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The effect of aperture shape, angle of incidence and polarization on shielding effectiveness of metallic enclosures

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\section*{ABSTRACT}
Apertures and slots of the enclosures come into prominence for heat allocation, ventilation, I/O cable, etc. These slots and apertures induce the coupling route of electromagnetic interference (EMI) from the inside to outside. So, electromagnetic shielding is usually used to decrease the emissions or to the progress of equipment immunity. In this paper, an effect of an aperture shape on the performance of electrical shielding effectiveness has been investigated by means of simulation. Rectangular, square, circular, equilateral triangle and hexagonal shape apertures that have a constant area of 5625 mm\(^2\) have been studied in addition to polarization type of applied electromagnetic field. It has been observed that ESE depends on the electric field direction and plane wave polarization and rectangular shape aperture has more effective ESE performance than square, circular, equilateral triangle and hexagonal type apertures. Rectangular shaped aperture has approximately 43 dB better performance than equilateral triangle one for whole frequency band of 100 MHz to 1GHz. Rectangular, square, circular, hexagonal and equilateral triangle type apertures have been ranked from best performance to the worst with respect to their ESE. There have been considerable findings that can be useful for enclosure designers about the effect of angle of incidence and polarization angle.

\section*{1. Introduction}
Electromagnetic interference (EMI) is one of the major problems for electronics and electronic infrastructures. Although the most basic way to get rid of electromagnetic interference/emissions is to design a closed enclosure, it is necessary to leave openings on those enclosures for reasons such as data bus, I/O cable, heat allocation, ventilation, etc. These apertures, cavities or slots cause electromagnetic interference from inside to outside or from the outside due to the coupling effect (Cakir et al. 2017). At
This point, cooling requirements and interference solutions conflict with one another. That’s why engineers need to consider shielding parameters during the design process of metallic enclosures. The electrical shielding effectiveness (ESE) can be explained by IEEE Standard 299 (IEEE 2012). ESE can be shown as the Equation (1). The case in which the probe is in the metallic box is $E_a$, where the probe is not in the metallic box (reference measurement) is $E_b$. In other words, $E_a$ and $E_b$ are the magnitude of the electric field intensity in V/m with absence and presence of an enclosure, respectively.

$$ESE = 20 \log_{10} \frac{E_a}{E_b} \text{ [dB]}$$  

ESE measurement is conducted by means of attenuation of received/transmitted wave. During measurement process ESE, the attenuation values in decibel (dB) of before shielding (absence of enclosure that is reference measurement) and after shielding (presence of enclosure) is different as expected. While the decrease of the magnitude of signal is exponential with distance, dB range drops along a logarithmic scale which means that attenuation rating of 50 dB indicates a shielding strength ten times that of 40 dB (Narendra and Harnadek 2012).

In general, the shielding ranges of 10 to 30 dB, 60 to 90 dB and 90 to 120 dB can mean there is a low, high and exceptional protection against interference, respectively (Marvin et al. 2009; Narendra and Harnadek 2012). However, it should be noted that these ranges of value are considered for fully closed enclosure that is with no aperture on its surface. Therefore, it is not right to expect to obtain/measure these values for the enclosures used in this study. Measurements of ESE obtained for the same frequency region is lower than values mentioned above. In this case, it can be considered that 40 dB for enclosures in this study is ideal and good value against interference. Also the value between 30 and 40 dB is acceptable, while the range of 20–30 dB has low protection. For enclosures as used in this study, it is possible to increase ESE by optimization of aperture shape and position according to the incident and polarization angles of waves from outside towards the box, or vice versa. But it is so important to say that 20–40 dB increasing ESE of enclosure with apertures used in high-precision military materials as missile, plane or EMC network analyzer, spectrum analyzer for very high frequency band happens under difficult conditions and very high costs due to the high radio frequency (RF) gasket prices and high precision mechanical workmanship.

In this paper, an analytical model (Robinson et al. 1998) has been preferred in the calculation of ESE for metallic enclosures with square and rectangular apertures in 0–1 GHz band region. According to (Liu et al. 2014), Robinson’s model can predict ESE of shielding enclosure with apertures faster and more accurately than other methods made by (Hussein 2013; Nobakhti et al. 2014; Solin 2015). The computation time and computer memory for Robinson models are also saved, which are very useful for the engineers that design the metallic enclosure (Wang et al. 2013). On the other hand, there are some limitations in Robinson model as follows: The higher order modes of the electromagnetic field in the cavity, the polarization angle and the incidence angle have been ignored in the model (Hao and Li 2014). Analytical
methods can only be applied to very simple geometries (square and rectangular apertures) with the use of approximations while it can be used to analyze the effects of many factors on ESE (Belkacem et al. 2011). Also, the aperture is placed centrally in the front face of the enclosure (Nie and Du 2015). Also it is possible to see some models based on electromagnetic new formulas on ESE in literature (Belkacem et al. 2011; Hussein 2013; Wang et al. 2013; Hao and Li 2014; Karami et al. 2014; Liu et al. 2014; Nobakhti et al. 2014; Nie and Du 2015; Solin 2015; Lei et al. 2007). These models run correctly and efficiently but, do not work properly in structures with much more complex and complex shape. There are also numbers of numerical methods for calculating ESE of enclosures with complex apertures in the literature (Dehkhoda et al. 2008, 2012; Xiong et al. 2012; Azizi et al. 2014). However, these numeric models lead to high memory usage and high CPU time on the computer.

We have investigated the effect of aperture size (Basyigit et al. 2011), multiple apertures (Basyigit et al. 2015) and wooden wall effect on SE (Basyigit et al. 2016) before. In this study, the effects of triangle and hexagonal apertures have been analyzed by means of COMSOL Multiphysics®. Additionally, aperture shape, polarization angles and angles of incidence of antenna have been investigated in detail to get more useful suggestions to designers in conclusion. The purpose of this paper is to confirm accuracy of the simulation model by measuring the simulation results and comparing them with the theory results. The secondary aim is to examine the parameters affecting ESE and give advice to the enclosure designers in this regard.

The paper is organized as follows: Gives information about the details of the measurement and simulation done in Section 2. In the Section 3, the parameters affecting the ESE (aperture shape, polarization angle and incidence angles) are shown to change according to the frequency. Section 4 mentions conclusion of results and future work.

2. Measurement campaign

Measurements have been conducted in an anechoic chamber having dimension of $4 \times 4 \times 8$ m that allows obtaining plane waves at 5 m distance from 100 MHz and up. Typical flange pin terminals with N-type connector (Product ID: PE4355; DC to 18GHz) as an antenna (probe) have been used. Pin antenna is 17.9 mm length and 4.1 mm in diameter. The flange pin is through the centre of bottom surface of the enclosure in 0.1–1 GHz. Also these flange pins have been used as receiving and transmitting antennas. Measurement setup can be seen in Figure 1. In this paper, 160 × 160 × 800 mm sized enclosure with a single aperture has been selected for all the analyses. Test environment has been shown in Figure 2 and measurements have been carried out between 0.1 and 1 GHz with the 10 MHz increments. Measurements have been repeated 20 times for a certain shape and illuminating angle to reduce measurement errors. Average error has been calculated in watt (W), and then results have been converted into decibel (dB). When the antenna is in an enclosure and operating in transmitting mode, mutual coupling between the antennas and shielded enclosure must be expected. This effect may result in VSWR change due to antenna
impedance change (Nie and Yuan 2008). This will be more affective at low frequencies rather than high frequencies due to the wavelength in comparison with enclosure dimension. One may think about the distance between the antennas and enclosures in the experimental study, note that ESE measurements held in this study are based on reference measurements as described in IEEE std 299-2006(R2012), and we have applied same procedures in a 3 m standard verified anechoic chamber (field uniformity in it between 80 MHz and 40 GHz is guaranteed).

\[ R_{21} = \frac{k}{2} \]

for ideal sources and

\[ R_{21} = \frac{2D^2}{k} \]

for relatively big physical structures (antennas and apertures) are two well-known far field boundary distance equations, where \( R \) is the smallest distance for far field, \( D \) is the largest dimension of a radiating element (biggest aperture dimension is 300 mm in this study) and \( k \) is the guided wavelength (wavelength in

Figure 1. Measurement details: (a) Measurement without shielding effect, (b) Measurement with shielding effect, (c) Network analyzer scene, (d) Enclosures with different aperture shape.

Figure 2. Test details in block diagram.
The anechoic chamber is expected to be smaller than free space wavelength. The measurement distance of 3 m shown in Figure 1 implies the standard EMC measurement distances, but in contrast to the illustration shown in Figure 1, the measuring distance is 4.5 m for ESE measurements in this study. That’s why applied measurement distance of 4.5 m satisfies far field conditions in the frequency band of 100 MHz and 1 GHz that planes waves have been obtained.

Results obtained by Robinson’s analytical model, simulation and measurements are in comparison in Figure 3. The thickness of aluminium metallic enclosure is 2 mm and there is a single aperture having a size of 300 mm × 18.75 mm on it. The receiver probe 80 mm apart from the aperture surface is at the centre of enclosure. The polarization angle $\alpha$ is 90° and the incident of plane wave is normal. That’s why the incidence angle $\theta$ is zero degree. Generally, for 0–1 GHz interval, ESE decreases with increased frequency until resonant frequencies. Onwards resonant frequencies, ESE increases with increased frequency. This result can be explained as that wavelength is inversely correlated with frequency. If the wave length is low (with increased frequency), higher amplitude of electrical field get in to aperture of enclosure. At resonance frequency, ESE is negative, which means that there are such sources which lead to the rise of noise and interference. That is the unwanted case for shielding and why we have high ESE at low frequencies in simulation model. As seen in Figure 3, simulation model has been verified through analytical and measurement results. So, we can go on working simulation models for investigating shielding parameters in other sections. The simulation software settings used are as follows: The technique is FETD in time-domain, the number of mesh cells is between 952 300 and 974 800, the shape of mesh is tetrahedral; the highest length of mesh is $\lambda_{\text{min}}/15$. The simulation software settings used are as follows: The technique is FETD in time-domain, the shape of mesh is tetrahedral; the number of mesh cells is 974 800 in case of that the length of mesh is $\lambda_{\text{min}}/15$. When performing all numerical problems in electromagnetic simulations, it is known that the quality and type of mesh used for discretizing the computational volume plays a critical role in simulation speed and accuracy. The number of mesh cells is determined by some parameters such as the size of CAD model in the simulation, the length of mesh and the shape of mesh. In this study, as the size of CAD model and the shape of mesh are fixed as no change, we have specified the
number of mesh cell by adjusting the length of mesh, e.g. for $\lambda_{\text{min}}/15$, the number of mesh cells is 974,800. In the simulation of this study, the computing time has been between 29 min and 33 min for simulations. It is important to say that all parameters have been simulated with a PC using a 128GB SSD and Intel Core i5 2.40GHz processor with 8GB RAM.

3. Analysis of ESE parameters

Aperture shape and physical structures of an enclosure, polarization and angle of incidence of impinging field are force-major parameters affecting ESE performance. The results have been presented in Figures 4–8. Observations and models have been predicted decreasing ESE performance till resonance frequencies. This is basically related to comparison of wavelength with aperture size. When the wavelength of high frequency electric field is smaller than aperture size, it has more potential to couple into an enclosure, as expected. At resonance frequencies, ESE is negative which is undesirable for shielding. Therefore it acts as if there were another source in the enclosure which leads to an increase in interference. So, at low frequencies we see high ESE values. Above resonance frequencies, ESE increases simultaneously with increased frequency.

3.1. Effect of aperture shape

In this section; aluminium enclosures with rectangular, square, circular, hexagonal and equilateral triangle type apertures have been selected. Each aperture area has been fixed at 5625 mm²; therefore the height of each aperture varies. As seen in Figure 4, 67.54 dB ESE performance has been obtained as the highest value for rectangular aperture and 24.46 dB lowest performance for equilateral triangle aperture. One may explain these results by means of Figure 5: When the polarization angle $\alpha$ is 90° (the angle between electric field and normal of aperture), electric field coupling into the enclosure will be more as expected. ESE performance gets lower with
Figure 5. The position and parameters of plane wave: (1) The polarization angle $\alpha$ is 90° where there is vertical polarization. This angle is between travelling wave direction z-axis and electric field. (2) Incidence angle is zero degree. This angle is between z-axis and travelling wave $k$. (3) Other Incident angle $\Phi$ is 90°. This angle is from positive x-axis on x-y plane up to 360°.

Figure 6. The effect of polarization angle ($\alpha$) on ESE.

Figure 7. The effect of angle of incidence ($\theta$) on ESE.
increased electric field amplitude $A_{mnp}$ (Balanis 2012), as described in Equations (2a)–(2d).

$$E_x = \frac{\beta_x}{\varepsilon} A_{mnp} \cos(\beta_x x) \sin(\beta_y y) \sin(\beta_z z) \quad \text{(V/m)}$$  \hspace{1cm} (2a)

$$E_y = -\frac{\beta_y}{\varepsilon} A_{mnp} \sin(\beta_x x) \sin(\beta_y y) \sin(\beta_z z) \quad \text{(V/m)}$$  \hspace{1cm} (2b)

$$E_z = 0 \quad \text{(V/m)}$$  \hspace{1cm} (2c)

$$\beta_x = \frac{m\pi}{a} , \beta_y = \frac{n\pi}{b} , \beta_z = \frac{p\pi}{d} \quad \text{(rad/m)}$$  \hspace{1cm} (2d)

Here $a$ is length of enclosure, $b$ is the width of enclosure and $d$ is the depth of enclosure. On TE mode, there are some parameters of phase constants which are $\beta_x$, $\beta_y$ and $\beta_z$. The electric field amplitude is $A_{mnp}$. There is a medium of which dielectric constant is $\varepsilon$. In this medium $m$, $n$, $p = 0, 1, 2, 3, \ldots$, except $m = n \neq 0$.

Finally, increasing aperture height (width) decreases ESE. It should be noted that for rectangular aperture, ESE is the highest value with minimum height $h = 18.75$ mm and is the lowest value with maximum height $h = 98.706$ mm. It can also be noted that the height of apertures has been changed due to the fixed an area (5625 mm$^2$). As a result, the ESE varies with the direction of the electric field and the plane wave polarization according to the aperture shape.

### 3.2. Effect of polarization angle ($\alpha$)

In this section, an aluminium enclosure with a single aperture size of 150 mm $\times$ 37.5 mm has been used. The angles of incidence of plane wave are $\theta = 45^\circ$ and $\phi = 0^\circ$. The polarization angle is $\alpha = 0^\circ \sim 180^\circ$. The effect of polarization angle ($\alpha$)
Table 1. Literature comparison.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Aperture shape</th>
<th>Angle of Polarization ($\alpha$)</th>
<th>Angle of Incidence ($\theta$)</th>
<th>Angle of Incidence ($\varphi$)</th>
<th>Simulation</th>
<th>Measurement</th>
<th>Analytic</th>
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on ESE is seen in Figure 6. ESE increases when the polarization angle varies between 0° and 90° and it reaches its highest value. However, beyond 90°, ESE decreases when the polarization angle varies between 90° and 180° and reaches its initial value. At $\theta = 45^\circ$, $\phi = 0^\circ$ and $\alpha = 60^\circ$, ESE is 37.276, 42.391 and 53.889 dB for 150, 350 and 450 MHz, respectively. Increased operating frequency increases the ESE value due to the decreased field penetration. At 90° and region near 90°, the ESE is higher due to the lower electric field penetration. Because the electric field goes to be parallel to the longitudinal dimension of the aperture in these angle region. So, there is H-polarized field at 90° due to the minimum penetration (Khan et al. 2005; Dehkhoda et al. 2012).

3.3. Effect of incidence angle ($\theta$)

An aluminium enclosure with a single aperture size of 150 mm $\times$ 37.5 mm has been used, and results can be seen Figure 7. The polarization angle $\alpha$ and angle of incidence $\phi$ of plane wave are set as 0°. Angle of incidence $\theta = -90^\circ \sim 90^\circ$. In this section, ESE decreases when the angle of incidence varies between $-90^\circ$ and 0° and it reaches the lowest value. However, ESE increases, when the angle of incidence varies between 0° and 90° and it reaches its initial value. At $\theta = 45^\circ$, $\phi = 0^\circ$ and $\alpha = 0^\circ$, ESE is 17.848 dB and -4.641 dB for 450 MHz and 900 MHz, respectively. At zero and near zero incident angles, ESE is lower due to the high electric field penetration. In that there is excitation of the induced electric fields at the apertures. That’s why ESE has the highest value when there is normal incidence (Khan et al. 2005; Dehkhoda et al. 2012).

3.4. Effect of incidence angle ($\phi$)

An aluminium enclosure with a single aperture size of 150 mm $\times$ 37.5 mm has been used, and related results can be seen Figure 8. The polarization angle $\alpha$ is 0° and angle of incidence $\theta = 45^\circ$. Angle of incidence $\phi = -180^\circ \sim 180^\circ$. ESE decreases when the angle of incidence varies between $-90^\circ$ and 0°, and ESE reaches the lowest value. However, ESE increases up to its initial value, when the angle of incidence varies between 0° and 90°. At $\theta = 45^\circ$, $\phi = 0^\circ$ and $\alpha = 0^\circ$, ESE is 16.691 dB and 2.374 dB for 450 MHz and 900 MHz, respectively. Consequently, these results have been expected in this section. The attenuation of induced field at the aperture position of enclosure is higher than in other regions of enclosure. In that the aperture is oriented such that its longitudinal section is along dimension. It is also possible to say that at the centre of the aperture, does not form a null at least for 0–1 GHz and at normal incidence the electric field penetration has been minimum (Khan et al. 2005; Dehkhoda et al. 2012).

4. Discussion

This paper provides insight into the effect of force major shielding parameters on ESE, and it has been observed that simulation results, analytical results and
measurement results are in good agreement. The differences in our study with similar studies in the literature are shown in Table 1. As seen in Table 1 that hexagonal and triangular apertures are new in the literature. In addition to those new approaches; the effect of aperture shape, polarization angle and polarization type in addition to angles of incidence on ESE performance have been investigated in detail to give suggestions to enclosure designers and device producers.

As a result, the ESE varies with the direction of the electric field and the plane wave polarization according to the aperture shape. ‘In this situation it’s aperture height (width)’ that vertically polarized sources inside enclosure requires narrow width apertures for emission control.

5. Conclusion

It has been concluded that designers should determine the location of apertures in enclosure according to the polarization and angles of incidence to get high ESE. Following statements are useful for system setup in a specific area that sensitive electronic devices are being used in it as practical applications. Before setting equipment, one needs to consider possible surrounding sources and their emitting directions.

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Disclosure statement

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