MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Optimization of sound absorption performance of woven fabric

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ABSTRACT

Well-designed thin lightweight fabrics can effectively replace bulky porous materials traditionally used in sound absorption. In this paper, a method based on Johnson-Champoux-Allard (JCA) model is proposed to optimize the sound absorption effect of wave fabrics. Detailed 3D geometric models are built for a set of weave samples. Geometric tortuosity, flow resistivity, and porosity are obtained numerically from finite element analysis. By the new method, the influence of the geometric parameters, such as the number of the weft yarns floating over a warp yarn (steps), diameter of yarns, yarns spacing, on the sound absorption is investigated. Experimental results from the impedance tube test agree well with the numerical predictions. Based on these results, one kind of woven fabric is produced which has good sound absorption effect.

Keywords: Sound-absorbing textile, Woven fabrics, Noise absorption
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

Textile curtains have been widely used to absorb sound for many years. Because of the flexibility in changing their configuration, people can adjust the reverberation time easier than other approaches. Generally, textile curtains need enough thickness and surface mass density to have good sound absorption performance. However, thin, light textile curtains are much cheaper and provide a promising alternative.

Recently, Pieren [1] presented a theoretical model to predict the absorption coefficient of a thin woven fabric backed by a cavity. The fabric impedance is represented by an air

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flow resistance and its surface mass density. An acoustic inverse method is employed to obtain the air flow resistance. Later, Pieren et.al [2] proposed a more elaborate model considering the intrayarn airflow. Ruiz et.al [3] developed a hybrid model describing the acoustic properties of macroperforated plates backed by woven meshes, in which the woven meshes are analysed by a simplified geometric model.

In this paper, we propose a new method to optimize the structure of woven fabric, and produce one kind of woven fabric which has good sound absorption effect.

2. MODELLING METHOD

2.1. Johnson-Champoux-Allard model

The Johnson-Champoux-Allard model is used in our new method to predict the normal sound absorption of woven fabrics. In JCA model, porous media is considered as fluid media. The dynamic density in the JCA model [4] [5] is given by

$$\rho(\omega) = \frac{\alpha_\infty \rho_0}{\phi}\left[1 + \frac{\sigma\phi}{j\omega\rho_0\alpha_\infty}\sqrt{1 + j\frac{4\alpha_\infty^2 \eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}}\right]. \tag{1}$$

The dynamic bulk modulus in the JCA model is given by

$$K(\omega) = \frac{\gamma P_0/\phi}{\gamma - (\gamma - 1)\left[1 - 8j\kappa/\Lambda'^2 C_p \rho_0 \omega \sqrt{1 + j\frac{\Lambda'^2 C_p \rho_0 \omega}{16\kappa}}\right]^{-1}} \tag{2}$$

where σ is the static air flow resistivity; ϕ is the open porosity; α_∞ is the high frequency limit of the dynamic tortuosity; Λ is the viscous characteristic length; Λ' is the thermal characteristic length; $\gamma = 1.4$ is heat capacity ratio; $\eta = 1.002\text{MPa} \cdot \text{s}$ is dynamic (shear) viscosity; $C_p = 1\text{kJ}/(\text{kg} \cdot \text{K})$ is isobaric mass heat capacity; $\rho_0 = 1.29\text{kg}/\text{m}^3$ is the density of air; $\kappa = 0.02\text{W}/(\text{m} \cdot \text{K})$ is the thermal conductivity.

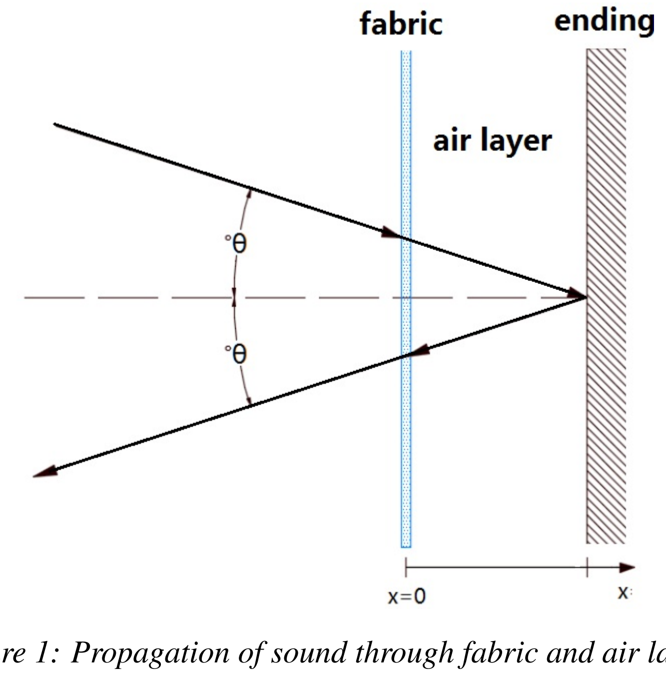


Figure 1: Propagation of sound through fabric and air layer

The Figure 1 illustrates how the acoustic wave propagate through fabric and air layer. For the case in this study, the surface impedance Z_s can be derived by Equation 1 and Equation 2 by transfer matrix method. The acoustic field can be represented by a row vector $\mathbf{V} = [p\ v]^T$, where p is the sound pressure and v is x-component of the particle velocity. According to [6], $\mathbf{V}$ on the left-hand end of the fabric can be calculated by

$$\mathbf{V} = \mathbf{T}_{fabric} \cdot \mathbf{T}_{air} \cdot \mathbf{B}. \tag{3}$$

Fluid layer can be represented by a 2×2 transfer matrix by:

$$\mathbf{T} = \begin{bmatrix} \cos(k\cos\theta D) & j\frac{\omega\rho}{k\cos\theta}\sin(k\cos\theta D) \\ j\frac{k\cos\theta}{\omega\rho}\sin(k\cos\theta D) & \cos(k\cos\theta D) \end{bmatrix} \tag{4}$$

where $k = \omega\sqrt{\rho/K}$, D is the thickness of fluid layer. Using the data of air and equivalent fluid respectively, we can obtain their transfer matrix $\mathbf{T}_{air}$ and $\mathbf{T}_{fabric}$.

For hard ending, $\mathbf{B} = [1\ 0]^T$, then

$$Z_s = \mathbf{V}(1)/\mathbf{V}(2) \tag{5}$$

then the absorption coefficient can be obtained by:

$$\alpha = 1 - \left[\frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}\right]^2. \tag{6}$$

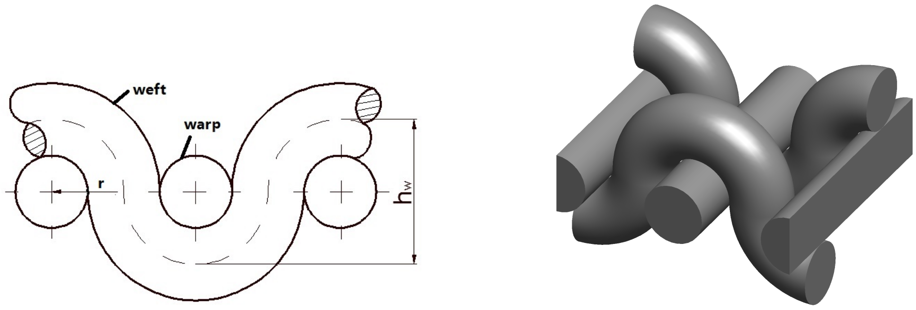
In this study, θ is zero (normal incidence). The FEM method is used to find the parameters of JCA model. By substituting these parameters into Equation 1-Equation 6, we can gain the sound absorption coefficient of a certain sample. In the Section 3.2, the numerical results will be validated by the experimental results.

2.2. Geometry model

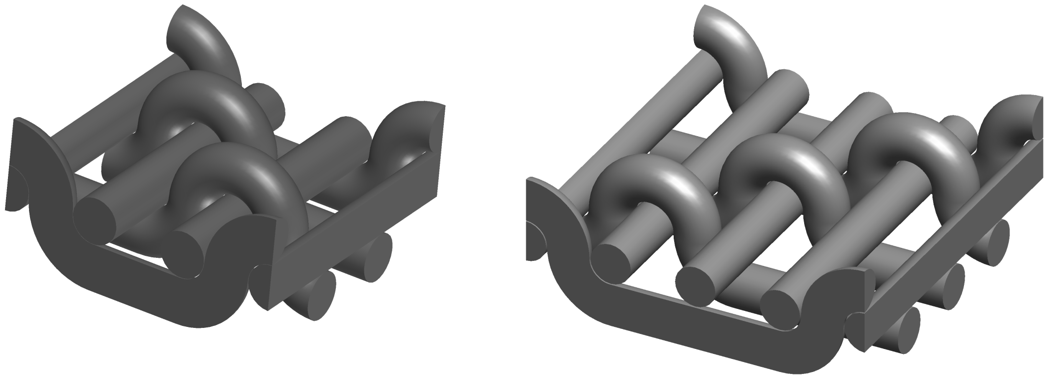
Based on following assumptions (cross-sectional drawing shown in Figure 2(a)):

- In a certain textile, the shape of cross sections of all of threads is circle with the same size of radii;
- The lengthwise sections of the textile are on the basis of the Peirce model [7];
- The threads in the structure are considered as uniform distributed;
- $\mathrm{h}_w = 4r$;

the simplified 3D model of woven fabric can be built (shown in Figure 2(b) to Figure 2(d)).



(a) Plain weave (b) Plain weave



(c) Twill weave A (d) Twill weave B

Figure 2: Cross-sectional drawing and simplified 3D models

Although in the Figure 2(c) and Figure 2(d), both of the two models are twill model, they have different step numbers. Besides, there are small air gaps between the two overlapped threads in order to avoid mistakes in Finite Element Method (FEM) method.

3. VALIDATION

3.1. Samples

In order to validate our model, three kinds of plain weave samples are picked up which have different data of diameter of monofilament and monofilament spacing, and their normal incidence absorption coefficients are measured by impedance tube [8]. All of three types of samples are made in nylon monofilament. In other words, there is no intrayarn air flow in our samples. The parameters of three kinds of sample are shown in Table 1:

Table 1: The parameters of material used in experimental method.

	diameter of monofilament(μm)	monofilament spacing(μm)
Sample1	35	35
Sample2	28	50
Sample3	48	100

According to the three types of samples mentioned above, the parameters are obtained which we need in the JCA model by using FEM method, which are listed in the Table 2.

Moreover, the data of optimal flow resistivity of every case is calculated according to the formula in Pieren [1].

Table 2: The parameters of 3D models.

	ϕ	$\Lambda(\mu m)$	$\Lambda'(\mu m)$	α_∞	$\sigma(Ns/m^4)$	$\sigma_{s,opt}(Ns/m^4)$
Sample1	0.70	15	30	1.3	765000	1600000
Sample2	0.76	30	70	1.2	230000	1660000
Sample3	0.82	60	110	1.15	56000	740000

We can gain the sound absorption of these samples by substituting the data in Table 2 into Equation 1-Equation 6.

3.2. Comparison and discussion

Normal incidence absorption coefficients of three samples are measured by a Brüel & Kjaer two-microphone impedance tube of Type 4206, according to the standard ISO 10534-2. The frequency range of measures is from 0 to 1600 Hz.

The comparisons between the numerical results which have obtained in the section 3.1 and experimental results are represented in Figure 3 (straight lines). The numerical results are showed by dash lines.

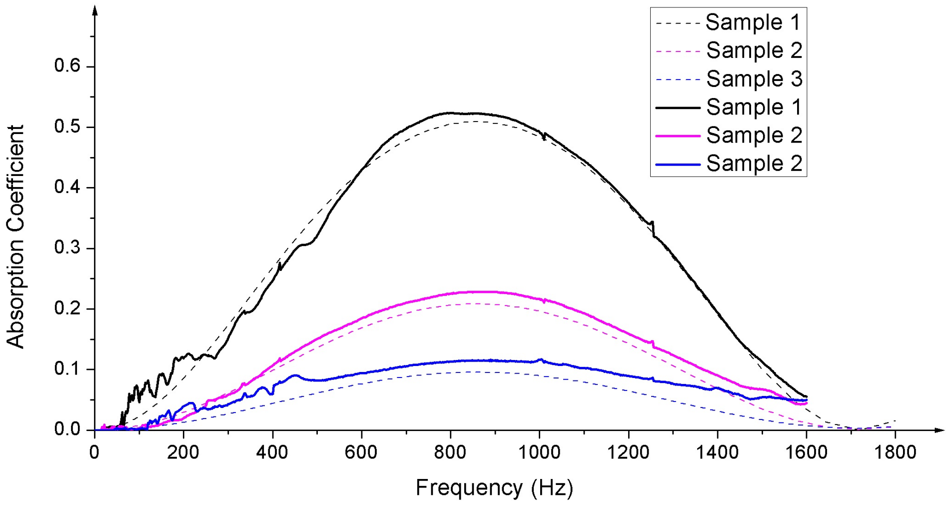


Figure 3: The results of numerical simulation method and experiments of sample 1, 2, 3 with the depth of air cavity D=100mm

According to Figure 3, the results of numerical simulation are consistent well with the results of experiment. In the next section, the numerical simulation method is used to analysis the effect of parameters on textile sound absorption.

4. OPTIMIZATION

The parameters of woven fabrics which related to the optimization in this paper are the steps number and the diameter of yarns.

4.1. Parameters

To investigate the influence of spacing and diameter of yarns on sound absorption performance, we choose five yarn diameters and eleven yarn spacings, and use the above FEM method to calculate the sound absorption in every 55 combination of diameter and spacing.

For each pairs of diameter and spacing of yarns, two kinds of 3D model with step numbers 1 and 2 are built and calculated. Finally, the peak values of the whole results are shown in Figure 4. The series 1 to 5 is twill weave, and the series 1' to 5' is plain weave.

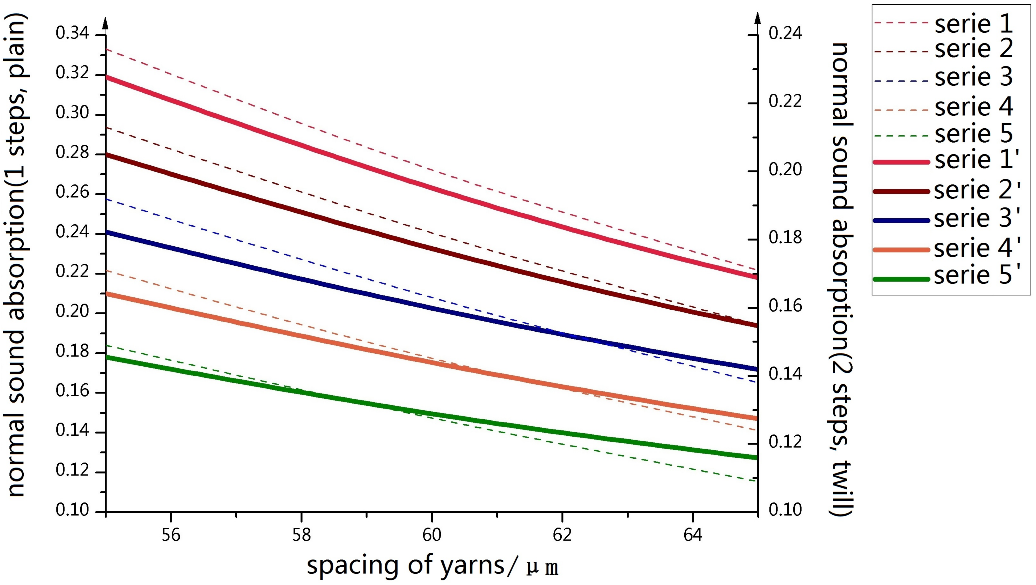


Figure 4: The peak values of sound absorption curve of all samples (full lines are plain weave results, dotted lines are twill weave results)

In the Figure 4, we can see that when the diameters become lager, the gradient of curves are also larger. Because for smaller yarns diameter, the augment of yarns spacing has smaller side-effect on sound absorption.

What's more, under the same yarn spacing, the sound absorption performance is declined in pace with the descend of yarn diameter. Because the increasement of yarns diameter or abate of yarns spacing leads to the decreasing of porosity. Moreover, in the same condition, the plain fabrics (left in Figure 4) have better sound absorption performance than the twill fabrics (right in Figure 4).

Comparing the full line (plain weave) and dot line (twill weave), we can see that in the same yarn condition, plain weave fabric has better sound absorption ability than twill weave fabric. Because the flow resistivity can be influenced by the crossover pattern. However, in the same yarns diameter, twill and satin weave fabric have higher density, so they have higher porosity and flow resistivity.

4.2. Optimized woven fabric

By using new method, the optimized yarn spacing, diameter of yarn, and woven pattern (related to step number) can be gained. One kind of optimized woven fabric with different cotton content are produced, see as Figure 5. The sound performance is showed in Figure 6.

Figure 5: The photo of the optimized cotton fabric

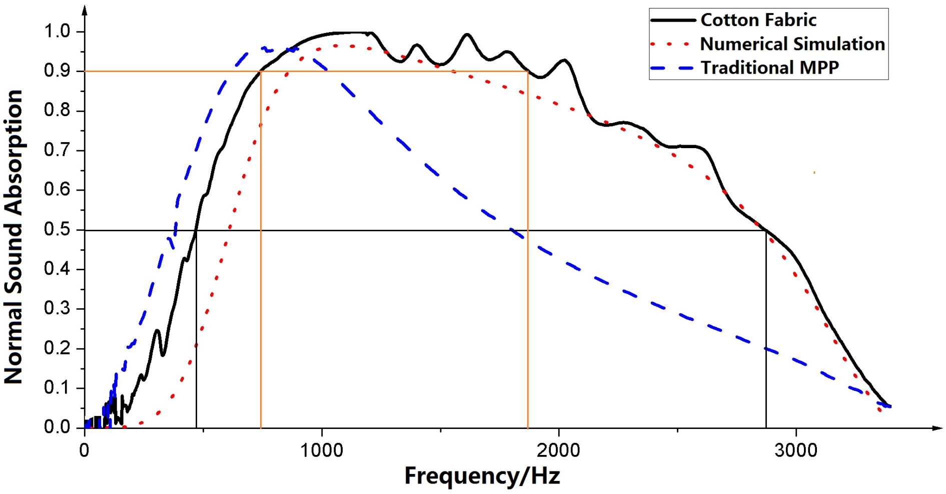


Figure 6: Comparison of optimized woven fabric and traditional MPP with the depth of air cavity D=50mm

In the Figure 6, the black line is the sound absorption curve of new fabric, which is made by cotton. The numerical results by new method is represented by red dot line, and the blue dash line shows the sound absorption curve of traditional MPP. Compared with traditional MPP, the optimized material has much wider bandwidth, which means that the new fabric have better sound absorption performance than MPP. As shown in the Figure 6, the bandwidth which has the sound absorption coefficients more than 0.5 is more than 2.5 octaves (in the range of two black vertical lines), and the bandwidth above 0.9 is more than one octaves (in the range of two yellow vertical lines). Moreover, because of the light weight and small thickness, the new fabric is more flexible than MPP and other traditional curtain materials.

5. CONCLUSION

A new and reliable method is proposed to predict the sound absorption coefficient. By using this method, the influence of geometric structures on the sound absorption performance is investigated: the sound absorption performance of woven fabric is influenced by step number with limits; in the same condition, the smaller step number, the better sound absorption ability; for smaller yarns diameter, the augment of yarns spacing has smaller side-effect on sound absorption. Based on anterior investigation, one kind of optimized woven fabric which has good performance in sound absorption is produced. The new fabric has much wider bandwidth than traditional MPP, and have lighter weight and smaller thickness than traditional curtain material. The new fabric material can be used in acoustic design of auditorium or home, office place,etc.

6. ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China No.11604015; Beijing Natural Science Foundation No.1172007, Beike Scholar project of Beijing Academy of Science and Technology; Xicheng District excellent talent project No.20180029.

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