APRIMER ON ANTENNA MODELING

1. Planar Antennas

Every wireless communication system has one or more antennas at its front end. Antennas are used to launch wireless signals into the free space in a transmitter system or pick up wireless signals from the free space in a receiver system. The last century has witnessed the evolution of antenna technology from simple Hertzian dipoles to sophisticated large-scale structures such as magnificent space-borne inflatable arrays. Of the great variety of antenna systems, planar antennas have gained wide popularity due to the ever-growing trend toward system integration and miniaturization. Planar antennas offer the advantages of low profile and small size, light weight, easy fabrication, low manufacturing cost, and easy integration with the rest of the electronics, to name a few.

The modeling and design of planar antenna systems have been the subject of extensive research in the last three decades. The modeling techniques have evolved alongside with the fabrication technology. The early work on the modeling involved the development of analytical models for simple elements and geometries. The advances in the antenna array technology resounded the urgent need for effective computer aided design (CAD) tools. During 80's, microwave CAD programs came into prominence. These programs utilized quasi-static models of planar components based on either analytical or data fitting techniques. Even though quasi-static CAD tools proved very useful for the design of simple microwave circuits, they were not able to meet the more challenging needs of antenna designers. The accurate modeling of the coupling effects in antenna arrays demanded rigorous full-wave numerical techniques.

The advance of digital computers during the last two decades brought computational electromagnetics into the spotlight as an active field of research. With high-performance computing resources available, antenna designers began to pay more attention to computer simulation as an effective alternative in laborious and costly trial-and-error-based design cycles. Besides exploring the phenomenology, numerical modeling was used to address intricate design issues. The last decade witnessed the introduction of several electromagnetic simulation tools based on full-wave numerical methods.

In spite of all the progress in the development of fast and efficient numerical techniques, full-wave simulation is still a very demanding and time-consuming computational process. Depending on the complexity of the problem at hand, its numerical solution may take hours of CPU time and require very large memory capacities. Although running computer simulations is by far less expensive than trial-and-error-based prototyping, the daunting simulation times usually deem the design-through-analysis approach completely impractical. At the end, the antenna designer needs to contemplate all the tradeoffs and create the right balance between computer simulation studies and experimental investigation.

2. Approximate Modeling Approaches

Electromagnetic problems are usually complex from a phenomenological point of view. They are governed by Maxwell's equations subject to certain boundary conditions. There are very few simple electromagnetic problems that have a canonical solution, i.e. you can find a mathematical solution for them expressible in an analytical form. The practical structures of interest are oftentimes more sophisticated than these canonical problems. For example, you can solve the problem of reflection and transmission of plane waves from and into layered media analytically. The solutions to the problem of scattering from a cylinder or propagation in a rectangular waveguide can be cast into analytical forms although they may involve infinite sums. However, the problem of radiation by a patch antenna has no analytical solution. Nor can you find a mathematical solution to the problem of characterizing microstrip discontinuities unless you resort to approximate modeling and thus allowing some level of error.

Before the advance of digital computers and computational electromagnetics, simplification and decomposition were the only vehicles that would make it possible to attack large problems. First, you would simplify the problem as much as possible into a form that you would know how to solve. If the simplified problem were still large, then you would break it down into smaller manageable ones. Then, you would combine the solutions in a sensible manner. As an example, consider the problem of radiation from an array of patch antennas. You can model a single patch element as a closed cavity with magnetic walls. Of course, in doing so, you are ignoring the open-boundary nature of the problem as well as the infinite extents of the dielectric substrate and the ground plane. Nevertheless, the closed cavity with magnetic walls is a problem that you can solve analytically. In this way you can find the current distribution and radiation pattern of a single patch element. Now, having the element pattern, you can use an array factor approach to calculate the radiation pattern of an array made of such patch elements. Note that such an approach ignores any coupling among the adjacent elements of the array. When the array elements are place at sufficiently large spacing from one another, the array factor approach usually provides satisfactory results. In condensed arrays, however, the coupling through the substrate surface waves can change the array performance drastically. As such, you cannot rely on such approximate methods to design your arrays.

We will come back to the concept of decomposition later when dealing with the design of large-scale structures. Breaking down a structure into smaller substructures and modeling each substructure independently can be done in PiCASSO using its Network Simulation Engine. Although this decomposition introduces a certain level of approximation and degrades the accuracy of the solution, you can still use a very accurate modeling technique for the simulation of the individual substructures. You will see how to use PiCASSO to incorporate accurate models of coupling effects among array elements to increase the accuracy of the network simulation.

3. What is Numerical Modeling?

In reality, all modeling techniques are approximate in nature but to different extents. When you try to model a physical phenomenon, you have to make some assumptions only to be able to formulate the problem. Consider the example of a patch antenna. You may assume an infinite or a large finite substrate or ground plane. For a microstrip-fed patch, you have to consider a feed line of finite length. In the practical situation, the microstrip feed line is either connected to some kind of connector or driven by a coaxial cable. You normally do not include the actual feed structure in the modeling problem, or it would become too complicated. Even if you include the feed mechanism as part of the antenna structure, you would intend to solve the isolated antenna problem. But the antenna is indeed part of a surrounding environment that may affect its performance.

Once you decide on the definition of the electromagnetic problem, you have to solve Maxwell's equations subject to the applicable boundary conditions. It is the complexity of these boundary conditions that deems the electromagnetic problem analytically unsolvable. Numerical modeling attempts to solve the governing equations in an approximate manner but with a controllable level of accuracy. To this end, numerical techniques discretize the domain of the problem into a large number of elementary cells. This is called meshing the structure. The mathematical equations are solved within each of these elementary cells of the mesh. The cell solutions are then assembled and consolidated in a logical manner to yield the overall solution of the problem. This is usually accomplished in the form of solving a linear system of equations. The boundary conditions are enforced in a variety of ways through the cell solutions or cell shapes.

4. Challenges of Numerical Modeling

Regardless of the type of technique used, the numerical solution of an electromagnetic problem is highly dependent on the characteristics of the mesh used to discretize the computational domain. Increasing the mesh resolution, i.e. having smaller elementary cells, naturally results in better accuracy. If you change the mesh size, you should oftentimes expect a slight change in the simulation results. If you reach a point that increasing the mesh resolution does not affect the solution tangibly, you have then achieved convergence of the solution. When using numerical techniques to solve an electromagnetic problem, it is very important to make sure that the solution has converged. A non-converging solution does not mean anything.

Another problem relevant to the performance of numerical techniques is stability. When dealing with large problems, the inversion of the linear system is usually the bottleneck of the process. Sometimes, the solution may converge very slowly, and under certain circumstances, it may not converge at all. The numerical stability is affected by many factors including the mesh structure. As a rule of thumb, a mesh with more consistent and regular cells is more stable than one with significant variations in cell size and shape.

5. A Review of Full-wave Numerical Techniques

The full-wave numerical techniques for the modeling of electromagnetic problems generally fall into two categories: differential and integral techniques. This division reflects the approach taken to the solution of Maxwell's equations given below:

$$\nabla . \mathbf{D} = r$$

$$\nabla . \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

where **E** and **H** are the electric and magnetic fields, respectively, **D** and **B** are the electric displacement and magnetic induction vectors, respectively, **J** is the conduction current density, ρ is the electric charge density and ∇ is the gradient operator.

Assuming a steady state regime with a time dependence of the form $e^{j\omega t}$, from Maxwell's equations one can derive the vector wave equations given below:

$$\nabla \times \nabla \times \mathbf{E} - k^2 \mathbf{E} = -jwm\, \mathbf{J}$$

$$\nabla \times \nabla \times \mathbf{H} - k^2 \mathbf{H} = \nabla \times \mathbf{J}$$

where $k = w\,(me)^{½}$ is the propagation constant in the medium, $w = 2pf$, f being the frequency, and e and m are the permittivity and permeability of the medium, respectively.

Differential Techniques

In differential techniques, the gradient and derivative operators are discretized properly, and Maxwell's equations are solved directly or indirectly in each elementary cell. Examples of this type of technique are finite element method (FEM), finite difference method (FD), finite difference time domain method (FDTD), Transmission line method (TLM) and method of lines (MOL). Instead of solving for the Maxwell's equations directly, the finite element method usually involves an energy-based functional derived based on variational principles. All the differential techniques require meshing of the entire computational domain. Naturally closed structures such as waveguides, cavity resonators and shielded circuits render themselves to this type of discretization. However, this creates a major problem for open-boundary problems like antennas. In this case, an appropriate mesh truncation scheme has to be adopted. Examples of mesh termination include artificial absorbers, perfectly matched layers (PML), absorbing boundary conditions (ABC), and hybrid techniques like boundary integral method. With differential techniques, the accuracy of the simulation results depends not only on the structure and resolution of the mesh, but also highly on the quality of the mesh termination. In this respect, differential techniques are more involved than their integral counterparts.

Integral Techniques

Integral techniques involve a large amount of analytical development in the form of Green's functions. In effect, they utilize the superposition principle to take advantage of the canonical problems. A Green's function is indeed the analytical solution to a given boundary-value problem, where the actual sources are replaced by an elementary point (delta) source. In the integral solution, the actual sources are discretized as a set of elementary sources. The discretization is done using an appropriate meshing scheme. The solution to the actual problem is then obtained by superposing all such elementary solutions. In comparison with differential methods, the integral methods are much more efficient in that they involve much smaller linear systems. This is because only the source regions are meshed as opposed to the entire computational domain of the problem. On the other hand, you can use integral techniques only wherever analytical Green's functions are available. In this regard, the applicability of these techniques is much more limited compared to differential methods. One of the most important advantages of integral techniques is their natural aptness for treating open-boundary problems. In this case, the infinite extent of the structure is already accounted for in the computation of the Green's functions, and there is no need for a fictitious mesh termination. As such, integral techniques offer the fastest and most accurate and efficient solution to antenna problems.

There is no general classification of integral techniques. Historically, different integral equations have been developed for different application areas. In some applications, different types of integral equations have been formulated for the same problem depending on the unknown field quantities. All of these techniques have one thing in common, and that is the use of the method of moment (MoM) for the numerical solution of the integral equations. PiCASSO offers a powerful and efficient MoM-based simulation engine for the full-wave analysis of planar structures. The next chapter presents a general overview of the method of moments.