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# Theoretical assessment of sound absorption coefficient for anisotropic nonwovens

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**ABSTRACT**
The anisotropy factor as a function of fiber arrangement, fiber fineness and sample thickness has been derived from the theories of soundwave transformation due to phase changing. The sound absorption coefficient of the anisotropic fibrous material is then theoretically calculated. The fibrous materials were prepared so that the fibers are arranged parallel (perpendicularly laid fiber web called STRUTO technology) in the direction of soundwave propagation or perpendicularly (longitudinally laid fiber web) to the direction of sound propagation. The sound absorption coefficient was measured due to the Impedance tube. The theoretical results are in good agreement with experimental findings.

*Keywords:* Nonwovens, sound absorption, anisotropy factor

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## 1. INTRODUCTION

The sound absorption coefficient is derived in theories of soundwave propagation in the porous elastic system.[1−4] The sound attenuation is due to the viscosity of the air, nonreversible deformation of material and the thermal conduction between the fibers and the air. Most of the acoustic energy is consumed by drag between the vibrating air particles and the pore surface where the kinetic energy of vibrating particles is changed into the thermal energy. Kawasima[2] alleged that the viscosity effect is much larger than that of heat conduction, which can be neglected. The sound absorption depends on structure characteristics, i.e., fiber arrangement, fiber fineness, density of fiber, porosity, etc.

Starting from the theory of Zwikker and Kosten[4] on sound propagation through porous systems, the mechanism of soundwave propagation in fiber web was studied and theoretically described in Shoshani and Yakubov.[5−7] Using MATLAB software, it is possible to calculate the sound absorption coefficient as a function of frequency, web thickness, fiber volume fraction and coupling parameter, representing the drag between the fiber and air phases. Starting from the generalized theory of acoustic propagation in a porous medium, it was found that the size of fibers is the main factor integrated.[8] They have derived the necessary constants from an idealized model of stacked cylinders.

In Lambert and Tesar's theoretical and experimental study, the propagation characteristics were determined on bulk fibrous Kevlar samples. Using Kozeny number, they determined the static flow resistance and the static structure factor based on flow permeability measurements. They also predicted the thermodynamic effect due to sound propagation within the sample.[9]

In various studies,[1−3,10] the effect of fiber motion has been considered. The fiber segment, fixed between two joints, is represented as a vibrating string and the fiber segment in the place of joint, behaves as a vibrating bar. The kinetic energy of moving fiber parts is changed into the thermal energy.

## 2. THEORETICAL AND EXPERIMENTAL RESULTS

### 2.1. Anisotropy factor derivation

In this part, the anisotropy factor will be derived from the theories of soundwave transformation due to a phase changing between fiber and air. When the plane longitudinal soundwave strike on the interface of two isotropic mediums, reflection and refraction will take place. A reflected wave propagates back into the primary space. The refracted wave propagates into the next space at different angle from incident. The refracted wave causes the amplitude lost.[11] Ratio of an incident angle sine on the refraction angle sine equals to a ratio of sound velocities in both mediums (see Figure 1). With an increasing incident angle the sound intensity of refracted wave decreases.[12]

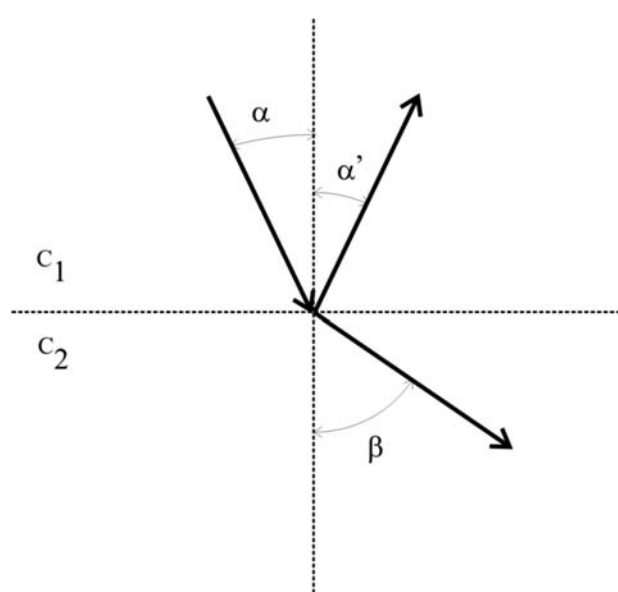


**Figure 1.** **The reflection and refraction of soundwaves on the interface of two isotropic mediums.**

The anisotropy factor will be derived from two basic fiber arrangements. The fiber was assumed to be continuous, have no curve. The fibers are arranged parallel in the direction of soundwave propagation or perpendicular to the direction of propagation (see Figure 2).

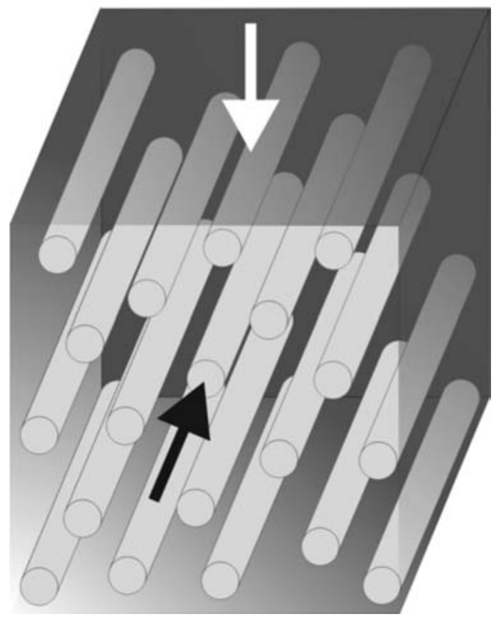

**Figure 2. Cubic element of fibrous system of side l. The soundwave propagates parallel in the direction of fiber arrangement (front view) or perpendicularly to the fiber arrangement (top view).**

Providing zero angle of incident wave, the interface area for parallel direction is given by total area of fiber cross-sectional (the front view of the cube with fibers on Figure 2).

$$S_{v//} = ns_v = \frac{n\pi d^2}{4}, \tag{1}$$

where ***n*** is a number of fibers in the system, $\boldsymbol{s_v}$ is a circular fiber cross-sectional area and ***d*** is fiber diameter. The interface area for perpendicular direction equals to the total area of fiber longitudinal sections (the top view of the cube with fibers on Figure 2).

$$S_{v\perp} = dL, \tag{2}$$

where ***L*** is a total fiber length in the system. The total area of system, where the soundwave strikes is

$$S = l^2, \tag{3}$$

where $l = L/n$. From the porosity ***h*** formula, or more precisely area packing density formula, it can be written

$$(1-h)_{//} = \frac{S_{v//}}{S} = \frac{n\pi d^2}{4l^2} \tag{4}$$

and

$$(1-h)_{\perp} = \frac{S_{v\perp}}{S} = \frac{dn}{l}. \tag{5}$$

The anisotropy factor is given by the ratio of terms 4 and 5

$$\vartheta = \frac{(1-h)_{\perp}}{(1-h)_{//}} = \frac{4l}{\pi d} \tag{6}$$

where $\boldsymbol{d}$ denotes an equivalent fiber diameter and $\boldsymbol{l}$ is a sample thickness as well as side of the cube element.

### 2.2. Flow resistance constant

Based on Poiseuille's law, the flow resistance constant may be written in the following form

$$\sigma = -\frac{S}{v}\frac{\partial p}{\partial x} \tag{7}$$

in which $v$ denotes velocity of volume displacement through a sample, $S$ is area of sample and $\partial p/\partial x$ is pressure gradient.

According to work,[4] the flow resistance constant can be calculated from the following equation

$$\sigma = \frac{32\eta}{hd_p^2}. \tag{8}$$

where $h$ is the porosity, $\eta$ denotes the viscosity of air and $d_p$ is average diameter of the pores.

For flow resistance constant formulation, the theoretical model of equivalent pore diameter assessment[13] was used

$$d_p = \frac{k}{1+q}\frac{h}{1-h}d \tag{9}$$

where $k$ is pore shape constant, $q$ is a fiber shape factor and $d$ is equivalent fiber diameter.

Then the flow resistance constant can be written

$$\sigma = \frac{32\eta(1-h)^2\left(1+q\right)^2}{h^3k^2d^2} \tag{10}$$

Providing that fibers have a circular cross-sectional area the fiber shape factor $q$ equals 0.

### 2.3. Sound absorption coefficient

The sound absorption calculation is based on equations that describe the sound propagation through porous material. The porous medium is a blend of two phases, solid material and air, where each responds differently to the soundwave. The two equations of motion for infinitesimal elements of fiber and air are,[4−7] respectively

$$-\frac{\partial p_f}{\partial x} = \rho_f\frac{\partial v_f}{\partial t} - \psi v_a + \psi v_f \tag{11}$$

and

$$-\frac{\partial p_a}{\partial x} = \rho_a\frac{\partial v_a}{\partial t} + \psi v_a - \psi v_f, \tag{12}$$

where all quantities relating to the fibers are written with an index f, those relating to the air with the index a, $v$ is the velocity, $p$ is the pressure, $\rho$ is the density as given by the mass of the component per unit volume porous material and the phase parameter $\psi$ is given by

$$\psi = \left(h^2\sigma + \vartheta\right) + j\omega\rho_a \tag{13}$$

where $\vartheta$ is given by equation 6 and $\sigma$ is determined by 10, $\omega = 2\pi f$ is the angular frequency.

The continuity equations for the fiber and air phase are[4−7]

$$-\frac{\partial p_f}{\partial t} = K_f\frac{\partial v_f}{\partial x} - \frac{1-h}{h}\frac{\partial p_a}{\partial t} \tag{14}$$

and

$$-\frac{\partial p_a}{\partial t} = hK_a\frac{\partial v_a}{\partial x} + (1-h)(K_a - P_0)\frac{\partial v_f}{\partial x} \tag{15}$$

where K is the bulk modulus and $P_o$ is the aerostatic pressure. The web impedance at the front face is given by

$$z_o = \frac{\Sigma p_f + \Sigma p_a}{\Sigma(1-h)v_f + \Sigma h v_a} \tag{16}$$

and sound absorption coefficient is calculated as follows

$$\alpha = 1 - \left|\frac{z_o - \rho_o c_o}{z_o + \rho_o c_o}\right|^2. \tag{17}$$

where $c_o$ and $\rho_o$ denote the velocity of soundwave in free air and the density of free air.

Two known materials are evaluated. Longitudinally laid fibrous material (with fibers parallel with fabric surface or soundwave propagation) obtains a perpendicular arrangement to the direction of sound propagation and perpendicular laid fibrous material (with fibers perpendicular to fabric surface, known technology called STRUTO)[14] obtains a parallel arrangement with the direction of soundwave propagation. The first material (L) was carded, longitudinally laid, through air thermobonded. The second material (P) was produced by carding, perpendicular layering (STRUTO technology), through air thermobonding. The concentrations of bicomponent fibers (polyester /co-polyester) were 20% and the length of the staple fibers was 80 mm. The bulk density of all samples is 26 kg m$^{-3}$ and the thickness is 35 mm. Fiber diameter of the first kind of sample is 18 μm, the second sample 25 μm and the third 40 μm.

A two-microphone impedance measurement tube was used to measure the sound absorption coefficient in the frequency ranges 50 Hz to 6,4 kHz (standard large tube setup for samples diameter 100 mm: 50 Hz to 1600 Hz, standard small tube setup for samples diameter 29 mm: 500 Hz to 6400 Hz). The curves from both measurements were merged. The values of sound absorption coefficient of common frequencies (500 − 1600 Hz) from one of tubes were multiplied by a number from 0 to 1, and the data from the second tube by the supplement of the number into 1, so that the sound absorption values of lower common frequencies (start from 500 Hz) were mainly from the large tube and the higher common frequencies (up to 1600 Hz) were mainly from the small tube.

Starting from the theory,[4] we calculated the absorption coefficient as a function of frequency using the excel software. In this section, the results between theoretical and experimental studies are compared. Both the measured and calculated sound absorption coefficients as a function of frequency can be seen in Figures 3–5. Calculated sound absorption coefficient depending on frequency and sample thickness is shown in Figure 6.

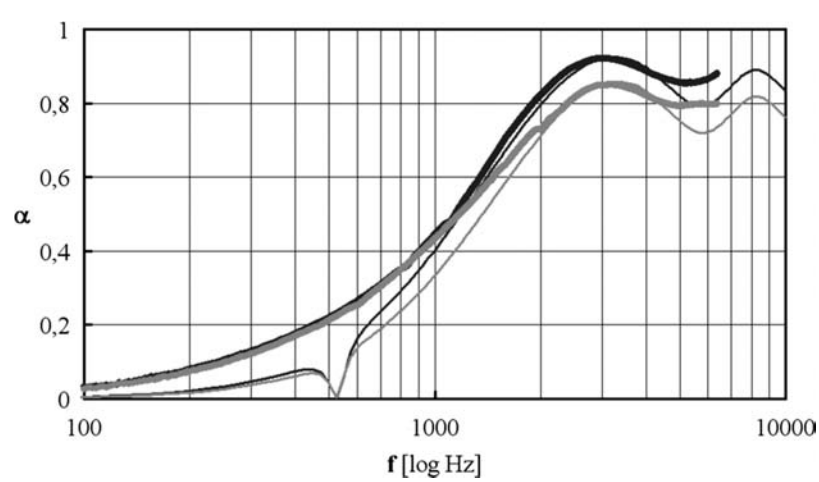


**Figure 3.** **Sound absorption coefficient as a function of frequency and fiber arrangement. A plot compares experimental (black thick curve – perpendicular arrangement to the direction of sound propagation, gray thick curve – parallel arrangement) and theoretical results (black thin curve – perpendicular arrangement to the direction of sound propagation, gray thin curve – parallel arrangement). The fiber diameter is 18 μm. The bulk density of all samples is 26 kg.m$^{-3}$ and the thickness is 35 mm.**

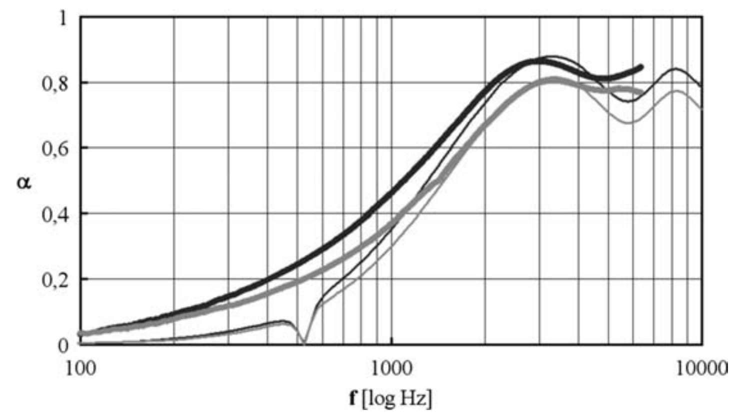


**Figure 4.** Sound absorption coefficient as a function of frequency and fiber arrangement. A plot compares experimental (black thick curve – perpendicular arrangement to the direction of sound propagation, gray thick curve – parallel arrangement) and theoretical results (black thin curve – perpendicular arrangement to the direction of sound propagation, gray thin curve – parallel arrangement). Fiber diameter is 25 $\mu$m. The bulk density of all samples is 26 kg m$^{-3}$ and the thickness is 35 mm.

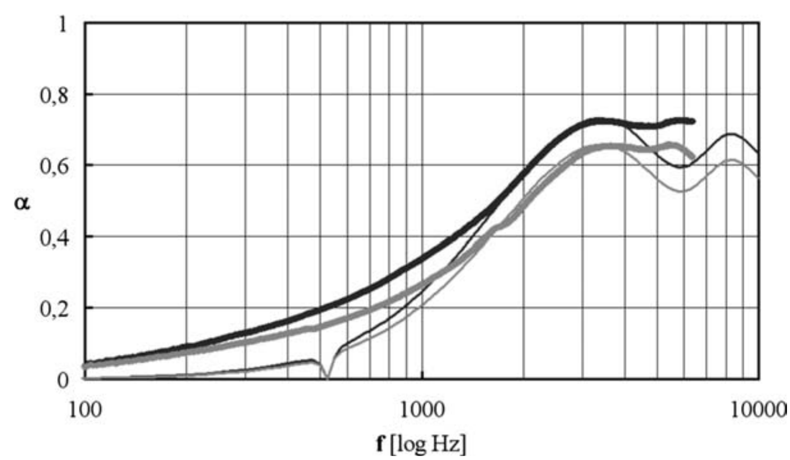


**Figure 5.** Sound absorption coefficient as a function of frequency and fiber arrangement. A plot compares experimental (black thick curve – perpendicular arrangement to the direction of sound propagation, gray thick curve – parallel arrangement) and theoretical results (black thin curve – perpendicular arrangement to the direction of sound propagation, gray thin curve – parallel arrangement). Fiber diameter is 40 $\mu$m. The bulk density of all samples is 26 kg m$^{-3}$ and the thickness is 35 mm.

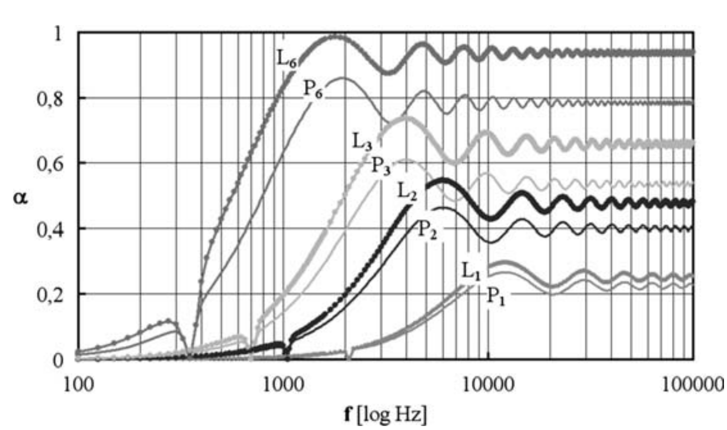


**Figure 6.** Theoretical plot of sound absorption coefficient as a function of frequency for different sample thickness (1, 2, 3 a 6 cm). The fibers are arranged perpendicular (L) or parallel (P) in the direction of sound propagation. The sample bulk density is taken 20 kg.m$^{-3}$ and the fiber diameter is taken 18 $\mu$m.

Based on previous works,[4−7] $P_o = 10{,}1325\ Pa$, $\rho_o = 1{,}2759\ kgm^{-3}$, $c_o = 343{,}32\ ms^{-1}$, $m = 1$ and $K_f = K_a$. We consider the circular cross-sectional area then the fiber shape factor $q$ equals $0$.

The values of $k$ are given in Table 1.

**Table 1. The values of "k" used for the sound absorption coefficient calculation. Whereas "k" is a pore shape constant calculated based on Neckář, B., Ibrahim, S. theory [13].**

| Figure | Sample density [kg.m$^{-3}$] | Fiber diameter [μm] | Sample thickness [mm] | k |
|---|---|---|---|---|
| 3 | 26 | 18 | 35 | 0,26 |
| 4 | 26 | 25 | 35 | 0,2 |
| 5 | 26 | 40 | 35 | 0,155 |
| 6 | 20 | 18 | 10, 20, 30 and 60 | 0,26 |

From the Figures 3–6, we can see that the sound absorption coefficient of the perpendicular arranged sample is higher than the parallel arranged sample. It is attributed to the acoustic energy lost due to a phase changing between fiber and air. The refracted wave propagates into the next space at different angle from incident and causes the amplitude lost.

The sound absorption coefficient of samples increases with the decreasing fiber diameter when the fabric parameters are kept constant. This is caused by the larger specific surface of thinner fibers, where the drag between the air and pore surface occurs on the bigger interactive surface and more acoustic energy is consumed.

The theoretical results are in very good agreement with experimental findings (see Figures 3–5).

The sound absorption coefficient of samples increases with the increasing sample thickness when the fabric parameters are kept constant. The difference between parallel and perpendicular fiber arrangement increases with the sample thickness. It is evident that the anisotropy factor (see Equation 6) increases with the sample thickness and decreases with the fiber diameter.

The absorption peaks are displaced in the direction of lower frequency when the sample thickness increases (see Figure 6).

## 3. CONCLUSIONS

The anisotropy factor as a function of fiber arrangement, fiber fineness and sample thickness has been derived from the theories of soundwave transformation due to a phase changing.

The sound absorption coefficient of porous anisotropic material was theoretically determined. The results are in very good agreement with experimental findings.

The structure characteristics of fibrous material have been studied in this paper. The first is the fiber arrangement, where the fibers are primarily aligned in one direction. It is parallel fiber alignment in the direction of soundwave propagation or perpendicular fiber alignment to the soundwave propagation. It was shown that the sound absorption coefficient of perpendicular arranged sample is higher than the parallel arranged sample. It is attributed to the acoustic energy lost due to a phase changing between fiber and air. The refracted wave propagates into the next space at different angle from incident and causes the lost amplitude. These findings are in agreement with the theory of Dahl et al.,[1] where sound absorption coefficient of the cylindrically shaped fibers arranged in a batting with the fibers primarily aligned parallel to the face of the batting (perpendicularly to the sound propagation) was higher than that of normal aligned fibers in a batting (parallel aligned fibers with the direction of soundwave propagation). The next structure characteristic studied was fineness of the fibers or more precisely the fiber diameter. It is evident that the specific surface of fibers increases with the decreasing fiber diameter when the fabric density was kept constant. In case of the smaller fiber diameter, it may be presumed that the drag between the air and pore surface occurs on the bigger interactive surface, so the sound absorption coefficient increases.

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