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Computation Model of Shielding Effectiveness of Electromagnetic Shielding Fabrics with Seaming Stitch

Xiuchen Wang*, Ying Su, Yaping Li, and Zhe Liu

Abstract—The influence of seaming stitches on the shielding effectiveness (SE) of electromagnetic shielding (EMS) fabric is huge, but there is not an ideal computation model for the SE of the EMS fabric with the seaming stitch at present. This paper proposes a computation model of the SE based on the equivalent seaming gap. Firstly, a structure model of the equivalent seaming gap is constructed according to the equivalent dielectric principle. The computation method of the structural size of the equivalent seaming gap model is determined by the parameters of the stitch length, number of the stitch type, needle number, and sewing thread. A computation model of the SE based on the equivalent seaming gap structure is built according to the EMS theory. The method of the correction coefficient of the model determination is given. Finally, the samples with seaming stitches are made to test the SE using the waveguide method. The computation results with the proposed model are compared with the experimental ones. The results show that the proposed model can well calculate the SE of the EMS fabric with the seaming stitch. The study in this paper can provide a foundation for further study of the influence of seaming stitches on the SE of the EMS fabric and possesses reference significance for the design, production, evaluation and related theoretical research of the EMS clothing.

1. INTRODUCTION

Electromagnetic shielding (EMS) clothing can prevent electromagnetic radiation hurting the human body, and it is widely used in civilian, military, electric power and various industries. Current researches mainly focus on improving the performance of the fabric to improve the shielding effectiveness (SE) of the EMS clothing. In fact, the high shielding performance of the clothing made of high-shielding fabric is not guaranteed. One important reason is that electromagnetic waves can easily go through the tiny gaps and holes of the seaming stitches to form a electromagnetic field in the clothing, causing the SE of the clothing to decrease [1, 2]. Therefore, it possesses great academic significance and application value to explore the influence of seaming stitches on the SE of the EMS clothing.

The influence of seaming stitches on the EMS clothing is evaluated by the SE change of the plain EMS fabric with seaming stitches because of the complex curve shape of the seaming stitches on the clothing. An important research point is the computation problem of the SE of the EMS fabric with seaming stitch. The research in this paper can rapidly predict the SE of the EMS fabric with the seaming stitch, which can provide the foundation for further study of the influence of seaming stitches on SE of the fabric and clothing. At present, there are few researches on EMS fabrics with seaming stitch. Related researches are divided into two aspects: one is the study of the stitching function of the seaming stitch [3, 4]. The researchers analyzed the configuration optimization of the stitch parameters and the influence factor of the sewing fastness and comfort. However, they all did not study the influence of the stitch on the SE of the clothing. The other is the study of the interstice and hole of the fabric [5–7], and they explored the influence of the tiny holes formed by the intertwined yarns on the SE. The study

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object is the gap or hole formed by the fabric itself, and its structure is completely inconsistent with the structure of the gap and hole of the seaming stitch. In addition to the above studies, the scholars in the field of electrical and electronic studied the calculation of the SE of the shield with interstice [8, 9]. However, the interstice structural characteristic of the electrical equipment is significantly different from the gap characteristic of the clothing. These results do not apply to the research in this paper.

In view of the above-mentioned situation, this paper establishes the SE computation model of the EMS fabric with seaming stitches according to the equivalent medium theory. An equivalent structure model of the seaming stitch is constructed according to the seaming stitch characteristic. A computation model of the SE based on the equivalent seaming gap structure is built according to the EMS theory. The computation results with the proposed model are compared with the experimental testing ones. The conclusion is that the proposed model can well and rapidly calculate the SE of the EMS fabric with the seaming stitch. The model can provide a foundation for further study of the influence of the seaming stitch on the SE of the EMS fabric and possesses reference significance for the design, production, evaluation and related theoretical research of the EMS clothing.

2. MODEL CONSTRUCTION

2.1. Characteristic Analysis of Seaming Stitch

Figure 1 is the plane existence form of two stitched fabrics attached to the human body. In general, seaming stitches are in the state shown in Figure 1 when the clothing is in wearing. Different tensile tensions of the fabric result in different sizes of the seaming gap. From Figure 1, it is observed that the influence factors of the leakage of the electromagnetic wave are the holes formed by the sewing needle, the seaming gap between the two fabrics and the diameter size of the sewing thread. Coupling phenomenon occurs in the pinholes, leading to the electromagnetic waves leaked to the clothing interior. Electromagnetic waves will be directly leaked between the joints of the seams. The size of the sewing thread can prevent the above two leakages because of its shielding effect. Therefore, the three factors need to be considered in order to study the influence of seaming stitches on the SE of the EMS fabric. The structural model including the factors of the electromagnetic wave leakage is built, as shown in Figure 2(a).

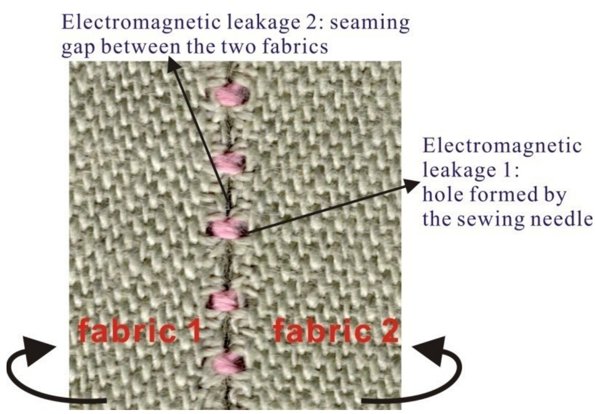


Figure 1. Plane existence form of two stitched fabrics attached to the human body.

2.2. Structure Model of Equivalent Seaming Gap

From above analysis, the electromagnetic wave leakage in the seaming stitches is a complex problem. It is difficult to analyze the problem with a specific mathematical approach because of the interaction of the three main influencing factors. Therefore, this paper proposes a structural model of the equivalent seaming gap to calculate the SE of the fabric with the seaming stitch.

As shown in Figure 2, suppose that the structural parameters and the sizes of the fabric in Figure 2(b) are the same as that of the fabric in Figure 2(a). There is a gap on the fabric. The

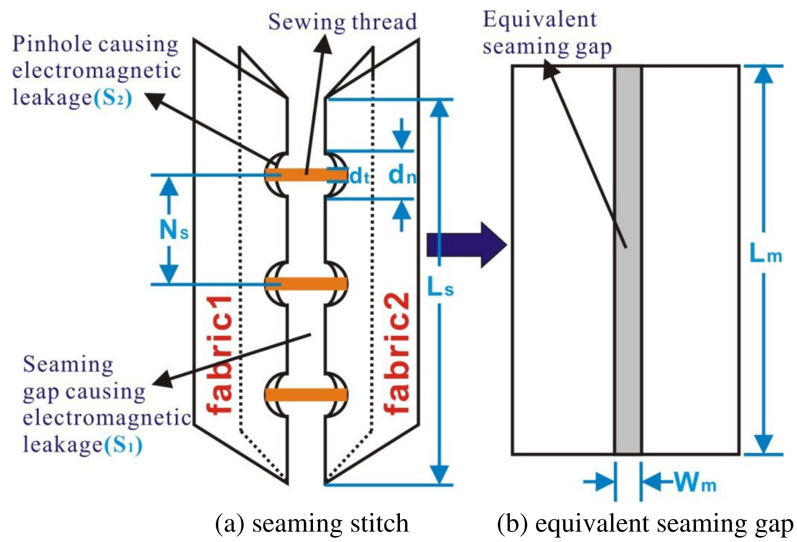


Figure 2. Structure model of equivalent seaming gap.

size parameters are calculated according to the parameters of the seaming length, size of the pinhole, and type of the sewing thread. The influence of the seaming gap on the SE of the fabric in Figure 2(b) is the same as that of the fabric in Figure 2(a). The gap in Figure 2(b) is regarded as the equivalent seaming gap model of the seaming stitch of the fabric in Figure 2(a). The total area S of the model is equal to the area S_1 formed by the gap and the area S_2 formed by the pinhole. Its length L_m is equal to the original length L_s of the total length of the seaming stitch. The new area S is divided by the original stitch length L_m to obtain the width W_m. The following is the calculation formulas:

$$L_m = L_s \tag{1}$$

$$W_m = \frac{S}{L_m} \tag{2}$$

$$S = S_1 + S_2 \tag{3}$$

where, the area formed by gap 1 can be approximated as a continuous rectangle. The length is L_1,and the width is W_1. The area S_1 can be obtained as:

$$S_1 = L_1 \times W_1 \tag{4}$$

Let the working diameter corresponding to the needle diameter be d_n(mm) and the density of the seaming stitches be $N_s(pcs/3\,\text{cm})$. The total length L_h caused by the pinholes can be denoted as:

$$L_1 = L_s - L_h \tag{5}$$

where,

$$L_h = \frac{\frac{L_s}{3} \times N_s \times d_n}{10} \tag{6}$$

In general, the gap in Figure 2(a) is caused by the elasticity of the sewing thread. The stretching is also related to the gap. This is a very complex situation. Different strengths will cause different results. The seaming gap is related to the thickness of the fabric. Let the total thickness of the two fabrics be T and the ratio of the width to the thickness be $\delta(\%)$, and the seaming gap coefficient δ can be calculated as:

$$W_1 = \frac{T \times \delta}{10} \tag{7}$$

In general, the seaming gap coefficient can be set according to fabric and location, and the normal range is from 0.5 to 3.

Substitute Equations (5) and (7) into Equation (4), then:

$$S_1 = (L_s - L_h) \times (\frac{T \times \delta}{10}). \tag{8}$$

Substitute Equation (6) into Equation (8), then:

$$S_1 = (L_s - \frac{\frac{L_s}{3} \times N_s \times d_n}{10}) \times \frac{(T \times \delta)}{10}. \tag{9}$$

The pinhole area minus the total area of the sewing thread is the area S_2 formed by the pinhole. The value can be calculated according to the number of pinholes and the diameters of the sewing thread. Let the diameter of the sewing thread be d_t (mm), and the pinhole area can be obtained as:

$$S_2 = 2 \times \frac{L_s}{3} \times N_s \times \pi \left(\left(\frac{d_n}{20} \right)^2 - \left(\frac{d_t}{20} \right)^2 \right) \tag{10}$$

Substitute Equations (9) and (10) into Equation (3), then:

$$S = \left(L_s - \frac{\frac{L_s}{3} \times N_s \times d_n}{10} \right) \times \frac{(T \times \delta)}{10} + 2 \times \frac{L_s}{3} \times N_s \times \pi \left(\left(\frac{d_n}{20} \right)^2 - \left(\frac{d_t}{20} \right)^2 \right). \tag{11}$$

Equation (11) is simplified as:

$$S = \frac{T\delta L_s}{10} - \frac{L_s N_s d_n T\delta}{300} + \frac{\pi L_s N_s}{600}(d_n^2 - d_t^2). \tag{12}$$

Substitute Equation (12) into Equation (2), then:

$$W_m = \frac{\frac{T\delta L_s}{10} - \frac{L_s N_s d_n T\delta}{300} + \frac{\pi L_s N_s}{600}(d_n^2 - d_t^2)}{L_m}. \tag{13}$$

According to Equation (1), length L_m is equal to the total length L_s of the original seaming stitch, and L_m is substituted by the L_s, then:

$$W_m = \frac{T\delta}{10} - \frac{N_s d_n T\delta}{300} + \frac{\pi N_s}{600}(d_n^2 - d_t^2). \tag{14}$$

2.3. Computation Model of Equivalent SE

According to the electromagnetic theory, for an infinite large ideal plane uniform metal plate with an infinite length gap, H_p is the magnetic field strength after the electromagnetic wave passed through the metal plate, and H_0 is the magnetic field strength without the metal plate on the same position, then [10]:

$$H_p = H_0^{-\pi t/g} \tag{15}$$

where, g denotes the width of the seaming gap, and t is the thickness of the fabric. The attenuation of the magnetic field through the gap is:

$$SE = 20 \log \frac{H_0}{H_p} = 27.27 \frac{t}{g} \tag{16}$$

Substitute Equation (14) into Equation (16), then:

$$SE{=}27.27 \frac{T}{10 \left(\frac{T\delta}{10} - \frac{N_s d_n T\delta}{300} + \frac{\pi N_s}{600} \left(d_n^2 - d_t^2 \right) \right)}. \tag{17}$$

Equation (17) is the calculation results of the SE of the shield with stitches on an ideal state. The stitches in the actual fabric are not in an ideal state, so that a correction coefficient ε is introduced to correct the equation. The correction coefficient is introduced considering the influence of the different types of the fabric weave, actual SE of the fabric and hairiness of different yarns on the size of the equivalent seaming gap model. Equation (17) is rewritten as:

$$SE{=}27.27\varepsilon\frac{T}{10\left(\dfrac{T\delta}{10}-\dfrac{N_s d_n T\delta}{300}+\dfrac{\pi N_s}{600}(d_n^2-d_t^2)\right)}. \tag{18}$$

The correction coefficient is obtained by the experimental method, and see the detail below.

3. EXPERIMENTAL VERIFICATION

3.1. Experimental Material

Two kinds of blended stainless steel EMS fabrics are selected as the experimental samples. The specifications are shown in Table 1. The size of the sample is 15 cm×15 cm; the seaming length of the sample is the same as the length of the fabric; the position of the seaming stitch is in the middle of the fabric. Considering that the experimental waveform is a parallel wave, only the vertical direction of the seaming stitch is selected for analysis.

Table 1. Specification of the experimental EMS fabric.

Fabric weave	Stainless steel/polyester/ cotton (/%)	Warp density (ends/10 cm)	Weft density (ends/10 cm)	Thickness (mm)
Plain	30/45/25	272	259	0.35
Twill	30/45/25	267	238	0.38

The silver-plated sewing thread is selected for sewing, and the parameters are shown in Table 2.

Table 2. Seaming stitch parameters.

The number of the stitch type	Sewing thread parameter	Measured extensibility of sewing thread	Length of the seaming stitch (cm)	Needle number	Pinhole size (mm)	Density of the stitch (pcs/3 cm)
1#	Silver-plated sewing thread 200D, 0.44 mm	0.03	11	8	0.6	12
2#				10	0.7	
3#				12	0.8	
4#				14	0.9	

3.2. Testing Method of SE

The SE of the sample is tested by a waveguide method. The waveguide system is developed by the Northwest institute of textile technology. For the electromagnetic materials with gaps and holes, the waveguide method is more sensitive and effective than the flange coaxial method and other method. The testing results using the waveguide method are correct and accord with the results of the actual state of the fabric. The frequency range of the waveguide is 2.2 GHz–2.65 GHz. The waveguide testing system [5] is shown in Figure 3.

In order to investigate the calculation results of the model with different sizes of the seaming gap, the sample is fixed with a tenser, and different tensions are applied. The SE of the sample is tested after testing the size of the seaming gap. The SE of the sample without seaming stitch at different frequencies is shown in Table 3.

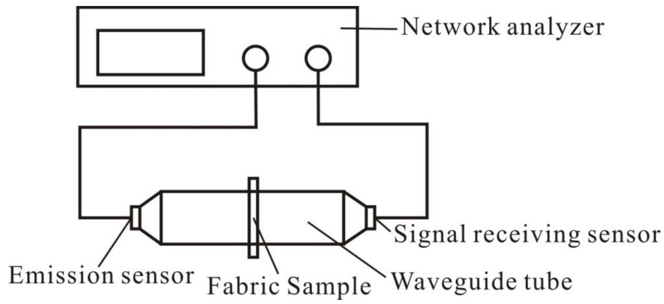


Figure 3. Schematic diagram of waveguide testing system.

Table 3. Testing results of SE of the sample without seaming stitch.

Fabric weave	2.3 GHz	2.5 GHz
Plain	45.8	45.5
Twill	45.1	44.9

3.3. Determination of Correction Coefficient ε and Thickness Coefficient δ

The correction coefficient of fabric is obtained by choosing the standard sample method in this paper. Ten EMS fabrics with plain weave are selected as the samples of group A. Ten EMS fabrics with twill weave are selected as the samples of group B. Flat seaming stitches are added to all samples. The SEs of the samples of group A and group B are tested. The values of the SE are averaged, and the average values are compared with the calculation results from Formula (14). The relationship is obtained as:

$$\varepsilon = \frac{SE' + 200h}{SE'} \tag{19}$$

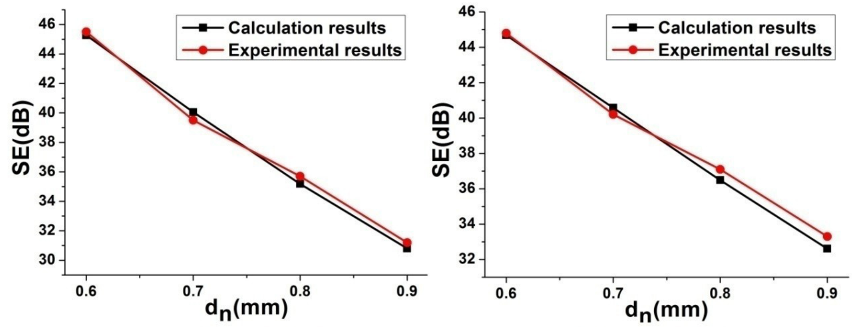
where, h denotes the hairiness coefficient of the fabric, and the value is [0.03, 0.08] [11].

A tenser applies different tensions to the sample. Ten lengths between the two needles are averaged. The average length is divided by the total thickness of the two sewing fabrics. The result is the thickness coefficient δ.

4. RESULTS AND ANALYSIS

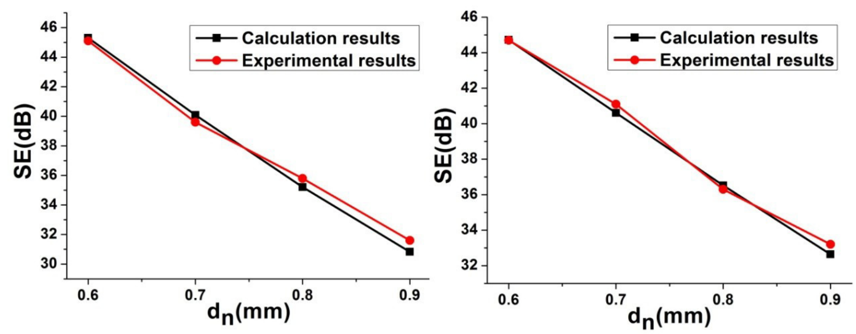
4.1. Comparisons between Calculated Results and Experimental Results as the Pinhole Sizes Change

Figures 4–5 show the comparisons between the calculated and experimental results of the EMS fabric with seaming stitches as the size of the pinhole is changed. From Figures 4–5, it is observed that the calculated results of the fabric using the proposed model accord with the experimental testing results. It is proved that the proposed model has good accuracy. It is also noticed that the SE is significantly reduced with the increase of the pinhole size when the pinhole size is changed, and other parameters are not changed. It is proved that the size of the pinhole has important effect on the leakage of electromagnetic waves. In practical application, the pinhole area should be minimized. The method is to reduce the sewing needle number (reduce the diameter of the needle) and to choose the appropriate yarn density of the conductive sewing thread, the needle diameter matches the pinhole as much as possible, reducing the interstices between the sewing thread and the pinhole.



(a) plain fabrics (b) twill fabrics

Figure 4. Comparisons between the calculated results and the experimental results as the diameter of the pinhole is different ($f = 2.3\,\text{GHz}$).



(a) plain fabrics (b) twill fabrics

Figure 5. Comparisons between the calculated results and the experimental results as the diameter of the pinhole is different ($f = 2.5\,\text{GHz}$).

4.2. Comparisons between Calculated Results and Experimental Results as the Seaming Gaps Change

Figures 6–7 show the comparisons between the calculated and experimental results of the EMS fabric with seaming stitches as the seaming gap is changed. From Figures 6–7, it is noticed that the calculated results of the fabric using the proposed model accord with the experimental testing ones. It is proved that the proposed model has good effectiveness. In fact, the frequency points at 2.3 GHz and 2.5 GHz for the experimental verification are the arbitrary choice from 2.2 to 2.65 GHz frequency range. Through a large number of experiments, the actual testing values at other frequencies in this range are in good agreement with the calculated values of the proposed method. Therefore, good coincidence between the testing and calculated results is ubiquitous in the frequency range. It is also observed that the SE deceases with the increase of the seaming gap when the seaming gap size is changed, and other parameters are not changed. It is proved that the seaming gap has important effect on the leakage of electromagnetic waves. According to the characteristic of the seaming stitch, the thickness and elasticity of the fabric, the elasticity of the sewing thread, and the tension of the fabric all influence the seaming gap. In order to reduce the seaming gap to improve the SE of the stitched EMS fabric, the thickness and elasticity of the fabric, the elasticity of the sewing thread and the stretched tension of the fabric should be reduced.

4.3. Analysis of the Influencing Factors of Error

According to the model building process, the calculation error of the model is mainly affected by the factors of the measurement accuracy of the seaming gap, pinhole, fabric thickness and sewing

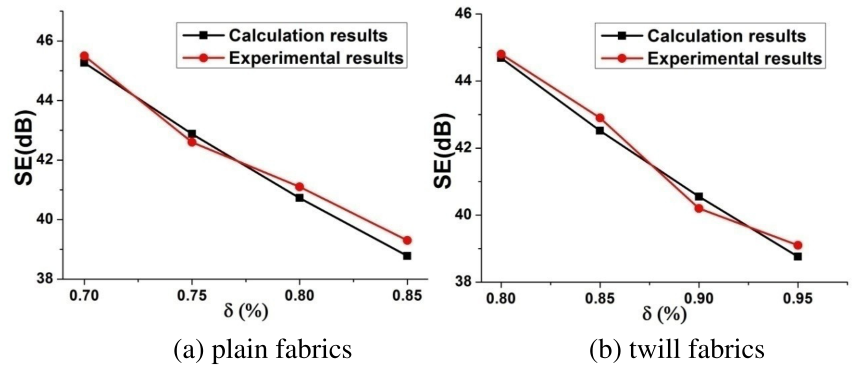


Figure 6. Comparisons between the calculated results and the experimental results as the seaming gap is different ($f = 2.3\,\text{GHz}$).

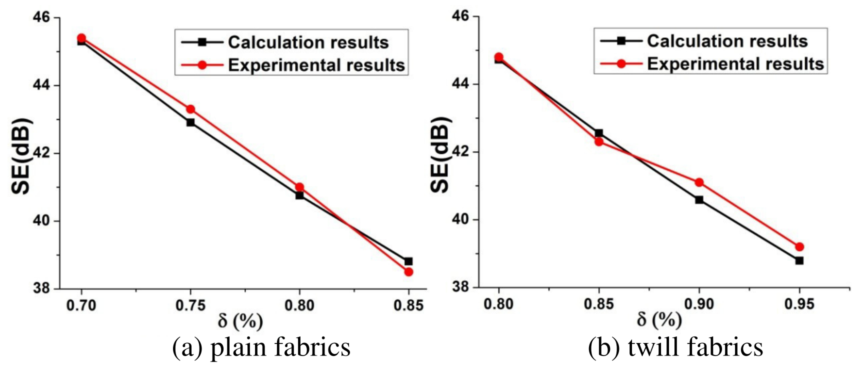


Figure 7. Comparisons between the calculated results and the experimental results as the seaming gap is different ($f = 2.5\,\text{GHz}$).

thread thickness. In order to control the errors caused by above factors, it is necessary to make scientific measurements on these parameters and to discard the variance values and obtain the average of measurements values, so that the results will be reliable. In addition, the impact from the hairiness of the yarn is also the main factor of the error. The length and density of the hairiness are different because of different materials. Therefore, the hairiness parameters must be obtained by scientific standards methods in order to ensure accurate measurement of hairiness parameters, ensuring the accuracy of the model calculation results. The above-mentioned influencing factors are a complicated process of mutual influence, and the influence rule on the calculation results has not been proved yet, which will be studied in the followup work.

5. CONCLUSION

1) The proposed structure model of the equivalent seaming gap can well describe the structure of the seaming stitch inducing the electromagnetic leakage, which provides a new method for studying the structure of the seaming stitch.
2) The constructed SE computation model of the equivalent seaming gap can calculate the SE of the EMS fabric with seaming stitch, which lays a foundation for the subsequent study of the influence of seaming stitches on the SE of the EMS fabric and clothing.
3) The proposed determining method of the correction coefficient and thickness coefficient has good accuracy, which can guarantee the correct calculation of the equivalent seaming gap model.
4) The calculated and experimental results show that the size of the pinhole and size of the seaming gap have a significant influence on the SE of the stitched EMS fabric, showing a negative growth relationship.

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