Introduction to Electromagnetic Theory, Radiation and Antenna Theory, by Nirod K. Das

Preface

The material in this book have been developed by the author over recent years of teaching electromagnetics and antenna courses at the Tandon School of Engineering, New York University. Material from earlier chapters of the book can be used for a one-semester course on introduction to electromagnetics, at an undergraduate level. Suitable topics from different parts of the book can be arranged, in order to accomplish different level of emphasis on the waves and antenna radiation aspect of the above course. Material from the later part of the book would be well suited for a senior-level elective course, which focuses only on antennas and radiation. This elective course would normally follow a standard one-semester course on introductory electromagnetics, which presumably does not adequately emphasize on the antenna theory and radiation concepts. Suitable parts of the material in the book, covering more advanced concepts, may also be selected for an introductory graduate level antenna or electromagnetics course.

The style and content of different parts of the book may distinguish in many ways from those covered in other current texts. They were developed in response to current academic and engineering needs as well as students interests. The material has evolved, particularly in response to perceived gaps in available texts and teaching methods. This is based on the authors experience, reflecting back when he was learning the subject as a undergraduate or graduate student, as well as on continual feedback from students the author has taught over recent years.

Some of the significant highlights of the book include:

(1) Maxwell's equations first, not statics. Minimal or no dependence on electro- and magneto-statics, before Maxwell's equations are introduced.

(2) From cicuit theory to electromagnetics. The Maxwell's equations are introduced as a generalization from simple circuit theory.

(3) From relativity to electromagnetics. Simple derivation of the electomagnetic theory from relativity, taking some mystery away from the Maxwell's equations.

(4) Physical conceptualization without differential operators. No dependence on curl, divergence and gradient in order to develop key concepts. Integral principles are used instead, which are much more effective for basic physical conceptualization.

(5) Radiation analysis using plane-wave synthesis. Fields of elementary radiation sources are developed by superposing current sources for plane-wave radiation.

(6) Electrodynamics of radiation. Fields of a moving charge are developed, providing an alternate view point for radiation as an electrodynamic phenomenon.

(7) Antenna in a general scattering environment. Modeling of antenna performance in a scattering environment is introduced, in addition to conventional modeling in an ideal open environment.

(8) Near-field antenna modeling using Fourier analysis. Antenna input reactance, resistance, resonant condition, and mutual coupling between elements are formulated based on plane-wave synthesis of near fields, using basic Fourier analysis.

The significant new features are further expanded in the following, discussed in general sequential order with the associated chapters of the book:

- Electrostatics and magnetostatics are usually covered in physics, and it may not be necessary to cover these topics again thoroughly in an electrical engineering course. Only essential material on electro and magneto statics are covered in the chapter 1. This material may be quickly reviewed, in reference to a basic physics text, for continuity with developments of the electromagnetic theory in the following chapters. This would allow introduction of the Maxwell's equations of chapter 2, essentially in the beginning of an undergraduate course. Electrostatics and magnetostatics may be shown in chapter 2 to be only simple specialization of the Maxwell's equations, when there is no time variation (DC condition). This would save time for more advanced topics of wave propagation and antenna radiation, allowing adequate coverage of the advanced topics in a single undergraduate level electromagnetics course.

- Electromagnetic theory is introduced (chapter 2) as a generalization of circuit theory concepts. Kirchoff's voltage law (KVL) is generalized including induced emf, using the Faraday's law. Kirchoff's Current Law (KCL) is generalized by including two types of currents, both conduction as well as displacement currents. The KVL (Faraday's Law) is coupled to the KCL through a generalized Ampere's Law, which relates the magnetic field in the KVL (Faraday's Law) to the the conduction and displacement currents in the KCL. These generalized laws constitute the Maxwell's equations of the electromagnetic theory.

This approach can be particularly effective for electrical engineering students, by linking an electromagnetics course directly to a circuit theory course. It would help students, particularly at the undergraduate level, to understand and value electromagnetic theory in relation to the conventional circuit concepts which they are assumed to be already familiar with.

The circuit concepts using summation over a finite number of discrete circuit elements is easy to appreciate and grasp in the beginning. The integral forms of the Maxwell's equations are then developed as generalization of the circuit concepts to a distributed medium, which maybe treated as a generalized circuit by decomposing it into a large number of inter-linked circuit elements. The simple summation forms of the circuit relations then naturally transform into the integral forms of the Maxwell's equations, in the limit of infinite number of elements. The required circuit concepts can be introduced with minimal efforts. Considering the simplicity and economy, the circuit approach of introducing electromagnatic theory can be quite effective, even for students from applied physics without any formal circuit-theory background in electrical engineering.

- It is of fundamental significance to introduce electromagnetics in relation to the theory of special relativity. Maxwell's equation are developed from Gauss' Laws of electricity and magnetism using relativity, using a new approach presented in chapter 3. It uses fairly simple analysis, which can be effective even at the undergraduate level. Such an approach is being tried here for the first time in an introductory electromagnetics text. Connecting Maxwell's equations to relativity concepts would provide a modern view of the electromagnetic theory. It may help develop deeper insight and understanding of the electromagnetic theory, by taking some mystery away from the Maxwell's equations. The topic can be introduced in the early or late stage of an undergraduate class. It may be skipped, depending on available time or scope of the class, without any loss of continuity with the following chapters. The topic may as well be used to supplement a graduate level electromagnetics course.

- All basic concepts are developed using only summation (in discrete circuits) or integral (in distributed fields) without need for differential operators like curl, divergence and gradient. The integral or summation forms are clearly more intuitive, as compared to the differential operations, and therefore can be more helpful in physical or conceptual reasoning. Heavy dependence on differential operators in an electromagnetics class is known to be a major hurdle in introducing basic electromagnetic concepts to beginners, as well as in developing deeper physical insight even for advanced students. The general integral approach followed in this text is aimed to address the above difficulties. However, selected key expressions are also presented using differential operators, only as an alternate approach, that may be preferred at an advanced stage of learning.

- Signal propagation in a transmission line is covered in chapter 4. This topic is introduced as a basic engineering application of the electromagnetic theory, sequenced after development of the Maxwell's equations in chapter 2 from circuit principles. An alternate sequencing of the topics may be possible. By selecting suitable sections in chapter 4, the transmission line may be studied using only circuit modeling concepts, without full knowledge of the Maxwell's equations developed in chapter 2. Through the simple transmission line analysis, some valuable principles of wave propagation in one dimension and associated mathematical analysis can be introduced, early on. This background may be valuable, preparing students to study more general circuit concepts and electromagnetic theory developed in chapter 2, as well as for modeling more advanced wave propagation in a 3-dimensional material medium covered in chapter 5.

- Signal propagation in a uniform material medium, in the form of a simple plane electromagnetic wave, is covered in chapter 5. This topic is introduced as one of the basic application of the electromagnetic theory developed in the chapter 2. Basic differential equations and relations for a plane wave are derived from the integral forms of Maxwell's equations developed in chapter 2. The analysis is relatively simple, established without use of differential operators. The plane-wave relations along a given direction are generalized for propagation in any arbitrary direction in a 3-dimensional space, using geometric and trigonometric transformation of the coordinate system. The generalization is extended to evanescent waves as well. Reflection and transmission of plane wave through a single or multiple material layers are analyzed using boundary conditions as well as using equivalent transmission line models.

The simple plane-wave analysis is used as a basis to introduce vector potential functions, and to relate them to different field components in rectangular coordinates. The potential-field relations are then expressed in cylindrical and spherical coordinates, using simple geometric and trigonometric transformation from the rectangular coordinates. Any arbitrary wave in a locally uniform medium can always be synthesized as a superposition of general plane waves. Accordingly, the above potential-field relations are recognized to be general in scope, applicable to any arbitrary fields in a uniform material medium. Development of the general potential-field relations using the above approach avoids use of any differential operators, making the potential-field relations much easier to understand and derive. These relations would be particularly useful to model antenna radiation in the following chapter 6.

- Radiation form a small dipole antenna element is derived in chapter 6 using a plane-wave decomposition approach. This is developed as an alternate approach to a conventional derivation, which is heavily dependent on differential-operators. The conventional approach starting from a vector potential, and following differential-operator analysis to derive fields, is considered to be heavily mathematical in nature, lacking in physical understanding or insight.

- In addition to the dipole element, other elementary radiation sources such as a loop element, an infinite line source, and a moving point charge, are covered in chapter 6. A point charge under a general motion is the basic source of all electromagnetic fields and radiation. Radiation may be interpreted and modeled in terms of a charge motion, which provides a valuable alternate model of radiation, in contrast to formulations in terms a time-varying current distribution. An accelerating charge experiences a self-force, which may be interpreted to be partly due to (a) an equivalent "electromagnetic mass" associated with the reactive fields, and partly to (b) a radiative force associated with energy escaping away from the charge as radiation. These electrodynamic characteristics supplement basic concepts of antenna impedance and radiation, as well as carry independent value as fundamental physical concepts.

- General antenna parameters are covered in chapter 7. The derivation of conventional antenna parameters in chapter 7 generally follow conventional antenna texts. There are some new contributions in presentation and composition of the material. A general antenna is studied under three separate conditions of operation as a transmitter, as a receiver, and in a communication link. Two complex-vector antenna parameters - transmit and receive vectors - are developed, and they are related to each other as well as to antenna directivity and effective area, which are the respective scalar parameters. The above presentation may provide a more comprehensive understanding of antenna performance and parameters. A reciprocity relation is developed in the Appendix using circuit principles, which may be used to establish reciprocity relations between transmit and receive antennas. Accordingly, derivation of the antenna reciprocity conditions in chapter 7 may be covered without dependence on a more involved derivation of the reciprocity theorem from the Maxwell's equations in chapter 2.

- Antenna performance in a scattering environment is presented in chapter 8. The topic supplements material in chapter 7, which covers antenna performance only in a open free-space environment without any signal reflection or scattering. A scattering environment is clearly a more practical or realistic scenario for ground-based wireless communication, and a suitable modeling in such an environment would account for any effects from the surrounding natural or man-made structures such as building, mountains and trees. Such modeling is not commonly covered in standard antenna texts, but are addressed in ad-hoc forms in different wireless communication texts. It would be valuable to give due coverage to this material in an antenna text, with appropriate rigor and depth from an antenna theory perspective. Basic antenna parameters, describing performance specifically under practical scattering conditions, are established based on antenna theory and wave propagation concepts developed in the earlier chapters.

- Useful antenna elements and arrays are studied in chapters 9 and 10. Plane-wave decomposition of fields allows use of Fourier analysis for modeling of planar antennas. Thin wire antennas can be modeled essentially as equivalent planar strip elements. Near-field analysis of antenna performance, such as input impedance, resonance condition, and mutual coupling between elements, as well as moment method analysis of antenna current distribution, are covered through Fourier integration. Radiation from an antenna array is formulated as a superposition of radiation from its individual elements, by treating the elements operating in isolation from each other as a first-order approximation, or by including mutual coupling between the different elements for a rigorous model. Sufficiently large periodic arrays may be approximated as infinite periodic arrays, which may be directly modeled using Fourier series expression of its periodic current distribution, without having to model individual antenna elements and mutual couplings between each elements.

All the formulations can be implemented using MATLAB or any other numerical programming, which are now commonly accessible to university students. This material has valuable overlap with conventional signal analysis and communication classes. This can be attractive to electrical engineering students with overlapping interests in both signal communications and antenna theory, particularly in the wireless communication area.

Deficiencies in the different proposed approaches are sure to surface in the process of continual delivery to students. The material would go through its normal process of experimentation and future improvement, based on class-room experience and feedback from students. However, the content in the present form are hoped to carry essential elements of value. They may serve as useful focal point or framework for teachers, students and engineers to debate about, build upon and reshape to their own liking.

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