Chapter 1

Computational Electromagnetics

Historically, the design and analysis of electromagnetic devices and structures was largely experimental. However, once the computer and numerical programming languages were developed, people immediately began using them to solve electromagnetic field problems of ever-increasing complexity. This pursuit of *computational electromagnetics* (CEM) has yielded many innovative, powerful analysis algorithms, and it now drives the development of electromagnetic devices people use every day. As the power of the computer continues to grow, so do the number of available algorithms as well as the size and complexity of the problems that can be solved. While the data gleaned from experimental measurements is invaluable, the entire process can be costly in both money and the manpower required to perform the machining, assembly, and data collection at the measurement range. One of the primary motivations for reliable computational electromagnetics algorithms is the ability to simulate the behavior of devices and systems before they are actually built. This allows engineers to engage in levels of optimization that would be painstaking or even impossible if done experimentally. CEM also helps to provide fundamental insights into electromagnetic problems through the power of computation and computer visualization, making it one of the most important areas of engineering today.

1.1 CEM Algorithms

The range of electromagnetic problems is extensive, and this has led to the development of different classes of CEM algorithms, each with its own benefits and limitations. In the "early days" of CEM, many problems of practical size could not be solved unless assumptions about the underlying physics were made and approximations applied, usually under the asymptotic or high-frequency limit. These approximate algorithms are now commonly known as "high-frequency" methods. Algorithms that do not make these sorts of approximations are more demanding in terms of CPU and system memory, and historically have been limited to problems of small electrical size. These are

usually referred to as "exact" or "low-frequency" algorithms. Both classes of algorithms can be further subdivided into time-domain and frequency-domain methods. We will now summarize some of the most commonly used methods to provide some context in how the Moment Method fits in the CEM environment.

1.1.1 Low-Frequency Methods

Low-frequency (LF) methods are so-named because they solve Maxwell's Equations without implicit approximations, and are typically limited to problems of small electrical size due to limitations of computation time and system memory. Though computers continue to grow more powerful and can solve problems of ever-increasing size, this nomenclature will likely remain common in the literature for the foreseeable future.

1.1.1.1 Finite Difference Time Domain Method

The Finite Difference Time Domain (FDTD) method [1, 2] uses finite differences to solve Maxwell's Equations in the time domain. The application of FDTD is usually very straightforward: the solution domain is discretized into small rectangular or curvilinear elements, and a leapfrog time-stepping scheme is used to compute electric and magnetic fields from one another at discrete time steps. FDTD excels at analysis of inhomogeneous and nonlinear media, though its demands for system memory are high due to discretization of the entire solution domain, and it suffers from dispersion issues and the need to artificially truncate the solution boundary. FDTD is typically applied in EM packaging and waveguide problems, as well as the study of wave propagation in complex (often composite) materials.

1.1.1.2 Finite Element Method

The Finite Element Method (FEM) [3, 4] is a method used to solve frequency-domain boundary-valued electromagnetic problems via variational techniques. It can be used with two- and three-dimensional canonical elements of differing shape, allowing for a highly accurate discretization of the solution domain. FEM is often used in the frequency domain for computing the field distribution in complex, closed regions such as cavities and waveguides. As in the FDTD, the solution domain must be discretized and truncated, making the FEM approach often unsuitable for radiation or scattering problems unless it is combined with a boundary-integral equation method such as the Method of Moments [3].

1.1.1.3 Method of Moments

The Method of Moments (MOM) is a technique used to solve electromagnetic surface[1] or volume integral equations in the frequency domain. MOM differs from FDTD and FEM in that the electromagnetic sources (surface or volume currents) are the quantities of interest, and so only the surface or volume of the antenna or scatterer must be discretized. As a result, the MOM is widely used in solving radiation and scattering

[1] In this context, it is also referred to as the Boundary Element Method (BEM).

problems. In this book, we focus on the practical solution of surface integral equations of radiation and scattering using MOM.

1.1.2 High-Frequency Methods

Electromagnetic problems of large size have existed long before the computers that could solve them. Common examples of larger problems are those involving radar cross section prediction, or the calculation of an antenna's radiation pattern when in close proximity to a large structure. Many approximations have been made to the equations of radiation and scattering to make these problems tractable. Most of these treat the fields in the asymptotic (high-frequency) limit and employ ray optics and edge diffraction. When the problem is electrically large, many asymptotic methods produce results that are accurate enough on their own, or can be used as a "first pass" before a more accurate and computationally demanding method is applied.

1.1.2.1 Geometrical Theory of Diffraction

The Geometrical Theory of Diffraction (GTD) [5, 6] uses ray-optics to determine electromagnetic wave propagation. The spreading, amplitude, and intensity decay of a ray bundle are computed using Fermat's principle and the radius of curvature at the bounce points. GTD attempts to account for the fields diffracted by edges, allowing for a calculation of the fields in shadow regions. GTD is fast but the its accuracy is often fair to poor for complex geometries.

1.1.2.2 Physical Optics

Physical Optics (PO) [7] is a method for approximating the surface currents, allowing a boundary integration to be performed to obtain the fields. As we will see, PO and the MOM are closely related as they use the same equations to integrate the surface currents, however the MOM calculates the surface currents directly instead of approximating them. While robust, PO does not account for the fields diffracted by edges or those from multiple reflections, so supplemental corrections are typically added to it. The PO method is used extensively in high-frequency reflector antenna analysis, as well as many radar cross section prediction codes.

1.1.2.3 Physical Theory of Diffraction

The Physical Theory of Diffraction (PTD) [8, 9] is a means for supplementing the PO solution by adding to it the fields radiated by nonuniform currents along diffracting edges of an object. PTD is commonly used in high-frequency radar cross section and scattering analysis.

1.1.2.4 Shooting and Bouncing Rays

The Shooting and Bouncing Ray (SBR) method [10, 11] was developed to predict the multiple-bounce scattered fields from complex objects. It uses the ray-optics model to determine the path and amplitude of a ray bundle, but uses a physical optics-based

scheme that integrates the surface currents induced by the ray at each bounce point. SBR is often used in scattering codes, such as Tripoint Industries' *lucernhammer MT*, to account for multiple reflections from a surface or within a cavity, and as such it supplements the fields computed by PO and the PTD. SBR is also used to predict wave propagation and scattering in complex urban environments to determine the coverage for cellular elephone service.

References

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