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EMC and BEM Engineering Education: Physics-Based Modeling, Hands-on Training, and Challenges

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Abstract

Educational challenges in EMC-BEM engineering and related issues are discussed in this paper. The importance of physics-based modeling and hands-on training are emphasized. Characteristic cases in EMC tests, measurements, modeling, and simulation are presented. Finally, some suggestions and a short-course outline are given for modern EMC-BEM education.

Keywords: Electromagnetic compatibility; engineering education; biomedical engineering education; modeling; simulation; electromagnetic measurements; electromagnetic scattering; FDTD methods; moment methods

1. Introduction

[This topic has also been invited for the special EMC Education Session at the IEEE EMC Symposium in Istanbul Turkey, May 11-16, 2003.]

Electromagnetic waves play an increasingly important role in communication, remote sensing, multi-sensor integrated systems, detection and identification (signal processing), microwave hardware design, compatibility, bio-electromagnetics and many other applications in extremely complex natural and/or man-made environments. Exponential growth in wireless communications and cellular telephony still continues. It has a critical importance in a wide range of applications, from education to health care, marketing to sports, etc. Wireless home networking methodologies, such as wireless local-area networks (WLANs) and wireless personal area networks (WPANs), have recently gained much of the technological attention. 3G technologies in wireless communication have started in service in a number of countries.

All these necessitate (1.) designing electronic devices and/or systems that mutually interfere less and less, and are less and less susceptible; (2.) a better understanding of the interaction between electromagnetic waves and human tissue, and taking precautionary steps against possible adverse health effects. These two requirements result in multidisciplinary EMC and BEM engineering. Roughly speaking, EMC (electromagnetic compatibility) and BEM (bio-electromagnetic) engineering deal with device-device and device-human interactions, respectively. EMC-BEM engineering is a multidisciplinary activity that involves electrical, mechanical, and system engineers, physicists, chemists, and medicine. It has design, testing, production, quality, marketing, and legal implications. EMC-BEM engineering is concerned with identifying, understanding, and managing the normally uncontrolled and very often unexpected transfer of electromagnetic energy from device to device, or from device to human tissue. A conventional electromagnetic engineer is concerned in great detail with a range of product-specific issues, whereas EMC-BEM engineers are concerned with all possible external electromagnetic influences on the environment.

Issues related to EMC-BEM engineering have been addressed from various platforms by experts for the last couple of years. For example, EMC education – or, broadly speaking, electromagnetic education – was addressed in a plenary session (organized by Leo Felsen) at the International Conference on Electromagnetics and Advanced Applications (ICEAA), held in Torino, Italy, in September, 2001; summaries of the presentations appeared in the *IEEE Antennas and Propagation Magazine* [2]. Certain technological and educational challenges that confront wave-oriented electromagnetic engineering in a complex computer and technology-driven world, with rapidly shifting societal and technological priorities in the 21st century – in a broad-brush look – were discussed by Leo Felsen and Levent Sevgi in [3]. They touched upon the educational issues required to ensure proper multidisciplinary exposure of new generations of computer-weaned students.

Allen Taflove, in his excellent feature article [4], presented basic motivations for studying electromagnetics. He outlined past and current military defense requirements first, and discussed important applications in high-speed communication, computing, and biomedicine that touch every of us. Dr. Taflove provided an inspiring look at how electromagnetics affects our lives. Levent Sevgi also discussed these issues in his book, to be published by the IEEE Press [5]. Part of his book, including educational and research issues related to numerical modeling and simulation, has just been taken into account in a special workshop/mini-symposium in Benevento, Italy [6], and will be presented in a tutorial session [7] in the IEEE EMC Symposium in Istanbul in May, 2003.

In this paper, first physics-based modeling and observable-based parameterization are taken into account. Educational challenges are then discussed. Designs, tests, and measurements in EMC engineering, modeling, and simulation challenges, and validation, verification, and accreditation (VV&A) aspects are presented. Finally, the conclusions are outlined.

2. Physics-based Modeling and Observable-Based Parameterization

Understanding EMC is important to the manufacture of less-interfering, less-susceptible, and more-compatible products [8]. The key issue here is the physics of the problem. Therefore, physics-based modeling and observable-based parameterization are essential.

Maxwell's well-known equations establish the physics of the electromagnetic waves and their interaction with matter, and form the basis for a real understanding of EMC-BEM problems and their solutions. There are two different solution approaches: analytical formulations, and direct numerical-simulation methods. An analytical model-based approach is shown schematically in Figure 1. The model is derived from Maxwell's equations under a given problem geometry (i.e., for given boundary conditions and medium parameters). Analytical models express solutions for the independent variables – such as electric- and magnetic-field components, or input-output voltages and currents – in terms of analytic functions (such as sine or cosine functions, Bessel and/or Hankel series, etc.). A computer program is required only to calculate an output value for a given input, supplied by the user.

The flowchart of a numerical model is given in Figure 2. The principal algorithm models the intrinsic behavior of electromagnetic fields, without reference to specific boundary and material configurations. Some well-known and widely used numerical approaches are listed in the figure. As shown, the generic numerical model is applied from the very beginning, and is augmented by boundary simulators and/or other peripheral units, such as near-field/far-field transformations. Different problems (with respect to geometry and medium parameters) can be accommodated by such models. The problem may be an antenna or a radar cross-section problem, where mostly far fields are of interest, or an EMC or BEM problem, where near fields are important.

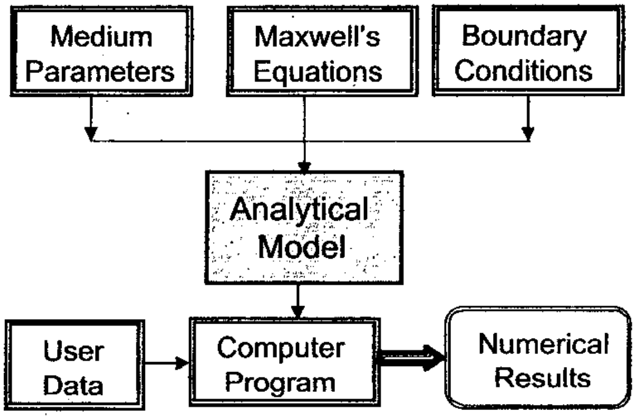

Figure 1. An analytical model-based approach.

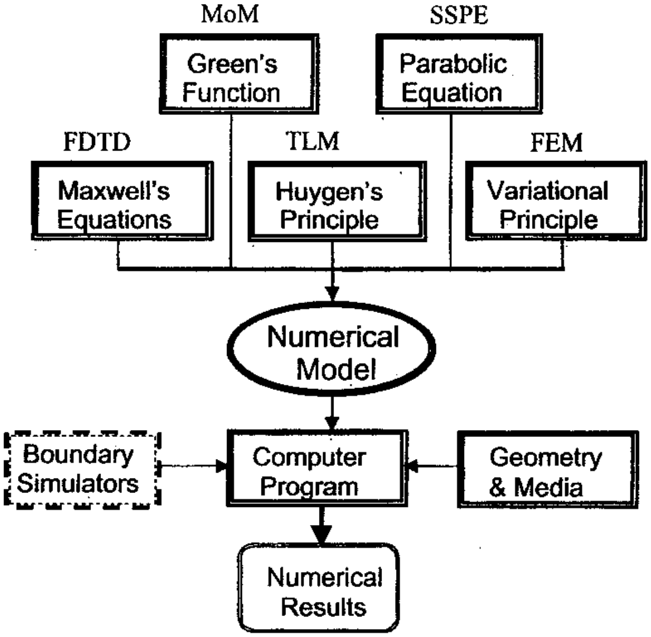

Figure 2. A numerical model-based solution.

Observable-based parameterization is as important as physics-based modeling. The models are established via well-known wave objects [3], such as wavefronts, wave packets, dispersive modes, or pulsed beams in the time domain; geometric-optic or uniform rays, normal, adiabatic, or intrinsic modes, or complex or parabolic beams, in the frequency domain; or hybrid forms of objects in both domains. The models parameterize a complex physical problem so as to take best advantage of the wave-oriented computational tools.

Whether analytical or numerical, models need to be coded for calculations by computer. While the model in analytical solutions is constructed according to the geometry of the problem (i.e., boundary conditions and medium parameters), the numerical model is general, and the geometry of the problem (together with the input parameters) is supplied after the model is built. That is, the boundary and/or initial conditions are supplied externally to the numerical model, together with the medium parameters, operating frequency, signal bandwidth, etc. Once these are specified, simulations are run, and sets of observable-based output parameters are computed for a given set of input parameters.

3. EMC-BEM Tests and Measurements

Most EMC-BEM problems do not obey regular rules and laws governed by well-known electromagnetic (wave-theory or circuit-theory) equations. They can be solely solved by experience, very often by trail and error. EMC deals with electromagnetic interference problems, where major design tools include screening, grounding, shielding, and filtering. BEM deals with understanding the effects of electromagnetic waves on human beings. They both concern tests and measurements in the near fields. Moreover, EMC-BEM problems should take into account the nonlinearity of the interactions, to some extent.

EMC activities include tests and measurements to determine the level of *emissions* from a product, and the product's *immunity* to the outside electrical environment, either by conduction or electromagnetic radiation. The frequency range has no specific limits, but is generally concerned with that part of the electromagnetic spectrum used for supply, industrial processes, communications, navigation, and radar. Immunity to disturbances and variations in the electrical-mains supply, such as spikes, surges, dips, and harmonics, are normally considered in EMC tests. The procedures for all EMC-BEM tests and measurements are specified by standards, either basic, generic, product-family, or product-specific.

Emission tests are quite straightforward. Although requirements like "the worst emission direction is determined first," or "main and auxiliary devices are connected in a way to yield highest emission," etc., make them difficult, emission tests and measurements are still easier than immunity tests. While measured emission values are recorded and compared with the threshold values specified in the related standards, quite different performance criteria are used for immunity tests, where the device under test is monitored in a high-level electromagnetic energy environment.

Concepts such as accuracy (the ability of an instrument to measure the true value within stated error specifications), precision (the ability to repeat measurements), and resolution (the smallest change in value that an instrument can detect) should be well-understood by EMC-BEM engineers. I've seen engineers who present their results with, for example, 12 digits of precision, while numerical errors limit them to, for example, eight digits, and while only two digits are meaningful, because of the approximations made.

4. Modeling and Simulation

Modeling and simulation are the most effective – if not the only – ways of solving complex electromagnetic problems, the analytical solutions of which cannot be obtained, or are yet unavailable. With today's high-capacity, high-speed computers, powerful numerical-simulation tools have been developed and successfully applied to a broad range of electromagnetic problems. EMC-BEM problems are among these types of problems. The methods listed in Figure 2 – such as the Finite-Difference Time-Domain (FDTD), the Transmission-Line Matrix (TLM), the Finite Element (FEM), and the Method of Moments (MoM) – have become among the most valuable tools in EMC-BEM engineering.

Simulation in electromagnetic engineering usually refers to the process of representing the dynamical behavior of a "real" system in terms of the behavior of an idealized, more-manageable model system, implemented through a computation via a simulator. The fundamental building blocks of a simulation are [9] the real-world problem entity being simulated, a conceptual model representation of that entity, and the computer-model implementation of the conceptual model. The suitability of the conceptual model, verification of the software, and data validity are the technical processes that must be addressed to make a model *credible*. Credibility resides in two important checks that must be made in every simulation: validation and verification. Validation is the process of determining that *the right model is built*, whereas verification is designed to see if *the model is built right*.

Doing numerical simulations in electromagnetics is as easy (as well as being as difficult) as doing measurements. It is easy, because we can purchase commercial codes that do almost everything for us, such as supplying a computer-controlled device for measurements. The simulation packages include almost everything, all are user-friendly, all have self-checking routines for control, and all are calibrated, like most high-tech measurement devices. On the other hand, we are in real trouble if we don't know what to do with the results (the numbers we obtain), or if we have no idea what to expect from the simulation or measurement. Unlike common opinion, we have to understand the physics of the problem well, since we may frequently be puzzled even with the simplest mathematical relations.

The interpretation of the results is as important as validation, verification, and accreditation in EMC-BEM simulations. Numerical modeling can easily lead to non-physical results, or results may be used beyond their range of validity. It should be remembered that every numerical simulation is the result of the addition of correctly represented physical process, errors caused by the numerical method itself, simplification of the physical structure, machine computation limitations, and more. It is a challenge to establish confidence in the results of numerical simulations.

An example is given in Figure 3 to emphasize the importance of the experience required when dealing with EMC-BEM tests, measurements, or simulations. Here, the scattering properties of a perfectly electrically conducting rectangular prism are shown for two different frequencies. The prism is illuminated by a plane wave from the direction shown in the figure, and its bistatic radar cross section is plotted. These represent the results of two different simulators (FDTD on the left, and MoM, on the right), where top

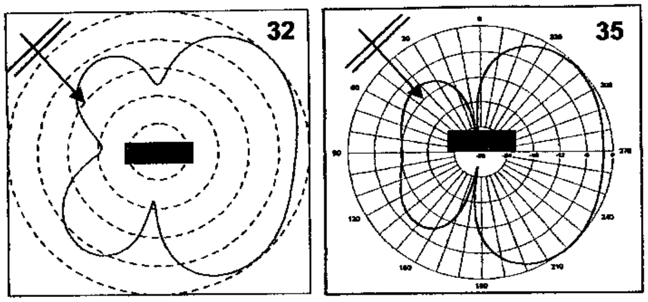

Figure 3a. A typical numerical result: FDTD (left) versus MoM (right), $f = 10$ MHz, $\ell = \lambda$.

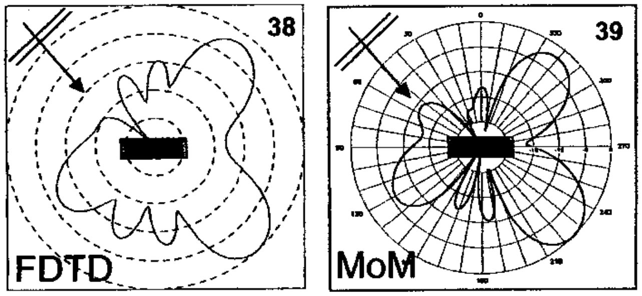

Figure 3b. A typical numerical result: FDTD (left) versus MoM (right), $f = 20$ MHz, $\ell = 2\lambda$.

views are plotted (other parameters are not mentioned, since the aim is not to discuss the problem itself). The results agree very well, but one should know the capabilities and accuracies of both methods, in order to describe the reasons for the slight discrepancies. The FDTD is based on discretization and a solution of Maxwell's equations directly in the time domain, so it may be accepted as a reference solution (as long as the parameters are chosen accordingly). On the other hand, the *NEC2* simulator was used for the MoM calculations. It does not take the (secondary) diffraction effects into account. With this in mind, one can understand why the nulls in the MoM results are much deeper than in the FDTD results (diffracted energy fills out the nulls, in this case).

Dealing with BEM problems certainly requires one to be more careful about the results, and more sensitive while doing interpretations and public announcements. As we all know, a new pollution discussion – EM pollution – has been raised in public all around the world, parallel to an exponential increase in the number of cellular phone users. Because of the lack of information and long-term experimental and epidemiological studies, there exist contradictory opinions on EM-exposure safety levels in society. Different governmental offices, universities, media, and non-profit organizations may have different approaches to this problem. Since the available scientific knowledge is far from ending these discussions, this is a normal situation. Beliefs may totally be different from one group to another. It is the obligation of the BEM engineers not to confuse beliefs with scientific studies and results. BEM engineers must be very careful when choosing words. For example, "effect" does not necessarily mean "harm." Saying "No adverse effect has been observed" does not necessarily mean "there is no adverse effect."

I've seen young EMC-BEM engineers who investigate, for example, the specific absorption rate (SAR) distribution inside a human head near a cellular phone, either experimentally or numerically. Finding a SAR distribution lower than permissible thresholds in the standards, they may directly derive a conclusion, such as "it is found that mobile phones do not cause any harm" or "base stations cause no adverse health effects," etc., instead of just saying "measured or simulated SAR levels were below the safety levels," while experts discuss risk assessment and precautionary principles because of the lack of dependable data. Some go further and use technical words, such as physiology or epidemiology without knowing their exact meanings.

5. EMC-BEM Education

Electromagnetic engineering, in general, and EMC-BEM engineering, to be specific, occupy a special place in electrical engineering, which is the foundation of many different disciplines. The interdisciplinary character of EMC-BEM engineering requires new approaches to educate the *modern* engineer. As pointed out by Felsen [2],

> To teach the necessary analytic underpinnings to a generation of students that has grown up with computers – commonly believing that computers, as such, solve complex problems, and that the printouts furnish physical insight – is a challenge to the academic community.

With what and to what extent a student will be equipped in engineering education should be specified according to the rapid shifts in societal needs.

An EMC-BEM engineer should question his/her results at each step of either experimental or numerical studies. Questions like

- Now, what? What am I going to do with these data?
- Are they meaningful? What do the numbers mean to me?
- What should I have expected before the experiment or simulation?
- How do I check my results? Are they in the validity region of my model?
- What physical conclusions should I derive?

must be asked, in order to avoid strange results and misleading conclusions. Some general remarks related to EMC-BEM engineering may be listed as follows:

- An EMC-BEM engineer should understand the physics of electromagnetics, fundamental theorems and principles.
- Hands-on training is a must in EMC-BEM engineering education.
- Although labs and test instruments have been simulated as virtual-reality environments that are as good as the real environment, I believe students still need hands-on training.
- Basic lectures, such as "measurement techniques," should be renewed accordingly.
- Computer simulations are as good as hands-on training, therefore, modeling and simulation lectures should be included in EMC-BEM discipline.

- EMC-BEM problems usually do not agree with our expectations. The most dangerous case may be the case when the results of the measurement or simulation agree with what we expect (i.e., what we feel, with our partial knowledge). Therefore, an EMC-BEM engineer should never be sure of the results until all critical checks are finished.

- EMC-BEM engineers become more publicized in parallel with the exponential growth in wireless communication. They may attend public meetings and regional activities to answer questions related to mobile phones, base stations, and safety. Therefore, lectures like "Science, Technology, and Society," or "Public Understanding of Science" should be included in this education [10].

Although not sufficient, electrical, electronic, and electromagnetic engineers may be trained as EMC-BEM engineers after a two-to-three-day condensed, post-university course, with a typical course outline as given below:

Day 1

- **EMI, Electromagnetic interference and compatibility**
  - Electromagnetic spectrum
  - Interference and coupling
  - Compatibility and susceptibility
- **EMC - BEM Organizations**
  - IEC, CENELEC, IEEE
  - IRPA, ICNIRP, WHO, European EMC Directive
- **Standards and limits**
  - Basic standards
  - Product family and product-specific standards
- **Electromagnetic concepts and definitions**
  - Electromagnetic fields and waves
  - Antennas and propagation
  - Electrical and magnetic sources
- **Transmission Line Modeling**
  - Lumped and scattered parameter modeling
  - Low and high-frequency equivalents of basic circuit elements
  - Filter design with RLCG
  - Crosstalk

Day 2

- **Nonlinearity and intermodulation effects**
  - Harmonics and their effects
  - Intermodulation effects
  - Flicker effects
- **Stochastic processes and noise analysis**
  - Signals and their behaviors
  - Noise spectrum, SNR, SIR
- **Frequency analysis**
  - Fourier transformation and series
  - Discrete Fourier transform
  - FFT, DFT
- **EMC and numerical modeling**
  - FDTD, TLM
  - MoM and SSPE
  - FEM

Day 3

- **Tests and measurement environments**
  - Open field test sites
  - Screened room measurements
  - Anechoic test rooms
- **EMC Tests and measurements**
  - Electromagnetic interference measurements
  - Conducted and radiated interference measurements
  - Electromagnetic compatibility and susceptibility measurements
  - Compatibility with conducted interference
  - Compatibility with radiated interference
  - Electrostatic Discharge tests, EMP, EFT
- **EMC Tests and Evaluation**
  - Error analysis
  - Evaluation and interpretation
- **EMC Design and protection techniques**
  - Screening, grounding, shielding, filtering
  - PCB design and microstrips
  - Cables and connectors
- **BEM and public concern**

There are departments, institutes, research teams, as well as EMC companies, which organize special EMC courses internationally. A quick search with this title on any Internet search engine will immediately list tens of them from the USA to Europe, Africa to the Far East, all around the world.

6. Conclusions and Discussion

Certain issues that confront EMC-BEM engineering in the 21st century have been addressed in this paper. Educational challenges that deserve the attention of the engineering community as a part of society in a rapidly changing, Internet-driven, globalized world have been discussed. The explosive growth of computer capabilities has revolutionized communication and the analysis of complex systems, and has made interdisciplinary exposure necessary in modern engineering.

The EMC-BEM engineer, either individually or as member of a team, can play an important role in this technically diverse mosaic. Rapid scientific advances, followed by rapid advances in technologies, are here to stay, and the engineering community must be prepared to adapt to frequent shifts in technical priorities.

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Limitations of the Thévenin and Norton Equivalent Circuits for a Receiving Antenna

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Keywords: Antennas; equivalent circuits; receiving antennas; electromagnetic scattering

The investigation carried out in this paper was stimulated by a recent paper published by Love, in which the appropriateness of the use of the Thévenin and Norton equivalent circuits for a receiving antenna was questioned [1]. A review of the available literature led to the conclusion that the limitations inherent in the Thévenin and Norton equivalent circuits had not been adequately examined, and this led to the investigation that is reported on in this paper. The Thévenin and Norton equivalent circuits are useful in the reduction of the equivalent circuit for a transmitting-receiving antenna system to simpler networks that facilitate the evaluation of the received power. One finds in the literature that the calculated power dissipation within these equivalent circuits is often equated to the reradiated and scattered power from the receiving antenna [2]. Such calculations are not correct, because power dissipation in the network from which the Thévenin and Norton equivalent circuits were obtained cannot be made using the Thévenin and Norton equivalent circuits. However, as we will show, the Thévenin and Norton equivalent circuits can be used to find a reradiated electromagnetic field that is a part of the total field scattered by a receiving antenna. As part of the derivation of this new result, we develop a derivation of the Thévenin and Norton equivalent circuits from the basic principles of uniqueness and superposition applied to electromagnetic fields.

Consider the representation of a transmitting and receiving antenna system as shown in Figure 1. The receiving antenna is terminated in a load impedance Z_L at its terminal plane, T_1, and the transmitting antenna has a generator with EMF V_g in series with an impedance, Z_g, connected at its terminal plane, T_2. Silver has shown that an equivalent circuit of the form shown in Figure 2 exists for any two antennas that are coupled to their respective source and load terminations by transmission lines or waveguides supporting single propagating modes, such that equivalent terminal voltages and currents can be defined on the terminal planes [3]. Power conservation for this transmitting-receiving antenna system can be established by integration of the real part of the Poynting-vector flux over the metal bounding surfaces of the two antennas, plus the terminal planes of the two antennas, and the surface of an

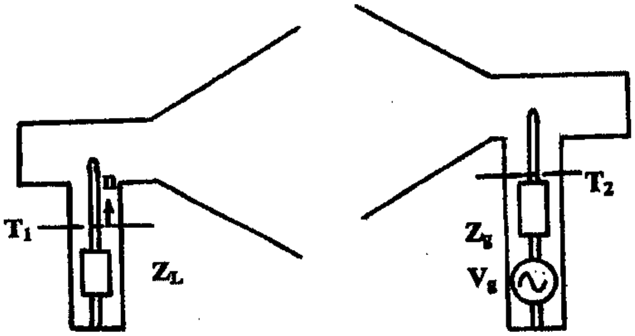

Figure 1. An arbitrary transmitting-receiving antenna system.

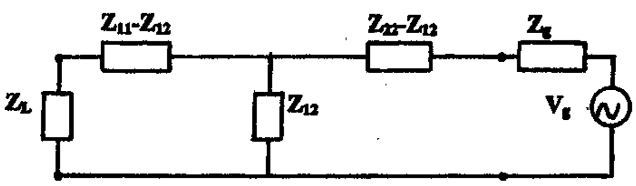

Figure 2. The equivalent network for the transmitting-receiving antenna system in Figure 1.