# Analysis of the Shielding Effectiveness of Enclosure with Multiple Circular Apertures on Adjacent Walls

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*Abstract* –**In this paper an electromagnetic coupling through apertures and its effect on shielding performance of enclosuresareanalyzed. Multiple apertures, represented by two groups of two circular aperturesplaced on the adjacent rectangular enclosure walls,are considered. The electric effectiveness has been calculatedin the frequency range of EMC interest by applying a numerical TLM method implemented through a commercial software package.A plane wave which propagates in a direction perpendicular to oneof the wallscontaining two aperturesis used as an excitation while the distance between the apertures in each group varies in horizontal or vertical direction.**

*Keywords*–**Enclosure, multiple aperture, coupling, shielding effectiveness.**

## I. INTRODUCTION

In order to reducean emissions from electronic equipment and/or achievean equipment immunity, an electromagnetic (EM) enclosure is being used. Thisenclosure, made of conductive material of suitable thickness and with different EM properties, affects on the amount of EM radiation that reaches the electric circuit from the external environment, but also determines how much energy from the circuit is radiated in the environment. Many devices have enclosures with more apertures for outgoing or incoming cable penetration, control panels, heat dissipation, airing or other purpose. The characteristics of electronic circuit blocks and devices housed within the enclosure can be affected by EM threates through various coupling ports commonly used in electronic systems. Performance of enclosure are determined by the shielding effectiveness (SE), which is defined as the ratio of field strength in the presence and absence of enclosure. The presence of apertures degrades the shielding effectiveness, so it is very important that the coupling through the apertures is taken into account for accurate calculations of SE. There are several methods already developed for the calculation of SE of metal enclosures with apertures on their walls, such as analytical formulations [1], which relies on Fourier transformation and the model analogy. A more complex approach to this problem requires solving the sophisticated problem of scattering using the Mendez`s method [2]. A slots and apertures have a tendency to become a coupling route of electromagnetic interference (EMI) from the external environment inside the enclosure, which degrades the shielding effectiveness. Due to EMI coupling an electronic equipment may degrade the operation of other equipment in the same frequency range. It is very important to understand how factors such as aperture size, shape and mutual spacing, thickness of the enclosure and the position of the apertures affect on the SE and how essential they are in reduction of EMI and sensitivity.

Differential numerical techniques in the time domain, such as the Finite-Difference Time Domain (FDTD) [3] and the method of modeling using trasnmission lines network (Transmission Line Matrix - TLM) [4], owing to its characteristics, have found their application in solving many EMC (*electromagnetic compatibility)* problems in a wide frequency range. The application of these numerical methods for the analysis of practical EMC problems requires a detailed description of geometrical and EM characteristics of the problem and calculation of appropriate parameters in the frequency range of interest. For the vast majority of EMC problems, as the basic requirement it is imposed an adequate numerical modeling of interactions of excited EM fields with geometry of small but in a electrically sense important structures (thin wire structures, complex wired circuits, slots, apertures, etc), embedded within the physical large and shielded systems.

Apertures presence influence to the shielding performance of enclosure has been extensively studied [5]. Simple aperture pattern and orientation has been studied in [6] and with its formulation, the electric and magnetic shielding effectiveness of a rectangular enclosure with one or more apertures in a wall can quickly be predicted. The radiation leakage through the array of apertures is also significantand presented in [7], by the method of moments (MoM). An enclosure with different apperture orientation and dimension is analysed by using FDTD numerical simulations in [8]. A quantitative relationship between EMI and number of apertures and their dimensions is given in the paper [9]. EMI shows a strong depedence on various factors like aperture patterns, their dimensions and number, as well as their orientation according to their orientation on the wall of the enclosure or a plane wave[10-12].Shielding effectiveness was calculated as functions of frequency, aperture dimensions and position not only of an aperturewithin the enclosure, but an incident plane wave also in [13-14].

In this paper, the TLM method implemented through a commercial software package was used to study an effect of

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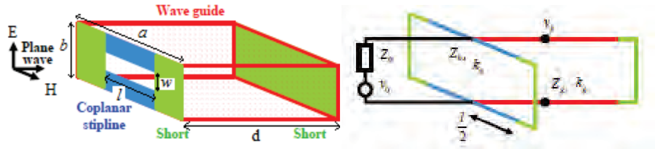
aperture spacing in vertical and horizontal direction on the electric SE ofrectangular enclosure over a frequency range up to 2 GHz. It is assumed that two groups of two circular apertures, placed on the adjacent enclosure walls are present due to outgoing or incoming cable penetration. On the basis of obtained numerical results, relevant conclusions are carried out from the point of effects of multiple aperture coupling to the shielding effectiveness of enclosure.

## II. MODELING OF APERTURES

### *A. Circuit Model for Shielding Effectiveness Calculation*

There are many techniques that deal with multiplenumbers of apertures in an enclosure. Approximate analytical methodsare accurate but applicable only to simple geometries. A simpleanalytical method has been introduced byRobinson et al. based on aTLM [7]. In this method, the rectangular enclosure(Fig. 1a) is modeled by a short-circuited rectangular waveguide, the apertureis represented by a coplanar strip transmission lineand the plane wave incident as excitation isThevenin equivalentwith parameters which represent the strength of the incident field, and $Z_0$ impedance of free space (~ 377 Ω) like in Fig.1b.The exact value of the voltage $v_0$ for the calculation of SE is not relevant because it is expressed as a ratio of two fields.By neglectingthe mutual coupling between multipleapertures, the perforated wallimpedance is the sum of the individual elements.



a) b)

Fig. 1. Rectangular enclosure with an aperture and its equivalent circuit

Characteristic impedance ofshort circuited coplanar strip transmission line section, representing an aperture, can be calculated as:

$$Z_{0cs} = 120\pi^2 \left[ ln \left( 2 \frac{1+\sqrt[4]{1-(2w_e/b)^2}}{1-\sqrt[4]{1-(2w_e/b)^2}} \right) \right]^{-1} \tag{1}$$

where

$$w_e = w - \frac{5t}{4\pi}\left(1+ln\left(\frac{4\pi w}{t}\right)\right) \tag{2}$$

Enclosure is presented as a shorted rectangular waveguide in which the propagation is along the z-axis. Assuming $TE_{10}$ mode, the characteristic impedance and phase constant in the waveguide can be expressed, respectively, as:

$$Z_g = Z_0 / \sqrt{1-(\lambda/2a)^2} \tag{3}$$

$$k_g = k_0\sqrt{1-(\lambda/2a)^2} \tag{4}$$

An equivalent circuit of complete problem is shown in Figure 2b, from which it can be seen that when a section of transmission line is short circuited at the load end, $Z_{ap\_half}$ and $Z_{ap}$ may be written, respectively, as:

$$Z_{ap\_half} = jZ_{0s}\, tan\frac{k_0 l}{2} \tag{5}$$

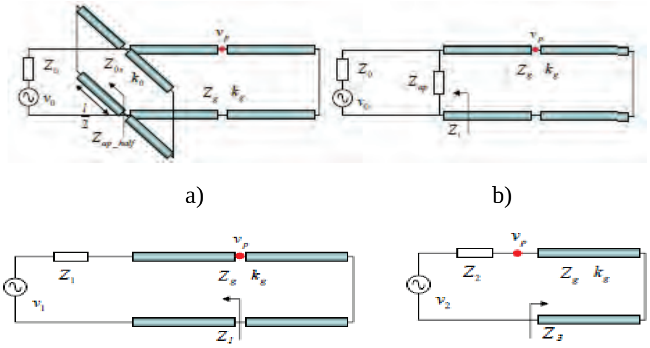
$$Z_{ap} = \frac{l}{a}(Z_{ap\_half} \| Z_{ap\_half}) = \frac{1}{2}\frac{l}{a} jZ_{0s} \tan\frac{k_0 l}{2} \tag{6}$$

Calculation of the electric field inside the enclosure at a distance $p$ from the wall with anaperture is reduced to the calculation of voltage $v_p$ in the equivalent circuit. Equivalent circuit can be further transformed into a Thevenin's equivalent circuit in Figure 2c, where $v_1$and $Z_1$are its components which represent incident field and the impedance of the aperture in Figure 2b. Finally, reduction of Thevenin's equivalent circuit, looking left and right from the coordinate z inside the enclosure gives the circuit in Figure 2d, whose elements are:

$$V_2 = \frac{V_1}{cos(Z_g p) + jZ_1 sin(k_g p)/Z_g}$$

$$Z_2 = \frac{Z_1 + jZ_g tan(k_g p)}{1 + jZ_s tan(k_g p)/Z_g}$$

$$Z_3 = jZ_g \tan[k_g(d-p)] \tag{7}$$



a) b)

c) d)

Fig. 2. Equivalent circuit of the complete problem

Voltage on the distance $p$can be then calculated as:

$$Vp = V_2 Z_3 / (Z_2 + Z_3) \tag{8}$$

Since in the absence of an enclosure electric field at the same point is equalto half of the voltage $V_0$, the final expression for SE is:

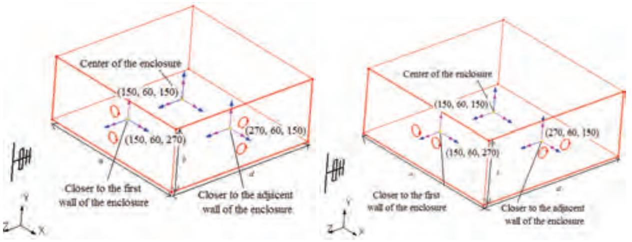
$$SE = 20\log\left(\frac{V_0}{2V(p)}\right) \tag{9}$$

It can be shown that the previously given equations can be also applied for the calculation SE of enclosure with a circular aperture of radius $r$ placed in the center of the front wall, with the approximation $l = w = \sqrt{\pi} r$ .

Limitations of previous circuit model are such that only aperture on single side for normal incident wave and single mode is supported.In cases where the aperture is not in the center of the wall, when there are two or more apertures in the same or different walls of the enclosure or when an incident wave encounters to the plane of the wall with apertures with different propagation and polarization angles,more complex techniques should be applied. Only then it is possible to get complete analysis of the influence of these factors on the SE of enclosure. In this paper,numerical TLM method, implemented through a commercial software package,is applied for the analysis of the impact of changing the horizontal or vertical spacing betweentwo circular apertures in each group of apertures positioned on the two adjacent walls, on the electrical efficiency of the enclosure, and results are presented in the next section.

### *B. Numerical analysis*

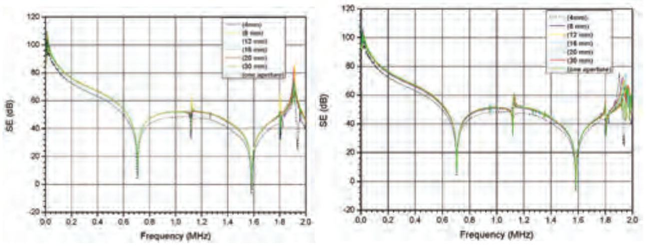
The purpose of this study is toexamine the role of various apertures on coupling behavior and assist the design of electronic systems.In this paper, the electrical SE of an enclosure of rectangular cross-section with following dimensions: a = 300 mm, b = 120 mm and d = 300 mm and with two round apertures on the front and adjacent walls (Fig.3) is calculated by the numerical simulation. Apertures are placed one above the other symmetrically according to the center of the wall (change of spacing between the apertures was performed in a vertical direction), or one nearanother (changing the spacing between the apertures was performed in a horizontal direction). The thickness of perfectly conducting metal walls with circular aperturesis t = 2 mm. An excitationin the form of a plane wave whose direction of propagation was normal to the plane of the front wall with apertures was used. Circular apertures have a diameter of 2r = 20 mm.



a) b)

Fig. 3. An enclosure with two round apertures

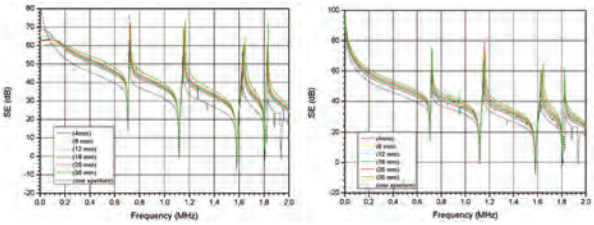
The effect of increasing the spacing between the apertures on the electrical SE is illustrated by the example of the circular apertures in the center point of the enclosure and in the points near apertures of adjacent walls for the vertical direction (Fig. 4a), and for the horizontal direction (Fig. 4b). The spacing between the circular apertures was beingincreased in steps of 4 mmup to 20 mm, but also the cases when the distance is greater than aperture diameter (30 mm) and when there is one larger circular aperture with the same size as the considered two small ones were considered. From Figures 4a and 4b it can be seen that, for various values of the spacing between the apertures, the electrical curves for SE, calculated at the center of the enclosure, partially overlap, where minimum SE is for one large aperture of the same area as two smaller apertures.Shape of the curve with the change spacing remains the same, indicating that the spacing considered only affects the field attenuation during the propagation through the inside of the aperture. A minimum value of electrical efficiency is obtained in the case of one larger aperture, which indicates that SE of enclosure is higher in case of having more small apertures than the aperture same size as one larger aperture.



a) b)

Fig. 4. SE of enclosureat the center point, with two apertures placed: a)one above another, b) one near another

In the point near apertures on the front wall (Fig. 5), aminimum value of SEis obtained for one larger aperture, and the maximum for the aperture spacing of 30 mm. Besides, SE curves progressively are decreasing with reducing vertical or horizontal aperture spacingwhere the higher values of SE are obtained for apertures placed one near another.

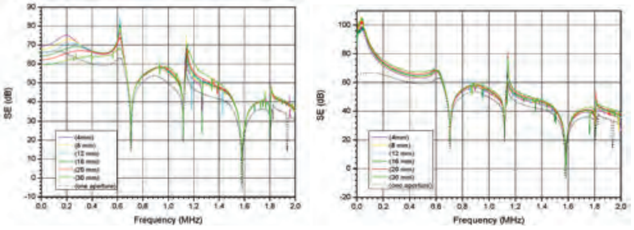


a) b)

Fig. 5. SE of enclosure at the point nearer to frontal wall, with two apertures placed: a) one above another, b) one near another

In the point near apertures on the adjacent wall (Fig. 6), aminimum value of SEis obtained for one larger aperture, and from 0 MHz to 0,6 GHz SE curves progressively are increasing with reducing vertical aperture spacingwherefrom 0,6 GHz to 2 GHzthe electrical curves for SE, partially overlap. At the other hand,SE curves for horizontal aperture spacingin the entire frequency range observed partially overlap. A minimum value of electrical efficiency is obtained in the case of one larger aperture.

Although the aperture spacing has an insignificant effect on the position of resonance points, it has a significant effect on SE of a shielding enclosure at resonance points, especially at higher frequencies. From Fig. 7 it can be seen that the SE does not change the valuewith changing the vertical aperture spacing for the first and third resonance, but gets negative around the third resonance, so it is advisable to avoid it in the design process. For the other resonance frequencies of the shielding enclosure, the SE is changing with the distance between the apertures.



a)    b)

Fig. 6. SE of enclosure at the point nearer second wall, with twoapertures placed: a) one above another, b) one near another

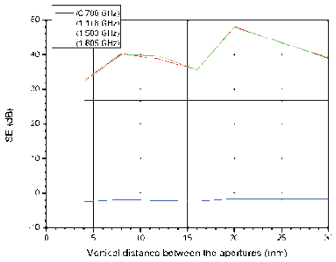


Fig. 7. SE for different resonant frequencies depending on the aperture spacing for the point in the center of enclosure

## III. CONCLUSION

The computationin the early stage of design allows the identification of potential problems such as interference from the environment, the position of the mutual coupling aperture in the enclosure, the sensitivity of the equipment inside the enclosure etc. In this paper, the impact of the mutual spacing of multiple circular apertures, whose diameters are significantly smaller than the wavelength, placed on adjacent walls is considered. It can be concluded that changing the distance between two circular aperturesfrom4 mm to 30 mm in the vertical direction does not affect greatly the SE, provided that the above mentioned effect was more pronounced at the point near the apertures especially at lower frequencies to 200 MHz, and that the lower efficiency is with a larger aperture of equal surfaceas small ones by 5 dB. When changing the distance in the horizontal direction the greatest impact in changing SE can be seen at high frequency and above 1.8 GHz. The calculations show that the enclosure resonates at approximately four frequencies(Fig. 7). Below the resonant frequency, SE decreases with frequencies and increases with distance from the aperture.In all of the above mentioned analysis it is noticed that the smallest SE is for the case of one larger aperture.The studies of resonance behavior are important in the electromagnetic compatibility field, which can help designers to avoid resonance phenomenon in design process.

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