HELMHOLTZ RESONATORS SYSTEMS TREATED WITH THE NANOFIBROUS MEMBRANE

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One of the current issues is a solution of an omnipresent background noise, which is really difficult to absorb in the area of low frequencies of sound waves. The basic principle of sound absorption deals with the fact that effectiveness of the sound absorbing material increases with its thickness. Absorbing sandwich-like solutions presented in this paper are based on a resonant principle of a nanofibrous membrane and they function successfully as slim broadband sound absorbing solutions. The resonant nanofibrous layer of insignificant thickness was prepared from a polymer solution of PA6 with the electrospinning method. Due to the possibility of resonating on its own resonant frequency the nanofibrous membrane is able to absorb critical lower sound frequencies. These unique properties come from the nature of nanofibrous layers – small fibrous diameter, respectively enormous surface area of the layer. This makes it possible to reach higher viscous loss inside the material. Optimal rigidity of the membrane then makes an acoustic system possible to vibrate easier. Thus were developed and optimized acoustic structures in the form of Helmholtz-based resonators – distributed cavity resonators, treated with the resonant nanofibrous membrane damped by the microfiber web. Material types and structural characteristics of the each acoustic component have been proposed. The earlier designed solutions were made and their sound absorption ability was estimated in the Two-microphone Impedance Tube. Hence the experimental study presented here was carried out on the basis of obtained sound absorption coefficients from the impedance tube. It turned out the acoustic systems with the nanofibrous layer increase value of sound absorption and move it to the range of lower frequencies. While the spatial demands of those absorption systems are decreased, sound absorption remains the same or higher.

Keywords: nanofibrous membrane, sound absorption, impedance tube, PA6, resonator

1. Introduction

To deal with the sound of higher frequencies, generally porous materials are used (e.g. polyurethane, polyethylene, melamine and metal foams or non-woven fabrics made from mineral or synthetic fibres). But, these materials are unsuitable for absorption of lower frequencies of sound due to their great material thickness.

Membrane resonators based on a resonant principle of a nanofibrous layer function effectively as slim lightweight absorbing solutions. Contrary to conventionally used microscale sound absorbers, sound absorbing membranes based on submicron fibres show a higher absorption abilities - due to the possibility of resonating on its own resonant frequency the nanofibrous membrane is able to absorb critical lower sound frequencies. The membrane is, upon impact of sound waves of lower frequencies, brought into forced vibrations, whereby the kinetic energy of the membrane is converted into thermal energy by friction of individual nanofibers, by the friction of the membrane with ambient air and possibly with other layers of material arranged in its proximity, and some energy can be also transmitted to the frame (if it is present). These unique properties come from the nature of nanofibrous layers, i.e. small fibrous diameter (respectively high specific surface area) and high porosity. This makes it possible to reach higher viscous loss inside the material and consequently to dissipate the acoustic energy. Nanofibrous elements and optimal rigidity of the membrane itself then allow an acoustic system to vibrate more efficiently [1, 2]. Resonant nanofibrous membranes of insignificant thickness are prepared from different polymers solutions in the form of electrospun nanofibers captured on a substrate layer via electrospinning method [3].

The theoretical basis of sound absorption characteristics the paper deals with are studies performed by Sakagami et al. The study [4] 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 of the membrane. The effects of the parameters of the sound absorption system are discussed in the light of the calculated results. Also, 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 and satisfactorily explains the relationship between the absorption characteristics and the parameters. The study [5] then shows analysis of the acoustic properties of a single-leaf permeable membrane in detail, considering effects of membrane parameters such as surface density and flow resistance. In the study [6] sound absorption characteristics of a wideband sound absorber consisting of a microperforated panel and a permeable membrane is proposed and also theoretically studied. Resonant behaviour of a microperforated panel for various perforation ratios in comparison with a panel/membrane-type absorber is presented in [7], considering back wall surface effect. In the research published by Onen et al. [8] the predictive model of sound absorption of microperforation configurations is compared with measurements inside the impedance tube. Absorption peaks are concentrated at sound frequencies around 500-1000 Hz, according to the perforation parameters. In the papers [2, 9] has been demonstrated that the nanofibrous layer has a resonant effect on sound absorption when the nanofibers are arranged with respect to the layer. The sound absorption coefficient of the material composed of nanofibrous web is significantly higher at lower frequencies than that basic material without nanofibers. Moreover, the sound absorption peaks of longitudinally laid samples occur at frequencies lower than those of samples laid perpendicularly.

The effectiveness of a fibre-based sound absorption material involves several parameters such as porosity, tortuosity, fibre diameter, surface density and thickness [10]. The optimal material types and structural characteristics of such membranes are in the deep interest of researchers and although some have been proposed, remains still as a subject of research. Kalinová has demonstrated that the resonance frequency of PVA nanofibrous acoustic membranes decreases with increasing surface density and average diameter of the nanofibers [2]. Comparing the sound absorption coefficient of electrospun silica fibres of different diameter to glass wool, Akasaka et al. found significant improvement in sound absorption of electrospun fibres over glass wool [11]. Rabbi et al. sandwiched PAN and PUR nanofibrous membrane between two nonwoven layers of PET and wool. All materials with electrospun membrane(s) were found to significantly increase its absorbance. Moreover, the effect of nanofibrous layers number and its surface density was investigated [12]. Asmatulu et al. tested the sound absorbance property of electrospun PVC mat of different thickness and with fibre diameters ranging from a few hundred nanometres to a few microns. When the fibre diameter goes beyond 500 nm, the sound absorbance shift towards the lower frequency with thicker mesh but absorption coefficients remains the same [1].

In accordance with the literature discussed above, the research is focusing on nanofibrous layer treatment of structures based on cavity resonators (Helmholtz resonators). These structures themselves absorb only sounds of certain frequency, while for other frequencies their absorption is negligible. Therefore, different combinations of perforated panel, a sound absorbing material and possibly air gap are most commonly used [13]. Beginning with the literature analysis and previous experiments, the paper is concerned with acoustic cassettes (panels) in the form of distributed cavity resonators to show the benefit of a nanofibrous layer integration. The general objective is then to combine the above-mentioned characteristics into one acoustic system based on nanofibrous layer which would be able to absorb sounds in a broad frequency range more efficiently. Here presented results, of such solutions, are in a form of graphs presenting their sound absorption ability as sound absorption coefficient dependence on sound frequency. The results were obtained from the Two-microphone Impedance Tube measurements.

2. Experimental part

2.1 Materials

The 14% (w/w) solution of PA6 in acetic/formic acid solvent has been used for nanofibrous membrane preparation. PA6 is a high performance polymer in terms of mechanical properties, durability (light) and dimensional stability, suitable for room acoustics application. PA6 nanofibers were then collected on a substrate layer of 50cm width in three area densities (0,2; 0,4; 1 g/m^2) during the electrospinning process. For the substrate, a nonwoven fabric with area density of 35 g/m^2 and 0,2mm thickness has been chosen.

From the one side veneered wooden pulp was the material of acoustic cassettes (perforated panels) in the form of distributed Helmholtz resonators. The core is made of MDF (Medium Density Fibreboard) fabricated without resin binder (formaldehyde), hence it is more ecological than other boards bonded chemically. MDF does not contain knots or rings, making it more uniform than natural woods during cutting and in service. The thickness of the cassettes was set to 16 mm, while the density was around 700 – 800 kg/m^3. Four types of cassettes with different perforations (Table 1) have been used: a cassette with circular holes only - AVS10, and other cassettes with circular holes covered by variously distant slits – AVS1,2,3 (Figure 1).

For lamination of the PA6 nanofibrous membrane with such panel resonators (from the unveneered side) a dispersive adhesive has been employed.

Table 1: Acoustic cassette parameters [mm]

Name	Thickness	Perforation	Hole radius/spacing	Slit width/depth/spacing
AVS10	16	Circular Holes	4/16x16	-
AVS1	16	Circular Holes + Slits	4/16x32	3/4/32
AVS2	16	Circular Holes + Slits	4/16x16	3/4/16
AVS3	16	Circular Holes + Slits	4/16x16*	3/4/8
**There is a second perforation right in the middle of the first one, also with the spacing 16x16.*				

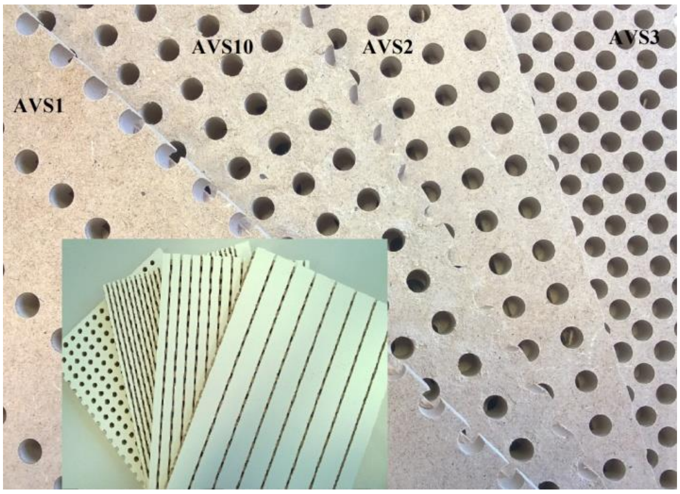

Figure 1: A picture of acoustic cassettes perforations.

2.2 Production of nanofibrous membrane

For production of PA6 nanofibrous membrane, a needless electrospinning method from a cord was employed (Nanospider™, NS 1WS500U). In this method [3], there is a solution carriage feeding liquid polymeric material around a moving stainless steel wire (cord). The wire electrode is connected to high voltage supplier and on the top, there is a grounded counter electrode. When the applied voltage exceeds a critical value, Taylor cones are then created on the wire surface, oriented towards the counter electrode. PA6 solution jets move toward the collector and as the solvent evaporates, the PA6 nanofibrous layer is collected on a moving substrate. (Figure 2).

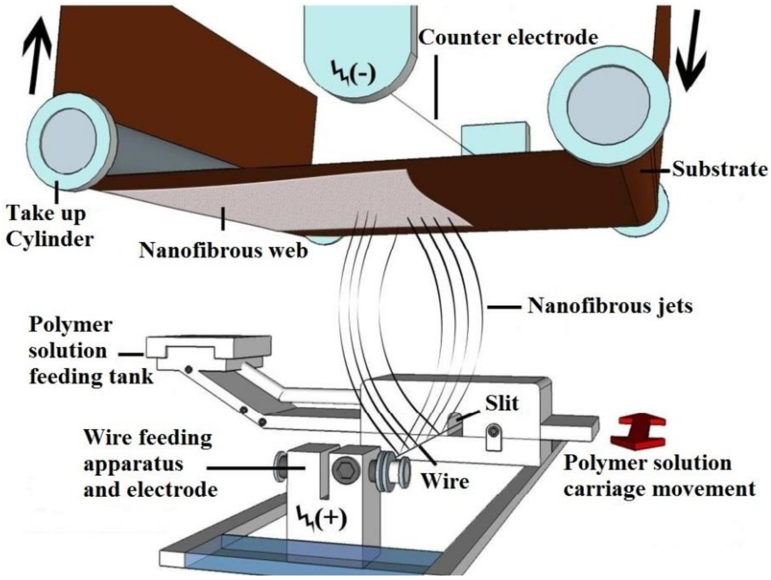

Figure 2: Schematic diagram of the cord electrospinning method (Nanospider™) used for PA6 nanofibres production [3].

Optimum process parameters such as speed of the carriage, distance between the electrodes, voltage etc. were applied during the process. Voltage of 60 kV, relative humidity of 43 %, and temperature of 22 °C were applied during the course of electrospinning. The average fibre diameter was 143 ± 27 nm and basis weights of nanofibrous membrane were 0,2 ± 0,02; 0,4 ± 0,02 and 1 ± 0,02 g/m^2, respectively.

2.3 Characterization

The fiber morphology and fiber diameter of the electrospun PA6 fibers (0,2 g/m^2) were determined using scanning electron microscopy (SEM). A small section of the fiber mat was placed on the SEM sample holder and sputter-coated with gold (Quorum Q150R Rotary-Pumped Sputter Coater). Carl Zeiss Ultra Plus Field Emission SEM using an accelerating voltage of 1.48 kV was employed to take the images (Figure 3).

The average fiber diameter was calculated from the SEM images using image analysis software (NIS Elements BR 3.2). More than 50 fibers were counted from a two SEM images which were taken from different places of a sample (Table 2).

Table 2: Average fibre diameter characteristics of the PA6 nanofibrous membrane

14% PA6 (140 nm)				
median [nm]	mean [nm]	st. deviation [nm]	min [nm]	max [nm]
139,7	142,9	27,3	90,6	196,8

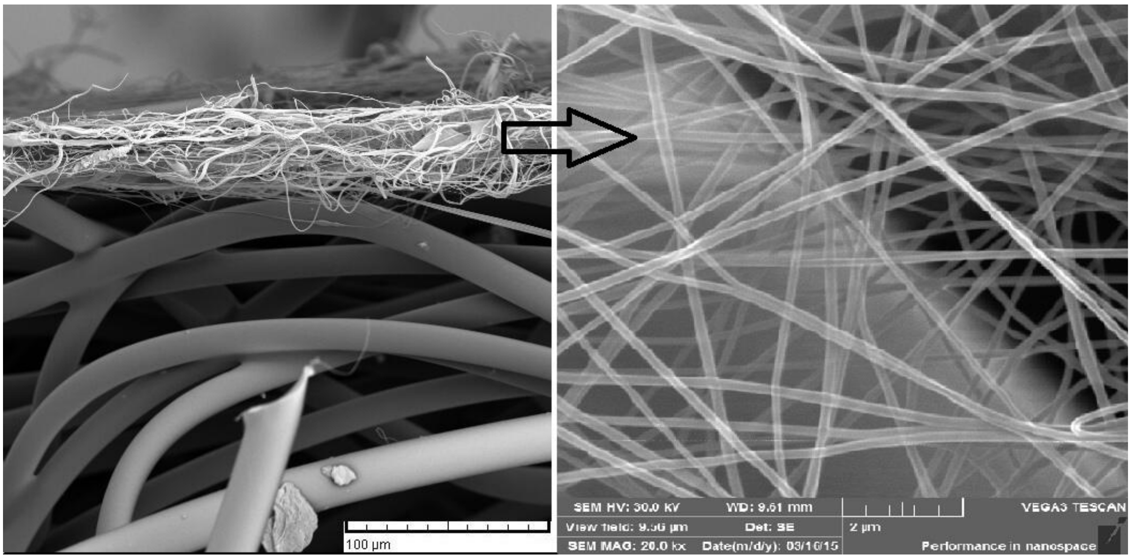

Figure 3: SEM images of a PA6 membrane cross-section (on the left) and morphology of the 14% PA6 nanofibers (on the right).

2.4 Method for determination of sound absorption ability

Sound absorption ability in the frequency range of 50 Hz to 1.6 kHz was estimated in the Two-microphone Impedance Measurement Tube (*Brüel & Kjær Type 4206*) in accordance with the *ČSN ISO 10534-2*. At first, the tube set-up was calibrated. The test samples of diameter of 10 cm each (turned earlier) were mounted and the measurements have been done. The analyzer (*Aubion X.8*) generates a random signal which is then amplified by a power amplifier (*B&K Type 2670, Crown D-75A*), frequency is weighted by the frequency weighting unit in the large tube, and then applied to the loudspeaker. The analyzer finally measures the response of the two microphones (*B&K Type 4187*) and calculates the H_1 frequency response function between these two microphone channels so the data can be obtained from it. The amount of sound energy which is absorbed is described as the ratio of sound energy absorbed to the sound energy incident, and is termed the sound absorption coefficient (α).

3. Results

For the sound absorption assessment all four acoustic cassettes have been studied. First set of measurements have been done with single cassettes test samples, while the next part has been realised with test samples treated with the nanofibrous layer of area density of 0,2 g/m^2. The damageable nanofibrous layer was secured between the supporting material and an acoustic cassette. All the samples have been measured inside the two-microphone impedance tube in the five different distances from the back wall for the resonant membrane vibrating ensure. The distances have been set up from 16 mm (no air gap), 20 mm (4 mm air gap), 30 mm, 40 mm to 50 mm (34 mm air gap). Each graph bellow then shows sound absorption coefficient curves for a non-treated acoustic cassette and for a treated one (put side by side in order to preserve the clarity).

Figure 4 shows the comparison of resonant frequencies for the acoustic cassette AVS10. As may be seen from the graph, the resonance peaks of the cassette alone are very low in the studied frequency range and follow a trend of decreasing value of the sound absorption coefficient when approaching lower frequencies. Whereas the employment of the PA6 nanofibrous membrane exhibits strong increase – high value of sound absorption coefficient ($\alpha > 0,8$), while the resonance peaks remain quite broad (hundreds of Hz), so the cassette treated with the nanofibrous membrane is able to absorb lower frequencies more effectively.

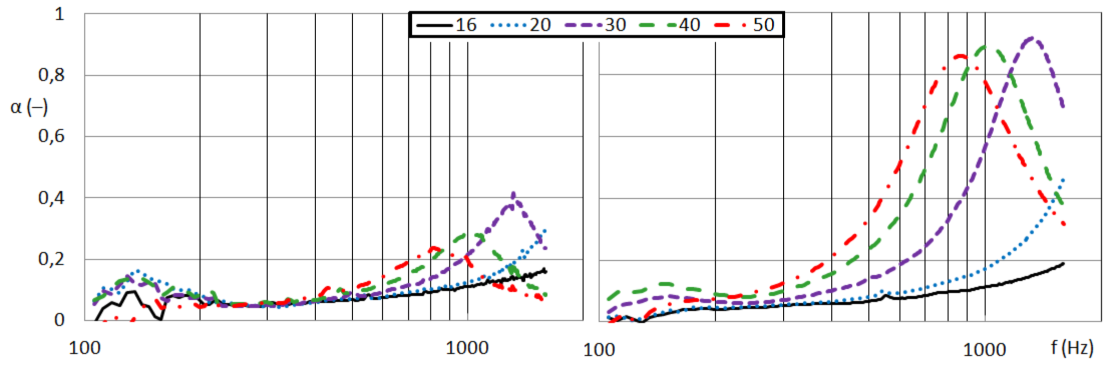

Figure 4: Comparison between dependence of sound absorption coefficient (α) on sound frequency for the acoustic cassette AVS10 with (on the right) and without (on the left) PA6 nanofibrous membrane. Distances from the wall used: 0 mm (16), 4 mm (20), 14 mm (30), 24 mm (40) and 34 mm (50).

Figure 5 shows the comparison of resonant frequencies for the acoustic cassette AVS2. From the graph can be seen how the resonance peaks of the cassette alone are also very low in the studied frequency range and follow a trend of decreasing value of the sound absorption coefficient when approaching lower frequencies similar to the cassette AVS10 (basically AVS2 without grooves). The employment of the PA6 nanofibrous membrane then exhibits strong increase – high value of sound absorption coefficient (α ± 0,9), while the resonance peaks remain quite broad (hundreds of Hz) as for AVS10. Moreover, the slits modification has shown a negligible acoustic effect.

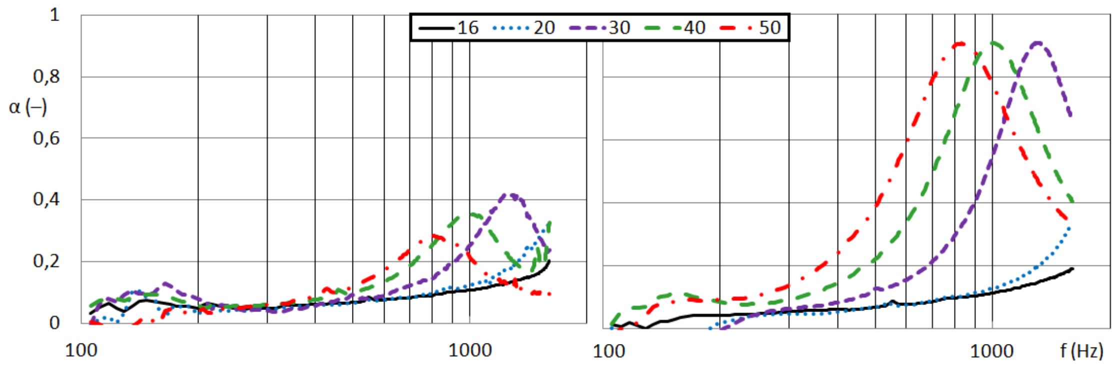

Figure 5: Comparison between dependence of sound absorption coefficient (α) on sound frequency for the acoustic cassette AVS2 with (on the right) and without (on the left) PA6 nanofibrous membrane. Distances from the wall used: 0 mm (16), 4 mm (20), 14 mm (30), 24 mm (40) and 34 mm (50).

Figure 6 indicates sound absorption ability of the acoustic cassette AVS3 – higher density of holes and slits shift resonance peaks to the area of higher frequencies. But the cassette with the nanofibrous membrane still causes sound absorption coefficient values to be higher (α ± 0,7).

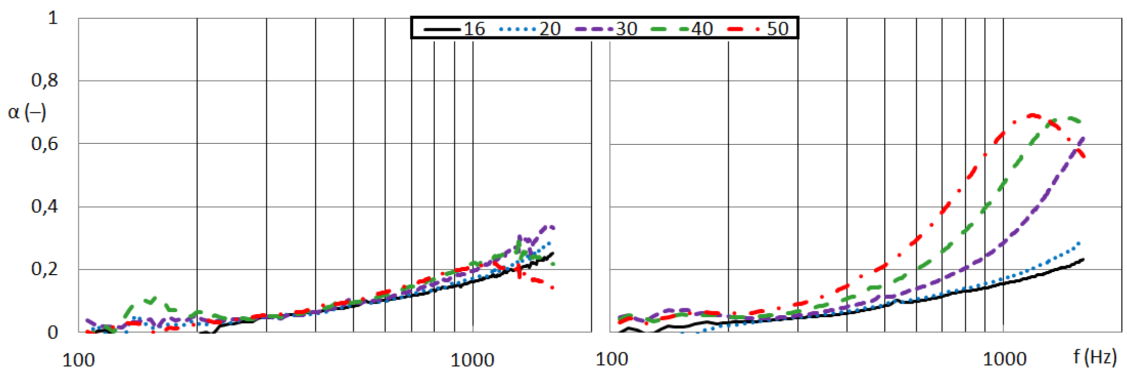

Figure 6: Comparison between dependence of sound absorption coefficient (α) on sound frequency for the acoustic cassette AVS3 with (on the right) and without (on the left) PA6 nanofibrous membrane. Distances from the wall used: 0 mm (16), 4 mm (20), 14 mm (30), 24 mm (40) and 34 mm (50).

From the Figure 7 it can be seen the comparison of resonant frequencies for the acoustic cassette AVS1. The resonance peaks of the cassette alone are significantly higher as compared with the other cassettes and follow a trend of decreasing value of the sound absorption coefficient when approaching lower frequencies.

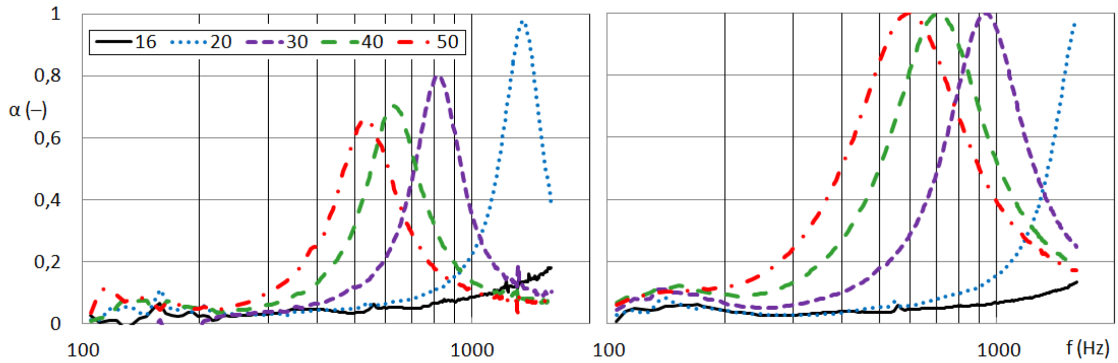

Figure 7: Comparison between dependence of sound absorption coefficient (α) on sound frequency for the acoustic cassette AVS1 with (on the right) and without (on the left) PA6 nanofibrous membrane. Distances from the wall used: 0 mm (16), 4 mm (20), 14 mm (30), 24 mm (40) and 34 mm (50).

The lowest density of perforation then particularly causes a serious rise in sound absorption. However, the employment of the PA6 nanofibrous membrane exhibits further increase – the highest value of sound absorption coefficients achieved (α = 1, i.e. maximum possible) for all distances, while the resonance peaks remain broad generally (hundreds of Hz). There is an obvious shift between sound absorption curves of regular AVS1 and treated one, where the curves of AVS1 cassette covered by the nanofibrous layer are slightly shifted towards the higher frequencies. Thus the resonant frequency of nanofibrous membrane affects the resonant behavior of final solution. But the cassette treated with the nanofibrous membrane is still able to absorb lower frequencies more efficiently.

4. Conclusion

It is evident the sound absorption depends on a motion degree of vibrating membrane during the sound impact as with a higher surface of the thinner fibers structure. The motion degree is directly influenced by the form of perforation, i.e. cavity resonators structure and their resonant behavior. It was found, better sound absorption ability is reached with a lower amount of perforation (in line with Morse and Ingard formulas), making membrane vibrations easier, resulting in more efficient energy dissipation. It is important to mention here, for the resonant behaviour of membrane its tension ratio is crucial. In this study, the tension ratio of nanofibrous membranes was kept constant (equal lamination conditions).

The study was dealing with acoustic cassettes in the form of distributed cavity resonators to show the benefits of a nanofibrous layer integration. The general finding was, that the acoustic system based on PA6 nanofibrous layer treatment of regular perforated panel exhibits enhanced sound absorption ability and works more efficiently in broader frequency range. However, in order to have an effective acoustic absorber it is always necessary to avoid poor acoustic performance at the frequencies near membrane antiresonance. Based on these results, there is an advantage to save both spatial demands and expenses and at the same time to absorb desired noise spectrum (at least equally) in case of such a solution with the PA6 nanofibrous membrane.

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