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PRACTICAL AND THEORETICAL EVALUATION OF EMC/EMI PROBLEMS OF METALLIC ENCLOSURES WITH APERTURES

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Abstract- In this paper, experimental and theoretical evaluation of coupling of electromagnetic radiation is reported. Validation of the results is obtained by comparing the experimental data with theoretical data both generated using CONCEPT Simulator and data from our hybrid MoM/FDTD formulation for the analysis of metallic enclosure with apertures. Both the CONCEPT Simulator and the hybrid MoM/FDTD formulation utilize the method of moments, however, the hybridization of the latter makes it more adaptive to the solutions of apertures of arbitrary shape within enclosures with inhomogeneous dielectrics. The problems analyzed are rectangular slot, cross-shaped aperture and diamond-shaped aperture. The experimental results and MoM/FDTD results also agree fairly well with those available in the literature.

Keywords: Shielding effectiveness, metallic enclosures, method of moments, finite difference time domain, EMI/EMC.

I. INTRODUCTION

Many approaches to limit the level of EMI by a device have been developed. One technique commonly used is to enclose the device in a metallic enclosure. Consequently, electronic devices are usually covered in metal coated enclosures for EMI/EMC reasons. These enclosures normally have various apertures for ventilation, cabling, displays etc. The apertures tend to adversely affect the ability of the enclosure to provide the required electromagnetic shielding. It is for this reason that EMI/EMC analysis has taken a prominent role in electronic system design.

An important parameter in enclosure studies is shielding effectiveness (SE). *SE* of an enclosure may be defined as the ratio of the electromagnetic energy level due to a source at a point without the enclosure to the electromagnetic energy at the same point with the enclosure. In terms of the electric field, *SE* may be expressed as:

$$SE = -20\log\left(\frac{E}{E_0}\right) \tag{1}$$

where $E=|\boldsymbol{E}|$ is the magnitude of the electric field at point P with the enclosure and $E_0=|\boldsymbol{E}_0|$ is the magnitude of the electric field at the same point without the enclosure.

SE of an enclosure can be estimated analytically, numerically or experimentally. Analytical methods include transmission line analogy, Robinson, et al [1] and circuit theory by Bridges in [2]. Analytical techniques demand that considerable simplification of the problem be made so that existing closed mathematical formulae can be applied. This simplicity is achieved at the expense of accuracy of the final solution. These techniques are therefore only applicable to problems with simple geometries. Experimental methods, while potentially the most reliable, can be expensive and time consuming even for simple problems. Numerical methods provide a convenient way of determining the SE of an enclosure where experimental work can be time consuming and/or analytical expressions become too complicated. The full wave analysis of Maxwell's equations characterizing numerical techniques also ensure that the solution can be carried to any desired order of accuracy depending on the availability of computational resources.

Excellent surveys of numerical methods commonly used are given by Hubing [3], Archambeault et al. in [4], Peterson et al. [5], Cerri et al. [6], and Kunz et al [7]. Azaro et al. [8] and Feng et al. [9] evaluated effects of an external incident electromagnetic wave on a metallic enclosure with rectangular apertures. However, their work only dealt with rectangular apertures. Ward W., et al [10] used a fast semi-analytical method to predict the shielding in the low-frequency and multiresonant region of realistic enclosures with many small apertures. Though their method results in a considerable saving of the CPU time, it is limited to rectangular apertures. Kantartzis et al [11] modeled complex EMC problems using a higher order nonstandard FDTD-PML method, however, their method was only limited to determining dispersion errors in curvatures. The work of Feng and Shen [9] which is similarly based on Finite Difference Time Domain (FDTD) and the Method of Moments (MoM) dealt only with apertures residing in a uniform medium. The Finite Element Method (TEM) and Transmission Line Matrix (TLM) have also been used. The merits and demerits of each technique are discussed in the literature [3], [4]. Park et al [12] analyzed the problem of electromagnetic penetration into a rectangular enclosure with multiple rectangular apertures. Yenikaya and Akman [13] modeled the problem of loaded enclosure with aperture in EMC problems.

The choice of numerical technique generally depends on the geometry of the problem and the accuracy of desired solution. Some problems may have complex geometries with inhomogeneities so that application of one numerical method is not computationally sufficient. In such cases, the equivalence principle [14] is used to sub-divide the problem into various smaller problem segments. Each problem segment is solved independently using the most suitable technique. The final solution to the entire problem is a cascaded combination of the solutions to the various problem segments. Such solution techniques are termed hybrid or mixed. Here, we propose an MOM/FDTD technique. The advantage of our method is that it is based upon the generalized network formulation for aperture problems [14]. In addition, the problem of inhomogeneities in the interior regions is taken care of by the FDTD technique. For the discretization of problem surface domain, we use MoM method as developed by Harrington [15] in conjunction with triangular patches proposed by Rao et al [16] for arbitrary shaped scattering surfaces and implemented by Konditi and Sinha [17] for radiating apertures of arbitrary shape. Triangular patch modeling has the property of conformity to arbitrary shapes. Problem singularities in the MoM method have been sufficiently dealt with as was proposed by Graglia [18] and implemented by Konditi and Sinha in [19].

Figure 1 shows a typical rectangular metallic enclosure with dimensions $l \times w \times h$ and one rectangular aperture on one of its faces. The enclosure is illuminated by a z polarized incident plane wave. The enclosure walls are assumed to be made of PEC material. This means that the penetration of the fields inside and outside the enclosure is only through the aperture. The main goal is to determine the shielding effectiveness of the enclosure using equation (1).

II. FORMULATION OF THE PROBLEM

The formulation proposed here is general and can be used for homogeneous as well as inhomogeneously–filled enclosures. Firstly, we look at the Method of Moments formulation followed by the Finite Difference Time Domain (FDTD).

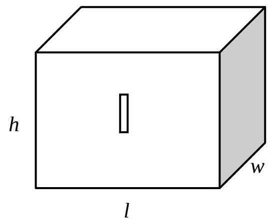

Figure 1. Typical rectangular metallic enclosure with a single rectangular aperture

A. Determination of Equivalent Aperture Magnetic Currents

The original problem can be separated into two regions: region 1 and region 2 as shown in Figure 2. The fields in region 1 are a superposition of the incident fields $\boldsymbol{H}^i$ and the fields due to equivalent surface magnetic currents $2\boldsymbol{M}_1$ over the aperture region radiating into free space. The field in region 2 is only due to the equivalent surface magnetic current $-2\boldsymbol{M}_1$ over the aperture region. The total magnetic field in region 1 is:

$$\boldsymbol{H}_1^{tot} = 2\boldsymbol{H}_1^t\left(\boldsymbol{M}_1\right) + \boldsymbol{H}_i^t \tag{2}$$

where $\boldsymbol{H}_1^{tot}$ the total magnetic field in region 1 while $\boldsymbol{H}_1^t(\boldsymbol{M}_1)$ and $\boldsymbol{H}_i^t$, is the tangential magnetic field due to magnetic current and tangential incident magnetic field respectively. In region 2:

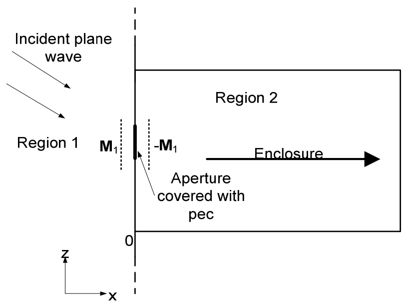

Figure 2. Equivalent problem for the interior region and exterior region

where $\boldsymbol{H}_1^{tot}$ the total magnetic field in region 1 while $\boldsymbol{H}_1^t(\boldsymbol{M}_1)$ and $\mathbf{H}_i^t$, is the tangential magnetic field due to magnetic current and tangential incident magnetic field respectively. In region 2:

$$\boldsymbol{H}_2^{tot} = -2\boldsymbol{H}_2^t\left(\boldsymbol{M}_1\right) \tag{3}$$

where $\boldsymbol{H}_2^{tot}$ and $\boldsymbol{H}_2^t(\boldsymbol{M}_1)$ are the total tangential magnetic field and tangential magnetic field due to magnetic current in region 2 respectively. To ensure that the electric field is continuous through the aperture, equation (3) and (4) must be equal i.e.:

$$2\boldsymbol{H}_t^1\left(\boldsymbol{M}_1\right) + \boldsymbol{H}_i^t = -2\boldsymbol{H}_2^t(\boldsymbol{M}_1) \tag{4}$$

Equation (5) is an operator equation which can be solved using the method of moments. The solution is based on the generalized network formulation for aperture problems as discussed in [5, 12]. The unknown magnetic currents are first expanded to obtain:

$$\boldsymbol{M}_1 = \sum_n V_n M_n \tag{5}$$

where V_n are unknown coefficients to be determined and M_n is a suitable expansion (basis) function. By choosing an inner product of the form:

$$\langle \boldsymbol{A}, \boldsymbol{B} \rangle = \iint_{aperture} \boldsymbol{A} \cdot \boldsymbol{B} dS' \tag{6}$$

where S' is the area of the aperture, and testing function W_m, equation (5) can be reduced into a matrix equation of the form:

$$[Y_1 + Y_2]\boldsymbol{V} = \boldsymbol{I}_i \tag{7}$$

where

$$[Y_1] = 2[\langle W_m, H_1^t(M_n) \rangle]_{N\times N} \tag{8}$$

is the admittance matrix for region 1.

$$[Y_2] = 2[\langle W_m, H_2^t(M_n) \rangle]_{N\times N} \tag{9}$$

is the admittance matrix for region 2.

$$\boldsymbol{I}^i = [-\langle W_m, H_i^t \rangle]_{N\times 1} \tag{10}$$

is the matrix containing the incident field and

$$\boldsymbol{V} = [V_n]_{N\times 1} \tag{11}$$

is the vector of unknown coefficients (voltage vector).

Therefore the resultant voltage vector is:

$$\boldsymbol{V} = [Y_1 + Y_2]^{-1} \boldsymbol{I}_i \tag{12}$$

This gives the vector of coefficients which can be used to determine $\boldsymbol{M}_1$ according to equation (6).

B. Evaluation of Matrix Elements

Since there are no sources at the boundary between the two regions, and assuming time harmonic fields, the magnetic potential integral equation for the aperture may be written as:

$$\boldsymbol{H}_i^t = -j\omega \boldsymbol{F}(\boldsymbol{r}) - \nabla \varphi(\boldsymbol{r}) \tag{13}$$

where $\boldsymbol{F}(\boldsymbol{r})$ and $\varphi(\boldsymbol{r})$ are the electric vector potential and magnetic scalar potentials respectively. These potentials may be expressed as:

$$\boldsymbol{F}(\boldsymbol{r}) = \varepsilon_0 \iint_S \boldsymbol{M_1}(\boldsymbol{r}) G(\boldsymbol{r}, \boldsymbol{r}') dS' \tag{14}$$

$$\varphi(\boldsymbol{r}) = -\frac{\nabla \cdot \boldsymbol{F}}{j\omega\varepsilon_0\mu_0} = \frac{j}{\omega\mu_0} \iint_S \nabla \bullet \boldsymbol{M}_1(\boldsymbol{r}) G(\boldsymbol{r}, \boldsymbol{r}') dS' \tag{15}$$

Equation (16) is the Lorenz gauge transformation. If we denote the magnetic charge density as ρ^m the magnetic current will be related to its corresponding charges density by the equation of continuity which may be written as:

$$-j\omega\rho^m(\boldsymbol{r}') = \nabla \bullet \boldsymbol{M}_1(\boldsymbol{r}') \tag{16}$$

The scalar potential may then be expressed in terms of the magnetic charge density as:

$$\varphi(\boldsymbol{r}) = \frac{1}{\mu_0} \iint_S \rho^m(\boldsymbol{r}) G(\boldsymbol{r}, \boldsymbol{r}') dS' \tag{17}$$

$G(\boldsymbol{r}, \boldsymbol{r}')$ is the three dimensional Green's function given by:

$$G(\boldsymbol{r}, \boldsymbol{r}') = \frac{e^{-jk|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|} \tag{18}$$

$\boldsymbol{r}$ and $\boldsymbol{r}'$ denote the source and field point co-ordinates respectively.

We use triangular patch modeling proposed by Rao et al. [16]. The aperture region is subdivided into small triangular cells each of which is treated separately. A pair of triangular faces denoted T_n^+ and T_n^- and having an n^{th} edge AB as their common edge are shown in the Figure 3. The local and global position vectors at any point within the triangle are denoted $\bar{\rho}_n^{\pm}$ and $\boldsymbol{r}$ respectively. Any point within a particular triangle may be located with respect to the local co-ordinate system or the global co-ordinate system as shown. A vector basis function associated with the n^{th} edge is defined as [17]:

$$\boldsymbol{M}_n = \begin{cases} \dfrac{l_n}{2A_n^+} & \boldsymbol{r} \text{in} T_n^+ \\ \dfrac{l_n}{2A_n^-} & \boldsymbol{r} \text{in} T_n^- \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

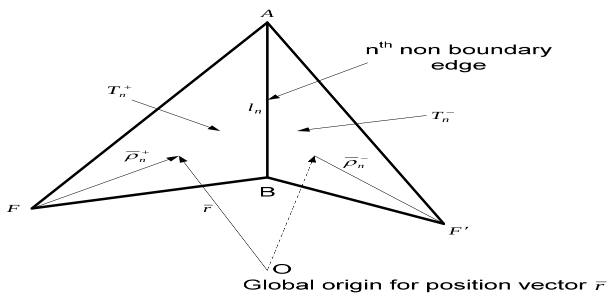

Figure 3. Triangle pair associated with the n^{th} edge

where l_n is the length of the n^{th} edge and $A_n^{\pm}$ is the area of the triangle $T_n^{\pm}$. The designation T_n^+ and T_n^- is determined by choosing a positive current reference direction for the n^{th} edge, which is assumed to be from T_n^+ to T_n^-. The associated equivalent magnetic charge density for the n^{th} edge is given using (17) as:

$$\rho_n^m = \frac{1}{j\omega} \nabla \cdot \boldsymbol{M}_n = \begin{cases} \dfrac{-l_n}{j\omega A_n^+} & \boldsymbol{r} \text{in} T_n^+ \\ \dfrac{+l_n}{j\omega A_n^-} & \boldsymbol{r} \text{in} T_n^- \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

It is found that ρ_n^m is constant in each triangle and the total charge associated with T_n^+ and T_n^- is zero. For simplicity, we follow Galerkin's procedure so that $\boldsymbol{W}_m = \boldsymbol{M}_m$. Implementing equations (14-18) over the region in Figure 3 and following the procedure described by Konditi and Sinha [17], the integrals over $T_m^{\pm}$ are approximated by their values at the centroids of the triangles to obtain:

$$Y^{r}_{mn} = -2l_m \left\{ \begin{aligned} & j\omega \left[\boldsymbol{F}_n(\boldsymbol{r}^{c+}_m) \cdot \frac{\overline{\rho}^{c+}_m}{2} + \boldsymbol{F}_n(\boldsymbol{r}^{c-}_m) \cdot \frac{\overline{\rho}^{c-}_m}{2} \right] \\ & + \varphi_n(\boldsymbol{r}^{c-}_m) - \varphi(\boldsymbol{r}^{c+}_m) \end{aligned} \right\} \quad (21)$$

where Y^{r}_{mn} is an element of the admittance matrix in the r^{th} region and:

$$\boldsymbol{F}_n(\boldsymbol{r}^{c\pm}_m) = \varepsilon^r \iint_{T^{\pm}_n} \overline{\overline{G}}(\boldsymbol{r}^{c\pm}, \boldsymbol{r}') \bullet \boldsymbol{M}_n(\boldsymbol{r}') ds \quad (22)$$

$$\varphi_n(\boldsymbol{r}^{c\pm}_m) = \frac{-1}{j\omega\mu^r} \iint_{T^{\pm}_n} \nabla \overline{\overline{G}}(\boldsymbol{r}^{c\pm}, \boldsymbol{r}') \bullet \boldsymbol{M}_n(\boldsymbol{r}') ds \quad (23)$$

In the above equations, $\overline{\rho}^{c\pm}_m$ are the local position vectors of the centroids of $T^{\pm}_m$ and $\boldsymbol{r}^{\pm}_m = (\boldsymbol{r}^{1\pm}_m + \boldsymbol{r}^{2\pm}_m + \boldsymbol{r}^{3\pm}_m)/3$ are the position vectors of the centroids of $T^{\pm}_m$ with respect to the global co-ordinate system. An element of the excitation vector in equation (11) may be written as:

$$I^{i}_m = -l_m \left(\boldsymbol{H}^{i}_t(\boldsymbol{r}^{c+}_m) \cdot \frac{\overline{\rho}^{c+}_m}{2} + \boldsymbol{H}^{i}_t(\boldsymbol{r}^{c-}_m) \cdot \frac{\overline{\rho}^{c-}_m}{2} \right) \quad (24)$$

The evaluation of the integrals in equation (22) depends on whether the Kernel of a particular integral is bounded or unbounded [17] over the integration domain. If the kernel is bounded, numerical quadrature is used. For unbounded Kernels, we use a procedure proposed in [18]. The evaluation of the elements of the excitation vector also follows the procedure detailed in [17].

C. FDTD Formulations

So far, the induced magnetic currents at the aperture by the known incident fields in region 1 have been determined using the method of moments. The next step is to use these currents to obtain the fields in region 2. One approach would be to compute these fields using the potentials with these induced aperture currents as the source. This approach however has three main limitations: Firstly, the Kernels of the resultant integral equations are usually difficult to integrate and would better be avoided. Secondly, such an approach would only be applicable to an empty or homogeneously filled enclosure and finally, the results obtained only apply to a single mode. To overcome these limitations, FDTD is proposed for the analysis of the fields in region 2. FDTD is based on the direct solution to Maxwell's curl equations given as:

$$\nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t} \quad (25)$$

$$\nabla \times \boldsymbol{H} = \varepsilon \frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J} \quad (26)$$

$$\nabla \bullet \boldsymbol{E} = \frac{\rho}{\varepsilon} \quad (27)$$

$$\nabla \bullet \boldsymbol{B} = 0 \quad (28)$$

Equations (27) and (28) are of no consequence to FDTD formulations since they are already contained within (25) and (26). The FDTD procedure entails discretization of the region through which the field propagates using the Yee cell shown in Figure 4. The fields can then be iteratively determined at specific points in the Yee cell using equations (25) and (26) with the spatial and temporal derivatives replaced with central finite differences.

Using the indices i, j, k, n where $x = i\Delta x$, $y = j\Delta y$, $z = k\Delta z$ and $t = n\Delta t$, the following system of update equations are obtained from (25) and (26),

$$H_x^{n+\frac{1}{2}}(i, j+\tfrac{1}{2}, k+\tfrac{1}{2}) = H_x^{n-\frac{1}{2}}(i, j+\tfrac{1}{2}, k+\tfrac{1}{2}) + \frac{\Delta t}{\mu(i, j+\frac{1}{2}, k+\frac{1}{2})} \cdot \left(\begin{aligned} & \frac{E^n_y(i, j, +\frac{1}{2}k+1) - E^n_y(i, j+\frac{1}{2}, k)}{\Delta x} - \\ & \frac{E^n_z(i, j+1, k+\frac{1}{2}) + E^n_z(i, j, k+\frac{1}{2})}{\Delta y} \end{aligned} \right) \quad (29)$$

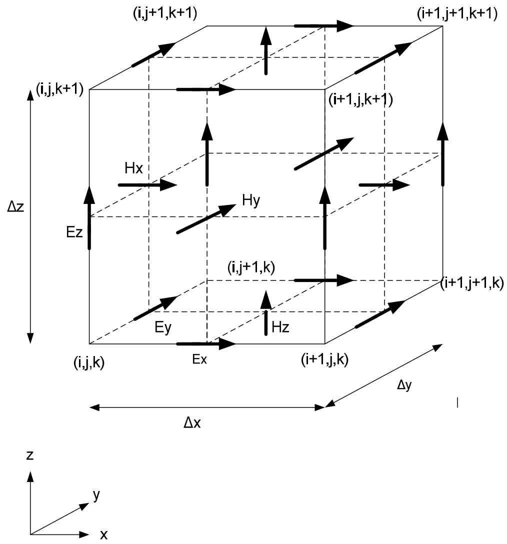

Figure 4. Three dimensional Yee cell

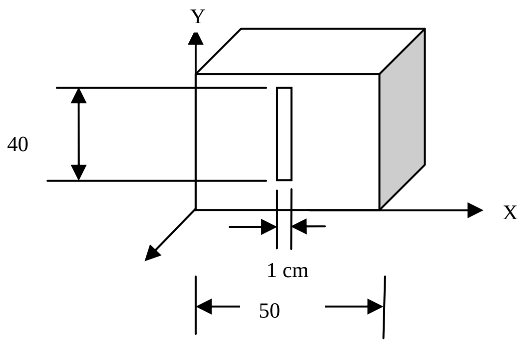

Figure 5. Enclosure used for validation with a centrally located 40x1 cm aperture

$$H_y^{n+\frac{1}{2}}(i+\tfrac{1}{2}, j, k+\tfrac{1}{2}) = H_y^{n-\frac{1}{2}}(i+\tfrac{1}{2}, j, k+\tfrac{1}{2}) + \frac{\Delta t}{\mu(i+\frac{1}{2}, j, k+\frac{1}{2})} \cdot \left(\begin{aligned} & \frac{E^n_z(i+1, j, k+\frac{1}{2}) - E^n_z(i, j, k+\frac{1}{2})}{\Delta x} - \\ & \frac{E^n_x(i+\frac{1}{2}, j, k+1) + E^n_z(i+\frac{1}{2}, j, k)}{\Delta y} \end{aligned} \right) \quad (30)$$

$$H_z^{n+\frac{1}{2}}(i+\tfrac{1}{2}, j+\tfrac{1}{2}, k) = H_z^{n-\frac{1}{2}}(i+\tfrac{1}{2}, j+\tfrac{1}{2}, k) + \frac{\Delta t}{\mu(i+\frac{1}{2}, j+\frac{1}{2}, k)}\left(\frac{E_x^n(i+\frac{1}{2}, j+1, k) - E_x^n(i+\frac{1}{2}, j, k)}{\Delta y} - \frac{E_y^n(i+1, j+\frac{1}{2}, k) + E_y^n(i, j+\frac{1}{2}, k)}{\Delta z}\right) \quad (31)$$

$$E_x^{n+1}(i+\tfrac{1}{2}, j, k) = E_x^n(i+\tfrac{1}{2}, j, k) + \frac{\Delta t}{\varepsilon(i+\frac{1}{2}, j, k)}\left(\frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k) - H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j-\frac{1}{2}, k)}{\Delta y} - \frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k+\frac{1}{2}) + H_y^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k-\frac{1}{2})}{\Delta z}\right) + E_x \quad (32)$$

$$E_y^{n+1}(i, j+\tfrac{1}{2}, k) = E_y^n(i, j+\tfrac{1}{2}, k) + \frac{\Delta t}{\varepsilon(i, j+\frac{1}{2}, k)}\left(\frac{H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) - H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k-\frac{1}{2})}{\Delta z} - \frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k) + H_z^{n+\frac{1}{2}}(i-\frac{1}{2}, j+\frac{1}{2}, k)}{\Delta x}\right) + E_y \quad (33)$$

$$E_z^{n+1}(i, j, k+\tfrac{1}{2}) = E_z^n(i, j, k+\tfrac{1}{2}) + \frac{\Delta t}{\varepsilon(i, j, k+\frac{1}{2})}\left(\frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k+\frac{1}{2}) - H_y^{n+\frac{1}{2}}(i-\frac{1}{2}, j, k+\frac{1}{2})}{\Delta x} - \frac{H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) + H_x^{n+\frac{1}{2}}(i, j-\frac{1}{2}, k+\frac{1}{2})}{\Delta y}\right) + E_z \quad (34)$$

Before implementing (29-34), suitable cell dimensions Δx, Δy, Δz need to be established. The selected cell size should be able to give a sufficiently accurate solution with minimum computation resources. Experience has shown that for sufficiently accurate results, the cell dimension should at least be a tenth of the shortest wavelength (wavelength at highest frequency). Also to avoid dispersion errors [4], the smallest cell dimension should at least be a third of the highest cell dimension. For example, if Δx is the smallest cell dimension and Δz is the largest, $\Delta x \geq \Delta z/3$. The choice of Δt is dictated by the Courant stability condition which requires that:

$$\Delta t \leq \frac{1}{c(1/\Delta x^2 + 1/\Delta y^2 + 1/\Delta z^2)^{1/2}} \quad (35)$$

The theoretical aspects of FDTD are well covered in published literature notably [7]. The induced aperture magnetic currents are directly incorporated into FDTD update equations as sources using the expression:

$$-2\boldsymbol{M} = \boldsymbol{E}_a \times \boldsymbol{n} \quad (36)$$

where $\boldsymbol{E}_a$ the electric is field at the aperture and $\boldsymbol{n}$ is a unit vector normal to the aperture. This eliminates the need for integral equations altogether. Also FDTD is most suited for problems involving complex geometries with inhomogeinities and is therefore an ideal choice since the enclosure must enclose some object in the general EMI/EMC problems of practical interest.

Since MoM is a frequency domain technique while FDTD is in time domain, some form of matching is needed for the hybrid model to be realizable. To achieve this, the magnitude of the current is directly incorporated into the FDTD update equations but its phase is interpreted as a time delay. Another approach is to use 'marching on in time' implementation of MoM (MoM Time Domain or MoM/TDTD) as proposed by Cerri et al. [6]. In this case, the following procedure is used for each time sample:

1. The MoM algorithm evaluates the induced magnetic current at the aperture. This current is a function of the incident field and the currents evaluated in the previous time steps. For each time step, the conventional MoM procedure is used.
2. The induced current distributions are provided by MoM to the FDTD algorithm which evaluates the fields at the centre of the enclosure (region 2).

The procedure is iterated for the next time step and steps (1) and (2) followed with updated values of the incident field at the aperture.

III. RESULTS AND DISCUSSIONS

In this section, some results obtained using the hybrid MoM/FDTD formulations developed are presented. The numerical data is compared to CONCEPT Simulator generated data and, in some cases, experimental results.

A. Validation of Formulation

To validate the formulations, a 50 cm cube enclosure with a rectangular aperture located at the centre of the front wall measuring 40 cm x 1 cm as shown in Figure 5 is chosen. This choice is dictated by the fact that the results for this problem are available in literature.

Shielding effectiveness for a rectangular slot 40 cm x 1 cm at the front face of the cube 50 cm x 50 cm is computed at the centre of the enclosure based on our MOM/FDTD technique and our experimental data is compared with the data generated from the CONCEPT Simulator as developed by Hafner [20].

From Figure 6, it is seen that the MOM/FDTD agree quite well with the CONCEPT Simulator results. However, there is a clear difference between these results and our experimental results. This can be attributed to the lack of anechoic chamber which could have cut out most of the reflections and other interferences.

B. Shielding Effectiveness of a Cube with a 40 cm x 5 cm Rectangular Slot

From Figure 7, it is observed that inserting a cube with a slot, to a large extent, shields the EM fields. However, at certain frequencies, resonances seem to occur obliterating shielding effectiveness of the cube.

C. Effect of Polarization on EM Coupling

It can be observed that polarization of the EM wave, Figure 8, seems to be insignificant in the frequency range between 300 MHz and 800 MHz, however at frequencies below and above this range, the effect is significant.

There is no clear explanation for this disparity, however both the experimental result and CONCEPT Simulator vindicate this contention.

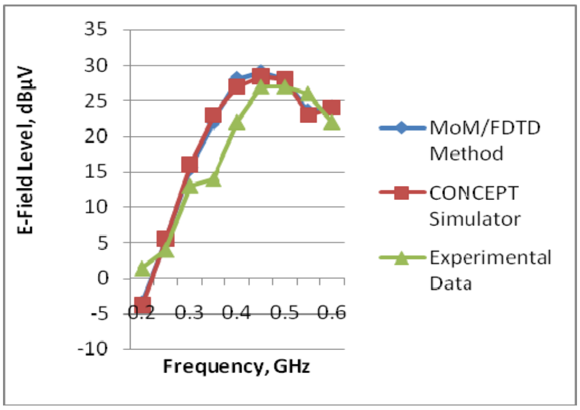

Figure 6. A monopole located 3-m away from a cube with a rectangular slot at the centre of its front face

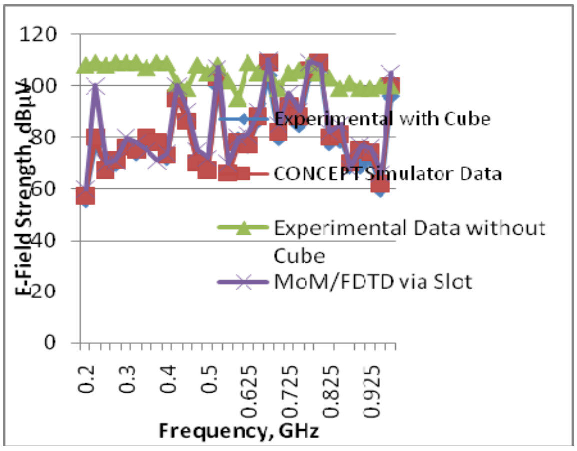

Figure 7. A dipole excited E-field coupling levels via a slot and without a slot both experimental and simulated

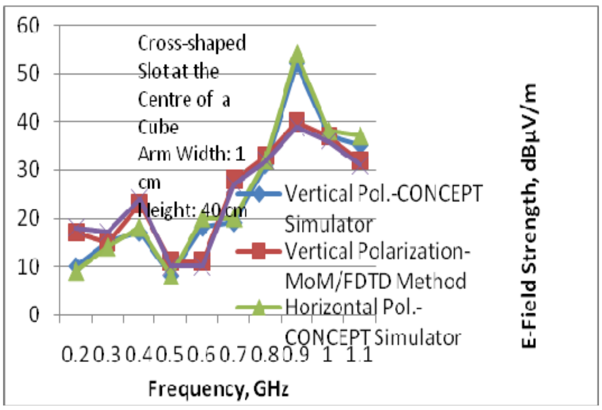

Figure 8. Vertically and horizontally polarized field experimental results for rectangular slot at the edge of a cube excited by 1-volt monopole located 2 metres away

D. Effect of Shape on EM Coupling

Figure 9 shows a diamond-shaped aperture centrally cut in the front-face of the cube. It is observed that with shape of aperture the coupling is much weaker than for rectangular slot. In other words, a cube with a diamond-shaped aperture is a better shield than with a rectangular slot. It is also noted that the curves have similar trends in both cases. Figure 10 shows a cross-shaped aperture centrally cut in the front-face of the cube. It also displays a similar trend like the diamond-shaped aperture and is similarly provides a better shield than the cube with a rectangular slot.

Figure 11 shows a H-shaped aperture centrally cut in the front-face of the cube. For this type of aperture, the trend of the coupling curves is more or less similar to that of a rectangular slot. Perhaps, this is because a an H-shaped slot composed of rectangular slots only in a slightly different configuration which now accounts for the low level of EM coupling relative to the slot. Shielding effectiveness can be improved by using apertures of other shapes other than a rectangular slot.

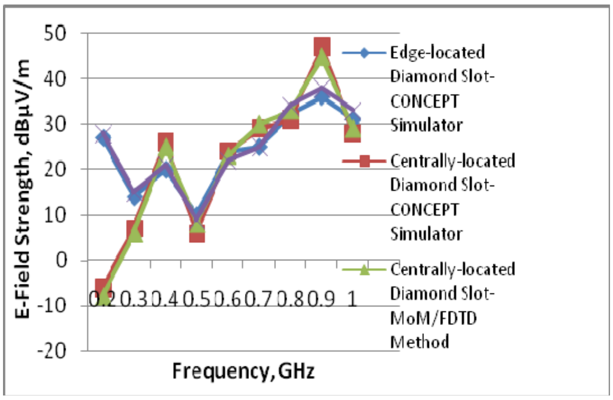

Figure 9. Electric field strength due to a diamond-shaped aperture different positions in the front-face of a 50 cm Cube excited by 1-volt monopole 3 metres away

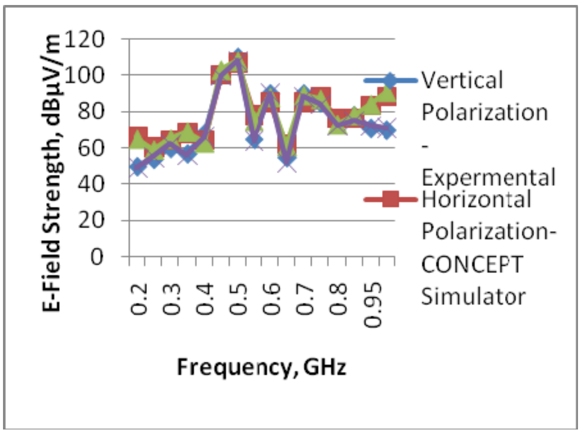

Figure 10. Electric field strength due to cross-shaped slot at the centre of a 50cm cube excited by 1-volt monopole 3 metres away

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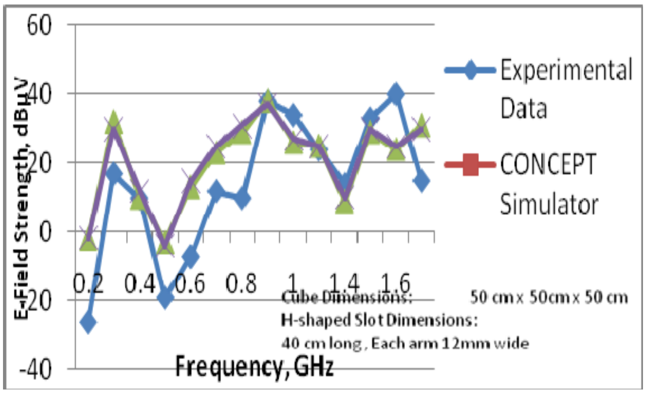

Figure 11. Electric field strength due to an H-shaped slot located at the face -edge of a conducting cube excited by a 1-volt monopole 3 metres away

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