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Noise Control in Air Mechanical Ventilation Systems with Three-Dimensional Metamaterials

Amelia Trematerra [1,*], Antonella Bevilacqua [2] and Gino Iannace [1]

[1] Department of Architecture and Industrial Design, University of Campania "Vanvitelli", 81031 Aversa, Italy
[2] Department of Industrial Engineering, University of Parma, Area delle Scienze, 43100 Parma, Italy
* Correspondence: amelia.trematerra@unicampania.it

Abstract: The diffusion of mechanical ventilation systems increased rapidly due to the climate changes in all parts of the world. The mechanical ventilation systems are mainly used in the summer for many difficulties to face very hot temperatures. One of the biggest problems considered if every residential unit is equipped with a mechanical ventilation system is the generation of noise by the rotating blades of the fan for refrigeration. This paper discusses the applications of metamaterials to create attenuation filters to be installed inside the encases of the mechanical ventilation systems in order to obtain sound attenuation. A three-dimensional reticular structure made with spheres has been studied in different configurations related to the numbers of layers employed. The sound attenuations were measured at some specific octaves, depending on the particular configurations. In general, the sound attenuation peaks have been measured between 4 kHz and 8 kHz; this is expected to mitigate the tonal noise component typical of fans based on different variables that compose the whole system (e.g., fan diameter, number of blades, fan speed). However, the outcomes shall be considered in terms of laboratory conditions since material properties of the enclosure and potential polarization effects due to reflection of sound waves at the boundaries may occur.

Keywords: spheres; acoustic filters; noise attenuation; refrigeration; metamaterials; three-dimensoional lattice

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1. Introduction

The efficient development of the mechanical ventilation systems inside buildings has been carried out especially during the latest years given the unsustainable temperature increase in the climate change. The concerns about this matter are especially accentuated during the summer seasons due to the climate tropicalization that enhances the level of heating and humidity. The installation of air-cooling systems became necessary to have optimal thermo-hygrometric conditions inside residential units, although one of the matters during their operation is the noise of the mechanical elements, such as the fans. The rotating components necessary to activate fans for moving the air flow inside duct lines, and the refrigerating systems (e.g., compressors, cooling fans) are the cause of generating noise [1,2]. On this basis, acoustic filters and attenuators have been studied to be employed in order to limit unpleasant effects and annoyance. One of the methodologies conventionally used for noise attenuation is the filling of the external cases with absorbing material. This solution is not always suitable due to the space requirement, and it is considerably expensive. Furthermore, it is not favorable under a load losses perspective due to motion speed that is higher in practice than the theoretically calculated, with a consequent overall increase in noise levels. To be in line with the environmental requirements, the noise emission of the mechanical ventilation system shall be controlled since a third of the global population is subject to levels of nuisance above the limits established by the World Health Organization (WHO), which define the cause of hearing loss and health diseases, which are sometimes also permanent [3]. On this basis, noise control inside residential living environments is of primary importance.

Previous research studies have already investigated that the high level of annoyance is due to spectral tones caused by the rotation of fans inside conduits whose frequency is in function of the number of blades.

This paper deals with an experimental research study focused on the disposition of filters to be placed inside the cases of the mechanical units. The filters consist of spheres staggered between piled layers in order to obtain the attenuation of noise created by mechanical ventilation systems. The proposed filters are composed of a three-dimensional structural frame metamaterial where the singular elements are spheres.

2. Literature review on 3D metamaterials

The term metamaterial was first introduced the mid-20th century to refer to a periodic cellular structure not found in nature [4,5]. At the atomic level, scientists identified metamaterials with lattice-type structures/architectures [6]. In the field of electromagnetism and thermal radiation, the metamaterials have been studied to control the electromagnetic waves; as such, the particles of the metamaterials immersed in a homogeneous fluid have been been compared with the thermal radiation between spheres and the convection motions generated in the cavities between composites [7].

The first research studies have been carried out by V. Veselago and J. Pendry based on the investigations of possible materials with negative electric permeability. Unfortunately, the theories about this negative refractive index did not arouse the interest of researchers at that time.

Considering the multifunctionality of composite materials, metamaterials can be classified into three main sectors, depending on the types of waves they influence. The authors of this manuscript consider only the acoustic metamaterials and the change in sound pressure alteration within a fluid (i.e., air), although the distinction of the classes is often mixed due to the analogies of application in different fields [6].

When J. Pendry in 2000 proposed the theory on electromagnetic metamaterials, these have been applied to acoustics and noise control fields with the name of sonic crystals [8–14]. The structural configuration as shown in Figure 1 can be described as follows:

- Type one-dimensional refers to planes elements, characterized by one periodic direction;
- Type two-dimensional refers to bars elements, characterized by two periodic directions;
- Type three-dimensional refers to spherical elements, characterized by three periodic directions.



(**a**) (**b**) (**c**)

Figure 1. Different configurations of scatterers for metamaterials: one-dimensional (**a**), two-dimensional (**b**), and three-dimensional (**c**).

The baseline concept of the metamaterials is that the control of sound propagation is obtained by the interaction between regular geometric components and incident soundwave. The sound attenuation is obtained by the destructive interference created while the soundwave propagates through the period disposition of the structures. This phenomenon is known as Bragg's law, based on which the specific frequency attenuation is in function of the soundwave length and the dimensions of the periodic structure, including the space between each other.

This concept follows the regime of Bragg's law, such that the band gap frequency (f_{BG}) depends on the incident angle of the wave (φ), the lattice constant (α), and the sound speed in the medium (c), as summarized in Equation (1).

$$f_{BG} = \frac{c}{2\alpha \sin(\Phi)} \quad (1)$$

On this basis, when a plane wave affects a structure composed of elements arranged with a regular geometry, the distance between the wavefronts can be described as a $\sin(\varphi)$, where φ is the angle of incidence of the plane wave, a is the distance between two consecutive rows of scatterers, and λ is the wavelength of the incident wave. The destructive interference accurses at $\lambda/2 = a \sin(\varphi)$. At normal incidence, this implies that the stop band or the Bragg's pass band frequency is equal to $f_{BG} = c/2a$. Figure 2 shows the scattering of a plane sound wave when hitting an array composed of rows of scatterers.

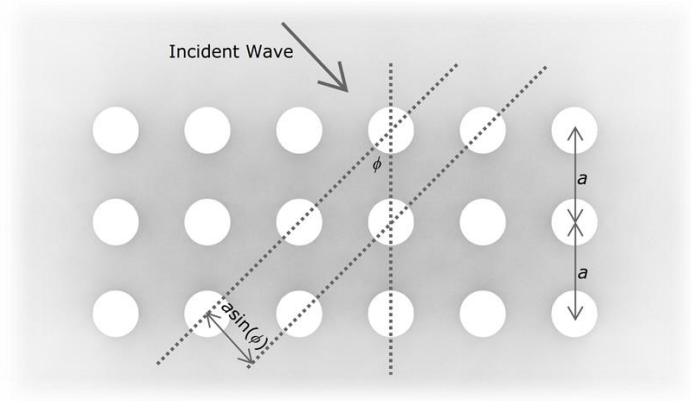

Figure 2. Scattering phenomenon of plane sound waves across an array of cylindrical scatterers.

Research studies state that the higher the distance between scatterers, the lower is the frequency band where the sound attenuation is more accentuated. Based on the disposition of the scatterers, it is possible to achieve the sound attenuation at any desired frequency range, which is an advantage compared to the standard sound absorbing panels.

The most representative example of metamaterial structure applied to the acoustics is the sculpture realized by Sempere. It is a two-dimensional structure placed in Madrid, composed of circular scatterers of 30 mm diameter, organized in a regular net frame having a constant distance of 100 mm between nodes. Some acoustic measurements showed that this configuration has a significant sound attenuation at 1700 Hz [15–19].

Other types of applications have been undertaken for the noise control of ships and submarines by employing Alberich coatings. This structure is composed of macro sequences periodically arranged, mostly applied to the cladding of underwater submarines to reduce echoes. This solution was introduced by Germans during the World War II by coating the submarines with resonant cavity lattices provided with sound absorbing properties [20–23].

Further developments can be achieved with the employment of three-dimensional printers, capable of realizing complex geometries to be used in the field of metamaterials. With the change in geometry and with the variation of the volumes of the objects, a sound attenuation can be obtained in the desired frequency range, a condition that often cannot be achieved with the traditional sound absorbing materials. The regular structures of the metamaterials can also be used to improve the sound absorption of membrane systems, in fact a membrane placed at a distance (d) from a rigid surface absorbs the frequency components equal to $\lambda/4$. Therefore, to absorb a frequency component equal to 100 Hz, a cavity with a thickness (d) of 0.8 m is required, while to absorb a frequency component equal to 1000 Hz, a cavity with a thickness (d) equal to 0.08 m is required.

The results related to sound absorption through the membrane have a bell-shaped trend with a maximum attenuation corresponding to the frequency considered. by adding appropriate masses to the membrane, it is possible to increase the membrane absorption

interval or shift the absorption peak towards desired frequencies. Furthermore, the sound absorption changes according to the weight of the masses applied [24–29].

The limitations of metamaterials applied in acoustics are the rigid geometries that make up the architecture, which can only provide an effective sound attenuator in certain frequency bands [7].

Future applications of metamaterials lie in three-dimensional and four-dimensional systems provided with variable geometries to manipulate electromagnetic fields with different wavelengths [7].

3. Materials and Methodologies

Since it was not possible to perform field measurements on real plants, the authors developed a measurement system in a laboratory. A sound source (RCF TWT 50) has been powered with a sine sweep signal generated by the Clio board simulating the fan noise of the mechanical system. The sound source was placed at one end of a tube having dimensions equal to 40 × 30 × 50 cm, standing on a layer of a sound absorbing material in order to lower unwanted reflections. On the opposite side of the tube, a condenser microphone was placed (Audiomatica 1/4-inch). An audio system (Clio hardware and software) was used to control the emission and the recording of the sound signal [30]. The Clio is a time-invariant system provided with only one channel.

Impulse responses (IRs) were analyzed in the frequency range of 1 kHz and 10 kHz for both configurations, with and without filter under test. The insertion loss (IL) and the sound attenuation were calculated as the difference between the levels measured without filter (L_{FF}) and with the filter in place (L_{filter}), as shown in Equation (2).

$$f_{BG} = \frac{c}{2\alpha \ \sin(\Phi)} \tag{2}$$

During the acquisition, the number of samples processed by each FFT was equal to 65,000, while the frequency sample rate was 48 kHz. The acoustic measurements were performed with the extremity of the tube open (free field). The tested spheres had a diameter of 24 mm, made of solid polystyrene. The choice of this lightweight material for the acoustic tests would be closer to the future realization of the spheres intended to be made with recycling materials, such as solid plastic or resins with wooden chipboard particles. The spheres were piled for the same filter and were staggered of half-sphere diameter with respect to the successive layers in order to interrupt the direct sight between source and receiver. Figure 3 shows the schematic configuration and the real filters realized for the acoustic measurements [31–34]. Note that the distance between the loudspeaker and the closest layer of spheres was constant and equal to 400 mm; the same distance has been kept constant between the microphone and the last layer of spheres.



(**a**) (**b**)

Figure 3. Configuration system used for the acoustic measurements: scheme out of scale (**a**), real filters (**b**).

The goal of testing different configurations of filters consists of collecting robust data output in order to compare the sound attenuation attributed to the spherical scatterers. A summary of the adopted configurations is described as follows:

- **Configuration 1**: the metamaterial filter is composed of one layer of spheres.
- **Configuration 2**: the metamaterial filter is composed of two layers of spheres with a gap distance in between equal to 10 mm.
- **Configuration 3**: the metamaterial filter is composed of two layers of spheres with a gap distance in between equal to 20 mm.
- **Configuration 4**: the metamaterial filter is composed of two layers of spheres with a gap distance in between equal to 30 mm.
- **Configuration 5**: the metamaterial filter is composed of two layers of spheres with a gap distance in between equal to 40 mm.
- **Configuration 6**: the metamaterial filter is composed of three layers of spheres with a gap distance equal to 10 mm between the first and the second layer, and with a gap distance equal to 20 mm between the second and the third layer.
- **Configuration 7**: the metamaterial filter is composed of three layers of spheres with a gap distance equal to 20 mm between the first and the second layer, and with a gap distance equal to 20 mm between the second and the third layer.

All the described configurations are summarized in Figure 4, where the blue cone stands for the loudspeaker, the green square represents the microphone, and the red spheres represents the acoustic filter. Table 1 summarizes the parameters that characterize each configuration.

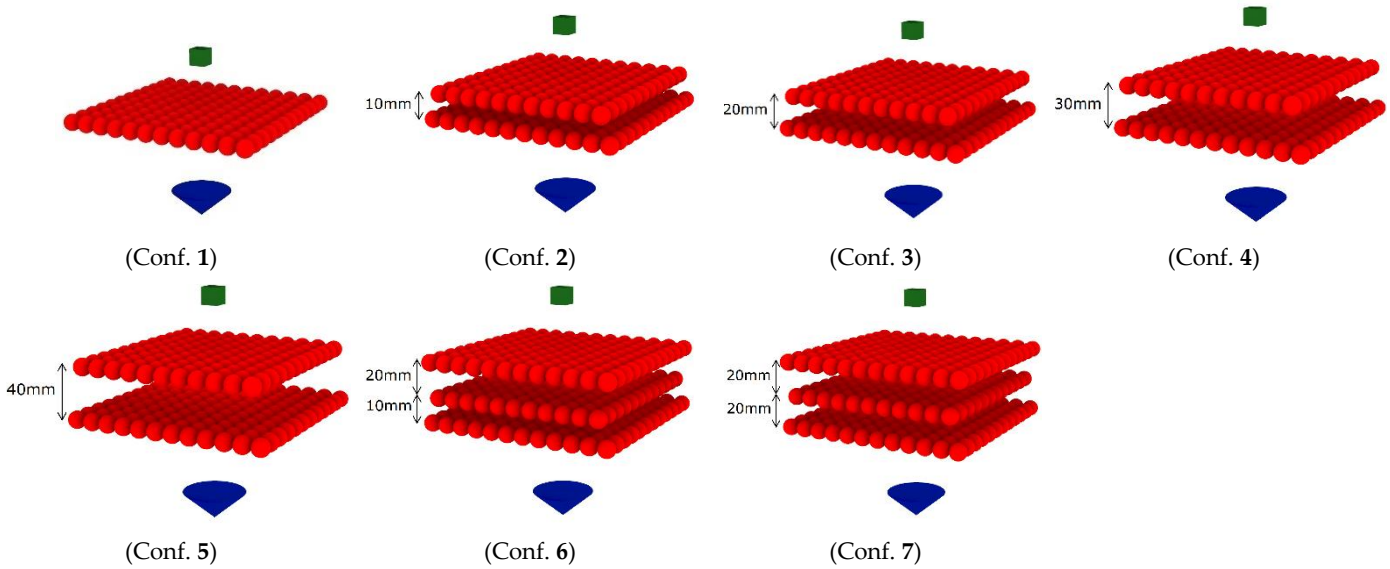

Figure 4. Out-of-scale schemes of all the configurations assumed for the three-dimensional metamaterial filter during the acoustic measurements.

As anticipated in the introduction, this study does not consider the interaction of sound between spheres, which is very important in the electromagnetic field, nor how sound can be vibrationally transmitted to adjacent spheres [35]. The measured models, which are studied from an acoustic perspective, also do not take into account the vectorial motions of the sound in the lattice cavities, which are instead studied from a thermal point of view. Other conditions for these experimental results include the negligibility of the scattered and polarized effect of the sound rays since the box where the sound source was placed has been filled with absorbing material, also to avoid standing waves inside the small volume [7].

Table 1. Parameters assumed for the configurations during the acoustic measurements, where D is the diameter of scatter, α is the lattice constant, Xs is the distance between the sound source and the closest edge of the filter, and Xr is the distance between the microphone and the closest edge of the filter.

Configuration Type	No. of Layers	Xs (mm)	Xr (mm)	Distance between 1st and 2nd layer (mm)	Distance between 2nd and 3rd layer (mm)
No. 1	1	400	400	-	-
No. 2	2			10	-
No. 3	2			20	-
No. 4	2			30	-
No. 5	2			40	-
No. 6	3			10	20
No. 7	3			20	20

The condition of a small-size mechanical unit is reproduced, consisting of a fan installed in the casing and a filter at the un-ducted end of the system. This may represent an optimistic and simplistic approach since it does not take into account the density and properties of the materials composing the housing and their interaction with the soundwaves. On this basis, the results should also be considered under the highlights of the laboratory conditions.

4. Results

The results related to the acoustic measurements with the filter assuming different configurations, as described in the previous section, have been analyzed in terms of insertion loss. In particular, Figure 5 summarizes the IL results related to the effect of one, two, and three layers of spheres composing the acoustic filter.

4.1. Analysis of acoustic filter consisting of one layer of spheres

Figure 5 shows that the maximum sound attenuation related to the configuration No. 1 of the filter is about 14 dB at 4 kHz. At the other third octaves the attenuation is less than 3 dB.

4.2. Analysis of acoustic filter consisting of two layers of spheres

When the acoustic filter is composed of two layers of spheres, the attenuation assumes a different behavior, based on the distance between the layers. In configuration No. 2, a greater attenuation corresponding to 12 dB occurs at 8.0 kHz.

If the distance between the layers increases by 10 mm, as indicated in configuration No. 3, the highest sound attenuation shifts to 4 kHz, followed by another peak at 6.3 kHz, corresponding to 12 dB and 10 dB, respectively. The graph for configuration No. 3 in Figure 5 highlights negative IL values; this phenomenon is due to the amplification of the sound at specific frequency bands caused by the reflection of some soundwaves that pass through the filter. In the case of configuration No. 3, the amplification occurs at 2.5 kHz.

If the distance between the layers of spheres increases, the graph related to configuration No. 4 indicates a more pronounced attenuation occurring at 4 kHz, which is 18 dB. This measured value is the maximum sound attenuation compared to the other selected configurations. At 8 kHz, a small peak of 8 dB is visible, but this can be considered negligible.

When the distance is even greater and is 40 mm, the graph related to configuration No. 5 shows a sound attenuation of 13 dB at 6.3 kHz. This line trend is similar to the measured values for configuration No. 1, but the peak is shifted to a higher frequency.

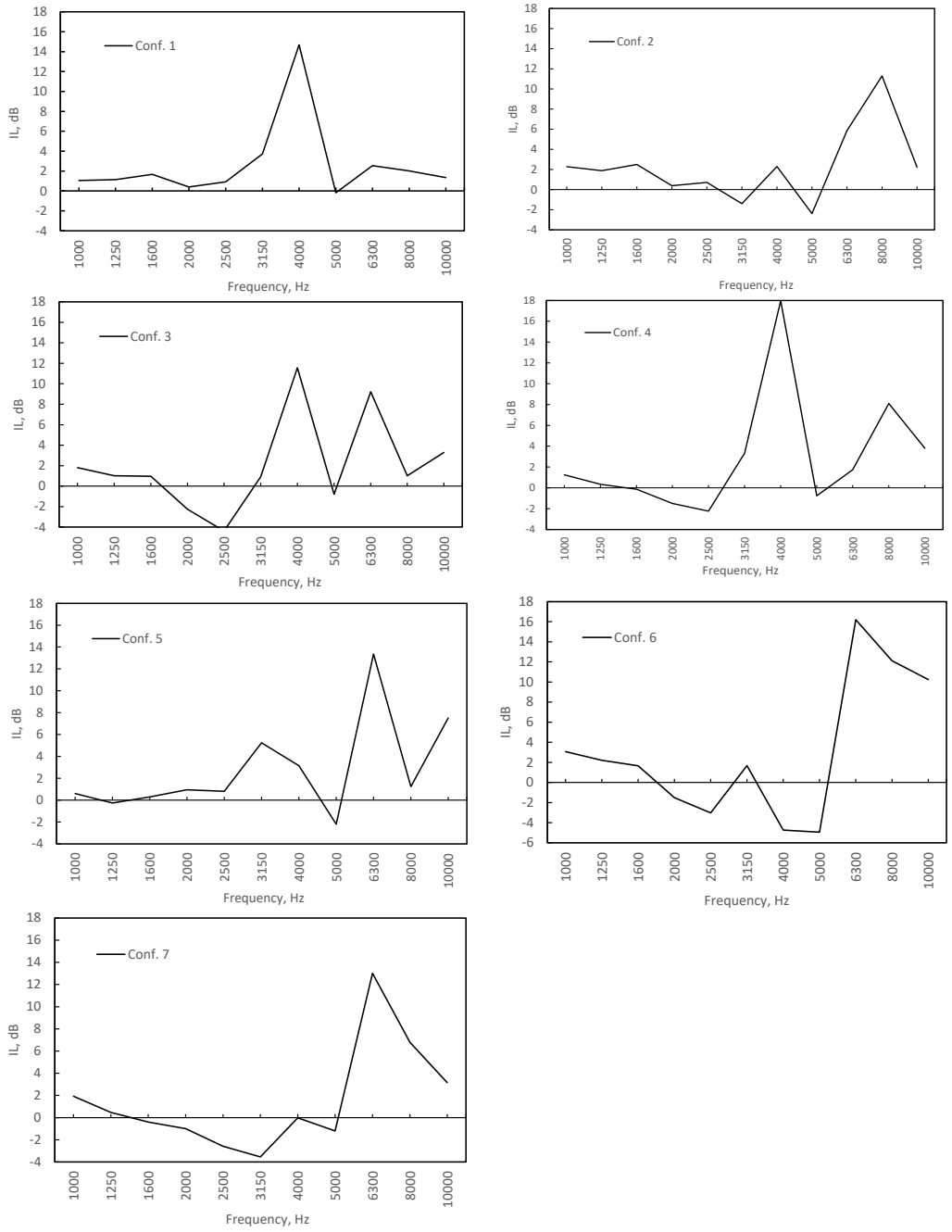

Figure 5. Insertion loss (IL) results related to all configurations of the three-dimensional metamaterial acoustic filter.

4.3. Analysis of acoustic filter consisting of three layers of spheres

A third set of acoustic measurements consists of testing three layers of spheres composing the filter. This more complex structure assumes two variable distances between the elements, which are equal in configuration No. 7 double between the second and third layer in configuration No. 6.

The measurements performed with configuration No. 6 show a significant around attenuation at 6.3 kHz, but the phenomenon of amplification around -5 dB occurs between 4 kHz and 5 kHz.

With configuration No. 7, the maximum sound attenuation occurs at 6.3 kHz and is about 13 dB.

5. Discussion

Mechanical ventilation systems are the cause of noise that many people find annoying. If noise control is conducted in the traditional way, the use of passive filters made of sound absorbing material leads to a certain loss of load. This phenomenon consequently increases the air speed of the fan to compensate for the pressure drop, and consequently the effective noise, which results in higher level than the estimated levels. The sound attenuation produced with three-dimensional metamaterial spheres arranged in layers with different space distances between each other indicates significant IL values at certain frequency bands. At constant diameter of the spheres, the most significant sound attenuation was measured between 4 kHz and 6.3 kHz [36–38].

If three layers of elements are in place, the frequency interval of sound attenuation can be increased. The research studies conducted with three-dimensional metamaterial spheres are considered to be more material-saving efficient, in line with the principles of environmental sustainability. In addition, the material for the spheres can be made of hard plastic or resins with a certain number of chipboards obtained from recycled building materials. When planning the life cycle of the material from which this type of acoustic filter is made, the use of recycled waste would be a 100% sustainability goal if at the end it can also be disposed of in the environment at the end.

The advantage of this proposed acoustic filter is its suitability to be used in small spaces, such as those offered by the enclosures of the mechanical ventilation systems next to the primary units, and the simplicity of its design together with the reduced pressure drop.

As mentioned, this study does not consider the behavior of sound between the interstices, which is a limitation of this research study, as well as the scattered and polarized effect of sound rays at the boundaries and within the small volume of the enclosure [7]. On this basis, the measured results should be considered optimistic, which may change when material properties are considered, as other factors and effects may occur.

Future research will focus on performing acoustic measurements on filters installed in real systems. This will provide the opportunity to compare the IL values of different fan types, characterized with unique spectrum and specific features, including fan diameter, number of blades, and overall speed. In addition, the real system would consider the effects of the material properties of the enclosure, so a different measurement method shall be in place, in which multiple microphones will be arranged at regular distance, along a grid disposition, homogeneously distributed over the surface of the three-dimensional architecture.

6. Conclusions

This paper deals with the acoustic measurements of acoustic filters realized with three-dimensional metamaterial structures. The filters are made with spheres of a diameter equal to 24 mm. The results are reported in terms of insertion loss obtained as the difference between the level measured without and with the filter installed. The goal of this research study is the realization of this acoustic filter with metamaterials to be applied for the sound attenuation produced by the mechanical ventilation systems. These conditions dictate an optimistic approach to the measured results since material properties of the enclosure can potentially create polarized effects inside the limited volume of the housing [39].

The results of the acoustic measurements show that the sound attenuation occurs in specific frequency bands, corresponding to the tonal components of the noise produced by a fan typical of a mechanical ventilation system. The advantage of this proposed acoustic filter consists of its suitability to be used in small spaces, such as those offered by the enclosures of the mechanical systems, in contrast to being 100% sustainable if recycled waste is employed for its creation, such as hard plastic and chipboards. The consequent advantage is the reduced cost of the final product for the manufacturers.

Extending the application of the three-dimensional lattice to environmental acoustics, attenuation of road traffic noise can be widely incorporated by developing an innovative aesthetic design representing a breathing structure instead of the traditional opaque and

continuous barrier. In addition, the automotive industry could also benefit from this type of study, as engine noise is one of those issues that car manufacturers tend to keep quiet about. As such, filters inside vehicles' exhaust pipes can help reduce noise.

Applications of this topic in other scientific fields relate to biomedicine with the control of frequencies within specific cells of the human body so as not to affect adjacent areas.

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