A hybrid algorithm method for calculating electromagnetic shielding effectiveness of apertured enclosure with an arbitrary inner window

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Abstract  A hybrid algorithm method for predicting the shielding effectiveness (SE) of apertured enclosure with an arbitrary inner window was proposed. By applying the concept of electromagnetic topology, equivalent circuit models of the enclosures are derived. The equivalent impedance of the arbitrary inner windows are calculated by a full-wave method. Then, the shielding effectiveness can be obtained using the extended BLT equation. Compared with full wave numerical simulation, the proposed method can reduce the computation time from 1000 seconds to 100 seconds while maintaining a very close accuracy.

key words: Shielding effectiveness, aperture coupling, general Baum-Liu-Tesche equation, electromagnetic compatibility

Classification: Electromagnetic theory

1. INTRODUCTION

Due to the complexity of the electromagnetic environment and the widespread use of highly sensitive electronic devices, problems with electromagnetic interference have become increasingly serious. Shielding is a widely used solution to reduce interference [1]. The performance of a shielding enclosure is quantified by its shielding effectiveness (SE), which is the ratio of the electric field at an observation point without and with the enclosure. Since a shielding enclosure always contains apertures, the electromagnetic shielding effectiveness of an enclosure with aperture is a typical problem in electromagnetic interference. The actual internal structure of the enclosure is more complex and contains structures including partitions, trays, etc. These window-like structures will also affect the shielding effectiveness.

The calculation methods for the shielding effectiveness (SE) of shielding enclosures with aperture mainly include numerical methods and analytical methods. Numerical methods include finite-difference time-domain method [2], method of moments [3, 4], Transmission Line Matrix (TLM) Method [5–7], Finite Element (FEM) Method [8]. Numerical methods can handle complicated structures, but require a lot of time to build the model and consume more and more computational resources.

The analytical formulations have many simplifications and approximations in the computational process, but they also have much higher computational efficiency and the input parameters are more concise. The equivalent circuit method proposed by Robinson [9, 10] has high accuracy and efficiency in prediction. There are some limitations with this model. To extend the application scope and consider the effects of other conditions, such as an off-center aperture or an arbitrarily positioned monitoring point, many methods have been developed based on Robinson’s method [11–14]. However, these models can hardly handle complex enclosure structures.

Electromagnetic topology (EMT) provides a useful tool for studying the coupling problems of complicated electrical systems, which treat the complex interaction problem into smaller and more manageable problems [15, 16]. By applying the EMT concept, the Baum-Liu-Tesche (BLT) equation can be derived to calculate the voltage and current responses at the nodes of a general multiconductor transmission-line network [17–19]. The extended BLT equation can handle the voltage and current at all junctions [20, 21]. After converting the enclosure and aperture into nodes, we can use the BLT equation to calculate the SE [22–26].

In this paper, we propose a hybrid algorithm based on EMT and FIT to predict shielding effectiveness for enclosure with an arbitrary inner window. This paper is organized as follows: Section 2. introduces electromagnetic topological models and equivalent circuits. Section 3. introduces and discusses the validation of the model. Section 4. summarizes the conclusions of this work.

2. Electromagnetic Topological Model

The geometry of the enclosure with an arbitrary inner window is shown in Figure 1. The overall size of the enclosure is \(a \times b \times c\), and the distance between the window structure and the front wall is \(c_1\).

The size of the aperture on front wall is \(l \times w\), and its central point locate at the centre of the wall. And the two monitor points \(P_1\) and \(P_2\) located in front and behind of the window have the coordinates of \((x_{p1}, y_{p1}, z_{p1})\) and \((x_{p2}, y_{p2}, z_{p2})\).
respectively. The other parameters have the same definition as described in Figure 1.

Fig. 1. Apertured enclosure with an arbitrary inner window, the aperture is positioned centrally in the walls.

Fig. 2. Equivalent circuit of the enclosure.

The scattering matrix $S$ contains the scattering coefficients as shown in equation (1):

\[
\begin{bmatrix}
\rho_1^1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & S_2^2 & S_1^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & S_2^2 & S_1^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & S_1^3 & S_2^4 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & S_2^4 & S_1^3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & S_2^4 & S_1^3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & S_2^4 & S_1^3 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & S_2^4 & S_1^3 \\
\end{bmatrix}
\begin{bmatrix}
V_{\text{ref}}^1 \\
V_{\text{ref}}^2 \\
V_{\text{ref}}^3 \\
V_{\text{ref}}^4 \\
V_{\text{ref}}^5 \\
V_{\text{ref}}^6 \\
\end{bmatrix}
= 
\begin{bmatrix}
\rho^6 \\
0 \\
S_1^3 S_2^4 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\begin{bmatrix}
V_{\text{inc}}^1 \\
V_{\text{inc}}^2 \\
V_{\text{inc}}^3 \\
V_{\text{inc}}^4 \\
V_{\text{inc}}^5 \\
V_{\text{inc}}^6 \\
\end{bmatrix}
\]

(1)

$\rho_1^1 = 0$ is the free space, and $\rho^6 = -1$ is the short end of the enclosure. $S^3$ and $S^5$ are the observation points $p_1$ and $p_2$:

\[
S^3 = S^5 = 
\begin{bmatrix}
0 & 1 \\
1 & 0 \\
\end{bmatrix}
\]

(2)

$S^2$ and $S^4$ represent the aperture and window respectively, they can be obtained from network $T_1$ and $T_2$ in Figure. 2, respectively:

\[
S^2 = \frac{Y_0 - Y_{ap} - Y_{inc}}{Y_0 - Y_{ap} + Y_{inc}} \
\]

(3)

\[
S^4 = \frac{Y_0 - Y_{ek} - Y_{inc}}{Y_0 - Y_{ek} + Y_{inc}}
\]

(4)

where $Y_0$, $Y_e$, $Y_{ap}$ and $Y_{inc}$ are the admittances of free space, rectangular waveguide, aperture, and the window structure respectively, and $Y_0 = \frac{1}{Z_0}$, $Y_e = \frac{1}{Z_0}$, $Y_{ap} = \frac{1}{Z_0}$, $Y_{inc} = \frac{1}{Z_0}$.

We can also write equation (1) as:

\[
V_{\text{ref}} = S \times V_{\text{inc}}
\]

(5)

The equivalent circuit of the enclosure in Figure. 1 is shown in Figure. 2. The side wall is treated as waveguide, then the impedance and propagation constant $z_g$ and $k_g$ are given by:

\[
k_g = k_0 \sqrt{1 - \frac{(m \lambda)^2}{2a} - \frac{(n \lambda)^2}{2b}}
\]

(6)

\[
Z_g = Z_0 / \sqrt{1 - \frac{(m \lambda)^2}{2a} - \frac{(n \lambda)^2}{2b}}
\]

(7)

The radiating source is represented by voltage $V_0$ and impedance of free space $Z_0 = 377 \Omega$. The aperture is treated as a coplanar strip transmission line which shorted at each end, its characteristic impedance is given by Gupta et al [27]:

\[
Z_{ap} = \frac{j}{2} \frac{Z_0 tan(k_0l)}{2}
\]

(8)

$x_a$ and $y_a$ are the position coordinate, $m$ and $n$ are mode indices.

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

(9)

Since the enclosure have a thickness, when $w_e \leq \frac{b}{\sqrt{2}}$, we have effective width $w_e$ :

\[
w_e = w - \frac{5t}{4\pi} \left[ 1 + \ln \frac{4\pi w}{t} \right]
\]

(10)

Where $t$ represents enclosure wall’s thickness, $w$ is the width of the slot.

The cross-sectional view of the window structure inside the enclosure is shown in Figure. 3.

Substituting the equivalent impedance $Z_w$ derivative of the window structure into Equation (4), then we can obtain $S^4$. The empirical formula can be used to calculate the equivalent parameters for some of the windows, but is limited by the shape and location of the windows.

In this paper, we use the FIT solver of CST-WMS calculating $S$ parameters. The simulation setup is shown in Figure. 4, where waveguide port 1 acts as the excitation source and
waveguide port 2 is the receiving terminal. The upper and lower boundaries are set as electric boundaries, and the side boundaries are set as magnetic boundaries to simulate the propagation conditions of the plane waves. Assuming there is no resistive loss, equivalent impedance $Z_w$ can be derived from:

$$Z_w = j \frac{Z_0 |S_{21}|}{1 - |S_{21}|}$$  \hspace{1cm} (11)

Then we combine the numerical method and the extended BLT equation so that the hybrid model can deal with arbitrary apertures while guaranteeing high calculation efficiency.

Figure 5 shows the electromagnetic topology for the enclosure shown in Figure 1. Node $N_1$ represents the observation point outside the enclosure, and the nodes $N_3$, $N_5$ denote the observation points $p_1$ and $p_2$ inside the enclosure. The aperture on the front wall is defined by the nodes $N_2$, the window structure inside the enclosure is represented by node $N_4$, and the shorted end by $N_6$. The observation point $N_1$ and $N_6$ are equivalenced by a one-port network. Tube 1 denotes electromagnetic wave propagation in free space, while Tube 2, Tube 3, and Tube 4 represent wave propagation between the observation points and the aperture/window. Tube 5 denotes the wave propagation to the short end of the rear enclosure. According to Figure 5, we have a propagation matrix as shown in Equation (12), where each sub-matrix defines the propagation terms for each transmission line:

$$\Gamma \times V^{inc} = V_s$$

The total voltage response is defined as $V = V^{ref} + V^{inc}$, we have the extensional BLT equation [20]:

$$V = (E + S) \times (\Gamma - S)^{-1} \times V_s$$  \hspace{1cm} (14)

Where $E$ is a unit matrix, $\Gamma$ is the propagation matrix as shown in equation (12), $S$ is the scattering matrix. $V_s$ is the source matrix, since we have only one source in tube 1, so the $V_s$ has only one element in the first row. The result of the equation (14) is the total voltage response on the center axis of the front wall of the enclosure. Then the SE at point $P$ is calculated by [28]: $SE = -20 \log(V_p/V_0)$.

3. RESULTS AND DISCUSSION

In this section, three case is performed to validate the proposed model. The result of the proposed model are compared with the CST-MWS software (2016), the enclosure walls are assumed to be perfectly conductive, and their thickness is defined as 1 mm. We chose the plane wave excitation source to simulate an incident wave from a source located at a very far away place. The electric field strength of the plane wave source is 1 V/m, all boundaries are set as open space. In the CST-MWS software, we use a frequency-domain solver which based on the finite integration technique to obtain simulation results, with the benefit of the volume meshing technique, the frequency domain solver performs best for high Q devices such as a resonant cavity [29].

3.1 Validation

In the first case, it is assumed that the dimensions of the enclosure are 300 mm × 120 mm × 600 mm. 1, l, w, c1, c2, a1 and a2 are 80mm, 10mm, 300mm, 300mm, 120 mm and 60 mm respectively. And the two monitor points $P_1$ and $P_2$ located at the enclosure have coordinates (150, 60, -150) mm and (150, 60, -450) mm, respectively.

Figure 6 and 7 showing the SE results of the monitor points $P_1$ and $P_2$ obtained with the CST and the proposed method, respectively. It can be observed that the SE results of these two methods agree well. Moreover, SE changes dramatically in a wide range of frequencies near the resonant frequency of the enclosure and even shows negative values. The physical significance of these values indicates that the apertured enclosure has the worst shielding performance under these conditions, and the phenomenon described above is due to the resonance effect. In Figure 6 and 7, the deviation SE can also be seen. Possible reasons for this deviation are: The energy flow in the complex structure of enclosures leads to reflection and diffraction.
In order to verify the adaptability of the proposed method for different problems, we considered more complex window structures. In case 2, we calculated a case with a cross-shaped window. Figure 8 showing a cross-shaped window, the window is located in the center of the inner wall and the dimensional parameters $a_1, a_2, b_1$ and $b_2$ are 20 mm, 80 mm, 20 mm and 80 mm respectively, all other parameters are the same as case 1. Figure 9 and 10 showing the SE results of the monitor points $P_1$ and $P_2$ obtained with the CST and the proposed method, respectively.

In case 3, we consider a case with three windows. Figure 11 showing a inner wall with three windows, the center coordinates of each window are (40, 40) mm, (150, 30) mm, (265, 90) mm, respectively. And the size of each window are 20 mm $\times$ 80 mm, 60 mm $\times$ 60 mm, and 30 mm $\times$ 60 mm, respectively. All other parameters are the same as case 1.

Figure 12 and 13 showing the SE results of the monitor points $P_1$ and $P_2$ obtained with the CST and the proposed method.
The mesh of the entire enclosure reached 26000, 23800, 23500 tetrahedra after 4 mesh adaptation steps in case 1, 2, 3, respectively. And the mesh of window structures reached 4900 tetrahedra after 4 mesh adaptation steps in each case. 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 adaptive meshes allow for a balance between computational speed and accuracy [30]. All cases were calculated on the same computer running a 2.2-GHz Intel i7-8750 CPU. The CST usually requires 20 minutes for a simulation with 200 frequency points, while the hybrid algorithm requires no more than 102 s for the same case. These contrasts indicate the high computational efficiency of the hybrid algorithm compared to the full-wave CST simulation.

4. Conclusion

A hybrid algorithm method based on EMT theory and the full-wave method is presented to analyze the shielding performance of an apertured enclosure with an arbitrary inner window. By calculating the equivalent impedance of the arbitrary inner window using full-wave simulation, we derive a scattering matrix to describe the coupling relationship of the window structure. The total electric field can be derived from the relationship between the voltage response and the field distribution inside the enclosure, so we can easily obtain the SE at the monitoring point. Three examples are presented to demonstrate the validity and accuracy of this method. The results show that the proposed method agrees well with full-wave numerical methods over a wide range of frequencies while being able to dramatically increase the computational speed.

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