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Shielding Effectiveness of Rectangular Enclosure with Off-center Aperture and Arbitrary Polarization Angle

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***Abstract*-This work intended to develop an analytical formulation for the shielding effectiveness (SE) of a rectangular enclosure with off center aperture. The formula under consideration is further extended to include high order modes and a formulation based on the angle of polarization is effectively determined using transmission line model (TLM). Considering high order modes is required when the aperture locates off-center.**

A single mode normal incident transverse electric wave containing arbitrary polarizations is decomposed into two orthogonal components in such a way that the electric field is situated perpendicular to both the long and the short sides of the aperture. Analysis of each individual component as per TE$_{10}$ mode is made by implementing TLM and then combined to obtain the SE. Simulation results shows that the SE is at its best when the electric field is perpendicular to the short side of the aperture and at the worst when the electric field is perpendicular to the long side of the aperture.

***Keywords:* Transmission line method, Transverse electric field, shielding effectiveness, arbitrary polarization, off-center, Aperture, Higher order mode.**

I. INTRODUCTION

Electromagnetic shielding effectively reduces emissions or enhances the immunity factors of electronic apparatus [1]. But the shielding effect is largely determined by the aperture located in the enclosure's wall. Aperture in the wall at times becomes indispensable for free air flow and dissipation of heat.

Thus shielding effectiveness of the enclosure with aperture is a hot topic for research. Shielding effectiveness can be found by several numerical methods or analytical approaches. Several studies have focused on this concept of the SE of enclosure with apertures. A focus on the SE of enclosure with center aperture and TE10 mode, using transmission line method can be found in [2]. Further analysis can be observed from [3] including the high order mode and enclosure-loss limited to centre aperture with only one perpendicular polarization of the happening electromagnetic field. These limitations have motivated further research with the objective of extending the model for wider applications.

An analytical approach to the SE estimation of a rectangular enclosure with aperture provides a cost-effective alternative to the numerical methods [4-7], thus saving significant computer resources.

The formula proposed in this paper is very general and deals with off-centre aperture, high order mode, enclosure loss and the consequences of normal incident electromagnetic wave having an arbitrary angle of polarization on the electric SE of a rectangular enclosure with aperture, by using TLM[8][9]. Here the electric field is decomposed into two orthogonal components. Analysis of each individual component as per TE$_{10}$ wave mode is made so that both propagate with normal incidence.

The relationship of the value of the two components of the electric fields depends on the polarization angle which determines the electric SE of the cavity of wall.

II. THEORY

According to the transmission line theory, the enclosure with off-centre aperture can be modeled as Fig.1 and the equivalent circuit is shown in Fig.2

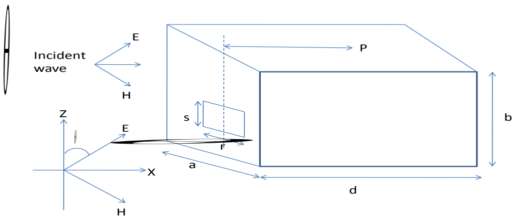

Fig.1. Rectangular enclosure with off center aperture

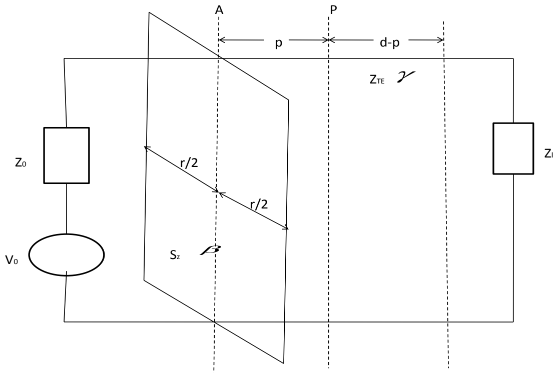

Fig.2. Equivalent circuit

The location of the test, P, is situated in the enclosure's middle portion. The normal irradiation of the electromagnetic wave is towards the front face of the cavity having an aperture.

A. *SE's formula for High Order Mode:*

The radiating source is represented by voltage V_0 and the impedance as Z_0=377. The representation of the enclosure is made by loaded lines of transmission whose characteristic impedance and propagation constants is Z_{TE} and γ respectively, determined by waveguide formulas. In addition load impedance η is included in the circuit model, which represents loss of enclosure.

According to [10], the characteristic impedance of the transmission line can be given by

$$S_z = 120\pi^2\left[\ln\left(2\frac{1+\sqrt[4]{1-h^2}}{1-\sqrt[4]{1-h^2}}\right)\right]^{-1} \qquad (1)$$

Where $h = w_e / b$ and the effective width w_e is

$$w_e = s - \frac{5t}{4\pi}\left[1+\ln\frac{4\pi s}{t}\right] \qquad (2)$$

Where't' is the thickness of the enclosure wall and's' is width of the aperture.

To calculate the aperture impedance A_z we transform the load impedance η at the ends of the aperture through a distance $r/2$ to the centre. A factor K_m is introduced to account for the high order mode and coupling between the aperture and the enclosure.

$$A_z = \frac{1}{2}K_m S_z \frac{\eta + jS_z \tan(\beta r/2)}{S_z + j\eta \tan(\beta r/2)} \qquad (3)$$

Where

$$\eta = (1+j)\sqrt{\frac{\pi f \mu}{\sigma}}\ ,\ \beta = \frac{2\pi}{\lambda_0} \qquad (4)$$

Where μ and σ are determined by property of the enclosure material.

Assuming the aperture field is of the form

$$E_{ay} = E_0 \sin\frac{m(l-l_o)\pi}{r}\cos\frac{n(k-k_o)\pi}{s}e^{(j\omega t_1-\gamma z)} \qquad (5)$$

r and s are the length and width of the aperture respectively. The co-ordinate system used in the rectangular waveguide is shown in Fig.3.

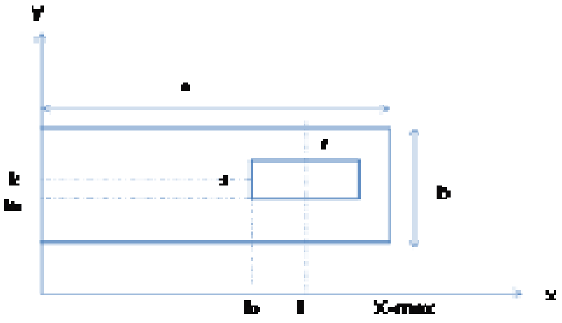

Fig.3. Coordinate System

The electric field y-component in TE_{mn} or TM_{mn} wave is

$$E_y = A\sin\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)e^{(j\omega t_1 - \gamma z)} \tag{6}$$

According to the field continuity at the aperture, coupling coefficient K_m can be obtained by the formulas (5) (6).

$$K_m = \frac{\int_{l_0}^{l_0+r}\int_{k_0}^{k_0+s}\cos\left(\frac{n\pi y}{b}\right)\cos\left(\frac{n(k-k_0)\pi}{s}\right)\sin\left(\frac{m\pi x}{a}\right)\sin\left(\frac{m(l-l_0)\pi}{r}\right)dxdy}{lk} \tag{7}$$

l and k are the aperture position from the origin to the centre of the aperture.

Fusion of Z_0 , V_0 *and* A_z through the application of thevenin's theorem provides corresponding voltage V_1 and impedance of source Z_1.

$$V_a = \frac{V_0 A_z}{Z_0 + A_z} \tag{8}$$

$$Z_a = \frac{Z_0 A_z}{Z_0 + A_z} \tag{9}$$

We now transform V_a and Z_a to point P, giving an equivalent voltage V_b and source impendence Z_b

$$V_b = \frac{V_a}{Cos(\gamma P) + jg\sin(\gamma p)} \tag{10}$$

Where $g = \frac{Z_a}{Z_{TE}}$

$$Z_b = Z_{TE}\frac{g + j\tan(\gamma p)}{1 + jg\tan(\gamma p)} \tag{11}$$

For the TE_{mn} mode of propagation, the waveguide impedance and propagation constant are represented by

$$Z_{TE} = Z_0 / \sqrt{1-(m\lambda_0/\lambda_c)^2-(n\lambda_0/\lambda_{c1})^2} \tag{12}$$

$$\gamma = \beta\sqrt{1-(m\lambda_0/\lambda_c)^2-(n\lambda_0/\lambda_{c1})^2} \tag{13}$$

Where $\lambda_c = 2a$ and $\lambda_{c1} = 2b$

Transforming the load impedance η at the end of the waveguide to P, we can get the load impedance Z_c .

$$Z_c = Z_{TE}\frac{q + j\tan\gamma(d-p)}{1 + jq\tan\gamma(d-p)} \tag{14}$$

From formulas (10)-(14), the voltage at P is $V = V_b Z_c / (Z_b + Z_c)$

For the multimode in enclosure, the total voltage at P is given by $V_{total} = \sum V$

In the absence of the enclosure, the load impedance at P is simply Z_0 and the voltage is $V_0 / 2$ .The electric shielding effectiveness is written as:

$$S_E = -20\log_{10}\left|\left(2V_{total}/V_0\right)\right| \tag{15}$$

B. *SE's formula for the Angle of Incidence along with Arbitrary Polarization.*

To any polarization angle θ , incident wave can be decomposed into two orthogonal components, of which electric strength is $E\cos\theta$ and $E\sin\theta$ respectively. Consequentially, we can obtain the source voltage $V_o\cos\theta$ and $V_o\sin\theta$ in the corresponding short end circuit.

Let us consider the situation where the electric field stays perpendicular to aperture's long side. In such cases, the impedance of the aperture can be modeled as

$$A_{zl} = \frac{1}{2}\frac{r}{a}jS_z\tan\frac{\beta r}{2} \tag{16}$$

Now from the point of incidence wave, the equivalent source voltage and source impedance are

$$V_{al} = V_0\cos\theta A_{zl} / (Z_0 + A_{zl}) \tag{17}$$

$$Z_{al} = Z_0 A_{zl} / (Z_0 + A_{zl}) \tag{18}$$

due to the existence of multiple mode such as $TE_{10}, TE_{20}, TE_{m0}$ etc. The characteristic impedance and propagation constants are

$$Z_{TEl} = Z_0 / \sqrt{1-(m\lambda_0/\lambda_c)^2} \tag{19}$$

$$\gamma_l = \beta\sqrt{1-(m\lambda_0/\lambda_c)^2} \qquad (20)$$

From the point of P, the equivalent source voltage V_{bl}, equivalent source impedance Z_{bl} and load impedance Z_{cl} are

$$V_{bl} = \frac{V_{al}}{\cos(\gamma_l p) + jg_l \sin(\gamma_l p)} \qquad (21)$$

Here $g_l = \dfrac{Z_{al}}{Z_{TEl}}$

$$Z_{bl} = Z_{TEl}\frac{g_l + j\tan(\gamma_l p)}{1 + jg_l \tan(\gamma_l p)} \qquad (22)$$

$$Z_{cl} = jZ_{TEl}\tan\gamma_l(d-p) \qquad (23)$$

For TE_{m0} mode, the total voltage at P is $V_{tl} = \sum_l V_l$ where $V_l = V_{bl}Z_{cl}/Z_{bl} + Z_{cl}$

Let us now consider another situation where the direction of the electric field remains perpendicular to the aperture's short side. In this situation we can analyze it in the same way as in the former, except with small modifications of the parameters r and a in the above formulation into s and b respectively.

For TE_{m0} mode, the total voltage at P is $V_{ts} = \sum_s V_s$ where $V_s = V_{bs}Z_{cs}/Z_{bs} + Z_{cs}$

The obtained end results regarding the two situations with the sum voltage at P can be represented as

$$V_{total} = \sqrt{V_{tl}{}^2 + V_{ts}{}^2} \qquad (24)$$

Without the shielding enclosure, the voltage at P is $V_o/2$.

As a result the shielding effectiveness is

$$SE = -20\log_{10}\left|\frac{2V_{total}}{V_0}\right| \qquad (25)$$

III. RESULTS

Fig.4 shows the calculated SE at P within 400mmx160mmx400mm (a x b x c) enclosure with a 100mmx10mm (r x s) aperture. The copper wall thickness of the enclosure is 1.5 mm. The aperture locates at X=300mm and Y=80mm off-center, P at X=300mm, Y=80mm and Z=200mm position.

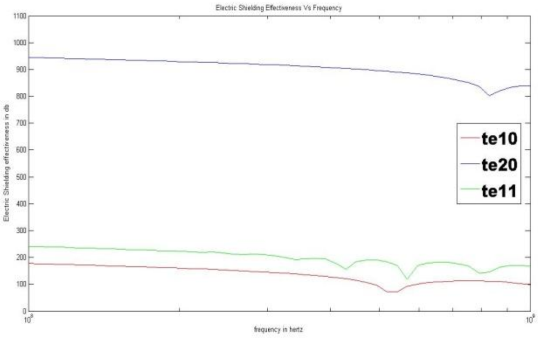

Fig.4. SE corresponded to different modes

This work proposes to investigate the SE of the enclosure containing the off center aperture. Unlike in Robinson's work, the aperture can locate anywhere in the wall of the enclosure. In the above fig, TE_{10} mode is included in bottom curve, TE_{11} is included in middle curve TE_{20} is included in top curve. High order mode should be included in the shielding effectiveness analysis of the enclosure with off-center aperture. It can be observed in the above figure that the resonance occurs at approximately 700MHz and 900MHz. 700MHz is typical for TE10 mode, and 900MHz is due to high-order mode existing in the enclosure.
Fig.5 shows the results in different polarization angle θ by using TLM.

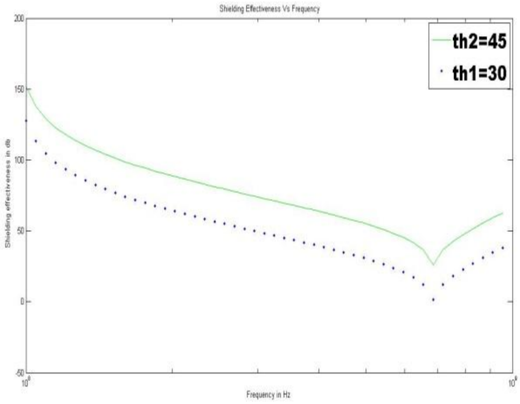

Fig.5. SE for different polarization angles θ_1=30, θ_2=45.

The above figure illustrates that the SE becomes correspondingly worse with the increase in frequency. When the frequency is around 700MHZ it can be observed that the resonance between the cavity and the aperture keeps in accordance with the Robinson's. The SE increases as the θ increases.

Fig.6 shows the results when electric field is perpendicular to the long side of the aperture.

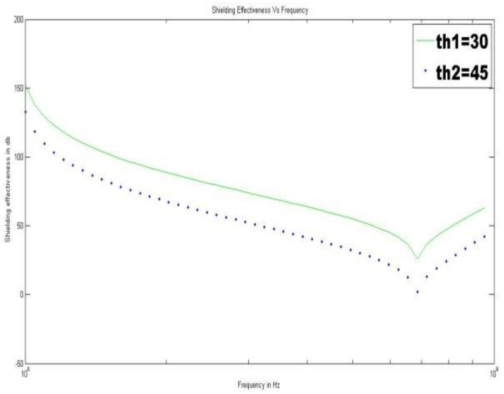

Fig.6. SE when electric field is perpendicular to the long side of the aperture.

The above figure demonstrates that the shielding effectiveness is at its worst when the electric field is perpendicular to the long side of the aperture, as the θ increases.

Fig.7 shows the results when electric field is perpendicular to the short side of the aperture.

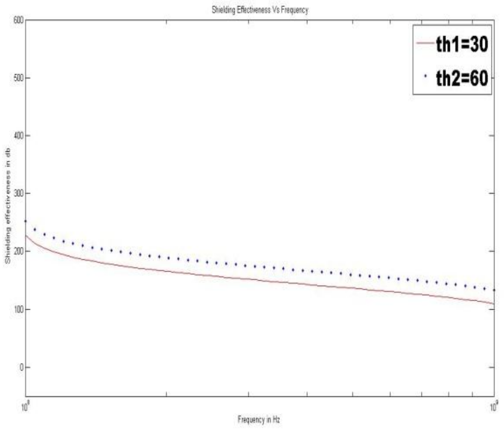

Fig.7. SE when electric field is perpendicular to the short side of the aperture.

The above figure displays that the best shielding effectiveness is obtained when the electric field is perpendicular to the short side of the aperture, as the θ increases.

Fig.8 shows the results of the two situations. Enhanced shielding effectiveness can be obtained when the electric field is perpendicular to the short side of the aperture as the theta increases compared to the electric field when it is perpendicular to the long side of the aperture.

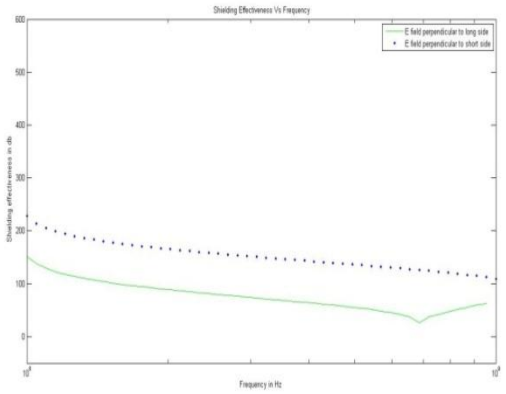

Fig.8. Comparison of SE when electric field is perpendicular to the long side of the aperture and short side of the aperture at θ =30·

Fig.9 shows the result of the two situations combined.

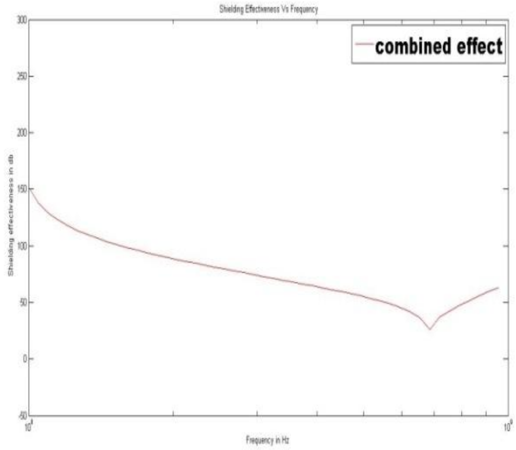

Fig.9. Calculated SE for combined situations at θ =30·

It is observed that shielding effectiveness decreases due to the combined effect of the electric field when it is perpendicular to both the long side and the short side of the aperture

IV. CONCLUSION

This paper attempts to investigate the SE of the enclosure with off- centre aperture i.e., the aperture can locate anywhere in the wall of the enclosure. Here, it is also considered that the high order mode must be included when aperture is off-centre and loss of the enclosure. The SE of a rectangular enclosure with an aperture when illuminated by plane wave with any polarization angle is also discussed here. By decomposing the incident wave into two orthogonal components, analyzing each component by TLM and finally combining them into a formulation between the SE and polarization, angle θ is obtained successfully and it is verified by using TLM. It can be noticed that the SE is at its best when the electric field is perpendicular to the short side of the aperture and at the worst when the electric field is perpendicular to the long side of the aperture. The transmission line approach offers a cost-effective alternative to the other exiting techniques, saving significant computing resources. The solution time is the key advantage of the developed analytical method.

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