Progress In Electromagnetics Research M, Vol. 98, 213–221, 2020

Hybrid Method for the EMI Analysis of Penetrated Wire of Electronic Device Excited by Space Electromagnetic Fields

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Abstract—An efficient field-to-circuit hybrid method is presented for the electromagnetic interference (EMI) analysis of penetrated wire of an electronic device excited by ambient wave, which consists of finite-difference time-domain (FDTD) method, transmission line (TL) equations, Thevenin's theorem, and circuit analysis method. The significant feature of this method is that it can avoid modelling the structures of penetrated wire and terminal circuit directly on the premise of guaranteeing sufficient accuracy. At first, the whole model of penetrated wire of an electronic device is decomposed into external and internal regions according to the shielded enclosure of the device. Then, the FDTD method combined with TL equations is applied to build the coupling model of an external transmission line with the shielded enclosure and extract the equivalent circuit model of external region based on Thevenin's theorem, which is further imported into the internal region as excitation source. Finally, the EMI analysis of internal region is executed by constructing the transmission parameter matrices of the two-port cascade network, which is contributed by the penetration node, internal transmission line, and terminal circuit. Then the interference response on terminal circuit can be obtained. Numerical simulations have been taken into account to verify the the accuracy and efficiency of this field-to-circuit hybrid method by comparing with the traditional FDTD method.

1. INTRODUCTION

Due to the requirements of power supply and signal transmission, the transmission lines need to be penetrated through the shielded enclosure of electronic devices, which are called as penetrated wires. According to reciprocity theorem, transmission lines can radiate electromagnetic waves and receive electromagnetic fields to create interference signals. Under this scenario, induced voltages and currents should be coupled on the penetrated wire and then entered into the terminal circuits to affect the normal operations of the circuits, when the penetrated wire is exposed to space electromagnetic fields. Therefore, studying the EMI analysis of space electromagnetic fields to penetrated wire of electronic device can provide important theoretical supports for the electromagnetic protection design of electronic device.

EMI analysis of penetrated wire of electronic device excited by ambient wave is very complex, because this process involves the radiation of space electromagnetic fields, coupling of penetrated wire and responses on the terminal circuits synchronously. Full wave algorithms, such as FDTD method [1, 2], finite element method (FEM) [3], and method of moments (MOM) [4], are the preferred ways to solve this problem. However, the efficiency of these full wave algorithms is not high, because the mesh number needed by these methods should be large due to the inherent features of meshing the structures of targets directly which contains local fine structures. Therefore, it is significant to develop efficient field-to-circuit hybrid algorithms.

Received 13 September 2020, Accepted 12 November 2020, Scheduled 21 November 2020

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Baum-Liu-Tesche (BLT) equation [5–8] is the first proposed field-to-circuit hybrid method, which constructs the relationship of space electromagnetic fields with transmission lines and terminal loads by nodes and pipes, and the voltage and current responses on terminal loads of transmission lines are obtained by solving this equation via matrix operation. However, traditional BLT equation is a frequency domain algorithm, which is not suitable for the EMI analysis of that ambient wave is broadband signal. Under this circumstance, some efficient field-to-circuit hybrid methods, combined the advantages of the full wave algorithms and circuit analysis methods, have been put forward. In [9], a hybrid method combined MOM with circuit analysis method is presented for the EMI analysis of PCB in shielded cavity excited by space electromagnetic fields. This method is a frequency domain algorithm and needs to mesh the structure of penetrated wire directly to extract the equivalent circuit model of the transmission line outside the shielded cavity. Based on BLT equation and full wave algorithm, a hybrid method is proposed for the EMI analysis of penetrated wire in shielded cavity excited by space electromagnetic fields in [10]. However, the accuracy of this method is not high, because the discontinuity of impedance at the penetrated node is not considered. In [11–14], the FDTD-SPICE method is proposed, which uses FDTD method to solve the excitation fields of transmission lines, and SPICE software to obtain the transient responses on the terminal circuits of transmission lines. Unfortunately, this method needs a number of theoretical derivations to establish the SPICE equivalent circuit of transmission lines and has not been used for the EMI analysis of penetrated wire of electronic device yet.

One field-to-circuit hybrid method based on FDTD method and transmission line equations (called as FDTD-TL method) [15–18] has been carried out, which is the previous research of this paper. In this method, the excitation fields of transmission lines are calculated by the FDTD method, which are introduced into the TL equations as equivalent distribution sources at each time step of FDTD. Then, the TL equations are discretized by the central difference scheme of FDTD method to obtain the transient responses on the transmission lines and terminal loads. However, this method can only deal with the EMI analysis of penetrated wire terminated with resistances currently.

To overcome the above-mentioned problems, an efficient field-to-circuit hybrid method consisting of FDTD-TL method, Thevenin's theorem, and two-port network cascade technique is presented, which can be well applied to the EMI analysis of penetrated wire terminated with lumped circuits under the premise of that the structure of penetrated wire does not need to be meshed. The theory of this hybrid method will be introduced in detail as follows.

2. THEORY OF THE FIELD-TO-CIRCUIT HYBRID METHOD

Figure 1 shows one physical model of penetrated wire of electronic device excited by ambient wave, where an electronic device with a shielded enclosure structure is placed on the perfect conductor (PEC) plane. Interference signals should be coupled on the external part of penetrated wire when it is under the irradiation of space electromagnetic fields, which are propagated through the internal penetrated wire and then entered into the terminal circuit to cause electromagnetic interference.

The EMI analysis of penetrated wire of electronic device irradiated by space electromagnetic fields fulfilled by the field-to-circuit hybrid method has three significant steps: Firstly, the penetrated wire

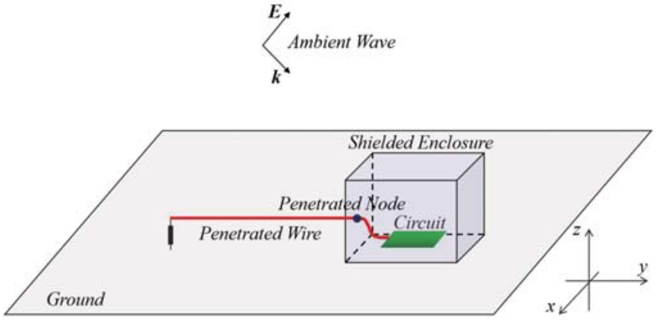


Figure 1. Typical coupling model of electronic device with penetrated wire.

of electronic device is divided into two regions according to the enclosure structure of the device, where the external region is composed of an external transmission line, ground plane, and a shielded enclosure structure. The internal region includes penetrated node, an internal transmission line, and a terminal circuit. Secondly, the FDTD method combined with TL equations is employed to extract the Thevenin's equivalent circuit model of external region, which is imported into the internal region as excitation source. Finally, the EMI analysis of terminal circuit of penetrated wire is completed by using the two-port network cascade technique. Next, the equivalent circuit extraction of external region and EMI analysis of internal region will be introduced in detail.

2.1. Equivalent Circuit Extraction of External Region

It is assumed that the external transmission line of penetrated wire is regarded as a linear two-port network, and under this scenario, it can be equivalent to a series circuit consisting of one open circuit voltage source and equivalent impedance based on Thevenin's theorem, as shown in Fig. 2.

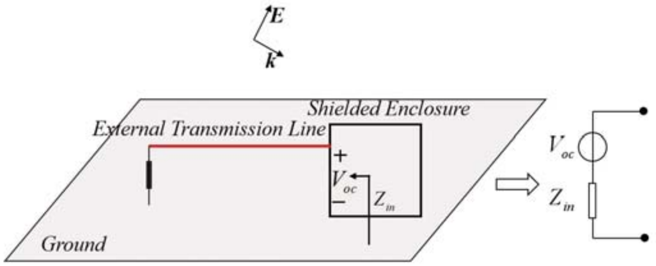


Figure 2. Thevenin equivalent circuit of external region.

Firstly, FDTD-TL method is applied to solve the open circuit voltage source V_{OC}. When the frequencies of space electromagnetic fields are not very high, the distance between the external transmission line and the ground plane will be less than the corresponding wavelengths of space electromagnetic fields. In this context, the radiation effect of external transmission line is very small and can be ignored [16]. Owing to the theory of distribution parameters of transmission line, the coupling model of external transmission line illuminated by space electromagnetic fields can be equivalent to a cascaded network of N circuit segments with π shape. The number of segments is determined by the frequencies of space electromagnetic fields, and each segment of π shaped circuit is contributed by a series circuit of distributed voltage source and inductance element, and a parallel circuit of distributed current source and capacitor element, as shown in Fig. 3. The values of V_{OC} will depend on the terminal port voltage of the π shaped circuit.

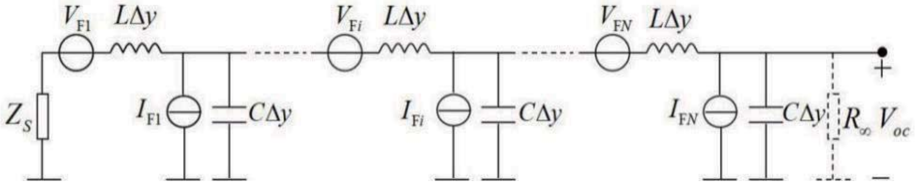


Figure 3. π shaped equivalent circuit of external transmission line irradiated by space EM fields.

To solve the port voltage of the π shaped circuit, the relationships of voltages and currents on the external transmission line can be described by the TL equations [16] as

$$\frac{\partial}{\partial y}V\left(y,t\right)+L\frac{\partial}{\partial t}I\left(y,t\right) = V_F(y,t) \tag{1}$$

$$\frac{\partial}{\partial y}I\left(y,t\right)+C\frac{\partial}{\partial t}V\left(y,t\right) = I_F(y,t) \tag{2}$$

where $I(y,t)$ and $V(y,t)$ represent the current and voltage vectors on external transmission line, respectively. L and C denote the per unit length (p.u.l) distributed inductance and capacitance parameters of the external transmission line, respectively. $V_F(y,t)$ and $I_F(y,t)$ are the equivalent distributed voltage and current source terms, respectively, which can be expressed as

$$V_F(y,t) = -\frac{\partial}{\partial y}E_T(y,t) + E_L(y,t) \tag{3}$$

$$I_F(y,t) = -C\frac{\partial}{\partial t}E_T(y,t) \tag{4}$$

where $E_T(y,t)$ and $E_L(y,t)$ are calculated from the space electromagnetic fields, which are written as

$$E_T(y,t) = \int_0^h e_z^{ex}(x,y,z,t)\,dz \tag{5}$$

$$E_L(y,t) = e_y^{ex}(x,y,h,t) - e_y^{ex}(x,y,0,t) \tag{6}$$

where $E_T(y,t)$ is the integral of incident electric field components perpendicular to external transmission line, and $E_L(y,t)$ is the difference of incident electric field components along the external transmission line and on the surface of the ground plane. Obviously, the equivalent distribution sources of TL equations are not relevant to the scattering fields of the external transmission line. Therefore, the transmission line can be removed when using FDTD method to model the structures of the shielded enclosure of electronic device and the ground plane, and calculate the incident electric field components e_y^{ex} and e_z^{ex} surrounding the external transmission line, as shown in Fig. 4.

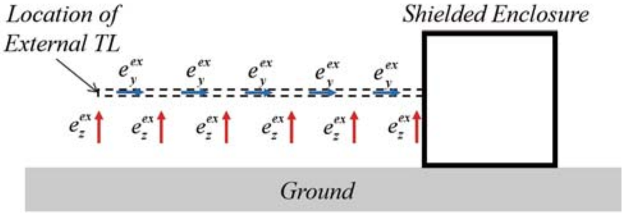


Figure 4. Calculation of incident electric field components surrounding the external transmission line.

For the convenience to represent the open-circuit state of the terminal port of the π shaped circuit, a resistor R_∞ with large value is added to the terminal port, as shown in Fig. 3. After the TL equations are established, the central difference scheme of FDTD is employed to discretize the TL equations [15] to obtain the voltage response on the terminal resistor R_∞, which is V_{OC} of Thevenin's equivalent circuit.

The equivalent impedance Z_{in} is equal to the port impedance which is obtained by that all source terms of equivalent π shaped circuit are set to zero, as shown in Fig. 5. In this context, the equivalent impedance can be written as

$$Z_{in} = Z_c\frac{Z_S + jZ_c\tan(\beta l)}{Z_c + jZ_S\tan(\beta l)} \tag{7}$$

where Z_S is the terminal load of the external transmission line, which is assumed as linear impedance. Z_c and l represent the characteristic impedance and length of external transmission line, respectively. β denotes the phase propagation constant of external transmission line, which can be expressed as

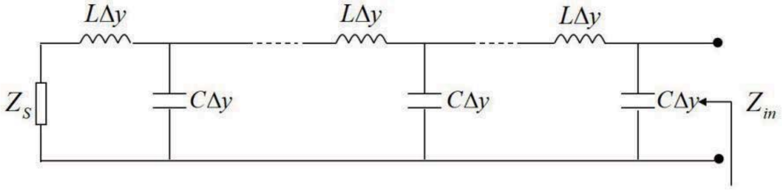


Figure 5. π shaped equivalent circuit with all source terms set to zero.

$\beta = j\omega\sqrt{LC}$. Here, L and C represent the per unit length inductance and capacitance parameters of external transmission line, respectively.

2.2. EMI Analysis of Internal Region

To complete the EMI analysis of internal region, the Thevenin's equivalent circuit of external region is introduced into internal region as excitation source. Because the heights of external and internal transmission lines to the ground plane are different, the impedance discontinuity should happen at the penetrated node, which should reflect the signals created by the excitation source when it passes the penetrated node. To inspect this reflection effect and avoid modelling the structures of internal transmission line and terminal circuit directly, the two-port network cascade technique is applied to the EMI analysis of internal region. It means that the penetrated node, internal transmission line, and terminal circuit are regarded as a two-port network, and then the voltage and current responses on the port of terminal circuit are obtained by solving the network parameter matrices, as shown in Fig. 6.

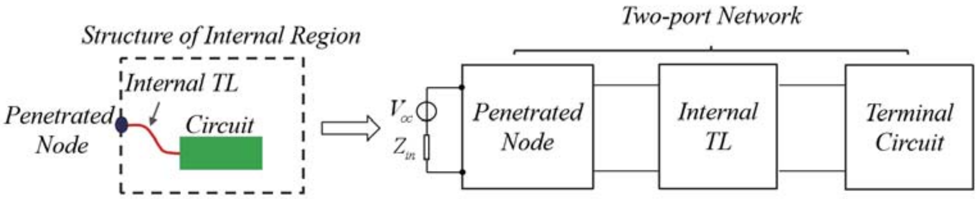


Figure 6. Two-port cascade network model of internal region.

The implementation process of this EMI analysis includes three steps:

Firstly, the **S** parameter matrix of penetrated node is calculated as follows:

$$[\mathbf{S}] = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \dfrac{Z_{in} - Z_{out}}{Z_{in} + Z_{out}} & \dfrac{2Z_{out}}{Z_{in} + Z_{out}} \\ -\dfrac{2Z_{in}}{Z_{in} + Z_{out}} & \dfrac{Z_{out} - Z_{in}}{Z_{in} + Z_{out}} \end{bmatrix} \tag{8}$$

where Z_{in} is the input impedance of external transmission line, which is equal to the equivalent impedance of Thevenin's circuit. Z_{out} is the input impedance of internal transmission line, which is expressed as

$$Z_{out} = Z_c' \frac{Z_L + jZ_c' \tan(\beta' l')}{Z_c' + jZ_L \tan(\beta' l')} \tag{9}$$

where l' and Z_c' are the length and characteristic impedance of internal transmission line, respectively. β denotes the phase propagation constant of the internal transmission line. Z_L is the impedance of terminal circuit of the internal transmission line.

Secondly, the **S** parameter matrix of penetrated node is converted to **A** parameter matrix and cascaded with the **A** parameter matrix of the internal transmission line to obtain the total **A** parameter matrix of this two-port cascade network consisting of the penetrated node and internal transmission line, which can be expressed as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \tag{10}$$

where $\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix}$ and $\begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix}$ are the **A** parameter matrices of the penetrated node and internal transmission line, respectively, which can be expressed as

$$\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} = \begin{bmatrix} \dfrac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}} & \dfrac{Z_{out}\left[(1+S_{11})(1+S_{22})-S_{12}S_{21}\right]}{2S_{21}} \\ \dfrac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}Z_{in}} & \dfrac{Z_{in}\left[(1+S_{11})(1-S_{22})+S_{12}S_{21}\right]}{2S_{21}Z_{out}} \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} = \begin{bmatrix} \cos(\beta' l') & Z'_c \sin(\beta' l') \\ \sin(\beta' l')/Z'_c & \cos(\beta' l') \end{bmatrix} \tag{12}$$

Finally, voltage response on the port of terminal circuit of internal transmission line is solved. As shown in Fig. 7, the **A** parameter matrix of two-port cascade network obtained in the second step is converted to the **Z** parameter matrix firstly, which is described as

$$\mathbf{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} A/C & (AD - BC)/C \\ 1/C & D/C \end{bmatrix} \tag{13}$$

It should be noted that the **Z** parameter matrix is in frequency domain format, so the open-circuit voltage source V_{OC} should be transferred from time domain to frequency domain via Fourier transform and then jointed with **Z** parameter matrix to obtain the voltage response V_L on the port of terminal circuit, which is written as

$$V_L = \frac{Z_L V_{oc} Z_{21}}{(Z_{in} + Z_{11})(Z_L + Z_{22}) - Z_{12} Z_{21}} \tag{14}$$

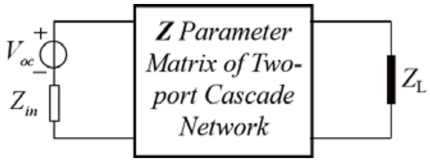


Figure 7. EMI analysis of termination circuit.

3. NUMERICAL SIMULATIONS

To verify the accuracy and efficiency of the proposed field-to-circuit hybrid method, two cases about the EMI analysis of penetrated wire of electronic device on the PEC ground and in the shielded cavity under the action of plane wave are employed to be simulated and compared with the FDTD method.

The first case is the EMI analysis of penetrated wire of electronic device on the PEC ground irradiated by plane wave, as shown in Fig. 8. The size and thickness of PEC ground are $L_G \times W_G = 30\,\text{cm} \times 60c\,\text{m}$ and 1 cm, respectively. The dimension and thickness of the shielded enclosure of the device are $L_C \times W_C \times H_C = 20c\,\text{m} \times 20\,\text{cm} \times 10\,\text{cm}$ and 1 cm, respectively. The radius and total length of penetrated wire are 2 mm and 0.36 m, respectively, where the length of the external transmission line is 0.31 m. The heights of the external transmission line to the ground and internal transmission line to the bottom of shielded enclosure are 2 cm and 1 cm, respectively. The beginning load of penetrated wire is $Z_1 = 50\,\Omega$, and the ending load is an RLC series circuit, which is contributed by $R_2 = 100\,\Omega$, $L_2 = 100\,\mu\text{H}$, and $C_2 = 50\,\text{nF}$. The incident wave is a Gaussian pulse, expressed as $E(t) = E_0 \exp\left[-4\pi(t - t_d)^2/\tau^2\right]$, and is perpendicular to the penetrated wire, where $E_0 = 1000\,\text{V/m}$, $t_d = 1.6\,\text{ns}$, $\tau = 2\,\text{ns}$.

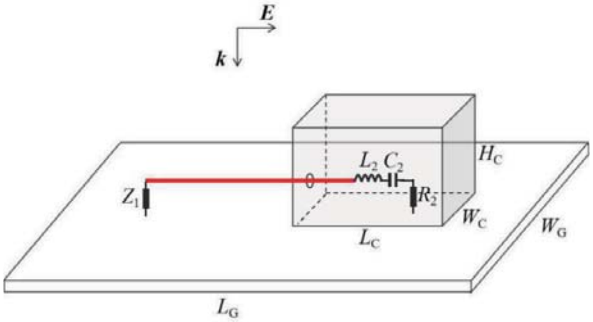
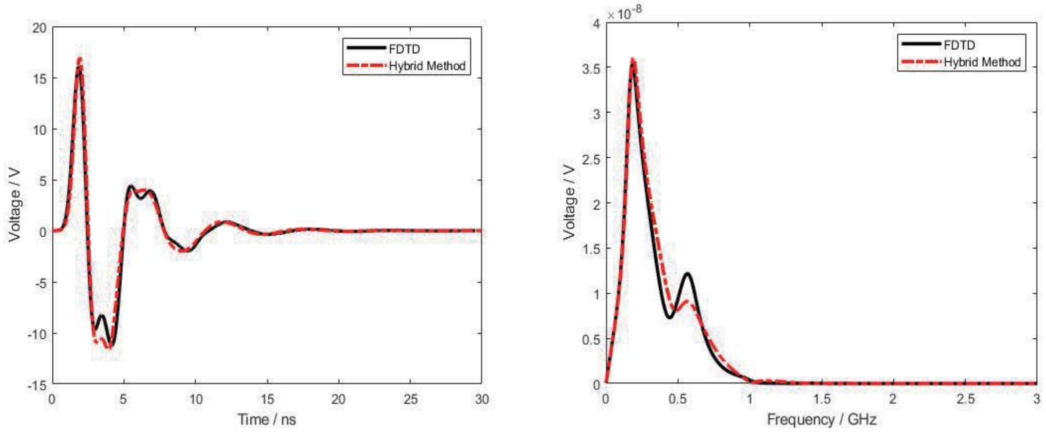


Figure 8. EMI model of penetrated wire on PEC ground irradiated by plane wave.



(a) Time domain waveform of voltages (b) Spectrum of voltages

Figure 9. Voltage responses on the port of terminal circuit for the first case.

The voltage responses on the port of RLC circuit computed by the field-to-circuit hybrid method and FDTD are shown in Fig. 9. We can see that the results of the two methods can keep good agreement in both time domain and frequency domain. By the way, it is necessary to explain that some values of the results computed by the two methods have certain errors, because the weak scattering fields caused by the fine structure of penetrated wire are ignored in this presented method. In addition, Table 1 gives the comparisons of the grid number and computation time required by the two methods under the same computer resource allocation. It can be seen that compared with FDTD method, this proposed method saves lots of computation time, because it avoids modelling the structure of penetrated wire directly.

Table 1. Grid number and computation time needed by the two methods.

Method	Grid number	Computation time (min)
FDTD	9.37×10^5	32
Hybrid Method	2.9×10^5	6

The second case is the EMI analysis of penetrated wire of the electronic device in shielded cavity irradiated by plane wave, as shown in Fig. 10. The structures of inner shielded enclosure and penetrated wire, and the incident wave are consistent with those of the first case. The dimension and thickness of the outer shielded enclosure are $L_S \times W_S \times H_S = 60\,\text{cm} \times 50\,\text{cm} \times 30\,\text{cm}$ and 1 cm, respectively. There are two rectangular slots with size 20 cm × 1 cm on the top surface of the shielded cavity. The beginning

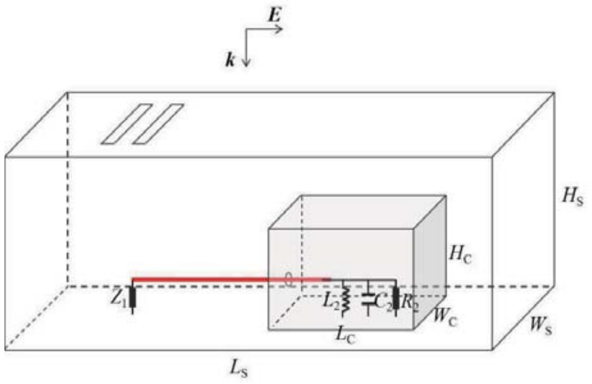
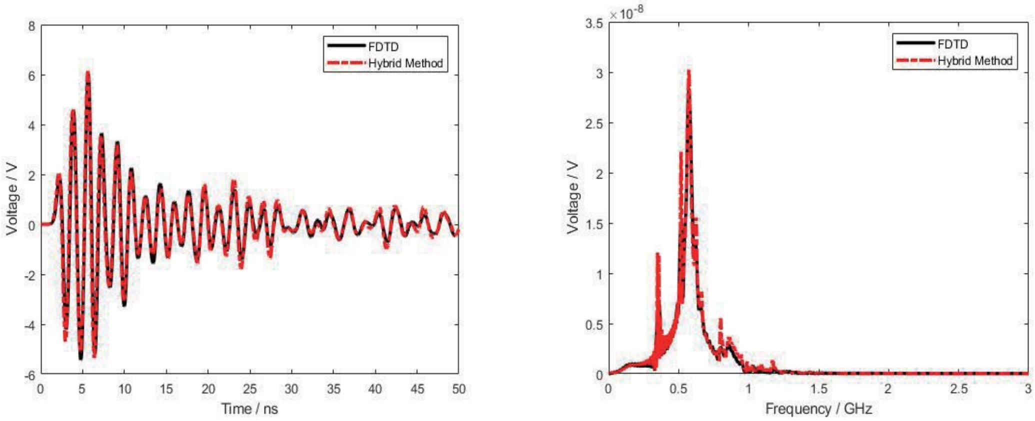


Figure 10. EMI analysis of penetrated wire of device in shielded cavity excited by plane wave.



(a) Time domain waveform of voltages (b) Spectrum of voltages

Figure 11. Voltage responses on the port of terminal circuit for the second case.

load of penetrated wire is $Z_1 = 100\,\Omega$, and the ending load is an RLC parallel circuit, which consists of $R_2 = 150\,\Omega$, $L_2 = 10\,\mu\text{H}$, and $C_2 = 0.5\,\text{pF}$.

Figure 11 shows the time domain and frequency domain voltage responses on the port of terminal circuit computed by this hybrid method and FDTD method. Similarly, it can be seen that the results of the two methods agree well to each other, which further proves that this hybrid method can be well applied to the EMI analysis of penetrated wire in a complex electromagnetic environment.

4. CONCLUSION

An efficient field-to-circuit hybrid method consisting of Thevenin's theorem, FDTD method, transmission line equations, and circuit analysis method is presented to be well applied to the EMI analysis of a penetrated wire of an electronic device excited by space electromagnetic fields. Firstly, the penetrated wire is decomposed into external and internal regions according to the shielded enclosure of the electronic device. Then, FDTD method combined with TL equations is used to model and extract the Thevenin's equivalent circuit of external region, which is introduced to the internal region as excitation source. Finally, the EMI analysis of internal region is completed by using the **S**, **A**, and **Z** parameter matrices of a two-port network. Numerical simulations indicate that the proposed method can maintain the same accuracy as full wave method. Meanwhile, it can save lots of computation time. Compared with other methods, this proposed method has two obvious advantages: (1) avoid modelling the structures of penetrated wire and terminal circuit directly; (2) the influence of impedance discontinuity of penetrated node on the transmission of interference signals is solved. In addition, the terminal loads of penetrated wire currently used in this method are contributed by linear elements, which should be extended to nonlinear loads to augment the applications of our algorithm in the next work.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 61701057) and the Chongqing Research Program of Basic Research and Frontier Technology (Grant No. cstc2017jcyjcx0345).

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