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Prediction Model of Shielding Effectiveness of Electromagnetic Shielding Fabric with Rectangular Hole

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Abstract—Electromagnetic shielding (EMS) fabrics often need to design rectangular holes for application. However, there is not a mature approach to predict the shielding effectiveness (SE) of the EMS fabric with rectangular hole. This paper proposes that there are a number of loose regions of conductive fibers on the hole edge of the EMS fabric, and establishes a SE prediction model of the EMS fabric with rectangular hole. Firstly, the loose region of conductive fiber is analyzed to build a model of the rectangular hole. Secondly, the SE prediction model of the EMS fabric with rectangular hole is deduced according to the transmission coefficient of the normal region, hole region and loose region, and the determining method of the loose region is given. Finally, the prediction model is verified by experiments. The results show that the model can successfully predict the SE of the EMS fabric with the plain, twill and satin weaves, and the factors such as frequency, fabric density and metal fiber content have little influence on the model. The proposed model can provide a valuable reference for the rational design of the rectangular hole of the EMS fabric.

1. INTRODUCTION

Electromagnetic shielding (EMS) fabric is an important EMS product and has important application in the civil, industrial and defense fields [1]. The holes are often designed in EMS fabric application, adding the leakage of the electromagnetic wave and affecting the shielding effectiveness (SE) of the fabric. Therefore, it is very important to correctly predict the SE of the EMS fabric with the hole, which is related to judge whether the hole design is reasonable and whether the SE of the fabric achieves the shielding requirement.

There are few researches about the SE prediction of the EMS fabric with rectangular hole at present. Related researches focus on the influence of the fabric density and tightness indicators on the SE [2–6]. The two indicators which describe the distribution of tiny interstices in the fabric are different from the indicator of the hole. Therefore, the results from the two indicators are not suitable for the SE prediction of the hole indicator. Other researches focus on the SE computation methods of the metal shield box with hole, and they are mainly analytical calculation method [7], transmission line method [8], finite-difference time-domain [9], moment method [10], and transmission line matrix method [11]. However, the metal box hole whose surface is smooth and shape is regular is different from the fabric hole which has a number of tiny fibers on the hole edge, and the shape is irregular. Therefore, the results from metal box are not suitable for the prediction of the EMS fabric.

This paper establishes a prediction model of the EMS fabric with rectangular hole according to the EMS fabric characteristic and transmission coefficient of the normal region, the hole region and the loose region of the conductive fiber. Experimental results show that the proposed model can predict the SE of the EMS fabric with rectangular hole. The prediction model can provide a valuable reference for the design of the rectangular hole of the EMS fabric.

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2. SE PREDICTION MODEL

2.1. Structural Model of Rectangular Hole

The hole in the metal box possesses the characteristics such as big hole, regular shape, smooth edge, hard texture and homogeneous medium material. However, the fabric hole is different, as shown in Figure 1. The fabric is soft and deformated so that the hole shape is irregular and there are a number of conductive fibers on the edge of the hole. The EMS fabric material is a non-homogeneous porous medium, and much electromagnetic wave leakage occurs outside the hole, influencing the SE computation of the fabric.

Therefore, a structural model of rectangular hole is established including the normal region, hole region and loose region of conductive fiber, as shown in Figure 2. The detailed dimension parameters of the model are given to provide a basis for further prediction model establishment.

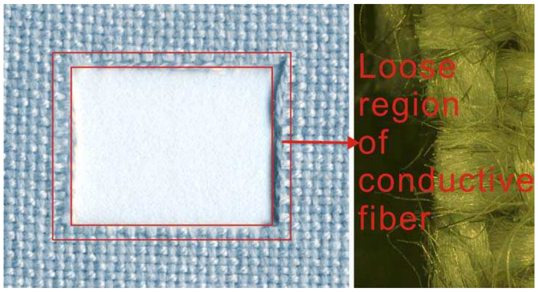

Figure 1. Loose region of conductive fiber on hole edge of EMS fabric.

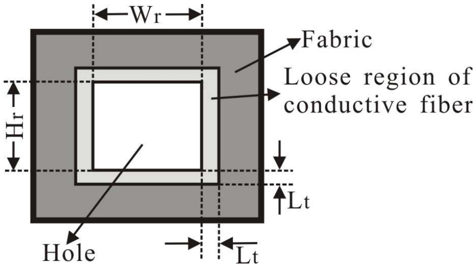

Figure 2. Structural mode of rectangular hole.

2.2. SE Prediction Model

According to the electromagnetic theory, for round and square holes on an ideal shield, let the area of the hole be S, the whole area of the shield is A. When $A \gg S$, the diameter of the round hole or the side length of the square hole is much smaller than the wave length. The leakage strength of the magnetic field can be calculated as [12]:

$$H_p = 4\left(\frac{S}{A}\right)^{\frac{3}{2}} H_0 \tag{1}$$

where, H_P refers to the leakage magnetic strength of holes of the shield and H_0 the magnetic field strength of the outside surface of the shield.

When the hole is rectangular, as illustrated in Figure 2, the short side is H_r, long side W_r, edge width L_t, and area S_{rect}, then

$$S_{rect} = (H_r + L_t)(W_r + L_t) \tag{2}$$

Let the circle area whose leakage is equivalent to the rectangular hole be S_{equ}, then

$$S_{equ} = k_s S_{rect} \tag{3}$$

where

$$k_s = \sqrt[3]{\frac{W_r + L_t}{H_r + L_t}\varepsilon^2} \tag{4}$$

$$\varepsilon = \begin{cases} 1 & (W_r = H_r) \\ \dfrac{W_r + L_r}{2(H_r + L_t)\ln\dfrac{0.63(W_r + L_t)}{(H_r + L_t)}} & (W_r > H_r) \end{cases} \tag{5}$$

Equation (4) is substituted into Equation (1), and H_P can be obtained as:

$$H_p = 4\left(\frac{k_s S_{rect}}{A}\right)^{\frac{3}{2}} H_0 = 4\left(\frac{\sqrt[3]{\frac{(W_r+L_t)}{(H_r+L_t)}\varepsilon^2 S_{rect}}}{A}\right)^{\frac{3}{2}} H_0 \tag{6}$$

When $W_r = H_r$, that is $\varepsilon = 1$, Equation (1) is the result.
When $W_r > H_r$, that is $\varepsilon = \frac{W_r+L_t}{2(H_r+L_t)\ln\frac{0.63(W_r+L_t)}{H_r+L_t}}$, then

$$H_p = 4\left(\frac{\sqrt[3]{\frac{(W_r+L_t)}{(H_r+L_t)}\left(\frac{W_r+L_t}{2(H_r+L_t)\ln\frac{0.63(W_r+L_t)}{H_r+L_t}}\right)^2 S_{rect}}}{A}\right)^{\frac{3}{2}} H_0 \tag{7}$$

The polynomial can be combined, and H_P can be calculated as:

$$H_p = \frac{\sqrt{\frac{(W_r+L_t)^3}{2\left(H_r+L_t\right)^3 \ln\frac{0.63\left(W_r+L_t\right)}{\left(H_r+L_t\right)}} S_{rect}}}{A^{\frac{3}{2}}} H_0 \tag{8}$$

Let the transmission coefficient of the EMS fabric be T_{self} and the transmission coefficient of the hole be T_{rect}. The total transmission coefficient under the rectangular holes can be written as:

$$T_z = T_{self} + T_{rect} \tag{9}$$

where

$$T_h = \frac{H_p}{H_0} = \frac{\sqrt{\frac{(W_r+L_t)^3}{2(H_r+L_t)^3 \ln\frac{0.63(W_r+L_t)}{(H_r+L_t)}} S_{rect}}}{A^{\frac{3}{2}}} \tag{10}$$

Then the SE of the EMS fabric with a rectangular hole can be calculated as:

$$SE_{cal} = 20\lg\left(\frac{1}{T_{self}+T_{rect}}\right) \tag{11}$$

$$SE_{cal} = 20\lg\left(\frac{1}{T_{self} + \frac{\sqrt{\frac{(W_r+L_t)^3}{2(H_r+L_t)^3 \ln\frac{0.63(W_r+L_t)}{(H_r+L_t)}} S_{rect}}}{A^{\frac{3}{2}}}}\right) \tag{12}$$

According to the fabric structure characteristic, the conductive fiber crosslink decreases because a number of fibers are dispersed and shed. The conductive performance of the hole edge decreases, and the electromagnetic leakage increases [13]. According to the characteristic of the yarn interwoven, the loose regions focus on the unstable regions of the interwoven. As shown in Figure 3, the broken region on the floating side of the interwoven is the loose region. The width is the diameter of the yarn and interstice.

Let the warp and weft densities of the fabric be D_v (ends/10 cm) and D_w (ends/10 cm), then L_t can be calculated as:

$$L_t = \frac{\left(\frac{10}{D_v} + \frac{10}{D_w}\right)}{2} = \frac{5}{D_v} + \frac{5}{D_w} \tag{13}$$

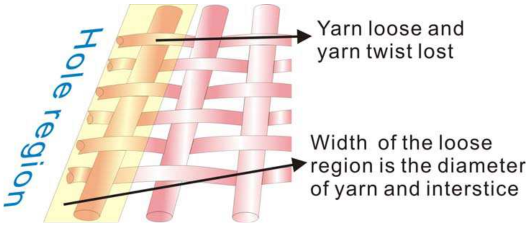

Figure 3. Schematic diagram of yarn in loose region of conductive fiber.

The broken yarn is warp or weft, so that one of warp and weft is loose and that the yarn twist is lost, and another yarn remains in original condition [14]. According to the theory that the SE is determined by the number of the crosslink fibers [6], the number of the conductive fibers is halved. Therefore, L_t can be rewritten as:

$$L_t = \frac{\frac{5}{D_v} + \frac{5}{D_w}}{2} = 2.5\left(\frac{1}{D_v} + \frac{1}{D_w}\right) \tag{14}$$

Let the SE of the EMS fabric without hole be SE_{whole}, and it can be calculated as:

$$T_s = \frac{1}{\left(\frac{\mathrm{SE}_{whole}}{20}\right)^{10}} \tag{15}$$

Equations (14) and (15) are substituted into Equation (12), and we can obtain:

$$\mathrm{SE}_{cal} = 20\lg\left(\frac{1}{\frac{1}{\left(\frac{\mathrm{SE}_{whole}}{20}\right)^{10}} + \frac{\sqrt{\frac{\left(W_r + \frac{2.5}{D_v} + \frac{2.5}{D_w}\right)^3}{2\left(H_r + \frac{2.5}{D_v} + \frac{2.5}{D_w}\right)^3 \ln \frac{0.63\left(W_r + \frac{2.5}{D_v} + \frac{2.5}{D_w}\right)}{\left(H_r + \frac{2.5}{D_v} + \frac{2.5}{D_w}\right)}}} S_{rect}}{A^{\frac{3}{2}}}}\right) \tag{16}$$

3. VERIFICATION METHOD

3.1. Experimental Materials

A number of EMS fabrics with the plain, twill and satin weaves are selected, and rectangular holes with various sizes are made on the fabrics as samples to verify the prediction model given in Equation (16). The size of the sample is 30 cm × 30 cm. Table 1 lists the specification of the part fabrics.

3.2. Experimental Methods

The SE of sample is tested by the waveguide testing system [15, 16]. The frequency range is selected from 2.0 GHz to 2.6 GHz. The distance between the signal transmission source and the sample is 0.7 m, and the distance between the signal receiver and the sample is 0.5 m. The signal transmission source and receiver are fixed on two sides of the waveguide. First, the SE values (SE_{whole}) of the samples without hole are tested, and then the SE values (SE_{test}) of the samples with a rectangular hole are tested. Each sample is tested three times, and the average is the final SE of the sample.

Table 1. Specification of part experimental sample.

	P_1	P_2	P_3	S_1	S_2	S_3	T_1	T_2	T_3
Fabric weave	Plain			Satin			Twill		
Warp density	386	323	295	392	361	320	379	351	312
Weft density	227	201	190	259	215	197	261	239	195
SE_{whole}	30.1	31.9	33.5	278	313	332	28.7	326	344
Metal fiber content	15%	20%	25%	15%	20%	25%	15%	20%	25%
W_r	0.4	0.7	0.9	0.5	0.8	1.1	0.3	0.5	0.6
H_r	0.7	1.3	1.5	0.9	1.3	1.8	0.5	0.9	1.1

4. RESULTS AND ANALYSIS

4.1. Results

The SE values (SE_{cal}) of the samples with hole are calculated by Equation (16) and compared with the experimental values (SE_{test}). Figure 4 illustrates the comparison results of the predication values (SE_{cal}) and experimental values (SE_{test}) of the samples listed in Table 1. The results show good consistency. It is proved that the proposed model can correctly predicate the SE of the EMS fabric with the rectangular hole.

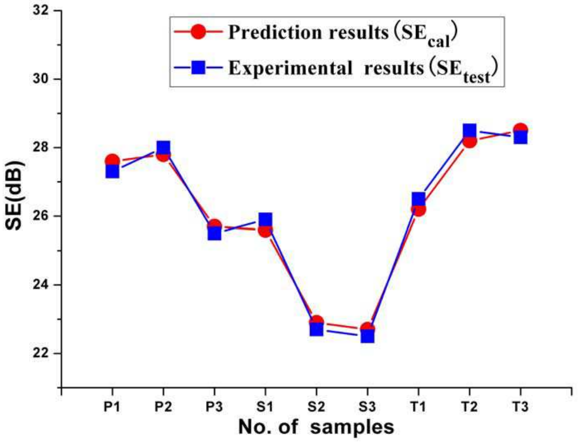

Figure 4. Comparison results of the predication values and experimental values of EMS fabric with rectangular hole ($f = 2.2\,\mathrm{GHz}$).

4.2. Discussion

The SE of the shield is determined by the frequency, conductivity and magnetic permeability. The SE of the EMS fabric is influenced by the density and metal fiber content which is determined by the frequency, conductivity and magnetic permeability [16]. Equation (16) shows that the SE_{cal} is determined by the SE_{whole} of the fabric without hole and the hole size. Therefore, the value of SE_{cal} is influenced by the value of SE_{whole}, including the frequency, metal fiber content and fabric density parameters, which is also illustrated by Figure 4. The SE consistency of the computation from Equation (16) and the experiments is good whether the fabric weaves are plain, twill and satin weaves, though each sample possesses different densities and metal fiber contents (as shown in Table 1).

The further experiments also verify the results. The results are the same as the case that frequencies are changed. Figures 5–7 show the comparison results with different frequencies.

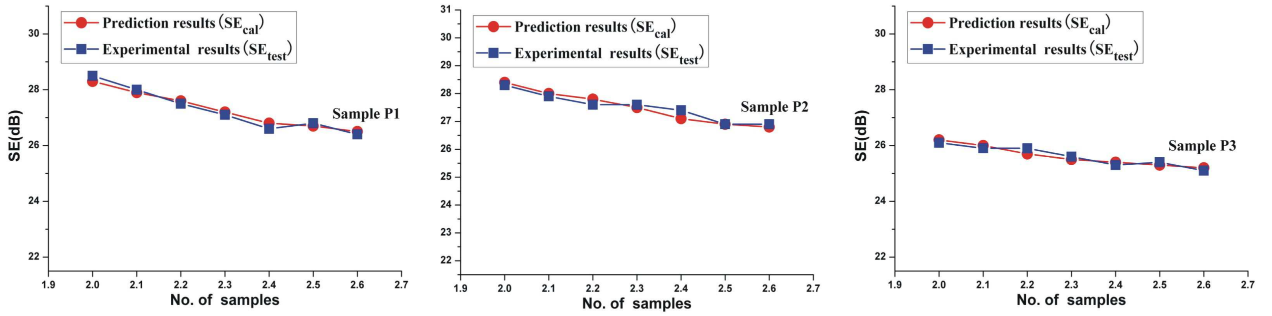

Figure 5. Comparison results of predication value and experimental value of samples P_1–P_3 over different frequencies.

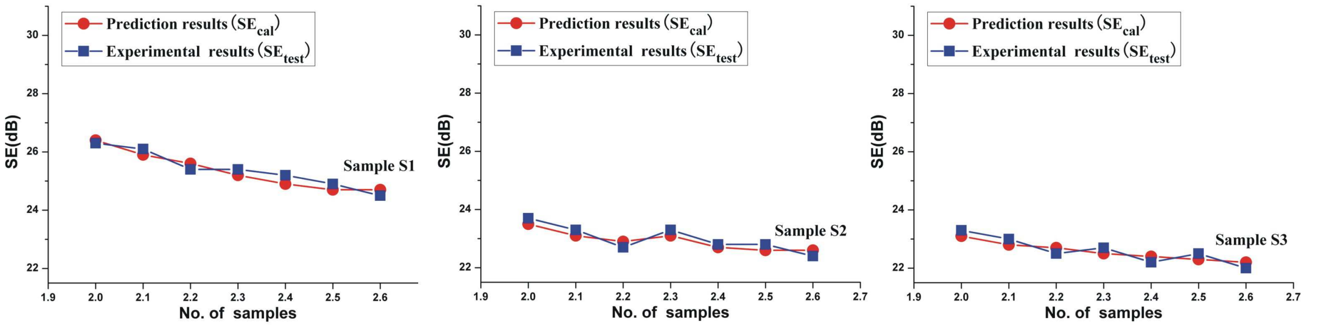

Figure 6. Comparison results of predication value and experimental value of samples S_1–S_3 over different frequencies.

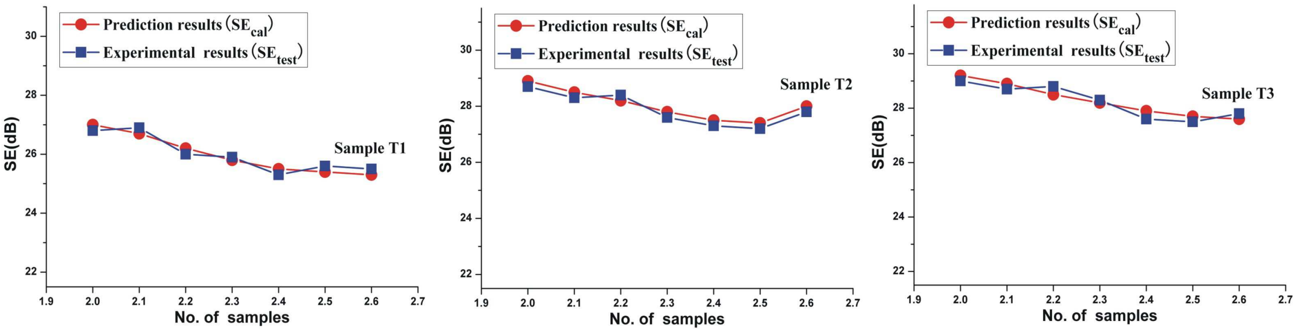

Figure 7. Comparison results of predication value and experimental value of samples T_1–T_3 over different frequencies.

5. CONCLUSIONS

1) The established prediction model of the SE of the EMS fabric with the rectangular hole has good accuracy and practical value under full consideration of the hole edge characteristic.
2) The established model can be applied to the EMS fabric with the plain, twill and satin weaves.
3) The prediction model still has good applicability with the change of the frequencies (the range of the frequencies is 2.0 GHz–2.6 GHz), densities and metal fibers content.

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