Shielding effectiveness analysis of a rectangular enclosure with wire mesh covering

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Abstract. Analytical model has been developed for the shielding effectiveness of a rectangular enclosure with wire mesh covering. The aperture covered by wire mesh is replaced by an equivalent impedance which contains the surface resistance of the wire mesh. Based on the transmission line theory, the enclosure is modelled as a length of rectangular waveguide ended with a short circuit, then the shielding effectiveness (SE) of the enclosure can be calculated. By comparing the calculation with the full-wave simulation software, the proposed method is validated.

1. Introduction

A shielding enclosure is usually used as a measure to improve the immunity of the electronic equipment. In real devices, due to the need of ventilation, heat dissipation, cable connection, etc., enclosure has many apertures [1-2]. However, these apertures can cause external electromagnetic waves enter the enclosure through apertures, so that the shielding effectiveness (SE) of the enclosure is reduced. To improve the shielding effectiveness, we can cover the aperture with wire mesh. Therefore, it is important to calculate the SE of the enclosure correctly.

We can calculate shielding effectiveness by numerical simulations or by analytical methods [3-4]. Numerical simulations can be used to simulate complex structures with high calculation accuracy. But it always requires a long calculating time and a high-performance computer. This means that it is meaningful to develop analytical methods with clear physical meaning and fast calculation speed. Robinson M P proposed a circuital approach which the aperture is assumed as a length of coplanar strip transmission line, and the enclosure is represented as a shorted waveguide [5-6]. The method is in good agreement with measurements. The transmission line method (TLM) is extended to take multiple modes, apertures on multiple sides, hole arrays, and the incoming plane wave in any direction of incidence and polarization into account. In [7], numerical method is used to evaluate the SE of the wire mesh covering aperture. However, the SE of the enclosure with wire mesh covering is not predicted by analytical methods.

In this paper, simple circuital approach is proposed to evaluate the SE of rectangular enclosure with wire mesh covering. Based on the equivalent circuit model, we replace the aperture which is covered by wire mesh with an equivalent impedance. The enclosure is represented as a length of a rectangular waveguide ended with a short circuit. Then the analytical formulas of SE of the enclosure can be derived. Finally, the proposed model has been verified by using a full-wave simulation software CST.
2. Analytical model

Fig.1(a) shows the model of the enclosure with wire mesh covering. The enclosure is of size \( a(x) \times d(y) \times b(z) \), the distance from the observation point P to the aperture is \( p \), and the enclosure is irradiated by a \( z \) polarized plane wave. Fig.1(b) shows the equivalent circuit. Fig.2 shows the aperture and the parameters of the wire mesh. The aperture is of size \( b \times w \), the hole diameter of the wire mesh is \( a_1 \), the wire diameter of the wire mesh is \( d_1 \). The enclosure is considered to be constructed from a perfect electrical conductor, and its thickness can be negligible.

The radiating source can be replaced by voltage \( v_0 \) and impedance \( Z_0 = 377 \Omega \), the aperture covered by wire mesh is represented by \( Z_{s_{eff}} \), the enclosure is modeled as a shorted waveguide whose characteristic impedance is \( Z_g \) and propagation constant is \( k_g \). The shielding effectiveness at P can be derived from the voltage and current at P.

\[
\begin{align*}
R_g &= \frac{4 a_1}{\pi d_1^2} \sqrt{\frac{j \omega \tau_w}{\ln \left( \frac{1}{2} \left( \sqrt{j \omega \tau_w} \right) \right)}} \\
L_s &= \frac{\mu_0 d_1}{2 \pi} \ln \left( \frac{1}{1 - e^{-\pi \delta a_0}} \right) \\
Z_s &= R_g + j \omega L_s \\
\tau_w &= \frac{\mu \sigma d_1}{4}
\end{align*}
\]

In these expressions, \( \omega \) is the angular frequency of electromagnetic wave, the term \( \mu_0 = 4\pi \times 10^{-7} \) H/m, \( \mu \) is the magnetic permeability of the wire mesh, \( \tau_w \) is the diffusion time in the wire mesh, \( \sigma \) and \( \varepsilon \) are the electrical conductivity and dielectric constant of the wire mesh, the \( I_0(\cdot) \) and \( I_1(\cdot) \) are the first kind modified Bessel functions.

To calculate the impedance \( Z_{s_{eff}} \), it is necessary to contain a factor \( lw/ab \) to account for the coupling between the aperture and the enclosure.
\[
Z_{s}^{\text{eff}} = Z_s \cdot \frac{lw}{ab}
\] (5)

In the proposed model, we assume a single mode of propagation (the TE_{10} mode) whose characteristic impedance is 
\[
Z_s = Z_0 \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}
\]
and propagation constant is 
\[
k_g = k_0 \sqrt{1 - \left(\frac{\lambda}{2a}\right)^2},
\]
where \(k_0 = 2\pi/\lambda\). On this basis, we can follow the procedures of Robinson et al. [5-6] to calculate SE

\[
v_1 = v_0 Z_s^{\text{eff}} \left(Z_0 + Z_s^{\text{eff}}\right)
\] (6)

\[
Z_1 = Z_0 Z_s^{\text{eff}} \left(Z_0 + Z_s^{\text{eff}}\right)
\] (7)

\[
v_2 = \frac{v_1}{\cos k_g p + j\left(Z_1/Z_s\right)\sin k_g p}
\] (8)

\[
Z_2 = \frac{Z_1 + jZ_s \tan k_g p}{1 + j(Z_1/Z_s)\tan k_g p}
\] (9)

\[
Z_3 = jZ_s \tan k_g (d - p)
\] (10)

The voltage at P is 
\(v_P = v_2 Z_3 / (Z_2 + Z_3)\), and the current at P is \(i_P = v_2 / (Z_2 + Z_3)\).

Finally, the SE at the observation point P can be calculated by

\[
S_E = -20 \log_{10} \left|\frac{2v_P}{v_0}\right|
\] (11)

\[
S_M = -20 \log_{10} \left|\frac{2i_P Z_0}{v_0}\right|
\] (12)

3. Model validation

According to the analytical model proposed in the previous section, this section verifies its effectiveness by some specific examples. The size of the enclosure is 300mm×300mm×120mm, and its thickness is 1mm. The aperture dimension is 100mm×80mm, the material of the wire mesh is copper, the hole diameter is 10mm, the wire diameter is 1mm.

Fig. 3 shows the analytical and simulation SE at the center of the enclosure \(p=150\)mm. Fig. 4 shows the analytical and simulation SM at the center of the enclosure \(p=150\)mm. The analytical results show that the resonant frequency of the enclosure is around 700MHz. There is good agreement below the resonant frequency, when the frequency is above the resonant frequency, agreement is slightly worse. The analytical results is 5dB higher than the simulation results, but it is within acceptable range.

Fig. 5 and Fig.6 show the trend of the SE with the change of the observation point position when \(f=1000\)MHz. In the graph, the analytical results and the simulation results are in good agreement except the region around the aperture. The error is lower than 5dB which is acceptable. In addition, we can see that SE increases sharply at some observation points which can be explained by the fact that the observation points are at the node (zero point) of the standing wave field.

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Figure 3. The trend of the electric shielding effectiveness with the change of frequency.

Figure 4. The trend of the magnetic shielding effectiveness with the change of frequency.

Figure 5. The trend of the electric shielding effectiveness with the change of observation position ($f=1000\text{MHz}$).
4. Conclusion
This paper presents an analytical model for quickly calculating the shielding effectiveness of an enclosure when aperture is covered with wire mesh. The analytical model applies the equivalent circuit method. The core of the analytical model is to replace the aperture covered by wire mesh with an equivalent impedance contains the surface resistance of the wire mesh. The analytical results and the results of full-wave simulation are in good agreement. The analytical model is also suitable for high frequency situations. When the frequency is higher than 1000MHz, the mode existing inside the enclosure is more than the TE10 mode. In this case, the propagation constant and characteristic impedance of the TE10 mode in the above formulas need to be replaced with the propagation constant and characteristic impedance of other modes in the enclosure. And then, the voltages of different modes at the observation point are added to calculate the total voltage and the total current, and the shielding effectiveness of the observation point can be obtained.

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