Progress In Electromagnetics Research Letters, Vol. 115, 9-14, 2024
PIER Letters

(Received 13 September 2023, Accepted 27 November 2023, Scheduled 5 December 2023)

Rapid Estimation of Shielding Effectiveness in Chest and Abdomen Regions of Electromagnetic Shielding Clothing

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ABSTRACT: The shielding effectiveness (SE) of electromagnetic shielding (EMS) clothing is primarily achieved through experimental testing, but this method comes with drawbacks such as high cost, extended time, and imprecise testing outcomes. In order to quickly and cost-effectively obtain the protective performance of clothing, this article proposes a fast estimation method for the local SE of EMS clothing, which can quickly estimate the SE in the chest and abdomen regions through human body shape parameters. Firstly, an elliptical conical surface model is established for the chest and abdomen regions according to the shape of the human body. Following the principle of calculus, a local SE solution method based on this model is constructed. Additionally, a model correction coefficient that takes into account the impact of holes and seams is offered. Finally, a rapid estimation method is established for the SE of the chest and abdomen regions of the clothing. Experiments are ultimately designed to validate the model. In conclusion, the estimated values of the model are in agreement with the measured values, and it exhibits fast and efficient performance. This paper provides a new way to rapidly estimate the SE of EMS clothing in local areas and plays an important role in promoting the design, evaluation, and related detection of EMS clothing.

1. INTRODUCTION

Electromagnetic radiation, considered a significant threat to human health, has been designated as a crucial pollutant to be internationally controlled [1]. Electromagnetic shielding (EMS) clothing is an ideal product for protecting the human body against electromagnetic waves [2]. However, its shielding effectiveness (SE) is currently obtained through experimental testing, which has drawbacks such as high cost, extended time, and inaccurate testing results. Therefore, there is an urgent need for a more effective method to quickly estimate the SE of clothing, so as to quickly and cost-effectively obtain the protective performance of clothing. This plays an important role in promoting the rapid progress of clothing design, production, evaluation, and commercial testing, and can significantly improve the efficiency of these tasks. However, the complex structure of clothing styles, including openings, seams, buttons, slide fasteners, and other inevitable hole and seam areas, poses difficulties in estimating the SE of the EMS clothing. After conducting extensive research, we have discovered a significant correlation between the SE of the EMS clothing and various body shapes. The changes in SE of clothing, with the fabric remaining constant, are primarily dependent on the shape of the human body. If a scientific and effective method can be established based on the human body morphology to quickly estimate the SE of the EMS clothing, it will offer a new solution to address the limitations of experimental testing, thereby acquiring significant application and scientific value.

There is a scarcity of research literatures on the estimation of the SE of the EMS clothing. The primary focus of the research associated with this article is on establishing simulation models. Zhang et al. [3] employed the electromagnetic field finite element method to simulate the SE of electromagnetic radiation protective clothing. Using the finite difference time domain method, Sun and colleagues [4] conducted a comprehensive investigation on the protective properties of protective clothing on the human body within the 0.3–3 GHz frequency band. Zhang and Chen [5] used the three-dimensional electromagnetic simulation software to create a test simulation model to determine the SE of clothing. Toghchi et al. [6] employed a parametric graphical method to create a 3D virtual human model during pregnancy and evaluated it against the actual body shape of pregnant women. They emphasized that the model had the potential to be utilized in the research of EMS clothing. Peng and colleagues [7] employed simulation software COSMOL to conduct a simulation of the SE of the EMS clothing and verified its functionality. Wang et al. [8] conducted research on the calculation method of the SE in curved surface morphology of the clothing.

The aforementioned simulation methods fail to consider curved surface characteristics of the human body, as they are often based on the stacking of geometric bodies, thereby providing an inaccurate depiction of the human body shape. Most importantly, these simulation methods are complex in modeling and parameter setting, and they only meet the specific human body feature specifications. Their universality and efficiency are not strong, making it difficult to quickly meet the requirements for the SE of clothing with size changes. The remaining research related to EMS clothing primarily concentrates on testing methods and product performance. Kurokawa and Sato [9] and Yoshimura et al. [10] used time-domain analysis to study the testing method of the SE of the EMS clothing. Chen and

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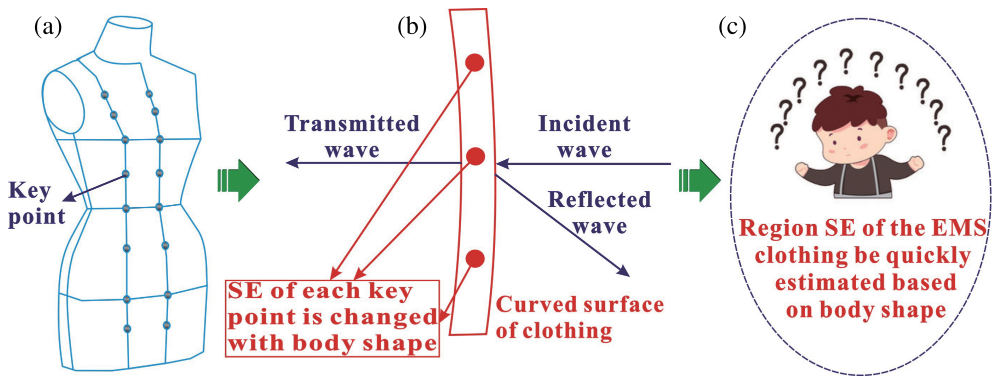

FIGURE 1. Estimation ideas of local SE of EMS clothing.

Tseng [11] studied the performance of the EMS clothing materials and their impact on the overall protective performance of the clothing. Wang et al. [12] analyzed the impact of various influencing factors on the protective effect of the clothing. In literature [2, 13], the authors analyzed the impact of necklines and cuffs on the SE of the clothing and explained the impact of these factors on the clothing performance according to test data.

In conclusion, the current EMS clothing models face challenges in accurately describing body shapes and curved surfaces. In particular, the models must be carefully designed in accordance with the actual structure of the human body. This method necessitates the setting of multiple parameters, often leading to a lack of efficiency and conciseness and consuming a significant amount of time, thus making it challenging to acquire the SE of the clothing.

This article proposes a method for quickly obtaining the local SE of EMS clothing based on local morphological parameters of the human body. A chest and abdomen model of clothing is constructed based on human body characteristics, and a fast estimation method based on this model is built using calculus method. By comparing with experiments, it is confirmed that the method is simple yet effective, and the calculation results are satisfactory.

2. ESTABLISHMENT OF ESTIMATING MODEL FOR THE SE OF EMS CLOTHING

2.1. Basic Ideas

Currently, numerous numerical simulation methods exist, such as finite-difference time-domain (FDTD) [14], moment method [15], finite element method [16], but they are all relatively complex. In our long-term research, we have found that the SE of EMS clothing is closely related to the local dimensions, curved surfaces, and other human body shapes when the fabric remains unchanged. It is an effective approach if the SE of the clothing area can be quickly estimated based on the SE of the fabric and human body shape.

As illustrated in Figure 1(a), the clothing items exhibit a mostly curved shape locally, with varying SE from each key point. A large number of experiments have found that when the shape of clothing changes, the SE of that area changes. That is, the SE of a local area of the clothing is determined by the human body shape, as shown in Figure 1(b) [17]. Specifically, it is determined by parameters such as the surface shape and size of the area. Therefore, in order to effectively evaluate the SE of the shielding clothing area, it is necessary to start from the human body shape and find the relationship between it and the SE of the clothing, in order to construct an estimation model of the SE based on the human body shape, as illustrated in Figure 1(c).

2.2. Estimating Model Construction

The chest and abdomen area of EMS clothing is a crucial protective zone, thus the modeling solely focuses on this localized region of the clothing. Due to electromagnetic waves permeating the cuffs, hem, and adjacent seams around the chest and abdomen area, resulting in a significant reduction in SE of clothing, the optimal model is further refined with the consideration of the hole and seam coefficient λ.

Firstly, establish the relationship between the main parameters in the chest and abdomen regions. As illustrated in Figure 2(a), choose the cross-section of the chest and abdomen to ascertain the extent of the human chest and abdomen region. The cross-sections of the chest and abdomen region are deemed as elliptical planes, as illustrated in Figure 2(b) [18]. It is an elliptical cone shaped by numerous elliptical surfaces in the Z-axis direction, located between the chest and waist. As illustrated in Figure 2(c), the cone vertex is designated as the origin O of the spatial coordinate system, and the cross-sectional circumference serves as the circumference L of the ellipse. The X-axis direction corresponds to the length a of the ellipse's major axis, and the Y-axis direction corresponds to the length b of the ellipse's minor axis. The relationship between them is:

$$L = 2\pi b + 4(a - b) \tag{1}$$

Secondly, model and digitize the chest and abdomen regions based on the above relationships. Set the Y-axis to represent the direction of the incident wave and the X-axis to represent the width of the human body. Divide the curved surface into n small planes ΔSi evenly, and let $p(x_{si}, y_{si}, z_{si})$ be a point arbitrarily determined above the small piece ΔSi. ni represents the unit normal vector of a plane ΔSi. $\cos\alpha i$, $\cos\beta i$, $\cos\gamma i$ are cosines of the angles between ni and positive directions of the X, Y, and Z axes, respectively. The equation for elliptical

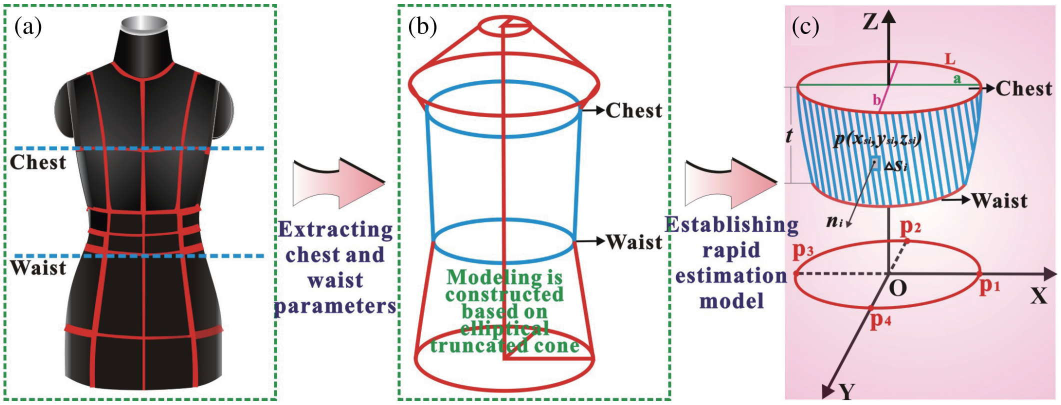

FIGURE 2. Estimation model construction for chest and abdomen regions of EMS clothing.

truncated cone is:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = z^2; \tag{2}$$

When $Z = t$, the equation is:

$$\frac{x^2}{(at)^2} + \frac{y^2}{(bt)^2} = 1 \tag{3}$$

Furthermore, calculate the SE of any point based on the above model. When $Z = t$, the projection of the elliptical truncated cone on the XOY coordinate plane is ellipse. Their intersection points on the coordinate axis are $p1$, $p2$, $p3$, and $p4$, respectively. Coordinates can be represented as $p1(at, o, t)$, $p2(-at, 0, t)$, $p3(0, bt, t)$, $p4(0, -bt, t)$. Assume the effectiveness of point $p(x_{si}, y_{si}, z_{si})$ which is infinitely close to the plane at a point is SE. SE_{xi}, SE_{yi}, SE_{zi} are the decomposition quantities of the SE in the direction of three coordinate axes in space. Then:

$$SE_{xi} = SE\cos\alpha i = SE\frac{zxi}{\sqrt{1+z^2xi+z^2yi}} \tag{4}$$

$$SE_{yi} = SE\cos\beta i = SE\frac{zyi}{\sqrt{1+z^2xi+z^2yi}} \tag{5}$$

$$SE_{zi} = SE\cos\gamma i = SE\frac{1}{\sqrt{1+z^2xi+z^2yi}} \tag{6}$$

Equations (4), (5), and (6) are mathematical expressions of the SE of the point $p(x_{si}, y_{si}, z_{si})$ in the X, Y, and Z directions. Set the shielding effectiveness of the fabric as SE_f, then:

$$SE_f = SE \tag{7}$$

The curved surface Equation (2) can be transformed into:

$$F(x, y, z) = \frac{x^2}{a^2} + \frac{y^2}{b^2} - z^2 = 0 \tag{8}$$

Then

$$\frac{\partial z}{\partial x} = -\frac{Fx}{Fz} = \frac{x}{a^2 z} \quad \frac{\partial z}{\partial y} = -\frac{Fy}{Fz} = \frac{y}{b^2 z} \tag{9}$$

Then:

$$\begin{cases} \cos\alpha = \dfrac{zx}{\sqrt{1+z^2x+z^2y}} = \dfrac{x}{\sqrt{a^4z^2+x^2+\frac{a^4}{b^4}y^2}} \\ \cos\beta = \dfrac{zy}{\sqrt{1+z^2x+z^2y}} = \dfrac{y}{\sqrt{b^4z^2+y^2+\frac{a^4}{b^4}x^2}} \\ \cos\gamma = \dfrac{1}{\sqrt{1+z^2x+z^2y}} = \dfrac{z}{\sqrt{z^2+\frac{x^2}{a^4}+\frac{y^2}{b^4}}} \end{cases} \tag{10}$$

Finally, calculate the SE of local area model of the clothing based on the above formulas. By substituting Equations (10) into (4), (5), and (6) and solving [17], the SE models for the X, Y, and Z axes on the entire curved surface can be obtained as:

$$SE_{xi} = SE\frac{xi}{\sqrt{a^4zi^2+xi^2+\frac{a^4}{b^4}yi^2}} \tag{11}$$

$$SE_{yi} = SE\frac{yi}{\sqrt{b^4zi^2+yi^2+\frac{a^4}{b^4}xi^2}} \tag{12}$$

$$SE_{zi} = SE\frac{zi}{\sqrt{zi^2+\frac{xi^2}{a^4}+\frac{yi^2}{b^4}}} \tag{13}$$

According to Equations (11), (12), and (13), the shielding effectiveness SE_c of the chest and abdomen areas can be obtained as:

$$SE_c = \sqrt{SE_{xi}^2 + SE_{yi}^2 + SE_{zi}^2} \tag{14}$$

Due to the ideal model established in Figure 2, which does not take into account the actual hole situation of the clothing, it was modified to introduce a hole and seam coefficient λ. The coefficient based on the projection of clothing holes is calculated as [19]:

$$\lambda = \frac{1}{10^{\frac{SE}{20}}} + 4\left(\frac{S_e}{A_e}\right)^{\frac{3}{2}} + \frac{L_e}{L_c} \times \frac{1}{10^{\frac{1.3635t_e}{g_e}}} \tag{15}$$

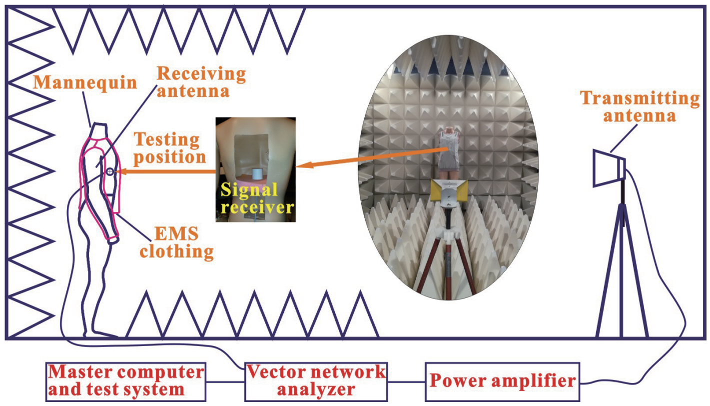

FIGURE 3. Practical testing system for SE of clothing.

TABLE 1. Actual measured dimensions, Unit: cm.

	Circumference (L)	Width (a)	Thickness (b)	Height (t)
Chest position	258	45	37	18
Waist position	208	37	29	

where S_e is total area of equivalent holes, A_e the total projected area of clothing, L_e the total length of equivalent seam, L_c the total length of projection perimeter of clothing, t_e the thickness of equivalent seam, and g_e the width of equivalent seam.

Equation (15) was given in [19] when the failure phenomenon of the EMS clothing is discussed, indicating the degree of reduction in SE of the clothing due to the presence of holes and seams. Normally, λ is less than 1, which means that the SE of the clothing with holes and seams is λ times that of clothing without holes and seams. This can be used as an important basis for model correction in this article. Therefore, Equation (14) is revised as:

$$SE_c = \lambda\sqrt{SE_{xi}^2 + SE_{yi}^2 + SE_{zi}^2} \quad (16)$$

3. TEST AND VERIFY

3.1. Test Method

The testing method is illustrated in Figure 3. The system selects a 3-meter semi-anechoic chamber to test the SE of chest and abdomen areas of the clothing, including semi-anechoic chamber, mannequin, DR6103 broadband double ridge horn antenna, signal receiver, DRA00818 power amplifier, and AV3629D microwave vector network analyzer. The transmission frequency range is from 1 GHz to 18 GHz, the testing distance 3 m, and the testing positions are selected as the abdomen and chest areas. The mannequin is placed in the semi-anechoic chamber; signals of different frequencies are transmitted through transmitting antenna; and the electric field strength is E. Wear the clothing on the mannequin, and obtain the electric field intensity as E_0 at this time. The SE of clothing can be calculated as:

$$SE = 20Lg\frac{E}{E_0} \quad (17)$$

3.2. Experimental Materials and Related Parameters

The clothing is manufactured using silver plated fiber blended shielding fabric (50% silver filament fiber/50% polyester filament fiber, yarn density of 70 D, fabric density of 130 $\times$ 98 ends/10 cm, fabric thickness of 0.249 mm) and stainless steel fiber blend shielding fabric (30% stainless steel/30% cotton/40% polyester staple fiber blend, yarn density of 32 tex, fabric density of 292 $\times$ 259 ends/10 cm, fabric thickness of 0.32 mm). Table 1 lists the dimension parameters for the chest and abdomen areas of the clothing.

4. RESULTS AND DISCUSSION

4.1. Comparison between Estimated and Measured Results

By utilizing Matlab to create a program for calculating the model described in this article, the calculated values of the model are obtained and subsequently compared with the measured values gathered from the experiment. The results are illustrated in Figure 4.

Figure 4 displays the model calculation and experimental measurement values in the chest and abdomen regions, revealing a high level of consistency whether constructed from silver-plated fiber blended fabric or stainless steel fiber blended fabric. The maximum deviation of the SE should not exceed 2 dB. In general, the calculated values of the model are higher than the actual measured values. This is because, despite the model's introduction of a hole and seam coefficient for model modification, it is unable to accurately account for the potential creation of new holes and seams between internal yarns due to stretching and twisting in fabrics containing holes and seams. These new holes and seams frequently cause a reduction in SE and cannot be quantitatively incorporated into Equation (15), which leads to model calculation values that are occasionally too large. Similarly, in practical testing, low measured values

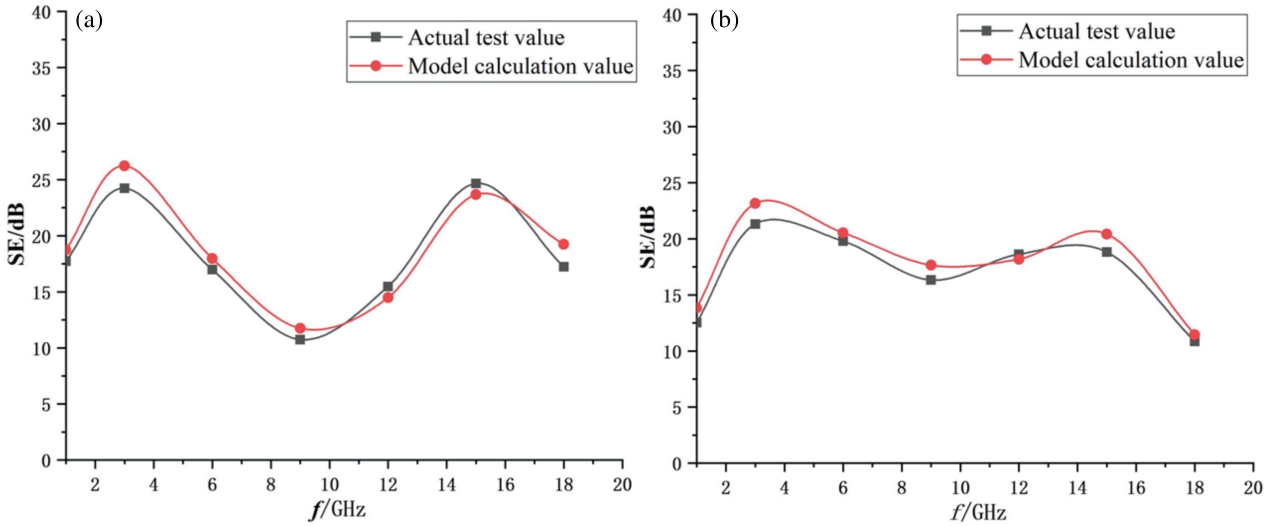

FIGURE 4. Comparison between actual test values and model calculation values of clothing with different fabrics. (a) Comparison of clothing of silver plated fiber blended fabric. (b) Comparison of clothing of stainless steel fiber blended fabric.

may also arise due to various factors such as bending deformation, external environmental influences, and errors.

4.2. Effectiveness and Influencing Factors of Model

The above analysis reveals that the model is capable of rapidly estimating the SE of chest and abdomen areas of clothing according to body parameters, exhibiting good accuracy, thereby significantly enhancing the efficiency of design, production, and evaluation, and reducing the cost of related work. However, it also possesses a specific scope of application. Firstly, the corresponding chest and abdomen regions of the model should not possess too many opening areas. For instance, the collar depth exceeds the appropriate range, or there are decorative holes in the chest and waist, which can impact the accuracy of hole and seam coefficient λ calculations and ultimately result in model failure. Similarly, in addition to normal side seams and other gaps, there should not be too many decorative seams in the corresponding area of the model, which can also lead to significant calculation errors and cause the model ineffective. Furthermore, for special body models, they may also fail. For instance, the substantial disparity in dimensions between the chest and waist sections may result in the model's calculation being unsuccessful.

The model in this article is a rapid estimation technique that is practical and suitable for most clothing items. However, it is also influenced by numerous factors, including the shape of the hole, the type of the seam, the type of the fabric, the number of layers in the fabric, the type of clothing style, the position of the emission source, and polarization direction. The impact of these factors is a highly intricate process, and we shall persist in examining this aspect in our future endeavors.

5. CONCLUSION

1) The established elliptical cone model of the chest and abdomen regions of clothing, which is based on body morphology, is suitable for human characteristics and can meet the calculation requirements of the SE of the EMS clothing.
2) The local SE solution method, established by the model using calculus principle, can quickly calculate the SE of local chest and abdomen areas of the clothing.
3) The hole and seam coefficient λ can fully consider the influence of normal openings and seams in the chest and abdomen regions and can effectively modify the ideal model to make the estimated model conform to reality.
4) The estimation model constructed in this article is fast and effective, and its calculation results are consistent with the measured values. The effectiveness is satisfactory.

The constructed model's accuracy is good, and it can quickly estimate the SE of the clothing in the chest and abdomen regions based on body shape parameters. This greatly improves the efficiency of design, production and evaluation, reduces costs, and provides a new approach for quickly estimating SE of EMS clothing in local areas.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (No. 61771500) and the Key Research and Development Plan Project of Shaanxi Province (No. 2022GY-277).

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