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ANALYSIS OF SHIELDING EFFECTIVENESS OF ENCLOSURES WITH APERTURES AND INNER WINDOWS WITH TLM

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Abstract—Derivation is presented for analysing the shielding effectiveness of an enclosure with apertures and inner windows with Transmission Line Method (TLM). Theoretical values of shielding effectiveness are in good agreement with the simulation results. Results indicate that the capacitive window lowers the resonance frequency while the inductive window enhances the resonance frequency, and both of them improve the shielding effectiveness of the enclosure. The effects of location of the inner windows is discussed. Moreover, the present method can also be used in the condition that the enclosure has both inductive and capacitive windows.

1. INTRODUCTION

Apertures are necessary to open on the shielding enclosure of devices for heat dissipation, and inner windows are often set in the box for some purposes, such as the metal plates in the server cabinet. The apertures and inner windows increase the complexity of numerical modelling and the time of computing the shielding effectiveness of the enclosure. Transmission Line Method (TLM) considers the enclosure as a waveguide and analyses the shielding effectiveness with the theory of transmission line, which is an efficient and reliable method for solving shielding effectiveness [1]. Previous work about TLM has been done. The TLM theory has been used for analysing shielding effectiveness of the enclosure with numerous apertures [2], and situation of oblique incident plane wave has been discussed in [3]. In the situation of incident wave with high frequency, results which are more exact are

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given with the higher-order mode transmission line model of the shielding effectiveness of enclosures with apertures [4]. The shielding effectiveness of a enclosure with circular apertures is also discussed [5]. In [6], combined model is applied to shielding effectiveness estimation of a metallic enclosure with apertures. Most of the previous work concerns parameters of the exterior of enclosures and the incident wave, but not enclosures with inner windows yet. In this paper, capacitive windows and inductive windows in the enclosure are considered as lumped elements, and their effects on shielding effectiveness are presented with the method of TLM.

2. THEORY

2.1. Enclosure and Equivalent Circuit Model of TLM

According to the theory of TLM [1], the enclosure is considered as a waveguide with a short-circuit terminal. The theory of transmission line is applied for analysing the shielding effectiveness of the enclosure with apertures and inner windows. Figure 1 shows the enclosure with apertures and inner windows and the TLM equivalent circuit model, where the size of the enclosure is $a \times b \times d$, the thickness is t, the size

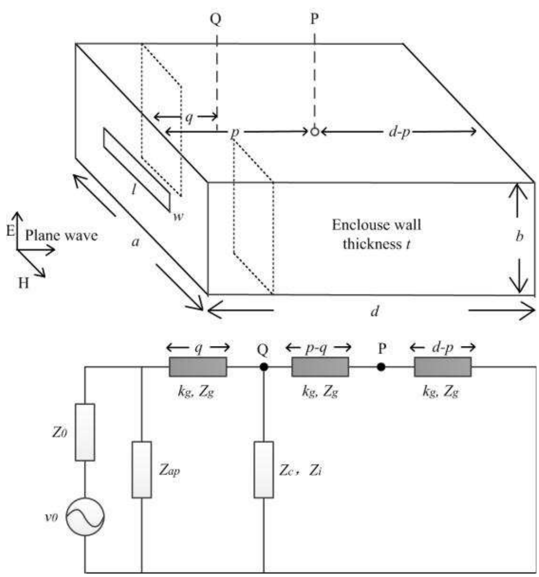

Figure 1. The enclosure with apertures and inner windows and the TLM equivalent circuit model.

of the aperture is $l \times w$, the distance between the aperture and the inner window is q and Q is the location of the inner windows. the distance between the aperture and the point to be tested is p, and P is the centre of the enclosure. The polarization of the radiating source is shown in Figure 1.

2.2. Equivalent Lumped Element of the Inner Windows

Figure 2 shows the models of rectangular waveguides with the capacitive window or the inductive window inside and the equivalent lumped element circuits. The capacitance windows shown in Figure 2(a) is an opening formed by two thin metal fins attached to the two long walls of a waveguide, respectively, while the inductance windows showed in Figure 2(b) is the opening formed by thin metal fins attached to the two short walls of a waveguide, respectively. The capacitive window is considered as a capacitive impedance [7]:

$$Z_c = -j\frac{\lambda_g Z_g}{4b \ln\left(\csc \frac{\pi d}{2b}\right)} \tag{1}$$

The equivalent impedance of the inductive windows is given by

$$Z_i = j\frac{aZ_g}{\lambda_g \cot^2\left(\frac{\pi d}{2b}\right)} \tag{2}$$

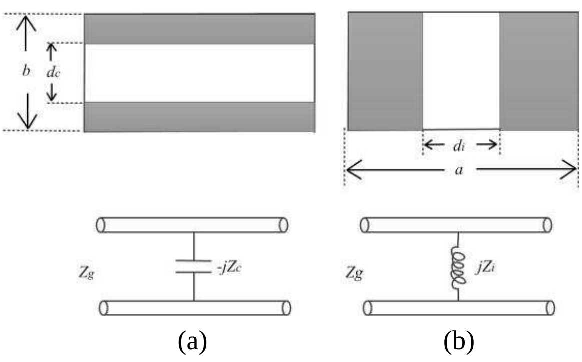

Figure 2. The capacitive window and the inductive in the waveguide and the equivalent circuit model.

2.3. Derivation of the Shielding Effectiveness

By the theory of TLM, the radiating source is represented by voltage v_0 and impedance $Z_0 = 377\,\Omega$. The aperture impedance Z_{ap} is given by

$$Z_{ap} = \frac{1}{2}\frac{l}{a} j Z_{0s} \tan\frac{k_0 l}{2} \tag{3}$$

where

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

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

For the TE_{10} mode of propagation, the waveguide has characteristic impedance $Z_g = Z_0/\sqrt{1-(\lambda/2a)^2}$ and propagation constant $k_g = k_0\sqrt{1-(\lambda/2a)^2}$, where $k_0 = 2\pi/\lambda$. By the Thevenin's theorem, combining v_0, Z_{ap}, Z_0, the equivalent source v_1 and source impedance Z_1 are given by

$$v_1 = v_0 Z_{ap}/(Z_0 + Z_{ap}) \tag{6}$$

$$Z_1 = Z_0 Z_{ap}/(Z_0 + Z_{ap}) \tag{7}$$

Through a q length of transmission line from the aperture to the capacitive window or inductive window, the equivalent source and source impedance are given by

$$v_2 = \frac{v_1}{\cos k_g q + j(Z_1/Z_g)\sin k_g q} \tag{8}$$

$$Z_2 = \frac{Z_1 + jZ_g \tan k_g q}{1 + j(Z_1/Z_g)\tan k_g q} \tag{9}$$

The equivalent impedance of the inner window Z_w can be given by (1) or (2). For the case of capacitive window shown in Figure 2(a), $Z_w = Z_c$; for the case of inductive window shown in Figure 2(b), $Z_w = Z_i$. By the Thevenin's theorem again, combining v_2, Z_2, and the equivalent impedance of the window Z_w, the equivalent source and source impedance are given by

$$v_3 = v_2 Z_w/(Z_w + Z_2) \tag{10}$$

$$Z_3 = Z_w Z_3/(Z_w + Z_3) \tag{11}$$

Through a p-q length of transmission line from the window to the point P, the equivalent source v_4 and source impedance Z_4 are given by

$$v_4 = \frac{v_3}{\cos k_g(p-q) + j(Z_3/Z_g)\sin k_g(p-q)} \tag{12}$$

$$Z_4 = \frac{Z_3 + jZ_g \tan k_g(p-q)}{1 + j(Z_3/Z_g)\tan k_g(p-q)} \tag{13}$$

The load impedance is $Z_p = jZ_g \tan k_g(d-p)$; the voltage at p is $v_p = v_4 Z_p/(Z_p + Z_4)$. In the absence of the enclosure, the load impedance at P is Z_0, the voltage at P is $v'_p = v_0/2$. The electric shielding effectiveness is given by

$$SE = -20\log_{10}(v_p/v'_p) = -20\log_{10}(2v_p/v_0) \tag{14}$$

3. SIMULATION AND ANALYSING

3.1. Verification of the Present Method

For verifying the present method, the results of TLM are compared with the results given by the simulation with the CST software. The TLM results are calculated with Matlab, and the CST results are given by the frequency domain solve in the CST software. The size of the enclosure is $300 \times 120 \times 300$ mm, the thickness is 1 mm, the size of the aperture is 100×5 mm, the window is 50 mm away from the aperture and $d_c/b = d_i/a = 1/2$, point P is the centre of the enclosure. Figure 3 and Figure 4 show the shielding effectiveness of the enclosure with a capacitive window and an inductive window, respectively. The agreement between results of TLM and CST simulation is good, which verifies the method of TLM in solving shielding effectiveness of enclosures with inner windows.

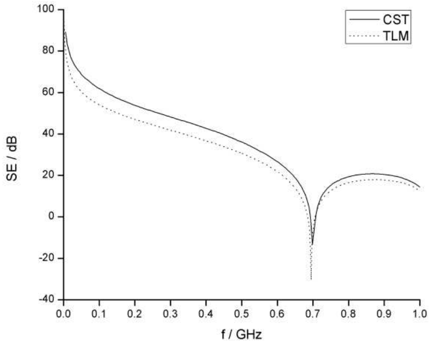

Figure 3. Shielding effectiveness of the enclosure with a capacitive window.

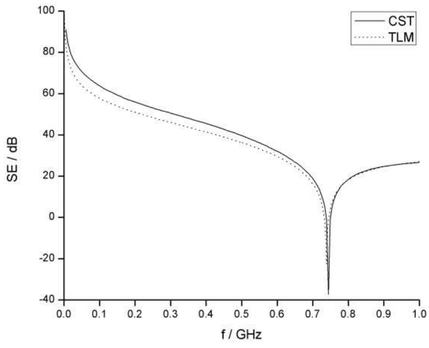

Figure 4. Shielding effectiveness of the enclosure with an inductive window.

3.2. The Effects of Capacitive Windows and Inductive Windows

Figure 5 shows the shielding effectiveness of an empty enclosure and enclosures with a capacitive window or an inductive window when

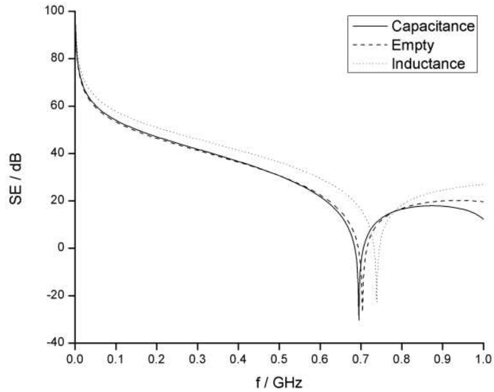

Figure 5. Shielding effectiveness of an empty enclosure and enclosures with a capacitive window or an inductive window.

$d_c/b = d_i/a = 1/2$ with the method of TLM. It can be seen that the capacitive window lowers the resonance frequency while the inductive window enhances the resonance frequency. The figure also shows that the inductive window has a greater effect on the value of shielding effectiveness and resonance frequency.

3.3. Effects of Windows with Different Sizes

Figure 6 and Figure 7 show the shielding effectiveness of enclosures with windows with different sizes. It can be seen from the Figure 6 that the larger the capacitive window is, the lower the resonance frequency

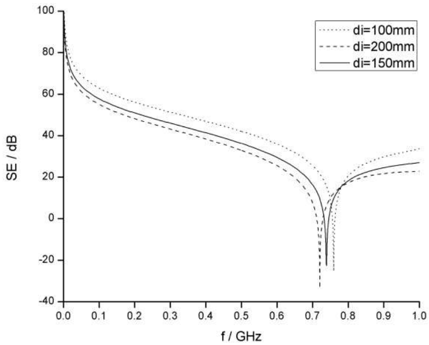

Figure 6. Shielding effectiveness of an empty enclosure and enclosures with a capacitive window or an inductive window.

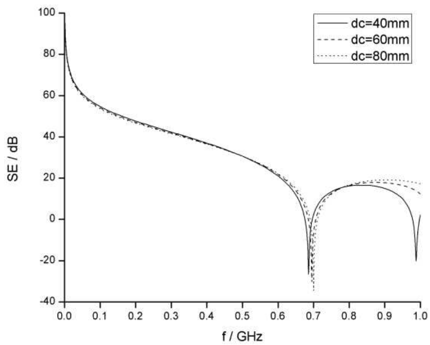

Figure 7. Shielding effectiveness of an empty enclosure and enclosures with a capacitive window or an inductive window.

and shielding effectiveness the enclosure has. In other words, as size of the metal fins is getting larger, which means the window is getting smaller; the enclosure has a higher resonance frequency and shielding effectiveness. On the contrary, the larger the capacitive window is, the higher resonance frequency the enclosure has, which is shown in Figure 7. As can be seen again, the capacitive windows have less impact on the resonance frequency and shielding effectiveness of the enclosure.

3.4. Effects of Windows with Different Locations

Shielding effectiveness varies when q (the distance between the aperture and the inner window) is changed. Figure 8 and Figure 9 show the shielding effectiveness of point P of enclosures with inductive and capacitive windows with different locations with the method of TLM, respectively. The size of the inner windows is $d_i = 150\,\mathrm{mm}$, $d_c = 60\,\mathrm{mm}$, the location of the inner windows is $q = 50$, 75, 100 mm. It can be seen in the Figure 8 that for the enclosure with a inductive window, the resonant frequency is getting higher when q is getting larger. While Figure 9 shows that for the enclosure with a capacitive window, the resonant frequency decreases when q increases.

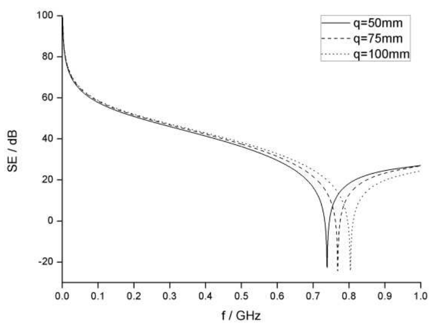

Figure 8. Shielding effectiveness of enclosures with inductive windows with different locations with TLM.

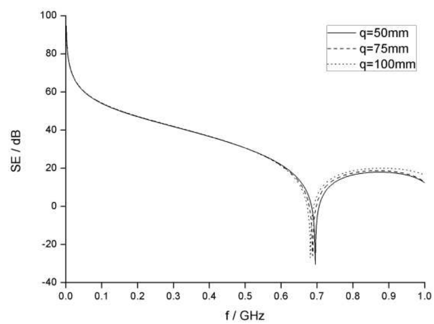

Figure 9. Shielding effectiveness of enclosures with capacitive windows with different locations with TLM.

Figure 10 and Figure 11 show the shielding effectiveness of enclosures with inductive and capacitive windows with different locations with the CST simulation, respectively. As can be seen in the figures, the resonant frequencies simulating by CST are in good agreement with results of TLM, which verifies the method of TLM again.

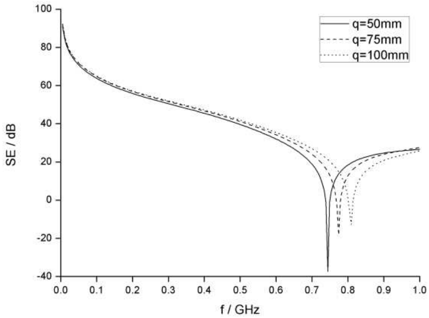

Figure 10. Shielding effectiveness of enclosures with inductive windows with different locations with CST simulation.

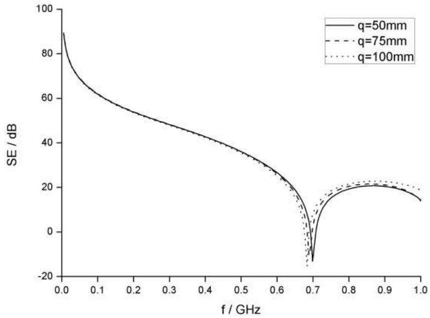

Figure 11. Shielding effectiveness of enclosures with capacitive windows with different locations with CST simulation.

3.5. Enclosures with Both Capacitive and Inductive Windows

The present method can also be used in the condition in which the enclosure has both capacitive and inductive windows. Figure 12 shows

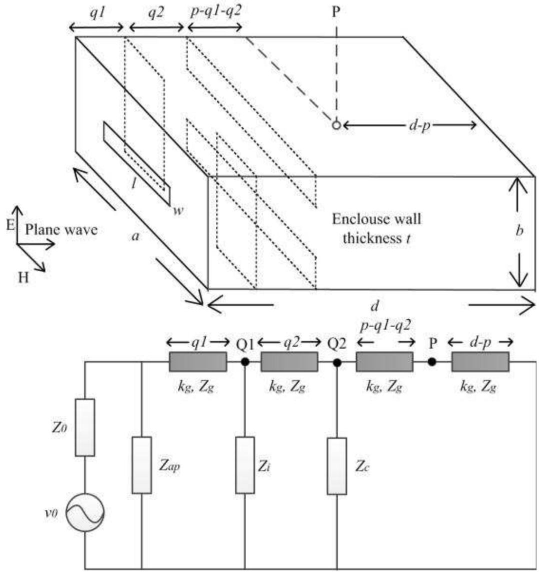

Figure 12. The enclosure with both inductive and capacitive windows and the TLM equivalent circuit model.

the equivalent circuit mode of the enclosure with an inductive window and an capacitive window. The shielding effectiveness is given by the similar process of the theory of TLM. In the Figure 12, $q_1 = 50\,\text{mm}$, $q_2 = 50\,\text{mm}$ and P is still the centre of the enclosure. $d_i = 150\,\text{mm}$ and $d_c = 60\,\text{mm}$.

Figure 13 shows the results of TLM and CST simulation, and it can be seen that the results of TLM is in agreement with the CST simulation results.

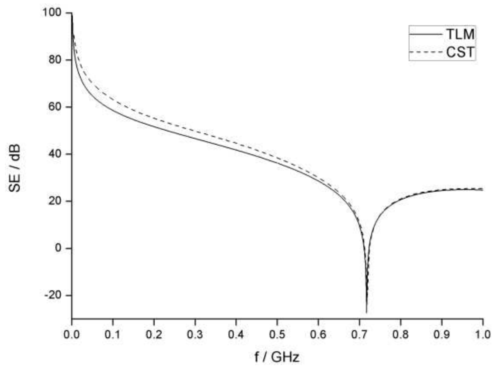

Figure 13. Shielding effectiveness of the enclosure with both inductive and capacitive windows.

4. CONCLUSIONS

TLM is extended to solve the shielding effectiveness of the enclosure with apertures and inner windows and it is a way much faster than the numerical methods do for computing the shielding effectiveness. The capacitive window lowers the resonance frequency while the inductive window enhances the resonance frequency, and the inductive window has a greater effect on the value of shielding effectiveness and resonance frequency. Results also show that the larger the capacitive window is, the lower the resonance frequency and shielding effectiveness the enclosure has. The present method can also be used in mixed condition that the enclosure has both inductive and capacitive windows.

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