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Analytical model of a shielding enclosure populated with arbitrary shaped dielectric obstacles

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Abstract. This paper proposes a new analytical model for an approximate evaluation of the shielding effectiveness (SE) for an enclosure populated with arbitrary shaped dielectric obstacles. The model is based on the enclosure equivalent circuit method proposed by Robinson et al. Dielectric obstacles are taken into account in the calculation of the characteristic impedance and the propagation constant for each regular part situated along the enclosure length. To do this, the model uses the effective value of relative permittivity, which is determined in the cross section of each regular part from a simple percentage ratio. Using the proposed model and the finite element method, the SE calculations were performed for three typical enclosures populated with different dielectric obstacles. The obtained results are in good agreement, and the average value of the absolute error does not exceed 4.4 dB.

1. Introduction

The important task of modern electronic engineering is to protect the devices being designed against the harmful effects of radiated emissions. One of the ways to overcome the influence of such emissions is to insert devices or their individual elements into a shielding enclosure. The shielding effectiveness (SE) of these enclosures is usually evaluated in accordance with IEEE-299 and MIL-STD-285 standards. However, this evaluation does not take into account the elements and units of the device located inside the enclosure. At the same time, modern studies [1–3] show that the enclosure filling significantly affects the SE. Therefore, any conductive and non-conductive obstacles populating the enclosure must be considered at the stage of designing a shielding enclosure. For this purpose, numerical methods can be applied, such as the finite element method (FEM) [4], the transmission line matrix method [5], the finite-difference time-domain method [6], etc. However, such methods require significant computational costs and are not suitable for performing multiple SE calculations, which are necessary if the location of the device elements inside the enclosure is not known in advance and several possible options need to be considered. It is obvious that for this task it is advisable to use analytical models. They have already been proposed for the analysis of enclosures populated with PCBs [7–9], wire interconnections [10] and metal posts [11]. The aim of this work is to develop an analytical model for a shielding enclosure populated with dielectric obstacles of arbitrary shapes.

2. Analytical model

The proposed model was based on the method from [12]. According to this method, an apertured enclosure irradiated by a plane wave can be represented as an equivalent circuit. In this circuit, the plane



wave is replaced by the voltage source V_0 and the resistance $Z_0=377 \Omega$; and the enclosure front wall containing the aperture is given as the Z_{ap} impedance. At the same time, the rest of the enclosure is replaced by a short-circuited section of the transmission line which has the characteristic impedance Z_g and the propagation constant k_g . After setting the necessary parameters, the equivalent circuit of the enclosure is transformed using Thevenin's theorem. The enclosure SE is then determined based on the current or voltage in the transformed equivalent circuit.

In the model proposed in this work, the enclosure is replaced by a set of n transmission lines segments to take into account dielectric obstacles in the equivalent circuit. Moreover, the number n of such segments corresponds to the number of regular enclosure parts located along its length d (see figure 1). The regular part of the enclosure is the part whose electrophysical parameters and cross-section do not change in the longitudinal direction (along the length d). For each of n parts, the characteristic impedance and propagation constant can be calculated as [13]

$$Z_{g(n)} = \frac{Z_0 / \sqrt{\epsilon_{eff(n)}}}{\sqrt{1 - (\lambda'_{(n)} / 2a)^2}},$$

$$k_{g(n)} = \frac{2\pi}{\lambda'_{(n)}} \sqrt{1 - (\lambda'_{(n)} / 2a)^2}$$

where a is the width of the enclosure, $\epsilon_{eff(n)}$ is the effective value of the relative permittivity in the cross-section of the n -th regular enclosure part, and

$$\lambda'_{(n)} = \lambda / \sqrt{\epsilon_{eff(n)}}$$

where λ is the wavelength of the source exciting the enclosure.

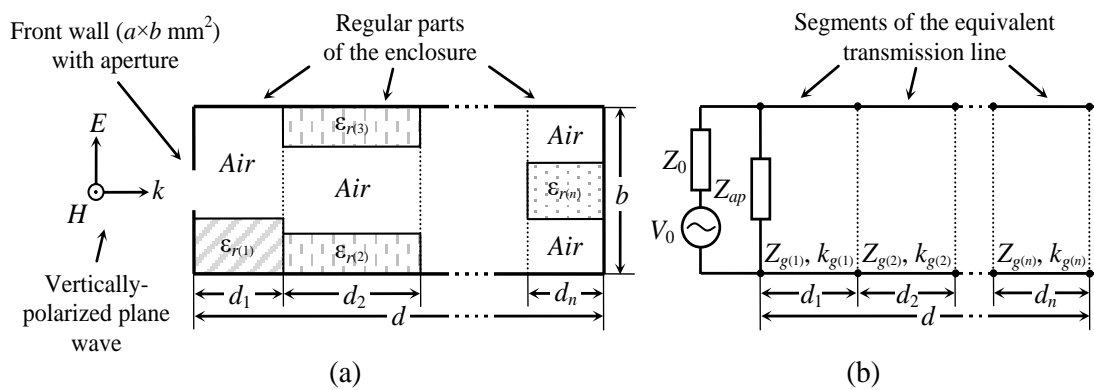


Figure 1. Side view of the rectangular enclosure populated with dielectric obstacles (a) and its equivalent circuit from a set transmission line segments (b).

The $\epsilon_{eff(n)}$ value can be approximately calculated using a simple analytical expression based on the percentage ratio of dielectrics areas in the cross section of the regular enclosure part [14]. In general, for the n -th structure populated with a set of m_n dielectric obstacles (figure 2), $\epsilon_{eff(n)}$ can be calculated as

$$\epsilon_{eff(n)} = \left(\sum_{i=0}^{m_n} \frac{S_{(i)}}{ab \sqrt{\epsilon_{r(i)}}} \right)^{-2}$$

where b is the height of the enclosure, $S_{(i)}$ is the area occupied by the m_n -th dielectric obstacle in the cross-section of the n -th part of the enclosure, $\epsilon_{r(i)}$ is the relative permittivity of the m_n -th dielectric

obstacle, and the lower limit of the summation is 0, since the calculation must take into account the area occupied by the air.

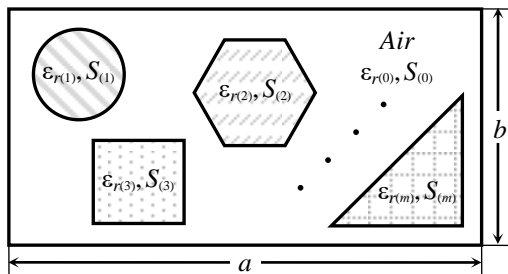


Figure 2. Cross-section of the n -th regular enclosure part populated with a set of m_n dielectric obstacles.

Using the proposed expressions, all subsequent calculations of the SE for the enclosure populated with dielectric obstacles can be performed in full accordance with the methodology described in [12]. In addition, the proposed model can be combined with other analytical models based on the equivalent circuit of the enclosure, for example with [7–11]. Thus, the SE of an enclosure can be calculated taking into account any conductive and non-conductive obstacles located inside it.

3. Calculation examples

To validate the proposed model, the SE calculations were performed for three enclosures populated with dielectric obstacles in the frequency range of 1–1000 MHz. In all cases, a standardized enclosure with dimensions of $a=d=300$ mm, $d=120$ mm and an aperture (80×80 mm²) was used [15]. The observation point was located in the center of the enclosure. The SE frequency dependences were also obtained using the FEM. When calculations were performed by the FEM, the SE was determined from the electric field strength, and a perfect conductor was used as the enclosure material. The discretization of the structure was carried out using adaptive mesh refinement. 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. The assigned values of the relative permittivity remained invariable over the entire frequency range.

In the first case, the SE was calculated for the enclosure whose bottom was completely coated with a dielectric material ($\epsilon_r=3$) 20 mm high (figure 3(a)). Since this enclosure is regular along the entire length d , its equivalent circuit for the SE calculation by the analytical model consisted of one short-circuited transmission line section. The frequency dependencies of the SE for this structure calculated by the analytical model and the FEM are shown in figure 3(b). The dependencies are in good agreement and the average value of the absolute error is 4.4 dB.

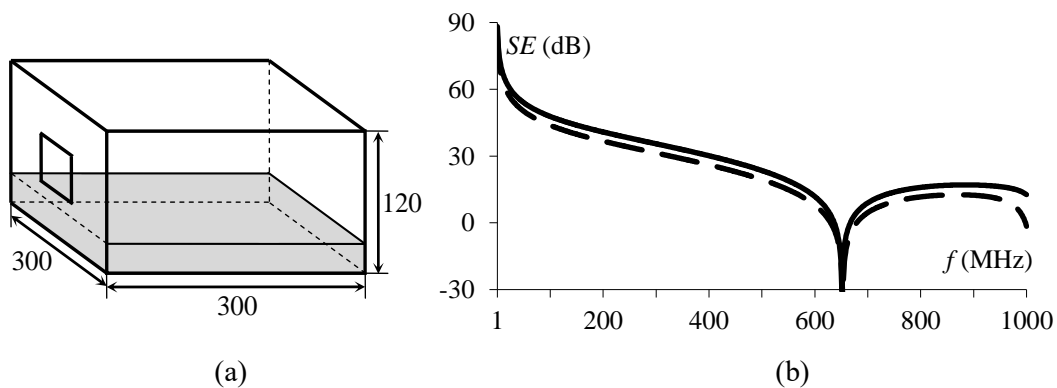


Figure 3. (a) Geometry of the enclosure with a coated bottom; (b) frequency dependencies of the enclosure SE, calculated by the proposed model (—) and the FEM (---).

While calculating the SE for the second enclosure, two the same rectangular dielectric obstacles ($\epsilon_r=5$) 100 mm long and 30 mm high were located inside it (figure 4(a)). The obstacles were placed at the walls of the enclosure in such way that it had three regular parts, i.e. the equivalent circuit consisted of three transmission lines sections. The results of the SE calculation for this case are shown in figure 4(b). It can be seen that the dependencies obtained by the FEM and the analytical model show a slight difference in the resonant frequencies of the enclosure (no more than 25 MHz or 3%). However, the average value of the absolute error is less than for the dependencies from figure 3(b) and is only 3.7 dB.

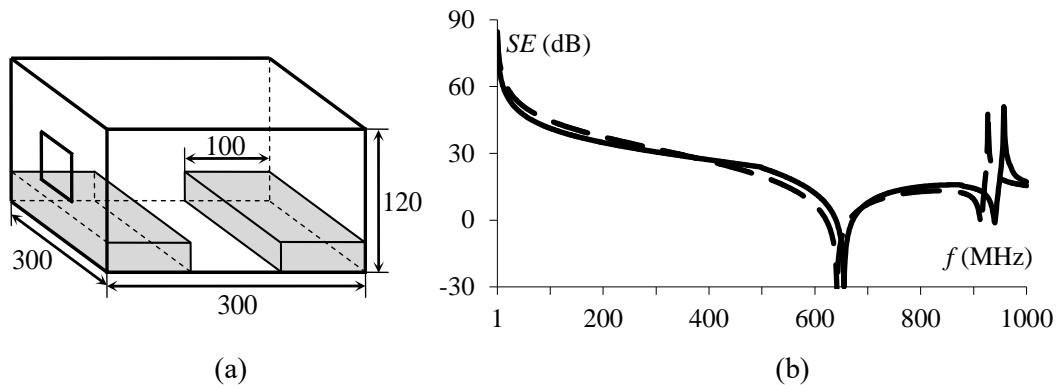


Figure 4. (a) Geometry of the enclosure populated with rectangular obstacles; (b) frequency dependencies of the enclosure SE calculated by the proposed model (—) and the FEM (---).

In the third case, the SE was calculated for the enclosure populated with two cylindrical obstacles 50 mm in diameter. The obstacles were located along the enclosure at the height of 60 mm from the bottom in such way that the enclosure was regular along its entire length d . The SE frequency dependencies, obtained by the proposed model and the FEM, are shown in figure 5(b). As can be seen, the results are in agreement but there is a slight difference in the resonance frequencies. In this case, the average value of the absolute error is 2.6 dB.

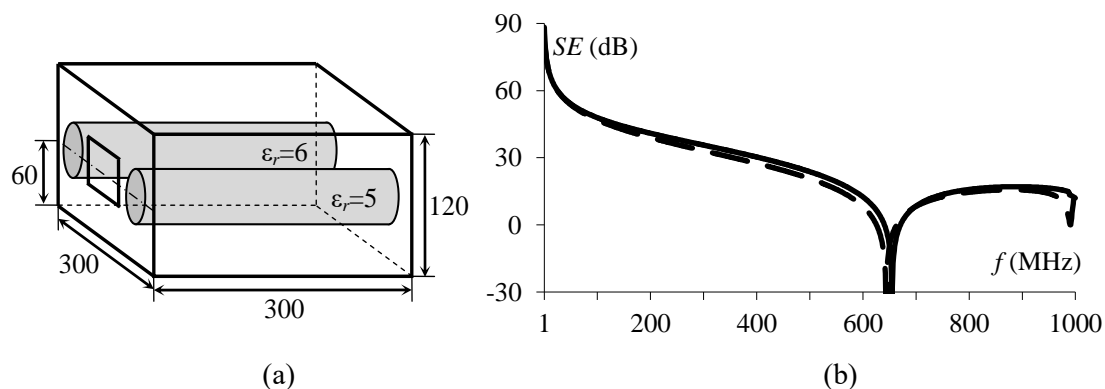


Figure 5. (a) Geometry of the enclosure populated with cylindrical obstacles; (b) frequency dependencies of the enclosure SE calculated by the proposed model (—) and the FEM (---).

4. Conclusion

This paper proposes a new analytical model for an enclosure populated with arbitrary shaped dielectric obstacles. The results obtained in the model validation confirmed that it has an acceptable accuracy and is suitable for an approximate evaluation of the SE for populated enclosures. Moreover, the presented model requires much lower computational costs than any numerical method. Thus, the proposed model can be useful in designing shielding structures that are widely used in modern electronic engineering.

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