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Research Article

Nanofibrous Resonant Membrane for Acoustic Applications

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Because the absorption of lower-frequency sound is problematic with fibrous material made up of coarser fibers, highly efficient sound absorption materials must be developed. The focus of this paper is on the development of a new material with high acoustic absorption characteristics. For low-frequency absorption, structures based upon the resonance principle of nanofibrous layers are employed in which the resonance of some elements allows acoustic energy to be converted into thermal energy. A nanofibrous membrane was produced by an electrostatic spinning process from an aqueous solution of polyvinyl alcohol and the acoustic characteristics of the material measured. The resonant frequency prediction for the nanofibrous membrane is based on research into its production parameters. The distance between electrodes during the electrostatic spinning process determines the average diameter of the nanofibers, and the outlet velocity of the material determines its area density. The average diameter of nanofibers was measured using the Lucia software package directly from an electron microscope image. The resonant frequency of nanofibrous membranes was determined from the sound absorption coefficient and transmission loss measurement.

1. Introduction

This paper deals with the acoustic behavior of a nanofibrous resonant membrane. A nanofibrous layer was produced by an electrical spinning process from an aqueous solution of polyvinyl alcohol and the resonance effect created by the nanofibrous layer then studied. Acoustic waves cause vibration in the resonant nanofibrous system with acoustic energy at the resonance frequency partially converted to kinetic energy, the remainder being acoustic energy at other frequencies. These frequencies are damped so that the majority of the acoustic energy, accumulated in the resonator, may be converted into heat.

This theoretical study of sound absorption characteristics [1] focuses on a membrane-type sound absorber. To analyze the absorption mechanism, the solution is rearranged in a form which points out the contribution from each element in the membrane-type sound absorber. The effects of the parameters of the sound absorption system are discussed in the light of the calculated results. In addition, the method used for predicting peak frequency and the peak value of the oblique-incident absorption coefficient of the membrane-type sound absorber is presented. This method satisfactorily explains the relationship between the absorption characteristics and the parameters.

A sound-absorbing structure using thin film is described in a patent [2]. When a soundwave makes contact with the sound-absorbing structure of the invention, the thin films vibrate and contacts between the overlapping portions rub against each other. The energy contained in the soundwave dissipates as a result, and a high sound absorption coefficient over a broad frequency band is obtained. The sound absorption effect is intensified by the addition of the damping effect as the soundwave passes through the interstices.

Because the absorption of lower-frequency sound is problematic with fibrous material made up of coarser fibers, highly efficient sound absorption materials must be developed. The focus of this paper is therefore on the development of a new material with high acoustic absorption characteristics.

Previous work [3, 4] has shown this nanofibrous material to be a highly efficient sound absorber. For low-frequency absorption, structures based upon the resonance principle are employed in which the resonance of some elements allows acoustic energy to be converted into thermal energy. Earlier work [3] has demonstrated that the nanofibrous

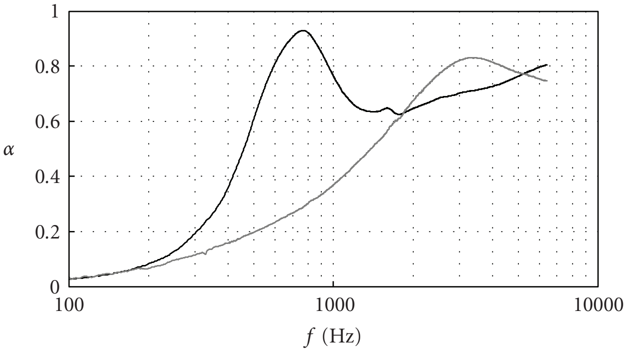


Figure 1: Frequency dependence of sound absorption coefficient α. Nanofibers creating a layer (black curve) and nanofibers distributed separately in the sample (grey curve). The final thickness of both materials is 30 mm, with a bulk density of 21 kg/m^{-3}.

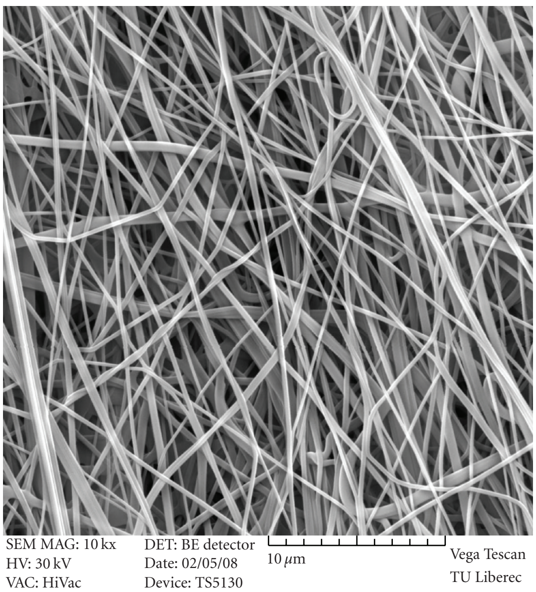


Figure 2: Snapshot of the nanofibrous structure.

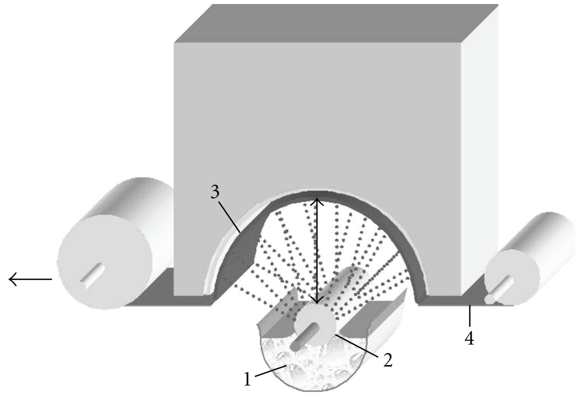


Figure 3: A device for the production of nanofibers from a polymer solution. The polymer solution (1) wets the cylindrical electrode (2). This electrode is matched with a counter electrode (3) whose potential differs. By rotating electrode (2), the polymer solution is drawn from the container into the counter electrode. The nanofibers form in the electrical field and are deposited on the support material (4). The electrode distance during electrostatic spinning and the outlet velocity of the material, which controls its area, may be altered.

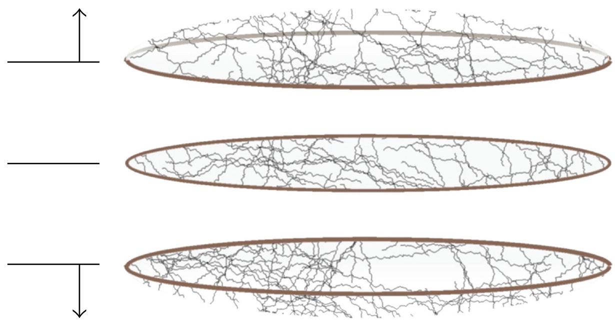


Figure 4: Nanofibrous membrane vibration at the first resonant frequency.

layer has a resonant effect on sound absorption when the nanofibers are arranged with respect to the layer. Then the tops of sound absorption coefficient are displaced to the lower frequencies than those of sample with nanofibers distributed separately (see Figure 1).

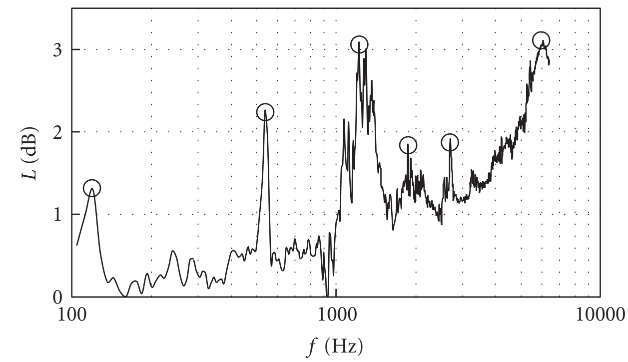
The sound absorption peaks of longitudinally laid samples occur at frequencies lower than those of samples laid perpendicularly [4].

This is attributable to motion in the nanofibrous layer. When the longitudinal soundwave propagates perpendicularly to the alignment of the membrane, the nanolayer is able to move and changes in acoustic energy may occur. The second effect is due to the viscosity of the surrounding air, where acoustic energy is consumed by the drag between vibrating air particles and the pore surface, converting the acoustic energy into thermal energy. These two nanofibrous layer phenomena together constitute the innovation of this acoustic product compared to current materials used for sound absorption such as foil and fibrous board.

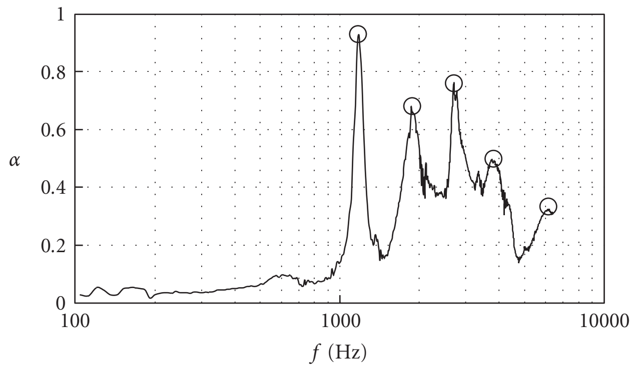
2. Experimental

The nanofibrous membrane was produced by an electrostatic spinning process from an aqueous solution of polyvinyl alcohol (see Figure 2), and two acoustic characteristics of the material, the sound absorption coefficient and the transmission loss, were measured. In this case, the nanofibrous membrane was created without any support materials from an aqueous solution, but a nonsoluble solution may also be used to produce a nanofibrous membrane possessing the same parameters and physical characteristics.

Two production parameters, the electrode distance during the electrostatic spinning process and the outlet velocity

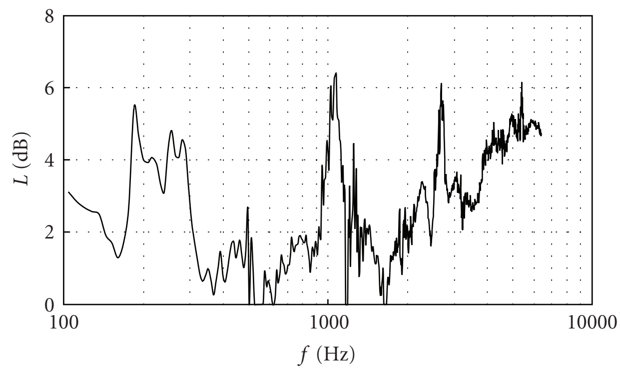


(a)



(b)

FIGURE 5: Frequency dependence of transmission loss L (dB) with denoted resonant peaks (a) and frequency dependence of sound absorption coefficient α with denoted resonant peaks (b).



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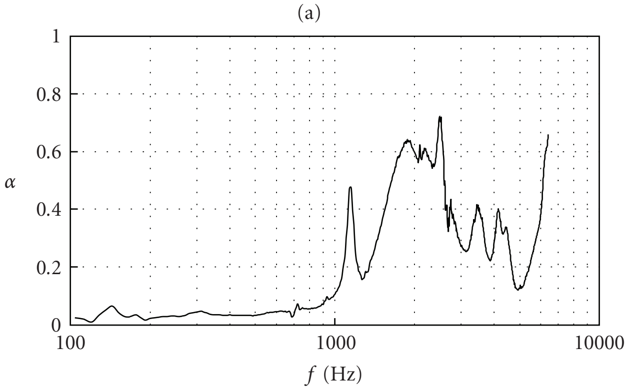
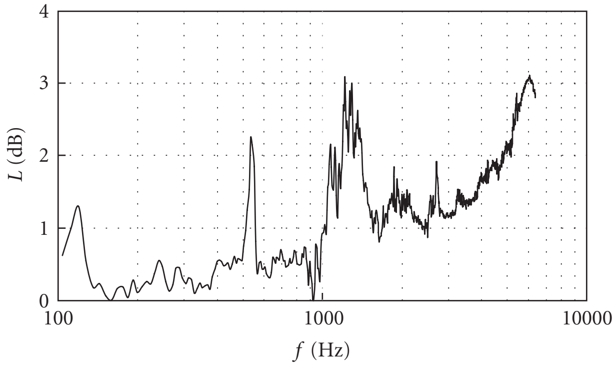


(b)

FIGURE 6: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The area density of the nanofibrous layer is 28.8 $g \cdot m^{-2}$.



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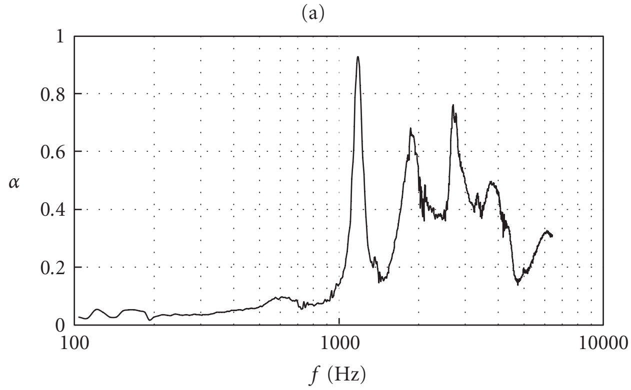
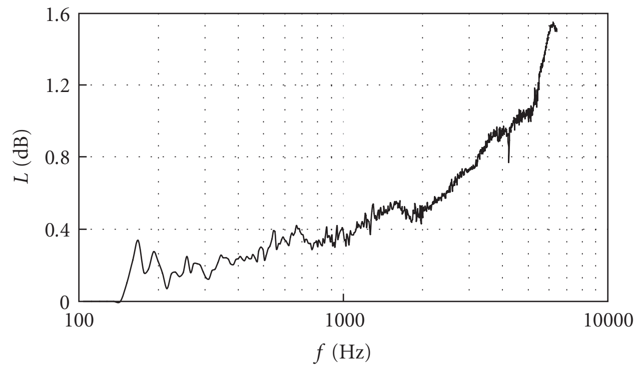


(b)

FIGURE 7: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The area density of the nanofibrous layer is 17.2 $g \cdot m^{-2}$.



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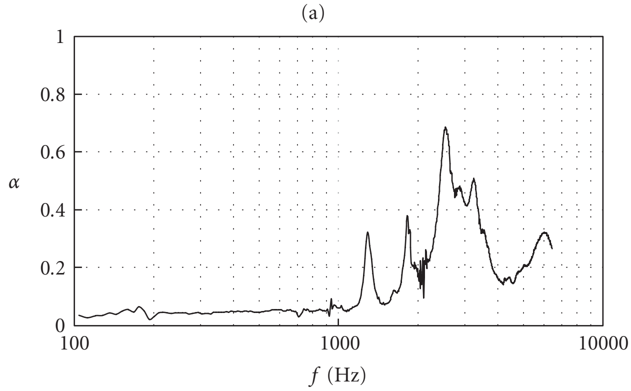

(b)

FIGURE 8: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The area density of the nanofibrous layer is 6.3 $g \cdot m^{-2}$.

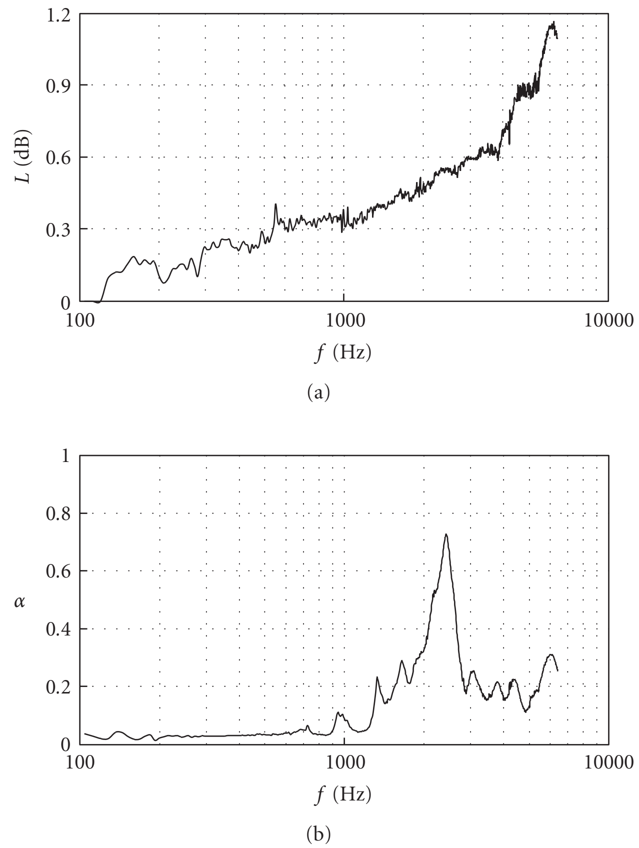

Figure 9: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The area density of the nanofibrous layer is 4.8 $g \cdot m^{-2}$.

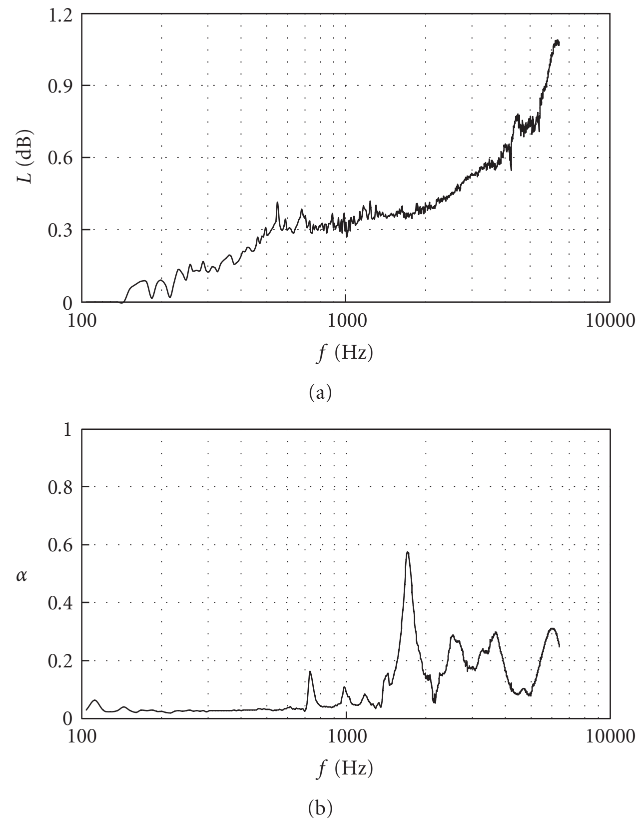

Figure 10: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The area density of the nanofibrous layer is 3.3 $g \cdot m^{-2}$.

of the material, which controls its area density, were altered (see Figure 3). Changes in the nanofibrous layer structure in terms of specific anisotropy and the diameter of the nanofibers are the result of the electrode distance setting.

A Type 4206 Impedance Measurement Tube featuring dual microphones was used to measure the sound absorption coefficient and transmission loss in the 50 Hz–6.4 kHz range.

In this experimental section, the resonant frequencies from the sound absorption coefficient and transmission loss measurement are compared. The maximum value of the sound absorption coefficient and transmission loss occurs along the resonant frequency of the thin membrane. Soundwaves vibrate the resonant nanofibrous system, with acoustic energy at the resonant frequency (see Figure 4) then partially converted to kinetic energy, the remainder being acoustic energy at other frequencies. These frequencies are damped so that the majority of the acoustic energy, accumulated in the resonator, may be converted to heat.

Resonant frequencies are labeled with circles in Figure 5.

The resonant frequency of nanofibrous membranes was determined from the sound absorption coefficient and transmission loss measurement. Two dependency relationships were studied to determine the resonant frequency.

Table 1: Production parameter during electrostatic spinning. Outlet velocity of material determining its area density.

Outlet velocity of nanofibrous material during electrostatic spinning ($m \cdot min^{-1}$)	Area density of the nanofibrous layer ($g \cdot m^{-2}$)
0.0171	28.8
0.0342	17.2
0.0855	6.3
0.1197	4.8
0.171	3.3

3. Results

In this section, the results measured for the frequency dependence of sound absorption coefficient α and transmission loss L (dB) are compared. The outlet velocity of the material determines its area density (see Table 1) and the distance between electrodes during the electrostatic spinning process determines the average diameter of the nanofibers (see Table 2).

3.1. Electrode Distance Constant (50 mm) *with Changing Area Density of the Nanofibrous Membrane.* From Figures 6, 7, 8, 9, and 10 (a), it is evident that the maximum value for transmission loss L (dB) decreases with decreasing

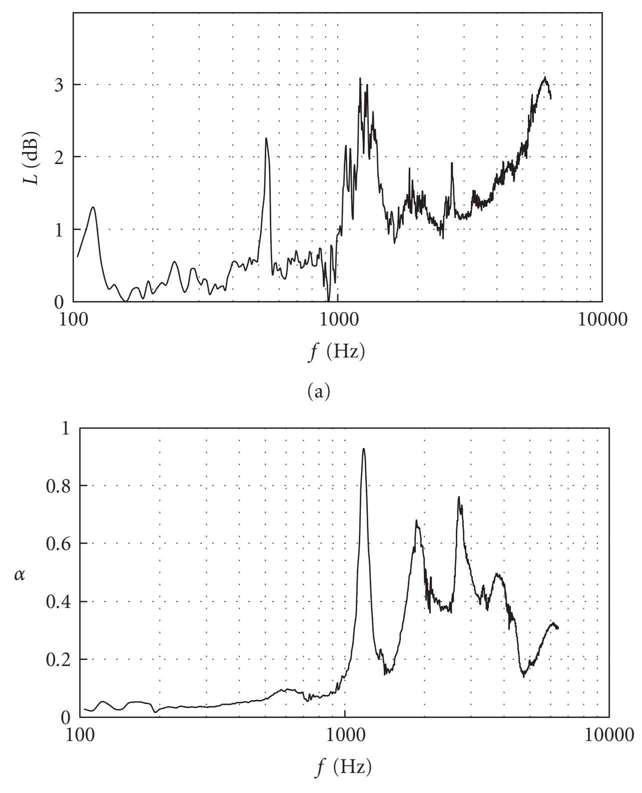

Figure 11: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The electrode distance is 50 mm.

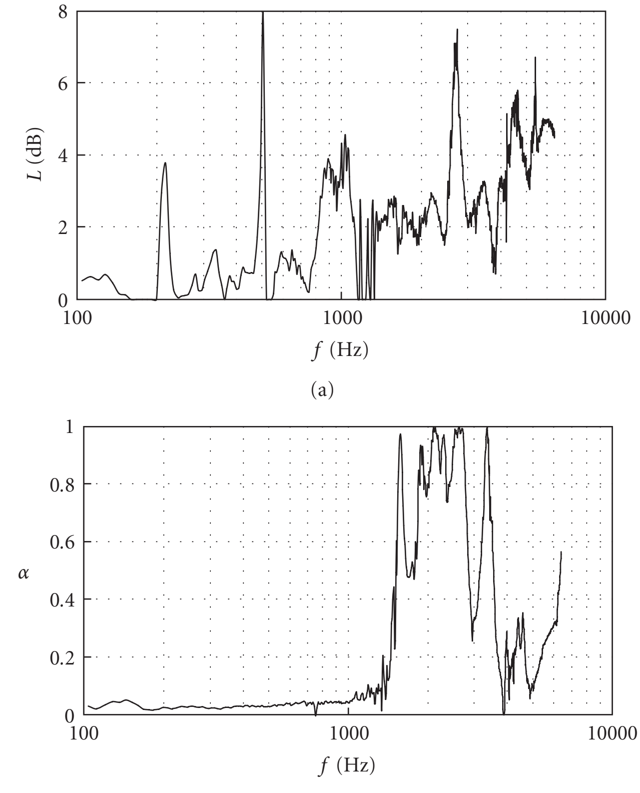

Figure 12: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The electrode distance is 90 mm.

Table 2: Production parameter during electrostatic spinning. Distance of electrodes during electrostatic spinning which determines the average diameter of nanofibers.

Distance of electrodes during electrostatic spinning (mm)	Average diameter of nanofibers (nm)
50	79.9
70	77.6
90	76.3
110	73.3
130	68.6

area density of the nanofibrous membrane. The resonant frequencies of the lower area density of the membrane (see Figures 8–10 (a)) are not uniquely determined.

Figures 6–10 (b) show that the first significant peak in the sound absorption coefficient α has been displaced in the direction of lower frequencies with increasing area density of the material, when the average nanofiber diameter (the electrode distance during electrostatic spinning) is held constant. The resonant frequency of the nanofibrous membrane thus decreases with the area density of the nanofibrous membrane.

Comparing results from the examination of both acoustic characteristics (see Figures 6–10, with transmission loss L (dB) (a) and the sound absorption coefficient α (b)) shows that the resonant frequencies are not in agreement. The peaks occurring under each measurement are formed at different frequencies.

3.2. Area Density of the Nanofibrous Membrane is Constant ($17.2\,\mathrm{g{\cdot}m^{-2}}$) *with Changing Electrode Distance.* Figures 11, 12, 13, and 14 (b) show that the first significant peak in the sound absorption coefficient α has been displaced in the direction of higher frequencies with decreasing average nanofiber diameter (increasing electrode distance during electrostatic spinning) when the area density of the material is held constant. The resonant frequency of the nanofibrous membrane thus increases with decreasing average nanofiber diameter.

Comparing results from the examination of both acoustic characteristics (see Figures 11–14, with transmission loss L (dB) (a) and the sound absorption coefficient α (b)) shows that the resonant frequencies are not in agreement. The peaks occurring under each measurement are formed at different frequencies.

The measurement of transmission loss shows two peaks, one at 530 Hz and one at 2700 Hz, for all measurements using constant area density (see Figures 11–14 (a)). 530 Hz and 2700 Hz would thus be resonant frequencies of the measuring apparatus during transmission loss measurement.

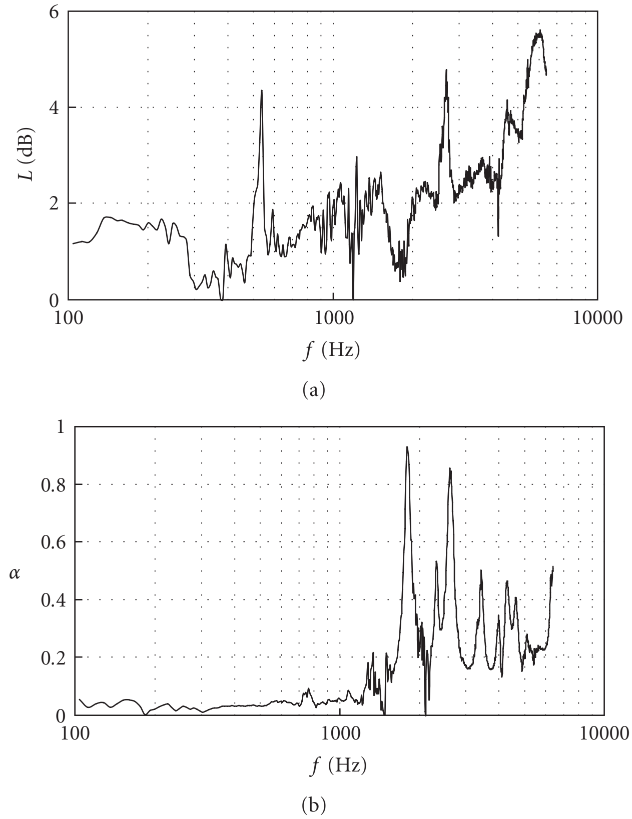

Figure 13: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The electrode distance is 110 mm.

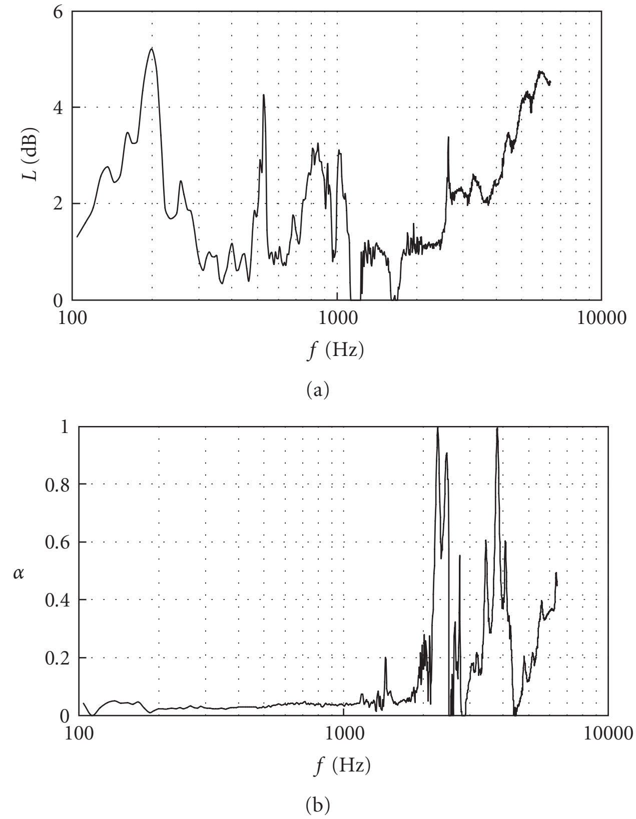

Figure 14: Measured frequency dependence of transmission loss L (dB) (a) and sound absorption coefficient α (b). The electrode distance is 130 mm.

One peak is constant for all measurements using both dependencies and both acoustic characteristics measured (see Figures 6, 7, and 11–14). The resonant frequency of the measuring apparatus while measuring both acoustic characteristics is around 2700 Hz.

4. Conclusions

These two phenomena, the vibration of the nanolayer and air friction inside the nanopores, constitute the innovation of this acoustic product compared to current materials used for sound absorption such as foil and fibrous board.

Sound absorption coefficient measurements show that the resonant frequency of the nanofibrous membrane decreases with increasing area density of the membrane and increases with decreasing average diameter of the nanofibers.

Comparing results from the examination of both acoustic characteristics (transmission loss L (dB) and the sound absorption coefficient α) shows that the resonant frequencies are not in agreement. The peaks occurring under each measurement are formed at different frequencies.

The transmission loss measurement shows that 530 Hz and 2700 Hz would be the resonant frequencies of the measuring apparatus during transmission loss measurement.

One peak is constant for all measurements using both dependencies and both acoustic characteristics measured. The resonant frequency of the measuring apparatus while measuring both acoustic characteristics is around 2700 Hz.

Acknowledgement

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