TELKOMNIKA, Vol.11, No.11, November 2013, pp. 6848~6854
e-ISSN: 2087-278X

Characteristics of Electromagnetic Pulse Coupling into Annular Apertures

Yan-Peng Sun*[1,2], Shi Zhang[1], Xiao-He An[*2], Hong-Peng Sun[3]
[1]College of Information Science and Engineering, Northeastern University, Shenyang, 110819, China
[2]School of Electronic and Information Engineering, Shenyang Aerospace University, Shenyang, 110136, China
[3]Shenyang Aircraft Design & Research Institute, Shenyang, 110136, China
*Corresponding author, e-mail: levelseven@126.com

Abstract

Electromagnetic pulse (EMP) coupling into the annular apertures can disturb or damage much electronic equipment. To enhance electronic system's capability of anti-electromagnetic interference, the finite difference time domain method (FDTD) was employed to study the characteristics of electromagnetic pulse coupling into the cavity enclosures with annular apertures. The coupling characteristics of annular apertures with different shapes (rectangle, square and circle) were discussed. It shows that, in the case of the same aperture area, the coupling energy of electromagnetic pulse into the circular annular aperture is smaller than that into the rectangular and the square ones. To the rectangular annular aperture, while the polarization direction of the incident electromagnetic pulse is perpendicular to the long side of the rectangular annular aperture, the coupling energy is larger when the aspect ratio of the rectangular annular aperture is larger. The coupling effect of incident pulse with short pulse width is obviously better than the one with longer pulse width. The resonance phenomenon of the coupled waveform occurs in the cavity.

Keywords: *electromagnetic coupling, annular aperture, electronic system, FDTD, aspect ratio*

1. Introduction

The extensive application of information technology greatly improves the performance of modern electronic system, but it also brought the problem of electromagnetic sensitivity and vulnerability. The reduction of electrical and electronic components parameters of modern electronic equipment (such as input voltage, power) makes the ability of anti-electromagnetic interference of the electronic equipment declined significantly. In order to meet the needs of electromagnetic shielding, the metal shielded cavity is commonly used to protect the electronic system from external radiation interference and internal leakage of electromagnetic. But due to the need for the equipment cooling, ventilation display and the circuit connection in outside, varieties of apertures exist inevitably on shielded cavity. Electromagnetic coupling occurs when the electromagnetic pulse couples with the circuits and devices through the window on the casing of the electronic equipment, the operation button ventilation holes, rivet seam and other forms of apertures. It greatly reduces the shielding effectiveness of shielded cavity or even damage the electronic equipment in shielded cavity. Electromagnetic pulse coupling into the aperture is a common coupling mode and difficult to protect. If the electromagnetic energy is coupled into the target, it will interfere with the sensitive electronic equipment or even destroy the electronic system. Therefore, in order to improve the safety performance of electronic equipment in the complex electromagnetic environment, electromagnetic pulse through the aperture coupling has become a research focus in the field of electromagnetic compatibility.

Scholars have done a lot of work for the study on electromagnetic compatibility [1, 2]. The study of electromagnetic pulse coupling into apertures was started from the study of the small hole coupling in a perfectly conducting plane. Firstly, H.A.Bethe proposed the hole coupling theory [3]. C.J.Bouwkamp analyzed the coupling problem of the small hole in a zero thickness perfectly conducting plane [4]. These research methods of the small hole coupling problem laid the foundation for the later study on the three-dimensional problem of the aperture coupling. Then Harrington proposed to use the moment method to analyze the problem of electromagnetic pulse coupling into apertures [5]. With the development of computer

Received May 8, 2013; Revised July 22, 2013; Accepted August 6, 2013

technology, people can study the problem of electromagnetic pulse coupling into the cavity enclosures with apertures under the condition of three-dimensional. There are many reliable modeling techniques, such as the finite element method (FEM) [6, 7], the finite difference time domain method (FDTD) [8, 9] and the Multilevel-Fast-Multipole-Method (MLFMM) [10]. The FDTD has advantage in analyzing the problem of transient electromagnetic field [11]. So it is widely used in the analysis of aperture coupling. But most of the research objects above for the aperture coupling are square, rectangular and other forms of regular apertures [12-14], and the study of the electromagnetic pulse coupling into the annular apertures widely exist is not enough and needs to be further. Therefore, it has significances to study the coupling effect of electromagnetic pulse into the annular aperture on exploring the protection research and the damage effect of electromagnetic pulse to the shielded cavity enclosures with apertures.

2. Modeling and Theory

2.1. Modeling

A rectangular shielded cavity constituted by the perfect conductor is modeled as shown in Figure 1. Different shapes of annular aperture are opened at one side of the cavity. The shielded cavity is a cube with a side length of 20cm. The thickness of the cavity wall is 2mm.

The shapes of annular aperture of this paper are square annular, rectangular annular and circular annular. The annular aperture geometry center is coincident with the geometry center of the yz plane of the cavity wall. Due to the size of the cooling holes, rivet joint and data interface belongs to mm order of magnitude. It has more practical significance to study the tiny apertures on the order of mm. Annular aperture width is 2mm. The area of annular aperture area is 200mm^2. As shown in Figure 2.

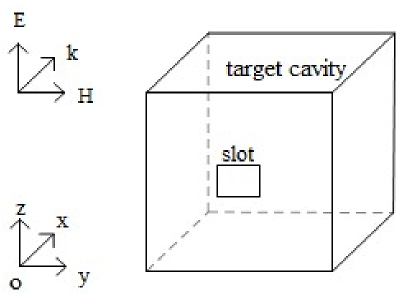

Figure 1. Shielded Cavity Model

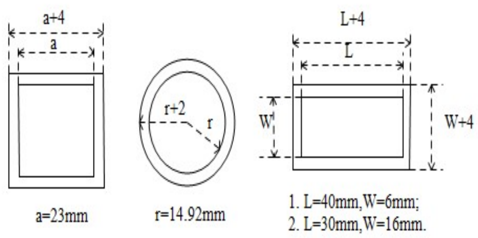

Figure 2. Annular Aperture Model

2.2. FDTD Theory

Finite difference time domain method (FDTD) is an effective numerical method for solving electromagnetic field problems [15]. It uses the central finite difference formula to replace the differential formula of Maxwell time domain curl equation to get the finite difference formula of field components, and it uses space grids with the same electrical parameters to simulation the object of study, set the appropriate boundary condition, solving the Maxwell equation, so as to obtaining the electric field distribution in grid space. When the incident electromagnetic pulse spreads to the surface of the shielded cavity with aperture, electromagnetic scattering occurs on the surface of the shielded cavity, the penetration phenomenon occurs in the aperture. Electromagnetic scattering and penetrate process satisfy the Maxwell equations. Therefore, the problem of solving aperture coupling is actually the problem of solving the passive Maxwell equations.

This method transforms the Maxwell curl equation into finite difference formula, and it establishes the increasing sequence of discrete time, to alternately calculate the electric field and magnetic field in the three dimensional space gird. It distributes the electric and the magnetic field of the space in grid form, and it uses the finite difference equations of second order accuracy central difference approximation to replace the Maxwell equations which depend on the time variables. Then equations can be solved with initial conditions and absorbing boundary conditions according to the time step progressive method, so as to obtaining the electromagnetic field distribution in the space. Using second order finite difference center formula to represent partial derivative of function to time and space, the following FDTD differential equations can be obtained (for example, in the z direction), as in formula (1).

$$\begin{aligned} H_z^{n+\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k) &= H_z^{n-\frac{1}{2}}(i+\frac{1}{2}, j+\frac{1}{2}, k)+\frac{\Delta t}{\mu}[\frac{E_x^n(i+\frac{1}{2}, j+1, k)-E_x^n(i+\frac{1}{2}, j, k)}{\Delta y} \\ &\quad -\frac{E_y^n(i+1, j+\frac{1}{2}, k)-E_y^n(i, j+\frac{1}{2}, k)}{\Delta x}] \\ E_z^{n+1}(i, j, k+\frac{1}{2}) &= E_z^n(i, j, k+\frac{1}{2})+\frac{\Delta t}{\varepsilon}[\frac{H_y^{n+\frac{1}{2}}(i+\frac{1}{2}, j, k+\frac{1}{2})-H_y^{n+\frac{1}{2}}(i-\frac{1}{2}, j, k+\frac{1}{2})}{\Delta x} \\ &\quad -\frac{H_x^{n+\frac{1}{2}}(i, j+\frac{1}{2}, k+\frac{1}{2})-H_x^{n+\frac{1}{2}}(i, j-\frac{1}{2}, k+\frac{1}{2})}{\Delta y}] \end{aligned} \quad (1)$$

where i, j, k and n are integers, i, j, k respectively indicate the grid number of the direction x, y, z in grid space, n indicates the number of the time step, μ and ε are the permeability and permittivity of the medium respectively, Δx, Δy, Δz are respectively the mesh size of the direction x, y, z in grid space, Δt represents the time step, $H_z^n(i, j, k)$ and $E_z^n(i, j, k)$ are respectively the magnetic field strength and the electric field strength in point $(i\Delta x, j\Delta y, k\Delta z)$ and n time steps.

In order to numerical stability and convergence, according to the Courant stability condition, the time step should meet:

$$\Delta t \le 1 \Big/ c\sqrt{1/\Delta x^2 + 1/\Delta y^2 + 1/\Delta z^2} \quad (2)$$

where $c = 1/\sqrt{\mu\varepsilon}$ is the speed of the light in the medium, and the mesh size should meet: $\lambda_{\min} \ge 10\max(\Delta x, \Delta y, \Delta z)$, $\lambda_{\min}$ is the minimum wavelength of the incident pulse. In this paper, we choose $\Delta x = \Delta y = \Delta z = 1.5$mm, $\Delta t = \Delta x / c\sqrt{3}$ =2.889×10^{-12}s.

2.3. Excitation Source

Currently, there are many types of excitation sources. The nuclear electromagnetic pulse (NEMP), the fast rise-time electromagnetic pulse (FREMP) and the ultra-wideband electromagnetic pulse (UWB) are all excitation sources, but there is a large difference in the mechanism of the generation and the waveform parameters. Nuclear electromagnetic pulse is generated by nuclear explosions. It has a strong amplitude and high spectrum. FREMP is an electromagnetic pulse that its rise forefront time belongs to the order of subnanosecond and its pulse width belongs to the order of nanoseconds. It has wide spectrum and rise fast, and it is a serious damage to the electronic system. Compared with NEMP and FREMP, the UWB electromagnetic pulse has a wider spectrum, and the high frequency components of it are richer. It is easier to realize no carrier emission of UWB electromagnetic than the other excitation sources, and the emission efficiency is also higher. UWB electromagnetic pulse coupling into the aperture is a common and difficult protection mode. So the UWB electromagnetic pulse is used as excitation source in this paper. The gaussian pulse is used to simulation it, and the time domain expression of the gaussian pulse is:

$$E_i(t) = E_0\exp[-4\pi(t-t_0)^2 / \tau^2] \quad (3)$$

Where $E_i(t)$ is the electric field strength of the incident gaussian pulse, E_0 is the maximum amplitude of the pulse, t_0 determines the moment of pulse peak, τ determines the pulse width. E_0 =1000V/m, t_0 =1.23×10^{-10}s, τ =9.4×10^{-11}. The pulse duration is about 128ps, the pulse width is about 87ps. The target cavity is set in the far field region of the source of the incident pulse. The incident pulse goes along the x axis direction and it is perpendicular to the yz plane. The electric field polarization is vertical polarization, and the polarization direction is the z axis direction.

2.4. Coupling Coefficient

The frequency domain characteristics can be obtained by the Fourier transform for the electric field to observe the effect of the electromagnetic pulse coupling into the annular aperture. The electric field shielding coefficient varied with frequency is defined in formula (4).

$$SE = 20\lg\left| E_i(f) / E(f) \right| \quad (4)$$

Where SE is the shielding coefficient, $E(f)$ is the electric field strength in frequency domain when the cavity does not exit, $E_i(f)$ is the electric field strength in frequency domain when the cavity exists.

The resonant frequency of rectangular cavity is shown in formula (5):

$$f = 0.5c\sqrt{(m/a)^2 + (n/b)^2 + (p/h)^2} \quad (5)$$

Where f is the resonant frequency of the cavity, a , b , c are respectively the length, the width and the height of the cavity, c is the speed of light in the medium, m , n , p are the modes of the resonant wave.

3. Results and Discussion

The electromagnetic coupling into annular apertures which have the same aperture area but different shapes (rectangle, square, circle) are calculated and analyzed respectively to compare the difference of shielding effect between different annular apertures.

3.1 Characteristics of Electromagnetic Pulse Coupling into Circular Annular Aperture

Figure 3 and Figure 4 are respectively electric field waveform of different point on the axis of the cavity. Figure 3 shows the electric field waveform of the place 3cm to circular annular aperture in the cavity. Figure 4 shows the electric field waveform of the center of the shielded cavity. The time required that electromagnetic pulse spreads from the place 3cm to aperutre in the cavity and the center of the cavity to the rear wall of the cavity and then reflects back are approximately 1.13ns and 0.67ns respectively by calculating. It meets the oscillating period of the coupling waveforms as shown in Figure 3 and Figure 4. Therefore, the first pulse in the figure is the main pulse of coupling pulse, and the subsequent pulse is the reflected pulse that the main pulse reflects back from the rear wall of the cavity. Due to the reflection effect of the shielded cavity, the cavity resonance phenomenon of electromagnetic pulse occurs periodically in the cavity. Electromagnetic pulse spreads in the cavity and radiates out from the annular aperture. So after a while, the amplitude of electric field inside the cavity decays. The electric field amplitude of main pulse in Figure 3 is larger than that in Figure 4. It means the closer to the center of the cavity is, the smaller the electric field amplitude of the main pulse is. This phenomenon occurs because the energy of electromagnetic pulse decays while the electromagnetic pulse spreads. The amplitude of electric field in Figure 4 has been enhanced after the main pulse, which is caused by the reflection effect of the rear wall of the shielded cavity. Then the electric field amplitude decays. It is because that the electromagnetic wave radiate outward energy from the annular aperture.

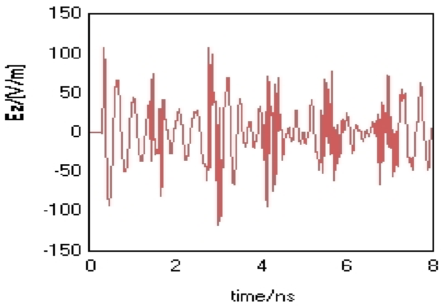

Figure 3. Electric Field of the Place 3cm to the Circular Annular Aperture in the Cavity

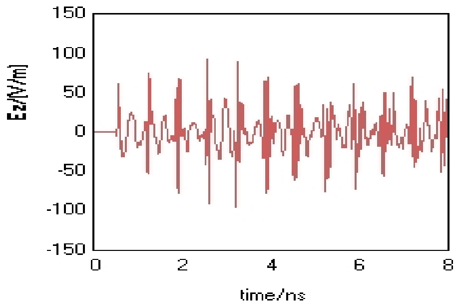

Figure 4. Electric Field of the Center of the Cavity with Circular Annular Aperture

3.2. Characteristics of Electromagnetic Pulse Coupling into Square Annular Aperture

Figure 5 shows the electric field waveform of the place 3cm to the square annular aperture in the cavity. Figure 6 shows the electric field of the center of the cavity with square annular aperture. Comparing Figure 5 and Figure 6 with Figure 3 and Figure 4, we can find that the coupling characteristics of the square annular aperture are similar with the circular annular aperture. The electric field amplitudes of the main pulse of the square annular aperture are a little larger than the circular annular aperture. Therefore, the shielding effect of the circular annular aperture is a little better than the square annular aperture.

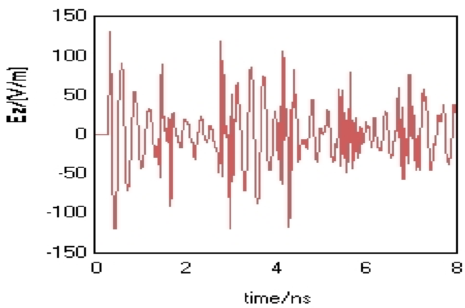

Figure 5. Electric Field of the Place 3cm to the Square Annular Aperture in the Cavity

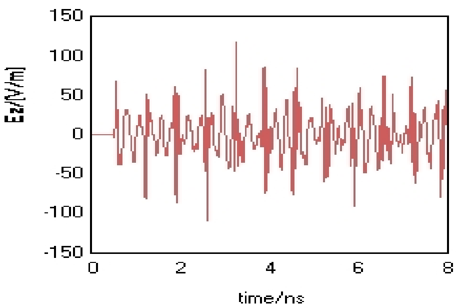

Figure 6. Electric Field of the Center of the Cavity with Square Annular Aperture

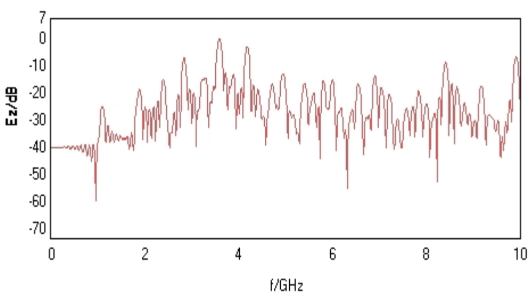

Figure 7. Electric Field in Frequency Domain of the Center of the Cavity

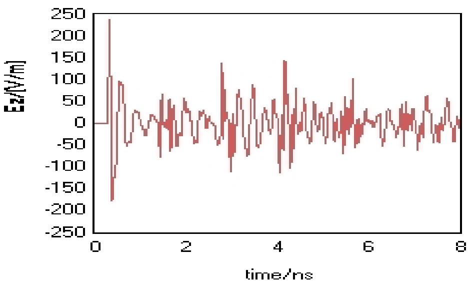

Figure 8. Electric Field of the Place 3cm to the Aperture in the Cavity when L=40MM, W=6mm

The electric field in frequency domain of the center point in the shielded cavity with square annular aperture is shown in Figure 7. Each peak in the figure corresponds to a mode of the cavity. The cavity frequency of the main mode TE_{101} of the shielded cavity calculated by formula (5) is about 1.06GHz. It is visible that the analytical results and the first resonance frequency are consistent. In the shielded cavity, whether low order modes or higher order modes are excited, and when the frequency is higher, the modes are more. At the resonant frequency, shielding effectiveness of the shielded cavity is very poor. As shown in Figure 7, the amplitude of electric field coupled in the high frequency band of 3-10GHz is greater than that in the low frequency band. It means the square annular aperture has a high pass coupling characteristic.

3.3. Characteristics of Electromagnetic Pulse Coupling into Rectangular Annular Apertures with Different Aspect Ratio

We select two kinds of rectangular annular apertures that have the same area but different ratio of length to width as the models to study the coupling characteristics of the rectangular annular apertures with different aspect ratio. The length and width of the two rectangular annular apertures are respectively: L=40mm, W=6mm; L=30mm, W=16mm. The area of the rectangular annular aperture is: $s=$(L+4)(W+4)-LW=200mm^2, as shown in Figure 2. Figure 8 shows the electric field waveform of the place 3cm to the aperture in the cavity with large aspect ratio rectangular annular aperture. Figure 9 shows the electric field waveform of the place 3cm to the aperture in the cavity with small aspect ratio rectangular annular aperture. The electric field amplitudes of the main pulse coupled are about 240V/m and 150V/m respectively. Therefore, the larger the ratio of length to width of the rectangular annular aperture is, the more easily the incident pulse coupled into is.

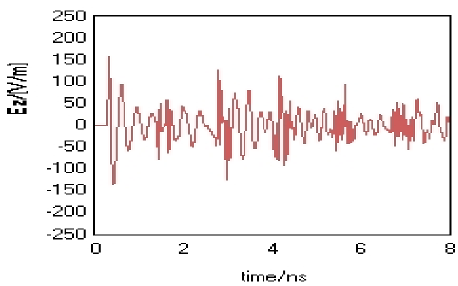

Figure 9. Electric Field of the Place 3cm to theAperture in the Cavity when L=30MM, W=16mm

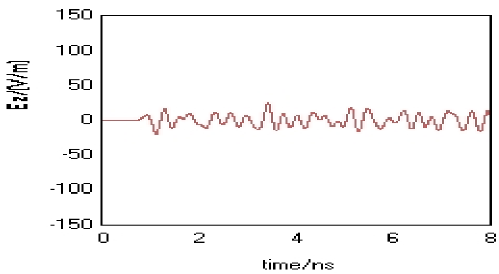

Figure 10. Electric Field of the Center of the Cavity when Pulse width is 500ps

3.4. Coupling Characteristics of Electromagnetic Pulse With Different Pulse Width

We select the gaussian pulse with approximately 500ps pulse width as the incident electromagnetic pulse and the square annular aperture as the aperture model, and record the electric field waveform of the center point of the cavity, as shown in Figure 10. Then we compare Figure 10 with the electric field waveform in Figure 6. The maximum amplitude of the electric field is about 110V/m when the pulse width of incident electromagnetic pulse is 87ps, and it is only 20V/m when the pulse width is 500ps. Therefore, the incident electromagnetic pulse with short pulse width is more easily to couple into the small annular aperture than the pulse with longer pulse width.

4. Conclusion

In this paper, the FDTD method is employed to study the characteristics of electromagnetic pulse coupling into the cavity enclosures with annular apertures. The coupling characteristics of annular apertures with different shapes and the electromagnetic pulse with different pulse width are discussed. The research shows that, the resonance phenomenon occurs after the incident pulse coupling into the shielded cavity. The shielding effectiveness of the shielded cavity is very poor at the resonant frequency point, and we should make the response frequency of the circuit avoid the resonant frequency of the shielded cavity when we design the circuit. The electric field in the shielded cavity is not uniform, and the amplitude of the electric field near the aperture is larger than the other places, so the electric equipments in the shielded cavity should be placed in the position away from the annular aperture. For the three kinds of shapes (rectangle, square and circle) of annular apertures with the same area, the coupling energy of the square annular aperture and the circular annular aperture is obviously smaller than the rectangular annular aperture, and the coupling energy of circular annular aperture is a little smaller than the square annular aperture, and the square annular aperture has a high pass coupling characteristic. The incident electromagnetic pulse with short pulse width is more easily coupled with the small annular aperture than the pulse with longer pulse width. When the polarization direction of the incident electromagnetic pulse is perpendicular to the longer side of the rectangular annular aperture, the coupling energy is larger when the ratio of length to width of the rectangular annular aperture is larger.

The contents of this paper have a certain significance on enhancing the capability of anti-electromagnetic interference of the electronic system. Therefore, the shape and the size of the annular aperture on shielded caviy should be properly set according to the conclusions so that the harm of electromagnetic pulse to the electronic system is minimized.

Acknowledgements

This work was supported by the Aeronautical Science Foundation of China (Grant No. 2011ZC54009), the Science and Technology Foundation of Liaonong Province of China (Grant No. 201202171) and the Application Foundation Research of Shenyang of China (Grant No. F11-264-1-04).

References

[1] Zhang W. The Electromagnetic Interference Model Analysis of the Power Switching Devices. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(1): 167-172.
[2] Konefal T, Dawson JF, Marvin AC. A Fast Multiple Mode Intermediate Level Circuit Model for the Prediction of Shielding Effectiveness of a Rectangular Box Containing a Rectangular Aperture. *IEEE Trans on Electromagnetic Compatibility*. 2005; 47(4): 678-691.
[3] Bethe HA. Theory of Diffraction by Small Holes. *Phys Rev*. 1944; 66(10): 163-182.
[4] CJ Bouwkamp. On Bethe Theory of Diffraction by Small Holes. *Philips Res.Rep*. 1950; 3: 321-332.
[5] Harrington RF, Mautz JR. A Generalized Network Formulation for Aperture Problems. *IEEE Trans on Antennas and Propagation*. 1976; 26(3): 870-874.
[6] Sarhan M Musa, Matthew NO Sadiku. Finite Element Approach for Coupled Striplines Embedded in Dielectric Material. *TELKOMNIKA*. 2013; 11(1): 47-54.
[7] EVC Sekhara Rao, PVN. Prasad. FEM Analysis of PMH Stepper Motor Using PDETOOL Simulations of Matlab for Different Topoligies. *TELKOMNIKA*. 2012; 10(4): 680-686.
[8] Li M, Nuebel J, Drewniak JL, et al. EMI from Cavity Modes of Shielding Enclosures-FDTD Modeling and Measurements. *IEEE Trans on Electromagnetic Compatibility*. 2000; 42(2): 29-38.
[9] Georgakopoulos SV, Birtcher CR, Balanis CA. HIRF Penetration Through Apertures: FDTD Versus Measurements. *IEEE Trans on Electromagnetic Compatibility*. 2001; 43(3): 282-294.
[10] Siah ES, Sertel K, Volankis J, et al. Coupling Studies and Shielding Techniques for Electromagnetic Penetration Through Apertures on Complex Cavities and Vehicular Platforms: *IEEE Trans on Electromagnetic Compatibility*. 2003; 45(2): 245-256.
[11] Lu YH. Numerical Methods in Computational Electromagnetic. Beijing: Tsinghua University Press. 2006.
[12] An J, Wu JF, Wu YH. Influence of Apertures on Shielding Effectiveness for Shell of Loaded PCB. *Journal of Microwaves*. 2011; 27(2): 34-37.
[13] Meng PW, Liu YF, Gu MM. Influence of Enclosure Holes or Slots on Electromagnetic Shielding Effectiveness. *Modern Electronics Technique*. 2012; 35(13): 155-158.
[14] Li CR, Wang XZ, Cui YF, Zhao ZJ. The Characteristics Analysis of Electromagnetic Pulse Coupling Through Wing-slot of Missile. *Journal of Projectiles, Rockets, Missiles and Guidance*. 2012; 32(3): 79-144.
[15] Ge DB, Yan YB. Finite-Difference Time-Domain Method for Electromagnetic Waves. Xi`an: Xi`an Electronic and Science University Press. 2002.