a least-squares minimisation problem for homogeneous domains with smooth boundaries. The use of edge elements was shown to be incompatible with that type of least-squares minimisation problem.

The present paper describes a new finite-element formulation which yields the least-squares minimisation of the error in modelling the field equations for domains of computation with a smooth outer boundary and smooth, non-intersecting internal interfaces. For conciseness, the media inside the domain of computation are assumed to be isotropic. Our results can be generalised to the case of anisotropic media for which the constitutive parameter is a diagonal tensor in a local reference frame. The constitutive parameters are assumed to be linear.

The theoretical results are supported by numerical results obtained by solving a test problem with a known analytical solution.

II. THE FIELD EQUATIONS

Let \mathcal{D} be an open domain of computation with a smooth outer boundary $\partial\mathcal{D}$. A finite number of smooth, non-intersecting interfaces \mathcal{I} between media with different material parameters can be located inside \mathcal{D} . The unit vectors along the outward oriented normal on $\partial\mathcal{D}$ and on interfaces are denoted as \mathbf{n} and $\boldsymbol{\nu}$, respectively. The following equations hold in the static and stationary limit of the electric and the magnetic fields [1]:

$$\nabla \times \mathbf{V} = \mathbf{Q}^{\text{imp}} \quad \text{in } \mathcal{D} \setminus \mathcal{I}, \quad (1)$$

$$\nabla \cdot \mathbf{F} = \rho^{\text{imp}} \quad \text{in } \mathcal{D} \setminus \mathcal{I}, \quad (2)$$

$$\mathbf{F} = \xi \mathbf{V} \quad \text{in } \mathcal{D} \setminus \mathcal{I}, \quad (3)$$

where \mathbf{V} denotes the field strength, \mathbf{F} the flux density, ξ the constitutive parameter, \mathbf{Q}^{imp} the impressed (known) source density of volume current, ρ^{imp} the impressed (known) volume density of charge. These equations are supplemented by the following interface conditions:

$$\boldsymbol{\nu} \times \mathbf{V}|_1^2 = \mathbf{Q}_{\mathcal{I}}^{\text{imp}} \quad \text{across } \mathcal{I}, \quad (4)$$

$$\boldsymbol{\nu} \cdot \mathbf{F}|_1^2 = \sigma^{\text{imp}} \quad \text{across } \mathcal{I}, \quad (5)$$

Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields

**Pavel Solin,Ivo Dolezel,Pavel
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Scientific Computing in Electrical Engineering SCEE 2008 Luis R.J. Costa, Janne Roos, 2010-06-14 This book is a collection of 65 selected papers presented at the 7th International Conference on Scientific Computing in Electrical Engineering SCEE held in Espoo Finland in 2008 The aim of the SCEE 2008 conference was to bring together scientists from academia and industry e g mathematicians electrical engineers computer scientists and physicists with the goal of intensive discussions on industrially relevant mathematical problems with an emphasis on modeling and numerical simulation of electronic circuits and devices electromagnetic fields and coupled problems This extensive reference work is divided into five parts 1 Computational electromagnetics 2 Circuit simulation 3 Coupled problems 4 Mathematical and computational methods and 5 Model order reduction Each part starts with an general introduction followed by the actual papers **The**

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Ulrych, 2009-08-11 A modern presentation of integral methods in low frequency electromagnetics This book provides state of the art knowledge on integral methods in low frequency electromagnetics Blending theory with numerous examples it introduces key aspects of the integral methods used in engineering as a powerful alternative to PDE based models Readers will get complete coverage of The electromagnetic field and its basic characteristics An overview of solution methods Solutions of electromagnetic fields by integral expressions Integral and integrodifferential methods Indirect solutions of electromagnetic fields by the boundary element method Integral equations in the solution of selected coupled problems Numerical methods for integral equations All computations presented in the book are done by means of the authors own codes and a significant amount of their own results is included At the book s end they also discuss novel integral techniques of a higher order of accuracy which are representative of the future of this rapidly advancing field Integral Methods in Low Frequency Electromagnetics is of immense interest to members of the electrical engineering and applied mathematics communities ranging from graduate students and PhD candidates to researchers in academia and practitioners in industry

Electromagnetics through the Finite Element Method José Roberto Cardoso, 2016-10-03 Shelving Guide Electrical Engineering Since the 1980s more than 100 books on the finite element method have been published making this numerical method the most popular The features of the finite element method gained worldwide popularity due to its flexibility for simulating not only any kind of physical phenomenon described by a set of differential equations but also for the possibility of simulating non linearity and time dependent studies Although a number of high quality books cover all subjects in engineering problems none of them seem to make this method simpler and easier to understand This book was written with the goal of simplifying the mathematics of the finite element method for electromagnetic students and professionals relying on the finite element method for solving design problems Filling a gap in existing literature that often uses complex mathematical formulas *Electromagnetics through the Finite Element Method* presents a new mathematical approach based on only direct integration of Maxwell's equation This book makes an original scholarly contribution to our current understanding of this important numerical method

Finite Element Analysis Farzad Ebrahimi, 2012-10-10 In the past few decades the Finite Element Method FEM has been developed into a key indispensable technology in the modeling and simulation of various engineering systems The present book reports on the state of the art research and development findings on this very broad matter through original and innovative research studies exhibiting various investigation directions of FEM in electrical civil materials and biomedical engineering This book is a result of contributions of experts from international scientific community working in different aspects of FEM The text is addressed not only to researchers but also to professional engineers students and other experts in a variety of disciplines both academic and industrial seeking to gain a better understanding of what has been done in the field recently and what kind of open problems are in this area

Partial Differential Equations and the Finite Element Method Pavel Šolín, 2005-12-13 A systematic introduction to partial differential equations and modern finite element methods for their efficient numerical solution Partial Differential Equations and the Finite Element Method provides a much needed clear and systematic introduction to modern theory of partial differential equations PDEs and finite element methods FEM Both nodal and hierarchic concepts of the FEM are examined Reflecting the growing complexity and multiscale nature of current engineering and scientific problems the author emphasizes higher order finite element methods such as the spectral or hp FEM A solid introduction to the theory of PDEs and FEM contained in Chapters 1-4 serves as the core and foundation of the publication Chapter 5 is devoted to modern higher order methods for the numerical solution of ordinary differential equations ODEs that arise in the semidiscretization of time dependent PDEs by the Method of Lines MOL Chapter 6 discusses fourth order PDEs rooted in the bending of elastic beams and plates and approximates their solution by means of higher order Hermite and Argyris elements Finally Chapter 7 introduces the reader to various PDEs governing computational electromagnetics and describes their finite element approximation including modern higher order edge elements for Maxwell's equations The understanding of many theoretical

and practical aspects of both PDEs and FEM requires a solid knowledge of linear algebra and elementary functional analysis such as functions and linear operators in the Lebesgue Hilbert and Sobolev spaces These topics are discussed with the help of many illustrative examples in Appendix A which is provided as a service for those readers who need to gain the necessary background or require a refresher tutorial Appendix B presents several finite element computations rooted in practical engineering problems and demonstrates the benefits of using higher order FEM Numerous finite element algorithms are written out in detail alongside implementation discussions Exercises including many that involve programming the FEM are designed to assist the reader in solving typical problems in engineering and science Specifically designed as a coursebook this student tested publication is geared to upper level undergraduates and graduate students in all disciplines of computational engineering and science It is also a practical problem solving reference for researchers engineers and physicists

Field Theory Concepts Adolf J. Schwab, 2012-12-06 Field Theory Concepts is a new approach to the teaching and understanding of field theory Exploiting formal analogies of electric magnetic and conduction fields and introducing generic concepts results in a transparently structured electromagnetic field theory Highly illustrative terms allow easy access to the concepts of curl and div which generally are conceptually demanding Emphasis is placed on the static quasistatic and dynamic nature of fields Eventually numerical field calculation algorithms e.g. Finite Element method and Monte Carlo method are presented in a concise yet illustrative manner

Electromagnetic Modeling by Finite Element Methods João Pedro A. Bastos, Nelson Sadowski, 2003-04-01 Unlike any other source in the field this valuable reference clearly examines key aspects of the finite element method FEM for electromagnetic analysis of low frequency electrical devices The authors examine phenomena such as nonlinearity mechanical force electrical circuit coupling vibration heat and movement for applications in the elect

A Least-squares Finite Element Method for Electromagnetic Scattering Problems Jie Wu, 1996 *Electromagnetics and Calculation of Fields* Nathan Ida, Joao P.A. Bastos, 2013-03-07 Intended for undergraduate students of electrical engineering this introduction to electromagnetic fields emphasizes the computation of fields as well as the development of theoretical relations The first part thus presents the electromagnetic field and Maxwell's equations with a view toward connecting the disparate applications to the underlying relations while the second part presents computational methods of solving the equations which for most practical cases cannot be solved analytically

Electric and Magnetic Fields R. Belmans, A. Nicolet, 2012-12-06 This book contains the edited versions of the papers presented at the Second International Workshop on Electric and Magnetic Fields held at the Katholieke Universiteit van Leuven Belgium in May 1994 This Workshop deals with numerical solutions of electromagnetic problems in real life applications The topics include coupled problems thermal mechanical electric circuits CAD/CAM applications 3D eddy current and high frequency problems optimisation and application oriented numerical problems This workshop was organised jointly by the AIM Association of Engineers graduated from de Montefiore Electrical Institute together with the Departments of Electrical Engineering of the

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Scientific and Technical Aerospace Reports ,1995 Numerical Methods for Energy Applications Naser Mahdavi Tabatabaei,Nicu Bizon,2021-03-22 This book provides a thorough guide to the use of numerical methods in energy systems and applications It presents methods for analysing engineering applications for energy systems discussing finite difference finite element and other advanced numerical methods Solutions to technical problems relating the application of these methods to energy systems are also thoroughly explored Readers will discover diverse perspectives of the contributing authors and extensive discussions of issues including a wide variety of numerical methods concepts and related energy systems applications systems equations and optimization partial differential equations and finite difference method methods for solving nonlinear equations special methods and their mathematical implementation in multi energy sources numerical investigations of electrochemical fields and devices and issues related to numerical approaches and optimal integration of energy consumption This is a highly informative and carefully presented book providing scientific and academic insight for readers with an interest in numerical methods and energy systems

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Effects of Time-Varying Magnetic Fields in the Frequency Range 1 KHz to 100 KHz Upon the Human Body Julia Bohnert,2014-05-12 In this work the physiological effects of time varying magnetic fields up to 100 kHz have been investigated namely magnetic stimulation and body warming Simulation studies were based on numerical calculations on sophisticated cell and body models In addition magnetic stimulation thresholds have been determined experimentally The project was carried out within the scope of the development of Magnetic Particle Imaging a new imaging technology for medical diagnostics

Models and Simulations of the Electric Field in Deep Brain Stimulation Fabiola Alonso,2018-09-10 Deep brain stimulation DBS is an established surgical therapy for movement disorders such as Parkinson s disease PD and essential tremor ET A thin electrode is implanted in a predefined area of the brain with the use of stereotactic neurosurgery In the last few years new DBS electrodes and systems have been developed with possibilities for using more parameters for control of the stimulation volume In this thesis simulations using the finite element method FEM have been developed and used for investigation of the electric field EF extension around different types of DBS lead designs symmetric steering and stimulation modes voltage current The electrode surrounding was represented either with a homogeneous model or a patient specific model based on individual preoperative magnetic resonance imaging MRI The EF was visualized and compared for different lead designs and operating modes In Paper I the EF was quantitatively investigated around two lead designs 3389 and 6148 simulated to operate in voltage and current mode under acute and chronic time points following implantation Simulations showed a major impact on the EF extension between postoperative time points which may explain the clinical decisions to change the stimulation amplitude weeks after implantation In Paper II the simulations were expanded to include two leads having steering function 6180 Surestim1 and patient specific FEM simulations in the zona incerta It was found that both the heterogeneity of the tissue and the operating mode influence the EF distribution and that equivalent contact configurations of the leads result in similar EF The steering mode presented larger volumes in current mode when using equivalent amplitudes Simulations comparing DBS and intraoperative stimulation test using a microelectrode recording MER system Paper III showed that several parallel MER leads and the presence of the non active DBS contacts influence the EF distribution and that the DBS EF volume can cover but also extend to other anatomical areas Paper IV introduces a method for an objective exploitation of intraoperative stimulation test data in order to identify the optimal implant position in the thalamus of the chronic DBS lead Patient specific EF simulations were related to the anatomy with the help of brain atlases and the clinical effects which were quantified by accelerometers The first results indicate that the good clinical effect in ET is due to several structures around the ventral intermediate nucleus of the thalamus

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Table of Contents Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields

1. Understanding the eBook Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - The Rise of Digital Reading Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Advantages of eBooks Over Traditional Books
2. Identifying Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - User-Friendly Interface
4. Exploring eBook Recommendations from Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Personalized Recommendations
 - Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields User Reviews and Ratings
 - Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields and Bestseller Lists
5. Accessing Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields Free and Paid eBooks
 - Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields Public Domain eBooks
 - Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields eBook Subscription Services

- Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields Budget-Friendly Options
- 6. Navigating Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields eBook Formats
 - ePub, PDF, MOBI, and More
 - Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields Compatibility with Devices
 - Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields Enhanced eBook Features
- 7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Highlighting and Note-Taking Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Interactive Elements Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
- 8. Staying Engaged with Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
- 9. Balancing eBooks and Physical Books Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
- 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
- 11. Cultivating a Reading Routine Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Setting Reading Goals Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Fact-Checking eBook Content of Finite Element Modelling Of Static And Stationary Electric And Magnetic Fields
 - Distinguishing Credible Sources
- 13. Promoting Lifelong Learning

- Utilizing eBooks for Skill Development
- Exploring Educational eBooks

14. Embracing eBook Trends

- Integration of Multimedia Elements
- Interactive and Gamified eBooks

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