Chapter 6

Visualizations of sound behind the space-coiling metamaterial

Grzegorz Szczepański, Adam Swidziński, Leszek Morzyński
Central Institute for Labour Protection – National Research Institute

DOI: 10.54215/Noise_Control_2022_A_Digital_Monograph_Szczepanski_G_Swidzinski_A_Morzynski_L

Abstract
Acoustic metamaterials are artificial structures that allow to control the propagation of the sound waves. Space-coiling structures are a specific type of metamaterial structure that have great potential to provide narrowband noise reduction and allow for efficiently reflect of sound waves especially in the low frequency range. Many examples of these structures were described with the results of numerical studies or results acquired by transmission loss measurements. The article concerns 3D-printed space-coiling type metamaterial. The construction of metamaterial as well as results of its tests in semi-anechoic chamber (including visualizations of sound intensity level distribution) were presented.

Keywords: space-coiling metamaterials, environmental engineering, sound visualizations

1. Introduction

Acoustic metamaterials are artificial materials, which can be used to control propagation of the sound waves and are used, for example, in acoustic cloaking [1, 2]. Properties of the acoustic metamaterials are determined by its internal structure. By using i.e. specific shape of the structure it is possible to obtain negative refraction [3-5], negative bulk modulus [6-8] or negative mass density [9-11]. The fact that such acoustic metamaterials can be used in acoustic lensing was proven and described [12, 13].

Certain group of acoustic metamaterials have a specific structure (called space-coiling) and are mainly used in aeroacoustics. Their principle of operation is to reduce the effective speed of sound wave, which is possible by extending the path of sound wave propagation. The fact that the space-coiling metamaterials can achieve negative refraction index has been confirmed experimentally [14]. It is also possible to create a space-coiling metamaterial which can enable almost any acoustic wavefront manipulation [15]. In most research described in the literature, the meander structure of space-coiling metamaterials are considered [14, 16, 17] and they are highly effective in controlling low-frequency sound [18]. These structures can be easily made by 3D printer [19, 20].

Initially, models of acoustic metamaterials are checked by numerical simulations which allow examine its properties before creating them [21]. To assess the properties of developed acoustic metamaterial the measurements with using a Impedance tube are performed [22, 23]. In this case it is possible to determinate sound absorption coefficient and sound transmission loss but it does not allow to illustrate the behavior of the sound wave behind the acoustic metamaterial.

This article presents visualizations of sound wave parameters like sound intensity level and sound pressure level behind the exemplary acoustic space-coiling metamaterials.

2. The structure of space-coiling metamaterial

As the space-coiling metamaterial typical labyrinthine structure with meander routes were designed in SolidWorks 2020. The dimensions of the metamaterial depended on possibility to its manufacture with use of 3D printer. For this reason the primary model (shown in Figure 1 included three meander routes in one piece were designed. The channel width was 3 mm, height of the primary model was equal 150 mm.

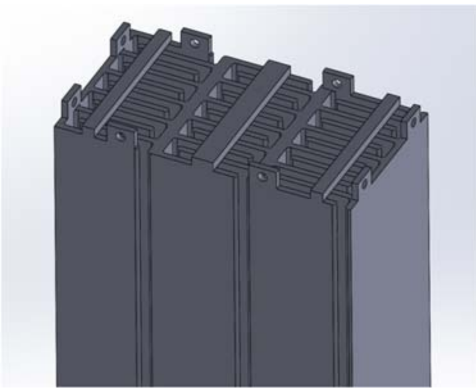

Figure 1. Primary model of space-coiling metamaterial structure

The primary model was created from PLA material by using a 3D printer. Diameter of nozzle was 0.6 mm, and the layer height was set at 0.4 mm. The infill has been set to 0%. Middle-walls of the structure has been fill with polyester resin. At the top of the each primary model a special mounting hooks were added, enabling serial and parallel connection of the metamaterial structure. The structures have been combined by screw connections. Two metamaterial construction was under investigation (shown in Figure 2), 8 primary models in: single and double row. Studies results for a single row structure were described in article [24]. In this article we consider on double row structure.

Figure 2. Space-coiling metamaterial construction under investigation

3. Results of the studies

3.1. Measurement setup

Measurements were carried out with using Scan & Paint 3D system in semi-anechoic acoustic chamber. The system include an anemometer probe that allows sound pressure measurement and direct measurement of acoustic particle velocity in three directions. Measurements were taken by moving the probe with the spherical marker. Marker combined with spherical camera and appropriate software enable to evaluate the position of the probe in relation to the tested metamaterial structure.

To reduce the impact of diffracted waves on measurement results the space-coiling metamaterial was placed in specific window made of wavy sound-absorbing foams. That window were suspended 1.2 meter above the floor and 1 meter away from noise source. As a white noise source Avantone MixCube loudspeaker driven by Behringer A800 amplifier and B&K1049 signal generator were used. The speaker was located in front of the structure. Experimental setup in shown in Figure 3.

Figure 3. The view of the measurement setup

Measurements were taken in front of and behind the metamaterial structure in the frequency range from 100 to 9000 Hz.

3.2. Results and discussion

Sound pressure level and particle velocity level were averaged for piece of volume with width 2 centimeters. From these parameters, the value and direction of the sound intensity vector, which characterize the sound wave propagation and energy distribution close to the metamaterial, were obtained. The obtained results were based on a 30-minute measurements. Each vector acquired in visualizations takes include at least half second of measurements. Due to wide frequency range of test signal, the results of measurements were mainly visualized in a one-third octave band. Three types of results were noticed during the analyzes. In first type, intensity vectors perpendicular to the metamaterial surface occurs. An example of such results are shown in Figure 4.

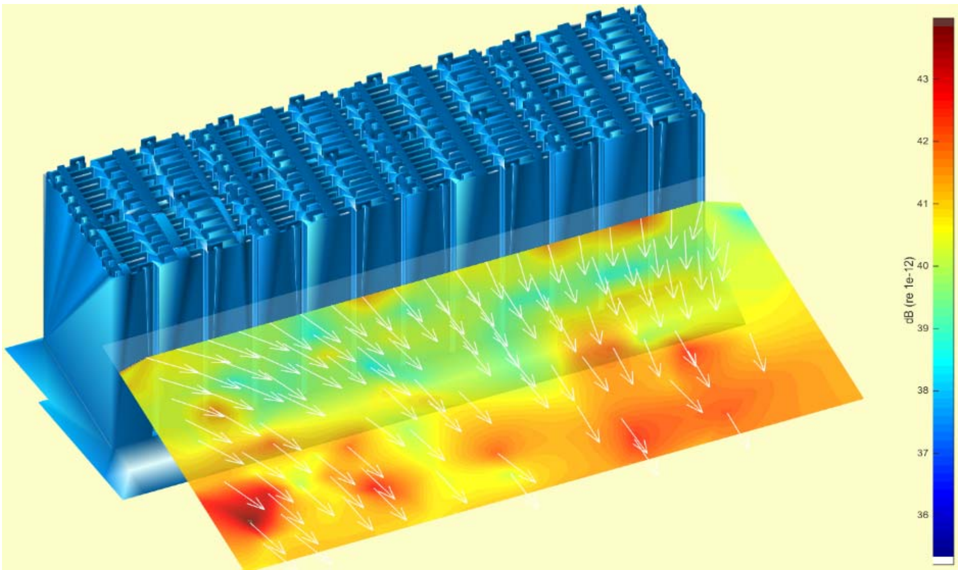

Figure 4. Visualization of sound intensity level distribution – nominal frequency 200 Hz (One-third octave band)

For nominal frequency of 200 Hz, the sound wave passes through the structure perpendicularly. Small deviations occur at the edges of the structure. This proves the low efficiency in eliminating noise for these frequency components. In second type of results, tendency of the sound intensity vectors to deviate can be observed. On Figure 5 the visualization of sound intensity level for nominal frequency 630 Hz are presented. The lowest values of sound intensity level can be found in the middle part of the structure. The vector distribution also indicates the propagation of sound energy from the side sectors of the structure. These results may indicate the insulating properties of the structure in this frequency range. Third group are results in which the intensity vectors form ordered patterns indicates properties of the structure to change direction of sound wave propagation. An example of such results can be visualizations for frequencies: 1600 Hz (Figure 6) and 2500 Hz (Figure 7). In order to better observe these properties, the visualizations were presented with increased mesh resolution (with width 5 millimeters).

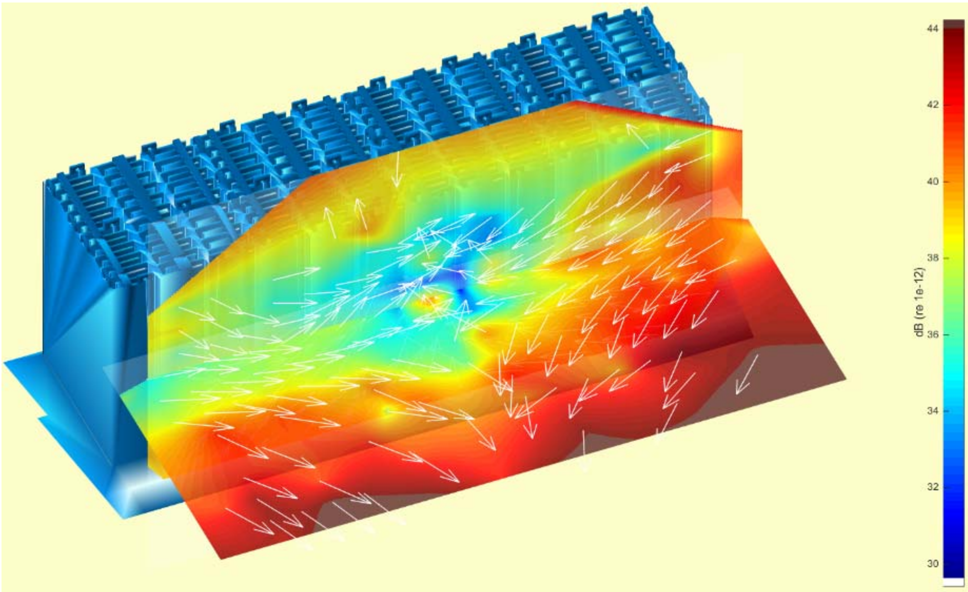

Figure 5. Visualization of sound intensity level distribution – nominal frequency 630 Hz (One-third octave band)

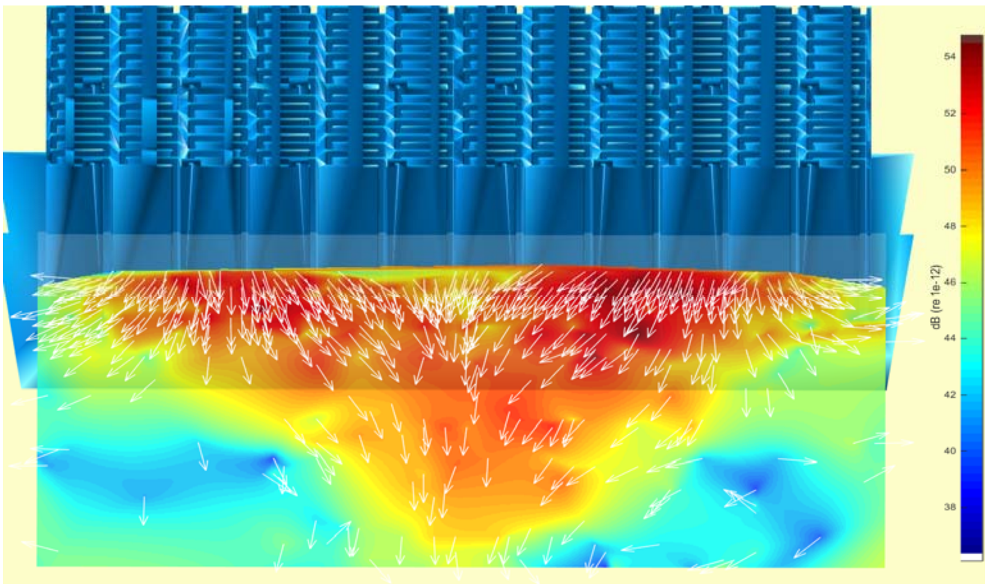

Figure 6. Visualization of sound intensity level distribution – nominal frequency 1600 Hz (One-third octave band)

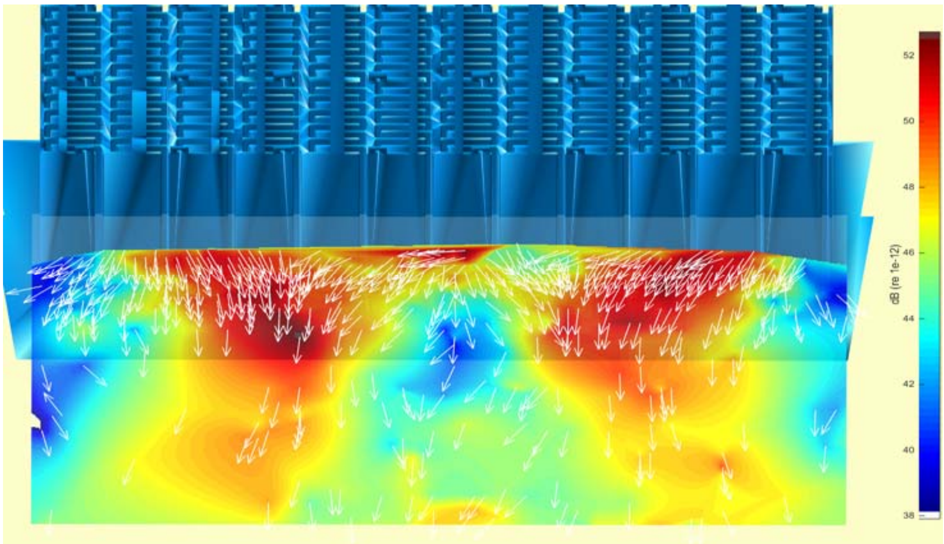

Figure 7. Visualization of sound intensity level distribution – nominal frequency 2500 Hz (One-third octave band)

In both cases two radiating zones of sound are visible. At 1600 Hz beam is created between these zones but at frequency two separate narrow beams occur. These effects appear in the range of the band gap typical for space-coiling metamaterials and they are due to local resonances inside the structure.

4. Conclusion

Studies were not intended to prove the occurrence of the phenomena typical for acoustic metamaterial (like negative bulk modulus or negative mass density) but for illustrate the energy distribution behind the designed structure. Achieved sound intensity patterns indicate the presence of local resonances in the structure. Visualizations of sound intensity level can be useful in evaluating the solution especially where the metamaterial structure is tested under laboratory conditions.

Acknowledgements

This paper has been based on the results of a research task carried out within the scope of the fifth stage of the National Programme "Improvement of safety and working conditions" partly supported in 2020-2022 – within the scope of research and development – by the Ministry of Science and Higher Education /National Centre for Research and Development. The Central Institute for Labour Protection – National Research Institute is the Programme's main coordinator.

References

[1] Popa BI, Zigoneanu L, Cummer SA. Experimental Acoustic Ground Cloak in Air. Phys Rev Lett. 2011;106 [Internet]. Available: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.106.253901

[2] Chen H, Chan CT. Acoustic cloaking in three dimensions using acoustic metamaterials. Applied Physics Letters. 2007;91(18) [Internet]. Available: https://aip.scitation.org/doi/10.1063/1.2803315

[3] Feng L, Liu X-P, Chen Y-B, et al. Negative refraction of acoustic waves in two dimensional sonic crystals. Phys. Rev. 2005;72(B) [Internet]. Available: https://journals.aps.org/prb/abstract/10.1103/PhysRevB.72.033108

[4] Shelby RA, Smith DR, Schultz S. Experimental verification of a negative index of refraction. Science. 2001;292(5514):77-79 [Internet]. Available: https://www.science.org/doi/10.1126/science.1058847

[5] Craster RV, Guenneau S (Ed). Acoustic Metamaterials: Negative Refraction, Imaging, Lensing and Cloaking. Dordrecht: Springer; 2013.

[6] Ding YQ, Liu Z, Qui Ch, et al. Metamaterial with Simultaneously Negative Bulk Modulus and Mass Density. Phys Rev Lett. 2007;99 [Internet]. Available: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.093904

[7] Xia B, Chen N, Xie L, et al. Temperature-controlled tunable acoustic metamaterial with active band gap and negative bulk modulus. Applied Acoustics. 2016;112:1-9 [Internet]. Available: https://www.sciencedirect.com/science/article/pii/S0003682X16301207?via%3Dihub

[8] Man X, Luo Z, Liu J, et al. Hilbert fractal acoustic metamaterials with negative mass density and bulk modulus on subwavelength scale. Materials & Design. 2019;180 [Internet]. Available: https://www.sciencedirect.com/science/article/pii/S0264127519303491?via%3Dihub

[9] Huang HH, Sun CT, Huang GL. On the negative effective mass density in acoustic metamaterials. International Journal of Engineering Science. 2009;47(4):610-617.

[10] Wu Y, Lai Y, Zhang ZQ. Elastic Metamaterials with Simultaneously Negative Effective Shear Modulus and Mass Density. Phys. Rev. Lett. 2011;107(10) [Internet]. Available: https://www.researchgate.net/publication/51701123_Elastic_Metamaterials_with_Simultaneously_Negative_Effective_Shear_Modulus_and_Mass_Density

[11] Zhu R, Liu XN, Huang GL, et al. Microstructural design and experimental validation of elastic metamaterial plates with anisotropic mass density. Phys. Rev. 2012;86(B) [Internet]. Available: https://journals.aps.org/prb/abstract/10.1103/PhysRevB.86.144307

[12] Li J, Fok L, Yin X, et al. Experimental Demonstration of an Acoustic Magnifying Hyperlens. Nat. Mater. 2009;8:931-934.

[13] Lee HJ, Kim HW, Ki YY. Far-field subwavelength Imaging for Ultrasonic Elastic Waves in a Plate Using an Elastic Hyperlens. Appl. Phys. Lett. 2011;98(24) [Internet]. Available: https://aip.scitation.org/doi/abs/10.1063/1.3600634

[14] Xie Y, Popa B-I, Zigoneanu L, et al. Measurement of a Broadband Negative Index with Space-Coiling Acoustic Metamaterials. Phys. Rev. Lett. 2013;110 [Internet]. Available: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.175501

[15] Xie Y, Wang H, Konneker A, et al. Wavefront modulation and subwavelength diffractive acoustics with an acoustic metasurface. Nat. Commun. 2014;5 [Internet]. Available: https://www.nature.com/articles/ncomms6553

[16] Cheng Y, Zhou C, Yuan BG, et al. Ultra-sparse metasurface for high reflection of low-frequency sound based on artificial Mie resonances. Nat Mater. 2015;14(10):1013-1019.

[17] Liang Z, Li J. Extreme Acoustic Metamaterial by Coiling Up Space. Phys. Rev. Lett. 2012;108 [Internet]. Available: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.108.114301

[18] Krushynska AO, Bosia F, Pugno NM. Labyrinthine acoustic metamaterials with space-coiling channels for low-frequency sound control. Acta Acustica United With Acustica. 2018;104(2):200-210.
[19] Aslan R, Turan O. Gypsum-based sound absorber produced by 3D printing technology. Applied Acoustics. 2020;161 [Internet]. Available: https://www.sciencedirect.com/science/article/pii/S0003682X19308345
[20] Fotsing ER, Dubourg A, Ross A, et al. Acoustic properties of periodic micro-structures obtained by additive manufacturing. Appl Acoust. 2019;148:322-331.
[21] Radosz J. Acoustic performance of noise barrier based on sonic crystals with resonant elements. Appl Acoust. 2019;155:492-499.
[22] Beyza Y, Zuhre SG. 3D Labyrinthine type Acoustical Metamaterial Proposals for Sound Control in Architectural Applications. In: INTER-NOISE and NOISE-CON Conference Proceedings, InterNoise19, Madrid, 16-19 June 2019; Institute of Noise Control Engineering (INCE); 2019 [Internet]. Available: http://repository.bilkent.edu.tr/handle/11693/52925
[23] Shao H, He H, Chen Y, et al. A tunable metamaterial muffler with a membrane structure based on Helmholtz cavities. Applied Acoustics. 2020; 157 [Internet]. Available: https://www.sciencedirect.com/science/article/pii/S0003682X19303019
[24] Szczepański G, Morzyński L, Świdziński A. Experimental visualization of sound of 3D printed labyrinthine type metamaterial. In: INTER-NOISE and NOISE-CON Conference Proceedings, Inter Noise20, Seoul, Korea, 23-26 August 2020; Institute of Noise Control Engineering (INCE); 2020. p. 483-490.