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Sound absorbtion in knitted structures for interior noise reduction in automobiles

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Abstract
Reduction of interior noise in modern automobiles is an important issue in the automobile industry. Textiles are one solution, as they can provide passive sound absorption in upholstery, headliners and other interior parts. Nonwovens have also been used, but they have a lesser aesthetic appearance and drapability compared with woven and knitted structures, which can provide a 3D seamless fabric and have a pleasing appearance. In this paper we test the sound absorption of plain knitted fabrics and compare this with a theoretical model.

Keywords: knitted fabrics, noise absorption, interior noise reduction, automobile industry

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Modern compact vehicles have a low-frequency noise environment in the passenger compartment. The frequency range is generally below 4000 Hz and is more predominant in the region from 100 to 1000 Hz, which on long journeys can cause fatigue for both driver and passengers. Currently there are two techniques used to solve this problem, known as active and passive methods. The active technique uses the phenomenon of wave interference [1, 2]. The passive technique uses acoustic materials to dampen the noise. Textiles provide a low-cost, environment-friendly material to absorb sound. Research has been conducted on nonwoven fibre webs in terms of their noise-absorption properties [3–6]. Commercial acoustic products have also been fabricated which are composed of nonwoven fabrics. However, even though their noise absorption properties are promising, it is difficult to produce a textured surface on nonwovens to give an aesthetically pleasing appearance. Thus they usually have to be draped with a woven textile. Some work has been done on the noise absorption properties of woven structures [7, 8], but was based only on empirical investigation.

The headliner, carpets, seats, door panels and other interior parts absorb much of the interior noise by passive means and it would be interesting to consider the use of knitted fabrics in all these areas. This paper will investigate the noise absorption mechanism of a plain knitted structure.

2. Sound absorption in knitted structures

2.1. Model of a plain knitted fabric as a porous material

The unit cell of a plain knitted structure is the stitch, which is created by intermeshing yarn loops. The stitches are organized in rows (courses) and columns (wales). W and C represent the wale spacing and course spacing respectively. The void space inside a unit cell of a plain knitted fabric can be approximated as a circular hole as shown in figure 1.

From figure 1 it can be seen that the void space of a unit cell can be approximated as a cylinder whose circumference is bounded by the yarns forming the loop. Thus the void space in a unit cell can be represented approximately as a circular cylinder. As there is a uniform distribution of stitches, which form the fabric, there exists a uniform array of circular cylinders in a unit area. Thereby the plain knitted fabric can be geometrically modelled approximately as a layer with identical cylindrical pores perpendicular to its surface (figure 2).

2.2. Analytical prediction of the sound absorption of a knitted fabric

2.2.1. Acoustic impedance of a unit cell. Consider the air inside the circular cylindrical pore formed by the unit cell of a plain knitted structure as a fluid layer of finite thickness l, which is also the thickness of the fabric. Further, consider the fabric placed on a rigid impervious wall such as a metal frame.

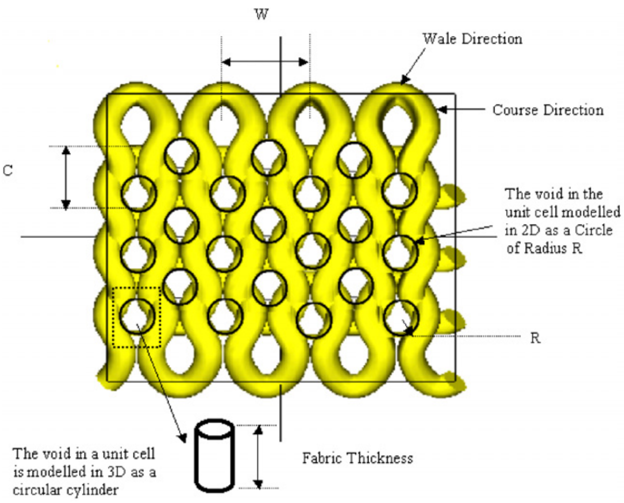

Figure 1. Technical face of a plain knitted structure.

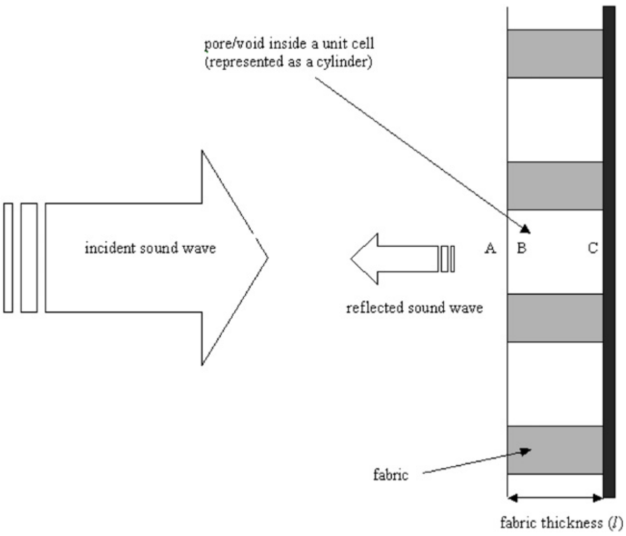

Figure 2. Sound absorption by a pore formed by the void of a unit cell, which is backed by a rigid wall.

Let a one-dimensional plane sound wave be incident normal to the surface of the unit cell as shown in figure 2.

As per figure 2, A is a point on the surface of the fabric, B is a point inside the void of the unit cell near the fabric surface and C is a point on the fabric near the rigid wall. The acoustic impedance at B is given by [9, 10]

$$Z_B = -\mathrm{j}Z_{\mathrm{c}}\cot(\beta \cdot l), \tag{1}$$

where Z_{c} is the characteristic impedance of the fluid layer (which in this case is the air inside the unit cell) and β is the wave number of the fluid. The characteristic impedance and the wave number are complex quantities, which are given by the following relationships [10]:

$$\beta = \omega\sqrt{\frac{\rho}{K}}, \tag{2}$$

$$Z_{\mathrm{c}} = \sqrt{K \cdot \rho}, \tag{3}$$

where ρ and K denote the effective density and the bulk modulus of the air in the cylindrical pores respectively, and ω is the angular frequency of the air column. Zwikker and Kosten [9] have modelled the air flow inside a circular cylinder of radius R as a laminar flow and derived relationships for ρ and K. These relationships have been derived by taking into consideration the thermal exchange effects between the air and the walls of the cylinder, and the viscous effects of the laminar flow of air in the cylinder as two separate issues. The derived formulae are given below:

$$\rho = \frac{\rho_0}{1 - \frac{2 \cdot J_1(\psi\sqrt{-\mathrm{j}})}{\psi\sqrt{-\mathrm{j}} \cdot J_0(\psi\sqrt{-\mathrm{j}})}}, \tag{4}$$

$$K = \frac{\kappa p_0}{1 + \frac{2}{B\psi\sqrt{-\mathrm{j}}} \cdot (\kappa - 1) \cdot \frac{J_1(B\psi\sqrt{-\mathrm{j}})}{J_0(B\psi\sqrt{-\mathrm{j}})}} \tag{5}$$

and

$$\psi = \sqrt{\frac{\omega\rho_0 R^2}{\eta}}, \tag{6}$$

where ρ_0 is the density of air, κ is the thermal conductivity of air, B is the square root of the Prandtl number, J_0 is the Bessel function of zero order, J_1 is the Bessel function of first order and η is the viscosity of air.

2.2.2. Acoustic impedance and sound absorption of the plain knitted fabric. As shown in figure 2, when sound energy is incident normal to the surface, the flow of air is from the surface of the fabric to the pore. Thus the acoustic impedance at the surface of the fabric at point A can be given as [10]

$$Z_A = \frac{Z_B}{\phi}, \tag{7}$$

where ϕ is the porosity of the material which is the ratio of the air volume (V_{a}) to the total volume of the material (V_{T}).

The noise absorption coefficient (NAC) of the fabric can be found by the use of the following relationship [9, 10]:

$$\mathrm{NAC} = 1 - \left(\left|\frac{Z_A - Z_{\mathrm{c}}}{Z_A + Z_{\mathrm{c}}}\right|\right)^2. \tag{8}$$

The NAC gives the amount of energy from the incident sound wave absorbed by the knitted fabric. Thus to analytically predict the sound absorbed by the knitted fabric the pore radius of the void formed by the unit cell and the porosity of the fabric should be determined.

2.2.3. Pore radius. To determine the pore radius of the cross-sectional area of the void in a unit cell the following assumptions are made:

(a) void area in a unit cell is approximated to the area of a circle of radius R;
(b) voids between crossover points of the stitch and voids between fibres of a yarn are negligible;
(c) stitches are composed of ideal yarns, i.e. they are of circular cross section and constant diameter throughout the length;
(d) the fabric is dry and relaxed;
(e) yarn deformation at crossover points is negligible.

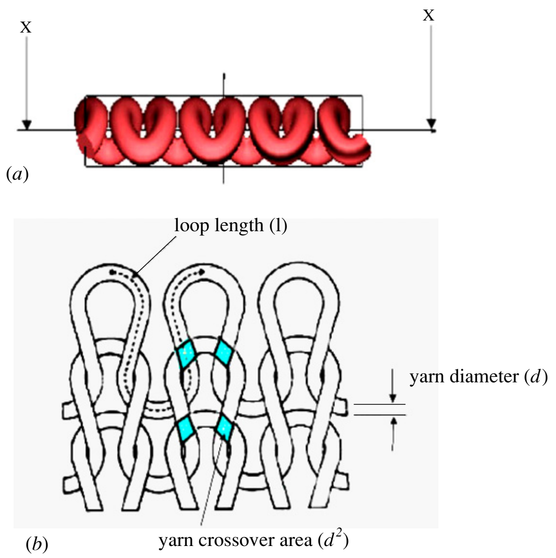

Figure 3. Sectional views of plain knitted fabric: (*a*) cross-section view; (*b*) view in the *XX* plane.

Peirce [11] defined the stitch (loop) length (l) in cm as follows:

$$l = 2/c + 1/w + 5.94 \cdot d, \tag{9}$$

where l is the length of yarn in one loop (cm), c is the number of courses per cm, w is the number of wales per cm and d is the diameter of the yarn (cm).

The number of stitches per cm^2 of fabric or stitch density, s, is defined as follows:

$$s = c \cdot w. \tag{10}$$

The yarn in the fabric can be regarded as a flat rectangular strip when the plain structure is viewed in the *XX* plane as shown in figure 3.

The total area of yarn (A_{yarn}) occupied in 1 cm^2 can be shown as

$$A_{\text{yarn}} = \text{stitch density} \times (\text{area of yarn occupied by unit cell})$$

$$A_{\text{yarn}} = s(ld - 4d^2). \tag{11}$$

Therefore, the total open area of the fabric (A_{open}) in 1 cm^2 is given as

$$A_{\text{open}} = 1 - A_{\text{yarn}}.$$

Further, the open area (void) in a unit cell (A_{sl}) is given by

$$A_{sl} = \frac{1 - s(ld - 4d^2)}{2s}. \tag{12}$$

Approximating this area as a perfect circle of radius R, the pore radius can be taken as

$$R = \sqrt{\frac{1 - s(ld - 4d^2)}{2s\pi}}. \tag{13}$$

Thus the pore radius of a single stitch of a plain knitted fabric can be calculated by using the stitch density, yarn diameter and stitch length of the fabric.

2.2.4. Porosity. Guidoin *et al* [12] defined porosity as the ratio of void space or volume of pores within the boundaries of a solid material, to the total volume. The porosity or void fraction of a solid material is usually expressed as a percentage, and was derived by him as shown below:

$$P = 100\left[\frac{V_{\text{v}}}{V_{\text{t}}}\right], \tag{14}$$

where V_{v} is the volume of void space (cm^3), V_{t} is the total volume of the fabric (cm^3),

$$V_{\text{t}} = V_{\text{m}} + V_{\text{v}}, \tag{15}$$

where V_{m} is the volume of yarn in the fabric. Using (14) in (15) gives

$$P = 100\left[1 - \frac{V_{\text{m}}}{V_{\text{t}}}\right]. \tag{16}$$

Considering the density of the fibres in the fabric as ρ_{m} and the total density as ρ_{t},

$$P = 100\left[1 - \frac{\rho_{\text{t}}}{\rho_{\text{m}}}\right]. \tag{17}$$

The definition of density is

- density = mass/volume
- or, density = mass/(area × thickness).

Defining M as mass per unit area of the fabric, and t as the thickness of the fabric,

$$\rho_{\text{t}} = \frac{M}{t}. \tag{18}$$

Using this relationship in equation (17) the following equation is obtained:

$$P = 100\left[1 - \frac{M}{t\rho_{\text{m}}}\right]. \tag{19}$$

Thus, to obtain the porosity of a knitted fabric, one has to obtain the fibre density, the mass per unit area and the thickness of the material. This value is used in equation (7).

3. Measurement of noise absorption coefficient

To validate the mathematical prediction of the NAC of plain knitted fabrics a measurement of the NAC was done using a standard two-microphone impedance tube provided by Spectronics Inc. USA, which has been designed as per the ISO 10534-2 standard.

The tube is 1 m long and 34 mm in diameter and is designed to measure the noise absorption of normal incident sound within 50–5000 Hz. The pseudo random white noise signal from 50 to 4000 Hz, required for the internal sound source of the impedance tube, was created using Labview. This signal was sent to the impedance tube via the M6259 National Instruments Data Acquisition device. Similarly the dual channel spectrum analyser required to calculate the complex acoustic transfer function from the microphone signals, as per the standard, was implemented using Labview. The microphone signals were taken to the respective X and Y channels of the dual channel analyser through two analogue inputs of the data acquisition device.

The real-time readings of the transfer function data were then averaged for 100 cycles in a repetitive loop in the software.

Table 1. Plain knitted structure sample details.

Sample number	Courses per cm	Wales per cm	Calculated stitch length (cm)	Measured stitch length (cm)	%|Error| in stitch length data	Measured pore area (mm^2)	Fabric thickness (mm)
A1	10.8	8.8	0.441	0.461	4.5	0.147	0.6
A2	10.23	4.52	0.559	0.538	3.8	0.427	0.6
A3	4.92	4.33	0.78	0.856	9.7	1.437	0.6

Table 2. Pore size and porosity data of the fabric samples.

Sample number	Pore radius from calculated data (cm)	Pore radius from measured data (cm)	%|Error|	Mass of 1 cm^2 of fabric (g)	Porosity (%)
A1	0.019	0.022	15.789	0.031	63.7
A2	0.041	0.037	9.846	0.018	78.102
A3	0.070	0.068	2.967	0.013	84.185

The resultant reading was then saved as a text file and was used by the ACUPRO software, which was provided by the tube manufacturer, to calculate and graphically display the NAC of the fabric for frequencies between 50 and 4000 Hz. As per the ISO standard and the impedance tube instructions, for each fabric the NAC measurements were done on three identical samples taken from different regions of the fabric and their average was taken.

4. Plain knitted fabric samples

For the initial validation of the mathematical prediction, plain knitted structures produced from PE yarn with a density of 1.37 g cm^{-3} and a yarn diameter of 0.2 mm (with a yarn count of 430 dtex) were used. The specifications of the plain structure samples are given in table 1. The stitch lengths were calculated as per equation (9) using the number of courses per cm and wales per cm of a given fabric.

The fabric thickness was measured using a thickness tester with a pressure of 100 kPa. The fabric samples were conditioned at atmospheric pressure, 20 °C and a relative humidity of 63% for 48 h.

The pore area of a stitch and the stitch length were measured using a Projectina optical microscope, and PIA 4000 digital image analysing software. The stitch length was determined by measuring the length of yarn in ten stitches. In practice the voids in unit cells of a plain knitted fabric are not uniform when seen under a microscope and there was a variation of 10% of the measured pore area. Therefore the pore area was obtained by averaging 50 readings to get a better accurate value. The pore radius of the fabric was calculated using equation (13).

The porosity for a given fabric was obtained by first measuring the weights of three samples (in grams) each having an area of 100 cm^2. Each sample was cut into a square of 10 cm by 10 cm for this purpose. The weights were then averaged and divided by 100 to obtain the mass per unit area of the fabric in grams per cm^2. This value with the measured thickness for the fabric was used in equations (18) and (19) to obtain the porosity of the fabric. The results are given in table 2.

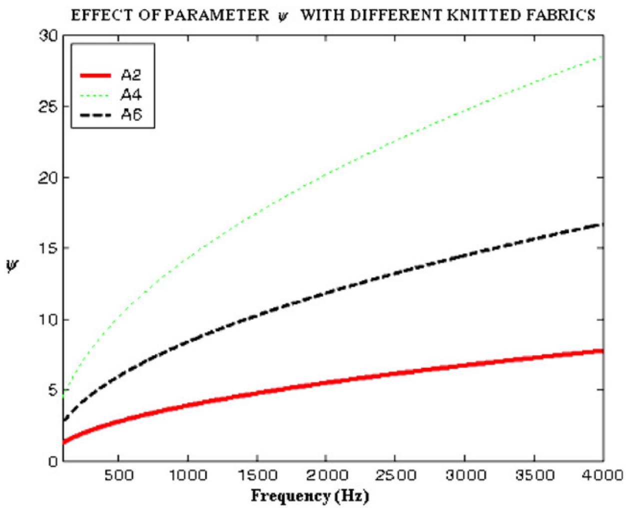

Figure 4. The variation of the dimensionless parameter ψ with the pore radius and frequency.

5. Simplification of mathematical analysis based on fabric data

The calculated pore radius values from table 2 are used in equation (6). Figure 4 illustrates the variation of the dimensionless parameter ψ of equation (6) with respect to frequency.

Figure 4 indicates that the parameter ψ is greater than 1, for the fabric pore sizes given in table 2, for the considered spectrum. As $\psi \geqslant 1$, the following approximations, $(-\mathrm{j})^{1/2} = (-1+\mathrm{j})/\sqrt{2}$ and $\frac{J_1}{J_0} = \mathrm{j}$ can be used in equations (5) and (6). Therefore the effective density and bulk modulus of the air inside the pores in the plain knitted fabric can be simplified further [9, 10]:

$$\rho = \rho_0 \left(1 - \frac{2(-1)}{\psi}\right), \tag{20}$$

$$K = \gamma \rho_0 \left[1 + \frac{\sqrt{2(-1+\mathrm{j}(\gamma-1))}}{B\psi}\right]. \tag{21}$$

These two simplified equations are then used with equations (2) and (3) which are used in equation (1)

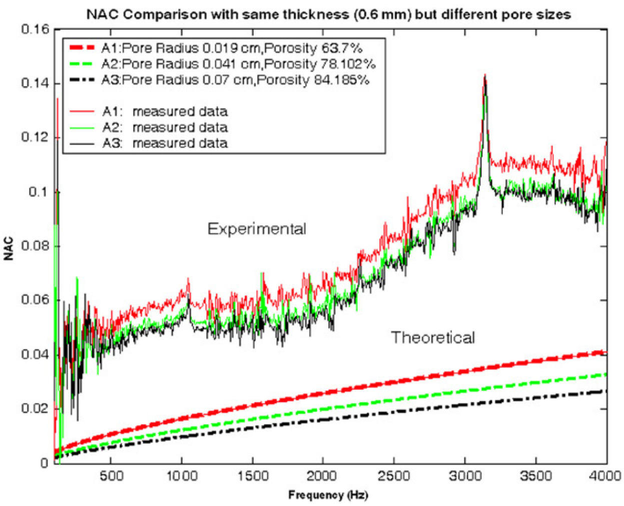

Figure 5. NAC for plain knitted structures with the same thickness but different pore sizes.

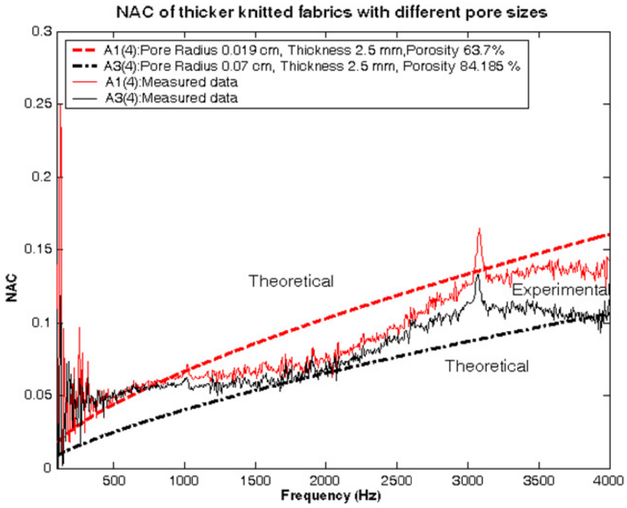

Figure 6. NAC of two knitted fabrics with different pore sizes with each fabric sample comprising four layers giving a total thickness of 2.5 mm.

to obtain the acoustic impedance of the air inside the unit cell near the surface of the fabric. This simplified value is used with equations (7) and (8) to obtain the noise absorption coefficient of the plain knitted fabric.

6. Study of the parameters of a plain knitted structure affecting its noise absorbency properties

The following values have been used in equations (6), (20) and (21). The values are based on the normal atmospheric conditions of 18 °C temperature and 1.1033 Pa pressure [10]:

$$\gamma = 1.4$$
$$B^2 = 0.71$$
$$P_0 = 1.0132 \times 10^5\,\mathrm{Pa}$$
$$\rho_0 = 1.213\,\mathrm{kg\,m^{-3}}$$
$$\eta = 1.84 \times 10^{-5}\,\text{poiseuille}.$$

It can be seen from table 2 that as the stitch size becomes smaller this results in a reduced pore size and porosity. This means that there will be more yarn in a unit area and the fabric becomes denser as per Guidon *et al* [12].

The next sections investigate the effect of pore size and thickness of a plain knitted fabric on the noise absorbent coefficient. For this purpose the pore radius, porosity and fabric thickness data given in table 2 are used in the analytical prediction described in section 2.2 to investigate whether the NAC increases or decreases with the pore size, porosity and fabric thickness.

From these results it can be determined whether or not a thicker fabric with reduced porosity will yield higher noise absorbency. The analytical predictions are then validated by measuring the NAC of the same fabric samples, using the NAC measuring system described in section 3.

6.1. Different stitch sizes but same thickness

The analytical prediction and the experimental data of the NAC for a single layer of the fabric samples are given in figure 5. The mathematical predictions have been obtained using the calculated data for the pore size and porosity in table 2.

It can be observed from figure 5 that as the stitch sizes become smaller the NAC increases. The impedance tube has a certain minimum threshold in measuring the NAC accurately; thus, as the measured structures are poor sound absorbers there is a difference between the predicted and experimental values. The impedance tube itself acts as a resonant sound absorber and its sound absorption effect is predominant on the experimental data as the fabric is a poor sound absorber. This may also explain the resonant profile of the experimental graphs.

As an aside we note that as the fabric sample is a poor sound absorber the experimental data give resonance peaks at 3000 Hz. This may be due to a very minute layer of air between the fabric and the sample holder of the tube acting as a resonant cavity, with the pores in the fabric acting as a thin micro-perforated panel (MPP). It can be observed that the noise absorption coefficient of the fabric only increases beyond 1900 Hz. This may be due to the fact that the fabric is a poor sound absorber. However the profiles of the experimental and analytical data show that there is a gradual increase of the NAC with the progression of the spectrum from low to high.

To obtain a more accurate result the same experiment was repeated with increased fabric thickness. The predicted and experimental data are shown in figure 6.

For this purpose four laminated layers of A1 and A3 fabrics were considered. These fabric samples were designated as A1 (4) and A3 (4) respectively. The total thickness of the A1 (4) and A3 (4) fabric samples was 25 mm (figure 7). The pores between successive layers were aligned as best as possible. The pore radius, porosity of a single layer of A1 fabric and A3 fabric and the total thickness of the layered fabric were considered for the mathematical analysis.

The NAC improved overall with increased thickness compared to the previous experiment with 0.6 mm thickness samples. The NAC increases for reduced pore size and porosity. As the sound absorption of the structure is improved there is a reasonable agreement between the predicted and the measured data and the NAC increases from 1000 Hz. There is very little sound absorption less than 1000 Hz. The resonance

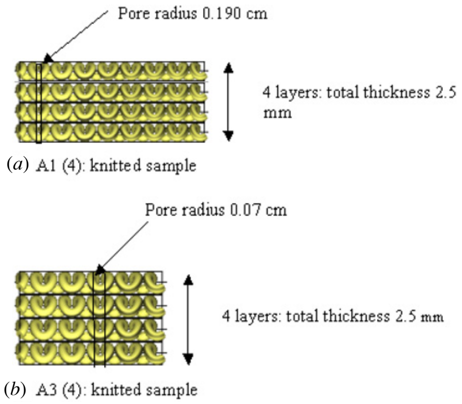

Figure 7. Simulated cross sectional representation of the knitted fabric samples used for the test.

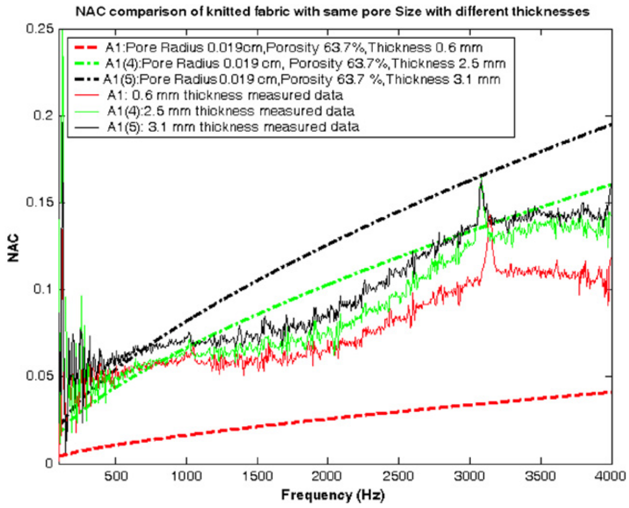

Figure 8. NAC data for different thicknesses of plain structure A1.

at 3000 Hz is also reduced in this case. This may be because the thick fabric changes the resonant cavity properties with reduced sound absorption.

6.2. Effect of thickness

The NAC variation can be predicted in a similar manner as in the previous case for different thicknesses but for the same pore radius and porosity. For this purpose the fabric sample A1 was chosen as it has the best noise absorption performance as seen in the preceding sections.

The predicted data for three different thicknesses are given in figure 8. The pore radius and the porosity of a single layer were used for the analytical prediction. The fabric A1 (4) is composed of four layers and A1 (5) is composed of five layers of A1 fabric, respectively (figure 9). The pores of successive layers were assumed to be in line in the mathematical prediction.

For the experimental validation the thicknesses were obtained by placing several layers of the fabric together (figure 9). Here utmost attention was paid to maintain the alignment of the individual stitches of the layers. The experimental validation is shown in figure 8.

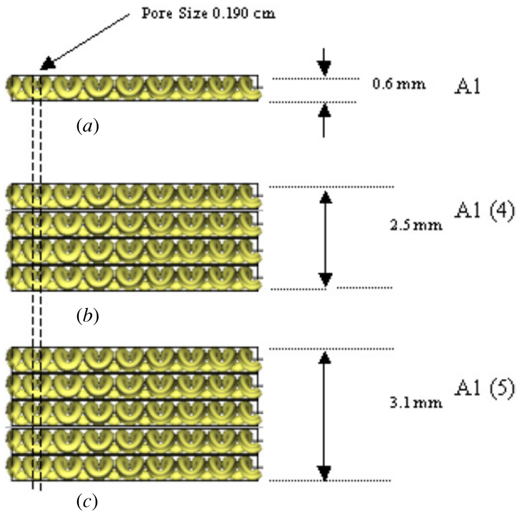

Figure 9. Simulated cross-sectional representation of the knitted samples of A1 fabric used for the test: (*a*) single layer of 0.6 mm thickness; (*b*) four layers with a total of 2.5 mm thickness; (*c*) five layers with a total of 3.1 mm thickness.

It can be seen from the mathematical prediction and the experimental results that as the thickness of the structure is increased, there is an increase in NAC. Moreover, the experimental results show that the NAC gradually increases with frequency from 1000 Hz. As in the preceding section, when the thickness of the fabric is increased the sound absorption of the fabric is improved and there is reasonable agreement between the experimental and the predicted data. Furthermore, the resonance at 3000 Hz of the experimental data is reduced as in the preceding section.

It was seen that there is only a slight effect on the lower frequency noise levels. Therefore apart from considering active noise control, it would be interesting to investigate the sound absorption properties of composite fabrics of knitted structures with foam or non-woven fibre webs to see its sound absorption effect in this region.

7. Conclusion

It was found that knitted structures with smaller pore sizes and a reduced porosity have good noise absorption and that knitted structures with smaller pore sizes and with increased thickness would be suitable materials to absorb sound in the passenger space within an automobile, i.e. a thicker and denser knitted fabric does have better sound absorbent properties.

The analytical model is in reasonable agreement with the experimental data. The NAC values of the experimental data correlate more with the predicted values when the fabric thickness is increased. The differences could be because

(1) the analytical model considers the pores in the fabric to be a uniform array of cylinders, but in practice they are not uniform and are not true cylinders;
(2) the accuracy of the measurements in the impedance tube at this low NAC level is poor.

However it is evident from the predicted data and the experimental data that the structure when placed against an impervious solid backing becomes an effective sound absorber only when the frequencies are above 1000 Hz. Thus this methodology would be suitable for reducing the higher frequency noise levels in the vehicle, such as from wind noise and road noise.

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