Modeling of the Cable-Induced Coupling into a Shielding Box Using BLT equation

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***Abstract*-The modeling of electromagnetic pulse coupling to a shielding device, which is connected with a shielded cable, is studied. The exciting fields of the shielded cable are solved by a full-wave commercial software. Thereafter, the current response of the device is simulated by the Agrawal's model and the BLT (Baum, Liu, Tesche) equation. It is shown that the simulated result is agreed well with that of full-wave commercial software, and the computational efficiency is improved over 80% by the proposed method.**

I. INTRODUCTION

With the development of the electronic technology and electromagnetic pulse (EMP) sources, it's important to analyze an EMP coupling to electronic devices and systems. A metal shielding box is widely used to protect the sensitive device from the electromagnetic interferences. However, there are mainly two inevitable coupling paths that the EMP interfere with the devices, apertures on the shielding box and the wires or shielded cables connect to the device. On the other hand, the presence of transmission lines through a shielding box increases computational difficulty as they provide additional electromagnetic coupling paths between outer and inner fields. Therefore, it is of great interest to develop a method to quickly predict the electromagnetic effects induced in a shielding box with various types of transmission lines.

Paletta et al. dealt with the application of electromagnetic field-to-transmission-line coupling models for large cable systems analysis [1]. The method uses a combination of a full-wave solver and transmission-line analysis. And an experiment has been performed on a prototype wiring installed in a Renault Laguna car to validate the efficiency of this methodology. The coupling of an incident electromagnetic wave to a device inside a shielding box penetrated by a wire or a shielded cable has received some attention in recent years. Lertsirimit et al. computed an electromagnetic wave coupling to a device on a printed circuit board inside a cavity from a wire penetrating a cavity aperture by a hybrid method. The exterior problem was analyzed by a full wave method, while the interior problem was analyzed by transmission-line theory [2]. Li et al. simulated an EMP induced interference current in circuits inside a shielding box by a wire penetrated through an aperture by the finite-difference time-domain (FDTD) method [3]. Hakan Bağci analyzed electromagnetic coupling into enclosures through coaxial cables by a fast hybrid time-domain method [4]. Sapuan et al. studied the shielding effectiveness and S_{21} of a rectangular enclosure with apertures and wire penetration experimentally and numerically by using the commercial software CST Microwave Studio [5]. Xie et al. analyzed an electromagnetic pulse coupling to a device from a wire penetrating a cavity aperture by applying the transient electromagnetic topology method [6]. The method uses a combination of the FDTD method and SPICE model.

There are mainly three models are used to describe the coupling of incident field to transmission lines, Taylor's model [7], Agrawal's model [8] and Rachidi's model [9]. Compare to Taylor's model and Rachidi's model, Agrawal's model has many advantages. First, the distributed voltage generators in Agrawal's model are directly equal to the incident electric field components tangent to the line. Second, the calculation of the BLT equation [10] is reduced because there are no equivalent current generators in the expression of source waves. Third, Agrawal's model requires less memory to store the data files of exciting fields . By using the Agrawal's model, only the incident electric field components tangent to the line and the electric fields along the terminals and the ground are needed. Therefore, the Agrawal's model is used to describe the coupling of incident field to the shielded cable in this paper.

The modeling of an electromagnetic pulse coupling to a shielding device is studied. The device is connected with a shielded cable that penetrates through an aperture on the shielding box. The method is based on the electromagnetic topology (EMT) technology [11]. The coupling of an external electromagnetic wave to the shielded cable is concerned while the influence of the shielded cable on external fields is neglected. Furthermore, the influence of the inner conductor on the shield layer of the shielded cable is neglected. The computation process of the method includes two steps: The exciting fields of the shielded cable are solved by a full-wave commercial software but the presence of the cables is at first neglected. Thereafter, the current response of the device is simulated by the Agrawal's model and the BLT equation (the key equation of EMT). The obtained result is compared with that solved by a full-wave commercial software. This paper is divided into four sections. In section 2, the computation model and the computation process of the proposed method is described. Results and discussion are provided in section 3 while conclude in section 4.

II. COMPUTATION MODEL AND METHOD DESCRIPTION

A. Computation Model

The schematic diagram of the system for computation is shown in Fig. 1. It consists of a shielded cable that penetrates through an aperture of a shielding box and then connects with a device inside the shielding box. The device is represented by a resistance $Z_2^{(i)}$ here. The length, the wide and the height of the shielding box is 41.0 cm, 10.5 cm and 27.3 cm respectively. And the back surface is 2 mm thick while others are 6 mm thick. The length of the shielded cable outside the shielding box and inside the shielding box is 2.57 m and 0.1 m respectively. The outer terminal loads of the shielded cable are both 100 Ω, and the loads between the inner conductor and the shield layer at the two terminations are both 50 Ω. The height of the shielded cable above the perfect ground plane is 0.2 m. The direction and polarization of the EMP is shown in Fig. 1

B. Computation Process

The computation process includes two steps: a full-wave commercial software is used to compute the exciting fields of the shielded cable at first, thereafter the Agrawal's model and the BLT equation are used to compute the current response of the shield device. The method is based on the electromagnetic topology theory. The influence of the shielded cable on external fields is neglected. For the calculation of the exciting fields , the shielded cable is removed at first. And then compute the fields at the exact positions of the shielded cable. As the cable does not need to meshed, the computation of the external fields just spend a few time. The source terms of the BLT equation is obtained by the exciting fields using the Agrawal's model.

In this paper, Agrawal's model is used as the equivalent model to analysis the shielded cable. A full-wave commercial software is used to compute the exciting fields of the shielded cable. Therefore, the exciting fields at the exact positions of the shielded cable are saved into data files. The date files are used to compute the current response on the shield layer of the shielded cable by Agrawal's model. And then the applied sources on the inner conductor of the shielded cable is obtained by the transfer impedance Z_t and transfer admittance Y_t . The current response of the device is computed by the BLT equation.

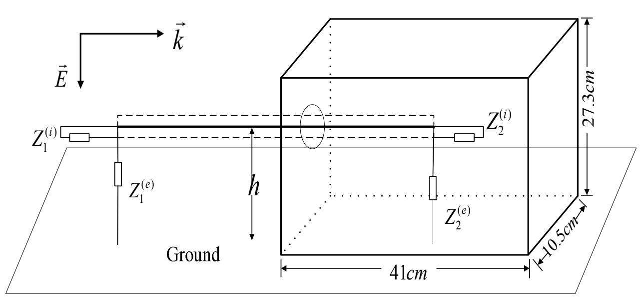

Figure 1 .Simple model of a shielded cable penetrates an aperture in a shielding box

There are two paths that the EMP coupling to the device as shown in Fig. 1, the shielded cable penetrating the shielding box and the aperture on the shielding box. In the computation model, the size of the aperture on the shielding box compare with the wavelength of the EMP is electrically small. Therefore the coupling effect through the aperture is neglected in this paper. As the heights of the outer part and the inner part of the shielded cable are different, the characteristic impedances of the two parts are different .The expression of the characteristic impedance Z_c is

$$Z_c = \sqrt{\frac{L'}{C'}} \tag{1}$$

where L' is the inductance per unit length, and C' is the capacitance per unit length. The expressions of them are

$$L' = \frac{\mu_0}{2\pi} \ln \frac{2h}{a} \tag{2}$$

$$C' = \frac{2\pi\varepsilon_0}{\ln(\frac{2h}{a})} \tag{3}$$

where a is the radius of shield layer of the shielded cable, h is the height of the shielded cable. The characteristic impedances is computed by these expressions. The characteristic impedance of the outer part is 329.55Ω, while the characteristic impedance of the inner part is 328.95Ω. As the characteristic impedance of the outer part is approximate to the characteristic impedance of the inner part, the shielded cable in Fig. 1 is regarded as a shielded cable over ground with the same height in this paper.

The shield layer of the shielded cable satisfies the good shielding approximation in this paper. The shielded cable is considered as two transmission line system, the external transmission line system which consists of the shield layer of the cable and the ground and the internal transmission line system which consists of the shield layer and the inner conductor of the cable [12]. The two transmission line systems are linked by the transfer impedance Z_t and transfer admittance Y_t of the shielded cable.

$$\begin{cases} V'_{si} = Z_t I_s \\ I'_{si} = -Y_t V_s \end{cases} \tag{4}$$

where I_s and V_s are the current response and the voltage response of the shielded layer of the cable, they are computed by the exciting fields using Agrawal's model. I'_{si} and V'_{si} are the sources of the inner conductor of the shielded cable respectively.

The current response of the shielded layer is solved by

$$I_s(x) = \int_0^L G_I(x;x_s) V'_s(x_s) dx_s - G_I(x;0)V_1 + G_I(x;L)V_2 \tag{5}$$

where $G_I(x;x_s)$ is a green function, it's represents the current response of voltage source per unit and connected with the characteristic impedance of the shield layer. The expression is

$$G_I(x;x_s)=\frac{e^{-\gamma L}}{2Z_c(1-\rho_1\rho_2 e^{-2\gamma L})}(e^{\gamma x_<}-\rho_1 e^{-\gamma x_<})\cdot [e^{-\gamma(x_>-L)}-\rho_2 e^{\gamma(x_>-L)}] \tag{6}$$

where $x_<$ is the smaller between x and x_s, $x_>$ is the bigger between x and x_s. $V_s^{'}$ is the distributed voltage sources on the shield layer of the shielded cable, and it is equal to tangential electric fields at the position of the shielded cable. V_1 and V_2 are the lumped voltage sources of the terminals of the shield layer in Agrawal's model. The expressions of them are

$$V_1=-\int_0^h E_z^{inc}(0,z)dz \tag{7}$$

$$V_2=-\int_0^h E_z^{inc}(L,z)dz \tag{8}$$

where E_z^{inc} is the exciting fields along the terminals, it is obtained by the exciting fields . h is the height of the shielded cable.

For the computation of transfer impedance Z_t, the diffusion and aperture penetration effects are taken into account in this paper. The expression of Z_t is

$$Z_t^{'}=Z_d^{'}+j\omega L_a^{'} \tag{9}$$

where
$$Z_d^{'}=R_0\frac{(1+j)d/\delta}{\sinh(1+j)d/\delta} \tag{10}$$

R_0 is the direct-current resistance of the shield layer. δ is the skin depth of the shield layer. d is the diameter of the thin metal wires in the shield layer. $L_a^{'}$ is the aperture leakage inductance.

The expression of transfer admittance Y_t is

$$Y_t^{'}=j\omega CS_s \tag{11}$$

where C is the inner coax capacitance. S_s is the electrostatic shield leakage parameter.

The internal sources of the inner conductor of the shielded cable $V_{si}^{'}$ and $I_{si}^{'}$ is calculated by transfer impedance Z_t and transfer admittance Y_t of the shielded cable, and then the BLT equation of the internal transmission line system is built.

$$\begin{bmatrix} I(0) \\ I(L) \end{bmatrix}=\frac{1}{Z_c}\begin{bmatrix} 1-\rho_1 & 0 \\ 0 & 1-\rho_2 \end{bmatrix}\begin{bmatrix} -\rho_1 & e^{\gamma L} \\ e^{\gamma L} & -\rho_2 \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} \tag{12}$$

where ρ_1 and ρ_2 are the reflection coefficient of the inner conductor. γ is the propagation constant. S_1 and S_2 are the source terms of the equation. The expressions of them are

$$S_1=\frac{1}{2}\int_0^L e^{\gamma^{(i)}x_s}[V_{si}^{'}(x_s)+Z_c^i I_{si}^{'}(x_s)]dx_s \tag{13}$$

$$S_2=-\frac{1}{2}\int_0^L e^{\gamma^{(i)}(L-x_s)}[V_{si}^{'}(x_s)+Z_c^i I_{si}^{'}(x_s)]dx_s \tag{14}$$

where $Z_c^{(i)}$ is the characteristic impedance of the inner conductor.

Because the exciting fields obtained by the full-wave commercial software are in time-domain, all the results is post-processed in frequency-domain using fast Fourier transforms (FFT).The current response of the device is solved by BLT equation. As the BLT equation is a frequency-domain equation, the results are in frequency-domain. The inverse fast Fourier transforms (IFFT) is needed to obtain the transient response of the device.

III. Result And Analysis

The expression of the incident field waveform in the computation model is

$$E(t)=kE_0(e^{-\beta_1 t}-e^{-\beta_2 t})$$

where E_0=50 kV/m, k=1.3, β_1=4.0×10^7 s^{-1}, β_2=6.0×10^8 s^{-1}.The direction and polarization of the EMP are given in Fig. 1.The shielded cable for analyzing is a RG-58 cable. The internal characteristic impedance of the RG-58 cable is 50 Ω. The radius of the shield layer a=0.152 cm. The thickness of the shielded layer Δ=0.127 mm. The direct-current resistance of the shield layer R_0=14.2 mΩ/m. The aperture leakage inductance $L_a^{'}$ =1.0 nH/m, the electrostatic shield leakage parameter S_s=6.6×10^7 m/F.

The transfer impedance Z_t is calculated by (9), and the amplitude of the shielded cable transfer impedance Z_t is shown in Fig. 2.

After the exciting fields calculated by a full-wave commercial software, the current of the shield layer of the cable is computed by Agrawal's model. The current response on the shield layer of the cable is shown in Fig. 3.

To verify the accuracy of the proposed method, a full-wave commercial software is used to analyze the same problem in Fig. 1. The full-wave commercial software that used in this paper is a powerful and easy-to-use package for the analysis of conducted transmission, electromagnetic interference and electromagnetic susceptibility on complex cable structures. The current response on the load $Z_2^{(i)}$ in Fig. 1 obtained by the proposed method and full-wave commercial software are shown in Fig. 4. All the simulations are performed on a personal computer with the Intel(R) Pentium(R) Dual-Core CPU E5200 with 2.50 GHz and 2.0 GB RAM.

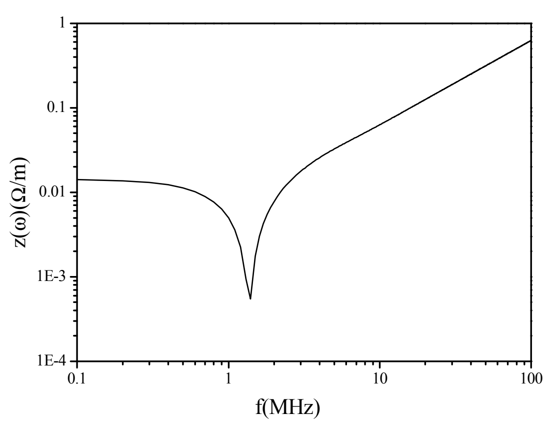

Figure 2. The amplitude of the shielded cable transfer impedance

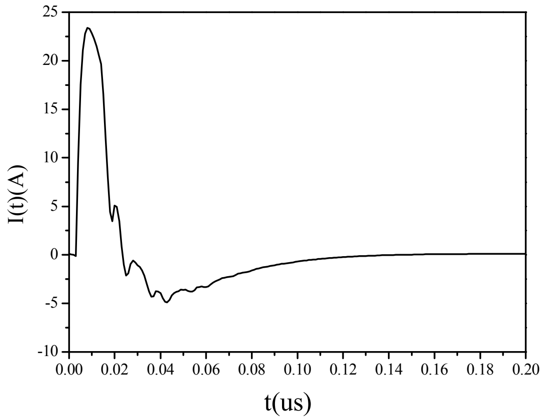

Figure 3. The current response of the shield layer of the cable

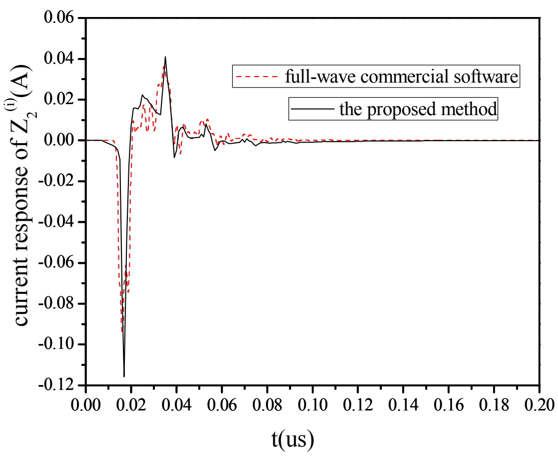

Figure 4. The current response of $Z_2^{(i)}$

From the results in Fig. 3 and Fig. 4, the shielding effectiveness of the shield layer is about 46 dB. The shield layer does a good job in protecting the internal electronics from the disturbance of the external EMP. In the proposed method, the cable does not need to be meshed in the process of compute the exciting fields . Furthermore, the transmission-line analysis just spent a few seconds. The calculation time of the proposed method is 17 minutes 36 seconds on a personal computer, including 17 minutes 30 seconds for the computation of the exciting fields and 6 seconds for the computation of the load current response, much less than 1 hour 37 minutes 29 seconds needed by the full-wave commercial software. As shown in Fig. 4, the result obtained by the proposed method and that obtained by the full-wave commercial software are in good agreement.

IV. Conclusion

The modeling of electromagnetic pulse coupling to a shielding device, which is connected with a shielded cable, is studied in this paper. The computation process of the method includes two steps: The exciting fields of the shielded cable are solved by a full-wave solver but the presence of the cables is at first neglected. Thereafter, the current response of the device is simulated by the Agrawal's model and the BLT equation. The results obtained by the proposed method and that solved by the full-wave commercial software verified the accuracy of the proposed method. These numerical results are helpful for further designing electromagnetic protection of the inner devices against the electromagnetic interference.

Acknowledgment

This research is support by the Aeronautical Science Foundation of China (20128052062) and A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

References

[1] Paletta, L., J. P. Parmantier, F. Issac, P. Dumas, and J. C. Alliot,"Susceptibility analysis of wiring in a complex system combining a 3-D solver and a transmission-line network simulation," *IEEE Trans. EMC*, Vol. 44, No. 2, 309-317, May 2002.

[2] Lertsirimit, C., R. Jackson, and D. R. Wilton, "An efficient hybrid method for calculating the EMC coupling to a device on a printed circuit board inside a cavity by a wire penetrating an aperture," *Electromagnetics*, Vol. 25, No. 7–8, 637–654, 2005.

[3] Li, X., J. Yu, Y. Li, Q. Wang, and Y. Zhang, "Simulation of the EMP coupling to circuits inside a shielding box by a wire penetrated with an aperture," *MAPE Proceedings*, 1345–1348, Hangzhou,China, 2007.

[4] Hakan Bağci, Ali E. Yılmaz, and Eric Michielssen, "A fast hybrid TDIE-FDTD-MNA scheme for analyzing cable-induced transient coupling into shielding enclosures," *in Proc. IEEE Int. Symp. EMC,* vol.3, pp.828-833,2005.

[5] Sapuan, S. Z. and M. Z. M. Jenu, "Shielding effectiveness of a rectangular enclosure with aperture and wire penetration," *ICMMT Proceedings*, 1–4, Guilin, China, 2007.

[6] H. Xie, J. Wang, D. Sun, and Y. Liu, "Analysis of EMP coupling to a device from a wire penetrating a cavity aperture using transient electromagnetic topology," *Journal of Electromagn. Waves and Appl*., 2009,23:2313-2322.

[7] C. D. Taylor, R. S. Satterwhite, and C. W. Harisson, "The response of a terminated two-wires transmission-line excited by a nonuniform electromagnetic field," *IEEE Trans. Antennas Propagat*., vol. 13, pp. 987–989, Nov. 1965.

[8] A. K. Agrawal, H. J. Price, and S. H. Gurbaxani, "Transient response of multiconductor transmission-lines excited by a nonuniform electromagnetic field," *IEEE Trans. Electromagn. Compat.*, vol. 22, pp. 119–129,May 1980.

[9] F. Rachidi, "Formulation of field to transmission-line coupling equations in terms of magnetic excitation field," *IEEE Trans. Electromagn. Compat.*, vol. 35, Aug. 1993.

[10] Baum, C. E., T. K. Liu, and F. M. Tesche, "On the analysis of general multiconductor transmission-line networks," *Interaction Note*, Vol. 350, 1–26, Nov. 1978.

[11] Baum C E. "How to think about EMP interaction," *Proc. 1974 Spring FULMEN Meeting*, Kirtland AFB, April 1974.

[12] Tesche F M, Ianoz M V, Karlsson T. *EMC Analysis Methods and Computational Models*. New York: Wiley, 1997.