SOUND ATTENUATION OF AN ACOUSTIC BARRIER MADE WITH METAMATERIALS

Gino Iannace *[1], Umberto Berardi †[2]; Giuseppe Ciaburro ‡[1] and Amelia Trematerra ♦[1]
[1] Università degli Studi della Campania « Luigi Vanvitelli », Borgo San Lorenzo Aversa (Ce), Italy
[2] Department of Architectural Science, Ryerson University, Toronto, Ontario, Canada.

Résumé

Bien que les premières études en ont été réalisées il y a un demi-siècle par Viselago, les métamatériaux représentent une nouvelle approche dans les domaines de l'acoustique appliquée et du contrôle du bruit. Dans cet article, après une brève introduction à l'état de l'art des métamatériaux pour des applications acoustiques, l'atténuation du son par une barrière acoustique créée à partir des lois des métamatériaux est examinée. Une maquette à l'échelle 1/10 a été construit à l'aide de barres cylindriques de 30 cm de hauteur et de 1,5 cm de diamètre. La longueur de la barrière était de 100 cm. La barrière a été étudiée pour quatre combinaisons de rangées de barres différentes, d'espacement de barres différents afin de créer différentes géométries régulières. Les pertes par insertion de chaque configuration sont rapportées.

Mots clefs: métamatériaux, barrière acoustique, perte par insertion, maquette acoustique.

Abstract

Although the first studies of them date back to a half century ago to Viselago, metamaterials represent a new solution in applied acoustics and noise control fields. In this paper, after a brief introduction to the state of art of metamaterials for acoustic applications, the sound attenuation of an acoustic barrier made following metamaterial rules is investigated. A 1:10 scale model was built using cylindrical bars, 30 cm high and 1.5 cm in diameter. The length of the barrier was 100 cm. The barrier was investigated for four combinations of the rows of the bars, spacing bars to create different regular geometries. The insertion losses of each configuration are reported.

Keywords: metamaterials, acoustic barrier, insertion loss, scale model.

1 Introduction

The study of metamaterials represents a new research line in the fields of applied acoustics and noise control. Metamaterials are structures designed to control the propagation of wave-like phenomena thanks to well-defined geometries. The control of the sound propagation is obtained by the interaction between the the sound waves and the regular geometric shapes of metamaterials. Periodic structures, constituted by the repetition of geometric elements, realize sound attenuation effects, due to the destructive interference of the waves that propagate through these elements. The periodic distribution of materials creates destructive effects due to interferences which depend on the frequency and therefore on the wavelength of the incident sound [1,2].

The first studies in this field date back to over half a century ago with the works of V. Viselago and J. Pendry [3], and were directed to the control of the propagation of electromagnetic waves. Only more recently, these theories have been applied to the fields of applied acoustics and noise control.

Metamaterials are obtained by geometric structures of regular shape. The word *metamaterial* is made of two words: meta and material. The word *meta*, from *metamorfosi* means a change in conditions. Metamaterials are usually periodically structured, with a local resonant component. Sound waves interact with these components and, since the dimensions of the elements are smaller compared to the sound wavelength, the metamaterials assume specific physical properties, such as a negative elastic modulus, a negative mass density or a negative refractive index.

Today, additive manufactures can lead to new practical applications of metamaterials, as complex geometries can be realized easily [4,5]. With the possibility to model ad build complicated geometries, it is possible to obtain sound attenuation in any desired frequency range, a condition that often cannot be reached with traditional sound-absorbing porous materials. For example, Berardi recently proposed 3D-printed twisted rubes with circular sections in which the sound enters, generating a negative interference between the sound wave at the input and the output ones [4,5]. The use of 3D printers made possible to obtain aesthetically pleasant structures that were transparent, and tunable to low frequency sound absorption.

Other interesting applications of metamaterials are in the aerospace field. In fact, at low frequencies, traditional materials are unable to prevent sound transmission [6]. Sound attenuation obtained with metamaterials can be used as urban furnishing elements or for sound-absorbing barriers in the

---

* gino.iannace@unicampania.it
† uberardi@ryerson.ca
‡ giuseppe.ciaburro@unicampania.it
♦ amelia.trematerra@unicampania.it

trasporation fields, replacing the traditional noise control systems [7,8]. In Madrid, there is a sculpture created in the 1950s by Eusebio Sempere in the garden of «Juan March Foundation», which consists of hollow steel bars of 3 cm in diameter arranged at a 10 cm distance from each other (Fig.1). Based on acoustic measurements, it was shown that when the sound propagated through this structure, specific frequency bands attenuated significantly [9,10].

Figure 1 – Sculpture « Organo » by Eusebio Sempere in Madrid.

The rows of trees, of appropriate diameter and height of the trunk, arranged on a regular grid, can provide an attenuation similar to traditional noise barriers, especially at low frequencies [11,12]. Further applications of regular rod structures, often known as sonyc cristals, have been developed for silencing the impellers of air conditioning systems and the noises generated by rotating parts [13]. This growing field is explored in the next section together with the discussion of a new barrier system.

2 Metamaterial Noise Barriers

Several studies have investigated bars arranged to generate a sonyc cristal barrier. The cylinders that constitute the elements of these structures can be either empty or full, without any change in the sound attenuation, as this occurs for the interaction with a solid surface (Fig. 2). Previos works have demonstrated the same sound absorption could be obtaniend when the elements were made with solid cylinders, hollow cylinders with openings (and therefore with resonant cavities), and hollow cylinders with openings with soundproofing material [14].

Other configurations for bars arranged as metamaterials combined together these structures with traditional acoustic screens, in order to increase the sound attenuation [15]. For example, the use of bamboo elements arranged regularly to obtain adequate sound attenuation [16], and then the bamboo rods were drilled to obtain a series of multiple resonant Helmholtz resonators to increase the sound attenuation at low frequencies.

The aim of this work is to perform acoustic measurements over a real-sized sample barrier in order to figure out diffraction components and to verify the main challenges for the application of standardised measurements to sonic crystals. As the anticipated application could be for controlling traffic noise, whose spectrum is centred around 1,000 Hz, the barrier will be designed to have a high absorbent coefficient in the range from 800 Hz to 1250 Hz.

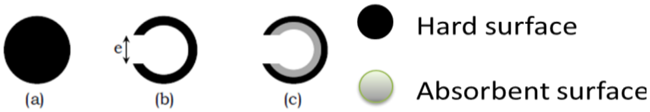

Figure 2 - Type of geometries considered in sonyc cristal studies, both ealing with hard surface and sound absorbent surfaces [17].

3 Design of Metamaterial Noise Barrier

In this section, a noise barrier built following a metamaterial approach is presented and investigated. The noise barrier model was built on a scale of 1:10 compared to the real dimensions. So, the frequency range from 500 Hz to 10 kHz was investigated instead of the equivalent range from 50 Hz to 1,000 Hz of the real full scale [18-21].

The barrier was built using cylindrical wooden bars, 30 cm high and 1.5 cm in diameter; the total length of the barrier was 100 cm. The overall geometry of the barrier was made with four rows of cylindrical rods, alternating with each other, spacing each row with an empty space equal to the size of the diameter of the sticks, creating a regular, empty-full geometry. The material chosen for construction was hardwood as it is an eco-friendly material, which can be disposed without damaging the environment. Based on the literature, it is evident that he acoustic characteristics of the sound attenuation effects of the barrier do not change with the type of material, as hey arrefected only by the different geometries of the elements.

The main purpose of this work was to analyze the challenges related to the acoustic measurements, the choice of the number of rows of cylindrical elements to be used, and the relative distance between them to obtain a suitable sound attenuation. The results were assessed based on the insertion loss, defined as the difference of the sound pressure levels measured without and with the barrier.

The sound source was an RCF TWT 50 dome tweeter. The sound source had a smooth free field response in the chosen frequency range, and it was located at a 4.5 cm height from the floor. The receiver was a condenser microphone GRAS Sound & Vibration A/S 40 AR, which was mounted on a little tripod at 5 cm height from the floor. The sound source was placed on one side of the barrier, while the microphone was placed on the opposite side; the floor was acoustically reflective.

All acoustic measurements were performed using an MLSSA system (MLS maximum length sequences), which allows the measurement of the impulse response of a time-invariant linear system by cross correlating the microphone output signal with the maximum length sequence signal feeding the loudspeaker [22]. The sound source was fed with an MLS acoustic signal in order to eliminate any unwanted reflections from the measurement environment from the signal detected by the microphone. The first step was the sound source characterization by measuring the field sound pressure impulse response along its principal radiation axis at a reference distance d=1.0 m, when sound source and microphone are on the floor, facing each other. Figure 3 shows the layout of the barrier with the position of the sound source and the receiver.

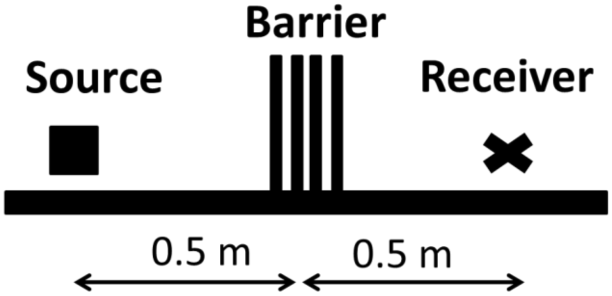

Figure 3 – Cross-sectional layout of the metamaterial barrier with the position of the sound source and receiver.

Figure 3 and 4 show the layout of the barrier with the position of the sound source and receiver, and the distance between the elements, and with the indication of the distance between the rows. Figure 4 shows the floor arrangement of the cylindrical elements that constitute the metamaterial barrier. The cylindrical elements were arranged with an empty and with a full geometry. The empty dimension was equal to the full one (1.5 cm). The elements of each row were mutually staggered, so that the line of sight was interrupted.

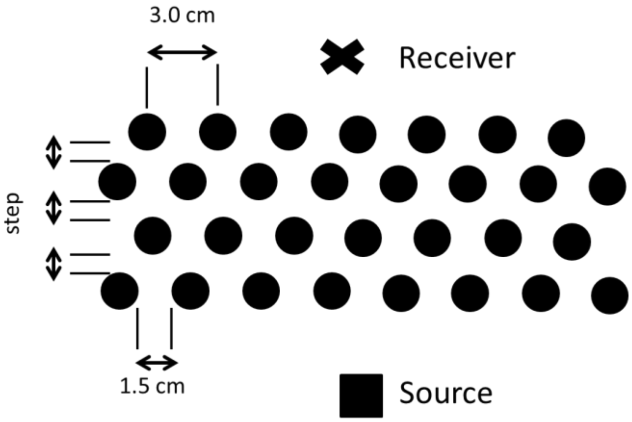

Figure 4 – Horizontal layout of the metamaterial barrier with the position of the sound source and receiver.

Different configurations were considered. The first configuration analyzed was with the distance between each row of 2 cm. The second configuration analyzed was with the distance between each row of 5 cm. The distance between the source-receiver was 100 cm, and the barrier was placed at 50 cm from the source and 50 cm from the receiver.

Figure 5 shows the frontal view photo of the barrier, and Figure 6 shows the aerial view during the acoustic measurement sessions.

The measurements of the acoustic characteristics of the metamaterial barrier were compared also with the sound attenuation measurements done with a traditional noise barrier. For this scope, a rigid 30 cm high screen was placed between the source and the receiver position, with a height equal to that of the barrier built with metamaterials; the position of the sound source and receiver have not been changed. In this way, at the same height, it was possible to evaluate the effects of sound attenuation of a barrier created with metamaterials compared to a traditional one.

Figure 5 - Frontal view of the metamaterial barrier, with sound source.

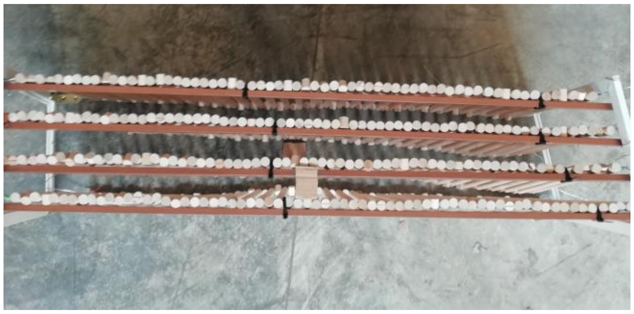

Figure 6 - Aerial view of the metamaterial barrier.

Figure 7 shows the impulse responses measured as direct sound (A) and after being diffracted by the barrier effect. In this figure, it is possible to note the effects of the presence of the barrier both in terms of increase in the length of the impulse response over time and for the decrease of the amplitude value of the first sound impulse detected by the microphone.

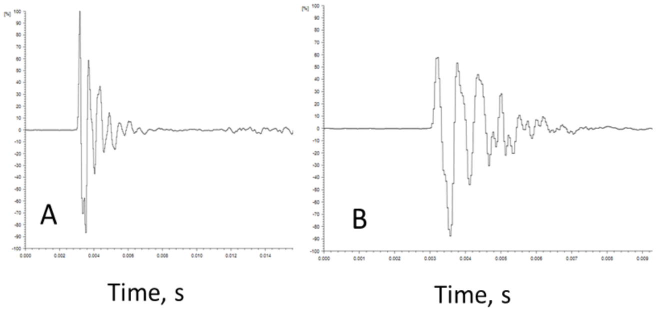

Figure 7 – Impulse responses measured. (A) Direct sound. (B) Diffracted sound by metamaterial barrier effect.

Figure 8 shows the measured values of the IL (dB) with a traditional noise barrier, metamaterial barrier step 5 cm and step 2 cm. In the field of low frequencies, the barrier built with metamaterials has a greater value than sound attenuation, compared to a traditional one. While at high frequencies the attenuation due to the traditional noise barrier is greater. This effect is known, as traditional barriers in the low frequency region are not very effective, and to increase the sound attenuation it is necessary to increase the height from the ground [23, 24]. It is important to note that there are differences in the values of sound attenuation in the configurations with a distance between the rows of 2 cm or 5 cm. Figure 8 shows that as the distance between the rows increases the sound attenuation (IL, dB) increases in the low-frequency region, while for the smaller distance (2 cm) the sound attenuation occurs towards higher frequencies. This result was somehow expected since the sound attenuation of the metamaterial is a function of the distance between the elements. However, this result suggests further studies to be addressed with variable distances between the rows and variations in the dimensions of the cylindrical elements.

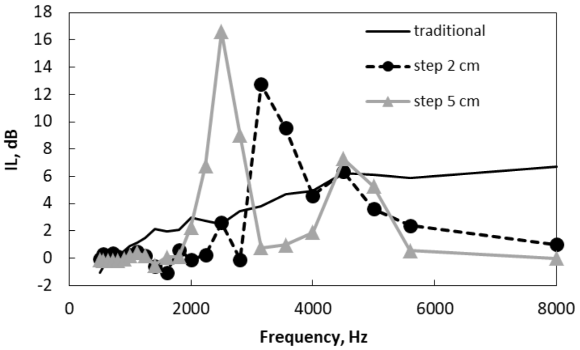

Figure 8 – Measured values of the IL (dB) with a traditional barrier. Metamaterial barrier: step 5 cm and step 2 cm.

4 Conclusions

In this paper, the study of the sound attenuation of a barrier made with metamaterials is reported. The study was preceded by a summary of the state of the art of this topic.

The final results of this work suggest that the barriers obtained with metamaterials can be used to mitigate noise due to road traffic because this type of noise is emitted in a particular frequency range (the traffic noise spectrum is centred at around the frequency of 1,000 Hz), or other noise sources emitted by a stationary sound source. As they can be a valid substitute for traditional barriers. Future studies will involve combined systems to different distances between the rows and combining different sizes of the diameters of the cylindrical bar elements that make up the barrier. Furthermore, the metamaterials can be used for the acoustic correction of enclosed spaces in the architectural acoustic field.

Acknowledgments

This work was financially supported by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) - PRIN 2017 Progetto Settore PE8 codice 2017T8SBH9_001 "Theoretical modelling and experimental characterization of sustainable porous materials and acoustic metamaterials for noise control"

References

[1] R.V. Craster, S. Guenneau. Acoustic Metamaterials: Negative Refraction, Imaging, Lensing and Cloaking. Springer Verlag, 2013.

[2] P.F. Pai, G. Huang. Theory and Design of Acoustic Metamaterials. *Society of Photo Optical*, 2015.

[3] A. Boardman. Pioneers in metamaterials: John Pendry and Victor Veselago. *J. Opt.* 13, 2011.

[4] U. Berardi. Destructive interferences created using additive manufacturing, *Canadian Acoustics*, 45(3), 2017.

[5] U. Berardi. Destructive interferences in resonators created using additive manufacturing, J*ournal of the Acoustical Society of America,* 2018. 144, 1755, https://doi.org/10.1121/1.5067775

[6] C. J. Naify, C. M. Chang, G. McKnight, S. R. Nutt. Scaling of membrane-type locally resonant acoustic metamaterial arrays. *Journal of the Acoustical Society of America,* 132, 2784 – 2792, 2012.

[7] J.V. Sánchez-Pérez, C. Rubio, R. Martínez-Sala, R. Sánchez-Grandia, V. Gómez. Acoustic barriers based on periodic arrays of scatterers. *Appl. Phys. Lett*., 8, 5240– 5242, 2002.

[8] J.V. Sánchez-Pérez, D. Caballero, C. Rubio, R. Martínez- Sala, J. Sánchez Dehesa, F. Meseguer, J. Llinares, F. Gálves. Sound attenuation by a two dimensional arrays of rigid cylinders. *Phys. Rev. Lett.,* 80, 5325– 5328, 1998.

[9] R. Martinez-Sala, J. Sancho, J.V. Sanchez, V. Gomez, J. Llinarez, F. Meseguer. Sound attenuation by sculpture. *Nature,* 378, 241, 1995.

[10] E. L. Thomas. Bubbly but quiet. *Nature,* 462, 990–991, 2009. https://www.nature.com/articles/462990a.

[11] R. Martinez-Sala, C. Rubio, L. M. Garcia-Raffi, J.V. Sanchez-Perez, E.A. Sanchez-Perez, J. Llinares. Control of noise by trees arranged like sonic crystals, *J. Sound Vib.,* 291(1-2), 100–106, 2006.

[12] Y. F. Liu, J. K. Huang, Y. G. Li, Z. F. Shi. Trees as large-scale natural metamaterials for low-frequency vibration reduction. *Constr. Build. Mater*., 199, 737–745, 2019.

[13] R. Ghaffarivardavagh, J. Nikolajczyk, S. Anderson, X. Zhang. Ultra-open acoustic metamaterial silencer based on Fano-like interference. *Physical Review B*, 99(2), 2019.

[14] F. Koussa, J. Defrance, P. Jean, P. Blanc-Benon. Acoustical Efficiency of a Sonic Crystal Assisted Noise Barrier. *Acta Acoust. with Acustica*, 99, 399 – 409, 2013. DOI 10.3813/AAA.918621

[15] A. Elayouch, M. Addouche, A. Khelif. Wide tailorability of sound absorption using acoustic metamaterials. *Applied Physics,* 124, 155103, 2018 DOI: https://doi.org/10.1063/1.5035129

[16] C. Lagarrigue, J. P. Groby, V.Tournat. Sustainable sonic crystal made of resonating bamboo rods. *Journal of the Acoustical Society of America*, 133 (1), 247-254, 2013.

[17] F. Morandi, M. Miniaci, A. Marzani, L. Barbaresi, M. Garai. Standardised acoustic characterisation of sonic crystals noise barriers: Sound insulation and reflection properties. *Applied Acoustics* 114, 294 – 306, 2016. DOI:

http://dx.doi.org/10.1016/j.apacoust.2016.07.028

[18] M. Hornikx, J. Forssén. A Scaale Model Study of Parallel Urban Canyons. *Acta Acustica united with Acustica*, 94(2), 265-281, 2008.

[19] G. Iannace, C. Ianniello, L. Maffei. Edge diffraction in a multireflective environment: Measured and calculated insertion loss of a retained cut. *Noise Control Engineering Journal* 47 (1), 8-16, 1999.

[20] R. Dragonetti, G. Iannace, C. Ianniello. Insertion loss of a heap of gravel outdoors. *Acta Acustica* 89, S56-S57, 2003.

[21] G. Iannace, L. Maffei. Measurement of the transient sound-intensity above a boxed surface with reference to the behaviour of boxes in Italian style historical theatres. In Proc. of *4th European Congress on Acustics, Forum Acusticum 2005*; Budapest; Hungary - 29 August - 2 September 2005; Code 916932005, 2263-2266

.[22] D. D. Rife, MLSSA, Maximum-Length Sequence System Analyzer Reference Manual DRA Laboratories, Sarasota, FL, 1991.

[23] Z. Maekawa. Noise reduction by screens. *Applied Acoustics* 1(3), 157-173, 1968. DOI: https://doi.org/10.1016/0003-682X(68)90020-0

[24] U. J. Kurze, G. S. Anderson. Sound attenuation by barriers. *Applied Acoustics* 4(1), 35-53, 1971.