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Simulation Model for the Absorption Coefficients of Double Layered Nonwovens

Abstract
In this paper, a more general sound absorption model for double layered nonwovens is proposed firstly by using the theory of C. Zwikker and C. W. Kosten for sound propagation through porous flexible media and sound propagation boundary conditions, and then a model simulation is detailed by changing the effective structure parameters of nonwovens. Double layered nonwovens composed of polyester fiber in the outer layer and nylon fiber in the inner layer is investigated in detail and the effects of acoustic parameters including the thickness and porosity of each layer on the absorption coefficient are analysed by numerical calculation, respectively. It shows that a double layered sound absorbing structure made of nonwovens has excellent sound absorption and can afford a sufficiently satisfying sound absorption level in a cared frequency range. In theory, this model can be used to calculate the absorption coefficients of double layered nonwovens composed of two different nonwoven materials . In practice, the sound absorption model for double layered nonwovens provides theoretical support for high performance sound absorber design and manufacture.

Key words: *absorption coefficient, double layered nonwovens, simulation model.*

Introduction

In recent years, with people's concern for noise pollution, research on sound absorption materials has been paid more and more attention [1 - 9]. Nonwovens can be used for controlling noise for a wide range of applications, such as wall claddings, acoustic ceilings and barriers, carpets, and so on [1 - 6]. Therefore the sound absorption mechanism of Nonwovens has been given more and more attention, achieving fruitful results. The first monumental work on this subject was presented by C. Zwikker and C. W. Kosten [10], which regarded a porous medium as a mixture of two phases, with air, solid material and sound wave reacting differently in the two phases. The mathematical analyses of the basic equations in this theory predict two forward and two backward waves travelling through the medium. Later a more appropriate model was suggested by Dent based on the theory of Zwikker and Kosten [11]. Subsequently some investigations on Nonwoven sound absorption were presented, for example sound absorption materials made of cylindrically shaped fibres arranged in a batting were examined in [12]; a model for high porosity Kevlar consisting of long flexible fibres was developed in [13, 14]; by incorporating two theoretical models for nonwoven and plain knitted fabrics, a suitable theoretical model was obtained for calculating the sound absorption coefficient of weft knitted fabrics with complex structures in [15]. Especially the noise absorption coefficient of some nonwovens was calculated based on Dent's work by using a different method, yielding the same analytical results as those of Shoshani [1]. Furthermore, some experimental studies have been presented for composite nonwovens, for example the noise absorption capacity of thermally bonded nonwovens in the range of audible frequencies (15 - 2500 Hz) was reviewed in [16]. In another study the noise absorption coefficients and sound transmission loss were measured for a nonwoven composite of activated carbon fibre nonwoven (ACF) with cotton nonwoven, where the composites of the cotton nonwoven base layer were with a layer of glass fibre nonwoven, and the cotton nonwoven base layer was with a layer of cotton fibre nonwoven respectively [17]. In another work the sound absorption coefficient was tested by the impedance tube method (ASTM E 1050) and three types of nonwovens were developed using the needle-punching technique by blending bamboo, banana, and jute fibres with polypropylene staple fibres in the ratio of 50:50 [18]. Motivated by all these research works, this paper attempted to investigate the acoustic performance of double layered nonwoven composed of two different nonwoven materials, and a more general model for calculating the absorption coefficients of double layered nonwovens is presented by using Shoshani's work.

The layered absorbing structure is composed of different sound absorption material according to certain parameters, making the acoustic attenuation in the absorbing layer structure achieve good sound absorption [19]. The results show that the layered absorbing structure can produce a sufficiently satisfying sound absorption level in a cared frequency range [8, 9, 13, 14, 20 - 23]. In order to design noise absorbers including several layers with different properties, a theoretical generalisation of the Zwikker and Kosten model was suggested in [20], and the effect of the variation in porosity on the sound absorption coefficients of three webs made of cotton, acrylic fibres and polyester were examined using this model, respectively [21]. Then the relationships between the material parameters, i.e. the fibre fineness, porosity, areal density, layering sequence and airflow resistivity with the normal-incidence sound absorption coefficient of nonwoven composites consisting of three layers were studied in [22]. Motivated by all these research works, in this paper, a more general model for calculating the absorption coefficients of double layered nonwovens is given using the theory of C. Zwikker and C. W. Kosten for sound propagation through porous flexible media and sound propagation boundary conditions on the interface, which can be used to calculate the absorption coefficients of double layered nonwovens composed of two different nonwoven materials normally and provide a theoretical support for product design.

Absorption model of single layered nonwoven

In this section, we review the sound absorption process of single layered nonwovens. When the sound waves propagate through nonwoven materials, part of the sound wave is reflected, part of the sound wave is absorbed, and the remaining sound wave is transmitted. This process is shown in ***Figure 1***. For convenience, we can denote it as follows:

$$p_i(x,t) = p_{ai}e^{j(\omega t - kx)}, \quad p_r(x,t) = p_{ar}e^{j(\omega t + kx)}$$

Where $p_i(x,t)$ and $p_r(x,t)$ are the incident and reflected sound pressure, respectively. Then $|r_p| = \left|\frac{p_{ar}}{p_{ai}}\right|$ is the reflection coefficient of sound pressure, and $r_I = |r_p|^2$ is the reflection coefficient of sound intensity.

Then, based on the Energy Conservation Law, the absorption coefficient is given as follows:

$$\alpha = 1 - r_I = 1 - |r_p|^2$$

If we denote the nonwoven impedance at the front face (x = 0) as

$$z_1 = \frac{p_1}{u_1}$$

Then, based on the analysis in [1], we can get the absorption coefficient of the single layered nonwoven as follows:

$$\alpha_1 = \frac{4AW_0}{(A+W_0)^2 + B^2} \qquad (1)$$

Where $p_1 = p_i(0,t) + p_r(0,t)$ is the total sound pressure and u_1 is the total velocity of the particle at the front face (x = 0). $A = z_1(R)$ and $B = z_1(I)$ denote the real and imaginary parts of z_1, respectively, $W_0 = \rho_0 c_0$ the characteristic impedance of free air, ρ_0, c_0 denote the density of free air and the sound speed therein, respectively.

Based on the theory of C. Zwikker and C. W. Kosten on sound propagation through porous media, the porous medium is regarded as a mixture of two phases: air and solid material, and the sound wave reacts differently in the two phases. Mathematical analyses of the basic equations in this theory predict two forward and two backward waves travelling through the medium. Therefore the total sound pressure $p_a(x,t)$, $p_f(x,t)$ and total particle velocity $u_a(x,t)$, $u_f(x,t)$ in the air and fibre are solved respectively, and the sound impedance at the front face (x = 0) is obtained as follows:

$$z_1 = \frac{p_1}{u_1} = \frac{p_a(0,t) + p_f(0,t)}{v_a u_a(0,t) + v_f u_f(0,t)} \qquad (2)$$

Where subscripts a and f refer to the air and fibre phases, respectively, and v_a and $v_f = 1 - v_a$ refer to the volume fraction of the air and fibre, respectively.

Sound absorption model of double layered nonwovens

In this section, according to the theory of C. Zwikker and C. W. Kosten for sound propagation through porous flexible media and sound propagation boundary conditions on the interface, a model for calculating the absorption coefficients of double layered nonwovens will be presented.

The layered absorption structure is composed of different sound absorption material according to certain parameters, making the acoustic attenuation in the absorbing layer structure achieve good sound absorption. An absorption model of double layered nonwoven materials is shown in ***Figure 2***. Here A and B denote

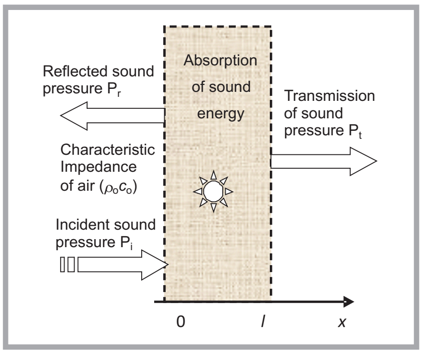

Figure 1. *Absorption model of single layered absorption materials.*

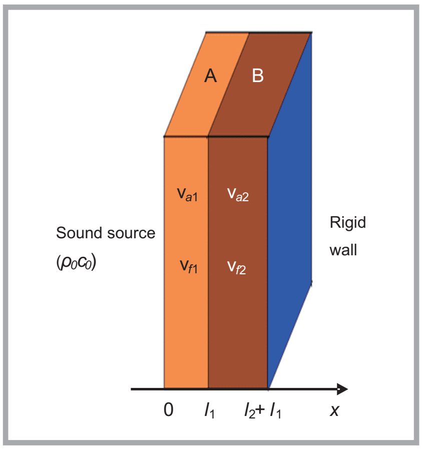

Figure 2. *Absorption model of double layered nonwoven materials.*

two different kinds of nonwoven sound absorption materials, and suppose that the double layered absorption structure close to the rigid wall, l_1 and l_2, are the thicknesses of nonwovens A and B. For convenience, we use Shoshani's notations here [1].

Let ρ_a and ρ_f be the densities of air and fibre per unit volume of the nonwoven sound absorption material, and ρ_p the density of the polymeric material. Then, $\rho_{as} = v_{as}\rho_0$ and $\rho_{fs} = v_{fs}\rho_{ps}$, where the subscripts $s = 1, 2$ refer to the number of layers.

Based on the discussions in literature [1], we can list the sequence of ***Equation 3.***

$$\begin{cases} p_{as}(x,t) = \sum_{j=1}^{4} C_{js} P_{as}^{k_{js}} e^{i(\omega t - k_{js}x)} \\ p_{fs}(x,t) = \sum_{j=1}^{4} C_{js} P_{fs}^{k_{js}} e^{i(\omega t - k_{js}x)} \\ u_{as}(x,t) = \sum_{j=1}^{4} C_{js} U_{as}^{k_{js}} e^{i(\omega t - k_{js}x)} \\ u_{fs}(x,t) = \sum_{j=1}^{4} C_{js} U_{fs}^{k_{js}} e^{i(\omega t - k_{js}x)} \end{cases} \qquad (3)$$

Where u is the velocity, p the pressure, C_{js} the undetermined coefficient for j = 1, 2, 3, 4 and $\omega = 2\pi f$ is the angular frequency. Further relations are presented in the set ***Equations 3'***.

$$\begin{aligned}
k_{1s} &= -k_{3s} = \omega\sqrt{\left(\frac{b_{1s}}{2}+\sqrt{\frac{b_{1s}^{2}}{4}-c_{1s}}\right)\frac{\rho_{as}}{v_{as}K_{as}}} \\
k_{2s} &= -k_{4s} = \omega\sqrt{\left(\frac{b_{1s}}{2}-\sqrt{\frac{b_{1s}^{2}}{4}-c_{1s}}\right)\frac{\rho_{as}}{v_{as}K_{as}}} \\
b_{1s} &= \left(1+v_{as}\frac{E_s}{R_s}+v_{fs}X_s\right)-i\theta_s(1+E_s+X_s) \\
c_{1s} &= v_{as}\frac{E_s}{R_s}(1-i\theta_s(1+R_s)) \\
R_s &= \frac{\rho_{as}}{\rho_{fs}},\ E_s=\frac{K_a}{K_{fs}},\ X_s=\frac{v_{fs}(K_{as}-P_0)}{v_{as}K_{fs}}
\end{aligned} \quad (3')$$

$\theta_s = \dfrac{\phi_s}{\rho_a \omega}$ is the dimensionless coupling coefficient, $\varphi_s = i\omega\rho_{as}(m_s-1)+v_{as}{}^2\delta$ the coupling parameter representing the drag between the fibre and air phases, m_s the structure constant, δ the resistance constant of air, K_{fs} the fibre bulk modulus, K_a the air bulk modulus, and P_0 = 1.47 Psi is the air pressure. In the open face case, the sound impedance at the front face (x = 0) is given in ***Equation 4***.

$$z_2 = \frac{p_2}{u_2} = \frac{p_{a1}(0,t)+p_{f1}(0,t)}{v_{a1}u_{a1}(0,t)+v_{f1}u_{f1}(0,t)} \quad (4)$$

In the following, we solve the sound impedance z_2. First, we consider the boundary conditions for the problem.

Boundary condition 1: Since the front is 'open', the pressure p is constant, i.e., the condition at the open surface (x = 0) is

$$v_{f1}p_{a1}(0,t) = v_{a1}p_{f1}(0,t) \quad (5)$$

Boundary condition 2: On the interface (x = l_1), when the acoustic propagates from the first layered nonwoven to the second, the following boundary conditions satisfy

$$\begin{aligned}
v_{a2}p_{a1}(l_1,t) &= v_{a1}p_{a2}(l_1,t) \\
u_{f1}(l_1,t) &= u_{f2}(l_1,t) \\
p_{a1}(l_1,t)+p_{f1}(l_1,t) &= \\
&= p_{a2}(l_1,t)+p_{f2}(l_1,t) \\
v_{a1}(l_1,t)-u_{f1}(l_1,t) &= \\
&= v_{a2}(l_1,t)-u_{f2}(l_1,t)
\end{aligned} \quad (6)$$

Boundary condition 3: At the back reflecting face (x = l_1+l_2), the velocities of both phases vanish

$$u_{a2}(l_1+l_2,t)=0, u_{f2}(l_1+l_2,t)=0 \quad (7)$$

Now, substituting ***Equation 3*** into boundary conditions ***Equations 5 ~ 7***, we get ***Equation 8***.

$$\begin{cases}
\sum_{j=1}^{4} C_{j22}U_a^{k_{j2}}e^{-ik_{j2}(l_1+l_2)} = 0 \\
\sum_{j=1}^{4} C_{j22}U_f^{k_{j2}}e^{-ik_{j2}(l_1+l_2)} = 0 \\
\sum_{j=1}^{4} C_{j1}(v_{a1}P_{f1}^{k_{j1}} - v_{f1}P_{a1}^{k_{j1}}) = 0 \\
\sum_{j=1}^{4} C_{j2}v_{a1}P_{a2}^{k_{j2}}e^{-iK_{j2}l_1} + \\
\quad - C_{j1}v_{a2}P_{a1}^{k_{j1}}e^{-ik_{j1}l_1} = 0 \\
\sum_{j=1}^{4} C_{j1}(P_{a1}^{k_{j1}} + P_{f1}^{k_{j1}})e^{-ik_{j1}l_1} + \\
\quad - C_{j2}(P_{a2}^{k_{j2}} + P_{f2}^{k_{j2}})e^{-ik_{j2}l_1} = 0 \\
\sum_{j=1}^{4} C_{j1}U_{f1}^{k_{j1}}e^{-ik_{j1}l_1} - C_{j2}U_{f2}^{k_{j2}}e^{-ik_{j2}l_1} = 0 \\
\sum_{j=1}^{4} C_{j1}v_{a1}(U_{a1}^{k_{j1}} - U_{f1}^{k_{j1}})e^{-ik_{j1}l_1} + \\
\quad - C_{j2}v_{a2}(U_{a2}^{k_{j2}} - U_{f2}^{k_{j2}})e^{-ik_{j2}l_1} = 0
\end{cases} \quad (8)$$

To solve ***Equation 8***, according to the results in literature [1], we denote a set of ***Equations 9***.

$$\begin{cases}
\alpha_{js} = \dfrac{U_{as}^{k_{js}}}{U_{fs}^{k_{js}}} = \dfrac{v_{as}\left(1-c_{fs}{}^2\left(\frac{k_{js}}{\omega}\right)^2\right)-iR_s\theta_s}{(v_{fs}-i\theta_s)R_s} \\
\beta_{js} = \dfrac{P_{as}^{k_{js}}}{P_{fs}^{k_{js}}} = \\
= v_{as}\dfrac{(1-i\theta_s)\left(1-c_{fs}{}^2\left(\frac{k_{js}}{\omega}\right)^2\right)-iR_s\theta_s}{v_{fs}(1-i\theta_s(1+R_s))-i\theta_s v_{as}c_{fs}{}^2\left(\frac{k_{js}}{\omega}\right)^2} \\
z_{fjs} = \dfrac{P_{as}^{k_{js}}}{U_{as}^{k_{js}}} = \\
= \rho_{fs}\dfrac{\omega}{k_{js}}\dfrac{v_{fs}(1-i\theta_s(1+R_s))-i\theta_s v_{as}c_{fs}{}^2\left(\frac{k_{js}}{\omega}\right)^2}{v_{fs}-i\theta_s} \\
z_{ajs} = \dfrac{P_{fs}^{k_{js}}}{U_{fs}^{k_{js}}} = \dfrac{\beta_{js}}{\alpha_{js}}z_{fjs} = \\
= \rho_{as}v_{as}\dfrac{\omega}{k_{js}}\dfrac{(1-i\theta_s)\left(1-c_{fs}{}^2\left(\frac{k_{js}}{\omega}\right)^2\right)-iR_s\theta_s}{v_{as}\left(1-c_{fs}{}^2\left(\frac{k_{js}}{\omega}\right)^2\right)-iR_s\theta_s}
\end{cases} \quad (9)$$

Here, $c_{fs}{}^2 = \dfrac{K_{fs}}{\rho_{fs}}$ is the square of the fibre wave velocity.

Note that k_{31} = -k_{11}, k_{41} = -k_{12}, k_{32} = -k_{12} and k_{42} = -k_{22}, and we know that

$$\begin{aligned}
&\alpha_{3s} = \alpha_{1s},\ \beta_{3s} = \beta_{1s},\ z_{a3s} = -z_{a1s}, \\
&z_{f3s} = -z_{f1s},\ \alpha_{4s} = \alpha_{2s},\ \beta_{4s} = \beta_{2s}, \\
&z_{a4s} = -z_{a2s},\ z_{f4s} = -z_{f2s}
\end{aligned} \quad (10)$$

for s = 1, 2.

Now taking into account ***Equations 3*** and ***8 ~ 10*** in ***Equation 4***, after some heavy calculations, we find ***Equation 11*** with matrixes for a particular D and all the individual coefficients.

Finally, according to ***Equation 1***, the absorption coefficient of the double layered nonwoven is given in ***Equation 12***

$$\alpha_2 = \frac{4z_2(R)W_0}{(z_2(R)+W_0)^2+(z_2(I))^2} \quad (12)$$

Model simulation and analysis

In this section, we report on various properties of the absorption coefficient α_2 using MATLAB. The double layered nonwovens composed of polyester fibres in the outer layer and nylon fibres in the inner layer are investigated by numerical simulation. Then programs were written that calculate the absorption coefficient α_2 as a function of the thickness and porosity of each layer.

The constants involved in the calculation of the sound absorption coefficient are set as follows: ρ_0 = 1.293 kg/m^3, c_0 = 340.29 m/s, P_0 = 1.47 Psi ≈ 101325 Pa, K_a = 1.01 × 10^5, K_{f1} = 1.1 × 10^{10}, K_{f2} = 4.7167 × 10^{10}, ρ_{p1} = 1380 kg/m^3, ρ_{p2} = 1140 kg/m^3, δ = 4168.6, m_1 = m_2 = 1.

If v_{a1} = 0.95, v_{a2} = 0.99, and l_1 = 2.5 cm, the theoretical plot of the absorption coefficient α_2 is as shown in ***Figure 3*** (see page 106), with the thickness of the inner layer set as l_2 = 0.5 cm, l_2 = 1.5 cm, l_2 = 2.5 cm, l_2 = 3.5 cm, and l_2 = 4.5 cm, respectively; while if we set l_2 = 2.5 cm, the theoretical plot of the absorption coefficient α_2 is as shown in ***Figure 4*** (see page 106), with the thickness of the outer layer set as l_1 = 0.5 cm, l_1 = 1.5 cm, l_1 = 2.5 cm, l_1 = 3.5 cm, and l_1 = 4.5 cm, respectively. If we take l_1 = 4.5 cm,

$$z_2 = \frac{(\beta_{11}+1)z_{f11}(\det(D_1)-\det(D_3)) + (\beta_{21}+1)z_{f21}(\det(D_2)-\det(D))}{(v_{f1}+\alpha_{11}v_{a1})(\det(D_1)+\det(D_3)) + (v_{f1}+\alpha_{21}v_{a1})(\det(D_2)+\det(D))} \qquad (11)$$

Here:

$$D = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad D_1 = \begin{bmatrix} b_1 & a_{12} & a_{13} \\ b_2 & a_{22} & a_{23} \\ b_3 & a_{32} & a_{33} \end{bmatrix} \quad D_2 = \begin{bmatrix} a_{11} & b_1 & a_{13} \\ a_{21} & b_2 & a_{23} \\ a_{31} & b_3 & a_{33} \end{bmatrix} \quad D_3 = \begin{bmatrix} a_{11} & a_{12} & b_1 \\ a_{21} & a_{22} & b_2 \\ a_{31} & a_{32} & b_3 \end{bmatrix}$$

$$a_{11} = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f22}}\left(\frac{v_{a2}}{v_{a1}}\beta_{11} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{11}+1\right)\beta_{12}\right)z_{f11}(e^{-i(k_{11}l_1+k_{22}l_2)} - e^{i(k_{22}l_2-k_{11}l_1)})$$
$$+\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{11}-\alpha_{12}\right)(e^{-i(k_{11}l_1+k_{22}l_2)} + e^{i(k_{22}l_2-k_{11}l_1)})$$

$$a_{12} = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f22}}\left(\frac{v_{a2}}{v_{a1}}\beta_{21} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{21}+1\right)\beta_{12}\right)z_{f21}(e^{-i(k_{21}l_1+k_{22}l_2)} - e^{i(k_{22}l_2-k_{21}l_1)})$$
$$+\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{21}-\alpha_{12}\right)(e^{-i(k_{21}l_1+k_{22}l_2)} + e^{i(k_{22}l_2-k_{21}l_1)})$$

$$a_{13} = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f22}}\left(\frac{v_{a2}}{v_{a1}}\beta_{11} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{11}+1\right)\beta_{12}\right)z_{f11}(e^{i(k_{22}l_2+k_{11}l_1)} - e^{i(k_{11}l_1-k_{22}l_2)})$$
$$+\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{11}-\alpha_{12}\right)(e^{i(k_{22}l_2+k_{11}l_1)} + e^{i(k_{11}l_1-k_{22}l_2)})$$

$$b_1 = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f22}}\left(\frac{v_{a2}}{v_{a1}}\beta_{21} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{21}+1\right)\beta_{12}\right)z_{f21}(e^{i(k_{21}l_1-k_{22}l_2)} - e^{i(k_{22}l_2+k_{21}l_1)})$$
$$-\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{21}-\alpha_{12}\right)(e^{i(k_{22}l_2+k_{21}l_1)} + e^{i(k_{21}l_1-k_{22}l_2)})$$

$$a_{21} = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f12}}\left(\frac{v_{a2}}{v_{a1}}\beta_{11} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{11}+1\right)\beta_{22}\right)z_{f11}(e^{-i(k_{11}l_1+k_{12}l_2)} - e^{i(k_{12}l_2-k_{11}l_1)})$$
$$+\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{11}-\alpha_{22}\right)(e^{-i(k_{11}l_1+k_{12}l_2)} + e^{i(k_{12}l_2-k_{11}l_1)})$$

$$a_{22} = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f12}}\left(\frac{v_{a2}}{v_{a1}}\beta_{21} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{21}+1\right)\beta_{22}\right)z_{f21}(e^{-i(k_{21}l_1+k_{12}l_2)} - e^{i(k_{12}l_2-k_{21}l_1)})$$
$$+\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{21}-\alpha_{22}\right)(e^{-i(k_{21}l_1+k_{12}l_2)} + e^{i(k_{12}l_2-k_{21}l_1)})$$

$$a_{23} = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f12}}\left(\frac{v_{a2}}{v_{a1}}\beta_{11} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{11}+1\right)\beta_{22}\right)z_{f11}(e^{i(k_{12}l_2+k_{11}l_1)} - e^{i(k_{11}l_1-k_{12}l_2)})$$
$$+\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{11}-\alpha_{22}\right)(e^{i(k_{12}l_2+k_{11}l_1)} + e^{i(k_{11}l_1-k_{12}l_2)})$$

$$b_2 = \frac{\alpha_{22}-\alpha_{12}}{2(\beta_{22}-\beta_{12})z_{f12}}\left(\frac{v_{a2}}{v_{a1}}\beta_{21} - \left(\left(1-\frac{v_{a2}}{v_{a1}}\right)\beta_{21}+1\right)\beta_{22}\right)z_{f21}(e^{i(k_{21}l_1-k_{12}l_2)} - e^{i(k_{12}l_2+k_{21}l_1)})$$
$$-\frac{1}{2}\left(1-\frac{v_{a1}}{v_{a2}}+\frac{v_{a1}}{v_{a2}}\alpha_{21}-\alpha_{22}\right)(e^{i(k_{12}l_2+k_{21}l_1)} + e^{i(k_{21}l_1-k_{12}l_2)})$$

$$a_{31} = (v_{a1}-v_{f1}\beta_{11})z_{f11} \qquad a_{32} = (v_{a1}-v_{f1}\beta_{21})z_{f21}$$
$$a_{33} = -(v_{a1}-v_{f1}\beta_{11})z_{f11} \qquad b_3 = (v_{a1}-v_{f1}\beta_{21})z_{f21}$$

Equation 11.

$l_1 = 2.5$ cm, and $v_{a1} = 0.99$, the theoretical plot of the absorption coefficient α_2 is as shown in ***Figure 5*** (see page 106), with the porosity of the inner layer set as $v_{a2} = 0.8$, $v_{a2} = 0.85$, $v_{a2} = 0.9$, $v_{a2} = 0.95$, and $v_{a2} = 0.99$, respectively; while, if $v_{a2} = 0.99$, the theoretical plot of the absorption coefficient α_2 is as shown in ***Figure 6*** (see page 106), with the porosity of the outer layer set as $l_1 = 0.5$ cm, $l_1 = 1.5$ cm, $l_1 = 2.5$ cm, $l_1 = 3.5$ cm, and $l_1 = 4.5$ cm, respectively.

Observing ***Figure 3*** to ***Figure 6*** carefully, we can see that the effects on the acoustic properties of double layered nonwovens are different for different frequency bands. We can state positively that with an increase in the thickness of the inner materials l_2, the absorption coefficient α_2 increases sharply, especially at a low and medium frequency (0 ~ 1500 Hz), which causes the maximum absorption coefficient to decrease (see ***Figure 3***). With an increase in the thickness of the outer materials l_1, the change in α_2 is similar to that in the case of l_2 (see ***Figure 3*** and ***Figure 4***), which is mainly due to the material properties of polyester and nylon being similar, such as the density, bulk modulus and so on. Additionally, with an increase in the porosity of the inner materials v_{a2}, the absorption coefficient α_2 changes little, especially at a higher frequency (see ***Figure 5***). However, with an increase in the porosity of the outer materials v_{a1}, the frequency that causes the maximum absorption coefficient to increase and the change in v_{a1} have a greater impact on high-frequency fluctuations (see ***Figure 6***).

In a word, changes in the outer material properties have a greater impact on the absorption coefficient at a higher frequency, whereas the absorption coefficient at low and medium frequencies is determined by the properties of the inner and outer materials together. This phenomenon can be explained as follows: for high-frequency sound signals, the wavelength is short and the 'wave number'

$$k = \frac{\omega}{c} \qquad (13)$$

is more in the outer layer, i.e., high-frequency sound signals have sufficient contact with the outer materials. Therefore, the outer materials have sufficient absorption for high-frequency sound signals. For low-frequency sound signals, the wavelength is large and the 'wave number' in the outer materials is less, i.e. low-frequency sound signals have sufficient contact with both the outer and inner materials. Therefore the sound absorption of the nonwoven can be considered as the comprehensive result of both two layered materials.

Therefore, for the design of a double layered absorption structure, the parameters of the outer material should be chosen firstly according to the high-frequency sound absorption performance. Then those of the inner material are determined

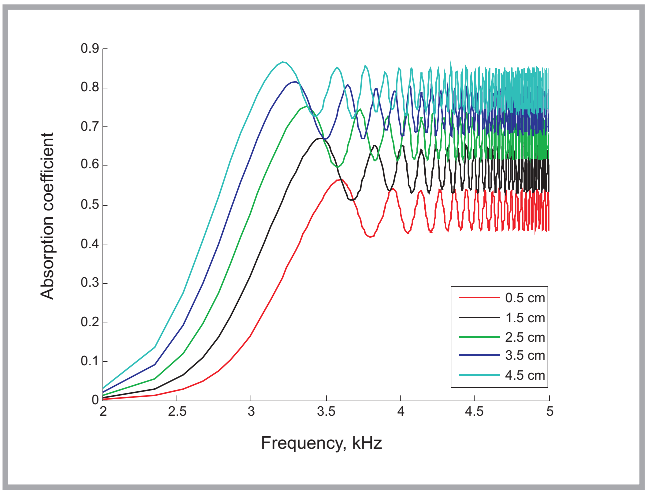

Figure 3. *Theoretical plot: absorption coefficient* α_2 *is a function of the frequency f for different web thicknesses of the inner materials - nylon fibre web.*

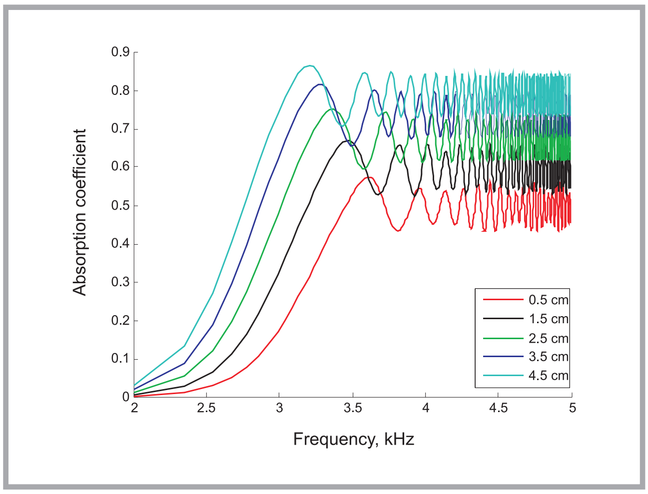

Figure 4. *Theoretical plot: absorption coefficient* α_2 *is a function of the frequency f for different web thicknesses of the outer materials - polyester fibre web.*

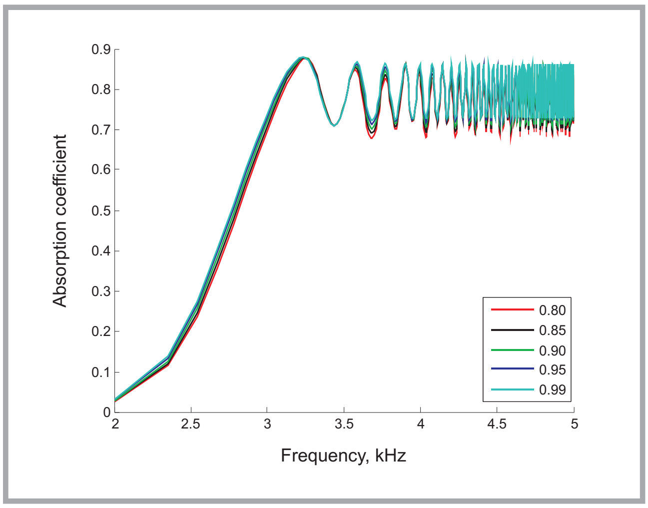

Figure 5. *Theoretical plot: absorption coefficient* α_2 *is a function of the frequency f for different web porosities of the inner materials - nylon fibre web.*

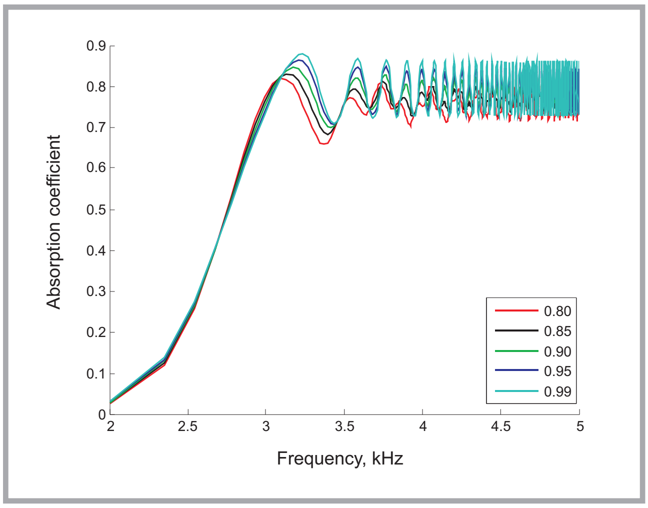

Figure 6. *Theoretical plot: absorption coefficient* α_2 *is a function of the frequency f for different web porosities of the outer materials - polyester fibre web.*

according to the low-frequency sound absorption performance, and the design parameters of the outer material are modified simultaneously. Finally we can make a double layered absorption structure that has a sufficiently satisfying sound absorption level in a cared frequency range.

Conclusion

By using the theory of C. Zwikker and C. W. Kosten for sound propagation through porous flexible media and the sound transmission boundary conditions between the first and second layer, a model for calculating the absorption coefficients of double layered nonwovens has been presented in this paper. Compared with the theoretical generalisation of the Zwikker and Kosten model presented by Shoshani, this model is more general and can be used to calculate the absorption coefficients of double layered nonwovens composed of two different nonwoven materials and provide theoretical support for product design. The simulations prove the correctness of the model obtained in this paper, showing that the properties of the outer material have a greater impact on the absorption coefficient at higher frequencies, whereas the absorption coefficient at low and medium frequencies is determined by the properties of the inner and outer materials together. It should be noted that only a double layered nonwoven sound absorption structure has been investigated in this paper; a general model for calculating the absorption coefficients of a multi-layer nonwoven structure remains a challenging subject for future research.

References

1. Shoshani Y, Yakubov Y. A model for calculating the noise absorption capacity of nonwovens. *Textile Research Journal* 1999; 7: 519-526.
2. Shoshani Y, Yakubov Y. Numerical assessment of maximal absorption coefficients for nonwovens. *Applied Acoustics* 2000; 59: 77-87.
3. Garai M, Pompoli F. A simple empirical model of polyester fibre materials for acoustical applications. *Applied Acoustics* 2005; 12: 1383-1398.
4. Shoshani Y. Studies of textile assemblies used for acoustic control. *Technical Textiles International* 1993; 3: 32-34.
5. Shoshani Y, Rosenhouse G. Noise insulating blankets made of textiles. *Applied Acoustics* 1992; 35:129-138.
6. Shoshani Y, Rosenhouse G. Use of nonwovens in the design of acoustic ceilings. In: *INDA conference*, St. Petersburg, Florida, 1995. pp. 267-274.
7. Sgard FC, Olny X, Atalla N. et al. On the use of perforations to improve the sound absorption of porous materials. *Applied Acoustics* 2008; 6: 625-651.

8. Mitri FG, Fellah ZEA. Theoretical calculation of the acoustic radiation force on layered cylinders in a plane standing wave-comparison of near- and far-field solutions. *Journal of Physics A-Mathematical and General* 2006; 20: 6085-6096.
9. Jansens G, Lauriks W, Vermeir G. et al. Free field measurements of the absorption coefficient for nonlocally reacting sound absorbing porous layers. *Journal of the acoustical society of America* 2002; 4: 1327-1334.
10. Zwikker C, Kosten CW. *Sound absorbing materials*. Oxford: Elsevier Pub Co, 1949.
11. Dent RW. The sound absorption properties of felts. In: *UMIST 1983 Conference* (ed Cusick GE), 1983, pp. 257-312.
12. Dahl MD, Rice EJ, Groesbeck DE. Effects of fibre motion on the acoustic behavior of an anisotropic, flexible fibrous material. *Journal of the Acoustical Society of America* 1990; 1: 54-66.
13. Lambert RF. Acoustic resonance in highly porous, flexible, layered fine fibre materials. *Journal of the Acoustical Society of America* 1993; 3: 1227-1234.
14. Lambert RF. Low Frequency Acoustic Behavior of Highly Porous, Layered, Flexible Fine Fibre Materials. *Journal of the Acoustical Society of America* 1995; 2: 818-821.
15. Honarvar MG, Jeddi AAA, Tehran MA. Noise Absorption Modeling of Rib Knitted Fabrics. *Textile Research Journal* 2010; 80: 1392-1404.
16. Lee YE, Joo CW. Sound absorption properties of thermally bonded nonwovens based on composing fibres and production parameters. *Journal of Applied Polymer Science* 2004; 92: 2295-2302.
17. Jiang N, Chen JY, Parikh DV. Acoustical evaluation of carbonized and activated cotton nonwovens. *Bioresource Technology* 2009; 100: 6533–6536.
18. Chen X, Vroman P, Lewandowski M, Perwuelz A, Zhang Y. Study of the Influence of Fibre Diameter and Fibre Blending on Liquid Absorption Inside Nonwoven Structures. *Textile Research Journal* 2009; 15: 1364-1370.
19. He L, Zhu HC, Qiu XJ, Du GH. *Acoustic Theory and Engineering Applications*. Beijing: Science press, 2006.
20. Shoshani Y, Yakubov Y. Generalization of Zwikker and Kosten Theory for Sound Absorption in Flexible Porous Media to the Case of Variable Parameters. *Journal of Computational Acoustics* 2000; 3: 415-441.
21. Shoshani Y, Yakubov Y. Use of nonwovens of variable porosity as noise control elements. *International Nonwovens Journal* 2001; 4: 23-28.
22. Yilmaz ND, Banks-Lee P, Powell NB, Michielsen S. Effects of Porosity, Fibre Size, and Layering Sequence on Sound Absorption Performance of Needle-Punched Nonwovens. *Journal of Applied Polymer Science* 2011; 5: 3056-3069.
23. Thilagavathi G, Pradeep E, Kannaian T, Sasikala L. Development of Natural Fibre Nonwovens for Application as Car Interiors for Noise Control. *Journal of Industrial Textiles* 2010; 3: 267-278.

Received 07.09.2011 Reviewed 23.11.2011