FDTD SIMULATION OF ELECTROMAGNETIC FIELDS DUE TO SPARK BETWEEN CHARGED METAL BARS WITH FERRITE CORE ATTACHMENT

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Abstract: The electromagnetic fields due to electrostatic discharge (ESD) between charged metals cause serious damage to high-tech equipment. For the purpose of reducing such ESD fields, we previously calculated the ESD fields due to a spark between the charged metals with ferrite core attachment, using the finite-difference time-domain (FDTD) method, and showed that the core attachment is effective in suppressing the ESD fields. In the present study, using our previously proposed FDTD algorithm based on a spark-resistance formula, we simulated both of the ESD and the resultant fields for the metal bars with ferrite core attachment, and demonstrated that the core attachment close to the discharge gap suppresses the magnetic filed level. This finding was also validated by measuring the magnetic fields.

Key words: ESD, metal bars, electromagnetic fields, ferrite core, FDTD algorithm.

1. Introduction

It has widely been recognized that the electromagnetic (EM) fields due to electrostatic discharge (ESD) have broadband frequency spectra over the microwave region [1], which gives serious damage to high-tech information devices.

For the ESD fields, considerable efforts specifically on analytical aspects [2]-[5] have been made, while the effects of metals on the ESD fields were unclear. We therefore analyzed the EM fields caused by the spark between spherical metals, using the finite-difference time-domain (FDTD) method, which was based on gap excitation by the source of a spark current or voltage, and revealed that the metals enhance the field level according to the metal dimension [6].

Furthermore, paying attention to ferrite material being commonly used for electromagnetic interference (EMI) countermeasures, we calculated the ESD fields due to the metal bars with ferrite core attachment, also with the same FDTD method, and showed that the core attachment near to the discharge gap suppresses the ESD filed level [7]. This finding, however, was confirmed by measuring not the ESD fields but the detection frequencies of the electric far-field with a commercially available ESD detector and by demonstrating that the core attachment reduces the detection distance.

In this paper, using the previously proposed FDTD algorithm based on a spark resistance formula [8], we simulated both of a spark between the metal bars with ferrite core attachment and the resultant ESD fields. The effect of the core attachment location on the ESD fields is examined, which is also validated by measuring the ESD fields.

2. FDTD Simulation

2.1 ESD Model

Figures 1(a) and 1(b) show an ESD model between the metal bars attached by ferrite cores and its FDTD model, respectively. Two cylindrical metals with a radius of $r$ and a length of $L$ were used and they were spaced at a gap of $l$. Two commercially available ferrite cores being frequently used for EMI countermeasures were attached to the cylinders as shown in Fig. 1(a). They had an internal diameter of $2d$, an external diameter of $2D$ and a length of $s$. For the FDTD model, the metal bars and ferrite cores were constructed by small cubic cells with a side of 0.5 mm. When the spark between the gap occurs, the metal bars emits the EM fields, which are calculated from the FDTD method.

2.2 Ferrite Core

Concerning the EM fields inside the ferrite core, we calculate them using the FDTD algorithm in

![Fig.1](image-url)
Ref. [7], which will be briefly described here.

We assume that the complex relative permeability
μ of the ferrite core used for EMI countermeasures follows the Naito's proposed frequency dispersion equation [9], which is given by
\[
\mu(j\omega) = \mu_0(1 + \frac{\mu_n}{1 + j\omega/\omega_s})
\]  
(1)

where \( \mu_0 \) is the permeability of free space, \( \mu_n \) is the initial relative permeability related to the spin rotation motion of the ferrite core and \( \omega_s \) is the spin resonance angular frequency.

In the FDTD computation, substituting Equation (1) into the following equation:
\[
B = \mu(j\omega)H
\]  
(2)
and then transforming this into the time domain, we have
\[
\frac{1}{\omega_s} \frac{\partial B}{\partial t} + B = \frac{\mu_0}{\omega_s} \frac{\partial H}{\partial t} + \mu_0(1 + \mu_n)H .
\]  
(3)

Denote by \( \delta x = \delta y = \delta z = \delta t \) the difference interval of space, and by \( \delta t \) the difference interval of time. Let the difference function of \( W = W(x, y, z, t) \) be
\[
W^*(i, j, k) = W(i\delta x, j\delta y, k\delta z, n\delta t) .
\]  
Assuming that the spark discharge between the cylindrical metals as shown in Fig. 1 (a) occurs in the z-direction, we have the z-component of the magnetic fields, for example, given by
\[
H_z^{n\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}, k) =
\]
\[
\frac{1}{1 + (1 + \mu_n(i + \frac{1}{2}, j, k + \frac{1}{2}, k))\omega_s(i + \frac{1}{2}, j, k + \frac{1}{2}, k)\delta t}
\]
\[
\{ H_z^{n\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}, k)
\]
\[
+ \omega_s(i + \frac{1}{2}, j, k + \frac{1}{2}, k)\delta t
\]
\[
\frac{1}{\mu_0(i + \frac{1}{2}, j, k + \frac{1}{2}, k)} B_z^{n\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}, k)
\]
\[
-B_z^{n\frac{1}{2}}(i + \frac{1}{2}, j, k, k + \frac{1}{2}, k)
\]  
(4)

\[
B_z^{n\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}, k) = B_z^{n\frac{1}{2}}(i + \frac{1}{2}, j, k + \frac{1}{2}, k)
\]
\[
+ \frac{\delta t}{\delta t}(E_z(i + \frac{1}{2}, j, k + \frac{1}{2}, k) - E_z(i + \frac{1}{2}, j, k))
\]
\[
- \frac{\delta t}{\delta t}(E_z(i + \frac{1}{2}, j, k + \frac{1}{2}, k) - E_z(i, j, k + \frac{1}{2}, k)).
\]  
(5)

The values of \( \mu_n \) and \( \omega_s \) in Equation (4) have those of the medium equivalent to each of the cells for the ferrite cores, and they thus become zero except the cells constructing the model of the ferrite cores.

2.3 Spark Channel

Figures 2(a) and 2(b) show the spark discharge between the charged metal bodies and the FDTD model for the spark channel, respectively. Here \( l \) is the gap length, \( i(t) \) the spark current at time \( t \) and \( v(t) \) the breakdown voltage. When the spark discharge occurs between metal bodies in the direction of \( z \) as shown in Fig. 2(b), we then have the resultant EM fields: \( E_x, E_y, \) and \( E_z \) are electric fields in \( x, y, \) and \( z \)-directions, respectively, and \( H_x, H_y, \) and \( H_z \) are magnetic fields in \( x, y, \) and \( z \)-directions, respectively. \( \delta x, \delta y, \) and \( \delta z \) are the sizes of the FDTD cell in \( x, y, \) and \( z \)-directions, respectively.

Based on the Rompe-Weizel formula for the spark resistance, the time varying conductivity \( \sigma(t) \) of the spark channel can be expressed as
\[
\frac{\partial \sigma(t)}{\partial t} = \frac{\alpha}{p} \sigma(t) E_x(t)^2
\]  
(6)
where \( p \) is the pressure of atmosphere that surrounds the electrical discharge part, and \( \alpha \) is a spark constant of \( \alpha = 1.1 \times 10^{-9} \text{atm} \times \text{m}^2/\text{N}^2 \times \text{s} \) [8]. Discretizing Equation (6) in terms of time and space, we have
\[
\sigma^{n+\frac{1}{2}}(i + \frac{1}{2}, j + \frac{1}{2}, k) =
\]
\[
2 + \frac{\alpha}{p} \frac{\partial E_x(i + \frac{1}{2}, j + \frac{1}{2}, k)}{\partial t} + \frac{\partial E_x(i, j + \frac{1}{2}, k)}{\partial t}
\]
\[
- 2 - \frac{\alpha}{p} \frac{\partial E_x(i + \frac{1}{2}, j + \frac{1}{2}, k)}{\partial t} + \frac{\partial E_x(i, j + \frac{1}{2}, k)}{\partial t}
\]

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where $\Delta t$ is the time step, and then the difference function of the electric field $E_x$ in the spark channel is given by

$$E_x(i+\frac{1}{2}, j+\frac{1}{2}, k) - E_x(i-\frac{1}{2}, j+\frac{1}{2}, k)$$

\[
\times \sigma^{n+1/2}(i, j, k)\]

\[
\Delta t \left(2E_x(i+\frac{1}{2}, j+\frac{1}{2}, k) + \sigma^{n+1/2}(i+\frac{1}{2}, j, k)\right)
\]

$$2E_x(i+\frac{1}{2}, j+\frac{1}{2}, k) + \sigma^{n+1/2}(i+\frac{1}{2}, j, k)$$

\[
+ \frac{1}{\Delta t} \left(2E_x(i+\frac{1}{2}, j+\frac{1}{2}, k) + \sigma^{n+1/2}(i+\frac{1}{2}, j, k)\right)
\]

$$\times \left[ H_y^{n+1/2}(i, j+1, k) - H_y^{n+1/2}(i, j, k)\right]$$

$$+ H_y^{n+1/2}(i, j, k) - H_y^{n+1/2}(i, j+1, k)\right].$$

The spark discharge was simulated separately in the process of charging and discharge. For the charging step, we injected a Gaussian pulse current $i(t)$ through the gap to reach the steady voltage between the metal objects, which also enables one to calculate the EM fields in space from the conventional FDTD method. For the discharge step, denote by $l$, the charging current when the charge finished, and by $V$, the spark voltage when the gap breakdown happened at time $t=0$, corresponding to the steady voltage in the charging process. Then the initial conductivity and initial electric field inside the channel are given by $\ell/\varepsilon^2 \cdot I_0/V$ and $V/\ell/\varepsilon$, respectively. Based on Equation (7) with these initial values, the spark discharge occurring between the metal bars can be simulated, which enables one to calculate the EM fields in space.

3. Experimental Verification

In order to validate the above-mentioned FDTD algorithm and also to examine the effect of the ferrite core attachment on the ESD fields, we calculated the magnetic field due to the ESD event as shown in Fig.1(a), and then compared the result with the measured ones by a spark experiment.

Figure 3 shows the FDTD computation region and arrangement of cylindrical metal bars. The region consisted of 320 x 113 x 505 cells with $\Delta = 0.5$ mm. The following three cases for the FDTD model were considered: the first model without any ferrite cores, the second and third models with the ferrite cores attached to the near end (side A) and to the far end side B) of the gap, respectively. Twelve perfectly reflected layers were used to absorb outgoing scattered waves for simulating an open space.

Figure 4 shows an experimental set up. An ignition coil driven by an electronic circuit generated a high voltage, which was led to the metal bars through carbon strings (250Ω/cm) with a length of 60 cm. The transient magnetic field due to the spark discharge was measured with a shielded loop antenna (outside diameter: 1.2 mm; loop diameter: 5 mm; loop area: $S = 78.5$ mm$^2$; Inductance: $L = 13.8$ nH), whose output terminal was connected to a wideband digital oscilloscope (input impedance: $Z = 50$ Ohm; bandwidth: $f = 6$ GHz; sampling frequency: 20 GHz).

The spark voltage $V$ was simultaneously measured through a high voltage probe with a digital phosphor oscilloscope with a bandwidth of 500 MHz. All these devices were set up on a wooden desk with a height of 0.8 m from the floor.

Figure 5 shows the voltage waveforms $v(t)$ observed through the shielded magnetic field probe. The solid and dotted lines are the calculated and measured results, respectively. The observed output waveform $v(t)$ in this experiment was calculated from the following equation:

$$v(t) = -\frac{R_i}{L_i} \times \int_0^\infty \frac{\partial S}{\partial \tau} \mu_0 H_\tau(\tau) \exp \left(-\frac{R_i}{L_i} (t - \tau) \right) d\tau.$$  

(9)

where $R_i (= 50$ Ohms) is the input impedance of the oscilloscope and $S$ is the probe area. $H(\tau)$ is
Using the previously proposed FDTD algorithm based on the spark resistance formula, we simulated the magnetic field due to the spark between metal bars with an attachment of EMI ferrite cores. For the FDTD calculation of the fields inside the ferrite core, we used the Naito’s formula for the relative complex permeability. As a result, we have confirmed that the previous proposed FDTD algorithm enables one to simulate the ESD event also in this case, and that the ferrite core attachment to the near end of the discharge gap is effective in suppressing the ESD fields.

Future subjects include the improvement of the FDTD simulation accuracy and mechanism elucidation of the field suppression effects due to ferrite core attachment.

## References


