

Modeling Experiences with Full-Wave Frequency-Domain Modeling Software

Changyi Su, Xinbo He, Hua Zeng, Haixin Ke, and Todd Hubing
Clemson Vehicular Electronics Laboratory
Clemson, SC, USA

Abstract— When evaluating electromagnetic modeling software, there is usually a significant focus on the “accuracy” of the software. Differences between the results generated by the software and the “correct” solution are the result of several potential sources of error including: approximations made in order to represent the actual configuration as a structure that the software can understand; approximations made during the discretization and solution of Maxwell’s equations; and differences between what the modeler wants to analyze and what the software is actually modeling. In this paper, three full-wave frequency-domain EM modeling codes are evaluated by analyzing three simple canonical problems. These codes employ the two most common frequency-domain modeling techniques; the Finite Element Method (FEM), and the Boundary Element Method (BEM). The three canonical problems are a center-driven dipole, a circuit board power-bus structure, and a power-bus structure with a cable attached. All of the codes are capable of yielding accurate results, but the differences in the specific technique employed and the user interface have a significant effect on the simulation time and the likelihood of getting the correct answer.

Keywords— Electromagnetic modeling, finite element methods, moment methods.

I. INTRODUCTION

Full-wave electromagnetic modeling software is widely used to analyze antenna and microwave circuit configurations. It also has many applications related to the analysis of unintentional RF transmitters or receivers where electromagnetic interference (EMI) or susceptibility to electromagnetic fields is a concern. There are many commercial EM modeling tools available [1] ranging in price from a few hundred dollars to tens of thousands of dollars. There are also several free codes available [2]. Most of these tools are capable of analyzing a wide range of configurations that are relevant to EMC engineers.

In this paper, three full-wave frequency-domain EM modeling codes are evaluated by analyzing three simple canonical problems. These codes employ the two most common frequency-domain modeling techniques; the Finite Element Method (FEM), and the Boundary Element Method (BEM). Frequency-domain codes, in general, are well suited to the analysis of narrow-band sources or structures where the properties of the materials are well defined functions of frequency. Frequency-domain codes are also well-suited for analysis by parallel machines, where each frequency can be analyzed independently on a different processor. They can be relatively inefficient for analyzing geometries with sharp

resonant peaks in the response, unless they employ interpolation software capable of detecting peaks that occur at frequencies in between the frequencies analyzed.

The three canonical problems analyzed in this paper are a center-driven dipole, a circuit board power-bus structure, and a power-bus structure with a cable attached. A companion paper, [3], analyzes these same three canonical problems using time-domain software.

II. FEM vs. BEM MODELING SOFTWARE

All of the most popular time-domain electromagnetic modeling software is based on techniques that solve Maxwell’s equations in their differential form. As a result, there is relatively little difference in the capabilities of these codes and choosing the best code is often more a matter of choosing the best implementation rather than the most appropriate technique. Frequency-domain software on the other hand comes in two very different varieties. Commercial FEM software employs a technique that solves Maxwell’s equations in their differential form (like most time-domain software). The solution procedure requires that the entire volume be gridded including any free space. Boundary conditions must be specified on the entire outer surface of the volume, so absorbing boundary elements are required to terminate the grid when modeling “open” radiation problems.

BEM software (also commonly referred to as Moment Method software by electromagnetic modelers) is based on a technique that solves Maxwell’s equations in their integral form. This procedure requires only the interfaces between any two different materials to be gridded. It is not necessary to grid the entire volume. Generally speaking, FEM electromagnetic modeling software excels at modeling confined structures with complex geometries and inhomogeneous materials. BEM software is better suited for modeling open metal structures. Modeling problems that combine large structures with regions of fine detail or complex materials can be extremely impractical using BEM software. On the other hand, modeling open radiating structures, particularly with long wires, can be equally difficult using FEM software.

Nevertheless, both FEM and BEM techniques are very powerful and widely used. Many people who rely heavily on electromagnetic modeling tools have both types of software. There are also hybrid codes that are capable of applying FEM and BEM techniques to different parts of a structure in one simulation.

III. CANONICAL PROBLEMS

In this paper three commercial frequency-domain codes were used to model three different canonical problems. Code A employs a FEM solver, Code B employs a BEM solver and Code C is a hybrid FEM/BEM code. The canonical problems evaluated are a 1-meter center-driven thin wire dipole, a parallel plate structure resembling a circuit board power bus, and the same parallel plate structure with a 1-meter wire attached.

These problems are generally simpler than the canonical structures described on the website of the IEEE EMC Society TC-9 subcommittee [4]. The reason for choosing the simpler structures was to reduce the number of possible interpretations of the structure and ensure that there was only one well defined solution to each problem.

All computations are carried out on a PC with a dual-processor CPU clocked at 2.13 GHz and 3.25 GB of RAM.

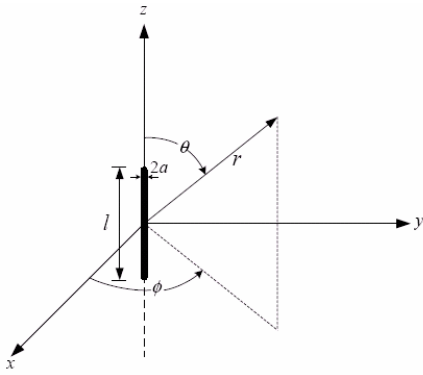


Fig. 1. Dipole antenna geometry.

A. 1-meter center-driven dipole

The geometry of the center-driven dipole is shown in Fig. 1. The dipole has a length, $l = 1$ meter and a radius, $a = 0.5$ mm. The half-wavelength resonant frequency is 150 MHz and the corresponding input impedance for an infinitely thin dipole would be $73 + j42.5$ ohms at this frequency. However, the input impedance varies as a function of the l/a ratio. A more accurate impedance is computed using Pocklington's integro-differential equation [5] and the actual input impedance of a 1-m long dipole with a radius of 0.5 mm is closer to $83 + j45$ ohms.

The user interface for each code allows the user to model the wire in different ways. The wire can be modeled like a cylinder by gridding around its surface with very small elements; it can be modeled as a flat ribbon that has a width equal to 4 times the wire radius; or it can be modeled using a thin-wire approximation where the wire is segmented into one dimensional current elements. The accuracy and the efficiency of the simulation are greatly affected by this choice, but the user interface generally provides no guidance to the user. In some cases, the default choice was not the most efficient.

The input resistance and reactance of the 1-m dipole computed using the three codes are listed in Table 1. All three codes compute a reasonably accurate input impedance at the

resonant frequency. Since both CODE B and CODE C use a BEM-based solver for this particular problem, it is not surprising that they calculate almost the same input impedance.

Table 1. Input impedances for the center-driven half-wave dipole.

Code	Real part (ohms)	Imaginary part (ohms)
CODE A	73.3	44.7
CODE B	81.56	45.49
CODE C	81.29	45.82

In FEM, absorbing boundaries are used to simulate open problems that allow waves to radiate to the far field. The accuracy of the radiation approximation depends on the distance between the absorbing boundary and the radiation source. Generally, the absorbing boundary surface must be located at least one-quarter wavelength from the radiating source. In this case, the FEM code self-selected a cylindrical radiation boundary whose radius was 0.5 m and height was 2 m. Since the entire volume inside the boundary had to be meshed, the FEM code was less efficient for analyzing this type of problem. This observation is illustrated by the simulation times shown in Table 2. The simulation times required by CODE B and CODE C were much less than that of CODE A. However, shorter simulation times were obtained using CODE A when the round wire was modeled as a flat ribbon with a 3.2-mm width. The input impedance obtained using this equivalent model was $71.6 + j35.3$ ohms and the simulation time was only 15 minutes. The reason for the efficiency difference between the two BEM methods (CODE B and CODE C) was that CODE B employed a built-in interpolation algorithm, that calculated the results at all frequencies based on a small number of sample frequencies (20 samples in this problem). CODE C, on the other hand, computed a fixed number of linearly spaced frequency points (91 points in this problem).

Table 2. Time required to analyze the center-driven half-wave dipole.

Code	Simulation time
CODE A	1 hr 6 mins
CODE B	1 min
CODE C	25 mins

B. Modeling a power bus structure

This canonical geometry is basically a pair of perfectly conducting planes with a slightly lossy dielectric material between them. It emulates a printed circuit board power bus (or microstrip patch antenna), which can be a significant source of radiated emissions at frequencies corresponding to resonances of the cavity formed between the planes. Fig. 2 shows the structure under study. The board dimensions are 125 mm x 100 mm x 1 mm. The relative permittivity of the dielectric is 4.5, and the loss tangent is 0.015. A 1-volt source is placed at the midpoint of the 100-mm edge. All conductors are assumed to be perfectly conducting. The input impedance and radiated electric field are calculated from 5 MHz to 2 GHz at a distance of 3 m.

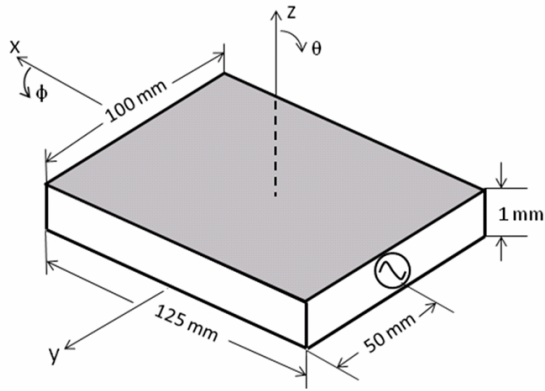


Fig. 2. Power bus geometry.

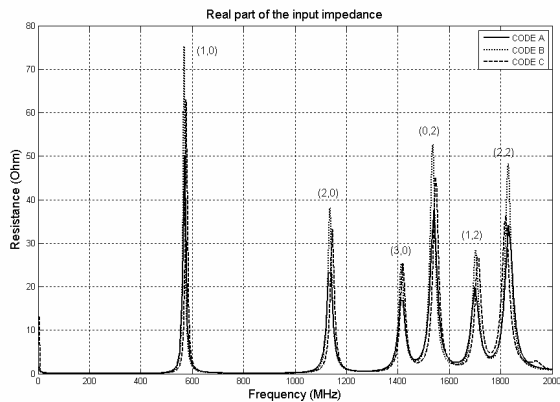


Fig. 3. Real part of the input impedance.

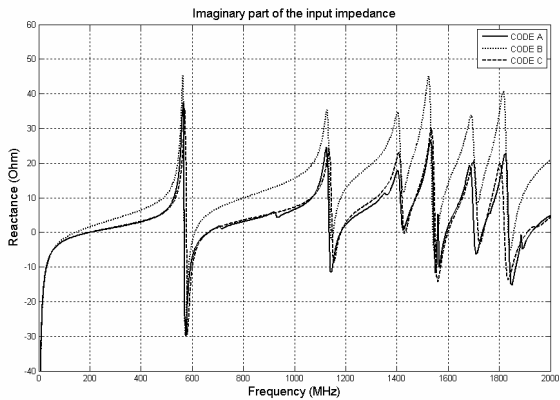


Fig. 4. Imaginary part of the input impedance.

The input impedance as shown in Figure 3 exhibits all the expected resonant frequencies associated with the power bus structure. The board is expected to resonate at 565 MHz (1, 0), 1.13 GHz (2, 0), 1.69 GHz (3, 0), 1.41 GHz (0, 2), 1.52 GHz (1, 2), and 1.81 GHz (2, 2). Since the voltage source is placed at the midpoint of the shorter edge of the board, three cavity resonances (0, 1), (1, 1), and (2, 1) are not excited. All three codes produce results that illustrate the resonant peaks below 2 GHz. However, the frequencies computed by CODE C are slightly shifted and the magnitude of the impedance computed by CODE B does not exactly match the results obtained from the other two codes.

The factors affecting the accuracy of the results come from the inherent limitations of the code and some of the decisions that the user must make before performing the simulation. In addition, user-defined simulation parameters affect the total simulation time. The power bus has a relatively simple conductor/dielectric region, which allows a pure BEM-based method with an ability to model dielectrics, such as CODE B, to work efficiently. As shown in Table 3, with a similar mesh density, CODE B is much faster than the other two codes. However, a BEM-based approach would not be able to model a highly inhomogeneous structure. By employing a FEM-BEM hybrid method, CODE C is capable of modeling structures with complex conductor/dielectric regions.

Table 3. Time required to analyze the power bus.

Code	Number of triangles	Number of tetrahedra	Simulation time
CODE A	0	39325	12 hrs
CODE C	952	2390	22 hrs
CODE B	938	0	2.5 hrs (discrete)
CODE B	938	0	15 mins (interpolated)

The interpolation capabilities of CODE A and CODE B are helpful when modeling high-Q problems. The time and memory requirements are greatly reduced for broadband characterization of resonant structures such as this. For the coarse mesh with 938 triangles, CODE B runs for only 15 minutes using the interpolated sweep.

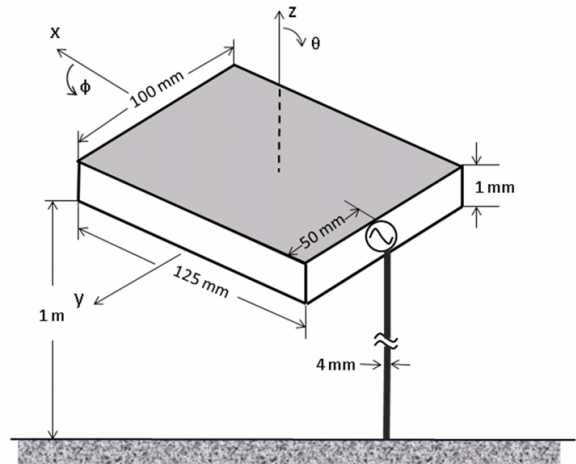


Fig. 5. Power bus with cable geometry.

C. Modeling a power bus structure with a cable attached

Modeling a printed circuit board alone in free space can be challenging, but printed circuit boards usually have cables attached to them and are nearly always tested above a conducting ground plane. Adding a cable and a ground plane to the geometry of the previous problem significantly complicates the modeling process. Several codes are not capable of modeling this geometry and nearly all of the codes have difficulty with it. This problem incorporates many basic features typically found in practical problems of interest to EMC engineers.

Fig. 5 shows the power bus with cable structure (not to scale). The circuit board has the same dimensions with the previous model. A 1-meter-long cable is attached to the ground plane of the PCB at the source location, and the other end is connected to an infinite ground plane.

For modeling a structure like this with a long thin cable using FEM, it is generally necessary to fill the empty space around the cable with many elements that transit from the object of interest to the absorbing boundary. This can require a very large number of elements to fill this volume. In this simulation, the first resonant frequency associated with the 1-m long cable appears at about 50 MHz. The radiation boundary needs to be at least a quarter wavelength (1500 mm @ 50 MHz) from the edge of the structure, so a cylindrical boundary with a radius of 1562 mm and height of 2000 mm was used. As shown in Fig. 6, with a smaller boundary radius (212 mm), the peak values of the electric field are inaccurate. However, all the resonant frequencies associated with the circuit board are higher than 550 MHz. At these frequencies, such a huge radiation boundary is totally unnecessary. The magnitude of the electric field at frequencies higher than 300 MHz was computed and illustrated in Fig. 7. The observation point is $\theta=90^\circ, \varphi=0^\circ$. To guarantee an accurate response at low frequencies (<300 MHz) and save time at high frequencies (>300 MHz), two meshes were used to solve the problem. This meant extra time was required to set up the model and post-process the data, but it significantly reduced the simulation time. Simulation times for each code are shown in Table 4. The simulations in Table 4 were done in 5 MHz steps. Both CODE A and CODE B have an option to calculate fewer frequency points with interpolation, which yields similar results in less time. CODE C uses BEM elements instead of absorbing boundary elements to terminate the open volume. These elements do not have to be a quarter-wavelength away from the radiating elements so the number of volume elements in the FEM region is greatly reduced (especially at low frequencies).

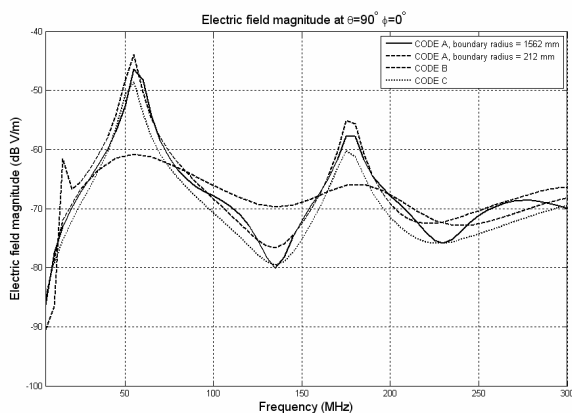


Fig. 6. Electric field magnitude 10 m from the power bus with cable geometry at $\theta = 90^\circ, \varphi = 0^\circ$ (5 MHz – 300 MHz).

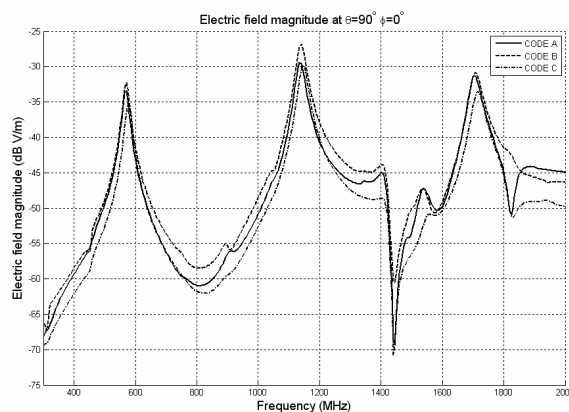


Fig. 7. Electric field magnitude 10 m from the power bus with cable geometry at $\theta = 90^\circ, \varphi = 0^\circ$ (300 MHz – 2 GHz).

Table 4. Time required to analyze the power bus with cable.

Code	Simulation time
CODE A	29 hrs
CODE B	26 hrs
CODE C	29 hrs

IV. CONCLUSIONS

In this paper, frequency domain electromagnetic modeling codes were evaluated by applying them to selected canonical problems. The results show that all three codes were capable of generating reasonably accurate solutions (within 3-5 dB of each other); however there was a significant difference in the efficiency of a given code depending on the type of problem being analyzed. Not only was the technique used by the code important, but the specific implementation of that technique and the user-interface were also significant factors in determining the accuracy and efficiency of a given code when applied to a specific problem.

Each of the codes evaluated required the user to have a great deal of knowledge about the software, the technique being applied and the expected solution. Accepting the defaults suggested by the software user interfaces often caused the software to produce incorrect results without any indication to the user that something was wrong.

REFERENCES

- [1] “Commercial Electromagnetic Modeling Codes,” Clemson Vehicular Electronics Laboratory website: <http://www.cvel.clemson.edu/modeling/EMAG/csoft.html>.
- [2] “Free Computational Electromagnetic Modeling Codes,” Clemson Vehicular Electronics Laboratory website: <http://www.cvel.clemson.edu/modeling/EMAG/free-codes.html>.
- [3] H. Zeng, et. al., “Modeling Experiences with Full-Wave Time-Domain Modeling Software,” to appear in the 2008 IEEE International Symposium on EMC, Detroit, MI, Aug. 2008.
- [4] IEEE TC-9 EMI Modeling web page: <http://www.ewh.ieee.org/cmte/tc9/>.
- [5] Balanis, C. A., *Antenna Theory: Analysis and Design*, 3rd edition, John Wiley & Sons, Inc., New York, 2005.