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A NEW COMPUTATION OF SHIELDING EFFECTIVENESS OF ELECTROMAGNETIC RADIATION SHIELDING FABRIC

X. C. Wang* **and Z. Liu**

[1]Zhongyuan University of Technology, Zhengzhou, Henan 450007, P. R. China

Abstract—In this paper, a new computation model of shielding effectiveness (SE) is proposed in order to calculate the SE of blended electromagnetic shielding fabric (BESF) by some structural parameters. Some computation equations of the SE for the BESF are given according to the theoretical deduction and previous experimental results. And then a shielding coefficient in the computation model is determined by experiments. The linear region boundary for the model is introduced to segment the computation of the SE. Results show that the SE obtained from the proposed model is consistent with that from experiments and the error is less than 2%. It can be concluded that the proposed model can accurately calculate the SE of plain, twill and satin weaves fabrics.

1. INTRODUCTION

Blended electromagnetic shielding fabric (BESF) is mainly used to manufacture shielding composite material, shielding clothing, and shielding textile product [1]. The shielding function of BESF is obtained by adding metal fiber. The shielding effectiveness (SE) is an important indicator to measure the shielding performance of BESF [2]. It is hoped that the SE can be calculated by some parameters so that the testing process will be simple and efficiency improved in the design, manufacture and testing of BESF.

Until recently the studies on the shielding fabric have mainly focused on model construction of the BESF [3, 4], performance of the BESF [5, 6], testing of the BESF [7], and shielding fiber [8]. We still possess poor information about the SE computation of BESF. However,

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* Corresponding author: Xiu Chen Wang (nbwangxiuchen@163.com).

there are more computation approaches in literatures on the SE computation of shield with aperture in electronic equipment fields [9–12]. The approaches mainly are analytical calculation, transmission line method, finite-difference time-domain method, moment method, and transmission line matrix. The aperture is considered as an idealized rectangular in above approaches. However, the apertures in the BESF are more, the size and shape are different, and much hairiness is filled in the apertures. The aperture in the BESF cannot be regarded as an ideal rectangular. Therefore, the methods which have applied to electronic equipment are not suitable for the BESF application.

In order to solve the problem of the SE computation of BESF, We construct a new computation model of the SE considering the main factors such as metal content, yarn diameter, fabric tightness. The detail calculation equations of the SE are given according to theoretical deduction and previous experimental results. Experimental results show that the proposed model can successfully calculate the SE of BESF.

2. COMPUTATION MODEL CONSTRUCTION

2.1. Theoretical Analysis

The main shielding ways of an idea metal shield are reflection, multiple reflection and absorption. The SE can be expressed as [13]

$$SE = R + A + B\,(\mathrm{dB}) \tag{1}$$

where R is the reflection loss, A is the absorption loss, and B is the multiple reflection loss. R, A and B are determined by the relative magnetic penetrability μ_r and the relative conductivity σ_r in the idea metal shield. However, the relative magnetic penetrability and the relative conductivity of each fabric are different and have no direct relations each other, so they must be specifically tested with some methods. Therefore, the SE of fabric cannot be calculated by testing the relative magnetic penetrability and the relative conductivity. A computation method that is suitable for fabric feature needs to be found.

The relative magnetic penetrability and the relative conductivity of the BESF are determined by the metal fiber per unit area because the non-metallic fiber is transparent to the electromagnetic wave. The metal fiber content per unit area of fabric is determined by the yarn linear density, the metal content of fiber, fabric's thickness, fabric's tightness, and the weave type of fabric. Therefore, the computation model of the SE can be established by these parameters.

According to Equation (1), electromagnetic radiation theory and previous experiments, we can do some inference as follows:

(1) The SE of BESF is proportional to the metal fiber content of the yarn. As other parameters are certain, the more the metal fibers of the yarn are, the more the metal fibers per unit area of fabric are, and the higher the SE is.

(2) The SE of BESF is inversely proportional to the yarn linear density. The lower the yarn linear density is, the thinner the yarn is. As other parameters are not changed, the number of yarns per unit area increases, the contact points of the yarn increase, the tiny apertures increase, so the SE of the fabric decreases.

(3) The SE is directly proportional to the tightness of BESF. Tightness E that is an indicator to reflect the degree of fabric density is defined as the fraction of the fabric area covered by the threads. Therefore, the tightness E is given as

$$E = E_t + E_w - 0.01 \times E_t \times E_w \tag{2}$$

where, E_t denotes the warp tightness (%), E_w refers to the weft tightness (%). The unit of tightness E is %.

The SE and the tightness of BESF are approximate positive growth relationship as shown in Figure 1. If the tightness is less than T_1, the shielding effect is very small because the interstice in the fabric is large, the SE trends to a small stable state. As the tightness reaches to T_1, the shielding effect of BESF begins to appear. Before the tightness reaches to T_2, the SE increases with the tightness of fabric increases. As the tightness is greater than T_2, the SE trends to a stable state. The SE is not influenced by the yarn extrusion in fabric. Therefore, we can consider the segment range of the tightness when we construct the computation model. It can be concluded that

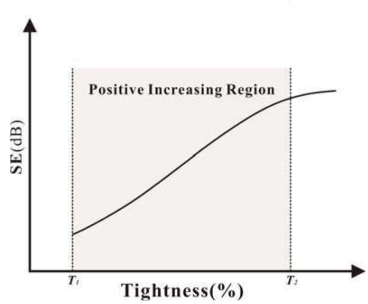


Figure 1. SE-tightness relationship.

the SE and the tightness are a positive increasing relationship when the tightness is in the range $[T_1, T_2]$, and the SE value is a stable value when the tightness is less than T_1 and greater than T_2.

2.2. Computation Model Construction of SE

According to above analysis, we establish a computation model of the SE with the fabric parameters.

Assuming that $E(\%)$ is the tightness of fabric, metric count N_m(m/g) denotes the yarn linear density, which is the yarn length in metres that weighs 1 gram. $M(\%)$ represents the metal fiber content of yarn. Let us presume the plane wave that the frequency is f is vertical incidence to the surface of the fabric, a point's SE of the fabric is S. Also presume there is an idea shield without aperture, the size of the shield is consistent to that of the fabric, its material is the fabric added metal, and the SE is S_1. According to the Equation (1), the S_1 can be calculated by [14]

$$S\_1 = 168.16 - 10\lg\frac{\mu_r f}{\sigma_r} + 1.31t\sqrt{f\mu_r\sigma_r} \quad (\text{dB}) \tag{3}$$

where t denotes the thickness of idea shield (cm), μ_r the relative magnetic penetrability, σ_r the relative conductivity, and f the frequency (H_z).

According to analysis of Section 2.1, the SE is proportional to the tightness of the fabric; it is inversely proportional to the yarn linear density; it is the ratio of the metal content. Therefore, the SE computation of the fabric can be established as

$$S = \lambda\frac{EM}{\sqrt{N_m}}S\_1 \tag{4}$$

where, λ denotes the correction coefficient which can be obtained from experiments.

Let

$$Q = \frac{EM}{\sqrt{N_m}}S\_1 \tag{5}$$

Then

$$S = \lambda Q \tag{6}$$

According to Equation (4), the coefficient λ can be calculated by

$$\lambda = \frac{S}{Q} = \frac{\sqrt{N_m}\times S}{E\times M\times\left(168.16 - 10\lg\frac{\mu_r f}{\sigma_r} + 1.31t\sqrt{f\mu_r\sigma_r}\right)} \tag{7}$$

3. COEFFICIENT DETERMINATION BY EXPERIMENTAL METHOD

3.1. Experimental Design

The SE of different BESFs is tested using the waveguide testing system. The waveguide testing system consists of analyzers, oscilloscopes, frequency sweep signal source, waveguide, waveguide coaxial converter constitutes. The signals are transmitted by the emission sensors, then are blocked by the fabric and received by signal receiving sensor and are input to network analyzer. Finally, the SE of fabric is calculated by the analyzer [15].

The SE of the fabric is expressed as

$$S_e = 20 \lg \frac{U_0}{U_S} \tag{8}$$

where U_0 and U_S refer to the amplitude of one frequency point without shield and with shield, respectively.

Some stainless steel fiber blended samples with different yarn linear densities and different tightnesses are made by a small experimental loom. The weaves of samples include plain, twill and satin. Each testing sample is tested three times with a setting frequency, and the average value is calculated and considered as the SE of sample. The frequency is set every 0.1 GHz from 1 GHz to 3.5 GHz as the transmitting frequency of waveguide.

A program is compiled with MATLAB7.0 to calculate the shielding coefficient λ of each sample according to Equation (5) and Equation (7). Here, the value of μ_r of stainless steel fiber is 0.02, and the value of σ_r is 500. Finally, the value of coefficient λ of each sample is determined by experimental error analysis, and then other samples are chosen to verify the results.

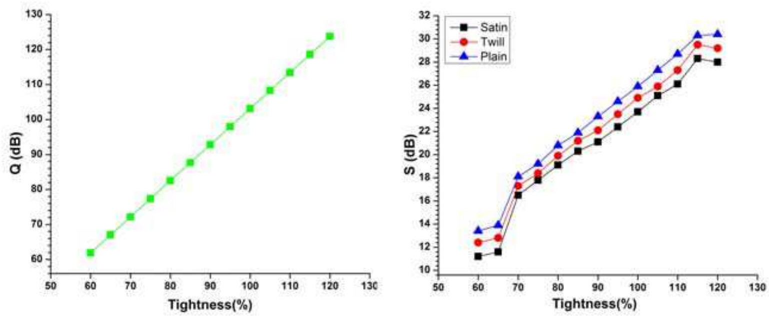
3.2. Coefficient Determination

Suppose the coefficient λ exists and is suitable for a wide range of fabrics. The value of Q is obtained by Equation (5), the value of S is tested by experiments, and the value of λ is calculated by Equation (7). Then the applicability of λ is verified when N_m and M are changed. According to the experimental frequency, the theoretical values (Q) of samples with different tightnesses and weaves are obtained, and are compared with the testing values (S). Figure 2 gives the theoretical value (Q) and testing value (S) at the frequency $f = 2.8$ GHz.

According to the computation results of Equation (7), it can be observed that the values of λ of plain, twill and satin samples are stable values in a linear increasing region $[T_1, T_2]$ at different frequencies, illustrated in Figure 3.

From Figure 3, it can be noticed that the tightness range $[70, 110]$ is the linear increasing range $[T_1, T_2]$ illustrated in Figure 1, and the value of λ is stable and trends to a constant as the tightness is in the linear increasing range. Considering the experimental error, we calculate the average value of shielding coefficient of all samples as the finial value of λ. The value of λ of the BESF is calculated as listed in Table 1.

By observing Figure 3, it can be noticed that as the tightness is less than T_1, the SE is very low and shows a ladder decrease and rapidly reach to 0. Here the fabric has not shielding effect feature, and the relationship between the SE and the tightness is not linear. The SE



(a) (b)

Figure 2. (a) Theoretical value (Q) and (b) testing value (S).

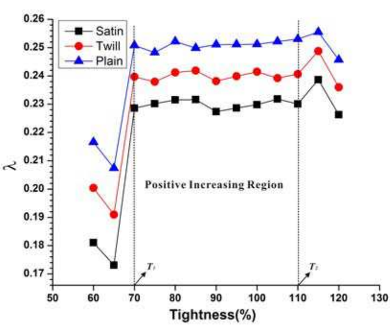


Figure 3. Shielding Coefficient λ of the Fabric.

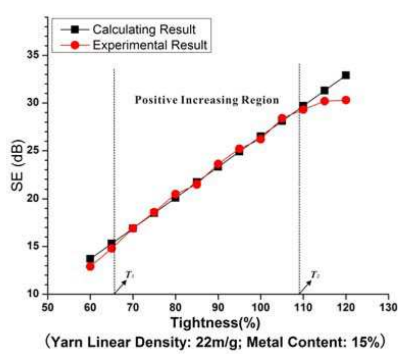


Figure 4. Comparison between computation value and testing value of plain fabric (yarn linear density: 22 m/g).

Table 1. Coefficient λ of different fabrics.

Coefficient	Satin	Twill	Plain
λ	0.232	0.252	0.271

trends to stable and reaches to a critical value as the tightness is more than T_2. Therefore, the SE can not be calculated with the coefficient λ in these two ranges, we should choose other methods.

4. VERIFICATION AND ANALYSIS

4.1. Results Verification

In order to verify the accuracy of Equation (5), we choose three groups of BESF as samples. The materials of samples are stainless metal fibers and cotton fibers, and the weaves of samples are plain, twill and satin. In each group, there are 13 samples which tightness is selected every 10% from 60% to 120%. The testing frequency is set every 0.2 GHz from 1 GHz to 3.5 GHz. We compare the SE from experimental data of samples with computation value of the SE according to the value λ listed in Table 1 and Equation (5). Limited by the space, we give the comparison results at the frequency $f = 2.5\,\text{GHz}$, as shown in Figures 4–6.

Observing above results from Figures 4–6, it is noted that the computation value almost coincides with the experimental value in the linear increasing region. It is concluded that the SE of BESF can be calculated by Equation (6). We further change the experimental frequency from 1 GHz to 3.5 GHz, the results is consistent with that of Figures 4–6.

4.2. Boundary Determination of Proper Range of Computation

The linear regions $[T_1, T_2]$ in the Figure 4, Figure 5 and Figure 6 are $[66, 109]$, $[73, 109]$ and $[75, 110]$, respectively. As the tightness equals T_1, there are no effective contact and large apertures among yarns, the SE of the fabric is low and even zero, and the SE is not abide by the linear variation. As the tightness equals T_2, yarns are full squeezed and reach to a stable and close state, and the SE of the fabric does not increase with the tightness increase and trends to a stable state.

According to above analysis and the definition of tightness, we give a computation for the boundary $[T_1, T_2]$ with the yarn diameter D_d (mm), hairiness thickness D_h (mm) as follows:

$$T_1 = \left(\frac{2D_d}{D_d + 2D_h} - 0.01 \times \frac{D_d^2}{(D_d + 2D_h)^2} \right) \times 100 \tag{9}$$

$$T_2 = \left(\frac{2D_d}{D_d - 2D_h} - 0.01 \times \frac{D_d^2}{(D_d - 2D_h)^2} \right) \times 100 \tag{10}$$

4.3. Computation Accuracy

According to analysis in Section 4.1, we find that the proposed model can successfully calculate the SE of fabric at 1 GHz–3.5 GHz frequencies.

Assuming the number of samples is N, the SE S_i of the ith sample is calculated by Equation (6). The SE Se_i of the ith sample is obtained from experiments. Then the accuracy can be calculated by the relative error R. The relative error R is established as

$$R = \frac{\sum_{i=1}^{N} |Se_i - S_i|}{\sum_{i=1}^{N} Se_i} \times 100\% \tag{11}$$

The results show that the relative error between the computation results and the experimental results is less than 2%. From Figure 4 to Figure 6, we have observed that the SE curve of computation coincides

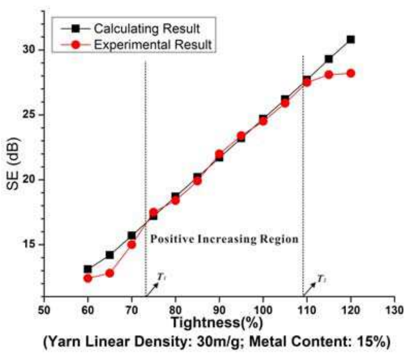


Figure 5. Comparison between computation value and testing value of twill fabric (yarn linear density: 30 m/g).

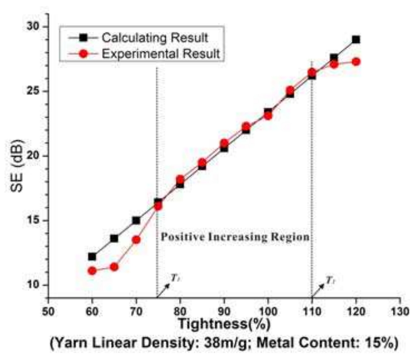


Figure 6. Comparison between computation value and testing value of twill fabric (yarn linear density: 38 m/g).

with that of real testing in the linear region, which shows that the computation results are more accurate.

5. CONCLUSIONS

(1) A new computation considering main factors of metal content, yarn linear density and fabric tightness is proposed in this paper. It can accurately calculate the SE of plain, twill and satin weaves BESFs at 1 GHz–3.5 GHz emission frequencies, and the results error is less than 2%.

(2) The experimental steps for shielding coefficient determination are reasonable and the results are more accurate. The shielding coefficient can reflect the differences between the SE of BESFs with basic weaves. The SE of BESF can be obtained by the proposed model with shielding coefficient.

(3) The linear region $[T_1, T_2]$ determination of the SE and the tightness limits the adapt range of the computation, so that the SE computation of BESF is segmented and calculated accurately.

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