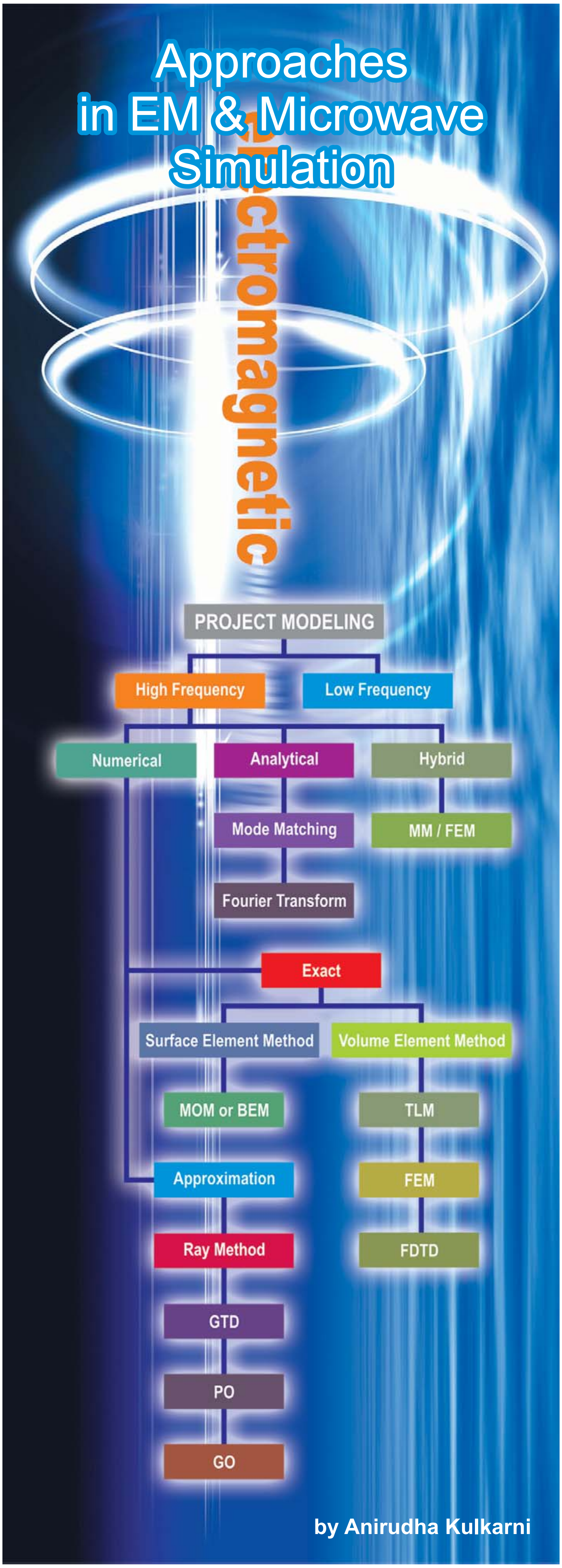
Approaches in EM & Microwave Simulation



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All Electromagnetic design and simulation tools essentially involve a mathematical model. The type of model used normally depends on parameters such as the required accuracy, the total simulation time, the type of results required, the frequency bandwidth. According to this classification the methods may be roughly divided' on analytical, numerical-analytical(Hybrid) and numerical ones.

Consider an example, modeling a system for its DC and low frequency characteristics normally it involves electrical energy sources (voltage and current), and components like resistance, capacitance and inductance. Voltages and currents within the system are then determined using impedance calculations.

Generally, for very high frequency simulations the physical structure of the system affects its electrical characteristics. For example, a bend on a copper track causes a reduction in signal strength because some of the electromagnetic waves reflect back from the mismatch caused by the bend. At low frequencies this effect would be negligible because of their relatively large wavelength. Take an example, in free-space a 50 Hz signal has a wavelength of 6,000,000m; whereas at 10 Ghz the wavelength is only 0.03m. Large wavelengths are generally less restricted by physical objects and discontinuities, and are also less affected by other effects, like skin effect, electromagnetic coupling.

At present there are a lot of commercial problem-oriented packets so called “Electromagnetic solvers”, that consist of two main blocks: 1) A Preprocessor aimed to create the required space lattice, taking into account object surface peculiarities, and 2) “The solver as itself” that realizes one or other numerical algorithm. They may be used immediately by engineers for preliminary calculations, rather than for multi-parametrical optimization and very exact design. The calculation efficiency is dramatically falling down at the growth of the volume being considered due to necessity to take into account the tens or hundreds or thousands of unknowns.

The main methods used in high frequency electromagnetic wave simulations are ones that take into account changes in the physical and dielectric structure, as shown in the fig on the left.

Transmission Line Matrix (TLM)

The TLM method is a time-domain method where an electromagnetic wave propagates through elements made from transmission lines. A Fast Fourier Transform converts the transient response into frequency response data. It is variation of the finite-difference method but the boundary splits into elements rather than the interior region. The elements used consist of a network of interconnected transmission lines.

Fig 1 shows a 2d element with 4 ports. The applied wave travels through the structure and is scattered by each of the lines within the element. These scattered waves then travel into neighbouring elements. The TLM Method accounts for material properties and

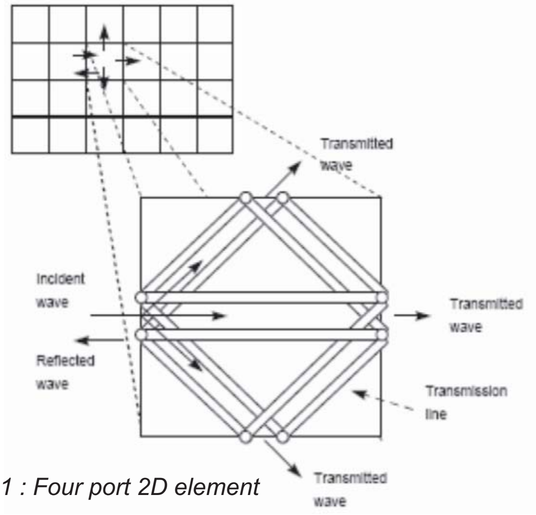

Fig 1 : Four port 2D element

boundaries by setting the properties of the transmission line.

The advantage of TLM is that it takes into account both electric and magnetic fields in a 3D model, and since it is a time-based simulation, it produces a wide-bandwidth response. (It is also relatively straight forward to implement and different physical structures can be modelled using non-linear grids.) This include hybrid variable meshes, multi-grid meshes and general curvilinear co-ordinates.

FDTD - Finite Difference Time Domain Method

The FDTD is a popular electromagnetic modelling technique based on central-difference equations, which can be easily implemented through softwares and are easy to understand. Keyline of FDTD is that equations are solved in a leap frog manner i.e. E field is solved at a given instant in time; and then H filed is solved at the next instant.

Summary

- Introduced by Itoh in 1989 and Hoefr in 1985
- Based on Time-Domain Maxwell's Equations
- Transient Fields, function of time are computed
- Good for Characterizations of Non Linear Devices
- Field Problem is Converted to 3D Equivalent problem of Transmission Line network

How does FDTD work?

When Maxwell's differential form equations are examined, it can be seen that the time derivative of the E field is dependent on the Curl of the H field. This can be simplified to state that the change in the E field (the time derivative) is dependent on the change in the H field across space (the Curl). This results in the basic FDTD equation that the new value of the E field is dependent on the old value of the E field (hence the difference in time) and the difference in the old value of the H field on either side of the E field point in space. Naturally this is a simplified description, which has omitted constants. The H field is found in the same manner. The new value of the H field is dependent on the old value of the H field (hence the difference in time), and also dependent on the difference in the E field on either side of the H field point.

Using FDTD

In order to use FDTD a computational domain must be established. The computational domain is simply the space where the simulation will be performed. The E and H fields will be determined at every point within the computational domain. The material of each cell within the computational domain must be specified. Typically, the material will be either free-space (air), metal (perfect electrical conductors (PEC)), or dielectrics. Any material can be used, as long as the permeability, permittivity, and conductivity can be specified.

Once the computational domain and the grid material is established, a source is specified. The source can be an impinging plane wave, a current on a wire, or an electric field between metal plates (basically a voltage between the two plates), depending on the type of situation to be modelled.

Since the E and H fields are determined directly, the output of the simulation is usually the E or H field at a point or a series of point within the computational domain.

Strengths

- FDTD is a very versatile modelling technique.
- Wide frequency range is solved with only one simulation.
- E/H field movement is possible throughout the model.
- FDTD allows the user to specify the material at all points within the computational domain.
- FDTD allows the effects of apertures to be determined directly. Shielding effects can be found, and the fields both inside and outside a structure can be found directly.
- The absorbing boundary condition (ABC) simulates the effect of free space beyond the boundary.

Weaknesses

- Since FDTD requires that the entire computational domain be gridded, and these grids must be small compared to the smallest wavelength and smaller than the smallest feature in the model, very large computational domains can be developed, which result in very long solution times
- Models with long, thin features, (like wires) are difficult to model in FDTD because of the excessively large computational domain required.
- FDTD finds the E/H fields directly everywhere in the computational domain. If the field values at some distance (like 10 meters away) are desired, it is likely that this distance will force the computational domain to be excessively large.
- Far field extensions are available for FDTD, but require some amount of post processing.

Summary

- First introduced by Yee in 1966
- Various versions of FDTD method exist
- An algorithm to solve Time Domain Maxwell's equations to compute 3D EM field
- Good for Non-Linear device characterizations
- Provides wide bandwidth information from single calculation
- Maxwell's equation discretised in space and time and solved explicitly
- Region is divided into small cells
- Field distribution is computed in consecutive moments of time

FEM - Finite Element Method

The term Finite Element Method refers to a broad range of techniques designed to calculate structural properties, flow and EM FIELDS, is widely used in engineering.

FEM Flow

The domain in which the field is to be computed, is broken up in a number of elements. The way the domain is divided into elements is called the mesh. For an instance, in 2 dimensions, an element could be a triangle, while in 3 dimensions typical elements include the tetrahedron and hexahedron. Elements never cross material boundaries; for example elements do no penetrate from a gas into a conductor, and the dielectric constant is always uniform throughout an element.

- A potential value is computed for each node of every element, respecting the boundary conditions and trying to best satisfy the Poisson's equation. As a rule, the vertices of an element are amongst the nodes of the element. But it is common that various other points, e.g. the half-way points between the vertices, are also treated as nodes. The nodes of one element are often the nodes of neighbouring elements. The potential values in such nodes are the same. Nodes located on the surface of a conductor that is kept at a fixed potential, will have the potential of the conductor. The potential of such conductors is treated as a boundary condition. The potential at any point inside an element is interpolated using the shape functions. These shape functions usually are 1st, 2nd or 3rd order polynomials.
- The potential thus obtained will not as a rule be an exact solution of the Poisson equation, because 2nd order polynomials are in general not solutions of the Poisson equation. One can improve the situation by sub-dividing those elements where the discrepancy is largest and then recomputing the potentials at the nodes. This process is repeated until the discrepancy drops below a threshold value.

How FEM Works

- Direct discretisation of partial differential equation
- Divide structure into pieces (elements with nodes)

- Describe the behaviour of the physical quantities on each element
- Connect (assemble) the elements at the nodes to form an approximate system of equations for the whole structure
- Solve the system of equations involving unknown quantities at the nodes (e.g., displacement)
- Calculate desired quantities (e.g., strain and stress) at selected elements

Advantages

The main advantage of using FEM is that dielectric media as well as arbitrarily shaped electrodes can be handled. Thus, the technique lends itself to a range of detectors where dielectrics are an important ingredient, such as GEMs and MSGCs, for which the fields can not be computed analytically.

The drawbacks of the method are:

- The potential is usually a low order polynomial, and the electric field is therefore an even lower order polynomial. These low order polynomials are not well suited to approximate the log(r) and $1/r^2$ field . It is therefore very difficult to obtain accurate estimates of the gain, for which precise knowledge is required of the high voltage fields.
- FEM computes the potential, which is irrelevant for physics processes, and unfortunately not the field. The finite element method guarantees that the potential is continuous but the electric field often is not, e.g. tracing particles through a discontinuous electric field poses problems.
- FEM tend to take significantly more time than analytic calculations. Other techniques, such as the integral equation method, have been devised which do not suffer from these problems - but programs that perform these calculations are rarely available

Available Commercial FEM Software packages

- ANSYS (General purpose, PC and workstations)
- MARC/MENTAT (General purpose, PC and workstations)
- SDRC/I-DEAS (Complete CAD/CAM/CAE package)
- NASTRAN (General purpose FEA on mainframes)
- ABAQUS (Nonlinear and dynamic analyses)
- ALGOR (PC and workstations)
- PATRAN (Pre/Post Processor)
- Hyper Mesh (Pre/Post Processor)
- Dyna-3D (Crash/impact analysis)
- QUICKFIELD (Advanced General purpose FEA)

Surface Element methods

In surface element methods, the electric and magnetic fields do not penetrate into elements. Surface element method requires much less elements than volume elements, but material properties are difficult to define. Disadvantage of surface element method is that techniques used to alter the properties increases the simulation time.

MOM - Methods of Moments

The fundamental concept behind the MOM employs orthogonal expansions and linear algebra to reduce the integral equation problem to a system of simultaneous linear equations. When an EM wave strikes a perfectly conducting object, it produces surface current. The solution procedure begins by defining this unknown current distribution Iz(z') in terms of an orthogonal set of basis functions. Two categories of basis functions exist: domain and sub-domain basis functions. The sub-domain basis function, significantly more popular in the industry, which subdivides the wire into small segments and model the current distribution on each segment by a simple geometrical construct, such as a rectangle, triangle, or sinusoidal arc. In domain basis method, the boundaries of elements are considered. The analysis is done more specifically at the interfaces of different element.

Limitations and Considerations

The validity of the assumptions introduced into MOM type formulations are established through empirical means. The codes incorporating these formulations are run for a large number of test cases with the results compared to experimental observation. Certain topics have received significant attention. The current distribution on the wire (the “thin wire approximation”), the orthogonality and completeness of the basis and testing functions, the modelling of the feed point excitation.

The surface current produces scattering field which is expressed as linear integral operator equation. The linear operator is expressed in Gn- Green function in order to reduce finite matrix equation Zmn. (The numerical evaluation of Zmn, and the solution technique which yields Gn from the set of simultaneous linear equations.) Although some of the assumptions continue to attract attention from a mathematically rigorous perspective, the codes incorporating them have been thoroughly exercised and deemed suitable for antenna engineering applications. The most well-known of the codes using the MoM is the Numerical Electromagnetic Code (NEC), which is widely used to solve problems that can be defined as sets.

Summary

Harrington introduced MOM in EM in 1968

MOM is a mathematical technique for solving inhomogeneous linear equations

Based on Integral equation method

- When EM waves strikes a perfectly conducting object, it produces surface current
- Scattered field is expressed as linear integral operator equation.
- Linear operator equations with green function are reduced to finite matrix equations and boundary condition is applied.

MM - Mode Matching

The demand for accuracy and speed of calculations cradled fruitful algorithms with the mode-matching procedure based on the field presentations by appropriate Fourier-expansions.

The main idea lies in considering the object specified with a general purpose CAD system. This CAD structure is divided into set of pieces of complicated waveguides.

The internal and external boundary conditions are defined for each complicated waveguide. Then the possible symmetries in the waveguide structures are arranged. Based on these symmetries they are further subdivided into subregions.

The field distribution in each subregion is then calculated in terms of S matrices. At the end S matrices of all the wave guides are connected to compute the final S matrix of the device.

Why Mode Matching

- Best numerical stability
- Good error estimation
- Least convergence time range of application is best for high power microwave migrate computational resource

How Mode Matching Works?

- Structure is divided into cylindrical slices.
- Set up the modes (Including Evanescent) which can propagate in the section. E and H component in each region expressed as Bessel Functions.
- Complex amplitude of modes are matched across boundary of slices according to boundary conditions to get a set of linear equations.
- Modal distribution is evaluated by solving simultaneous equations
- Mode coupling coefficients at each junction are computed and scattering matrix at each junction are formed.

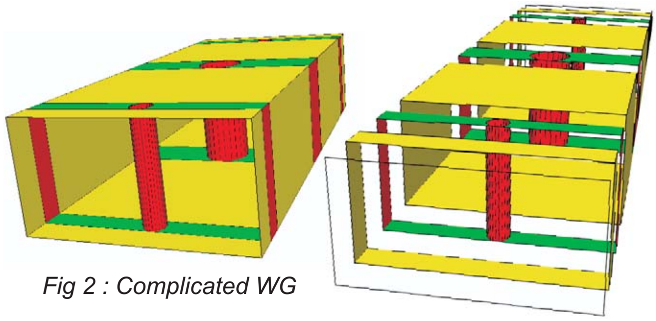

Fig 2 : Complicated WG

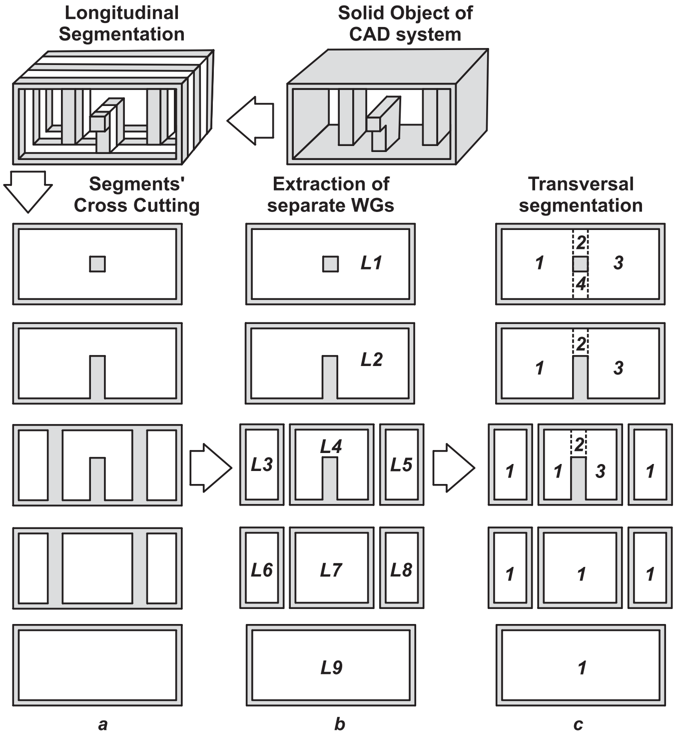

Fig 3 : Preprocessing flow

- Cascading of junction scattering matrix gives the overall scattering matrix.

Preprocessing Procedure

This procedure is represented in the flow chart (fig 4). To understand the flow chart consider the solid object realised in a CAD system as shown in fig 3.

The first step consist in dividing the object into sequence of N regular fragments. Each fragment is a complicated WG or set of parallel WGs. The procedure to search such set of complicated WGs is known as longitudinal segmentation.

Segment cross cutting

Here the transfer plane cuts the WGs in N generalise cross sections, which are presented by set of step contours. Then it describes internal and external boundaries of WGs.

Construction of separate waveguide

As shown in fig 3, column B, a special procedure is employed to extract and present a separate closed waveguide lines (L1, ...L9).

Analysis of possible symmetries

In order to reduce the CPU time, the possible symmetries are taken into account.

Determination of connectivity

Each separate waveguide is considered as a line with N internal conductors. The calculation of field distribution of N fold degenerated TEM modes is performed. In order to do this the series of N corresponding potential distribution are needed to be set. The operation on naming of internal conductors and creation of linearly independent potentials is performed after determination of connectivity if N>1. Of N corresponding potential distribution are needed to be set. The operation on naming of internal conductors and creation of linearly independent potentials is performed after determination of connectivity if N>1.

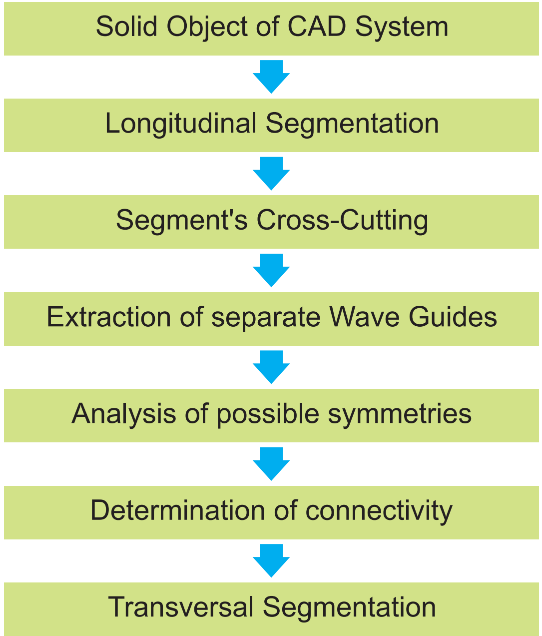

Fig 4 : Flow chart

For the complicated WG the most important part of preprocessing consists in the final transversal segmentation of complicated cross-sections for each of obtained Lines into the set of the simplest rectangular sub regions (See Fig. 2). Each sub region has the upper and lower metallized walls and opened or shorted sidewalls. These subregions are real “atomic” objects for the field presentation by the Fourier series. Therefore such a procedure may be considered as a “large scale” transversal discretization. The result of transversal discretization at preprocessing consists in the set of G-matrices that contain coordinates and: dimensions of all subregions. G-matrix describes cross-section completely and uniquely. The final stage of preprocessing is aimed to prepare the input data for calculation of the plane junction S matrices. They have to be calculated for every junction of different, complicated WGs. As the mode field's distributions are specified by the piecewise-prescribed functions the required coupling integrals at mode matching will be presented as the sums on the overlapping of the one and another WGs subregions. To expand the area of applications the procedure “Determination of matrices of subregion overlapping” includes an automatic tool for the implementation of intermediate “virtual WGs” of zero-length. The cross-sections of them are determined as Boolean production of the cross-section of the WGs being connected. This provides adaptability of direct mode-matching procedure to the successive junctions of small WG-virtual W G and virtual WG-big WG.

Conclusion

The limitations of individual- analytical and numerical methods compel and motivate us to adapt hybrid method of modelling, which caters the elimination of unavoidable constraints such as large convergence time, numerical instability, computational resources etc. Hybrid methods allows us to couple conventional numerical methods (eg. Mode-matching/ FEM, MoM/ FDTD) broadening the spectrum of application and at the same time giving best modelling solution.

So next time whenever you see an electromagnetic device, think of which modeling technique might have been used to design it ..?