Simulation and Analysis of HEMP Coupling Effect on Wires Inside a Cylindrical Shielding Cavity with Apertures

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Abstract: High altitude nuclear electromagnetic pulse (HEMP) can damage electronic equipments of radar and communication systems. Back door coupling is one of the main ways of HEMP attacks on the electronic devices. In this paper, using the transmission line matrix (TLM) method, based on the three-dimensional electromagnetic (EM) simulation software MicroStripes 7.5, we investigate the problem of the HEMP coupling effect on wires inside a shielding cavity with apertures. The EM model of a wire and a cylindrical shielding cavity with apertures is constructed, and the induced wire circuits through apertures of cavity is simulated and analyzed. By comparing the simulation results of wire with and without shield of the cavity, respectively, the shielding effectiveness is obtained. Further, the affect of single-aperture and multiple-aperture on the induced wire circuits is compared and analyzed.

Keywords: HEMP, EM Simulation, Wire, Shielding Cavity, Aperture

1. Introduction

With the miniaturization of electronic and electrical equipments and systems, the electronic equipments become more sensitive and vulnerable to electromagnetic pulses (EMP). High altitude nuclear electromagnetic pulse (HEMP) is produced by nuclear explosion at high altitude, characterized by intense electric field strength, short duration, wideband frequency coverage and wide range coverage, which can damage electronic equipments of radar and communication systems, inculding wires, crystal diodes, transistors, integrated circuits resistors, capacitors, filters, relays and other components. HEMP protection technologies and methods [1] have become one of the most important research fields in many applications.

Back door coupling through apertures is one of the main ways of HEMP attacks on the electronic devices. Some literatures have studied the methods of wire coupling effects of electromagnetic pulse. For example, the electromagnetic field energy flow on a thin wire is measured using Hallén integral equations [2]. Resonance of the wire is formulated using the theory of the linear antenna [3]. A ‘diffuse-field reciprocity principle’ has been applied to electromagnetic (EM) systems, enabling the currents induced in a wiring system to be computed in an efficient manner [4].

However, these researches focus on the coupling effects of unshielded wire. In practice, wires are often in enclosure by a shielding cavity for the electromagnetic pulse pretection. Inevitably, if the shielding cavity has some apertures, the wire induced circuits will be produced through aperture coupling.

For aperture coupling, some methods have been proposed. The coupling coefficient of different apertures in the range of 2-18GHz is researched using the experimental method [5]. EMP coupling rules of different apertures is also researched, and the rules of coupling energy is discussed in the condition of different polarization [6]. The process of high power microwave pulse coupling to the holes with finite thickness has been researched with the simulation method [7]. The fast prediction of the electromagnetic shielding performances of aperture loaded by resistive thin film coatings is investigated [8].

For the shielding effectiveness of a cavity, rectangular shielding cavity has been mostly studied so far, but few for the cylindrical shielding cavity. For example, the shielding effectiveness is evaluated for a rectangular enclosure with numerous apertures [9].

In the paper, based on the transmission line matrix (TLM) method, we investigate the problem of the HEMP coupling effect on the wire inside a cylindrical shielding cavity with apertures by using MicroStripes 7.5, a three-dimensional EM simulation software. We first construct the EM models of a wire and a cylindrical shielding cavity with apertures, and then simulate and analyze the induced wire circuits through apertures on the cavity. The results of two cases that the wire is shielded and not shielded by the cavity are compared, then the shielding effectiveness is obtained. Further, the affect of the number of apertures on the induced wire circuits is compared and analyzed. The conclusion is given finally.

2. EM Simulation Software and TLM Method

Three-dimensional EM simulation software, MicroStripes7.5, is used in this paper to analyze the HEMP coupling effect on wires located in a shielding cavity with apertures. MicroStripes7.5 adopts the transmission line matrix (TLM) method.

TLM method [10] is a time-domain, differential numerical technique for modelling electromagnetic and other field problems. Its computational efficiency, stability, and calculation accuracy have all been well proven. TLM has some advantages over frequency domain finite-difference time-domain (FDTD). Firstly, it can calculate electric and magnetic fields on exactly the same mesh, without the half cell offset characteristic of FDTD. Also, TLM is unconditionally stable, the timestep being determined by the mesh resolution.

MicroStripes7.5 software has been widely used in vehicles, ships, aviation, and also used in evaluation of human absorption of electromagnetic fields, to solve the issues of antenna design, installation performance assessment, RF or microwave devices, radar cross section (RCS), electromagnetic compatibility (EMC), electromagnetic interference (EMI), electromagnetic pulse (EMP) , and lightning strikes and other issues.

3. HEMP Waveform

HEMP waveform standards promulgated by the standard of MIL-STL-461F [11] is adopted in this paper, the electric field description can be expressed as

$$E(t) = kE_p(e^{-\alpha t} - e^{-\beta t}) \tag{1}$$

where $k = 1.3$, $E_p = 50kV/m$, $\alpha = 4\times10^7 s^{-1}$, $\beta = 6\times10^8 s^{-1}$.

We take an observation point in infinite space near the ground, and HEMP waveform at the point in time domain and frequency domain can be simulated by MicroStripes7.5, as shown in Fig. 1.

The HEMP energy mainly focuses on the frequency range of 200 ~ 300*MHz*, and the energy is low when the frequency is over 3GHz. Therefore, the following simulation and analysis of electric field strength is within the frequency range of 0~3GHz.

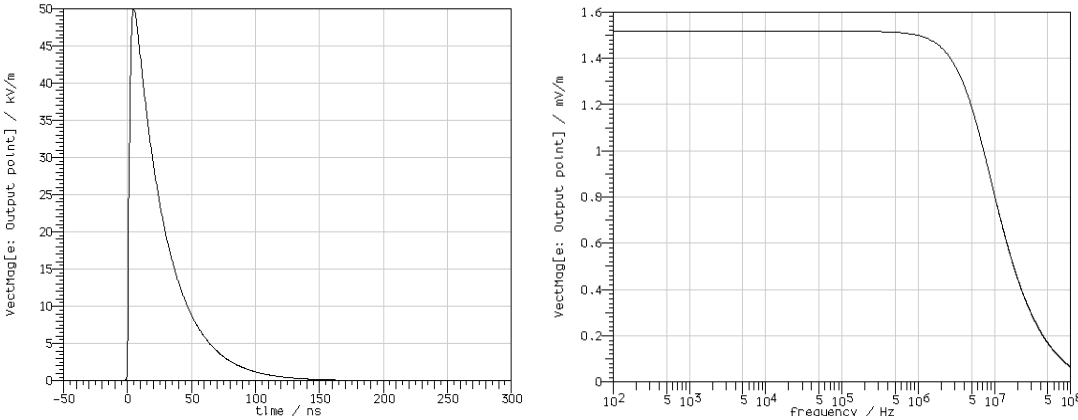

Fig. 1 HEMP waveform in time domain and frequency domain described by MIL-STL-461F standard.

4. Simulation Modeling and Analysis of Wire Circuit in a Cylindrical Shielding Cavity

A. Simulation Model

In this section, a wire with radius of 0.25mm is modeled in the EM simulation. The wire is assumed to be an ideal conductor line, so its resistivity $\gamma \to 0$, its length is 13 cm, being placed parallel to the ground, and the height is 6.8cm above the ground.

First, we place the wire without a shield of the cavity. The model built using the simulation software is shown in Fig. 2.

Secondly, we place the wire with a shield of the cavity with an aperture. The size of a cylindrical cavity is as follows: its bottom radius is 5cm, its height is 20cm, and its wall thickness is 0.5cm. On the bottom of the cavity there is a rectangular aperture with the size 0.5cm$\times$3cm. The wire is insulately placed inside the cavity. The model is shown in Fig. 3.

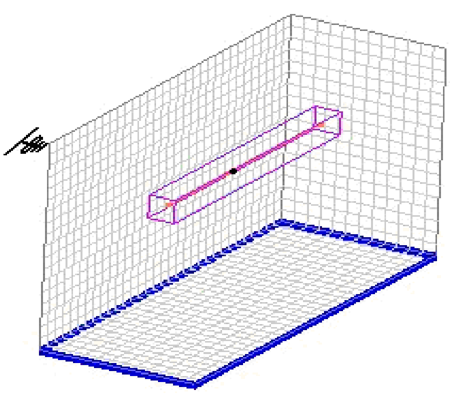

Fig. 2 The model of the wire.

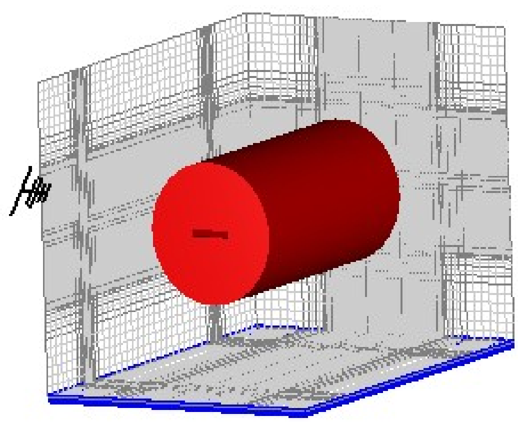

Fig. 3 The model of the cavity with a wire inside.

In the simulation, the incident angle of HEMP is configured as $10°$ such that the induced current on the wire is the largest. We take two observation points on the wires in Fig. 2. and Fig. 3, respectively. The observation point on the wire without the cavity is named Ioutput1, and the observation point on the wire inside the cavity is named Ioutput2.

B. Results Analysis

The time-domain waveforms of Ioutput1 and Ioutput2 are shown in Fig. 4 and Fig. 5, respectively.

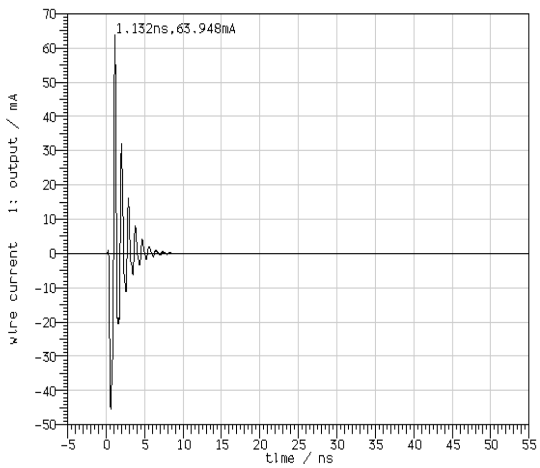

Fig. 4 Ioutput1`s current waveform in time domain.

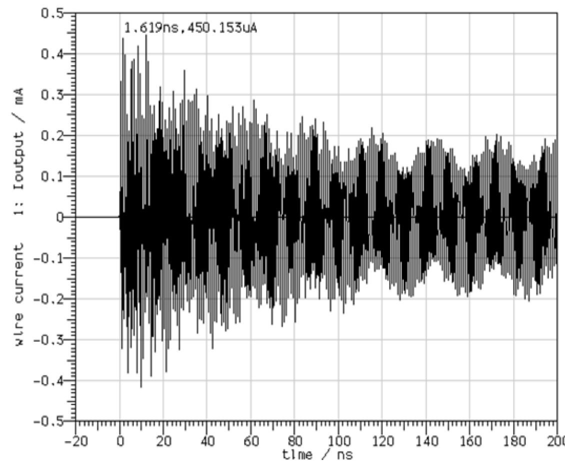

Fig. 5 Ioutput2`s current waveform in time domain.

Since the induced current on the wire bounces back and forth, the oscillation waveform is formed, as shown in the above figures. With the wire length increasing, the induced current oscillation period also increases. The maximum oscillation amplitude at Ioutput1 point is 63.948*mA*, occurred at the time of 1.132*ns*, and then decay gradually to zero after 10*ns*.

The current in the wire inside the cavity is mainly high-frequency oscillating current, this is caused by the reflection of the cavity wall. Electromagnetic pulse energy couples to the cavity shielding and generates resonance. Then in the wire induces the high-frequency oscillatory current. In the initial time, the amplitude of oscillation current is high, the maximum amplitude is 450.153*μA*.

Therefore, compared with the wire without a shield of the cavity, the induced current is decreased by 21.5dB, which is shown as the shielding effectiveness.

The frequency-domain waveforms of Ioutput1 and Ioutput2 are shown in Fig. 6 and Fig. 7, respectively.

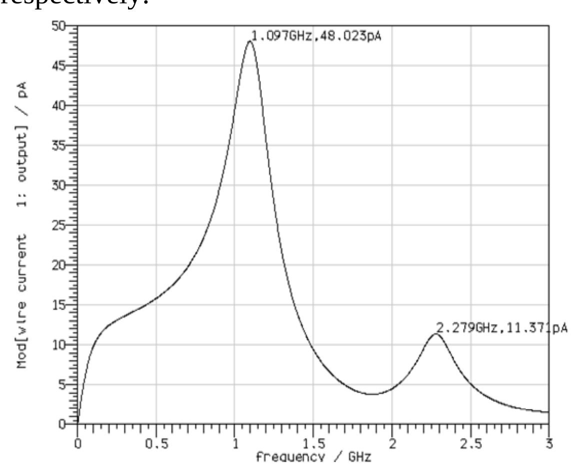

Fig. 6 Ioutput1's current waveform in frequency-domain.

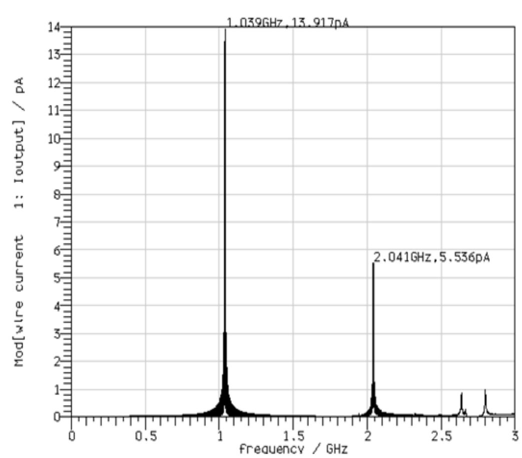

Fig. 7 Ioutput2's current waveform in frequency-domain.

By analyzing the frequency-spectrum, we can see that within the frequency-range of 0~3GHz, the optimal coupling frequency is between 1.0 GHz ~ 1.10GHz and 2.25GHz ~ 2.3GHz. By comparing the two figures, we can also see that, because the wire inside the cavity is shielded, the frequency current components coupled into the wire is much less than the case of the wire without shielding cavity. From this, we know that the cavity with aperture plays a very good role of protection. But in practice, specific evaluation of protective levels is based on the damage threshold of the electronic equipment inside the cavity.

5. Simulation and Analysis of the Impact of the Numbers of Apertures

A. Simulation Model

This section is primarily based on two models to compare the impact of different numbers of apertures on the induced current. The two models are shown in Fig. 8 and Fig. 9, respectively.

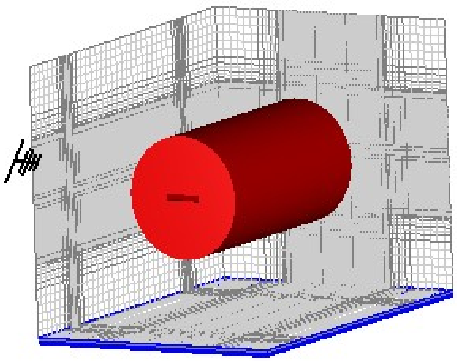

Fig. 8 Single aperture.

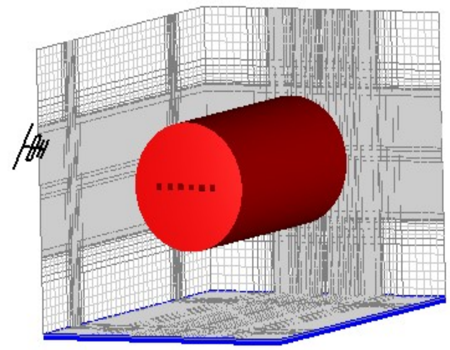

Fig. 9 Multiple apertures.

The cavity material in both Fig.8 and Fig.9 is iron. Its bottom radius is 5cm, its height is 20cm, and its wall thickness is 0.5cm. The size of the rectangular aperture in the first model is 0.5cm$\times$3cm. The apertures in the second model are composed of six same squares with side length of 0.5cm, the total area of which is the same as the first one. The incident angle of HEMP is still configured as $10°$. Inside the cavity, insulately places a wire having the same parameters with the wire in section 4.

B. Results Analysis

Fig. 10 and Fig. 11 show the time-domain current waveforms of the wire inside the cavities with single aperture and multiple apertures, respectively.

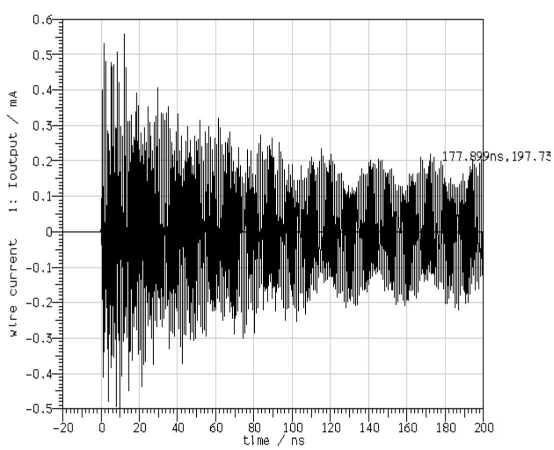

Fig. 10 Wire current waveform in single-aperture cavity.

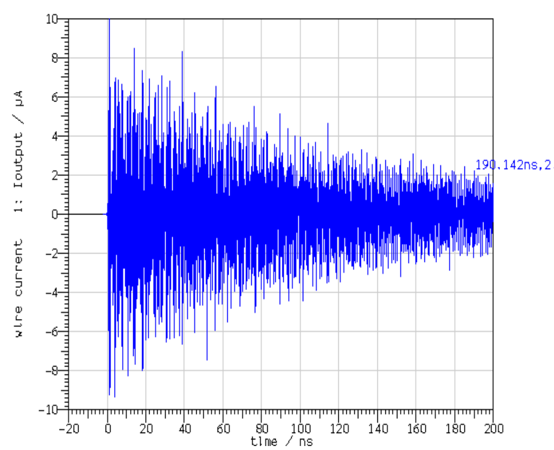

Fig. 11 Wire current waveform in multiple-aperture cavity.

The maximum coupling current peak of the wire inside the cavity with single-aperture is 2.8*mA*. However, the maximum value inside the cavity with multiple-aperture is less than 10μA, the shielding effectiveness of which is 24dB higher than that of the single-apertured cavity.

6. Conclusion

In the paper, we use the EM simulation software MicroStripes7.5 to simulate the environment of HEMP, modeling and analyzing the effect of HEMP coupling on the wire inside the shielding cavity through apertures on the cavity. When adopting the model used in this experiment, the induced currents on the wire inside the shielding cavity decreases about 21dB compared with the wire without cavity. Aperture characteristic is the main factor which determine the strength of HEMP coupling to the cavity. When the total area of the aperture is the same, the coupling coefficient of multiple-apertured cavity is much better than that of single-apertured cavity, decreasing about 24dB.

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