Time-Domain Investigation on Ribbon Cable-Induced Transient Coupling into Enclosure

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Abstract

A hybrid time-domain method is proposed for characterizing electromagnetic interference (EMI) signals in some composite structures with two-wire ribbon cable transmission lines, metallic enclosures, and even lumped active devices involved. In order to fast capture the inner EMI signals induced, Finite Difference Time-Domain (FDTD), and multi-conductor transmission lines (MTL) methods are combined together and implemented successfully. Numerical investigation is carried out to show the induced current, voltage, and enclosure shielding effectiveness of some practical geometry with metallic enclosure and ribbon cables, and even a cable networks.

1. Introduction

In practical applications, some thin slots, apertures, windows, even some cables must be introduced in the metallic enclosure, which will provide directive electromagnetic energy coupling paths resulting in serious inner EMC/EMI problem. Therefore, many theoretical and experimental studies have been performed to investigate electromagnetic coupling with and penetrating into different metallic geometries in the past two decades [1-2]. Actually, the presence of cable transmission lines will increase computational difficulty significantly as they provide additional coupling paths between outer and inner electromagnetic fields of a metallic enclosure. The most rigorous method is to simultaneously solve for external and cables guide fields. For example, the method presented in [3] uses a FDTD-base solver to compute both external and guide fields, while those in [4] employ a time-domain integral-equation (TDIE)-based solver to compute external field and an FDTD-based solver to compute guided fields.

In this paper, a rigorous time-domain method for analyzing EMC/EMI problems involving complex structures loaded with ribbon cables, which are illuminated by an electromagnetic pulse (EMP). In Section II, the EM field-to-transmission-line coupling models and thin slot/wire sub-cellular models are described, with proposed time-domain solver given. In Section III, the hybrid time-domain solver is proposed for modeling of metallic rectangular enclosures with thin slots, ribbon cables and the characterization of SE and induced voltage at the load are performed. Some conclusions are drawn in Section IV.

2. Hybrid Finite-Difference Time Domain Method

A. Coupling Models between EM Field and Ribbon-Cables

In order to combine FDTD method with multiconductor transmission line (MTL) equations, the effects of geometrical parameters of the ribbon cables must be treated appropriately. The cable will be divided into many small segments placed into the electric field Yee cell. Inside each cell, a quasi-TEM approximation is assumed and the transversal dimension of the ribbon cable is treated just by modifying the thin wire formalism.

Assume a quasi-TEM mode of propagation along an MTL constituted of $n+1$ conductors, the time dependent

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voltage $\mathbf{V}(t,z)$ and current, $\mathbf{I}(t,z)$ along the conductors can be modeled by the following system of coupled partial differential equations:

$$\frac{\partial}{\partial z}\mathbf{V}(t,z)+\mathbf{RI}(z,t)+\mathbf{L}\frac{\partial}{\partial t}\mathbf{I}(t,z)=\mathbf{V}_F(t,z)\,,\qquad \frac{\partial}{\partial z}\mathbf{I}(t,z)+\mathbf{GV}(z,t)+\mathbf{C}\frac{\partial}{\partial t}\mathbf{V}(t,z)=\mathbf{I}_F(t,z) \tag{1}$$

$$\mathbf{V}_F(t,z)=\begin{bmatrix}\cdots\\ -\frac{\partial}{\partial z}\int_a^{a'}\vec{E}_t^i\cdot d\vec{l}+E_z^i(t,x_i,y_i,z)-E_z^i(t,x_0,y_0,z)\\ \cdots\end{bmatrix},\quad \mathbf{I}_F(t,z)=-\mathbf{G}\begin{bmatrix}\cdots\\ \int_a^{a'}\vec{E}_t^i\cdot d\vec{l}\\ \end{bmatrix}-\mathbf{C}\frac{\partial}{\partial t}\begin{bmatrix}\cdots\\ \int_a^{a'}\vec{E}_t^i\cdot d\vec{l}\\ \end{bmatrix} \tag{2}$$

where $\mathbf{R},\mathbf{L},\mathbf{C}$ and $\mathbf{G}$ are the per-unit-length (p.u.l) inductance, capacitance, resistive and conductance $n\times n$ matrices, respectively. The $n\times 1$ vector forcing distributed source $\mathbf{V}_F(t,z)$ and $\mathbf{I}_F(t,z)$ represent the distributed voltages and distributed currents which are due to the external electromagnetic field illumination. The incident field of the forcing functions as represented by (2) are not a plane ware, which is necessary to evaluate in the integral terms of (2) obtained by using an FDTD analysis of the MTL structures carried out in the absence of the conductors themselves. The forcing terms give by (2) can be discretized as

$$[\mathbf{V}_F]_k^n=-\frac{[S_t^i]_{k+1}^n-[S_t^i]_k^n}{\Delta z}+[S_z^i]_k^n,\quad [\mathbf{I}_F]_{k+1/2}^n=-\mathbf{G}\frac{[S_t^i]_k^{n+1}+[S_t^i]_k^n}{2}-\mathbf{C}\frac{[S_t^i]_k^{n+1}-[S_t^i]_k^n}{\Delta t} \tag{3}$$

$$S_t^i=\int_a^{a'}\vec{E}_t^i\cdot d\vec{l}\,,\quad S_z^i=E_z^i(t,x_i,y_i,z)-E_z^i(t,x_0,y_0,z) \tag{4}$$

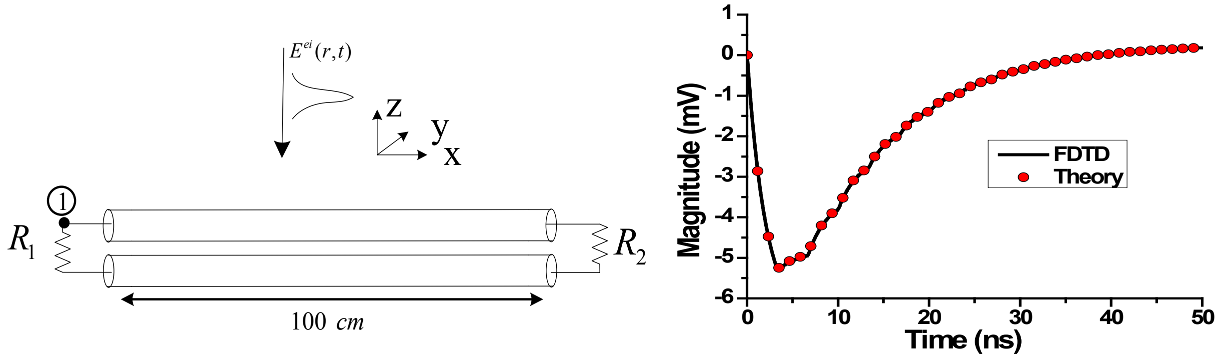
B. Time-Domain Combined Solution

By the FDTD method with leap-frog scheme, the explicit solution of the field equations, and thin-wire and slot formulation can be combined with the MTL telegraphers' equations [2],[5]. Obviously appropriate boundary conditions and load terminal conditions must be respectively applied to the field and MTL equations.

3. Simulation Results and Discussions

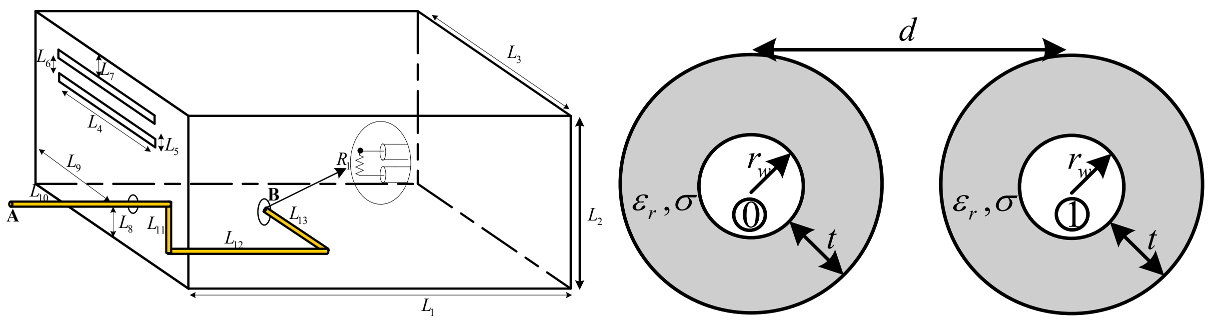
The hybrid time-domain solver described above are integrated and coded to handle realistic metallic enclosures that may contain thin slots, apertures and ribbon cable simultaneously. At first, in order to ensure the validity of our code, a simplified structure for which is easy to judge is computed. The case for our numerical verification is to calculate the induced currents at terminals of the free-standing ribbon-cable line of length 100 cm, excited by an external electromagnetic wave, as shown in Fig. 1(a). For the case of a transmission line, the characteristics of the transmission line are as follows: the terminal resistor $R_1=R_2=50\ \Omega$, the radius of the upper and lower conductor $r_1=r_2=3\ mm$, the distance of separation between the conductors $d=5\ cm$, and the impinging wave is taken to be of the form $E^{inc}(t)=1.05\cdot(e^{-4\cdot 10^6 t}-e^{-4.76\cdot 10^6 t})$. Fig. 1(b) shows the computed results in comparison with the theoretical results. A good agreement between the models was observed.

Then the time-domain solver is coded to handle metallic rectangular enclosures, as shown in Figs. 2 with two-wire ribbon cable. As the literature appears to contain no numerical data for the interaction of an EMP with a metallic rectangular enclosure with multiple thin slots and ribbon cables, a direct comparison seems impossible. The parameters are $L_1=L_3=30$ cm, L_2=12 cm, L_4=20 cm, $L_5=2$ mm, $L_6=1$ cm, L_7=2 cm, L_8=6 cm, $L_9=10$ cm, $L_{10}=10$ cm, L_{11}=3 cm, $L_{12}=10$ cm, and L_{13}=5 cm. The far- and near-end of the ribbon cable are both connect to the 50 Ω resistor load. The computational domain was discretrized with cubic cells of $\Delta x=\Delta y=\Delta z=1$cm, and the time step was set to be $\Delta t = \Delta x/(2c_0)$. All six walls of the enclosure were modeled as perfectly electric walls. The second-order Mur absorbing boundary is employed to truncate the computational domain.



(a) (b)

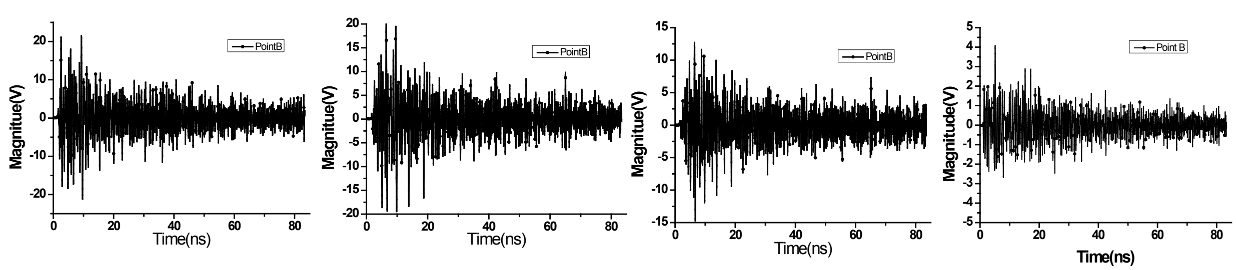
Fig. 1. (a) Geometry description and the plane wave excitation. (b) Coupled normalized voltage at node 1.



(a) (b)

Fig.2. (a) Geometry of a rectangular metallic enclosure with some thin slots, and two braid cables are loaded by a frequency-dependent impedance or a transmission line network; and (b) the configuration of ribbon cable and its cross section.

Fig. 3(a) shows the transient coupled voltages observed at load due to the external plane excitation. As $\varphi = 90^o$, the induced voltage reaches its lowest among four cases of $\varphi = 15^o$, 45^o, 65^o, and 90^o. This is reasonable because $\varphi = 90^o$ means that the incident electric field is vertical to the ribbon cable, which results in the minimum of distributed voltage source along the cable, and then induce the minimal voltage at point B for the four cases.



(a) $\varphi = 15^o$ (b) $\varphi = 45^o$ (c) $\varphi = 65^o$ (d) $\varphi = 90^o$

Fig. 3. Coupled transient voltages at point B due to the illumination of an external EMP with $\theta = 90^o$, the polarization angle of 90^o, and $\varphi = 15^o, 45^o, 65^o$, and 90^o, respectively.

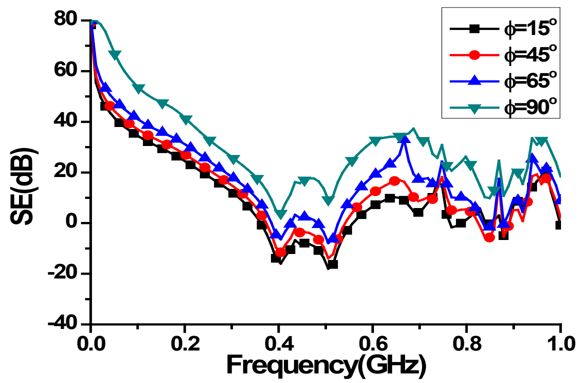


Fig. 4. The computed SE as a function of operating frequency for different values of the polarization angle φ , and $\theta = \psi = 90^o$.

Fig. 4 shows the computed SE with different incident angles. It is shown that at a given frequency and when $\psi = \theta = 90^o$ the SE level just changes slightly with increasing the value of ϕ . As $\phi = 15^o$, the SE reaches its lowest level among the cases of $\varphi = 15^o$, 45^o, 65^o, and 90^o . It is shown that at a given frequency the value of SE level is increased as ϕ increases from 15^o to 90^o . This is reasonable because $\theta = 15^o$ means that the incident electric field is oriented approximatively along the thin slot, which results in the maximum of z-component field induced by the thin slot.

4. Conclusion

In this paper, a hybrid time-domain method for analyzing electromagnetic compatibility (EMC) phenomena on complex structures that involved metallic enclosure along with ribbon cable is proposed, so as to capture the frequency-dependent shielding effectiveness and induced voltage. Based on our developed time-domain solver code, the internal induced voltage is also predicted. Since the induced voltage and shielding effectiveness is a function of all geometrical and physical parameters of the metallic enclosure, further optimization methodology should be implemented so as to achieve high shielding performance to protect the system.

6. References

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