# Common-Mode Current on a Wire through a Corrugated Aperture

Hyun Ho Park, Jae Wook Lee, Jong-Hwa Kwon, and Hyung-Soo Lee

**This paper investigates the effect of a corrugated aperture on a common-mode current traveling along a penetrating wire. Computational results illustrate that the corrugated aperture acts as a filter, significantly reducing the common-mode current on the wire. This effect causes a reduction of radiated emission from cables passing through apertures on shielding enclosures. To predict and analyze the characteristics of the common-mode current on a straight wire passing through a corrugated aperture with cylindrical symmetry, the finite-difference time-domain (FDTD) method is applied.**

## I. INTRODUCTION

Electronic equipment needs a metallic enclosure for protecting and shielding the interior printed circuit boards (PCBs) mechanically and electrically. The many apertures or slots for heat dissipation and input/output (I/O) cabling are essential parts of the shielding enclosure. Recently, as the clock speed of signals and the density of signal traces on PCBs have increased, electromagnetic interference (EMI) problems, such as radiated emission from I/O cables and apertures and coupling among the cables or traces on the PCB, make it more difficult to improve the reliability of electronic systems. To minimize EMI arising from electronic products, researchers have investigated appropriate design guidelines for shielding enclosures with apertures and coupling mechanisms between the interior PCBs and I/O cables [1], [2]. These previous studies have demonstrated that radiation from the common-mode current flowing along the cables of PCBs and shielding enclosures is a primary EMI source. The reason is that the cable acts as an antenna. A general method for suppressing common-mode currents on cables is to place several ferrite beads around the cables [3]. Ferrite devices offer an effective means of providing EMI suppression on cables by presenting high impedance. However, it is not efficient to connect ferrite beads to every cable in large telecommunication equipment with many cables such as an asynchronous transfer mode (ATM) switching machine. For such equipment, modifying the aperture geometry or adding gaskets on the apertures is more efficient in reducing the common-mode current on cables.

The purpose of this paper is to propose an alternative for suppressing EMI from multiple cables passing through an aperture in large electronic equipment. We investigate the effect of a corrugated aperture on the transmission performance of

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common-mode current on a wire. Corrugations have been generally used for passing signals at a specific frequency [4] or reducing the leakage of electromagnetic fields through slots [5]. This paper presents an effective method of reducing the radiated emissions from cables going out of shielding enclosures through corrugated apertures. The aperture with corrugations acts as a filter to suppress the common-mode currents at a specific frequency band.

## II. COMMON-MODE AND DIFFERENTIAL-MODE CURRENTS

On most cables used for transmitting data and providing power, such as the unshielded twisted-pair (UTP), shielded twisted-pair (STP), and universal serial bus (USB), there are generally two kinds of current modes. One is the differential-mode current of normal or functional signals that flow on two wires with equal magnitude but in opposite directions. The other is the common-mode current of noise signals that flow on two wires with equal magnitude and in the same direction. The common-mode current can be generated by coupling between traces on a PCB, asymmetric placement of the traces, and the difference of ground voltages between the PCB and the shielding enclosure (Fig. 1). Differential-mode currents are modeled with Kirchhoff's circuit theory, but common-mode currents are not easily described due to the existence of displacement currents [6]. Although the magnitude of common-mode currents is considerably less than that of differential-mode currents on PCBs and cables, common-mode currents are one of the most significant causes of electromagnetic radiation. This is because common-mode radiation is additive but differential-mode radiation is subtractive [6].

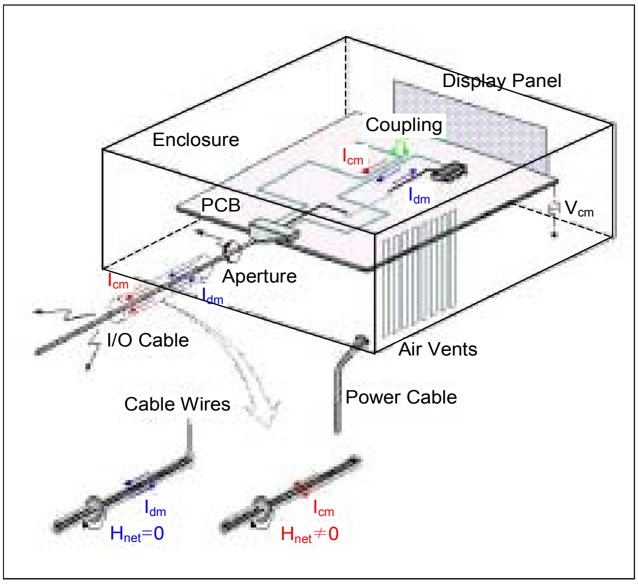

Fig. 1. Common-mode and differential-mode currents of simple electronic system with I/O cable.

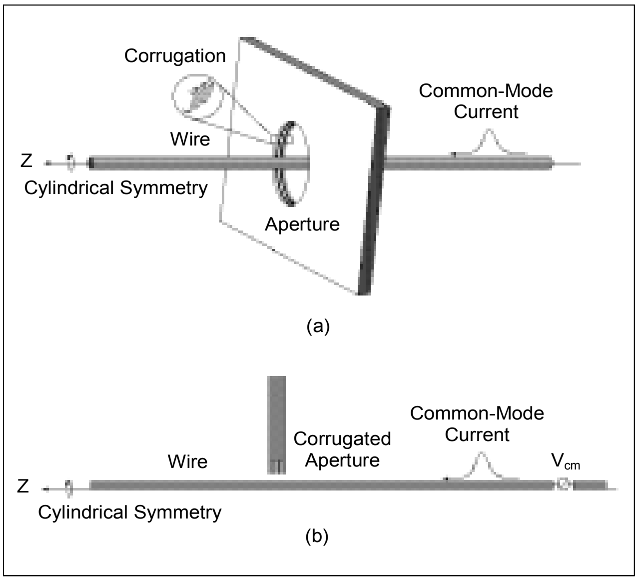

Fig. 2. A wire through corrugated aperture: (a) Physical geometry, (b) Computational geometry.

In our study, we assumed that the magnetic fields radiating from the two wires with differential-mode currents are almost zero because the currents run in opposite directions, and thus there are no interactions or scattering phenomena between the differential-mode currents on the wire and the corrugated aperture. When the cable is composed of twisted wires, this assumption is even more reasonable. Therefore, a single wire with only common-mode currents is suitable for modeling cables comprising many wires with both differential-mode and common-mode currents.

## III. FORMULATION OF THE PROBLEM

Figure 2 shows a wire through a corrugated circular aperture in an infinite conducting plane, which is part of the model in Fig. 1. The wire can be modeled as a dipole antenna with a voltage source as depicted in Fig. 2(b). Since the geometry has cylindrical symmetry, a rotationally symmetric finite-difference time-domain (FDTD) code is used in two-dimension to save computation time. Maxwell's curl equations in cylindrical coordinates can be discretized both in space (as $\Delta r$ and $\Delta z$ ) and time (as $\Delta t$ ) with $(i, j)$ and $n$ representing the discrete space and time nodes. The $\hat{r}$-component of the electric field is expressed as $E_r(r, z; t) = E_r^n(i, j)$, where $r = \Delta r \times i$, $z = \Delta z \times j$, and $t = \Delta t \times n$. For convenience, we took the space increments $\Delta r$ and $\Delta z$ as the same. Applying the discretization to Maxwell's curl equations using the centered finite-difference expressions for space and time and rearranging the equations to become suitable for iterative calculations give the following equations:

$$\begin{aligned} H_\phi^{n+1/2}(i,j) &= H_\phi^{n-1/2}(i,j) \\ &\quad - \frac{\Delta t}{\mu\Delta}\left[E_r^n(i,j+1) - E_r^n(i,j)\right] \\ &\quad + \frac{\Delta t}{\mu\Delta}\left[E_z^n(i+1,j) - E_z^n(i,j)\right], \end{aligned} \tag{1}$$

$$\begin{aligned} E_r^{n+1}(i,j) &= C_r^e(i,j)E_r^n(i,j) \\ &\quad - \frac{C_r^h(i,j)}{\Delta}\left[H_\phi^{n+1/2}(i,j) - H_\phi^{n+1/2}(i,j-1)\right], \end{aligned} \tag{2}$$

$$\begin{aligned} E_z^{n+1}(i,j) &= C_z^e(i,j)E_z^n(i,j) \\ &\quad - \frac{C_z^h(i,j)}{\Delta}\left[\frac{r_{i+1/2}}{r_i}H_\phi^{n+1/2}(i,j) - \frac{r_{i-1/2}}{r_i}H_\phi^{n+1/2}(i-1,j)\right], \end{aligned} \tag{3}$$

where

$$C_l^e(i,j) = \frac{2\varepsilon_l(i,j) - \sigma_l(i,j)\Delta t}{2\varepsilon_l(i,j) + \sigma_l(i,j)\Delta t},$$

$$C_l^h(i,j) = \frac{2\Delta t}{2\varepsilon_l(i,j) + \sigma_l(i,j)\Delta t},$$

and $l = r, z$. The parameters $\mu$, $\varepsilon_l(i,j)$, and $\sigma_l(i,j)$ are the permeability, permittivity, and conductivity, respectively. Equations (1), (2), and (3), known as Yee's equations, are used to calculate the electric and the magnetic fields in the whole region except near the absorbing boundaries. The parameters $\varepsilon_l(i,j)$ and $\sigma_l(i,j)$ are defined at all nodes where the electric field is calculated. The unit cell size $\Delta$ used for the simulations is taken to be 1 cm. The aperture conducting plane and wire are made of aluminum ($\sigma = 3.72 \times 10^5$ S/cm). The time increment $\Delta t$ is given by $\Delta t = \Delta/(2c_0)$ for the stability of Yee's algorithm, where $c_0$ is the speed of light in free space. A first-order Mur-absorbing boundary condition is used to absorb the electromagnetic waves propagating toward the computational boundaries. The source voltage $V_{cm}$ used in the FDTD modeling is a Gaussian pulse $\exp\{-(t-t_0)^2/T^2\}$, which is polarized in the $\hat{z}$-direction at the dipole gap. The transient currents are calculated by integrating the nearest magnetic fields around the wire. In order to obtain the results in the frequency domain, we used the fast Fourier transform (FFT) algorithm with 4,096 points.

## IV. NUMERICAL RESULTS

The radius of the wire is 1 cm for all computations in this paper. To detect the common-mode currents flowing along the wire, the observation positions are fixed at $P_1$ and $P_2$, which are 21 cm and 130 cm away from the center point of the source voltage $P_0$, respectively. The width of all corrugations is set to 1 cm and the number of corrugations determines the thickness of the aperture. The magnitude of every current is normalized by the maximum value of the source current at $P_0$ in both the time and frequency domains when there is only a single wire.

Figure 3 shows a transient common-mode current propagating along a wire without an aperture. As it gets farther away from the voltage source, the current on the wire decays gradually due to radiation, but the rate of decay decreases as the current propagates down the wire. Figure 4 shows the common-mode current at $P_2$ in the frequency domain as a function of the depth of corrugation when there is a single corrugation on the aperture. The current curves have deep valleys indicating the frequency bands that represent the occurrence of the suppression of transmitted common-mode currents. These frequencies are related to the depth of the corrugation. Figure 4 shows that the resonance frequency becomes lower as the depth of corrugation increases. In [5], the resonance frequencies were determined by the depth of the corrugations when the ratio of depth to width was larger than 5. The resonant condition in which the quarter wavelength is equal to the depth of corrugations is not rigorously satisfied in our results. The reason is that the source wire does directly penetrate through the corrugated aperture and the sidewall of

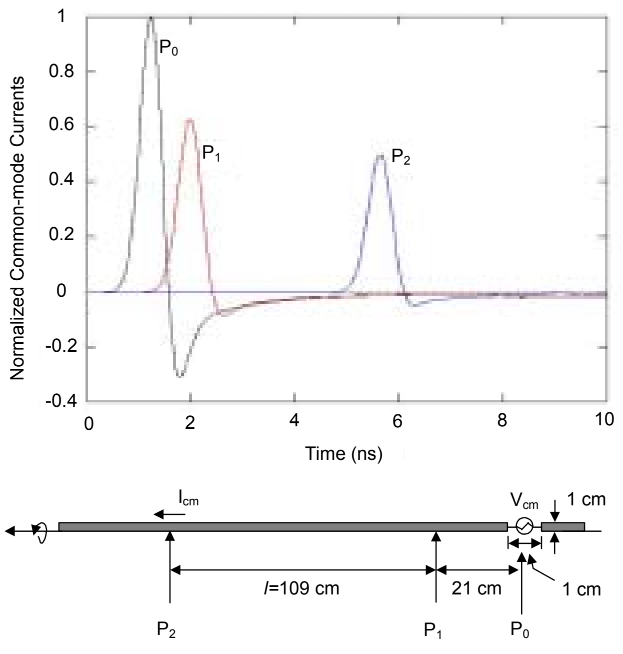

Fig. 3. Normalized transient common-mode currents on the wire; $T = 20\Delta t$, $t_0 = 4T$.

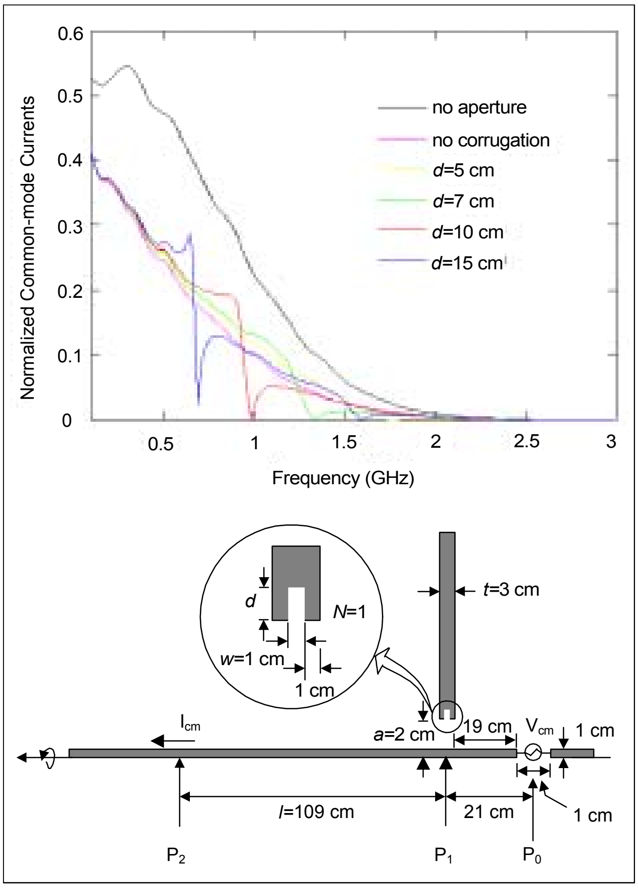

Fig. 4. Normalized common-mode currents in frequency-domain on the wire through aperture with corrugation as a function of corrugations depth; $T = 20\Delta t,\ t_0 = 4T$.

the corrugation is not sufficiently thick, so the effect of the sidewall on the current transmission can be ignored. Hence, it is difficult to obtain the direct relations between the frequency of suppressing the common-mode currents and the geometric parameters of corrugations on the aperture. The effects of multiple corrugations are shown in Figs. 5 and 6 when the multiple corrugations ($N = 5$) have the same or different depth. In Fig. 5, the frequency responses of the common-mode current are similar to those of Fig. 4 except that the valleys broaden more because of the five corrugations. Figure 5(a) reveals that fluctuations of transient currents arise from the resonance of corrugations. When there is no corrugation, the sharp transient current with a high frequency spectrum becomes smoother with a specific frequency when there is corrugation. The fluctuation with a specific frequency is greater as the corrugations deepen. When $d = 10$ cm, the period of the transient current is about 2 to 2.5 ns. This means that the normalized common-mode current in the frequency domain has a peak at about 0.5 GHz, which is shown in Fig. 5(b). The bandwidth of the suppression of the common-mode current increases when more corrugations are introduced. From these results, we conclude that the corrugated aperture reduces well the common-mode current at a certain frequency band, but increases the current at a lower frequency. If the corrugations have a different depth, the peak of the current at a specific frequency can be alleviated due to the multiple but weak resonances of the corrugations (this will be explained later). Figure 6 shows the effects of multiple corrugations loaded with

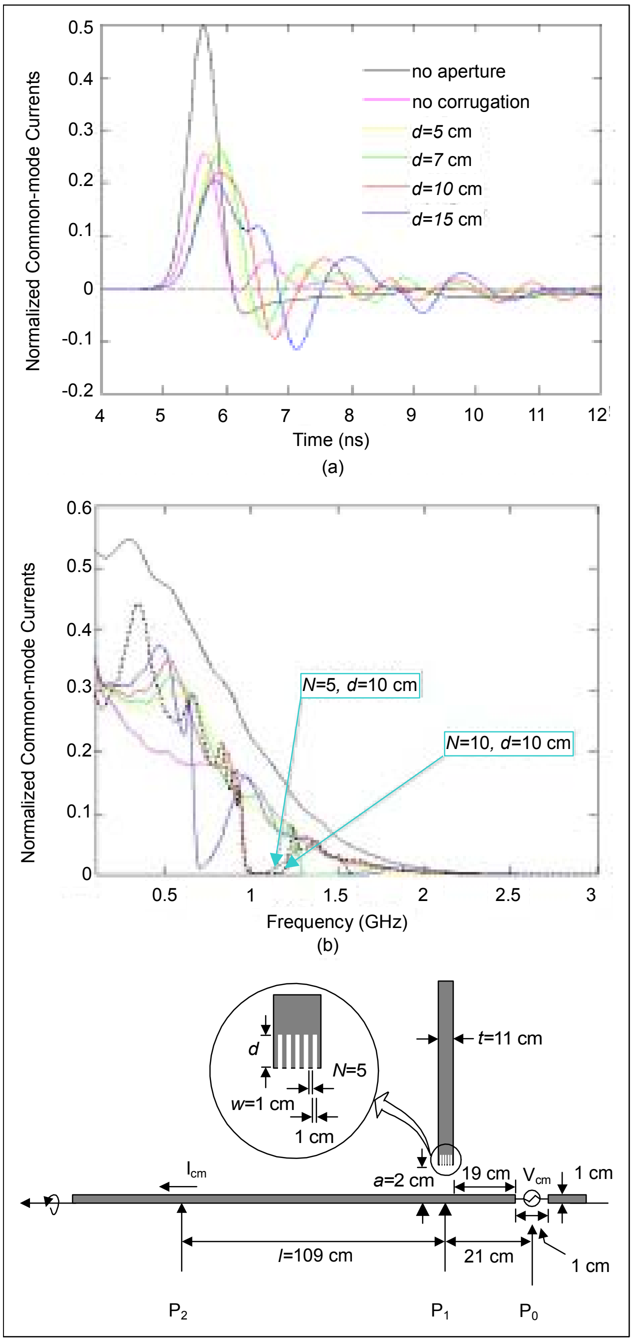

Fig. 5. Normalized common-mode currents on the wire through aperture with the same corrugations as a function of corrugations depth; $T = 20\Delta t,\ t_0 = 4T$: (a) Time responses, (b) Frequency responses.

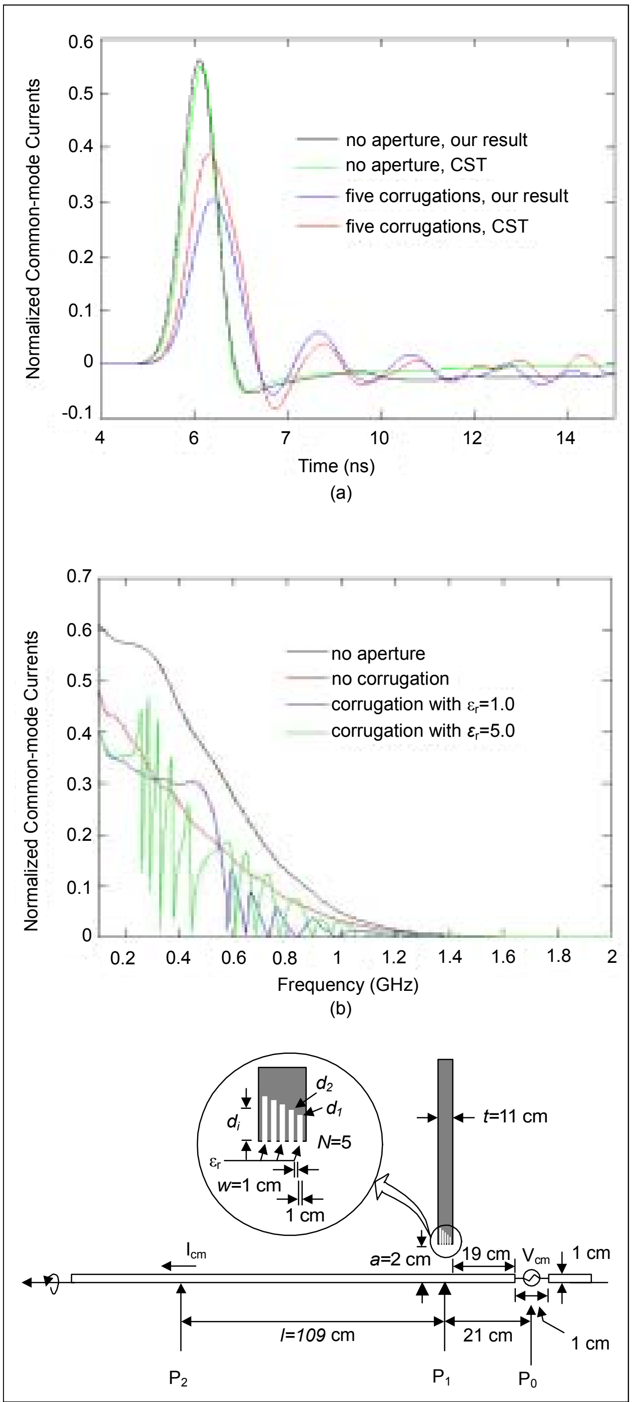

Fig. 6. Normalized common-mode currents on the wire through aperture with five corrugations having different depth ($d_1$=10 cm, $d_2$=12 cm, $d_3$=14 cm, $d_4$=16 cm, $d_5$=18 cm); $T = 32\Delta t$, $t_0 = 3.44T$ : (a) Time responses ($\varepsilon_r = 1.0$), (b) Frequency responses.

lossless dielectric material with different but linearly growing depths. Figure 6(a) compares our results with the data obtained from the Computer Simulation Technology (CST) MW Studio, which is a commercial program for the design of antennas and microwave circuits. An acceptable agreement is shown in the transient responses of the common-mode currents. As mentioned previously, the peak of the current at about 0.5 GHz, which was due to using a single size of corrugation depth, was mitigated by using a linearly growing depth (when $\varepsilon_r = 1.0$) (Fig. 6(b)). In addition, corrugation with a linearly growing depth effectively suppresses the common-mode current above 0.6 GHz more than the aperture without corrugation, though the suppression band has some ripples. The effect of lossless dielectric material lowers the resonant frequency of the corrugations. This means that common-mode currents with low frequencies can be suppressed without increasing the size of the corrugations. Using lossy materials will mitigate the sharp filtering characteristics at low frequencies and broaden the bandwidth (Fig. 6(b)).

## V. CONCLUSIONS AND FUTURE WORK

In this paper, we presented the idea of using corrugations to reduce the common-mode currents on a wire penetrating through an aperture. We applied the FDTD method to obtain the temporal and spectral responses of the common-mode current when the geometric parameters of corrugation on the aperture are changed. We found that the corrugations affect the transmission characteristics of the common-mode currents on the penetrating wire. The corrugations act as a band rejection filter to suppress the common-mode current in a certain frequency band. To reduce cost and simplify the manufacturing process, using a corrugated aperture to reduce the common-mode current on cables, especially in large-sized telecommunication equipment, is more efficient than using ferrite cores placed on each cable. The technique presented in this paper will be helpful for reducing radiated emission from cables going through shielding enclosures.

In a future investigation, we plan to use a subgrid algorithm to finely resolve the corrugations for more accurate FDTD simulations. To show the suppression of common-mode current flowing along the wire at frequency ranges ($\leq 1$ GHz) regulated by the FCC and CISPR, we used a few tens of centimeters for the depths of the corrugations and the thicknesses of the apertures. The dimensions in the models are directly applicable to large-sized telecommunication equipment but not to small-sized electronic equipment. We briefly mentioned in this paper that high dielectric and magnetic lossy materials in corrugations could be applied to small-sized electronic systems; we will seek more precise explanations in the future. Finally, we plan to calculate radiated emissions from wires through corrugated apertures to compare them with the regulation limits of the FCC and CISPR.

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