USAGE OF NUMERICAL METHODS FOR ELECTROMAGNETIC SHIELDS OPTIMIZATION

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Abstract **– This paper is a brief presentation of some numerical methods usable for simulation of electromagnetic shields behavior. The presentation is focused on those methods that are appropriate for high frequency shields. Some simulation results are also presented in the final part of the paper.**

Keywords: *numerical methods for electromagnetism, FDTD, MoM (BEM), electromagnetic shielding.*

1. INTRODUCTION

Numerical methods have been applied to many of electrical engineering problems over the years. By reason of the high computer development these methods are tailored for software implementation.

The purpose of all numerical methods used in electromagnetism is to find approximate solutions to Maxwell's equations, or of equations derived from them, that satisfy given boundary and initial conditions. Formulating an electromagnetic problem means to specifying the properties that a solution must have, properties that can be specified as local (differential) or global (integral) properties, both in the studied space and at its boundaries. This means that we must solve a differential or an integral equation to specific conditions. A way to find the solution is to try to guess a solution and then verify if it has indeed the required properties. If it does, the problem is solved, if not the next step is to improve the guess until its properties meet the specifications, at least approximately, in other words, to optimize the guess. To implement this algorithm on a computer, it must formulated in such a way that it converges accurately, quickly, and reliably in a wide variety of electromagnetic scenarios. The basis for such a computer solution is the classical mathematical technique of approximating a function (the unknown solution) by a sum of known functions also called expansion functions or basis functions (eg. Fourier series).

In fact, all numerical methods used in electromagnetism employ this common strategy: the unknown solution is expanded in terms of known expansion functions with unknown coefficients. The coefficients are then determined such that the sum meets, as closely as possible, all the criteria stated in the formulation of the problem.

The difference between numerical techniques resides essentially in the following aspects: the electromagnetic quantity that is being approximated, the expansion functions that are used to approximate the unknown solution, the strategy employed to determine the coefficients of the expansion functions.

2. CATEGORIES OF NUMERICAL METHODS

Numerical methods can be placed in two main categories: frequency domain and time domain methods. This distinction reflects the difference in our perception of space and time. In the formal sense, frequency domain formulations are time domain formulations in which the time dimension has been subject to a Fourier transform, thus reducing the number of independent variables by one.

Another way of categorizing both the numerical techniques and the computer tools based on them relies on the number of independent space variables upon which the field and source functions depend. In all categories we can again distinguish between frequency domain and time domain formulations.

1D Methods – These are methods for solving problems where the field and source functions depend on one space dimension only. Typical applications are transmission line problems, uniform plane wave propagation, and spherically or cylindrically symmetrical problems with only radial dependence

2D Methods – These are methods for solving problems where the field and source functions depend on two space dimensions. Typical applications are cross-section problems in transmission lines and waveguides, waveguide structures, coaxial TEM problems, and spherical problems depending only on radius and azimuth or radius and elevation.

2.5D Methods – These are methods for solving problems where the fields depend on three space dimensions, while their sources (the currents) are mainly confined planes with two space dimensions. Typical examples are planar structures.

3D Methods – These are methods for solving problems where both the field and source functions depend on three space dimensions. This category comprises all volumic full-wave general-purpose formulations. The most prominent 3D frequency domain methods are finite element, finite difference, and method of moments formulations. Among the 3D time domain methods, the FDTD, FIT, and TLM formulations dominate. Hybrid formulations combining two or more different numerical techniques have been developed and implemented for particular applications.

3. DESCRIPTION OF SOME METHODS

3.1 Finite difference time domain method (FDTD)

FDTD is a popular computational technique. It is considered easy to understand and easy to implement in software. Since it is a time-domain method, solutions can cover a wide frequency range with a single simulation run. Maxwell's equations (in partial differential form) are modified to central-difference equations, discretized, and implemented in software. The equations are solved in a leapfrog manner: the electric field is solved at a given instant in time, then the magnetic field is solved at the next instant in time, and the process is repeated over and over again.
The basic FDTD space grid (Fig.1) and time-stepping algorithm trace back to a seminal 1966 paper by Kane Yee in IEEE Transactions on Antennas and Propagation[1].
In order to use FDTD a computational domain must be established. The computational domain is simply the physical region over which the simulation will be performed. The E and H fields are determined at every point in space within that computational domain. The material of each cell within the computational domain must be specified by its permeability, permittivity, and conductivity.
Once the computational domain and the grid materials are established, a source is specified. The source can be an impinging plane wave, a current on a wire, or an applied electric field, depending on the application. 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 points within the computational domain. The simulation evolves the E and H fields forward in time. Processing may be done

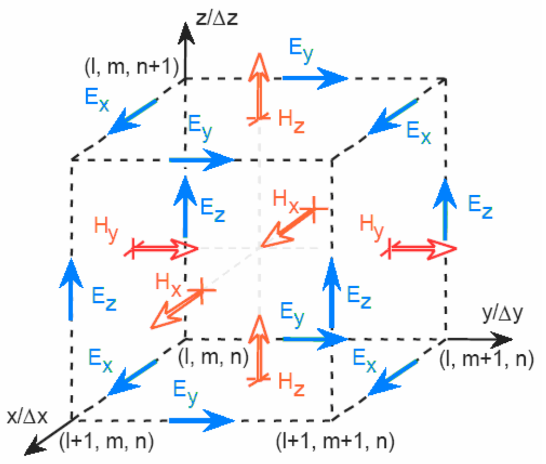

Fig.1: Three-dimensional Yee cell showing the staggered positions of the field component samples.

on the E and H fields returned by the simulation. Data processing may also occur while the simulation is ongoing.

3.1.1. Strength points of FDTD method

FDTD is a versatile modelling technique used to solve Maxwell's equations. It is intuitive, so users can easily understand how to use it and know what to expect from a given model.
FDTD is a time-domain technique, and when a broadband pulse (such as a Gaussian pulse) is used as the source, then the response of the system over a wide range of frequencies can be obtained with a single simulation. This is useful in applications where resonant frequencies are not exactly known, or anytime that a broadband result is desired.
Since FDTD calculates the E and H fields everywhere in the computational domain as they evolve in time, it lends itself to providing animated displays of the electromagnetic field movement through the model. This type of display is useful in understanding what is going on in the model, and to help ensure that the model is working correctly.
The FDTD technique allows the user to specify the material at all points within the computational domain. A wide variety of linear and nonlinear dielectric and magnetic materials can be naturally and easily modelled.
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 or indirectly.
FDTD uses the E and H fields directly. Since shielding modelling applications are interested in the E and H fields, it is convenient that no conversions must be made after the simulation has run to get these values.

3.1.2. Weak points of FDTD method

Since FDTD requires that the entire computational domain be girded, and the grid spatial discretization must be sufficiently fine to resolve both the smallest electromagnetic wavelength and the smallest geometrical feature in the model, very large computational domains can be developed, which results in very long processing 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 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.
Since FDTD simulations calculate the E and H fields at all points within the computational domain, the computational domain must be finite to permit its

residence in the computer memory. In many cases this is achieved by inserting artificial boundaries into the simulation space. Care must be taken to minimize errors introduced by such boundaries. There are a number of available highly effective absorbing boundary conditions (ABCs) to simulate an infinite unbounded computational domain. Most modern FDTD implementations instead use a special absorbing "material", called a perfectly matched layer (PML) [2] to implement absorbing boundaries.

Because FDTD is solved by propagating the fields forward in the time domain, the electromagnetic time response of the medium must be modelled explicitly. For an arbitrary response, this involves a computationally expensive time convolution, although in most cases the time response of the medium can be adequately and simply modelled using either the recursive convolution (RC) technique, the auxiliary differential equation (ADE) technique, or the Z-transform technique.

3.2 METHOD OF MOMENTS (MoM)

The Method of moments (MOM) or boundary element method (BEM) [3] is a numerical computational method of solving linear partial differential equations which have been formulated as integral equations (i.e. in boundary integral form). Conceptually, it works by constructing a "mesh" over the modelled surface. MoM is applicable to problems for which Green's functions can be calculated. These usually involve fields in linear homogeneous media; e.g. problems involving currents on metallic and dielectric structures and radiation in free space. The structures must be electrically small and are typically made of metals, although special extensions allow the inclusion of dielectrics, either as layered dielectrics or as finite sized shapes.

3.2.1 Strength points of the MoM

An advantage of the MoM is that it is a "source method" meaning that only the structure in question is discretized, not free space as with "field methods".

Because it requires calculating only boundary values, rather than values throughout the space defined by a partial differential equation, it is significantly more efficient in terms of computational resources for problems where there is a small surface/volume ratio.

3.2.2. Weak points of the MoM

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.

The fact that studied structures must be electrically small and made of metal places considerable restrictions on the range and generality of problems to which boundary elements can usefully be applied. For many problems boundary element methods are significantly less efficient than volume-discretization methods (FDTD).

Boundary element formulations typically give rise to fully populated matrices. This means that the storage requirements and computational time will tend to grow according to the square of the problem size. By contrast, finite element matrices are typically banded (elements are only locally connected) and the storage requirements for the system matrices typically grow quite linearly with the problem size. Compression techniques can be used to ameliorate these problems, though at the cost of added complexity and with a success-rate that depends heavily on the nature of the problem being solved and the geometry involved.

Nonlinearities can be included in the formulation, although they will generally introduce volume integrals which then require the volume to be discretized before solution can be attempted, removing one of the most often cited advantages of BEM.

4. AN EXAMPLE OF SHIELD OPTIMISATION USING NUMERICAL TECHNICS

For a easier validation of results we have chosen to optimise a well known shield type. The **Salisbury Screen,** Fig.2, is a resonant absorber, that consists of a resistive sheet placed an odd multiple of ¼ wavelengths in front of a metal (conducting) wall usually separated by an air gap. A material with higher permittivity can replace the air gap. This decreases the required gap thickness at the expense of bandwidth. In terms of transmission line theory, the quarter wavelength transmission line transforms the short circuit at the metal into an open circuit at the resistive sheet. The effective impedance of the structure is the sheet resistance. If the sheet resistance is 377 ohms/square (i.e. the impedance of air), then good impedance matching occurs.

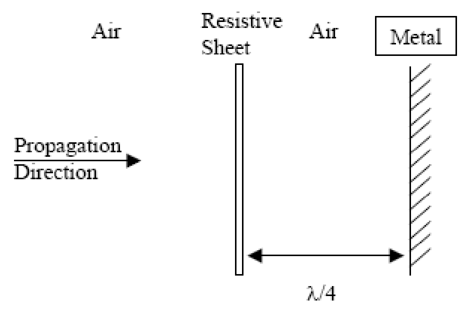

Fig.2: Salisbury Screen

Using the FDTD technique we have obtained results that respect strictly the theory and experimental observations.

The optimum thickness of the resistive sheet (case of impedance matching) is given by:

$$d = \frac{1}{Z_0 \sigma} \quad (1)$$

where σ is the conductivity of the sheet and Z_0 is the air impedance.

The optimum gap thickness is:

$$H = \frac{\lambda}{4} = \frac{c}{4f} \quad (2)$$

For a resonant frequency of 0.93 GHz the optimum thickness of the air gap is 80 mm, the optimum thickness of the resistive sheet at a conductivity σ = 13.26 S/m is d = 0.2 mm. The simulation result using FDTD method can be seen in Fig.3 as reflectivity coefficient S_{11} vs frequency.

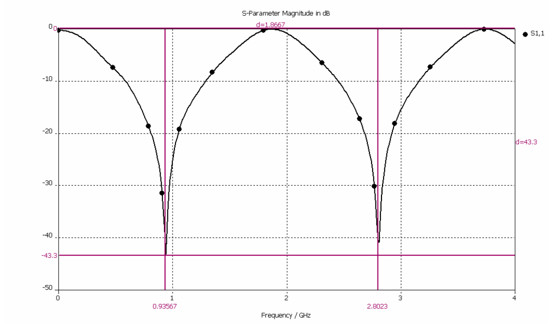

Fig.3: Reflectivity coefficient S11 for a Salisbury screen

In case of replacing the air gap whit a material with higher permittivity the relation for optimum gap thickness becomes:

$$H = \frac{\lambda}{4\sqrt{\varepsilon}} = \frac{c}{4\sqrt{\varepsilon} f} \quad (3)$$

For the same frequency f = 0.93 GHz and a dielectric gap with a permittivity ε = 3.5 the optimum gap thickness decrees to 43mm but whit a cost in bandwidth as is clearly seen in simulation results presented in Fig.4 as reflectivity coefficient S_{11} vs frequency.

The bandwidth of the Salisbury Screen can be improved by adding more quarter wavelength-spaced layers. This structure, represented in Fig.5, is called a **Jaumann** device, and is analogous to the anti-reflective coatings found in visible optics, which is comprised of stacks if high and low refractive index material to reduce reflections.

Beyond two layers the problem cannot be analytically optimised and iterative optimisation routines are

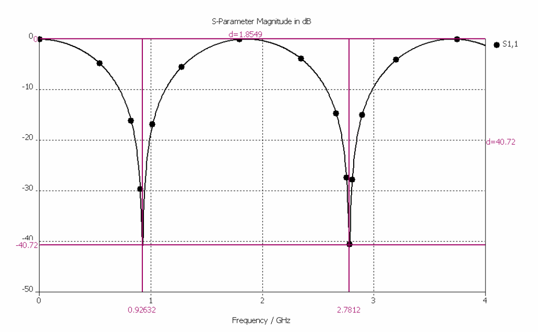

Fig. 4: Reflectivity coefficient S11 for a Salisbury screen whit a dielectric gap with ε = 3.5

required to maximize bandwidth while minimizing reflectivity and thickness.

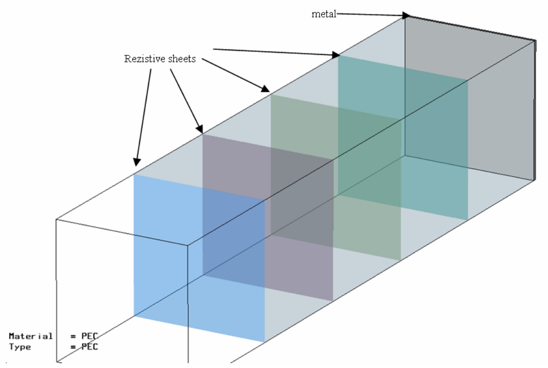

Fig. 5: Jaumann device

The optimization of a 4 resistive sheet becomes very difficult due to the number of variables.

Figure 6 shows the effect of increased number of layers on the bandwidth. The results obtained using a FDTD tool, represents the reflection coefficient of three different Jaumann devices, with 2, 3 and 4 layers , compared with a Salisbury screen.

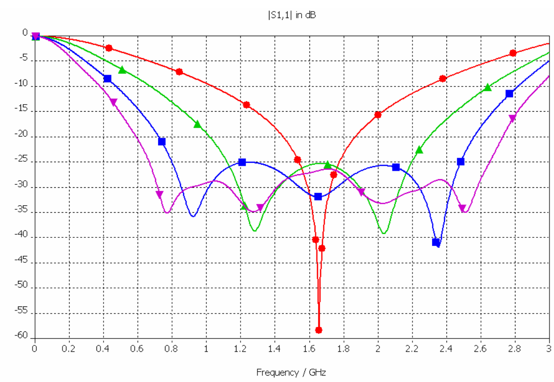

Fig. 6: Reflectivity coefficient S11 for a Jaumann device with 1, 2, 3 and 4 layers

Using an iterative optimization, conductivities for the Jaumann layers were obtained as follows:

for 2 layers : $\sigma_1 = 8.5 \ \ \sigma_2 = 33.5$

for 3 layers : $\sigma_1 = 5.5 \ \ \sigma_2 = 12.5 \ \ \sigma_3 = 37$

for 4 layers $\sigma_1 = 2.9 \ \ \sigma_2 = 7.8 \ \ \sigma_3 = 17.5$

$\sigma_4 = 36$ (all conductivities are expressed in S/m)

5. CONCLUSIONS

Because of the high complexity of electromagnetic shields optimisation problems, we used numerical techniques (FDTD) to simulate shields. For validation, we have chosen to optimize some well known shields. The obtained results were the same with those obtained by manual calculation. This allows us to use numerical techniques for optimisation of more complex shields such as composite honeycomb materials.

Acknowledgments

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