

## Research Article

Hocine Menana\*, Mohamad Farhat, Melika Hinaje, Kevin Berger, Bruno Douine, and Jean Lévêque

# Eddy current modeling in linear and nonlinear multifilamentary composite materials

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**Abstract:** In this work, a numerical model is developed for a rapid computation of eddy currents in composite materials, adaptable for both carbon fiber reinforced polymers (CFRPs) for NDT applications and multifilamentary high temperature superconductive (HTS) tapes for AC loss evaluation. The proposed model is based on an integro-differential formulation in terms of the electric vector potential in the frequency domain. The high anisotropy and the nonlinearity of the considered materials are easily handled in the frequency domain.

**Keywords:** Eddy current, multifilamentary composite materials, anisotropy, nonlinearity, numerical modeling

**PACS:** 85.25.Am, 84.71.Mn, 74.25.N-, 02.60.Cb, 02.70.Bf

## 1 Introduction

Electromagnetic field modeling in composite materials such as carbon fiber reinforced polymers (CFRPs) or multifilamentary high-temperature superconductive (HTS) tapes, is in many cases a challenging task. Numerical modeling is then often necessary [1, 2], where the conventional numerical tools have difficulties to provide accurate solutions in reasonable computing times due to multi-scale dimensions, nonlinearities and high anisotropies. In these cases, specific modeling approaches meeting a better compromise between accuracy and computing time are needed.

In previous works, we have developed an electromagnetic model, based on an integro-differential formulation, for a rapid eddy current computation in carbon fiber reinforced composite polymers for nondestructive testing (NDT) applications [2]. In this work, this model is extended to model eddy current losses in multifilamentary HTS composite tapes submitted to external sinusoidal time varying magnetic fields. Indeed, both materials have similarities in their geometrical structures, constituted of filaments embedded in a matrix. In the case of CFRPs, the filaments are carbon fibers embedded in a polymer matrix resulting in poor conductivities and high anisotropies, whereas in the HTS tapes, the filaments are made of a nonlinear conductive material (HTS) and the matrix is made of a high conductive material. A numerical scheme is proposed to take into account the nonlinearity of the constitutive law, relating the electrical current density to the electrical field, in the frequency domain rather than in the time domain as it is commonly done. This ensures the stability and the rapidity of convergence of the numerical scheme. The proposed approach is validated by comparison to theoretical and experimental results. For loss computation, it is particularly shown that the nonlinearity of the HTS tapes can be avoided by considering a high anisotropy factor as reported in [3].

The modeled system and the electromagnetic formulation are presented in the next sections. Numerical results and validation are given in the last section.

## 2 The modeled system

The modeled system (Figure 1) consists of a multifilamentary composite sample of length  $L_c$ , width  $W$ , and thickness  $T_c$ , constituted of filaments embedded in a matrix. The sample is submitted to an external sinusoidal time varying magnetic flux density ( $\vec{B}^e$ ). The whole system is characterized by the vacuum magnetic permeability ( $\mu_0$ ). To avoid the modeling at the filament scale, a homogenized nonlinear electrical conductivity tensor is defined for the sample, given by (1), where  $\sigma_{ij}$  and  $\sigma_T$  denote the

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# Eddy Currents In Linear And Nonlinear Media

**Isaak D. Mayergoyz**



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**Advanced Computer Techniques in Applied Electromagnetics** Andrzej Krawczyk, Sławomir Wiak, Ivo Doležel,2008 Includes contributions on electromagnetic fields in electrical engineering which intends at joining theory and practice This book helps the world wide electromagnetic community both academic and engineering in understanding electromagnetism itself and its application to technical problems

*Pulse Width Modulation In Power Electronics* Isaak D Mayergoyz, Siddharth Tyagi,2021-05-05 This book provides a theoretical discussion of pulse width modulation PWM in power electronic inverters Pulse width modulation is widely used for the frequency control of speed of ac motors the design of uninterruptible power supplies UPS as well as the integration of renewable energy sources into existing power grid systems PWM technique is based on approximation of sinusoidal waveforms by sequences trains of rectangular pulses whose widths are properly modulated This width modulation results in the suppression of low order harmonics at the expense of amplification of high order harmonics which are suppressed by energy storage elements in load circuits The discussion covers various PWM techniques with a focus on the optimal time domain PWM techniques proposed by the authors

Non-linear Electromagnetic Systems Paolo Di Barba,A. Savini,2000 This text is a collection of contributions covering a wide range of topics of interdisciplinary character from materials to systems from microdevices to large equipment with special emphasis on emerging subjects and particular attention to advanced computational methods in order to model both devices and systems The book provides the solution to challenging problems of research on non linear electromagnetic systems and is expected to help researchers working in this broad area

**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 electrical mechanical nuclear aeronautics and transportation industries Electromagnetic Modeling by Finite Element Methods offers a wide range of examples including torque vibration and iron loss calculation coupling of the FEM with mechanical equations circuits converters and thermal effects material modeling and proven

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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 *Journal of the Institution of Engineers (India).* ,2002

*Advances in Induction and Microwave Heating of Mineral and Organic Materials* Stanisław Grundas,2011-02-14 The book offers comprehensive coverage of the broad range of scientific knowledge in the fields of advances in induction and microwave heating of mineral and organic materials Beginning with industry application in many areas of practical application to mineral materials and ending with raw materials of agriculture origin the authors specialists in different scientific area present their results in the two sections Section 1 Induction and Microwave Heating of Mineral Materials and Section 2 Microwave Heating of Organic Materials Mathematical Models of Hysteresis and their Applications Isaak D.

Mayergoyz,2003-10-01 This new edition has been significantly revised and updated to reflect advances in the field since the publication of the first edition such as the systematic experimental testing of Preisach models of hysteresis The author has however retained the two most salient features of the original the emphasis on the universal nature of mathematical models of hysteresis and their applicability to the description of hysteresis phenomena in various areas of science technology and economics and its accessibility to a broad audience of researchers engineers and students Provides a unique emphasis on the

development of universal mathematical models of hysteresis Accessibility to a broad audience using simple and complex mathematical tools application to various areas of science Presents new theoretical and experimental results Scientific and Technical Aerospace Reports ,1995      **Sensors and Actuators** Clarence W. de Silva,2015-07-30 This introductory textbook on engineering system instrumentation emphasizes sensors transducers actuators and devices for component interconnection The book deals with instrumenting an engineering system through the incorporation of suitable sensors actuators and associated interface hardware including filters amplifiers and other signal modifiers In view of the practical considerations design issues and industrial techniques that are presented throughout the book and in view of the simplified and snap shot style presentation of more advanced theory and concepts it also serves as a useful reference for engineers technicians project managers and other practicing professionals in industry and in research laboratories      Scattering, Two-Volume Set E. R. Pike,Pierre C. Sabatier,2001-10-09 Scattering is the collision of two objects that results in a change of trajectory and energy For example in particle physics such as electrons photons or neutrons are scattered off of a target specimen resulting in a different energy and direction In the field of electromagnetism scattering is the random diffusion of electromagnetic radiation from air masses is an aid in the long range sending of radio signals over geographic obstacles such as mountains This type of scattering applied to the field of acoustics is the spreading of sound in many directions due to irregularities in the transmission medium Volume I of Scattering will be devoted to basic theoretical ideas approximation methods numerical techniques and mathematical modeling Volume II will be concerned with basic experimental techniques technological practices and comparisons with relevant theoretical work including seismology medical applications meteorological phenomena and astronomy This reference will be used by researchers and graduate students in physics applied physics biophysics chemical physics medical physics acoustics geosciences optics mathematics and engineering This is the first encyclopedic range work on the topic of scattering theory in quantum mechanics elastodynamics acoustics and electromagnetics It serves as a comprehensive interdisciplinary presentation of scattering and inverse scattering theory and applications in a wide range of scientific fields with an emphasis and details up to date developments Scattering also places an emphasis on the problems that are still in active current research The first interdisciplinary reference source on scattering to gather all world expertise in this techniqueCovers the major aspects of scattering in a common language helping to widening the knowledge of researchers across disciplinesThe list of editors associate editors and contributors reads like an international Who s Who in the interdisciplinary field of scattering      **Modeling of Dynamic Systems with Engineering Applications** Clarence W. de Silva,2017-10-16 MODELING OF DYNAMIC SYSTEMS takes a unique up to date approach to systems dynamics and related controls coverage for undergraduate students and practicing engineers It focuses on the model development of engineering problems rather than response analysis and simulation once a model is available though these are also covered Linear graphing and bond graph approaches are both discussed and computational tools are

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In a digital era where connections and knowledge reign supreme, the enchanting power of language has become more apparent than ever. Its ability to stir emotions, provoke thought, and instigate transformation is really remarkable. This extraordinary book, aptly titled "**Eddy Currents In Linear And Nonlinear Media**," compiled by a very acclaimed author, immerses readers in a captivating exploration of the significance of language and its profound impact on our existence. Throughout this critique, we shall delve into the book's central themes, evaluate its unique writing style, and assess its overall influence on its readership.

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web we aim to improve quality of care patient safety and patient family experience in ccm practice through the utilisation of a standardised repeatable and multidimensional performance scorecard designed to provide a continuous review of icu physician and nurse practice as well as departmental metrics