Preface

A few years ago, a colleague wrote a note in which he reviewed the state of the art in eddy-current probes that were to address new problems in the nation's steam generators. With respect to calibration standards, he stated

> The performance of these probes will not be realized unless calibration standards that accurately simulate the range of expected defects are used. This means a series of axial and/or circumferential notches, on both the tube od and id must be used to accurately calibrate these probes. The ASME Section XI standard with flat bottomed holes is a very poor representation of cracks, particularly for directional probes. In addition, the cable between the instrument and the probe should be as short as reasonable and should be low capacitance, low noise and low loss.

The purpose of this book is to address the entirety of issues raised in this quote, and beyond, and to effectively resolve them favorably through the use of computational electromagnetics and model-based inversion methods as a replacement for expensive and unreliable standards. Indeed, we hope to demonstrate that our assertion, that the computer will soon be the most important instrument in eddy-current nondestructive evaluation (NDE), is only a mild stretch.

The book, like Gaul, is divided into three parts whose intention is to show that computational electromagnetics is more than simply solving Maxwell's equations for various configurations of "anomalies" in hosts. Rather, it becomes a part of system science of engineering, which is where we hope to elevate the notion of 'nondestructive evaluation'. Maxwell, himself, might not have envisioned the ramifications of his theory, but surely he would have admired the results. (We are reminded that a well-known aerospace NDE engineer once told us that had he realized that you could make money solving Maxwell's equations, he would have paid more attention in his undergraduate E&M course.)

In the first part, we compute the Green's dyad by working with the field equations directly, without the intervening use of potential functions (Heaviside would be proud!). Indeed, it isn't until the derivation of the "vector form" of the volume-integral equations in Chap. 3 that we first see potential functions explicitly stated. We applied this approach originally to model electromagnetic responses in plane-layered anisotropic bodies, such as advanced composites made of carbon-fiber reinforced polymers, which will be an important part of the second volume in this series. This approach works well in cylindrical coordinates, as is demonstrated in Chap. 9.

The discretization of the volume-integral equation via Galerkin's method on a regular grid is certainly well known in the method of moments, and much of the remainder of the book attempts to show the advantage of this approach in solving large problems with reasonable computer resources.

Starting in Part I, and continuing throughout the remainder of the book, we have sought to impress upon the reader the value of using equivalent electric circuits or networks to interpret the physical response of the volume-integral equation. This makes eddy-current NDE a subset of electrical engineering and should allow those familiar with the basic concepts of electrical engineering lead into the further development of eddy-current NDE.

The development of advanced probe models in Chap. 6 is original, especially in treating coils, of whatever shape or orientation, as generalized magnetic dipoles comprising solenoidal currents flowing in closed loops. This has allowed us to model rectangular coils, or D-shaped coils, in a consistent numerical manner. We have validated several of these models against benchmark data, as shown in Chap. 6. What was especially pleasant, however, was the realization that we could take the dual of the magnetic-dipole approach and model planar spiral-coil probes assuming that the source is an electric dipole (Chap. 7). This allows us to compute capacitive effects, as well as the usual inductive effects, thereby enabling a more efficient design process for high-frequency applications. Problems of this type—for example, spiral antennas—are usually treated by boundary-integral equations, assuming perhaps that the metallic traces are perfect conductors. We have applied the volume-integral approach, treating the spiral traces as an "anomaly" in free space that is excited by an electric dipole, rather than an anomaly in a host that is excited by a magnetic dipole, and are able to compute the capacitive and inductive reactances and resistance of the probe as a function of frequency. Clearly, this approach allows a single code to solve a greater variety of problems than originally assumed. We can now treat resonance phenomena rigorously on the computer, without relying on trial-and-error laboratory mockups.

Because of the increasing use of transmit–receive (T/R) arrays in eddy-current NDE, we have included a discussion of N-port analysis of T/R arrays in Chap. 8. We tie N-port theory of microwave networks with chain matrices to derive equivalent networks for these arrays. This should help in designing and understanding the behavior of these networks, especially at higher frequencies, where resonance effects become important.

Part II is really where the fun begins, and computational electromagnetics becomes a part of NDE system theory. We believe that the application of sophisticated signal-processing and inversion algorithms lies at the heart of the future development of NDE into a solid engineering discipline that is capable of handling the challenging problems that new structures and materials introduce. Indeed, it will lead NDE into the digital age, in which the computer replaces the oscilloscope as the instrument of choice.

The mathematical algorithms of Part II, of course, were developed independently of computational EM, but it is here that the advantages of modern developments in computational EM are manifest. For example, the use of volume-integral equations leads quickly to the efficient calculation of "surrogate structures," such as the interpolation tables that are used in NLSE, the nonlinear least-squares estimator that is introduced in Chap. 12. NLSE is the workhorse for the rest of the book and has proven to be quite flexible and robust in solving a large class of problems, namely, those in which the anomalous region can be defined through the use of models containing a few parameters. (In the second volume in this series, we will introduce certain voxel-based inversion algorithms which are more powerful than model-based algorithms. The use of volume-integral methods will be even more crucial in the application of these algorithms. The reader will have to take our word for it, and be patient.)

The iterative algorithm described in Fig. 14.3 of Chap. 14 is reminiscent of the projection onto convex sets (POCS) that is described in Fig. 14.1, so we refer to the former algorithm as "POCS" occasionally in the remainder of the book, even though we have not yet proved that the relevant sets are in fact convex. At other times, bowing to the purists among us, we simply refer to it as "the iterative algorithm." We have plans to resolve the matter in the future, but in any case, the algorithms cited in Chap. 14 are not there simply for their looks; we will use all of them in this book or its sequel, especially in connection with voxel-based inversion algorithms.

The high point of the book, from our perspective, is Part III, where we tie the material of the first two parts into a demonstration of the power of computer-aided modeling and design in solving realistic problems in eddy-current NDE. The examples described in this part are taken from real-life problems that the authors have explored (and continue to explore), principally in the areas of aerospace and nuclear power. It is here that we hope to demonstrate the future of eddy-current NDE and make a case for the aforementioned assertion about the supremacy of the computer in that future. But the computer is useless without algorithms that are based on fundamental physics, and this is nowhere illustrated better than in Chap. 19, where we demonstrate that a straightforward application of electromagnetic theory via Maxwell's equations solves the problem of ferritic heat-exchanger tubes in an elegant manner. Prior to this application, the orthodox view of "eddy currents" was an inspection technique that relied on analog instruments and could only be applied to isotropic, nonpermeable conductors. This chapter, therefore, shows that the phrase "eddy-current NDE" really implies "electromagnetic NDE," in which "electric" and "magnetic" are unified, as Maxwell envisioned a century-and-a-half ago.

At times, the book may appear to be a user's manual, theoretical manual, or simply an advertisement for Victor Technologies' proprietary volume-integral code, **VIC-3D®** [40]. There are two reasons for this: first, **VIC-3D®** was written to solve precisely the problems that are described in the book and is the code best known to us for doing that, and second, we believe that it is important for the reader and industry to understand that computational electromagnetics is not reserved for graduate theses and academic papers but is a commercially viable tool for solving those problems that the industry needs to solve. **VIC-3D®** is our contribution to the list of codes that solve Maxwell's equations for profit.

This book is not an introductory text; it will require a good background in electric circuit theory, especially in understanding the concepts of phasors, impedance and admittance, magnetic fields, magnetic induction and inductances, and magnetically coupled circuits, as well as electromagnetic field theory, including Maxwell's equations. Material on electric circuits is usually covered in the sophomore year in electrical engineering courses, whereas the required background in electromagnetic fields is covered in upper-level undergraduate courses.

In teaching courses on electric circuits, we have found *Circuit Analysis*, by Elias M. Sabbagh, Ronald Press, 1961, to be excellent preparation. It covers all aspects listed above. Although long out of print, it is available on the internet at *very* low prices. Of more recent vintage is *Linear Circuit Analysis*, by Raymond A. DeCarlo and Pen-Min Lin, Oxford University Press, 2001.

When it comes to senior-level undergraduate texts on electromagnetic theory, we can do no better than to recommend the classic *Fields and Waves in Communication Electronics*, by Simon Ramo, John R. Whinnery, and Theodore Van Duzer, John Wiley & Sons, New York, 1965. It not only gives a precise development of electromagnetic theory, including Maxwell's equations and their applications, but also derives circuit concepts that are consistent with Maxwell's equations.

If the reader wishes to develop his/her own code for Green's functions, he/she will need to become familiar quite quickly with the notion of "special functions." The classic reference on this subject, *Handbook of Mathematical Functions*, edited by Milton Abramowitz and Irene A. Stegun, National Bureau of Standards, 1970, has been superseded by *NIST Handbook of Mathematical Functions*, edited by F.W.J. Olver, D.W. Lozier, R.F. Boisvert, and C.W. Clark, Cambridge University Press, 2010. We have also found *Table of Integrals, Series, and Products*, by I.S. Gradshteyn and I.M. Ryzhik, Academic Press, 1980, to be useful. Finally, to tie all of this together in meaningful computer codes, we recommend *Numerical Recipes: The Art of Scientific Computing*, by W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling, Cambridge University Press, 1986.

We hope that you, the reader, will find this book useful and that you will agree that it brings us closer to the goal of making eddy-current NDE a systematic branch of engineering science, resulting in a more reliable system for making products and materials safer.

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