Enhanced Thin-Slot Formalism for the FDTD Analysis of Thin-Slot Penetration

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***Abstract*—The inclusion of the singularities of the field variation near a thin-slot is validated to be a useful enhancement of the standard thin-slot formalism for the finite-difference time-domain analysis of thin-slot penetration.**

I. Introduction

THE STANDARD thin-slot formalisms (TSF's) by Gilbert and Holland [1] and Taflove [2] have been around for quite some time in the finite-difference time-domain (FDTD) analyses of thin-slot penetration problems. The Gilbert/Holland method does not make of any inherent assumptions about the behavior of the electric field in the slot, whereas the method by Taflove assumes the slot electric field is a constant. Riley and Turner give a hybrid thin-slot algorithm in [3], which needs to incorporate an independent time-marching solution for the aperture problem into the FDTD code. In this letter, we present a enhanced thin-slot formalism (ETSF) which includes the singularities of field variation near the thin-slot. The results given by the ETSF are much better than those by a standard TSF.

II. Enhanced TSF

Without lossing generality, the linear slot shown in Fig. 1 is taken as an example. A TEM mode Gaussian pulse, $E_x^{\text{in}} = \exp[-(n\Delta t - t_0)^2/T^2]$, is applied as the incident pulse, where $t_0 = 3T$, $T = 0.5$ ns, and the effective frequency spectrum of the pulse ranges from DC to 1 GHz. The penetrating electric field component E_x^p is monitored at the middle point of the reference plane which is 0.03 m away from the slot plane.

For the thin-slot ($w \ll \lambda$), the main electric field component in the aperture is E_x. Based on the Yee's mesh, the typical FDTD mesh for modeling the electromagnetic field near the aperture is shown in Fig. 2. For loop C_1, which penetrates the slot, passes through the nodes for H_y and H_z, and surrounds the node for the aperture electric field E_x, we assume that H_y are constants along the corresponding sides of C_1, and E_x and H_z have the following singularities of $1/z$ near the aperture

$$E_x(y,z) \approx \begin{cases} E_x\left(i+\frac{1}{2}, j, k\right), & |z-k\Delta z| \le a, |y - j\Delta y| \le \frac{\Delta y}{2} \\ E_x\left(i+\frac{1}{2}, j, k\right) \cdot \frac{a}{|z-k\Delta z|}, & a < |z-k\Delta z| \le \frac{\Delta z}{2}, |y-j\Delta y| \le \frac{\Delta y}{2} \end{cases} \quad (1)$$

$$H_z(y,z) \approx \begin{cases} H_z\left(i+\frac{1}{2}, j\pm\frac{1}{2}, k\right), & |z-k\Delta z| \le a, y = \left(j\pm\frac{1}{2}\right)\Delta y \\ H_z\left(i+\frac{1}{2}, j\pm\frac{1}{2}, k\right) \cdot \frac{a}{|z-k\Delta z|}, & a < |z-k\Delta z| \le \frac{\Delta z}{2}, y = \left(j\pm\frac{1}{2}\right)\Delta y \end{cases} \quad (2)$$

where $a =$ w/4 denotes the equivalent antenna radius for the slot. Applying the Ampere's law, $(\partial/\partial t)\int\int_S \boldsymbol{D}\cdot dS = \oint \boldsymbol{H}\cdot dl$, to loop C_1, and using (1) and (2), we get in the enhanced TSF for E_x

$$\begin{aligned} E_x^{n+1}\left(i+\frac{1}{2}, j, k\right) &= E_x^n\left(i+\frac{1}{2}, j, k\right) + \frac{\Delta t}{\varepsilon} \\ &\cdot \left\{ \frac{H_y^{n+1/2}(i+\frac{1}{2}, j, k-\frac{1}{2}) - H_y^{n+1/2}(i+\frac{1}{2}, j, k+\frac{1}{2})}{\Delta z} \right. \\ &\cdot \left[\frac{2\Delta z/w}{1+\ln(2\Delta z/w)}\right] \\ &\left. + \frac{H_z^{n+1/2}(i+\frac{1}{2}, j+\frac{1}{2}, k) - H_z^{n+1/2}(i+\frac{1}{2}, j-\frac{1}{2}, k)}{\Delta y} \right\} \end{aligned} \quad (3)$$

For loop C_2 which is in the slot plane and passes through the left-end edge of the slot, we assume that E_x in the slot does not vary with x, and H_z has a $1/\sqrt{y}$ variation near the edge,

$$H_z(x,y) \approx \sqrt{\frac{\Delta y/2}{y-(j-1)\Delta y}} H\left(i+\frac{1}{2}, j-\frac{1}{2}, k\right), \quad (j-1)\Delta y < y < j\Delta y, x \in \text{slot} \quad (4)$$

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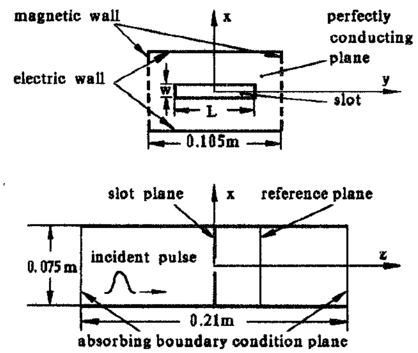

Fig. 1. Slot in a perfectly conducting plane, $w = 0.005$ m, $L = 0.06$ m.

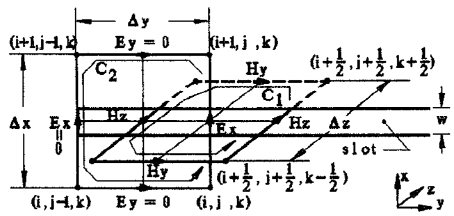

Fig. 2. Typical FDTD mesh near the aperture.

Applying the Faraday's law, $(\partial/\partial t)\iint_S \boldsymbol{B}\cdot d\boldsymbol{S} = -\oint_c \boldsymbol{E}\cdot dl$, to loop C_2, and using (4), we get the following ETSF for the H_z:

$$H_z^{n+1/2}\left(i+\frac{1}{2}, j-\frac{1}{2}, k\right) = H_z^{n-1/2}\left(i+\frac{1}{2}, j-\frac{1}{2}, k\right) + \left(\frac{1}{\sqrt{2}}\right)\frac{\Delta t}{\mu_0 \Delta y} \cdot E_x^n\left(i+\frac{1}{2}, j, k\right) \tag{5}$$

which is different from the ordinary FDTD formula by a factor of $(1/\sqrt{2})$. Similarly, an ETSF can be obtained for the H_z at the node adjacent to the right-end edge of the slot. For other field components, Taflove's standard TSF can be used.

III. Numerical Results

To validate the ETSF outlined above, the problem shown in Fig. 1 with $w = 0.005$ m and $L = 0.06$ m is simulated by incorporating the ETSF into the ordinary FDTD algorithm.

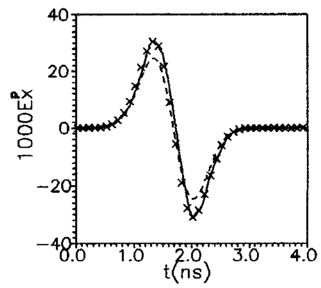

Fig. 3. Waveforms of the penetrating electric field E_x^p. ××××: ETSF with a resolution of h;—-: standard TSF with a resolution of h; ——: ordinary FDTD with a much finer resolution of $h/9$.

Fig. 3 shows the waveforms of E_x^p calculated by the ETSF and the standard TSF, respectively, with a spatial step of $h = x = y = z = 0.015$ m, and a time step $\Delta t = h/2c$ where c is the speed of light in free space. The results by an ordinary FDTD algorithm (without TSF or ETSF) with a much finer resolution of $h/9$ ($= w/3$) are also shown in Fig. 3, and display a good agreement with those by the ETSF, while much of the computing time and computer resources are saved by the ETSF. It is obvious that, the results given by the ETSF are much better than those by a standard TSF when both of them have the same resolution of h.

IV. Conclusion

The inclusion of the singularities of the field variation near a thin-slot is validated to be a useful enhancement of the standard TSF. Due to the inherent versatility of the FDTD method, the ETSF reported here can be used to solve many complex electromagnetic penetration problems with thin slots.

References

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