Extension of the 2-D CP-FDTD Thin Slot Algorithm to 3-D for Shielding Analysis

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Abstract **–** The two-dimensional CP-FDTD thin slot algorithm is extended to three-dimensions for the application to shielding analysis in electromagnetic compatibility. The accuracy and the applicability of the 3-D CP-FDTD scheme to the slot width were validated with finer mesh model and capacitive thin-slot formalism (C-TSF). The model taken by the comparison is originated from a thin slot in an enclosure wall. The numerical results indicate that the performance or accuracy will descend with the augment of the slot width. Good agreements with the results of finer mesh modeling can be expected as the slot width is on the order of the mesh dimension, and quite large discrepancies from the results of C-TSF with the slot width far less than mesh dimension. The 3D CP-FDTD algorithm will be utilized when the slot width is comparatively large and otherwise C-TSF will be used. Taking advantage of both of them will avoid finer mesh in thin slots modeling such as the shielding analysis of the electronic enclosure.

I. INTRODUCTION

The integrity of shielding enclosures is compromised by apertures and seams required for heat dissipation, cable penetration, and modular construction, among other possibilities [1]. These perforations allow energy to be radiated to the external environment from interior electronics, or energy coupled from the exterior to interfere with interior circuits [2, 3]. An understanding of energy coupling mechanisms to and from the enclosure is essential to minimize the EMI and susceptibility risk in a new design.

Some numerical methods have been applied to solve these EMI/EMC problems such as the finite difference time domain (FDTD) method [4], finite element method (FEM) [5], method of moments (MoM) [6], etc. Among these methods, the FDTD method is one of the most effective tools for the analysis of varieties electromagnetic problems, and has previously been applied for modeling apertures in shielding enclosures. If the physical size of the aperture is on the order of, or larger than the spatial cell size, then modeling this aperture with FDTD is not a problem, however, if the aperture is narrow with respect to the spatial cell, one must either reduce the spatial cell size down to that require to resolve the aperture, or adopt an alternative method to characterize the aperture. The reduction of the cell size is often not a feasible approach, and therefore alternative methods have been investigated [7]. Two of the more popular thin slot formalisms (TSF) have been proposed by Gilbert and Holland (C-TSF) [8] and Taflove (CP-FDTD) [9]. Utilizing these TSF, a thin slot segment can be modeled with a single cell, thereby saving computational resources while retaining accuracy. Previous results for slots in infinite or large planes show C-TSF computation results agree well with experimental data [4]. The two-dimensional (CP-FDTD) study based on contour path method by Taflove generally found superior accuracy of the TSF, but it can’t be applied in solving 3D electromagnetic problems.

To implement the TSF, the two-dimensional CP-FDTD thin slot algorithm is extended to three-dimensional for the application to shielding analysis in electromagnetic compatibility. The accuracy and the applicability of the 3-D CP-FDTD scheme to the slot width were validated with finer mesh model [10] and capacitive thin slot formalism (C-TSF). Results indicate that the 3D CP-FDTD algorithm will be utilized when the slot width is comparatively large and otherwise C-TSF. Taking advantage of both of them will avoid finer mesh in thin slots modeling.

II. C-TSF ALGORITHMS

Different subcellular thin-slot algorithms are employed for modeling thin slots in enclosures and conducting plates. The popular method introduced by Gilbert and Holland [8], denoted herein as the C-TSF, is based on a straight-forward quasi-static approximation. The Yee cells around a slot oriented along *z*-axis is shown in Fig. 1. Employing a quasi static approximation for narrow slots, and assuming the field quantities vary slowly in the *z*-direction, the slot can be viewed as a coplanar, parallel strip capacitor. The slot is then modeled by modifying the relative permittivity and relative permeability in the FDTD algorithm for the electric and magnetic field components in the slot.

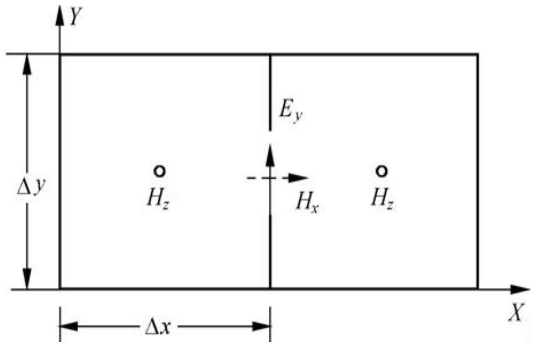

Fig. 1. FDTD cells around the slot for the C-TSF algorithm.

The C-TSF time-marching equations can be obtained for the electric field and magnetic field components in the slot by defining two line integrals, one transverse to the slot, and the other across the slot. These line integrals can be employed with the integral form of Maxwell's equations to obtain modified FDTD update equations for the field components in the slot. An extra parameter results in the finite-difference equation which is the ratio of the two line integrals, and can be shown to be an effective permittivity for the slot. The relative permittivity in the slot is then written as,

$$\varepsilon_{\mathrm{r}} = \frac{1}{\varepsilon_0} \frac{\Delta y}{\Delta x} C \tag{1}$$

where C is the parallel strip per unit length capacitance. The capacitance is evaluated within only one FDTD cell, and is denoted as the in cell capacitance. In order to maintain the free space phase velocity through the slot $v = 1\big/\sqrt{\varepsilon_r \mu_r \varepsilon_0 \mu_0}$, the relative permeability in the slot is given by $\mu_r=1/\varepsilon_r$. For the slot shown in Fig. 1., the tilde terms are the average values in and across the slot for the electric and magnetic field components, respectively. The slot capacitance per unit length is,

$$\varepsilon_{\mathrm{r}} = \frac{\Delta y}{\Delta x} \frac{K\left[\sqrt{1 - w^2/\Delta y^2}\right]}{K\left[w/\Delta y\right]} \tag{2}$$

where $K(\cdot)$ is the complete elliptic integral of the first kind, w is the slot width. The relative permittivity is then related to the slot capacitance by equation (1). Therefore, the electric and magnetic field components in the slot can be updated by modifying only the permittivity and permeability in the respective equations as,

$$E^{n+1}_{y(i,j+1/2,k)} = E^{n}_{y(i,j+1/2,k)} + \frac{\Delta t}{\varepsilon_r \varepsilon_0 \Delta s}\Big[H^{n+1/2}_{x(i,j+1/2,k+1/2)} - H^{n+1/2}_{x(i,j+1/2,k-1/2)} - H^{n+1/2}_{z(i+1/2,j+1/2,k)} + H^{n+1/2}_{z(i-1/2,j+1/2,k)}\Big] \tag{3}$$

$$H^{n+1/2}_{x(i,j+1/2,k+1/2)} = H^{n-1/2}_{x(i,j+1/2,k+1/2)} - \frac{\Delta t}{\mu_r \mu_0 \Delta s}\Big[E^{n}_{y(i,j+1/2,k+1)} - E^{n}_{y(i,j+1/2,k)} - E^{n}_{z(i,j+1,k+1/2)} + E^{n}_{z(i,j,k+1/2)}\Big]. \tag{4}$$

III. 3-D CP-FDTD ALGORITHMS

The CP-FDTD method is not based on Maxwell's equations in differential form but in integral form using Ampère's and Faraday's laws, indicated as follows,

$$\frac{\partial}{\partial t}\iint_s \boldsymbol{H} \bullet \mathrm{d}\boldsymbol{S} = -\frac{1}{\mu}\oint_c \boldsymbol{E} \bullet \mathrm{d}\boldsymbol{L} \tag{5}$$

$$\frac{\partial}{\partial t}\iint_s \boldsymbol{E} \bullet \mathrm{d}\boldsymbol{S} = -\frac{1}{\varepsilon}\oint_c \boldsymbol{H} \bullet \mathrm{d}\boldsymbol{L}\,. \tag{6}$$

Applying Faraday's law along contour L_1—L_2—L_3—L_4 in Fig. 2, and assuming that the field value at a midpoint of one side of the contour equals the average value of that field component along that side.

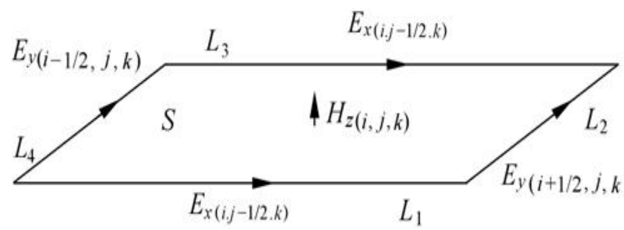

Fig. 2. Faraday's law for H_z.

Now, further assuming that $H_{z(i,j,k)}$ equals the average value of H_z over the surface S, and then the time derivative of H_z can be obtained using a central difference expression, as follows,

$$H_z^{n+1/2}(i,j,k) = H_z^{n-1/2}(i,j,k) - \frac{\Delta t}{S\mu(i,j,k)}\Big[E_x^n(i,j-1/2,k)L_1 + E_y^n(i+1/2,j,k)L_2 - E_x^n(i,j+1/2,k)L_3 - E_y^n(i-1/2,j,k)L_4\Big]. \tag{7}$$

In the same manner, we can obtain other field components.

Figures 3 and 4 illustrate the front view and vertical view of a thin slot, respectively. Width of the slot is g, assuming that the cell size is $\Delta x=\Delta y=\Delta z=\Delta s$. For Fig. 3 field components H_z is assumed to has no variation in the z direction (perpendicular to the slot gap), and the electric components E_y located within the conducting screen are assumed to zero. For Fig. 4 field components E_x are assumed to have no variation in the x direction (across the slot gap).

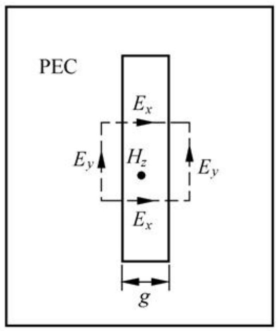

Fig. 3. Vertical view of the thin slot.

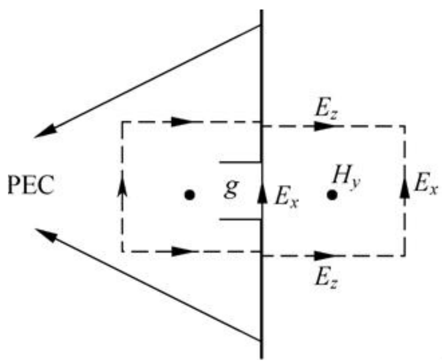

Fig. 4. Front view of the thin slot.

Subject to the foregoing algorithms, lets the contours length $L_1=L_3=g$, $L_2=L_4=\Delta s$ for Fig. 3, and then substituting the contours area $S=g\Delta s$ into equation (7), the H_z in Fig. 3 becomes,

$$H^{n+1/2}_{z(i+1/2,j+1/2,k)} = H^{n-1/2}_{z(i+1/2,j+1/2,k)} - \frac{\Delta t}{\Delta s\,\mu}\left[E^{n}_{x(i+1/2,j+1,k)} - E^{n}_{x(i+1/2,j,k)}\right]. \quad (8)$$

The electric components E_x in Fig. 3 and Fig. 4 can use the basic FDTD method to calculate as follows,

$$E^{n+1}_{x(i+1/2,j,k)} = E^{n}_{x(i+1/2,j,k)} + \frac{\Delta t}{\varepsilon\Delta s}\left[H^{n+1/2}_{z(i+1/2,j+1/2,k)} - H^{n+1/2}_{z(i+1/2,j-1/2,k)} - H^{n+1/2}_{y(i+1/2,j,k+1/2)} + H^{n+1/2}_{y(i+1/2,j,k-1/2)}\right]. \quad (9)$$

The basic FDTD are also used to calculate electric components E_z as follows,

$$E^{n+1}_{z(i,j,k+1/2)} = E^{n}_{z(i,j,k+1/2)} + \frac{\Delta t}{\varepsilon\Delta s}\left[H^{n+\frac{1}{2}}_{y(i+\frac{1}{2},j,k+\frac{1}{2})} - H^{n+\frac{1}{2}}_{y(i+\frac{1}{2},j,k-\frac{1}{2})} - H^{n+\frac{1}{2}}_{x(i,j+\frac{1}{2},k+\frac{1}{2})} + H^{n+\frac{1}{2}}_{x(i,j+\frac{1}{2},k-\frac{1}{2})}\right]. \quad (10)$$

Assuming that the side contour along H_y are Δs, Δs, Δs and g, the contour is Δs^2, then using the time-stepping expression for H_y, and let $\omega=g/\Delta s$ we obtain,

$$H^{n+1/2}_{y(i+1/2,j,k+1/2)} = H^{n-1/2}_{y(i+1/2,j,k+1/2)} - \frac{\Delta t}{\mu\Delta s}\left[E^{n}_{z(i+1,j,k+1/2)} - E^{n}_{z(i,j,k+1/2)} - \omega E^{n}_{x(i+1/2,j,k+1)} + E^{n}_{x(i+1/2,j,k)}\right]. \quad (11)$$

The algorithm described above is the basis of the 3-D CP-FDTD method, and equations (8) to (11) are the slot algorithm for computation the field components near the slot gap region.

IV. NUMERICAL RESULTS AND DISCUSSION

To demonstrate the accuracy and applicability of the mentioned 3-D CP-FDTD scheme for EMI issues, a model of metallic rectangular enclosure with one thin slot is presented here as shown in Fig. 5.

The inside dimension of the enclosure is 20cm×40cm×50cm, and the thin slot in an enclosure wall is 8 cm long (x direction) by w cm wide (y direction), as shown in Fig. 6. In our simulation we let w=0.6cm, 0.1cm, 0.01cm, respectively.

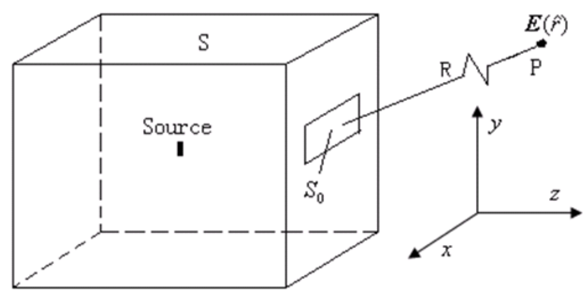

Fig. 5. Shielding enclosure with one slot.

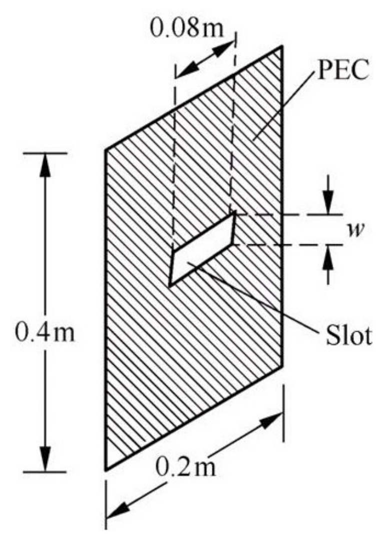

Fig. 6. Thin slot in an enclosure wall.

The elemental electric dipole oriented along *x*-direction is placed in the center of the enclosure. The electric dipole moment is a Gaussian pulse with T=0.0167ns wide,

$$P(t) = 10^{-12}\exp\left[-\left(\frac{t-3T}{T}\right)^2\right] . \qquad (12)$$

For the sake of comparison, numerical simulations are carried out using the 3-D CP-FDTD, C-TSF and finer grid FDTD methods. Perfectly matched layer (PML) absorbing boundary conditions are employed for the three dimensional FDTD program and choose the space increments $\Delta x=\Delta y=\Delta z=\delta$. For the 3-D CP-FDTD and the C-TSF method, we choose δ=1cm. For finer grid FDTD method we choose δ=0.2cm.

When the slot width is w=0.6cm, we calculated the electric fields at the point with 10cm far away from the center slot wall by using 3-D CP-FDTD method and finer grid FDTD methods, the time domain and frequency domain simulation results of E_z at the point are shown in Figs. 7 and 8, respectively.

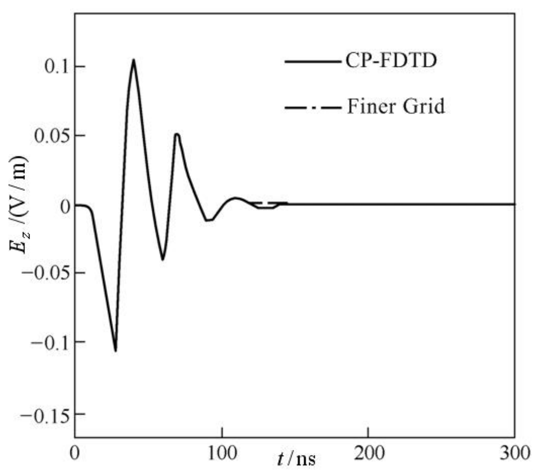

Fig. 7. Time domain results of E_z with 0.6cm slot width by using CP-FDTD and finer grid method.

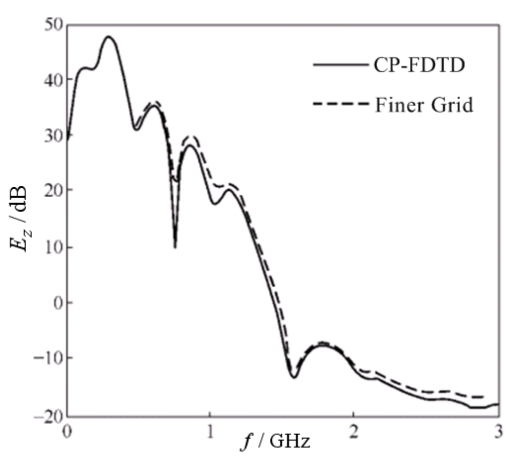

Fig. 8. Frequency domain results of E_z with 0.6cm slot width by using CP-FDTD and finer grid method.

The accurate agreements field simulation results for the slot in Figs. 7 and 8 clearly shows that the proposed 3-D CP-FDTD method can successfully works for the slot width is on the order of the mesh dimension, and can be obtained considerable high computation efficiency compared to the finer grid FDTD method.

It has been demonstrated that EMI issues associated with thin slots can computation efficiency and accuracy by C-TSF method with $w/\delta \le 0.1$, and Two-dimensional (2-D) C-TSF results for plane-wave scattering from a slot in an infinite conducting plane have been shown to agree well with method of moments (MoM) results. Typical discrepancies of less than 10% can be expected for the field quantities at locations near the slot region [10]. So, we calculated the electric field E_z at the same point by using 3-D CP-FDTD and C-TSF methods with slot width w=0.1cm, w=0.01cm, respectively. The frequency domain simulation results are shown in Figs. 9 and 10, respectively.

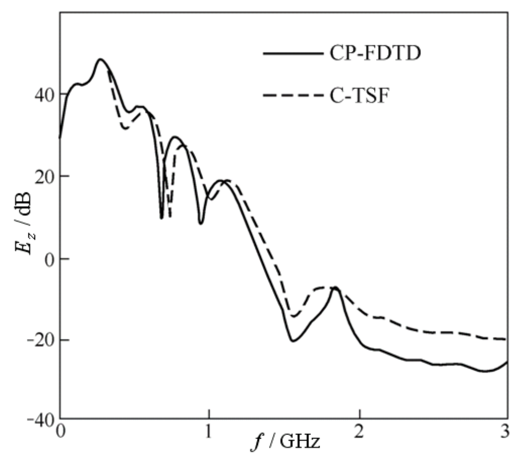

Fig. 9. Frequency domain results of E_z with 0.1cm slot width by using CP-FDTD and C-TSF method.

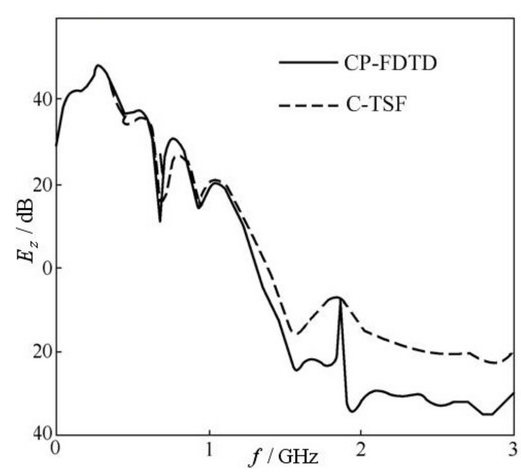

Fig. 10. Frequency domain results of E_z with 0.01cm slot width by using CP-FDTD and C-TSF method.

Figures 9 and 10 show that when w=0.1cm, 0.01cm, the results calculated by the 3-D CP-FDTD method deviate from the results calculated by the C-TSF method significantly, especially when the frequency is high, and it is apparent that result deviation is larger for w=0.01cm than that of for w=0.1cm. So, it is easy to draw a conclusion that with the slot width far less than mesh dimension, the 3-D CP-FDTD will lead to quite large discrepancies from the results of C-TSF, the reason is because the 3-D CP-FDTD based on a quasi-static approximation for narrow slots and we take for field components has no variation near the slot region, but actually field vary greatly when the slot gap is too thin, especially with the slot width far less than mesh dimension.

V. CONCLUSION

In this paper, we extended the two-dimensional CP-FDTD thin slot algorithm to three-dimensions for the application to shielding analysis in electromagnetic compatibility. The accuracy and the applicability of the 3-D CP-FDTD to the slot width were validated with finer mesh model and capacitive thin-slot formalism (C-TSF) model. The numerical results indicate that the performance or accuracy will descend with the augment of the slot width. Good agreements with the results of finer mesh modeling can be expected as the slot width is on the order of the mesh dimension, and quite large discrepancies from the results of C-TSF with the slot width far less than mesh dimension. The 3-D CP-FDTD algorithm will be utilized when the slot width is comparatively large and otherwise C-TSF. Taking advantage of both of them will avoid finer mesh in thin slots modeling such as the shielding analysis of the electronic enclosure.

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