Coupling analysis of transmission lines excited by space electromagnetic fields based on time domain hybrid method using parallel technique*

Zhi-Hong Ye(叶志红)[1,†], Xiao-Lin Wu(吴小林)[1,†], and Yao-Yao Li(李尧尧)[2,‡]

[1] *School of Communication and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing* 400065, *China*
[2] *School of Electronic and Information Engineering, Beihang University, Beijing* 100083, *China*

(Received 11 March 2020; revised manuscript received 4 May 2020; accepted manuscript online 27 May 2020)

We present a time domain hybrid method to realize the fast coupling analysis of transmission lines excited by space electromagnetic fields, in which parallel finite-difference time-domain (FDTD) method, interpolation scheme, and Agrawal model-based transmission line (TL) equations are organically integrated together. Specifically, the Agrawal model is employed to establish the TL equations to describe the coupling effects of space electromagnetic fields on transmission lines. Then, the excitation fields functioning as distribution sources in TL equations are calculated by the parallel FDTD method through using the message passing interface (MPI) library scheme and interpolation scheme. Finally, the TL equations are discretized by the central difference scheme of FDTD and assigned to multiple processors to obtain the transient responses on the terminal loads of these lines. The significant feature of the presented method is embodied in its parallel and synchronous calculations of the space electromagnetic fields and transient responses on the lines. Numerical simulations of ambient wave acting on multi-conductor transmission lines (MTLs), which are located on the PEC ground and in the shielded cavity respectively, are implemented to verify the accuracy and efficiency of the presented method.

Keywords: Agrawal model, transmission line equations, parallel FDTD method, message passing interface (MPI) library

PACS: 07.05.Tp, 41.20.Jb **DOI:** 10.1088/1674-1056/ab96a6

1. Introduction

Transmission lines (TL) function as data communication channels between the circuits in electronic devices. Meanwhile, they are also the paths where space electromagnetic fields couple to the terminal circuits of these TLs, especially when the electronic devices are under complex electromagnetic environments. To guarantee the safety of electronic devices, it is necessary to study the coupling effects of TLs excited by space electromagnetic fields.

At present, several efficient field-to-line numerical methods have been presented. Among these methods, Baum–Liu–Tesche (BLT) equation was first proposed by Baum *et al.* in 1978[1] and has been developed for decades.[2–5] Traditional BLT equation is a frequency–domain method, which is not suitable for the coupling analysis under the scenario of ambient wave that is a broadband signal. Although this method has been extended to time domain later, it needs a great number of convolution operations which should definitely reduce the computation efficiency. Thus, to better deal with the coupling problems of broadband signals acting on TLs, the efficient time domain algorithms are necessary to be studied.

On the other hand, FDTD-SPICE and FDTD-TL methods are the two classical numerical methods in time domain. In FDTD-SPICE methods[6–10] the excitation fields of TLs are computed by the FDTD method firstly, and then the SPICE equivalent circuit model[11] of TLs is established and solved by SPICE software to obtain the transient responses on the loads of TLs. Unfortunately, it needs a large quantity of theoretical derivations, and the calculations of electromagnetic fields and transient responses on the loads are obtained respectively. The significant feature of FDTD-TL method[12–14] compared with that of FDTD-SPICE method, lies in the fact that it can realize the co-calculations of space electromagnetic fields and transient responses on TLs and loads. In this method, the space electromagnetic fields are computed by the FDTD method firstly. After these field values are substituted into the TL equations as distribution sources, the TL equations are solved by the difference scheme of FDTD method to obtain the responses on the lines. However, the type of TL equations used by this method is the Taylor model. It needs to store the horizontal and vertical electric field components in the planes between the TLs and the ground, which should occupy many memories when the lengths of TLs are long. Besides, these field-to-line methods tries to avoid modeling the fine struc-

*Project supported by the National Natural Science Foundation of China (Grant No. 61701057) and the Chongqing Research Program of Basic Research and Frontier Technology, China (Grant No. cstc2017jcyjAX0345).

†The first two authors contributed equally to this work.

‡Corresponding author. E-mail: liyaoyao@buaa.edu.cn

 http://iopscience.iop.org/cpb http://cpb.iphy.ac.cn

tures of MTLs, but they still have to mesh the shielded enclosure structure of electronic device. Thus, if the enclosure structure of device is electrically large and complex, the mesh number needed by these methods should be very large. Under this circumstance, one computer with using one processor cannot complete the simulations of these methods. Furthermore, the parallel techniques of FDTD using MPI and OpenMP interfaces have been developed for decades,[15–18] however, its application to these field-to-line methods is not realized yet, for some difficulties or/and limits still exist. Even though the parallel computation of FDTD method used in FDTD-SPICE can be achieved to obtain the excitation sources of TLs, the SPICE softwares cannot be run in parallel. Compared with FDTD-SPICE method, FDTD-TL method is easy to implement parallel computation, as long as the grid sizes required for FDTD and the discretization of TL equations are consistent. However, the space electromagnetic fields needed by the distributed sources of TLs are stored in different processors, which needs to be shared between different processors via the operations of broadcasting and collection.

To solve the above-mentioned problems, a time domain hybrid method consisting of parallel FDTD method, TL equations based on Agrawal model, and interpolation schemes is presented for efficient coupling analysis of the MTLs excited by space electromagnetic fields. It can be executed parallel without some extra operations, and thus realizing the synchronous calculations of the space electromagnetic fields and transient responses on the lines.

2. Theory of this hybrid method

The typical model of ambient wave coupling to multiconductor transmission lines (MTLs) on the ground is shown in Fig. 1. The ground is assumed to a perfect conductor (PEC) plane. MTLs are all straight lines and parallel to the ground, which are terminated with impedance loads. The direction of the ambient wave is set to be denoted as $\boldsymbol{k}$, and the incident angles are selected as θ, φ, and α. Here, the losses of MTLs are neglected.

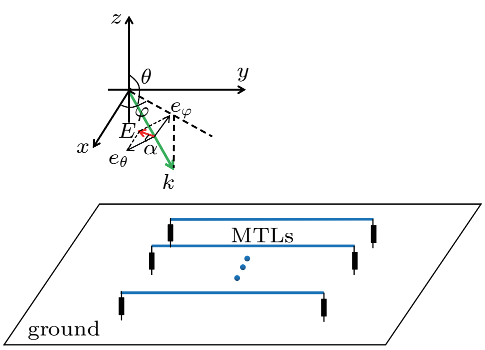

Fig. 1. Typical model of ambient wave coupling to MTLs.

Generally, the distances between the locations of MTLs and the ground are electrically small sizes by comparing with the minimum wavelength of ambient wave. Under this scenario, it is reasonable to ignore the radiation of MTLs according to image theorem.[7] With these assumptions in mind, two important steps have been involved in the presented method for the coupling analysis of MTLs. One step is to build the coupling model of electromagnetic field to the MTLs, which is achieved by the TL equations of Agrawal model. And the other step is to fast calculate the excitation fields of the MTLs and transient responses on the MTLs, which are obtained by the parallel FDTD method and interpolation schemes. Details of these steps are described as follows.

2.1. Agrawal model for coupling analysis of MTLs

The time domain transmission line equations based on Agrawal model used for the coupling analysis of MTLs can be expressed as

$$\frac{\partial}{\partial y}\boldsymbol{V}^{\text{sca}}(y,t)+\boldsymbol{L}\frac{\partial}{\partial t}\boldsymbol{I}(y,t)=\boldsymbol{V}_{\text{F}}(y,t), \tag{1}$$

$$\frac{\partial}{\partial y}\boldsymbol{I}(y,t)+\boldsymbol{C}\frac{\partial}{\partial t}\boldsymbol{V}^{\text{sca}}(y,t)=0, \tag{2}$$

where $\boldsymbol{V}^{\text{sca}}(y,t)$ and $\boldsymbol{I}(y,t)$ are the scattered voltage vector and total current vector of MTLs, respectively; $\boldsymbol{L}$ and $\boldsymbol{C}$ denote the per unit length inductance and capacitance matrices of MTLs respectively, and they can be computed by the empirical formulas used in Ref. [14]; $\boldsymbol{V}_{\text{F}}(y,t)$ is the equivalent distribution source vector of MTLs, which can be expressed as

$$[\boldsymbol{V}_{\text{F}}(y,t)]_i=E_y^{\text{inc}}(x_i,y,h,t)-E_y^{\text{inc}}(x_i,y,0,t), \tag{3}$$

where i represents the i-th transmission line of MTLs, h is the height of i-th line to the ground, and E_y^{inc} is the incident electric fields along the MTLs. The structures of MTLs can be removed when calculating the incident electric fields due to its independence of the scattering fields of MTLs.

It should be noted that the voltages at the terminal ports of MTLs must satisfy the conditions expressed as

$$\boldsymbol{V}^{\text{sca}}(0,t)=-\boldsymbol{Z}_1\boldsymbol{I}(0,t)+\boldsymbol{U}_1, \tag{4}$$

$$\boldsymbol{V}^{\text{sca}}(L,t)=\boldsymbol{Z}_2\boldsymbol{I}(L,t)+\boldsymbol{U}_2, \tag{5}$$

where L represents the length of MTLs; $\boldsymbol{Z}_1$ and $\boldsymbol{Z}_2$ are the impedance matrices of beginning and ending ports of MTLs respectively; $\boldsymbol{U}_1$ and $\boldsymbol{U}_2$ are the equivalent voltage sources of beginning and ending ports of MTLs respectively, which can be expressed, respectively, as

$$[\boldsymbol{U}_1]_i=\int_0^h E_z^{\text{inc}}(x_i,0,z,t)\text{d}z, \tag{6}$$

$$[\boldsymbol{U}_2]_i = \int_0^h E_z^{\text{inc}}(x_i, L, z, t)\mathrm{d}z, \tag{7}$$

where E_z^{inc} represents the incident electric fields perpendicular to the MTLs.

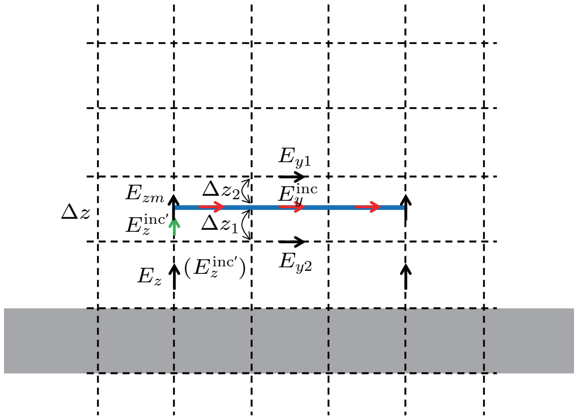

Fig. 2. Interpolation scheme of the incident electric fields along and vertical to the lines.

Now, we come to consider a non-particular situation, *i.e.*, the MTLs are not located exactly on the edges of FDTD grids as shown in Fig. 2. Under this circumstance, interpolation technique should be taken into account to obtain the electric fields along the line and vertical to the line, respectively. For electric field E_y^{inc}, the interpolation scheme can be expressed as $E_y^{\text{inc}} = (\Delta z_2/\Delta z)E_{y1} + (\Delta z_1/\Delta z)E_{y2}$, where Δz is the space step of FDTD, E_{y1} and E_{y2} are the electric fields on FDTD girds, and Δz_1 and Δz_2 are the scale factors for the lines located on the grids. For electric fields E_z^{inc}, they can be obtained from the electric fields E_z on FDTD grids when the locations of E_z^{inc} and E_z are the same. Note that the electric fields $E_z^{\text{inc}'}$ near the lines cannot be obtained directly, but they can be achieved by interpolation from the electric fields E_{zm} on FDTD grids. The interpolation scheme is described as $E_z^{\text{inc}'} = (\Delta z_1/\Delta z)E_{zm}$.

2.2. Parallel computation of hybrid method

Considering the differential characteristics of TL equations, the central difference scheme of FDTD is most suitable for the TL equations. We assume that the MTLs are divided into N segments according to the FDTD gird, so the iteration formulas of currents and voltages on the MTLs can be expressed as

$$\boldsymbol{I}^{n+1/2}(k+1/2) = \boldsymbol{I}^{n-1/2}(k+1/2) - \left[\frac{\boldsymbol{L}}{\Delta t}\right]^{-1}\left[\frac{\boldsymbol{V}^{\text{sca}(n)}(k+1) - \boldsymbol{V}^{\text{sca}(n)}(k)}{\Delta y} - \boldsymbol{V}_{\text{F}}^{n}(k+1/2)\right], \tag{8}$$

$$\boldsymbol{V}^{\text{sca}(n+1)}(k) = \boldsymbol{V}^{\text{sca}(n)}(k) - \left[\frac{\boldsymbol{C}}{\Delta t}\right]^{-1}\left[\frac{\boldsymbol{I}^{n+1/2}(k+1/2) - \boldsymbol{I}^{n+1/2}(k-1/2)}{\Delta y}\right], \tag{9}$$

$$\boldsymbol{V}^{\text{sca}(n+1)}(0) = \left[\frac{\boldsymbol{C}}{\Delta t} + \frac{\boldsymbol{Z}_1^{-1}}{\Delta y}\right]^{-1}\left[\left(\frac{\boldsymbol{C}}{\Delta t} - \frac{\boldsymbol{Z}_1^{-1}}{\Delta y}\right)\boldsymbol{V}^{\text{sca}(n)}(0) - \frac{2}{\Delta y}\boldsymbol{I}^{n+1/2}(1/2) + \frac{2\boldsymbol{Z}_1^{-1}}{\Delta y}\boldsymbol{U}_1^{n+1/2}\right], \tag{10}$$

$$\boldsymbol{V}^{\text{sca}(n+1)}(N) = \left[\frac{\boldsymbol{C}}{\Delta t} + \frac{\boldsymbol{Z}_2^{-1}}{\Delta y}\right]^{-1}\left[\left(\frac{\boldsymbol{C}}{\Delta t} - \frac{\boldsymbol{Z}_2^{-1}}{\Delta y}\right)\boldsymbol{V}^{\text{sca}(n)}(N) + \frac{2}{\Delta y}\boldsymbol{I}^{n+1/2}(N-1/2) + \frac{2\boldsymbol{Z}_2^{-1}}{\Delta y}\boldsymbol{U}_2^{n+1/2}\right], \tag{11}$$

where $k = 1, \ldots, N-1$.

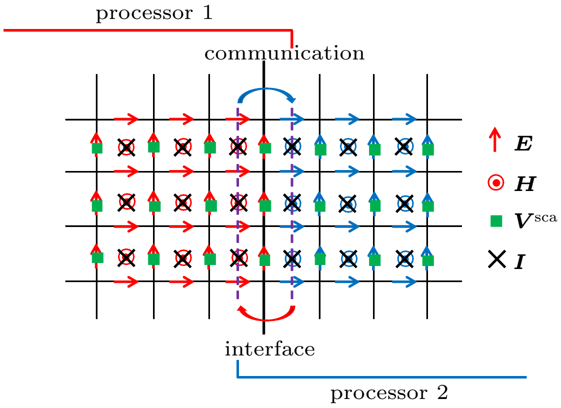

Fig. 3. Data communications between adjacent processors.

It should be emphasized that to guarantee the co-calculations of space electric fields and transient responses on the MTLs, the space and time steps needed by the FDTD method for the discretization of TL equations must be as the same as that of FDTD method applied to the calculation of space electric fields. After this operation, the positions of electric and magnetic fields, voltages and currents on the FDTD grids keep fit to each other as shown in Fig. 3. This means that the magnetic fields and currents are in the center of FDTD grids, and the electric fields and voltages are on the edges of the grids. Next, the parallel computation of this hybrid method is performed by dividing the computation regions into several sub-domains, and the latter ones are assigned to different processors respectively. Meanwhile, in Fig. 3, MPI library is used to realize the data communication of electric and magnetic fields, voltages, and currents on the interface between adjacent processors. The iteration of the parallel procedure of this hybrid method is summarized in Fig. 4, where n steps represent the total number of time steps.

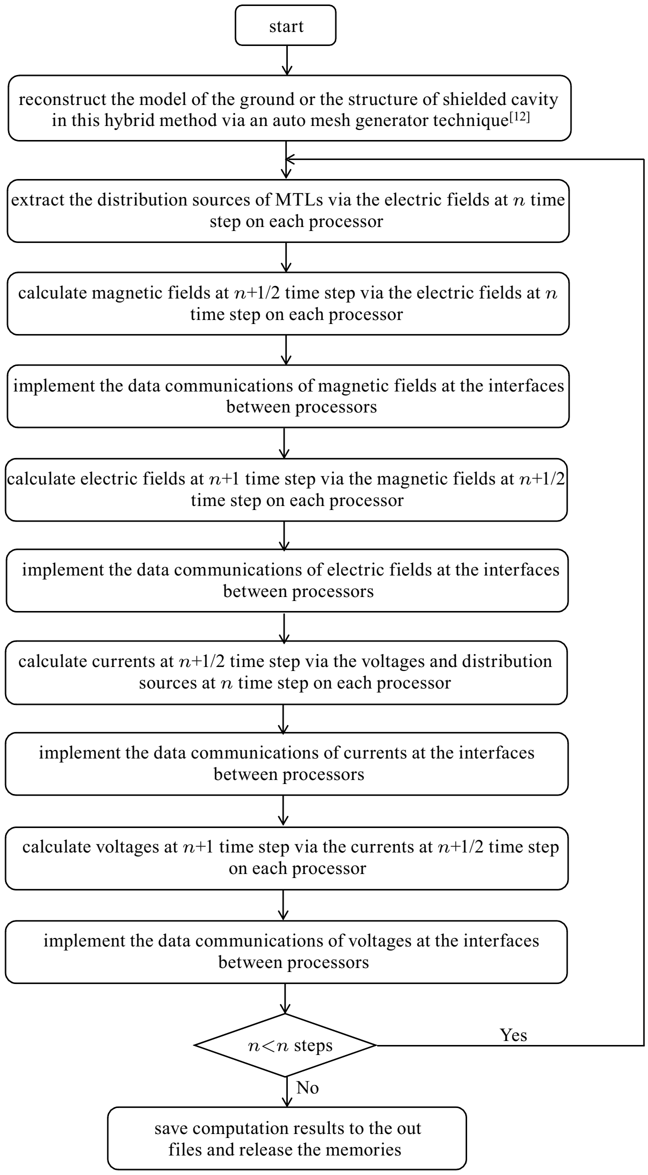

Fig. 4. Flow chart of this presented method.

3. Numerical simulations

To verify the accuracy and efficiency of this presented method, two cases involve ambient wave coupling to MTLs on the PEC ground and in the shielded cavity are simulated and compared with the results from the conventional FDTD method.

The first case is for the coupling analysis of three transmission lines on the PEC ground excited by a plane wave as shown in Fig. 5. The radius, length and height of each of these lines are 1 mm, 80 cm, and 1.1 cm respectively. The distance between the three lines is 5 mm. The beginning and ending loads of the lines are $Z_1 = Z_2 = Z_3 = 50\ \Omega$ and $Z_4 = Z_5 = Z_6 = 100\ \Omega$ respectively. The size of the ground is 0.3 m×1.0 m. A Gaussian pulse, expressed as $E_0 \exp\left(-4\pi(t-t_0)^2/\tau^2\right)$, is perpendicular to the lines, where $E_0 = 1000$ V/m, $t_0 = 1.6$ ns, and $\tau = 2$ ns.

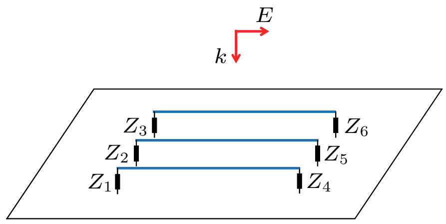

Fig. 5. Coupling model of MTLs on PEC ground excited by ambient wave.

The hybrid method and parallel FDTD method are used to compute the transient responses on the loads of the lines, which are both run on the Dawning server with using 4 processors. Figure 6 shows the voltage responses on the loads Z_1 and Z_5, which are computed by the two methods. We can see that the voltages computed by the hybrid method are in good agreement with that by FDTD method.

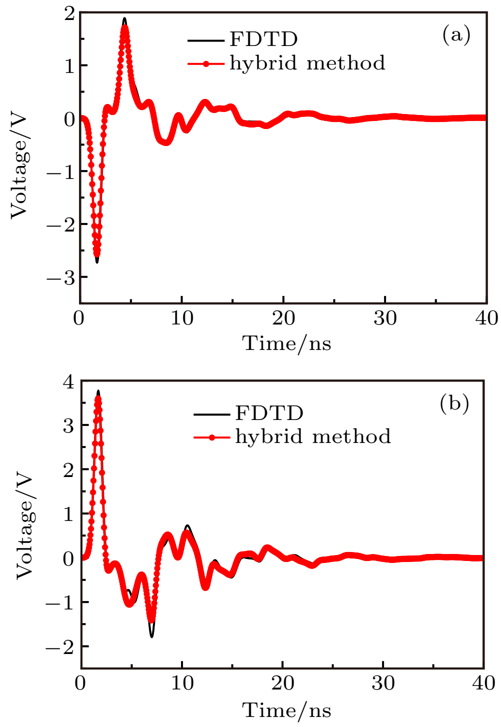

Fig. 6. Transient responses on loads of MTLs, computed by two methods for the first case, showing (a) voltage responses on Z_1; (b) voltage responses on Z_5.

In order to further demonstrate the efficiency of this presented method, we compare the computation times and mesh numbers between the two methods as shown in Table 1. Here, the UPML absorbing boundary with eight layers and SF/TF boundary are employed in the two methods to configure the simulation settings of FDTD. Due to the restrictions of calculation precision and Courant condition of FDTD method, the mesh size selected by the hybrid method is 5 mm. Meanwhile, the non-uniform mesh is employed in the parallel FDTD method to avoid meshing the computation domain finely. The minimum mesh of FDTD method is 1 mm, which is determined by the structures of TLs, and the maximum mesh of FDTD method is the same as the mesh used by the hybrid method. Obviously, the hybrid method saves a certain number of meshes and large amount of computation time, because the structures of MTLs do not need to be meshed in this method. In addition, the computation time of this method should be greatly reduced when more processors are used.

Table 1. Mesh number and computation time needed by two methods.

Method	Mesh number/10^6	Computation time/min
Parallel FDTD	2.0	7
Hybrid Method	1.2	1.3

The second case is for the coupling analysis of three transmission lines in a shielded cavity excited by a plane wave as shown in Fig. 7. The dimension of the cavity is $L_c \times W_c \times H_c =$ 40 cm $\times$20 cm $\times$ 30 cm. There are three slots with a size of 10 cm $\times$ 1 cm and a distance of 2 cm on the top surface of the cavity. Three transmission lines are located on the bottom of the cavity with a radius of 1 mm, length of 30 cm, height of 1.1 cm, and distance of 5 mm. The terminal loads of the lines, and the waveform and incident angles of ambient wave are the same as those for the first case.

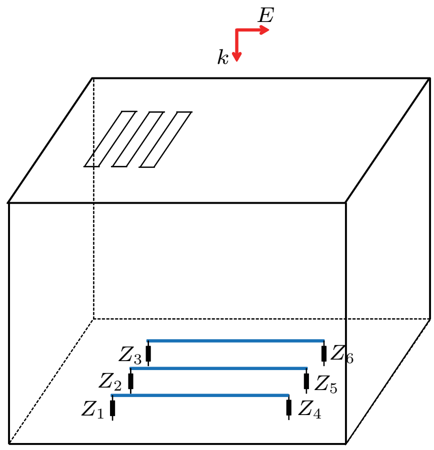

Fig. 7. Coupling model of MTLs in shielded cavity excited by ambient wave.

In Fig. 8, the voltage responses on the loads Z_1 and Z_5, computed by the hybrid method and parallel FDTD method, are observed to verify the accuracy of the presented method of making the coupling analysis of MTLs in a complex environment. Similarly, we can see that the results of the two methods agree well with each other.

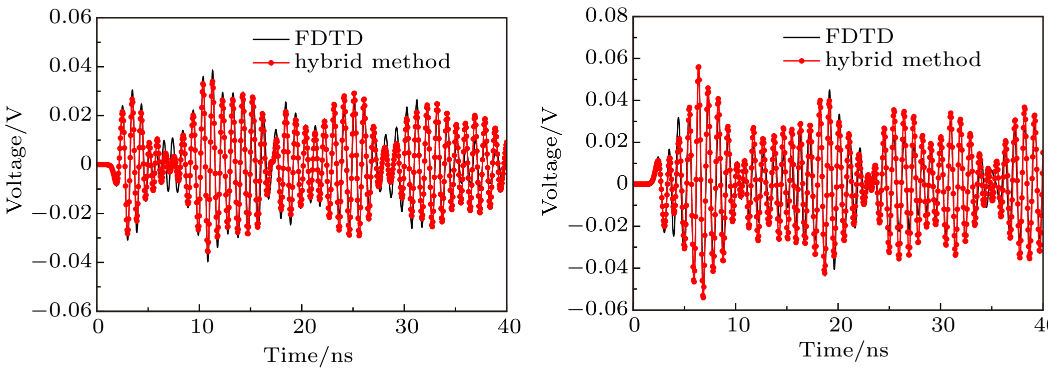

Fig. 8. Transient responses on loads of MTLs, computed by two methods for the second case showing (a) voltage responses on Z_1 and (b) voltage responses on Z_5.

It is needed to explain that some values of the results computed by the two methods for the two cases have certain errors, because the scattering fields caused by the structures of MTLs are ignored in this presented method.

4. Conclusions

Parallel FDTD method using MPI library, transmission line equations of Agrawal model, and interpolation scheme are combined together to form a parallel hybrid method to solve the coupling problem of multi-conductor transmission lines excited by space electromagnetic fields with high efficiency. Compared with other methods, this method has two prominent advantages. One is that the TL equations of Agrawal model used to establish the coupling process of field-to-line can significantly reduce the number of electric fields that need to be stored, and the other is that the calculation of this method can be run on multiple processors or computers, which can save a large amount of computation time expediently.

Two cases about MTLs, on the ground and in the shielded cavity respectively, excited by a plane wave are studied to verify the accuracy and efficiency of the presented method. To evaluate the performance of the hybrid method, we compare the results obtained by the presented method with those by conventional parallel FDTD method, and find that they accord with each other to a good degree. In addition, the hybrid method can save a large amount of computation time, for the structures of MTLs do not require to be meshed any more.

References

[1] Baum C E, Liu T E and Tesche F M 1978 *Interaction Notes* **350** 467
[2] Agrawal A K, Price H J, and Gurbaxani S H 1980 *IEEE Trans. Electromagn. Compat.* **22** 119
[3] Du J K, Hwang S M, Ahn J W and Yook J G 2013 *IEEE Trans. Microw. Theory Tech.* **61** 3514

[4] Luo J W, Du P A, Ren D and Nie B L 2015 *Acta Phys. Sin.* **64** 010701 (in Chinese)

[5] Ni G Y, Yan L and Yuan N C 2008 *Chin. Phys. B* **17** 3629

[6] Erdin I, Dounavis A and Achar R 2001 *IEEE Trans. Electromagn. Compat.* **43** 485

[7] Xie H Y, Wang J G, Fan R Y and Liu Y N 2009 *IEEE Trans. Electromagn. Compat.* **51** 811

[8] Paul C R 1994 *IEEE Trans. Electromagn. Compat.* **36** 342

[9] Xie H Y, Wang J G, Li Y and Xia H F 2014 *IEEE Trans. Electromagn. Compat.* **56** 1623

[10] Xie H Y, Li Y, Qiao H L and Wang J G 2016 *IEEE Trans. Electromagn. Compat.* **58** 581

[11] Fang X D, Tang Y H and Wu J J 2012 *Chin. Phys. B* **21** 098901

[12] Ye Z H, Xiong X Z, Liao C and Li Y 2015 *Prog. Electromagn. Res. M* **42** 85

[13] Ye Z H, Liao C, Xiong X Z and Zhang M 2017 *IEEE Trans. Electromagn. Compat.* **59** 1211

[14] Ye Z H, Zhang J, Zhou J J and Gou D 2020 *Acta Phys. Sin.* **69** 060701 (in Chinese)

[15] Volakis J L, Davidson D B, Guiffaut C and Mahdjoubi K 2001 *IEEE Antennas Propag. Mag.* **43** 94

[16] Varadarajan V and Mittra R 1994 *IEEE Microw. Guided Wave Lett.* **4** 144

[17] Alighanbari A and Sarris C D 2009 *IEEE Trans. Antennas Propag.* **57** 231

[18] He X B, Wei B, Fan K H, Li Y W and Wei X L 2019 *Chin. Phys. B* **28** 074102