Preface

This book addresses numerical full-wave methods for the analysis and design of antennas and microwave structures. In the last decades these numerical methods that are used to calculate approximate solutions of Maxwell's equations have evolved from pure academic disciplines to powerful and user-friendly engineering software tools. Meanwhile numerous commercial software packages exist that are widely used in the RF engineering community. Developments in the software accompanied by progress in computer technology allow nowadays many practical problems to be solved on standard PC systems.

The text is written with different groups of readers in mind. First it addresses RF engineers who embark on numerical modeling using commercial field solvers. Second it addresses graduate students taking practical courses in electromagnetic field simulation. Both groups need a basic understanding of the mathematical background and both groups need a practical introduction to commercial EM modeling software to make their first simulation experience a success.

There are numerous books on the market that deal with mathematical details of different numerical methods for the calculation of electromagnetic fields. For engineers who want to know what these methods can do for them and how to use the software tools, these theoretical books are too far away from daily work. On the other hand, there are tutorials and manuals that provide information on how to use specific software packages. These tutorials focus on the handling and special features of the software and methods applied therein. However, the theoretical background and broader scope is generally neglected. This book tries to fill the gap by providing a practical and comprehensive introduction for engineers involved in the numerical analysis and design of antennas and radio frequency components for wireless communication systems. The reader will find a down-to-earth approach to full-wave high-frequency simulation tools and how to use these tools efficiently in applied industrial engineering.

The book begins with an introduction in Chapter 1 that approaches the subject of field simulation by general considerations about modeling strategies as well as capabilities and limitations of the software tools. Part I covers the basic electromagnetic theory and definitions of the most important antenna and circuit parameters. Chapter 2 starts with Maxwell's equations in differential and integral form as well as boundary conditions for the electric and magnetic fields. Next the propagation of waves in lossless and lossy media is discussed. In this context uniform waves are used to illustrate different types of polarization. The general concept of energy conservation is transferred to the electromagnetic field by defining electric and magnetic energy density as well as power flow and power loss. The chapter moves on to a definition of the electromagnetic potentials and ends with a short review of waves on transmission lines. Altogether, this chapter serves as a basis for the understanding of the numerical methods presented in Chapter 4. Since there are time-domain and frequency-domain methods, the time-dependent and phasor representation of the fields are described in parallel throughout this chapter.

The electromagnetic field theory provides a complete set of equations and quantities to solve any electrodynamic problem. Unfortunately, the quantities defined so far are difficult to handle. Therefore, a set of more easily accessible quantities has been defined to characterize the electromagnetic features of antennas and circuits. Chapter 3 reviews these technically important radio-frequency measures. The chapter starts with the introduction of the scattering parameters that link circuit-based quantities like impedance and voltage to field-based quantities like electric and magnetic field strength. Using the example of a dipole the antenna parameters are introduced: radiation pattern, gain, efficiency, directivity, nearfield, farfield and bandwidth. Finally, antenna arrays and the concept of beam steering are discussed.

Part II is concerned with the mathematical basis of numerical methods as well as instructions for their practical use. Commercial software is generally based on one of the following methods: Finite-Difference Time-Domain method (FDTD), Finite Element Method (FEM) or Method of Moments (MoM). Consequently, Chapter 4 focuses on these methods and illustrates their underlying theoretical concepts and mathematical implementations. Each of the methods could fill a book in itself, and there are numerous excellent textbooks on the market. Therefore, the chapter concentrates on the aspects that are essential when applying rather than programming the numerical methods. Other - currently less popular - methods are mentioned briefly to show the reader that additional tools exist for special applications.

Chapters 5 and 6 represent the core of the book. Chapter 5 discusses the steps usually undertaken when creating an antenna or RF component simulation model with up-to-date full-wave engineering software. The process of modeling can be divided into three parts: pre-processing (setting up the model), solving (generating an approximate solution of Maxwell's equations by applying one of the discussed numerical methods) and post-processing (evaluating the results and calculation of additional quantities from the solution of the solver). Concerning pre-processing the following topics are addressed: creating geometry using CAD capabilities, importing CAD data, defining material properties, applying boundary conditions and sources and setting up solver parameters. The process of meshing (subdivision of the computational domain into smaller elements) can be regarded as part of the pre-processing or − if adaptive mesh refinement is considered − meshing represents an essential part of the solution process itself. Depending on the numerical method used, the solver determines the electric and magnetic fields within the computational domain or the surface current densities on the interfaces between different materials. During the post-processing, additional quantities like circuit and scattering parameters and farfield pattern are calculated from the fields or current densities. At the end of the chapter, advantages and disadvantages of the numerical methods for different types of problems are presented in a list to provide a summary that can be used as a checklist later on.

Chapter 6 illustrates the application of the different numerical methods on a variety of canonical examples. The examples address a broad field of applications: coaxial line discontinuities, aperture antenna, dipoles, microstrip antennas, microstrip filter and cavity. These simple structures can be used for validation purposes when starting with new software. After studying these two core chapters, the reader should have a clear vision on how to choose the right numerical software for a particular problem and how to devise an efficient simulation model.

Part III is concerned with practical applications to demonstrate the use of field simulation software in industrial projects. Chapter 7 starts with the design process of a planar GPS receive antenna. The different parts of the model are tuned separately and are afterwards combined to a final design. Second, the radiation characteristics of a GSM base station antenna are analyzed including exposure of a realistic human body model. The modeling process originates from a simple pure metal design which is validated by manufacturers data sheets and an alternative simulation model. Third, the design of mobile phone antennas and the influence of the user on the antenna are investigated. Finally, an Ultra-Wideband (UWB) antenna is described and integrated in a realistic scenario.

Throughout this book, the following EM software tools have been used:

- *Microwave Studio* from CST GmbH, Darmstadt, Germany
- *HFSS* from Ansoft Corporation, Pittsburgh, USA
- *ADS/Momentum* from Agilent Technologies, Inc., Palo Alto, USA
- *EMPIRE* from IMST GmbH, Kamp-Lintfort, Germany
- *4NEC2* based on NEC2 from Lawrence Livermore National Laboratory, USA
- *Concept II* from the Technical University Hamburg-Harburg, Germany

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Creating an Efficient Simulation Model

In this chapter we describe the general structure of numerical modeling software and the different steps towards an efficient simulation model.

5.1 General Structure of Numerical Modeling Software

Numerical simulation software consists of three main components *preprocessor*, *solver*, and *postprocessor* as shown in Fig. 5.1.

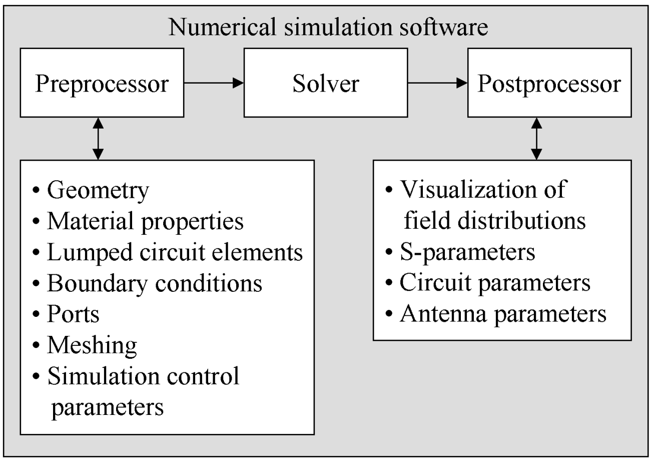

Fig. 5.1. Main components of numerical simulation software

The pre- and postprocessor are incorporated into an interactive Graphical User Interface (GUI). The solver is started and controlled from this interface. Although today the user may *feel* only *one* software, the division of the software into three main components makes sense from a logical and didactic point of view.

5.1.1 Preprocessor

The *preprocessor* is used to set up the simulation model as shown in Fig. 5.2.

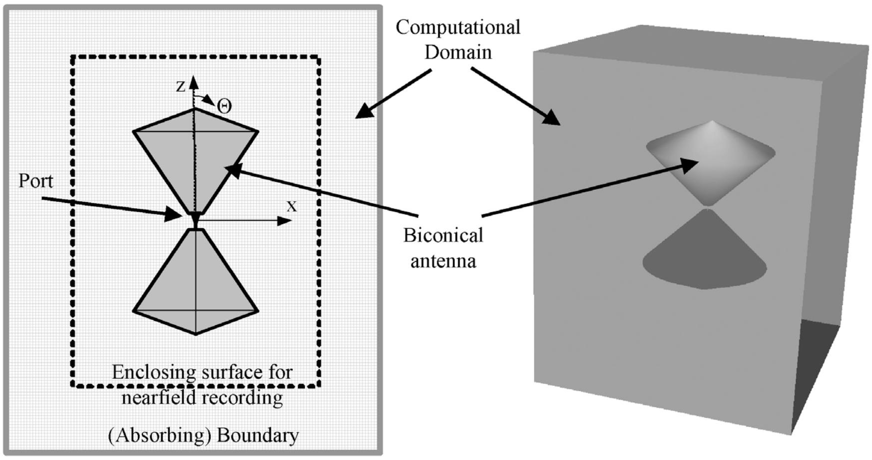

Fig. 5.2. Basic simulation model including antenna geometry, material properties, ports, boundary conditions, box for nearfield recording

In the following list we give a short overview over the tasks that are addressed within the process of model generation. Each item is explained in more detail in the subsequent sections.

General definitions: At this stage different layers or components are defined to organize the data. Furthermore, the units of physical quantities are selected, e.g., length in millimeters, frequency in GHz.

Geometry: The geometrical shapes of the objects are defined. There are in general three different approaches that can be combined: The geometry is entered interactively by a graphical user interface (GUI), the geometrical data is imported from a CAD file, or the objects are described by a macro language.

Material properties: Dielectric properties are assigned to the geometrical objects that have been modeled in the first step. Materials are selected from a database of predefined commonly used materials or new materials are defined by specifying dielectric and magnetic properties.

Excitation: Ports are defined in order to excite the structure and to evaluate circuit-based quantities like scattering parameters, impedances, voltages and currents.

Boundary conditions: At the outer boundary of the simulation volume different kinds of boundary conditions are applied in order to represent free space, electric and magnetic walls or planes of symmetry.

Meshing: The structure is discretized into small elements with homogeneous material properties. The discretization of the model is a crucial step since it affects the required numerical effort and the accuracy of the solution.

Simulation parameters: Additional parameters are defined to control the solution process, e.g., the kind of solver to be used, definition of an end-criterion for time-stepping algorithms, desired accuracy, AR filtering, multiport excitation, number of port modes.

5.1.2 Solver

The *solver* calculates the approximate solution of the electromagnetic problem based on the data generated during preprocessing. The solution process is typically documented in a so-called *log*-file that lists important details and statistics of the simulation, for example: time need for the solution, number of unknowns, memory requirements, as well as warnings and errors encountered during the solution process.

5.1.3 Postprocessor

The *postprocessor* is used to evaluate the results of the solver. The results can be displayed in tables, 1D-, 2D- and 3D-plots.

Port-related parameters: Parameters like input impedances, scattering parameters, voltages and currents are extracted from the field solver results. These parameters are needed to specify the behavior of the structure when connected to a circuit or other RF components.

Visualization: Field distributions (contour and arrow plots) of different nearfield quantities are displayed. The visualization of field distributions gives the user insights into the way the structure works. This understanding can help to improve the performance of the structure or help to identify errors in the model.

Antenna parameters: Antenna parameters like radiation pattern, gain, directivity, half-power beam width, side lobe suppression and radiation efficiency are calculated.

Additional parameters: For example, evaluation of specific absorption rate (SAR) and EMC related data like field strengths in a specified distance in comparison to EMC limits.

5.2 Geometry

The first step in setting up the simulation model is the generation of the three-dimensional structure, e.g., the shape of an antenna or of a filter.

In up-to-date electromagnetic modeling software usually three ways exist to accomplish this goal:

- interactive construction via Graphical User Interface (GUI),
- import of CAD (Computer Aided Design) data and
- object definition via macro language.

5.2.1 Interactive Construction via Graphical User Interface (GUI)

A *Graphical User Interface* (GUI) helps the user to create interactively the geometry of his model. The GUI construction capabilities are very similar to those that are available in basic *Computer Aided Design* (CAD) software.

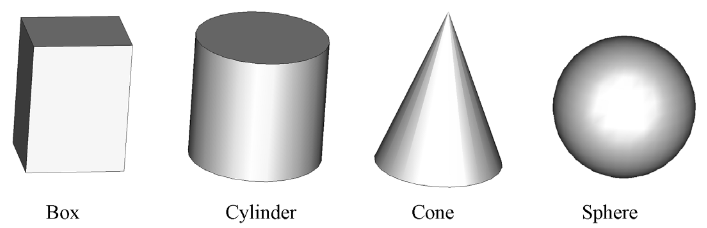

Fig. 5.3. Simple three-dimensional objects

Usually the construction starts with the definition of simple objects. More complex objects can be generated by combining and manipulating simple objects. *Simple objects* can be classified into one-, two- and three-dimensional shapes. Simple one-dimensional objects include line, polygon and spline segment. Simple two-dimensional objects include triangle, rectangle, circle, ellipse and closed polygon. Simple three-dimensional objects include box, cylinder, cone and sphere (see Fig. 5.3). Depending on the software more complex basic shapes like toroid, spiral, helix, ellipsoid, and bond-wires are available.

These simple objects can be modified, i.e., rotated, moved, mirrored, copied, scaled or stretched. Furthermore, *boolean operations* can be applied on overlapping elements. In Fig. 5.4 the effects of subtraction, addition and intersection are shown. If we draw two overlapping 3D objects like a box and a sphere (Fig. 5.4a) and we *subtract* the sphere from the box the resulting shape is a box with a spherical cut-out in it as shown in Fig. 5.4b. The boolean operation *addition* combines the two objects as shown in Fig. 5.4c. If we *intersect* the two objects we get an object that consists of the common parts of the box and sphere as shown in Fig. 5.4d.

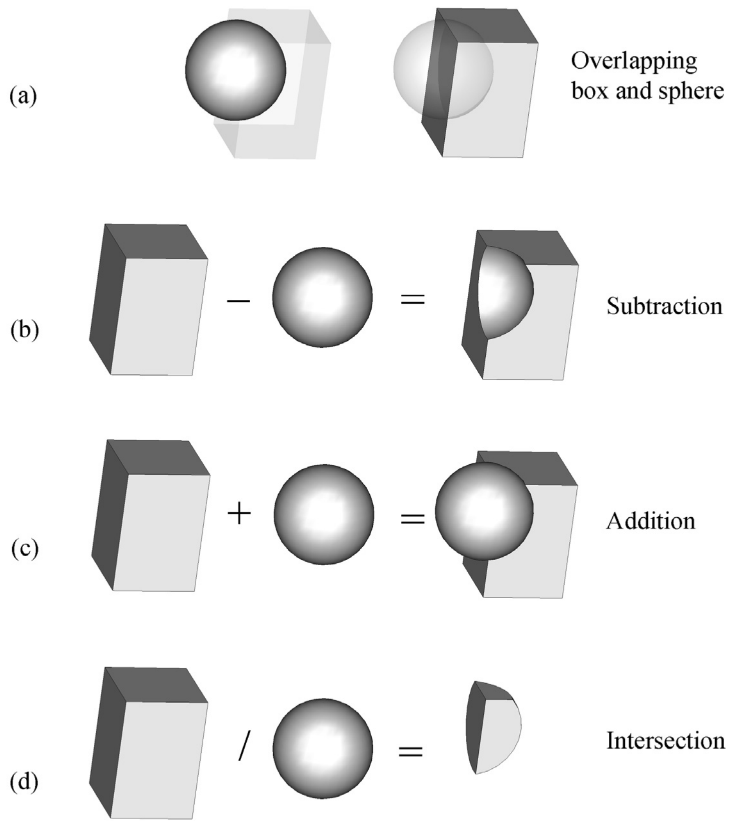

Fig. 5.4. Objects modified by different boolean operations: **(a)** overlapping box and sphere, **(b)** subtraction of sphere from box, **(c)** addition and **(d)** intersection of box and sphere

Another way to create more complex 3D objects is to extrude, twist, or rotate 2D entities. Figure 5.5 shows the basic concepts. In Fig. 5.5a a 2D face is extruded along a vector. In Fig. 5.5b a 2D face is twisted along a curve and in Fig. 5.5c a 2D face is rotated around an axis. These operations are very powerful in creating complex geometries. Usually the output can be controlled by additional options, for example the object can be tapered, i.e., the size of the 2D face varies as it propagates along the extrusion vector (Fig. 5.5d). Sometimes the GUI includes advanced features like the description of objects by complex mathematical formulas or the smoothening (rounding) of edges.

Although the graphical generation of geometrical shapes has become very powerful, the geometry should be kept as simple as possible. Only details that affect the electromagnetic behavior should be included. Rounded edges result

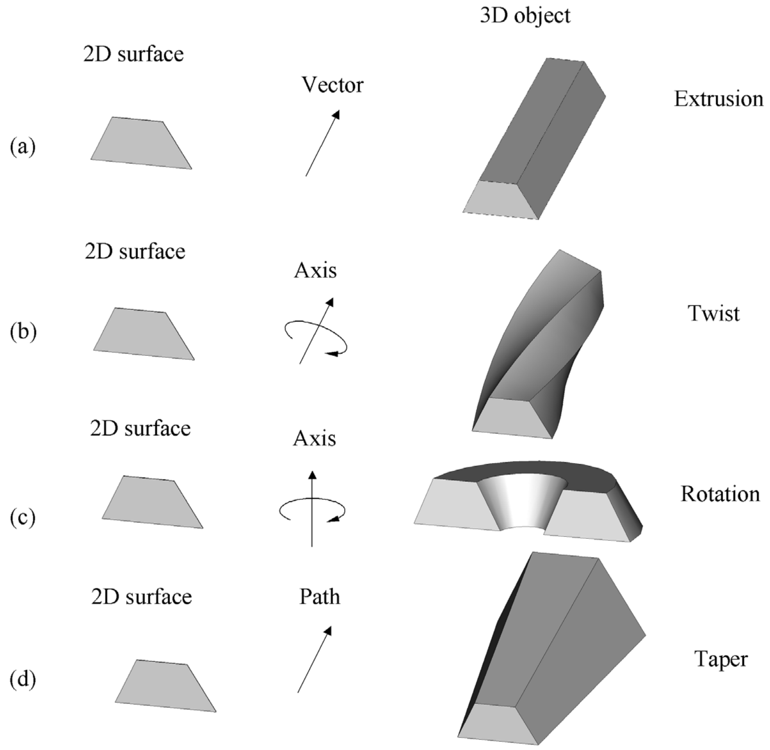

Fig. 5.5. Creation of 3D objects from 2D contours

in an appealing model but lead to a finer discretization of the structure and thus increase the computational burden.

5.2.2 Object Definition via Macro Language

In the early days of EM modeling the definition of a model by a text-based input file was common use. Today this kind of model creation is still useful if many structures with similar geometry are analyzed. Geometrical features can be defined by variables and are easily changed. Therefore, text-based input files are suited for parameter studies and optimization routines. Most EM modeling software packages provide a macro language for the text-based definition of models.

5.2.3 Import of CAD (Computer Aided Design) Data

In EM modeling we can distinguish between *design* and *analysis* of microwave components. In the latter case it may be possible to use CAD data of actual microwave components from the production process. Figure 5.6 shows as an example an antenna module consisting of a three-dimensional carrier with a complex-shaped antenna plate.

Mechanical CAD software like *ProEngineer*, *SolidWorks* or *Catia* possess many more powerful features for the design of complex-shaped mechanical objects than the basic CAD tools that are incorporated in EM simulation software. In order to import models originating from mechanical CAD software one can use standardized exchange data formats like

- STEP (STandard for the Exchange of Product model data)
- IGES (Initial Graphics Exchange Specification)
- DXF (Drawing eXchange Format).

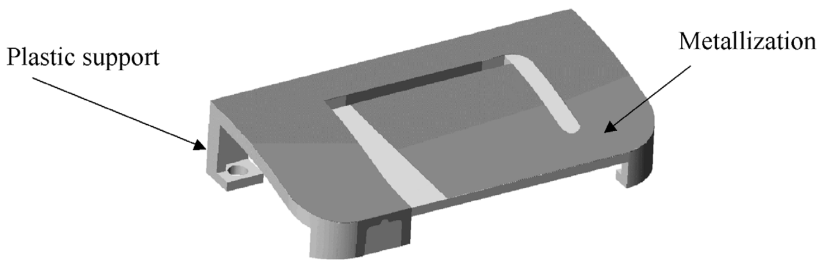

Fig. 5.6. CAD model of an antenna module

Although import of CAD data may seem a very elegant way of modeling there are some drawbacks. The first problem with CAD data is that many mechanically important but electrically irrelevant details are included. These CAD details result in a finer mesh and therefore increase the simulation time without significantly improving the accuracy of the results. Another problem with CAD data may arise from geometrical accuracy (precision). If the CAD system and the GUI of the EM modeling software apply different degrees of geometrical precision unexpected errors may occur. For example, primary connected objects show overlapping areas or are separated.

From this we conclude that CAD import is seldom a *one-click* task. The subsequent model simplification and data healing are cumbersome tasks.

As an example Fig. 5.7a shows an antenna module that includes small holes and gaps. These details are included in the original CAD file for mechanical reasons (fastening) but are electrically irrelevant. Figure 5.7b shows the antenna module after the unnecessary details are removed. Figures 5.7c−f show how the small details result in finer meshes that lead to longer simulation times.

Another example concerns thin metallic structures. These thin structures, e.g., a strip conductor of a microstrip line shown in Fig. 5.8, can be modeled as a two-dimensional (flat) object. This modeling approach leads to simulation

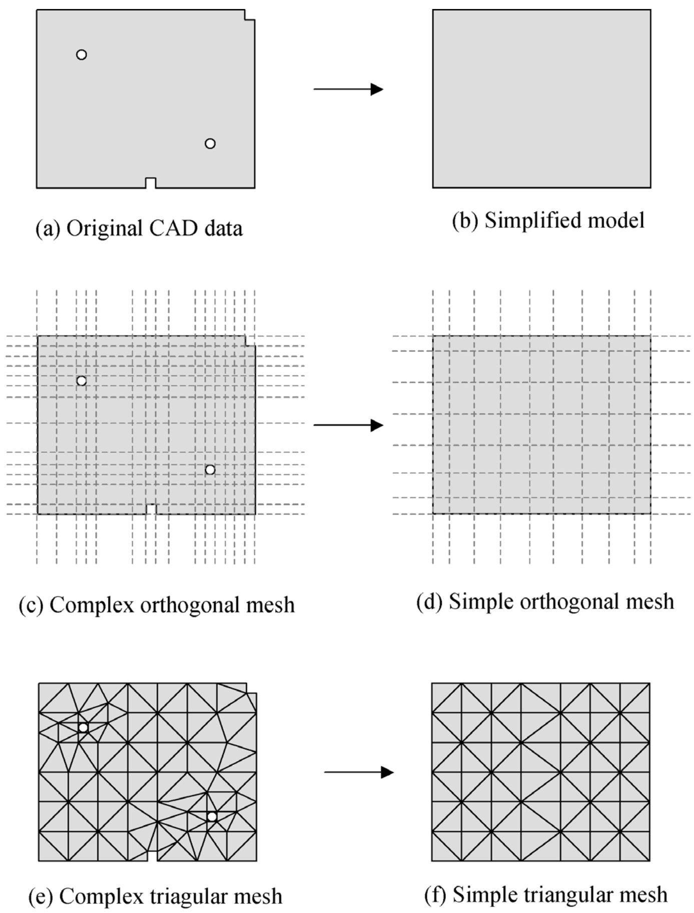

Fig. 5.7. Removal of details from a CAD model: **(a)** Original CAD data containing small irrelevant details, **(b)** simplified model (details removed), **(c-f)** Effects on orthogonal and triangular meshing

models with less unknowns and increased cell sizes compared to volumetric modeling.

5.2.4 Summary

When setting up the geometry of a simulation model the intention should not be to draw the most accurate structure from the visual point of view but the simplest one that represents the electromagnetic phenomena of the structure under consideration. Moreover, too many details can enlarge the computational effort, on the one hand, and result in an error-prone, difficult to validate simulation model.

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