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INTRODUCTION TO COMPUTATIONAL ELECTROMAGNETICS AND ELECTROMAGNETIC COMPATIBILITY

This chapter deals with some introductory considerations related to the two basic topics of this book: computational electromagnetics (CEM) and electromagnetic compatibility (EMC). Specific topics on CEM and EMC topics have been dealt throughout this book.

1.1 HISTORICAL NOTE ON MODELING IN ELECTROMAGNETICS

Electromagnetics as a rigorous theory started when James Clerk Maxwell derived his celebrated four equations and published this work in the famous treatise in 1865 [1]. In addition to Maxwell's equations themselves, relating the behavior of electromagnetic fields and sources, several other physical relationships are necessary for their solution. The most important are Ohm's law, the equation of continuity, and the constitutive relations of the medium and the imposed boundary conditions of the physical problem of interest. Before Maxwell, the science of electromagnetism had existed mostly as an experimental discipline for several centuries through the works of scientists such as Benjamin Franklin, Charles Augustin de Coulomb, André Marie Ampère, Hans Christian Oersted, and Michael Faraday. The early doubt about Maxwell's theory vanished in 1888 when Heinrich Hertz transmitted and received radio waves, thus having demonstrated the validity of the Maxwell theory.

The early works on analytical solution methods in electromagnetics, based on Maxwell's equations, were mainly focused on the area of radio science. Some of

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such applications of the electromagnetic theory started to appear not long after Maxwell's treatise had appeared. Among the analyzed simple geometries were the fields radiated from the Hertzian dipole, an infinitely long straight circular wire and two coaxial cones [2]. In most of the cases, the equations were solved as boundary value problems having yielded to the solution in terms of infinite series expansions.

Analytical methods in electromagnetics were unable to handle the practical engineering problems until computational electromagnetics came along. This was brought on by the advent of the digital computer in the 1960s. While much effort of the early research based on analytical methods was focused on the study of antennas in radio science, the emergence of computational electromagnetics opened up a number of new areas of applications. At the beginning, the emphasis was on high frequency radar systems related to defense. This was mainly due to the concentration of available research funds for such a work during that time. Indeed, in what is reported as one of the earliest cases of solving electromagnetic problems on a digital computer in the 1950s, the machine was built prompted by the need for calculating artillery ballistic tables [3].

Since that time, a continuing advancement in computational methods has been prompted by the rapid progress in computer hardware. Frequency domain integral equation techniques having simpler mathematical framework than their time domain counterpart started to appear in the mid 1960s [4–6]. One of the first digital computer solution of the Pocklington's equation was reported in 1965 [7]. This was followed by one of the first implementations of the finite difference method (FDM) to the solution of partial differential equations in 1966 [8] and time domain integral equation formulations in 1968 [9,10] and 1973 [11,12]. Through 1970s, the finite element method (FEM) became widely used in almost all areas of applied electromagnetism encompassing power engineering and electronics applications, microwaves, antennas and propagation, and electromagnetic compatibility. Good review of many important FEM applications in electrical engineering and electronics till date has been presented in Ref. [13]. The boundary element method (BEM) developed in the late seventies for the purposes of civil and mechanical engineering [14] started to be used in electromagnetics in 1980s [15,16]. Nevertheless, there have been many applications of BEM in electromagnetics; the primer of BEM for electrical engineers appeared quite recently [17].

With up to a dozen or more computational methods are nowadays commonly in use for electromagnetic modeling purposes, there is no particular method which can claim superiority over the whole range of applications [18]. The physical and mathematical base on which specific method has been built often gives it some advantage when dealing with a particular class of problem. Nevertheless, the integral equation formulation handled via the *method of moments* (MoM) with its wide application and versatility is accepted by many researchers to be a sort of "workhorse" in computational electromagnetics [19]. An excellent review of the numerical methods used in computational electromagnetics has been given in paper by Miller in 1998 [20]. Among many others, a rather comprehensive textbook on numerical methods in electromagnetics is the one by Sadiku [21], whereas a relevant review of theoretical models and computational methods used in electromagnetic compatibility is available in Ref. [22].

Analysis of wire antennas and scatterers and related EMC applications by using the integral equation approach has been presented in Ref. [23]. Direct time domain techniques for the solution of certain classes of EMC problems have been documented in Refs. [24, 25].

The present book features both frequency and time domain integral equation approach to the analysis of various problems arising in electromagnetic compatibility by using some direct and indirect schemes of the BEM.

Topics of particular interest covered in this book are related to wire configurations, that is, antennas, transmission lines, and grounding systems. The last chapter is devoted to human exposure to extremely low frequency (ELF) and transient exposures.

1.2 ELECTROMAGNETIC COMPATIBILITY AND ELECTROMAGNETIC INTERFERENCE

EMC is usually regarded as the ability of a device to function satisfactorily within its electromagnetic environment, that is a device, system, or equipment is assumed not only to be unaffected by external fields but also not to cause interference in sense of intolerable electromagnetic disturbances to a nearby system or anything in that environment. Satisfactory operation of a device, equipment, or system implies their functional work and immunity to certain interference levels which can be regarded as normal in the environment even under these circumstances.

Therefore, the principal task of EMC is to suppress any kind of electromagnetic interference (EMI). The first request is often regarded as *immunity testing*, that is, once the device is constructed it is necessary to check if it can be a potential victim of EMI or if it satisfies the EMC request of being unaffected by an external source produced by its electromagnetic environment.

The second request raised in the design process that device is not a potential EMI source that is its normal operation does not interfere with other electrical systems, is referred to as the *emission testing*.

In a theoretical sense, the aspects of immunity and emission testing, respectively, are related through the reciprocity theorem in electromagnetics [22, 23].

Generally, the methods used in EMC are not only to visualize electromagnetic phenomena but also to predict and suppress interferences can be regarded as either theoretical or experimental. This book is strictly oriented to the consideration of theoretical approach and related computational models in the analysis of EMC problems.

1.2.1 EMC Computational Models and Solution Methods

It is the rapid progress in the development of digital computers that has provided advances in EMC computational models in last few decades.

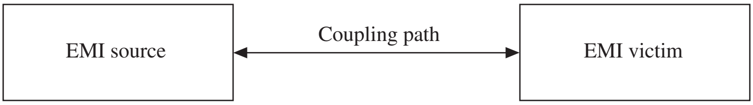

Figure 1.1 A basic EMC model.

Electromagnetic modeling provides the simulation of an electrical system electromagnetic behavior for a rather wide variety of parameters including different initial and boundary conditions, excitation types, and different configuration of the system itself. The important fact is that modeling can be undertaken within a significantly shorter time than it would be necessary for building and testing the appropriate prototype via experimental procedures. The basic purpose of an EMC computational model is to predict a victim response to the external excitation generated by a certain EMI source.

A basic EMC model, Figure 1.1, includes EMI source (radio transmitter, mobile phone, lightning strike, or any kind of undesired electromagnetic pulse (EMP), coupling path which is related to electromagnetic fields propagating in free space, material medium, or conductors, and finally, EMI victim that represents any kind of electrical equipment (e.g., radio-receiver), medical electronic equipment (e.g., pacemaker), or even the human body itself.

It is worth mentioning that the cost of EMC analysis at the design level represents up to 7% of the total product cost [22]. On the contrary, if a prototype is already produced, the subsequent incorporation of EMC measures can increase the cost of the product up to 50% of the total cost [22].

In principle, all EMC models arise from the rigorous electromagnetic theory concepts and foundations are based on Maxwell equations. The governing equations of a particular problem in differential, integral, or integro-differential form can be readily derived from the four Maxwell equations.

EMC models are analyzed using either analytical or numerical methods. Though both approaches can be used in the design of the electrical systems, analytical models are not useful for accurate simulation of electric systems or their use is restricted to the solution of rather simplified geometries with a high degree of symmetry (canonical problems).

On the contrary, a more accurate simulation of various practical engineering problems is possible by the use of numerical methods. In this case errors are primarily related to the limitations of mathematical model itself and the applied numerical method of solution, respectively.

In general, analytical and numerical techniques are used for a wide variety of purposes such as

- predicting system-level responses to EMI sources,
- evaluating the behavior of EMC protection measures,
- processing measures system test data.

The development of analytical and numerical modeling techniques has had a marked impact on the area of EMC. These techniques are used in the design, construction, test, and evaluation phases of Ref. [22]:

- defense electronic systems,
- communications and data transmission systems,
- power utilities,
- consumer electronics.

EMC computational models can be validated via experimental measurements or theoretically comparing the results to already well-established numerical models.

It is also possible to test a new model on some standard benchmark problems or on some canonical problems for which the closed-form solution is available.

1.2.2 Classification of EMC Models

There are many possible classifications of EMC computational models used in research and practical purposes [22–26].

Regarding underlying theoretical background EMC models can be classified as

- circuit theory models featuring the concentrated electrical parameters,
- transmission line models using distributed parameters in which low frequency electromagnetic field coupling are taken into account,
- models based on the full-wave approach taking into account radiation effects for the treatment of electromagnetic wave propagation problems

It is worth emphasizing that this book deals mostly with the full-wave EMC models based on the thin-wire antenna (scattering) theory.

Furthermore, taking into account different character of EMI sources, EMC problems [22–26]can be classified as

- continuous wave (CW) problems,
- transient phenomena.

The most general classification of EMI sources is the one related to natural and artificial (man-made) sources, respectively. The natural EMI source most commonly being analyzed is lightning. Regarding coupling path, EMI can be divided in two groups:

- conducted disturbances (induced overvoltages, voltage dips, switching, harmonics),
- radiated disturbances (lightning induced voltages, antenna radiation, crosstalk).

1.2.3 Summary Remarks on EMC Modeling

To reliably separate EMI source from its victim, regulations and standards become necessary. Standards set limits defining the acceptable and plausible (reasonable) level of susceptibility and provide individual testing of equipment.

EMI measurements and calculations carried out are related to

- radiated and conducted emission,
- radiated and conducted susceptibility.

Physical phenomena that represent EMI source, EMI victim, and coupling path between an EMI source and susceptible device can be modeled to a certain degree. The most important question is the level of the accuracy achieved within a given model. The main limits to EMC modeling arise from the physical complexity of the considered electric system. Sometimes even the electrical properties of the system are too difficult to determine or the number of independent parameters necessary for building a valid EMC model is too large for a practical computer code to handle.

The EMC modeling approach presented in this book is based on integral equation formulations in the frequency and time domain and related boundary element method of solution featuring the direct and indirect approach, respectively.

This approach is preferred over a partial differential equation formulations and related numerical methods of solution, as the integral equation approach is based on the corresponding fundamental solution of the linear operator and, therefore, provides more accurate results. This higher accuracy level is paid with more complex formulation than is required within the framework of the partial differential equation approach and related computational cost.

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