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Efficient Prediction of RF Interference in a Shielding Enclosure with PCBs Using a General Segmentation Method

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Abstract—**Cavity model with segmentation method is extended to the analysis of radio frequency interference (RFI) problems in a shielding enclosure with printed circuit boards (PCBs) . Sixteen different Green's functions, instead of one in the conventional segmentation method developed for PCB cavities, are introduced to describe the fields in various cavities formed by enclosure walls and PCB copper planes. Both horizontal and vertical connections among these cavities are achieved by enforcing the boundary conditions along their common interfaces. Numerical examples demonstrate the efficiency and accuracy of the method by compared with full wave simulations.**

Keywords—**Cavity model, RFI, segmentation method, shielding enclosure**

I. Introduction

Shielding enclosures are often used to prevent the radiations from, as well as provide immunity to, the printed circuit boards (PCBs) installed inside[1][2]. Many authors have investigated the shielding performance or effectiveness of enclosures with apertures or slots. However, the noise coupling issues between the components inside an enclosure traditionally are not well addressed since they do not directly result in problems in regulatory compliance. With the continuous development of wireless, internet, and computer technologies, a category of electronic devices are moving toward the direction of smaller sizes and increased functionalities. In other words, more RF radios are integrated with higher-speed and more complex digital circuits into more compact components. As a consequence, interference inside an enclosure becomes a critical issue that could significantly affect the performance of the system, especially the noise coupled from the digital part to the RF part.

While numerical techniques, such as finite element (FEM) and finite difference time domain (FDTD) methods, are well suited for noise coupling study inside an enclosure, they are often mesh-based, time-consuming and resource intensive for complex structures. Fast methods are needed for practical engineering designs, especially in the pre-layout phase for component placements. In this paper, a general segmentation method is proposed to efficiently evaluate the coupling effects among various locations inside an enclosure. The segmentation method was first introduced for microwave planar circuit analysis and designs[3]-[5]. Later, together with the cavity model[6][7], it found new applications in power/ground characterizations for high-speed power bus analysis[8]-[9]. Here, the method is further extended to the radio-frequency interference (RFI) modeling in an enclosure with PCBs.

In this category of RFI problems, PCB copper planes divide the entire enclosure into multiple cavities, whose sidewalls could be either perfect electric conductors (PEC) or perfect magnetic conductors (PMC), while the top an dbottom walls are always PECs. As a result, sixteen types of cavities are possible, thus sixteen different Green's functions are necessary. Furthermore, these multiple cavities need to be connected both horizontally and vertically. This can be achieved by neglecting the fringing fields along the common interfaces of adjacent cavities. This approximation is valid when the height of cavity is very small compared to the wavelength of interest, which is often the case for compact shielding enclosures. The general segmentation method has been validated by compared with the results obtained from a full wave CST Microwave Studio simulations.

II. Green's functions and Impedance matrices for various Cavities

For the conventional power-ground plane analysis, only one Green's function is needed since all the cavities have PEC top and bottom parallel planes and PMC sidewalls. However, the RFI analysis in an enclosure with PCBs needs to deal with cavities with a combination of various PEC and PMC sidewalls as shown in Fig. 1. Therefore, sixteen Green's functions are necessary. They are expressed as It is very cumbersome to list all these 16 Green's functions. Fortunately, a united expression has been found as

$$g(x,y|x_0,y_0) = \frac{j4\omega\mu h}{ab}\sum_{m=s_x}^{\infty}\sum_{n=s_y}^{\infty}\frac{f(k_{xm}x_0)g(k_{yn}y_0)}{k^2-k_{xm}^2-k_{yn}^2}\frac{f(k_{xm}x)g(k_{yn}y)}{(1+\delta_{m0})(1+\delta_{n0})} \tag{1}$$

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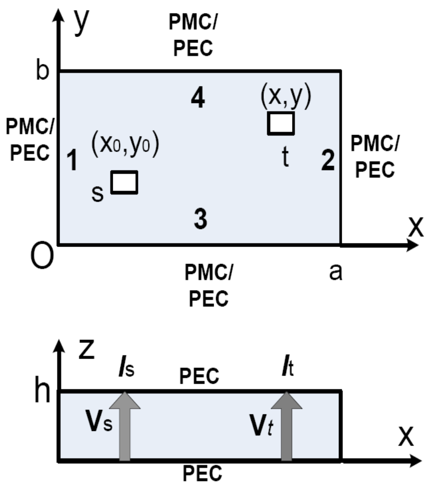


Figure 1. Various possible cavity boundaries for RFI analysis.

TABLE I. THE SELECTION OF FUNCTION $f(\cdot)$ AND WAVENUMBER k_{xm} FOR THE GREEN'S FUNCTION IN (1)

Side wall	1 $(x=0)$		
		PMC	PEC
2 $(x=a)$	PMC	$f(\cdot)=\cos(\cdot)$ $k_{xm}=\frac{m\pi}{a}$ $s_x=0$	$f(\cdot)=\sin(\cdot)$ $k_{xm}=\frac{(2m-1)\pi}{2a}$ $s_x=1$
	PEC	$f(\cdot)=\cos(\cdot)$ $k_{xm}=\frac{(2m-1)\pi}{2a}$ $s_x=1$	$f(\cdot)=\sin(\cdot)$ $k_{xm}=\frac{m\pi}{a}$ $s_x=1$

where ω is the radial frequency; wavenumber $k=\omega\sqrt{\mu\varepsilon}$, and μ,ε are the permeability and permittivity of the dielectrics, respectively. δ_{m0} and δ_{n0} are the Kronecker's delta. a, b and h are the length, width and height of the rectangular cavity, respectively. The function $f(\cdot)$ and wavenumber k_{xm} are determined according to the boundary conditions on the planes $x=0$ and $x=a$ as listed in Table I. Similarly, the function $g(\cdot)$ and k_{yn} can be selected from Table II.

Similar to the formula given in [7], the impedance between source port s and target port t can be obtained as

TABLE II. THE SELECTION OF FUNCTION $g(\cdot)$ AND WAVENUMBER k_{yn} FOR THE GREEN'S FUNCTION IN (1)

Side wall	3 $(y=0)$		
		PMC	PEC
4 $(y=b)$	PMC	$g(\cdot)=\cos(\cdot)$ $k_{yn}=\frac{n\pi}{b}$ $s_y=0$	$g(\cdot)=\sin(\cdot)$ $k_{yn}=\frac{(2n-1)\pi}{2b}$ $s_y=1$
	PEC	$g(\cdot)=\cos(\cdot)$ $k_{yn}=\frac{(2n-1)\pi}{2b}$ $s_y=1$	$g(\cdot)=\sin(\cdot)$ $k_{yn}=\frac{n\pi}{b}$ $s_y=1$

$$\begin{aligned} Z_{ts} &= \frac{1}{L_sW_sL_tW_t}\int\int_s\int\int_t g(x,y|x_0,y_0)dsdt \\ &= \frac{j4\omega\mu h}{ab}\sum_{m=s_x}^{\infty}\sum_{n=s_y}^{\infty}\frac{f(k_{xm}x_0)g(k_{yn}y_0)}{k^2-k_{xm}^2-k_{yn}^2} \\ &\quad \cdot\frac{f(k_{xm}x)g(k_{yn}y)}{(1+\delta_{m0})(1+\delta_{n0})} \\ &\quad \cdot\left[\frac{\sin(k_{xm}L_s/2)}{k_{xm}L_s/2}\right]\left[\frac{\sin(k_{xm}L_t/2)}{k_{xm}L_t/2}\right] \\ &\quad \cdot\left[\frac{\sin(k_{yn}W_s/2)}{k_{yn}W_s/2}\right]\left[\frac{\sin(k_{yn}W_t/2)}{k_{yn}W_t/2}\right] \end{aligned} \quad (2)$$

where $L_{s(t)}, W_{s(t)}$ are the length and width of the source (target) port; (x_0,y_0) and (x,y) are the center coordinates of source and target ports, respectively.

III. GENERAL SEGMENTATION METHOD

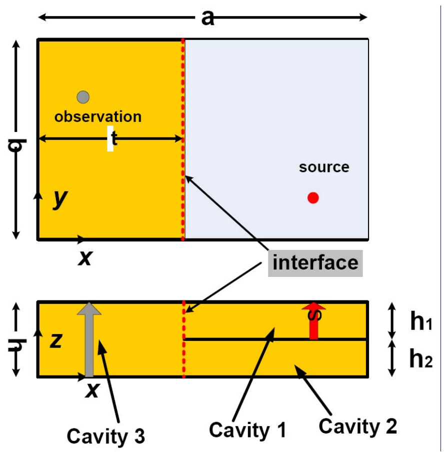


Figure 2. Model of a PCB plate located in a PEC Box

The conventional segmentation method has been explained clearly in [9]. It can be used to analyze an arbitrary shaped power and ground plane pair that can be divided into multiple rectangular and triangular cavities. However, for the case shown in Fig. 2, The PCB plane inside the PEC box divides the entire enclosure into three cavities, where cavities 1 and 2 are vertically aligned and are then connected to cavity 3 horizontally. To implement the segmentation method, the fringing fields caused by the discontinuity at the common interface of cavities 1, 2 and 3 are neglected. This approximation is reasonable only when the heights of the cavities, h_1, h_2 and h are quite smaller than the wavelength of interest. This is usually the case for RFI analysis for the PCB in a compact enclosure. Fig. 3 shows the vertical connection scheme according to this approximation, which was previously introduced in [10] for multiple power/ground plane pairs analysis.

Multiple cavities are connected by enforcing the continuous boundary conditions along the interfaces. To implement

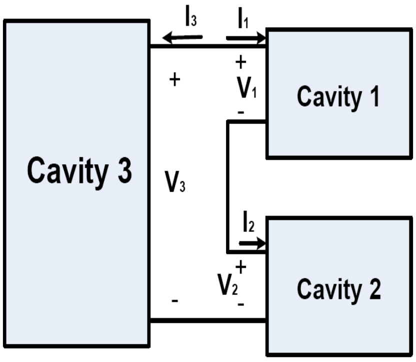


Figure 3. Schematic of a vertical connection.

this, multiple auxiliary ports are asigned at each interface. For the example geometry shown in Fig. 2, Fig. 3 shows the connection of the cavities with the auxiliary port defined at the interface. When multiple auxiliary ports are assigned, $\mathbf{V}_N^{(i)}, \mathbf{I}_N^{(i)}$ can be used to denote the voltage and current vectors for the auxiliary ports, and $\mathbf{V}_S^{(i)}, \mathbf{I}_S^{(i)}$ are the voltage and current vectors of the internal ports. The superscript i indicates the ports are defined for cavity i ($i = 1, 2, 3$). Then, the voltages and currents can be related by the impedance matrices as

$$\mathbf{V}_N^{(i)} = \mathbf{Z}_{NN}^{(i)}\mathbf{I}_N^{(i)} + \mathbf{Z}_{NS}^{(i)}\mathbf{I}_S^{(i)} \quad (3)$$

$$\mathbf{V}_S^{(i)} = \mathbf{Z}_{SN}^{(i)}\mathbf{I}_N^{(i)} + \mathbf{Z}_{SS}^{(i)}\mathbf{I}_S^{(i)}, i = 1, 2, 3 \quad (4)$$

where the impedance matrices $\mathbf{Z}_{NN}^{(i)}, \mathbf{Z}_{NS}^{(i)}, \mathbf{Z}_{SN}^{(i)}$ and $\mathbf{Z}_{SS}^{(i)}$ can be obtained from (2).

By neglecting the fringing fields along the interface , the continuity of voltages and currents forces

$$\mathbf{V}_N^{(3)} = \mathbf{V}_N^{(1)} + \mathbf{V}_N^{(2)} \quad (5)$$

$$\mathbf{I}_N^{(1)} = \mathbf{I}_N^{(2)} = -\mathbf{I}_N^{(3)} \quad (6)$$

Deleting the auxiliary voltage and current vectors from (3) to (6) yields

$$\begin{bmatrix} \mathbf{V}_S^{(1)} \\ \mathbf{V}_S^{(2)} \\ \mathbf{V}_S^{(3)} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_{SS}^{(11)} & \mathbf{Z}_{SS}^{(12)} & \mathbf{Z}_{SS}^{(13)} \\ \mathbf{Z}_{SS}^{(21)} & \mathbf{Z}_{SS}^{(22)} & \mathbf{Z}_{SS}^{(23)} \\ \mathbf{Z}_{SS}^{(31)} & \mathbf{Z}_{SS}^{(32)} & \mathbf{Z}_{SS}^{(33)} \end{bmatrix} \begin{bmatrix} \mathbf{I}_S^{(1)} \\ \mathbf{I}_S^{(2)} \\ \mathbf{I}_S^{(3)} \end{bmatrix} \quad (7)$$

where

$$\mathbf{Z}_{SS}^{(ii)} = \mathbf{Z}_{SS}^{(i)} - \mathbf{Z}_{SN}^{(i)}\mathbf{W}\mathbf{Z}_{NS}^{(i)} \quad (8)$$

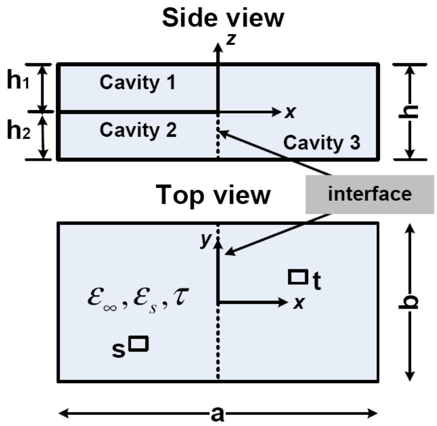
$$\mathbf{Z}_{SS}^{(ij)} = sign(i,j)\mathbf{Z}_{SN}^{(i)}\mathbf{W}\mathbf{Z}_{NS}^{(j)} \quad \text{for i} \neq \text{j} \quad (9)$$

and $sign(i,j) = sign(j,i)$, and $sign(1,2) = -1; sign(1,3) = 1; sign(2,3) = 1$, and the auxiliary matrix $\mathbf{W}$ is obtained by

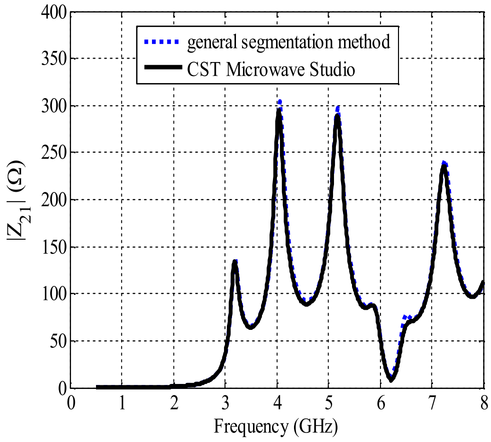
$$\mathbf{W} = \left[\mathbf{Z}_{NN}^{(1)} + \mathbf{Z}_{NN}^{(2)} + \mathbf{Z}_{NN}^{(3)}\right]^{-1} \quad (10)$$

Combining the conventional horizontal and the vertical connections, the general segmentation method can analyze the coupling effects among various locations in a complex enclosure structure with both horizontally and vertically aligned cavities.

IV. Numerical Examples



(a)

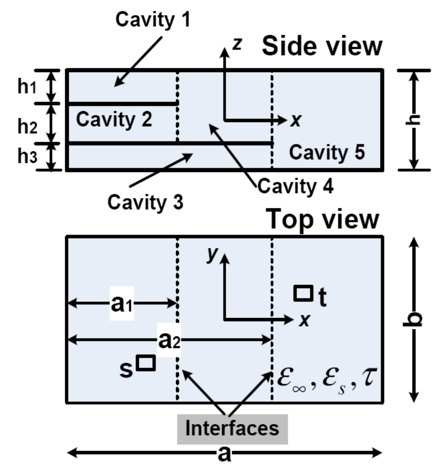


(b)

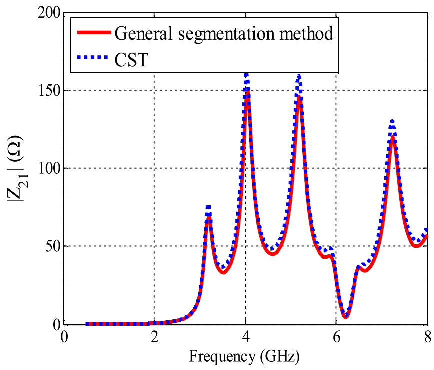
Figure 4. (a) Geometric structure for a PCB installed in an enclosure. (b) Comparison of transfer impedance obtained by segmentation method and that of full wave solver (Finite integration technique in CST Microwave Studio).

Fig. 4 (a) shows a simple case where a PCB is located in an enclosure. The dimensions of the enclosure are $a \times b \times h = 10 \times 5 \times 2cm^3$. The PCB in this example is an infinitely thin PEC plane with dimensions of $5 \times 5cm^2$ and is located in the left side of the enclosure with cavity heights $h_1 = h_2 = 1cm$. The enclosure is filled with a Debye dielectric material with the infinity permittivity of $\varepsilon_\infty = 1.05$, the static permittivity of $\varepsilon_s = 1.15$ and the relaxation time of $\tau = 4 \times 10^{-11}s$. A cartesian coordinate system is set up as shown in Fig. 4 (a) with the center of the enclosure as the origin. A source port (port 1) is in Cavity 1 and its coordinates are $(-1.5, -3.0)cm$. An observation port (port 2) is located in Cavity 3 with the coordinates of $(0.5, 3.5)cm$.

Fig. 4 (b) compares the transfer impedance results between Ports 1 and 2, $|Z_{21}|$, obtained using the general segmentation method and the CST Microwave Studio. It can be seen that the segmentation method predicts almost same resonant frequencies of the structure and the amplitudes agree very well between the two approaches.



(a)



(b)

Figure 5. (a) Detailed geometry of an enclosure with PCBs. (b) Comparison of the transfer impedance obtained by the general segmentation method and the CST Microwave Studio.

To demonstrate the efficiency of the general segmentation method, a more complex case is analyzed as shown in Fig. 5 (a). In this example, two different sized PCBs,infinitely thin copper planes, are located in an enclosure. The geometric dimensions of the enclosure are $a \times b \times h = 10 \times 5 \times 2cm^3$. The locations of the two PCBs in the vertical direction are $h_1 = 0.67cm$ and $h_2 = 1.33cm$. The width of these two PCBs is same to the enclosure and the lengthes are $a_1 =$ and $a_2 =$, respectively. The same Debye dielectric material as in the previous case is adopted. The source and observation ports are located in Cavities 1 and 5, respectively, and their coordinates are $(-1.5, -3.0)cm$ and $(0.5, 3.5)cm$.

Fig. 5 (b) shows the comparison of the transfer impedance, $|Z_{21}|$, obtained using the general segmentation method and the CST Microwave Studio. Agreement is again very good. More importantly, the simulation time was approximately 10 minutes in an ordinary PCwhen using the general segmentation method, compared with approximately 10 hours with the CST Microwave Studio. Obviously, the general segmentation method is much more suitable for RFI evaluations in practical engineering applications.

V. Conclusions

A general segmentation method is proposed to investigate the RFI issues in a shielding enclosure with PCBs. A unified Green's function is derived for up to 16 types of cavities with different PEC or PMC sidewalls. Vertical connection formulas are provided to enforce the boundary conditions along the interfaces of adjacent cavities. Numerical examples demonstrated the accuracy and efficiency of the general segmentation method, which is very suitable for fast engineering estimations of noise coupling inside a metal enclosure.

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