

Special Issue “Numerical and Analytical Methods in Electromagnetics”

Hristos T. Anastassiou

Department of Informatics, Computer and Communications Engineering, International Hellenic University, Serres Campus, End of Magnisias Str., GR-62124 Serres, Greece; hristosa@teiser.gr

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1. Introduction

Like all branches of physics and engineering, electromagnetics relies on mathematical methods for modeling, simulation, and design procedures in all of its aspects (radiation, propagation, scattering, imaging, etc.). Originally, rigorous analytical techniques were the only machinery available to produce any useful results. Essentially, the aim was the solution of partial differential equations (such as the Laplace, Poisson, Helmholtz, and wave equations) since the electric and magnetic fields are the unknown quantities in such expressions, although exact analytical methods (e.g., the Wiener–Hopf technique) were limited to canonical geometries, which are unfortunately rare in nature. Hence, in the 1960s and 1970s, emphasis was placed on asymptotic techniques, which produced approximations of the fields for very high frequencies when closed-form solutions were not feasible. Typical examples of such techniques were the geometrical and physical optics (GO and PO, respectively), improved by the geometrical, physical, and uniform theories of diffraction (GTD, PTD and UTD, respectively). Later, when computers demonstrated explosive progress, numerical techniques were utilized to develop approximate results of controllable accuracy for arbitrary geometries. Either differential or integral equations were discretized, leading to standard techniques, such as the method of moments (MoM), finite element method (FEM), the finite difference time domain method (FDTD), finite integration technique (FIT), and the method of auxiliary sources (MAS). Researchers soon realized that several practical problems required extremely high computational resources, in terms of memory and CPU time, to handle, typically, millions of unknowns. Therefore, “fast” variants of the latter techniques were developed to suppress the computational cost, such as the adaptive integral method (AIM); the fast multipole method (FMM); its parallel version, called the multi-level fast multipole algorithm (MLFMA); and its time domain counterpart, i.e., the plane wave time domain (PWTD) method. The lists above are by no means exhaustive; there is a plethora of additional algorithms, having evolved particularly over the last few years, designed to reduce the complexity and simultaneously improve the accuracy of calculations. In this Special Issue, the most recent advances thereof were presented to illustrate the state-of-the-art mathematical techniques in electromagnetics.

2. The Contents of This Special Issue

A wide variety of practical electromagnetic problems were addressed in this Special Issue and further solved via appropriate mathematical methods. In [1], Wei Gao et al. used partial differential equation techniques to solve the nonlinear Schrödinger equations applied to wave propagation in optical fibers with nonlinear impacts. Two powerful analytical methods, namely the $(m+G'/G)$ improved expansion method and the $\exp(-\phi(\xi))$ expansion method were utilized to construct novel solutions of the governing equations.

In [2], the application topic is geophysics; Yanju Ji et al. propose an efficient approach of the Grounded Electrical-source Airborne Transient Electromagnetics (GREATEM), which is a widespread detection method among researchers in the field. Maxwell's equations are transformed via the relationship between the diffusion field and fictitious wave field. The fractional order Cole–Cole model is introduced into the fictitious wave field and the final solution is obtained by using the finite difference time domain (FDTD) method. Finally, an integral transformation is applied to obtain the calculation results in the actual diffusion field form.

Moreover, electromagnetic properties of composites filled with carbon nano tubes (CNTs) are modeled by A. Plyushch et al. in [3]. The total conductivity of the composite is governed by the inter-tube tunneling equation. In this framework, the direction for the conductivity computation is selected and the nanotubes near the initial and final borders are collected. The Dijkstra algorithm is used to trace the paths of minimal resistance between the initial and final tubes, and, finally, conductivity is computed in a highly accurate way.

Electromagnetic wave amplification by non-linear wave mixing is targeted in [4] by Ö. E. Aşırım and M. Kuzuoglu. Suitable numerical analysis is performed that provides evidence for the high-gain amplification of a low-power stimulus wave, via intense pump waves of ultra-short duration, inside a several-micrometers-long micro-resonator, by maximizing the electric energy density of the pump wave in the resonator. In order to perform the optimization of the stimulus wave magnitude at a given wave frequency, an efficient optimization procedure, namely the quasi-Newton Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm is implemented.

Although analytical solutions are rare in real-world problems, efficient approximations are still applicable to important devices. Such a case is a birdcage radio frequency coil used in nuclear magnetic resonance (NMR) imaging applications, as demonstrated in [5] by Young Cheol Kim et al. A novel analytical solution for the characteristic properties of the coil is derived via equivalent circuit modeling and T-matrix theory, facilitating and efficient design strategy.

Scattering analysis is another important aspect of applied electromagnetics which is in need of powerful mathematical tools. In [6], V.G. Iatropoulos et al. describe how the method of auxiliary sources (MAS) can be optimized for cylindrical scattering geometries containing curvilinear wedges. Instead of retaining a conformal auxiliary surface, which is customary in MAS, auxiliary sources are locally positioned close to the wedge tips with variable density. Numerical results clearly show the reduction of the calculation error and the improvement in the accuracy of the radar cross section.

An enjoyable application of numerical techniques to robotic system design is described in [7]: a coil gun found in soccer ball launchers is analyzed and designed by V. Gies et al. A coupled electromagnetic, electrical and mechanical model is used to simulate the performance of reluctance coil guns. Four different mechatronic coupled models thereof are proposed, and for each one of these the electromagnetic behavior is investigated on the basis of a finite element (FEM) software tool, whereas commercial software was used for modeling the electrical and mechanical parts.

Comparison of simplified analytical models based on the principles of superposition and reflections and the finite element method (FEM) was performed by R. Deltuva and R. Lukočius in [8], where the modeling of electric power lines is facilitated. The target of the analysis is an actual high-voltage AC, double-circuit 400 kV overhead power transmission line that runs from the city of Elk, Poland, to the city of Alytus, Lithuania.

Integral equation methods could by no means be absent from this Special Issue. Indeed, an integral formulation was used in [9] by Tung Le-Duc and G. Meunier to model thin surfaces coupled with an external circuit. A hybrid integral formulation is proposed to allow for the modeling of an inhomogeneous structure constituted by conductors and thin magnetic and conducting shells. The resulting integral equations are discretized via a Galerkin procedure and are further transformed to a linear system of equations, finally solved by standard linear algebra techniques.

The impressive application range of computational electromagnetics is clearly demonstrated in [10]. I. B. Yeboah et al. address a problem in biomedical engineering, namely fibroadenoma, which is one of the commonest benign female breast diseases. A particular form of treatment involves nanomedicine, which is based on the use of nanomaterials—metallic and ceramic (iron-oxide)

nanoparticles (NPs)—for theranostic purposes in living organisms. The authors characterize the material properties and quantify the photothermal heat generation of specific NPs by experimental measurements, obtain their optical absorption coefficient via experimentally guided Mie scattering theory and integrate it into a computational—finite element method (FEM)—model to predict the in-vivo thermal damage of an NP-embedded tumor located in a multi-tissue breast model during irradiation by a near-infrared (NIR) 810 nm laser.

Finally, the relationship of mathematical methods in electromagnetics with other research disciplines is underlined in multiphysics problems, such as the rail launcher addressed in [11]. The in-house integral equation code named “EN4EM” (Equivalent Network for Electromagnetic Modeling), developed by V. Consolo et al., is able to take into account all relevant electromechanical quantities and phenomena (i.e., eddy currents, velocity skin effect, sliding contacts etc.).

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