Letters

Analytical Model for Evaluating Shielding Effectiveness of an Enclosure Populated With Conducting Plates

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Abstract—**An analytical model is proposed for evaluating shielding effectiveness (SE) of a rectangular enclosure populated with conducting plates. The conducting plates are considered as capacitive diaphragms that fill the width of the enclosure, and SE is calculated using the equivalent circuit of the enclosure. The letter presents an improved approach to evaluating enclosures populated with printed circuit boards (PCBs) or plates coated with a composite or radar-absorbing material. The evaluation of the model error was performed when the plate height changed. Both this model and finite element method were used to calculate the SE for enclosures populated with conducting plates, PCBs and the plate coated with a magnetic composite material. The results obtained in the range up to 1 GHz are in good agreement.**

Index Terms—**Conducting plate, electromagnetic shielding, enclosure, equivalent circuit method, printed circuit board (PCB).**

I. Introduction

METAL enclosures are often used to protect electronic devices (ED) against natural and man-made electromagnetic interference. Apertures in the walls, as well as the filling of an enclosure, have a significant influence on shielding effectiveness (SE) of metal enclosures [1]. In the early stages of design, the evaluation of SE for populated enclosures is a difficult task because the location of the ED elements is often unknown.

The evaluation of the enclosure SE can be performed using numerical methods [2]–[4], but their application requires significant computational costs. Therefore, in the early stages of ED design it is more preferable to use analytical methods [5]. One of these methods has been proposed in [6] to evaluate the SE of a rectangular enclosure with the aperture by using an equivalent circuit. This method assumes that the aperture is located in the center of the front wall, and the enclosure filling is not taken into account.

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Based on the equivalent circuit, models for rectangular enclosures filled with thin wires [7] and dielectric plates as printed circuit boards (PCBs) [8] have been proposed. The equivalent circuit has also been improved to analyze the shielding properties of cylindrical shells with dielectric filling [9]. To evaluate the SE of an enclosure with conducting plates, a model [10] has been proposed. This model uses the dyadic Green's functions and numerical integration, which makes it rather complicated to perform calculations.

The purpose of this letter is to present a model that allows a reasonable approximation for evaluating the SE of a rectangular enclosure filled with conductive plates or PCBs. Such structures are considered here as asymmetric capacitive waveguide diaphragms that fill the entire width of the enclosure. Waveguide diaphragms have previously been used to improve the method [6]. For example, in [11] and [12], the enclosure wall with an aperture is represented in the equivalent circuit as the susceptance of asymmetric diaphragm. In [13], it is used to calculate the SE of an enclosure with an LCD in the aperture. However, in this letter, the susceptance of the diaphragm is used to evaluate the SE of populated enclosures.

II. Theory

A. Extended Equivalent Circuit

According to the model in [6], a rectangular enclosure with an aperture can be replaced by an equivalent circuit in which the incident plane wave is represented by the voltage source V_0 with the impedance $Z_0 = 120\pi\ \Omega$, and the enclosure wall with an aperture is replaced by the impedance Z_{ap}. The enclosure is considered as a short-circuited waveguide with characteristic impedance Z_g and a propagation constant k_g. To calculate the SE, the equivalent circuit is transformed using the Thevenin's theorem and formulas for the input impedance of the transmission line.

The process of scattering electromagnetic field by a conducting plate located inside the enclosure can be represented by additional impedance in the equivalent circuit [10]. Thus, Fig. 1(a) shows an enclosure with dimensions $a \times b \times d$ populated with a conducting plate of height h. The aperture of height r is formed between the enclosure upper wall and the plate. The plate is located at a distance g from the front wall of the enclosure. The observation point P is located between the enclosure rear

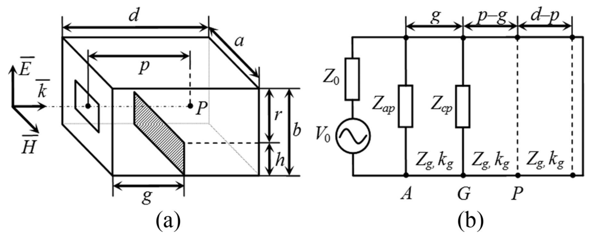

Fig. 1. (a) Metal rectangular enclosure populated with the conducting plate and (b) the equivalent circuit for calculating SE.

wall and the plate. The equivalent circuit for this structure is shown in Fig. 1(b), where the conducting plate is represented by the impedance Z_{cp}. If the enclosure is populated with a set of conducting plates, then the equivalent circuit must be changed so that each of the plates has corresponding impedance Z_{cp}.

B. Conducting Plate Impedance

The impedance of the conducting plate can be calculated as $Z_{cp} = 1/jB$, where B is the susceptance of an infinitely thin unsymmetrical capacitive waveguide diaphragm. When the enclosure is excited by TE_{10} mode, for a plate of a small height ($h/b<<1$) B is given by [14]

$$B = \frac{8b}{\lambda_g Z_0}\left\{\ln\left(\frac{2b}{\pi r}\right) + \frac{1}{6}\left(\frac{\pi r}{2b}\right)^2 + \frac{1}{2}\left(\frac{2b}{\lambda_g}\right)^2\left[1-\frac{1}{2}\left(\frac{\pi r}{2b}\right)^2\right]^4\right\} \tag{1}$$

where λ_g is the enclosure wavelength, which can be calculated as a function of a source wavelength λ from

$$\lambda_g = \lambda\Big/\sqrt{1-(\lambda/2a)^2}.$$

If the plate has a large height ($r/b<<1$), then B can be calculated as [14]

$$B = \frac{4b}{\lambda_g Z_0}\left[\frac{\pi h}{2b} + \frac{1}{6}\left(\frac{\pi h}{2b}\right)^2 + \frac{3}{2}\left(\frac{2b}{\lambda_g}\right)^2\left(\frac{\pi h}{2b}\right)^4\right]. \tag{2}$$

In the case where the plate height is close to the aperture height ($h = r = b/2$), B is given by [14]

$$B = \frac{8bY_0}{\lambda_g}\left\{\ln\left[\csc\left(\frac{\pi r}{2b}\right)\right] + \frac{Q\cos^4\left(\frac{\pi r}{2b}\right)}{1+Q\sin^4\left(\frac{\pi r}{2b}\right)} + \frac{1}{4}\left(\frac{b}{\lambda_g}\right)^2\left[1-3\sin^2\left(\frac{\pi r}{2b}\right)\right]^2\cos^4\left(\frac{\pi r}{2b}\right)\right\} \tag{3}$$

where $Q = [1-(2b/\lambda_g)^2]^{-0.5} - 1$.

If the relations between h, b, and r are broken, then the calculation error increases. However, (1)–(3) can still be used to evaluate the SE with reasonable accuracy. It was proved by the results of the error evaluation (see Section III).

The proposed model can be improved for the analysis of finite thickness plates. In order to do that, the impedance Z_{cp} in the equivalent circuit must be replaced by a π-circuit [14], which consists of one inductive and two capacitive reactances.

C. PCBs or Coated Plates

Modern PCBs are made up of conductive tracks, ground planes, electronic components and dielectric layers. In the early stages of the ED design, to evaluate SE the conductive layers of a PCB can be replaced by a plate. The attenuation of electromagnetic field in the dielectric layers can be taken into account if we coat the conducting plate with a material of thickness t equal to the thickness of the PCB [10]. In order to do that, it is necessary to change the characteristic impedance and the propagation constant of the waveguide in the plate region. In general terms, Z_g and k_g can be calculated as [15]

$$Z_g = \frac{Z_0\sqrt{\mu_r/\varepsilon_r}}{\sqrt{1-(\lambda_s/2a)}}$$

$$k_g = \frac{2\pi}{\lambda_s}\sqrt{1-(\lambda_s/2a)^2}$$

where $\lambda_s = \lambda/(\varepsilon_r\mu_r)^{1/2}$ is the wavelength in a homogeneous medium filled with a material with the relative permittivity ε_r and the relative permeability μ_r. In this model, we use relative values of ε_r and μ_r rather than effective ones, because they are enough for making an approximate evaluation of the SE. The presented equations can be used to evaluate the SE of an enclosure populated with PCBs. They can also be used for plates coated with composite or radar-absorbing materials with $\mu_r > 1$.

III. Validation of the Analytical Model

To validate the model, SE calculations were performed in the frequency range of 1–1000 MHz. The enclosure used had the dimensions of $300 \times 120 \times 300$ mm^3 and the aperture of 80×80 mm^2 in the center of the front wall. The results obtained by the presented model were compared with the results obtained by the finite element method (FEM). When calculations were performed by FEM, adaptive mesh refinement was used. The initial number of cells per wavelength was 40, and the mesh refinement percentage did not exceed 30% of the total number of elements at each step. A perfect conductor was used as the material for the enclosure and plates, and the SE was determined from the electric field strength.

A. Analytical Model Error

To evaluate the error of the model, the SE of the enclosure with one conductive plate was calculated at $g = 150$ mm, $P = 225$ mm, and $h = 10, 20\ldots110$ mm. Equations (1)–(3) were used in the ranges of $h = 10\ldots40$ mm, $h = 80\ldots110$ mm, and $h = 40\ldots80$ mm, respectively. Fig. 2(a) shows the dependence of the average (in the entire frequency range) value of the SE absolute error (Δ) on the value of h. For the structure under investigation, the maximum value of Δ was 3.7 dB at $h = 80$ mm. Moreover, the behavior of Δ is similar to the deviation (δ) of the first resonant frequency values obtained by the analytical model and FEM [see Fig. 2(b)].

Fig. 3 shows the difference between the results obtained using FEM, (2) and (3) for the enclosure populated with the plate of

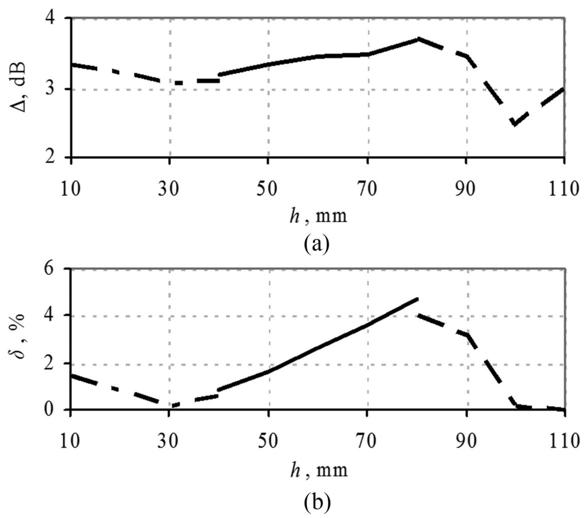

Fig. 2. (a) Dependencies of the average value of the absolute error and (b) the resonance frequency deviation on h for the SE results obtained using (1) (– - –), (2) (– – –) and (3) (——).

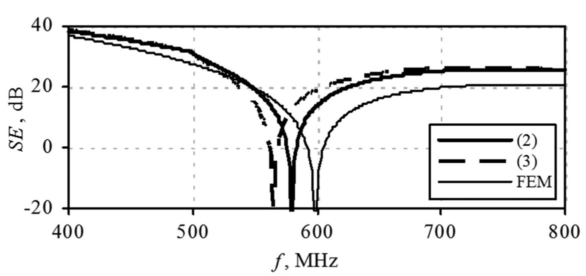

Fig. 3. Frequency dependencies of the SE for the enclosure populated with the conducting plate with a height of $h = 80$ mm.

$h = 80$ mm, i.e., when δ and Δ were maximal. The difference between the resonant frequencies is 19 and 34 MHz for the frequency dependencies (2) and (3), respectively, which means that δ does not exceed 5%. The results show that the model allows for the calculation of the populated enclosure SE with a reasonable accuracy.

B. Enclosure Populated With Conducting Plate Set

Using both the proposed model and FEM, the SE was calculated for the enclosure with a set of three conducting plates at $P =$ 240 mm. The dimensions of the enclosure and plates are shown in Fig. 4(a). The equivalent circuit for this structure is shown in Fig. 4(b). The plate of height h_2 is represented by the impedance Z_{cp2}, which was calculated using (2). The impedance Z_{cp1} for the plate of height h_1 was calculated using (1).

The results of SE calculations for the populated enclosure and the empty one (using FEM) are presented in Fig. 4(c). It can be seen that in the frequency range up to 550 MHz, the SE of the populated enclosure and the empty one are approximately equal. However, the first resonant frequency decreases by more than 80 MHz for the populated enclosure. The SE dependencies obtained by FEM and the analytical model are in good agreement up to a frequency of 900 MHz. In this range, the average value of the absolute error for the frequency dependencies was

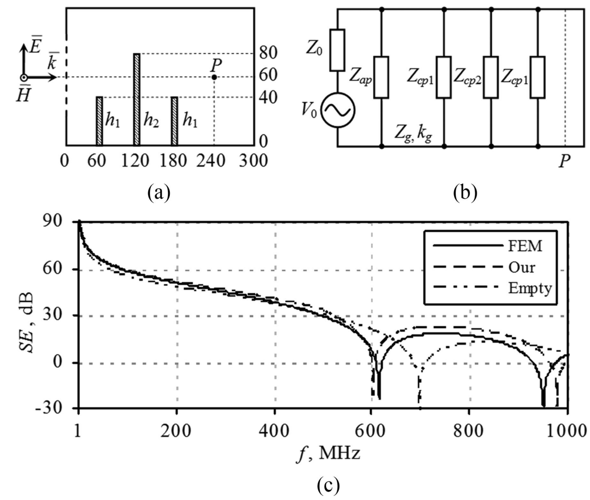

Fig. 4. (a) Geometry of the enclosure populated with three conducting plates, (b) its equivalent circuit, and (c) the frequency dependencies of the SE.

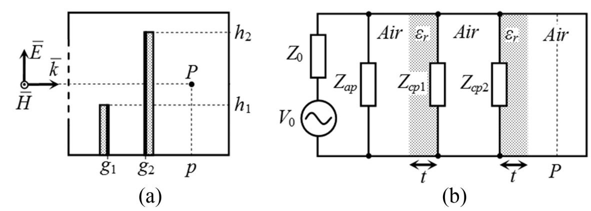

Fig. 5. (a) Side view of the enclosure populated with two PCBs (b) and its equivalent circuit.

2.6 dB. However, in Fig. 4(c) the error in determining the second resonant frequency by the analytical model increased to 3%.

C. PCBs or Coated Plates

Using the proposed model, the SE of the enclosure populated with two PCBs was calculated. The enclosure geometry and its equivalent circuit are shown in Fig. 5. The first PCB with a height of $h_1 = 40$ mm is located at $g_1 = 75$ mm, and the second PCB with a height of $h_2 = 100$ mm is located at $g_2 = 150$ mm. The thickness t of the PCBs was 1.5 mm, and $P = 225$ mm. To calculate Z_{cp1} and Z_{cp2}, (1) and (2) were used, respectively. As the material for the PCBs, fiberglass with $\varepsilon_r = 4.5\ (\mu_r = 1)$ was used. In calculations performed with the use of FEM, the values of ε_r and μ_r were assumed to be constant over the entire frequency range. Also, FEM was used to calculate the SE of the empty enclosure at $P = 225$ mm.

The SE calculation results are presented in Fig. 6. It can be seen that the frequency dependencies obtained by the analytical model and FEM are in good agreement. The average value of the absolute error was 3.4 dB. In the frequency range up to 500 MHz, at the selected observation point, the SE values of the empty enclosure and the populated one are approximately equal (the difference is no more than 5 dB). But the first resonant frequency of the empty enclosure is 135 MHz larger.

Next, for $P = 150$ mm, the SE was calculated for the enclosure populated with one conducting plate coated with a composite material ($t = 2$ mm, $\varepsilon_r = 9.2$ and $\mu_r = 1.5$) from the side of the

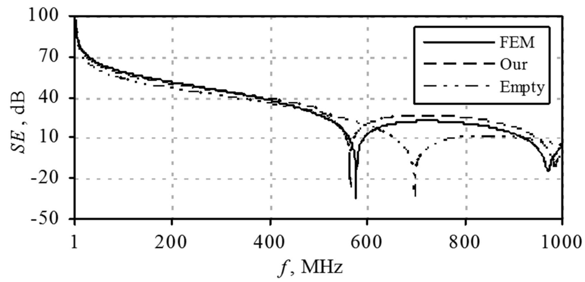

Fig. 6. Frequency dependencies of the SE for the enclosure populated with two PCBs.

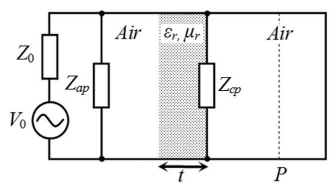

Fig. 7. Equivalent circuit of the enclosure populated with the coated plate.

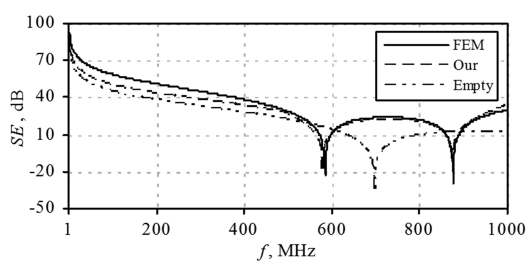

Fig. 8. Frequency dependencies of the SE for the enclosure populated with a coated conducting plate.

aperture. The plate with a height of $h = 100$ mm was located at $g = 75$ mm. The equivalent circuit for this structure is shown in Fig. 7.

The calculation results are shown in Fig. 8. The frequency dependencies obtained by the analytical model and FEM are in good agreement. The maximum difference between the results does not exceed 9.2 dB, and the average value of the absolute error was 4.6 dB. In the range up to 550 MHz, the SE of the populated enclosure is 10–14 dB higher than of the empty one. In the results described above, this does not happen because the plate located in the enclosure is equivalent to the capacitive reactance Z_{cp}, which changes only the resonant frequencies. In this structure, the SE increases due to the use of a magnetic material with $\mu_r > 1$.

IV. Conclusion

This letter presents the analytical model for evaluating the SE of the rectangular enclosure populated with conducting plates. The model can be used to calculate the SE when the enclosure is populated with one or more plates of different heights. In addition, the work describes the improved approach for evaluating the SE of an enclosure populated with PCBs or conducting plates coated with a composite or radar-absorbing material. The results obtained by using this model are in good agreement with the results obtained with FEM. Moreover, the model is simpler than in [10], and it requires significantly less computational resources compared to numerical methods. Therefore, it can be successfully applied in the design of ED, taking into account the requirements of electromagnetic compatibility.

It should be noted that individual details related to the proposed model (mutual interaction of plates, calculation of SE in a wider frequency range or for large-sized enclosures, analysis of finite thickness plates, etc.) are beyond the scope of this letter, but will be investigated in the future.

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