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Characteristics of Electromagnetic Coupling with A Wire Through Enclosure

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Abstract
Electromagnetic interference can be easily coupled into metallic shielding enclosure that is penetrated with a conducting wire, which having a harmful effect on electrical and electronic devices. To sudy the characteristics, Finite Difference Time Domain (FDTD) is applied in both frequency and time domain for modeling the coupling of an incident electromagnetic pulse (EMP) with a conducting wire through a metallic shielding enclosure with a small aperture. Simulation and analysis are done by radius, length, and number of the wires, the incidence angle of EMP and the polaration angle of electric field in consideration. The simulation result shows that interference of the electromagnetic coupling into the shielding enclosure can be affected in different degrees by above factors. At low frequency, the larger the leakage length, the radius or the number of the wire penetrated into the cavity, the more interference is coupled into the shielding cavity from electromagnetic field. Also, the smaller the incident direction angle of propagation of the electromagnetic pulse or the polarization direction angle of the incident electric field, the more easily the electromagnetic interference is coupled into the cavity.

***Keywords**: FDTD, a conducting wire through a metallic shielding enclosure, EMP, interference of the electromagnetic coupling*

1. Introduction

When electrical and electronic equipment are in the work, on one hand, they radiate electromagnetic energy outward. The formation of electromagnetic interference has a harmful effect on itself or other equipments, and even cause serious harm. On the other hand, they also work in the environment with electromagnetic that other devices produce [1]. Although shielding cavity can be used on the electrical and electronic devices against external electromagnetic interference, electromagnetic interference energy can still be coupled into shielding cavity by the wire that penetrated into the cavity, for the reason that a variety of electrical and electronic equipments have external conducting wire, such as communication lines, signal lines, and power cables, etc [2]. This makes the electromagnetic environment in the shielding cavity more complicated, and affects the stability and reliability of the equipment of system, or even destroys the electronic system.

Chivington EP presents an analytical technique and experimental verifica-tion for the response of shielded twisted pair cables to ionizing radiation [3]. Tang J provides an insight on how to control the generated electromagnetic interference in the dc line on account of the induced voltage from the neighboring ac line [4]. In order to maintain electromagnetic compatibility of transmission lines in cable television, Hayashi YL presents one model that provides an explanation of contact failures caused by faulty transmission line connectors for the purpose of investigating the common-mode (CM) current, which is one of the factors that cause noise radiation [5]. These researches do much prediction and analysis on response to electromagnetic interference of transmission lines, but very little on the effect of interference from coupling electromagnetic field in shielding enclosure with penetrated wires. The model of shielding enclosure with a conducting wire through a small aperture is made, for studying the effect and role of interference in the cavity by radius, length, and number of the wires, the incidence angle of EMP and the polaration angle of electric field in consideration.

This research topic comes from several items as followings:

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"The Research in Function Mechanism and Protective Method of Electromagnetic Pulse in Plane", The Shenyang Funds Project (the item number: F11-264-1-04);

2. Research Method

The thickness of enclosure must be greater than its skin depth to achieve a better shielding effectiveness [6-8]. When the strong electromagnetic field needs shielding, only single-layer shielding materials could reach littlle shielding requirements or lead to saturation. There are two solutions as follows: one approach is to use a combination of shielding, another method is to increase the thickness of the shielding material [9, 10]. The skin depth δ is:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

Where f is the stimulated frequency, μ is the permeability, and σ is the conductivity.

The paper calculates in the range of frequency 0~30GHZ, to observe the change of electric field frequency domain component in the center of the cavity. A simple model of a wire penetrated into a shielding enclosure cavity is created as Figure 1 shown. Choose the perfect shield conductor cavity whose the external dimensions of $a*b*c$, which a is 200 mm, b is 200 mm, c is 200mm, the thickness of 2mm, the aperture with the size of 12mm*12mm in the center plane xoy. The cavity natural resonant frequency is about 1.06GHz. The radius of the wire inserted in the center of the aperture is r. The total length of wire is 100mm. The length L of wire exposed outside the shield cavity is 50mm. Electromagnetic excitation source is a plane wave of which propagation direction parallel to the wire (i.e., along the z-axis), incident electric polarization direction parallel to the y-axis.

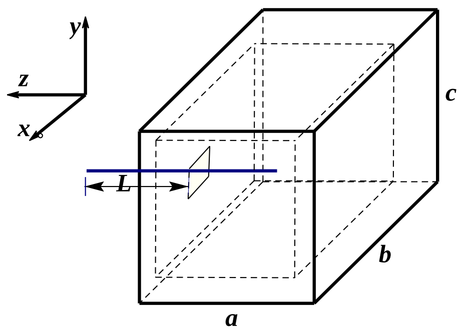

Figure 1. The Model of Cavity

Finite Difference Time Domain (FDTD) method is used in this paper can simulate the propagation of electromagnetic pulse and the process of the transmission function among objects. Based on FDTD method, this paper simulates the coupling effect of electromagnetic pulse and shielding cavity penetrated with conductor wire by establishing 3-D simulation model, and find out the coupling rule between electromagnetic pulse and penetrated conductor [11].

The FDTD method is a direct solution of Maxwell's time-dependent curl equations. The goal is to model the propagation of an electromagnetic wave into a volume of space containing a dielectric or conducting structure. Firstly Maxwell's curl equations are made into equations of the generative of the Cartesian components in the Cartesian coordinate system. Order differential equation is replaced by second-order central difference equation to get time recursive type of mutual coupling field component, which can be solved by iterative method of leapfrog algorithm in time. The component of the electric field at each lattice point is only related to its surrounding components of the magnetic field. The same is that the component of the magnetic field at each lattice point is only related to its surrounding components of the electric field [12]. The space lattices are shown in Figure 2. The difference equation of E_x and H_x can be obtained by using Yee's difference form in the scalar form of Maxwell's equations in FDTD algorithm. The expressions are shown as Expression (2) and (3).

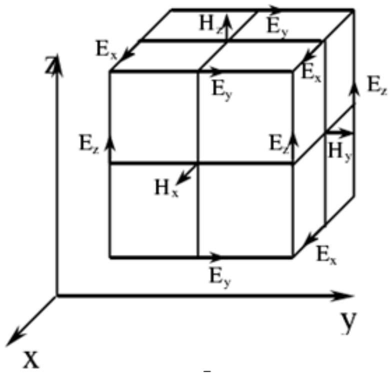

Figure 2. Distribution of Field Components about A Unit Cell of Yee Lattice

$$H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) = \frac{\mu_x - 0.5\Delta t\sigma_x^m}{\mu_x + 0.5\Delta t\sigma_x^m} \cdot H_x^{n-\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2}) + \frac{\Delta t}{\mu_x + 0.5\Delta t\sigma_x^m} \cdot \left[\frac{E_y^n(i, j+\frac{1}{2}, k+1) - E_y^n(i, j+\frac{1}{2}, k)}{\Delta z} - \frac{E_z^n(i, j+1, k+\frac{1}{2}) - E_z^n(i, j, k+\frac{1}{2})}{\Delta y} \right] \tag{2}$$

$$E_x^{n+1}(i+\frac{1}{2}, j, k) = \frac{\varepsilon_x - 0.5\Delta t\sigma_x}{\varepsilon_x + 0.5\Delta t\sigma_x} E_x^n(i+\frac{1}{2}, j, k) + \frac{\Delta t}{\varepsilon_x + 0.5\Delta t\sigma_x} \cdot \left[\frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k)}{\Delta y} - \frac{H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j-\frac{1}{2}, k)}{\Delta y} - \frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k+\frac{1}{2})}{\Delta z} + \frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k-\frac{1}{2})}{\Delta z} \right] \tag{3}$$

Space lattice stepping must have something with time stepping in order to guarantee the stability of the numerical counts in the iterative calculation, of which the relationship is:

$$\Delta t \le \frac{1}{v\sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2 + \left(\frac{1}{\Delta z}\right)^2}} \tag{4}$$

Where Δt is the time of stepping, v is the propagation speed of light in medium, $\Delta x, \Delta y, \Delta z$ is the length of space lattice stepping in each direction of the cartesian coordinate.

Space lattice needs truncating in FDTD algorithm, to ensure the approximate infinite large opening space of limited lattice space with absorbing boundary conditions. Therefore, absorbing boundary is an important link in FDTD algorithm, which directly affects the size of the computational domain, the length of time needed for calculation and the accuracy of the calculation results [13]. Perfectly matched layer (PML) absorbing boundary conditions has received widely using and peer recognition since it was put forward in 1994, which is used to realize truncating the boundary in the simulation. Its principle is to set absorbing medium layer outside the calculation area, to reach the purpose of absorbing electromagnetic wave. It can guarantee the high accuracy of numerical simulation and the validity of the simulation for a long time, by largely reducing the reflection of numerical wave on absorbing boundary [14].

3. Results and Discussion

Unipolar Gaussian pulse is applicated as the electromagnetic interference outside, its expression is:

$$E_{in}(t) = E_0 \exp[-\frac{4\pi(t-t_0)^2}{\tau^2}] \quad (5)$$

In which E_0 = 1000V, length of space lattice stepping $\Delta x = \Delta y = \Delta z$ =1mm, time of stepping Δt = 1.926ps, τ = 100Δt , t_0 = 3τ .

3.1. The Inference of Wire Radius

The selection of wire radius is based on American Wire Gauge (AWG) standard in this paper [15]. Calculate espectively the central location of the cavity when wire radius r = 0.51mm, 1.15mm, 2.31mm and 5.2mm, to obtain the electic field frequency domain, as shown in Figure 3.

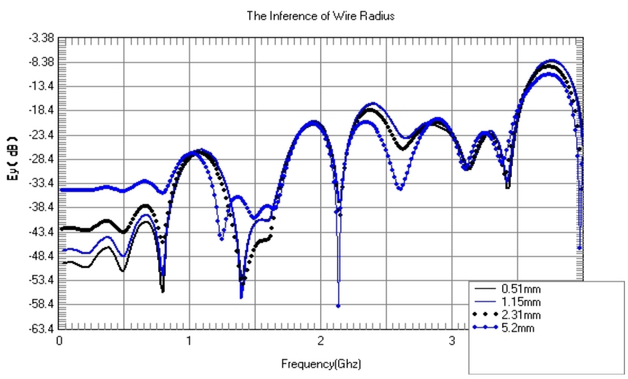

Figure 3. The Inference of Wire Radius

As shown in Figure 3, we can see that: (1) At low frequency, the frequency component of electromagnetic interference in cavity has increased significantly with the radius of wire the penetrated into wire cavity becoming larger. It indicates that electromagnetic interference frequency component of the low frequency band is more easier coupled into the cavity through the wire with larger radius. The difference of component at high frequency and the resonance frequency is not so much related to the radius of wire, for the reason that the ability in radiation of the wire greatly enhanced when the frequency is higher. (2) The degree of suffering each electromagnetic interference at resonance frequency is the strongest. From what has been discussed as above two points, we can see that the larger the radius of wire, the more the frequency domain component of electric field is intoduced into the cavity through the wire, and the more easier the interference energy is coupled into the cavity to cause significant interference in the cavity.

3.2. The Inference of Wire Length

Calculatee spectively the central location of the cavity with a Penetrated wire when the wire leakage length L=50mm and L=100mm, to obtain the electic field frequency domain, as shown in Figure 4.

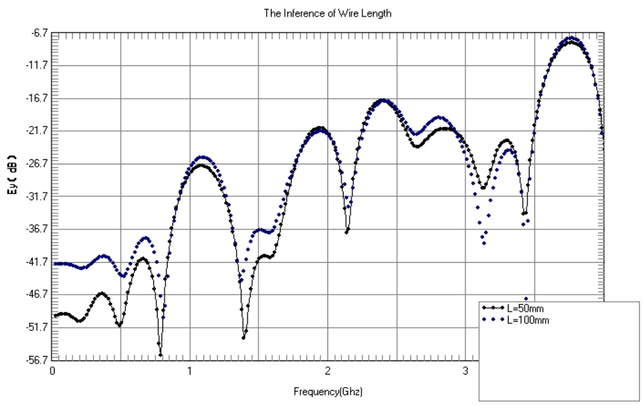

Figure 4. The Inference of Wire Length

As shown in Figure 4, compared with the cavity with wire of 50 mm in leakage length under the same other conditions, the cavity with wire of 100 mm in leakage length has significantly higher electromagnetic interference frequency component at low frequencies. The wire of 100 mm in leakage length can apparently introduced more interference of electromagnetic field frequency compared coupled into the cavity, because with the length of wire increasing, the wire's ability in the validity of the transmission line enhances, while the difference in component at high frequency is smaller. Therefore, the leakage length of the penetrated wires should be as short as possible, to prevent from the radiating electromagnetic interference.

3.3. The Inference of Wire Number

Take the same cavity model as above with the radius of the penetrated conductor wire r=0.51mm and leakage wire length L=50mm. The polarization direction of the incident electric field is parallel to the y-axis. Take the center of the cavity as the observation point to calculate component of the electric field time domain in the central enclosure when the number of the internal penetrated wires is 1, 3, and 5 respectively.

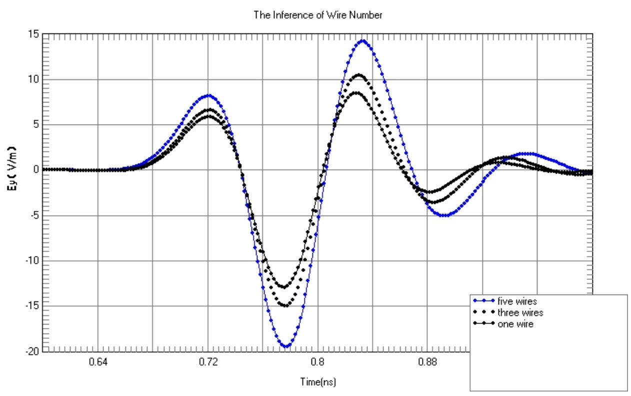

Figure 5. The Inference of Wire Number

As shown in Figure 5, the electric field intensity introduced by 5 wires in the center of cavity is higher than that introduced by 1 and 3 wires. It shows that the electromagnetic wave coupled into more electric field intensity with the number of wires which penetrated the cavity increasing, for the reason that the penetrated wires play the role of radiating antenna. The more wires penetrated through the enclosure, the more radiating coupling from the electromagnetic interference of radiating energy.

3.4. The Inference of Incident Direction of Propagation of Electromagnetic Field

Assuming the radius of the penetrated conductor wire r=0.51mm and leakage wire length L=50mm. Calculate the current on the penetrated wire in the shielding cavity with considering the incident direction of propagation of the electromagnetic field, respectively, theta $=0^{\circ}$, 30° , 45° , 60° and 90° to obtain the time domain as shown in Figure 6.

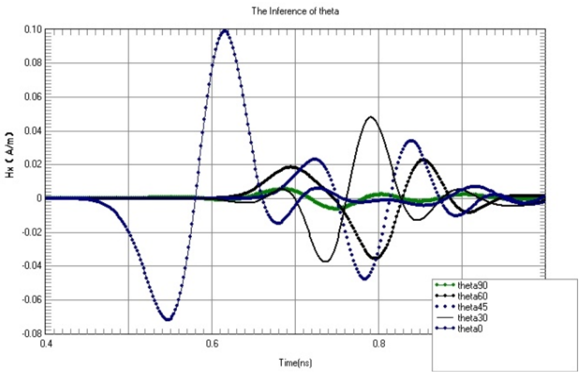

Figure 6. The Inference of Incident Direction of Propagation of Electromagnetic Field

As shown in Figure 6, when theta = 0° , the peak value of interference currents goes to 0.1A and goes down with the angle theta becoming larger. Especially, the degree of interference current decreasing becomes significant after the angle theta lager than 30° . And interference current on the wire is almost zero when theta= 90° . It showes that the coupling interference current on wire penetrated into the cavity is related to the propagation direction of electromagnetic field, which is, the larger the angle between the propagation direction of the electromagnetic field and penetrated wire, the smaller the current intensity on the wire in the cavity.

3.5. The Inference of Incident Direction of Polarization Direction of Incident Electric Field

Assuming the propagation direction of electromagnetic field is parallel to the wire, the radius of the penetrated conductor wire r=0.51mm and leakage wire length L=50mm. Take the polarization direction of the incident electric field, respectively, phi= 0° , 30° , 60° and 90° , to calculate the current on the penetrated wire in the shielding cavity, in order to observe the coupling effect caused by polarization direction of the incident electric field. The time domain is shown in Figure 7.

As seen from Figure 7, the peak value of interference current on the wire goes to 0.1A when phi = 0° , 0.07 A when phi= 30° , only 0.04 A when phi= 60° , and almost to zero when phi= 90° . It illustrates that the coupling interference current on the wire penetrated into enclosure is related to the polarization direction of the incident electric field. The larger the polarization direction of the incident electric field, the smaller the current intensity on the wire penetrated into the cavity.

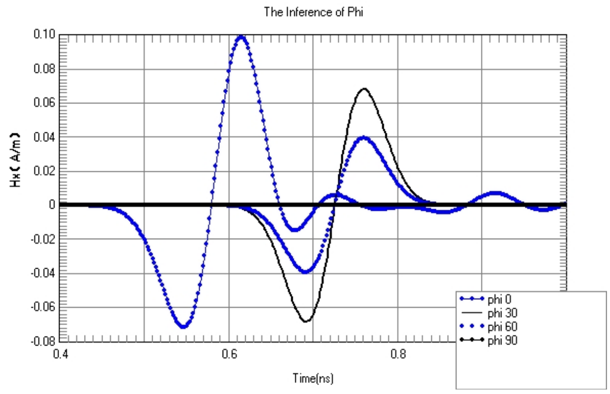

Figure 7. The Inference of Incident Direction of Polarization Direction of Incident Electric Field

4. Conclusion

Finite difference time domain (FDTD) method is applied in this article, to model and simulatie the coupling interference in the body of shielding cavity with a penetrated wire under the action of the electromagnetic pulse. The experiment data shows that:

(1) The larger the leakage length or the radius of the wire penetrated into the cavity, the more electric field intensity in the center of the cavity is enhanced.

(2) At low frequency, the number of penetrated wires is related to the changing rule of coupling interference in the shielding cavity from electromagnetic field. The coupling interference is enhanced with the number of penetrated wires increasing, for the penetrated wires playing the role as radiating antenna.

(3) The interference current on the wire penetrated into the cavity is also affected by the incident direction of propagation of the electromagnetic pulse and the polarization direction of the incident electric field. The smaller the incident direction angle of propagation of the electromagnetic pulse or the polarization direction angle of the incident electric field, the more easily the electromagnetic interference is coupled into the cavity. When the incident direction of propagation of the electromagnetic pulse is parallel to the wire or the polarization direction angle of the incident electric field is zero, the electromagnetic interference goes to the strongest.

(4) The low frequency component of interference of electromagnetic field or the interference of electromagnetic field at low frequency more intends to couple interference energy into the cavity. However, the difference among those situations is not so obvious at high frequency, for the reason of the ability in radiation of the wire at high frequency.

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