Analytically calculating the shielding effectiveness of rectangular enclosure with circular aperture arrays in two adjacent walls

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Abstract. For the rectangular enclosure with circular aperture arrays in two adjacent walls, the polarization and propagation constant of the incident plane wave can be decomposed. Therefore, the original enclosure can be equivalent to two enclosures with a circular aperture array in the front panel, respectively. The equivalent induction voltages of each equivalent enclosure are calculated and synthesized to obtain the equivalent induction and voltage of original enclosure, and further to evaluate its shielding effectiveness.

1. Introduction
Many researchers have taken efforts to calculate the shielding effectiveness (SE) of enclosures. For example, the Finite-difference time-domain (FDTD) method [1], the Method of moment (MOM)[2], the Transmission line matrix (TLM) method [3-4], and the hybrid methods[5]. All of these numerical methods require very much computing resources, especially for multi-scale structures. Therefore, to fast extract the SE for some special but widespread used structures in the practical applications, like the rectangular enclosures, some analytical methods are developed. For example, a rectangular enclosure with a horizontal rectangular aperture is considered as a length of rectangular waveguide shorted at the end [6]. And the aperture is treated as a length of transmission line shorted at both ends. Then the rectangular enclosure with a horizontal rectangular aperture can be solved according to its equivalent circuit. Dehkhoda P et al proposed an efficient analytical and accurate model to predict the shielding effectiveness of a rectangular enclosure with numerous small apertures [7]. In their paper, an appropriate equivalent admittance for the perforated side is suggested amid the free space and the enclosure, utilizing the traditional waveguide circuit model where the enclosure is represented by a short-circuited rectangular waveguide. What pity is, their method only can solve the SE of a rectangular enclosure with aperture array in the front panel of the enclosure. For a rectangular enclosure with circular aperture arrays in two adjacent walls, the method proposed by Dehkhoda P et al can help nothing for calculating SE.

In this paper, an analytical method for solving the SE of a rectangular enclosure with circular aperture arrays in two adjacent walls, based on the equation for calculating the equivalent resistance of the circular aperture array proposed by a simple analytical method is proposed. In this method, the
polarization and propagation constant of the incident plane wave is decomposed. Therefore, the original enclosure can be equivalent to two enclosures with a circular aperture array in the front panel, respectively. The equivalent induction voltages of each equivalent enclosure are calculated and synthesized to obtain the equivalent induction and voltage of original enclosure, and further to evaluate its shielding effectiveness.

2. The Equations For decomposing the polarization and propagation constant of the incident plane wave
As shown in figure 1, the incident plane wave's pitch angle is $\theta$, the azimuth angle is $\varphi$, and the polarization angle is $\psi$.

![Figure 1. Oblique incident plane wave incidence in Cartesian coordinate system.](image)

According to the vector theory, the incident electric field $E$ can be decomposed by the following equation:

$$
E = \tilde{x}(\cos \theta \cos \phi \cos \psi - \sin \phi \sin \psi) E_0 + \tilde{y}(\cos \theta \sin \phi \cos \psi + \cos \phi \sin \psi) E_0 + \tilde{z} \sin \theta \cos \psi E_0 = \tilde{x} F_{x} E_0 + \tilde{y} F_{y} E_0 + \tilde{z} F_{z} E_0
$$

(1)

where $E_0$ is the amplitude of the incident electric field $E$.

Similarly, the propagation constant of the plane wave, that is $\beta$, can be decomposed by the following equation:

$$
\beta = \tilde{x}(\cos \phi \sin \theta) \beta_0 + \tilde{y}(\sin \phi \sin \theta) \beta_0 + \tilde{z}(\cos \theta) \beta_0 = \tilde{x} F_{\beta x} \beta_0 + \tilde{y} F_{\beta y} \beta_0 + \tilde{z} F_{\beta z} \beta_0
$$

(2)

3. The Equivalent circuits of Rectangular Enclosure With Circular Aperture Arrays in two Adjacent Walls
As shown in figure 2, the rectangular enclosure with circular aperture arrays in two adjacent walls is irradiated by oblique incident plane wave. In figure 2, $\phi = 60^\circ$, $\theta = 90^\circ$, $\psi = 60^\circ$. The size of the $x$-normal wall is shown in figure 3, and the size of the $y$-normal wall is shown in figure 4.

![Figure 2. The rectangular enclosure with circular aperture arrays in two adjacent walls is irradiated by oblique incident plane wave.](image)
According to Dehkhoda P et al’s formula [7], for an array of circular apertures,

$$\frac{Y_{ab}}{Y_0} = -j \frac{3d_s d_j \lambda_0}{\pi d^3 \lambda W l} \tag{3}$$

where $Y_{ab} = \frac{1}{Z_{ab}}$, $Y_0 = \frac{1}{Z_0}$, $d_s$ is the horizontal period of the circular aperture array and $d_j$ is the vertical period of the circular aperture array. The $W$ is the width of the aperture array, $l$ is the length of the aperture array. The $a$ is the length of the front panel and $b$ is the width of the front panel.

Then the original enclosure shown in figure 2 can be considered as the combination of two equivalent enclosures and their equivalent circuits is shown in figure 5.

4. The Shielding Effectiveness

In the equivalent circuit shown in figure 4(a), the $Z_{ap}$ can be calculated by (3). The $V_0$ and $Z_0$ can be considered as an equivalent voltage source $V_i = V_0 Z_{ap} / (Z_0 + Z_{ap})$ with an equivalent impedance
\[ Z_i = Z_0 Z_{ap} \left/ \left( Z_0 + Z_{ap} \right) \right. \], where \( Z_0 = 377 \Omega \). At the TE10 mode, for the equivalent enclosure shown in figure 5(a), \( Z_{gr} = Z_0 \sqrt{1 - \left( \lambda/2l_i \right)^2} \) and \( k_{gr} = k_0 \sqrt{1 - \left( \lambda/2l_i \right)^2} \).

Similarly, in the equivalent circuit shown in figure 4(b), \( V_o \), \( Z_0 \) and can be considered as an equivalent voltage source \( V_i = V_o Z_{ap} \left/ \left( Z_0 + Z_{ap} \right) \right. \) with an equivalent impedance \( Z_i = Z_0 Z_{ap} \left/ \left( Z_0 + Z_{ap} \right) \right. \), where \( Z_0 = 377 \Omega \). At the TE10 mode, for the equivalent enclosure shown in figure 5(b), \( Z_{gr} = Z_0 \sqrt{1 - \left( \lambda/2l_i \right)^2} \) and \( k_{gr} = k_0 \sqrt{1 - \left( \lambda/2l_i \right)^2} \).

The point \( p_s \) is at the center of the enclosure shown in figure 5(a). According to the Thevenin Theorems, when \( V_i \), \( Z_i \) and the short circuit of waveguide is transformed to the point \( p_s \), we can get the equivalent voltage source [1]

\[ V_2 = V_i Z_{gr} \left/ \left( Z_{gr} \cos k_{gr} p_s + j Z_i \sin k_{gr} p_s \right) \right. \]  

(4)

and the equivalent impedance

\[ Z_2 = Z_{gr} \left( Z_i + j Z_{gr} \tan k_{gr} p_s \right) \left/ \left( Z_{gr} + j Z_i \tan k_{gr} p_s \right) \right. \]  

(5)

and the load impedance

\[ Z_3 = j Z_{gr} \tan k_{gr} \left( l_s - p_s \right) \]  

(6)

The voltage at the point \( p_s \) can be calculated by

\[ V_{p_s} = F_{eg} F_{eg} V_2 Z_3 \left/ \left( Z_2 + Z_3 \right) \right. \]  

(7)

Similarly, the point \( p_s \) is at the center of the enclosure shown in figure 5(b). According to the Thevenin Theorems, when \( V_i \), \( Z_i \) and the short circuit of waveguide is transformed to the point \( p_s \), we can get the equivalent voltage source [1]

\[ V_2 = V_i Z_{gr} \left/ \left( Z_{gr} \cos k_{gr} p_s + j Z_i \sin k_{gr} p_s \right) \right. \]  

(8)

and the equivalent impedance

\[ Z_2 = Z_{gr} \left( Z_i + j Z_{gr} \tan k_{gr} p_s \right) \left/ \left( Z_{gr} + j Z_i \tan k_{gr} p_s \right) \right. \]  

(9)

and the load impedance

\[ Z_3 = j Z_{gr} \tan k_{gr} \left( l_s - p_s \right) \]  

(10)

The voltage at the point \( p_s \) can be calculated by

\[ V_{p_s} = F_{eg} F_{eg} V_2 Z_3 \left/ \left( Z_2 + Z_3 \right) \right. \]  

(11)

Then, \( SE_p \), which stands for the Shielding Effectiveness at the point \( p \) of the cavity shown in figure 5 can be calculated by

\[ SE_p = -20 \log \left| V_p / V_o \right| \]  

(12)

where \( V_p = V_{p_s} + V_{p_s} \).

The result is shown in figure 6. Comparing with the results obtained from the proposed method and transmission line matrix method (TLM), it is easy to find that good agreement can be observed.
5. Conclusions
A new analytical method is proposed to calculate the SE of an enclosure with circular aperture arrays in two adjacent walls over a wide frequency range efficiently and accurately. The accuracy of the proposed method is very high. The proposed method could extract the SE of the enclosure nearly no time rather than several hours when TLM is used.

References
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