Analysis of Wideband Electromagnetic Field Penetration into a Multiply Slotted Metal Plate Coated with a Ferrite Sheet

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This paper presents a rigorous analysis of electromagnetic field penetration into multiple slots on a metal plate loaded with a ferrite sheet having frequency-dependent complex permeability. The Fourier transform is used to represent the electromagnetic fields in the spectral domain and the mode matching technique is enforced to obtain a solution in rapidly converging series form, leading to numerically efficient results. Shielding effectiveness of electric and magnetic fields are investigated in terms of the geometrical parameters of multiple slots and ferrite sheet with frequency-dependent magnetic permeability.

***Index Terms*—Electromagnetic shielding, electromagnetic pulse, ferrite sheet, frequency-dependent complex permeability, slots.**

I. INTRODUCTION

WITH the recent increasing threat from wideband electromagnetic pulse (EMP) such as a high-altitude electromagnetic pulse (HEMP) and ultrawideband (UWB) pulse, the wideband electromagnetic shielding becomes more and more important for designing commercial electronic equipments as well as military shelters. Most shielding structures inevitably have seams or joints where edges of the metallic panels overlap or join. The leakage of electromagnetic fields through the seams or joints should be under control to ensure the shielding performance in a wideband-frequency range from DC to several gigahertz. Many papers have dealt with electromagnetic shielding in both static and time-varying situations. At high-frequency range, the shielding characterization for metallic enclosures with multiple slots have been investigated by different numerical methods such as the method of moments [1] and the finite-difference time-domain method [2]. At low-frequency range, many studies have been conducted to analyze the magnetic shielding characteristics of various shaped shields based on the magnetostatic or quasistatic approaches, where the permeability of the magnetic material is usually assumed to be a constant [3], [4]. In recent, a shielding analysis of the reinforced concrete structures under HEMP illumination was recently presented by considering the complex effective permittivity for the lossy material [5].

In this paper, a rigorous analysis of electromagnetic field penetration into multiply slotted metal plate loaded with a ferrite sheet having frequency-dependent complex magnetic permeability is proposed. The Fourier integral and series are used to represent the electric and magnetic fields. The mode matching technique based on the boundary conditions is utilized to obtain simultaneous equations for the modal coefficients in the slots. Shielding effectiveness is examined in terms of the geometrical parameters of the multiple slots and the ferrite sheet with frequency-dependent complex permeability.

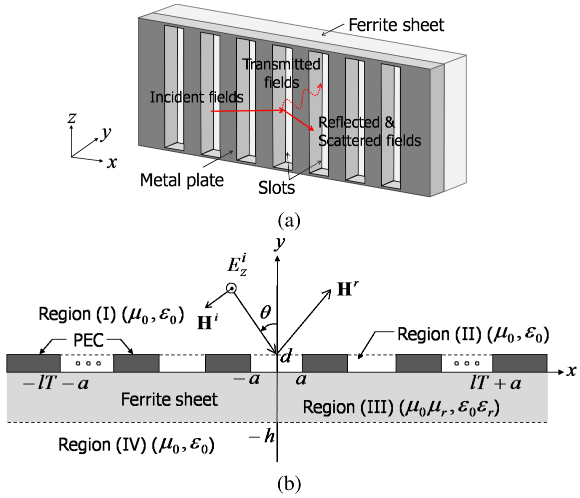

Fig. 1. Geometry of a multiply slotted metal plate coated with a ferrite sheet. (a) 3-D configuration. (b) 2-D approximation.

II. FORMULATION AND VALIDATION

Consider multiple slots (width: $2a$; thickness: d; period: T) on a metal plate loaded with a ferrite sheet (thickness: h), as shown in Fig. 1. The metal plate is assumed to be a perfect electric conductor (PEC). Regions (I), (II), and (IV) denote the free-space. Region (III) is a ferrite sheet with a frequency-dependent complex permeability (μ_r) but a very low conductivity, where the ferrite works at the linear region. When a TE polarized plane wave is excited, the incident, reflected, and scattered electric fields in region (I) ($-\infty < x < \infty$, $y > d$) with the $e^{-i\omega t}$ time convention are

$$E_z^i(x,y) = Z_0 e^{ik_x x - ik_y(y-d)}, \tag{1}$$

$$E_z^r(x,y) = -Z_0 e^{ik_x x + ik_y(y-d)}, \tag{2}$$

$$E_z^s(x,y) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{E}_z^s(\zeta) e^{-i\zeta x + i\kappa_0(y-d)} d\zeta, \tag{3}$$

where $k_x = k_0 \sin\theta$, $k_y = k_0 \cos\theta$, $k_0 = \omega\sqrt{\mu_0\epsilon_0}$, $Z_0 = \sqrt{\mu_0/\epsilon_0}$, $\kappa_0 = \sqrt{k_0^2 - \zeta^2}$, and $\tilde{E}_z^s(\zeta) = \int_{-\infty}^{\infty} E_z^s(x,d) e^{i\zeta x} dx$. Assuming that the slots are long enough along z-axis, the electric field

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in the l-th slot of region (II) ($lT-a<x<lT+a$, $0<y<d$) is

$$E_z^l(x,y) = \sum_{m=1}^{\infty}\left[b_m^l\cos(\xi_m y) + c_m^l\sin(\xi_m y)\right] \times \sin a_m(x-lT+a), \tag{4}$$

where $l = -L_1, \cdots, -1, 0, 1, \cdots, L_2$, $a_m = m\pi/(2a)$, and $\xi_m = \sqrt{k_0^2 - a_m^2}$. The total number of slots is $N = L_1 + L_2 + 1$.

In region (III) ($-\infty<x<\infty$, $-h<y<0$), the electric field within the ferrite sheet is

$$E_z^f(x,y) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left[\tilde{E}_z^+(\zeta)e^{i\kappa y} + \tilde{E}_z^-(\zeta)e^{-i\kappa y}\right]e^{-i\zeta x}d\zeta, \tag{5}$$

where $\kappa = \sqrt{k^2-\zeta^2}$, $k = k_0\sqrt{\mu_r\varepsilon_r}$, and μ_r is the complex relative permeability of the ferrite that has a frequency dispersion characteristic containing two components owing to domain-wall and gyromagnetic spin motions represented in [6]. Similarly, $\tilde{E}_z^+(\zeta)+\tilde{E}_z^-(\zeta)$ is defined by the Fourier transform at $y=0$. In region (IV) ($-\infty<x<\infty$, $y<-h$), the transmitted electric field is

$$E_z^t(x,y) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{E}_z^t(\zeta)e^{-i\zeta x - i\kappa_0(y+h)}d\zeta. \tag{6}$$

where $\tilde{E}_z^t(\zeta) = \int_{-\infty}^{\infty}E_z^t(x,-h)e^{i\zeta x}dx$.

To determine unknown modal coefficients b_m^l and c_m^l, it is necessary to enforce the boundary conditions which are the continuities of tangential electric and magnetic fields at $y=d$, $y=0$, and $y=-h$. The tangential magnetic field H_x in each region can be formulated as $H_x = (1/i\omega\mu_0\mu_r)(\partial E_z/\partial y)$.

First, applying the inverse Fourier transform to the tangential electric field continuity at $y=d$ yields

$$\tilde{E}_z^s(\zeta) = \sum_{l=-L_1}^{L_2}\sum_{m=1}^{\infty}\left[b_m^l\cos(\xi_m d) + c_m^l\sin(\xi_m d)\right] \times a_m F_m(\zeta)e^{i\zeta lT}, \tag{7}$$

where $F_m(\zeta) = \left[(-1)^m e^{i\zeta a} - e^{-i\zeta a}\right]/\left[\zeta^2 - a_m^2\right]$.

Substituting (7) into the equation from the continuity of the tangential magnetic field at $y=d$, multiplying the equation by $\sin a_n(x-rT+a)$, and performing integration over $rT-a<x<rT+a$ ($r=-L_1, -L_1+1, \cdots, -1, 0, 1, \cdots, L_2-1, L_2$), we obtain a simultaneous equation for b_m^l and c_m^l as follows:

$$s_n - \left[b_n^r\sin(\xi_n d) - c_n^r\cos(\xi_n d)\right]\xi_n a\delta_{mn}\delta_{lr} = \frac{ia_n}{2\pi}\sum_{l=-L_1}^{L_2}\sum_{m=1}^{\infty}\left[b_m^l\cos(\xi_m d) + c_m^l\sin(\xi_m d)\right]a_m I_{mn}^{(1)}, \tag{8}$$

where $s_n = 2ik_y Z_0 a_n F_n(k_x)e^{ik_x rT}$, δ_{mn} is the Kronecker delta and $I_{mn}^{(1)}$ is given by a rapidly convergent integral in [7].

Similarly, using the boundary conditions at $y=0$ and $y=-h$, we obtain the other simultaneous equation for b_m^l and c_m^l as follows:

$$\frac{ia_n}{2\pi\mu_r}\sum_{l=-L_1}^{L_2}\sum_{m=1}^{\infty}b_m^l a_m I_{mn}^{(2)} = -c_n^r\xi_n a\delta_{mn}\delta_{lr}, \tag{9}$$

where $\chi(\zeta) = [(\kappa-\kappa_0\mu_r)/(\kappa+\kappa_0\mu_r)]e^{2i\kappa h}$ and

$$I_{mn}^{(2)} = \int_{-\infty}^{\infty}\frac{[1-\chi(\zeta)]}{[1+\chi(\zeta)]}\kappa F_m(\zeta)F_n(-\zeta)e^{i\zeta(l-r)T}d\zeta. \tag{10}$$

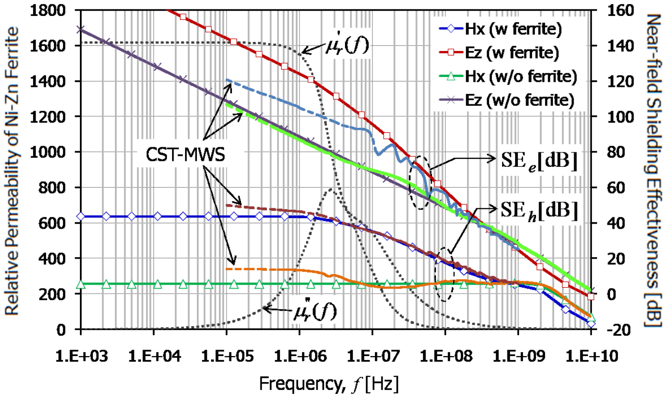

Fig. 2. Shielding effectiveness of electric and magnetic fields over a wideband frequency range. (A Ni-Zn ferrite [6] was used in simulation).

Using two simultaneous equations (8) and (9), we can obtain the modal coefficients b_m^l and c_m^l. Once the modal coefficients in the slot regions are determined, the electromagnetic fields in all regions can be calculated. To evaluate the shielding performance of the multiply slotted metal plate coated with a ferrite sheet, the shielding effectiveness of electric and magnetic fields were defined as $\mathrm{SE}_e = 20\log|E^i/E^t|$ and $\mathrm{SE}_h = 20\log|H^i/H^t|$, respectively.

Fig. 2 represents the effect of the frequency-dependent complex permeability on the electric and magnetic shielding effectiveness at $(x,y) = (0,-10)$ mm in region (IV) for the case of $N=3$, $a=5$ mm, $d=1$ mm, $T=4$ mm, $h=2$ mm, and normal incidence ($\theta=0$). As can be seen from the results, the SE_e was larger than the SE_h over a whole frequency range from 1 kHz to 10 GHz. When $f<1$ GHz, the shielding effectiveness of the slotted metal plate coated with a ferrite sheet was about 40 dB greater than that of the slotted metal plate alone in both electric and magnetic fields. Note that the SE_h with the ferrite sheet was constant in the frequency range up to 1 MHz and started to decrease because the real permeability (μ_r') decreased rapidly as the frequency increased from 1 MHz. Our results were compared with those of CST Microwave Studio (MWS). Good agreement was generally achieved except that a deviation in CST MWS results occurred at low-frequency range.

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