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Semi-analytical Approach for Calculating Shielding Effectiveness of an Enclosure with a Filled Aperture

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ABSTRACT

The paper proposes a semi-analytical approach to improve the analytical method of an enclosure equivalent circuit. This approach is based on the application of a quasi-static analysis of coplanar striplines in the calculation of the Z_{ap} impedance for an enclosure wall with an aperture. Using this approach in conjunction with existing analytical models, the shielding effectiveness can be calculated for an enclosure with an aperture filled with an arbitrary dielectric or magnetic content. The study also presents the results of extensive validation of the proposed approach in the frequency range up to 3 GHz.

Index Terms—Shielding effectiveness, enclosure, equivalent circuit method, quasi-static simulation, coplanar stripline

I. INTRODUCTION

In the process of designing a shielding enclosure, it is necessary to take into account all the features of its construct that can affect the shielding effectiveness (SE). For example, the enclosure content [1-4] or its apertures filling [5,6] can have a significant effect on the SE. The SE of a highly-detailed enclosure can be determined using different numerical methods [7-9], but it can require significant computational costs [10]. For this reason, the development and improvement of fast hybrid, analytical and semi-analytical methods for calculating the SE is an actual task.

This paper proposes a semi-analytical approach for calculating the SE of an enclosure with an aperture filled with a dielectric or magnetic material. The proposed approach makes it possible to improve the analytical method of an enclosure equivalent circuit [11] by applying quasi-static simulation in the calculation of the Z_{ap} impedance for a wall with an aperture. This approach to the SE evaluation is faster than methods of computational electrodynamics and different semi-analytical techniques based on them [12,13]. It can be combined with many existing analytical models formulated for evaluating the SE of filled enclosures [2,3], enclosures with apertures on several walls [14], etc.

II. THEORY

According to [11], a shielding enclosure with an aperture excited by a plane wave can be represented in the form of an equivalent circuit (Fig. 1). In this circuit, the plane wave is replaced by the voltage source V_0 with an internal resistance $Z_0 = 120\,\pi\,\Omega$, the enclosure is presented as a short-circuited segment of a rectangular waveguide, and the enclosure front wall is replaced by the Z_{ap} impedance. In return, the value of Z_{ap} is determined based on parameters of the coplanar stripline (CPS) as [11]

$$Z_{ap} = j\frac{1}{2}C_a Z_c \tan\left(k_c \frac{l}{2}\right) \tag{1}$$

where l is the aperture width, C_a is a correction factor that determines the coupling between the enclosure and its front wall, Z_c is the characteristic impedance of the CPS, and k_c is the propagation constant.

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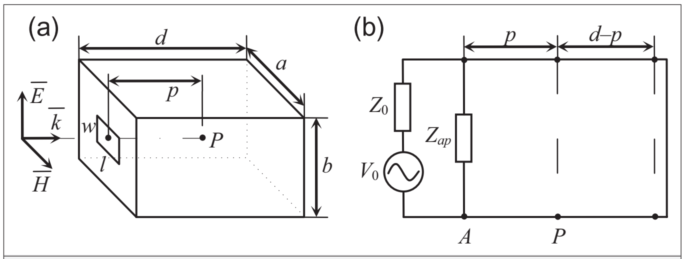

Fig. 1. (a) Shielding enclosure with aperture and (b) its equivalent circuit for calculating the SE. SE, shielding effectiveness.

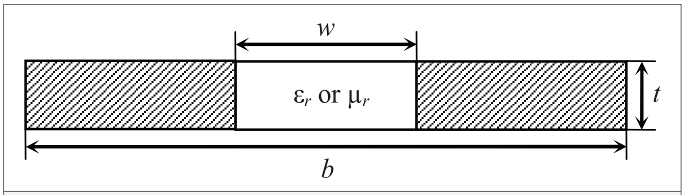

Fig. 2. Cross-section of a CPS with an arbitrary filling of the aperture (the ε_r and μ_r values represent a relative permittivity and a relative permeability of the material).CPS, coplanar stripline.

When the enclosure aperture is filled with a dielectric or magnetic material, the value of k_c for the equivalent CPS (see Fig. 2) can be calculated as

$$k_c = \frac{2\pi}{\lambda}\sqrt{\varepsilon_{re}\mu_{re}} \tag{2}$$

where λ is the wavelength of the plane wave source, εre and μre are effective values of relative permittivity and a relative permeability of the material filling the CPS, respectively.

The values of ε_{re} and μ_{re} in (2) can be obtained using quasi-static simulation of the CPS per-unit-length parameters as $\varepsilon_{re} = C/C_0$ and $\mu_{re} = L/L_0$, where C_0 and L_0 are the per-unit-length capacitance and inductance of the CPS without filling, C and L are the same capacitance and inductance but with dielectric or magnetic filling of the CPS, respectively. Moreover, if we use the electrostatic analogy proposed in [15], then the value of μ_{re} can be calculated as $\mu_{re} = C_0/C'$, where C' is the additional per-unit-length capacitance of the CPS, in which the space between the conductor edges is filled with a material that has $\varepsilon'_r = 1/\mu_r$.

Combining the above and taking into account $Z_c = (L/C)^{1/2}$ and $L = \mu_0\varepsilon_0 (C')^{-1}$ [15], the impedance of a wall with an aperture can be calculated for several cases. Thus, if the material filled the aperture has $\mu_r = 1$ and $\varepsilon_r > 1$, then

$$Z_{ap} = j\frac{1}{2}C_a\frac{1}{c\sqrt{CC_0}}\tan\left(\frac{\pi l}{\lambda}\sqrt{\frac{C}{C_0}}\right) \tag{3}$$

where $c \approx 3\times10^8$ m/s is the speed of light in free space. When the aperture is filled with a material with $\mu_r > 1$ and $\varepsilon_r = 1$

$$Z_{ap} = j\frac{1}{2}C_a\frac{1}{c\sqrt{C'C_0}}\tan\left(\frac{\pi l}{\lambda}\sqrt{\frac{C_0}{C'}}\right). \tag{4}$$

Finally, combining (3) – (4), Z_{ap} can be calculated when the aperture filling has $\mu_r > 1$ and $\varepsilon_r > 1$ as

$$Z_{ap} = j\frac{1}{2}C_a\frac{1}{c\sqrt{C'C}}\tan\left(\frac{\pi l}{\lambda}\sqrt{\frac{C}{C'}}\right). \tag{5}$$

Using (3)–(5) in conjunction with quasi-static simulation, it is possible to calculate the Z_{ap} impedance of a wall with an aperture filled with dielectric or magnetic content of arbitrary shape. In the process, a simple l/a ratio from [11] or one of the improved coupling coefficients from [16,17] can be used as C_a. As a result, the calculated Z_{ap} value can be used to evaluate the enclosure SE according to the model from [11] or another model based on an enclosure equivalent circuit.

III. EFFECT OF APERTURE FILLING

To validate the proposed approach, the influence of ε_r and μ_r values on the resonance frequencies of the filled aperture was evaluated. The wall ($a \times b = 300 \times 120$ mm^2 and $t = 1$ mm) with an aperture of 160×4 mm^2 filled with a material with $\varepsilon_r = 1$, 5, 10 and $\mu_r = 1$, 2, 5 was used as a structure under test (many modern polymer composite materials, e.g., based on ferrite particles [18,19], have such values of ε_r and μ_r). The Z_{ap} impedance was calculated according to (3)–(4) using a quasi-static analysis by the method of moments [20] at $C_a = l/a$. The change in resonance frequencies was also evaluated using the finite-difference time-domain method (FDTD). For this purpose, the frequency dependencies of the *E*-field strength behind an infinitely extended plane shield with the aperture were calculated (see the model in Fig. 3). In the FDTD simulation, the number of cells per wavelength was 60, and a perfect conductor was used as the shield material. The frequency dependencies of the $|E|$ and the Im(Z_{ap}) in the range of 1–3000 MHz for different values of ε_r and μ_r are presented in Figs. 4 and 5.

The results show that the dielectric or magnetic filling of the aperture leads to a significant change in its resonance frequencies. It proves the importance of taking into account the content of the aperture at the SE analysis. The results also confirm that the proposed semi-analytical approach makes it possible to determine the resonance frequency of the filled aperture with acceptable accuracy. For example, in Fig. 4, the difference between the resonance frequencies calculated by the proposed approach and using the FDTD does not exceed 4%. However, the use of tan function in (3)–(5) leads to the fact that Z_{ap} goes to infinity at the aperture resonance frequencies, which limits the accuracy of the SE evaluation at these frequencies.

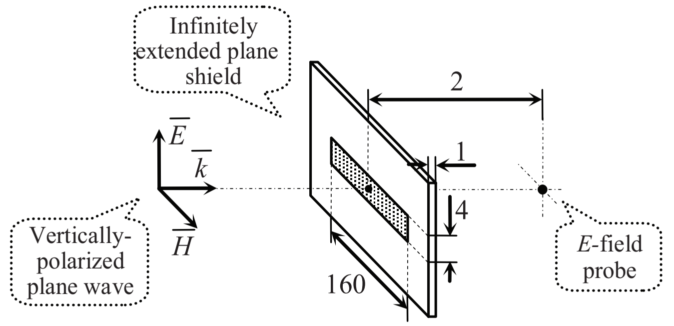

Fig. 3. Plane-wave incidence on an infinitely extended plane shield with an aperture (dimensions are in mm).

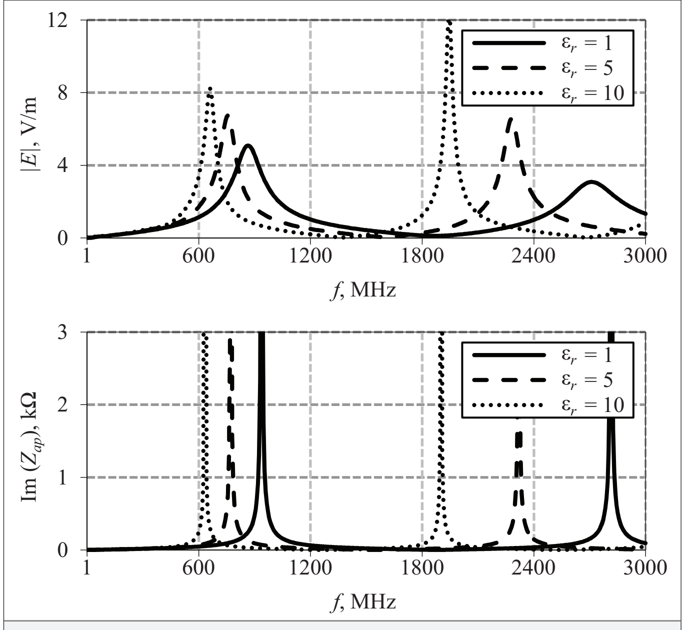

Fig. 4. Frequency dependencies of |*E*| and Im(Z_{ap}) when the value of ε_r for the aperture filling change (at resonance frequencies Im(Z_{ap}) goes to infinity).

IV. CALCULATION OF SHIELDING EFFECTIVENESS

Using the proposed approach and the finite element method (FEM), in the frequency range of 1–3000 MHz, the SE of the enclosure (300 × 120 × 240 mm^3) with the aperture of 160 × 4 mm^2 was calculated. Four cases were considered. In the first case, the aperture was unfilled and Z_{ap} was calculated using (3) at $\varepsilon_r = \mu_r = 1$ (or $C = C_0$). In the second and third cases, to validate (3) and (4), the values $\varepsilon_r = 10$ and $\mu_r = 5$ were used, which earlier gave the largest change in resonant frequencies (Figs. 4, 5). In the fourth case, (5) was validated and the aperture was filled with a composite material based on ferrite powder with $\varepsilon_r = 12$ and $\mu_r = 5$. In all cases, the plane wave was vertically polarized and oriented toward the enclosure wall as shown in Fig. 1(a). Values of ε_r and μ_r remained constant over the entire frequency range.

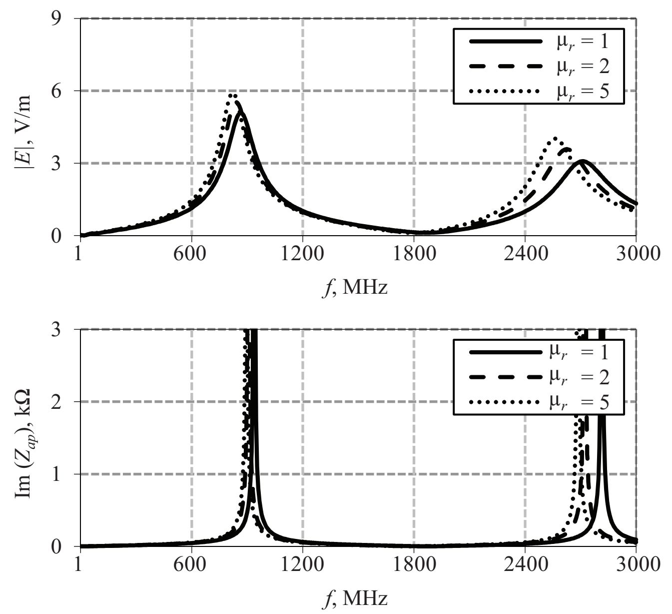

Fig. 5. Frequency dependencies of |*E*| and Im(Z_{ap}) when the value of ε_r for the aperture filling change.

By the semi-analytical approach calculation, the SE was determined based on the technique from [17], which allows one to take into account the propagation of higher-order modes in the enclosure. In the FEM simulation, the SE was calculated from the *E*-field strength, and a perfect conductor was used as the enclosure material. The number of cells per wavelength was 70, and the mesh became more frequent in the area of the enclosure aperture. The obtained frequency dependencies of the SE for all described cases are presented in Fig. 6.

It can be seen that the results obtained by the FEM and the proposed approach are in agreement. Resonance frequencies of the aperture differ by not more than 4%. The average value of the absolute error for the results is 9.4 dB, and the main contribution to the error is made by the SE maxima caused by the use of [17]. The average time (for all considered cases) for calculating the frequency dependencies of the SE from 1200 points using the FEM and the proposed approach was 48834 s and 5.58 s, respectively (PC with Intel Core i9-7980XE and 128 GB of RAM). Thus, the acceleration of computations is 8751 times.

The obtained results show that the filling of an aperture leads to a shift of its resonance frequencies and hence to a shift of the corresponding SE minima. Moreover, ε_r affects the change in resonance frequencies more significantly than μ_r. At high values of ε_r and μ_r, resonance frequencies of an aperture can change so much that in the investigated frequency range, the number of these resonances increases, which can be seen from the comparison of Fig. 5(a) and (d). At the same time, the SE can increase in a certain frequency range due to the shift of the aperture resonance. For example, frequency dependencies calculated by the FEM show that for the unfilled aperture, the SE is 7 dB at the 1.2 GHz (Fig. 5(a)), and for the aperture filled with the dielectric (Fig. 5(b)), the SE reaches 15 dB at the same frequency. Thus, Fig. 5 proves that the frequency dependence of the SE can change significantly when the enclosure aperture is filled.

V. DISCUSSION

Figs. 4–5 prove the validity and acceptable accuracy of the proposed approach. However, the variant of this approach described in this study has a few limitations. For example, Z_{ap} does not take into account the losses in the material filling the aperture, since in (3)–(5), only the per-unit-length capacitances of the CPS are used. This limitation can be overcome by taking into account quasi-static simulation of the per-unit-length conductivity *G* and resistance *R*, which determine the losses in the filling material and CPS conductors, respectively. However, in this case, (3) – (5) should be modified in order for Z_{ap} to be calculated from the characteristic impedance of the CPS. Another limitation is the impossibility of taking into account the arbitrary position of the aperture in the enclosure wall at $C_a = l/a$. Nevertheless, the aperture offset can be performed using the C_a coefficient from [16,17] or an asymmetric CPS in the simulation.

The main error in (3)–(5) is introduced by the results of calculating the per-unit-length capacities of the CPS, since they define the

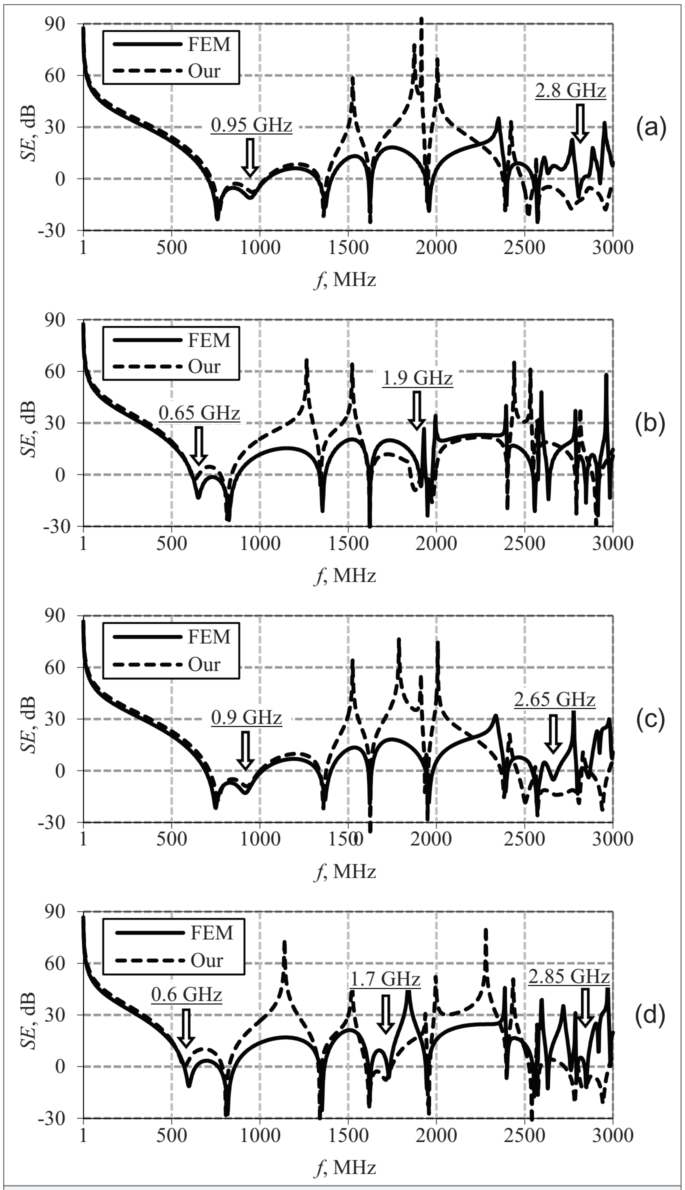

Fig. 6. Frequency dependencies of the SE for the enclosure with the filled aperture: (a) $\varepsilon_r = \mu_r = 1$ (unfilled); (b) $\varepsilon_r = 10$ и $\mu_r = 1$; (c) $\varepsilon_r = 1$ и $\mu_r = 5$; (d) $\varepsilon_r = 12$ и $\mu_r = 5$. SE, shielding effectiveness. Arrows denote resonances of the aperture.

argument of the tan function and the value of the impedance Z_c. At the same time, for most real enclosures, the equivalent CPS has a significant width and small thickness of conductors. To analyze such structures, a high mesh density is required, which leads to an increase in computational costs. Therefore, in the simulation of the CPS, it is most rational to use numerical methods with the surface discretization of structure boundaries (e.g., as the method of moments used in this paper).

VI. CONCLUSION

The paper presents a semi-analytical approach for calculating the SE for enclosures with an aperture filled with a dielectric or magnetic material. The proposed approach was validated. It was shown that it has an acceptable accuracy in comparison with numerical methods and at the same time requires much less time. The results of evaluations made by numerical methods and the proposed approach show that the aperture filling can significantly affect the SE of the enclosure. Therefore, in the process of designing a shielding enclosure, it is necessary to pay considerable attention to the internal contents of the enclosure, in particular, to the filling of its apertures.

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