A Review of Acoustic Metamaterials applied to noise control in Civil Engineering

Caio Zanin[1], Jaime Guilherme Leal Guimarães Alves[1], Paulo César Gonçalves[1], Jesús Antonio García Sánchez[2], Noé Geraldo Rocha de Melo Filho[3]

,[1]*Natural Resources Institute, Federal University of Itajubá.*
Av. BPS, 37500903, Minas Gerais, Brazil.
caiozanin@unifei.edu.br, jaimeguilherme@unifei.edu.br, paulocg9@unifei.edu.br.
[2]*Institut of mechanical engineering, Federal University of Itajubá.*
Av. BPS, 37500903, Minas Gerais, Brazil.
jesus@unifei.edu.br
[3] *Autonomous Researcher*
noegeraldof@gmail.com.

Abstract. Over the past 10 years, the research of acoustic metamaterials has branched out in many directions, presenting numerous potentially applicable geometries for the composition of noise control structures, such as structural resonators, acoustic resonators, and membranes. Therefore, keeping track of these multiple applications can be considered a rather difficult task. Moreover, the application of this novel concept in civil engineering has a high potential. In this context, an article review is proposed, identifying the most important acoustic metamaterial concepts that were applied or could be applied in civil engineering. The study performs a qualitative survey of articles in this segment, classifying the leading literature proposals, according to physical principles of cells working and to the facility of application in civil engineering, considering the production factors and construction implementation. It was found that the number of works with this focus is incipient when compared to the strictly theoretical works. A great number of articles contain dimensions and geometric propositions that feature difficulties of precise and large-scale manufacturing in the current civil construction scenario, which is traditionally less industrialized and technological. Finally, the advantages and disadvantages of the physical principles and acoustic structures were compared to point out ways that allow the development and popularization of acoustic metamaterials in civil engineering.

Keywords: review, acoustic metamaterials, civil engineering, noise control.

1 Introduction

Noise pollution is a problem discussed for a few decades in different fields, as health, building acoustics, urban acoustics, traffic, and the environment [1]. The process of normatization in Europe in the last years [2] and recently in Brazil with the Performance Standard for Housing Buildings (ABNT NBR 15575:2013) [3-4] , has demonstrated the importance of this theme to society. With the new standards, acoustic materials for airborne sound insulation are increasingly being used, especially for public spaces, such as temples and concert halls, but also in multi-family buildings. Despite the considerable efficiency of foams and fibers as sound absorbers for medium and high-frequency waves, new materials have been studied to achieve a relevant challenge in this area, which is the sound insulation of low-frequency waves. Among these different solutions, metamaterials come to the fore as a highly potential solution.

Metamaterials are engineered structures with unusual characteristics among conventional materials. The first researcher to propose metamaterials was Veselago in 1968 [5], who obtained negative permeability and permissiveness at the same time in a material. Later, Pendry and Li [6-7] demonstrated the possibility of the coexistence of the two negative parameters, and it was later observed that the effects of this experiment were potentially applicable in several areas that intended to manipulate electromagnetic or mechanical waves.

In the study of acoustic metamaterials, which are these artificial materials engineered to have superior noise and vibration insulation performance, the physical parameters analogous to those of Veselago's proposal are the Bulk compressibility module (C) and the mass density (ρ) [8]. Figure 1 [9] shows in coordinated axes an outline of the possible regions for the known materials, in the 1st quadrant, the 3rd one containing the simultaneity of the negative parameters, which can be obtained from known physical phenomena, such as Bragg scattering [10-16] Helmholtz resonators [17-28] local and Fano-like resonance [10,12, 29, 30] and coiling-up space [6, 31, 40, 32–39].

In this way, it is possible to develop acoustic metamaterials from different physical principles to obtain

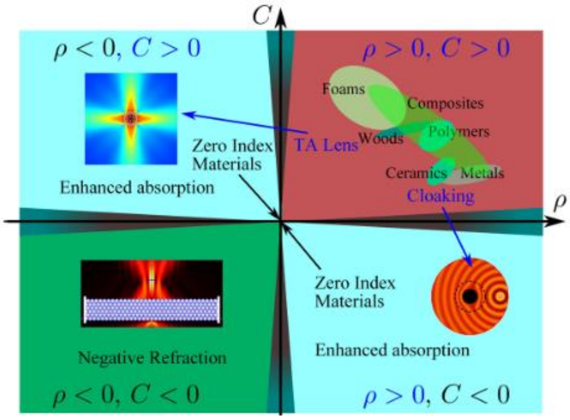

Figure 1: Haberman and Norris [9] division within the types of AMs. On the first quadrant, there are the typical acoustic materials. The rest are the possibilities that exist when one of the mentioned parameters becomes negative.

stopbands, which are frequency regions of no free-wave propagation. Xia et al [38] discuss in their article the advancement of acoustic metamaterials, exploring the various principles worked in researches over the past decades.

2 Resonators

According to Mason and Fahy [25], resonators are reactive acoustic or vibrational devices that use the wave itself to attenuate it. This is achieved by the abrupt change in the geometry of the medium where the wave was generated up to the resonator, i.e., there is a large variation of impedance. The same author mentions that resonators can be of several types, such as those of half and Quarter wavelength, expansion chambers, or Helmholtz resonators. Besides these types of resonators, there are other possibilities, such as vibrational systems that can also increase energy losses. Some metamaterials enable high absorption rates in restricted frequency ranges [25]; these devices can be applied in situations with tonal noises, greatly favoring comfort and noise control. Other ones, search for wider absorption ranges, even with lower peak values [21].

There is a reasonable application potential among resonators because designing them to a tonal noise is relatively simple and therefore a wide range of noise and vibration issues, such as motors, can be treated with this device. Thus, below are discussed: Helmholtz Resonator, Half- and Quarter-wavelength Resonators, Coiling-up Resonators, Locally Resonant Materials, in sequence.

2.1 Helmholtz Resonators

Helmholtz resonators (HRs) are often used alone or in arrangements for solving problems such as absorption at low frequencies. Ingard [26] defines the HRs as analogous to a spring-mass system, where the neck, which is the aperture of the tube, behaves as the mass, whose value is defined by $M = \rho \cdot S \cdot (L + \Delta L)$, where ρ is the density of the air, S, is the area of the cross-section, $(L + \Delta L)$ is the length of the tube with the ends correction. This mass resonates and the volume of the tube is the spring with rigidity $\rho \cdot c^2$. Deep analysis of the shape of the resonator neck and the corrections coming from this geometry are introduced by Ingard. The resonance frequency could be calculated with:

$$f_r = \frac{c}{2\pi} \cdot \sqrt{\frac{S}{V \cdot (L + 1.7r)}},$$

where f_r the resonance frequency, c, sound velocity, V the HR volume, S, L and $1.7r$ the area, length, and neck correction factor, respectively.

One of the HRs arrangements is the creation of perforated [24] and micro-perforated panels (MPP) [17–21, 23-28, 40] that is, the holes in the front plate act as the necks and an influence volume between the double sandwich [22]. Maa [18] was the first to develop the MPP theory and Mason and Fahy [25] were responsible for the theoretical development of the double panels. Mason and Fahy [25] demonstrates that if the distance between the resonators is of the wavelength order, there is an improvement in performance to the same isolated resonators.

Pan, Guo and Ayres [17] proposes the use of honeycomb in panels for sound absorption that can be applied in industrial buildings or ships. Tang et al [19] suggests a MPP that contains resonators of different volumes to achieve a large absorption range. Yamamoto [23] demonstrates numerically a potential application of embedded HRs, i.e., with the incidence through the air cavity. A high STL was found in narrow frequency ranges, but they can be increased with slight changes in the dimensions of the resonators.

There are results like Jimenez's et. al [21] that demonstrate efficiency for broadband frequency and with potential application in enclosures. Another benefit is that the panels are easily transported because they are light and can replace drywall, which is already common in offices, as well as covering a wall or facade [20].

2.2 Half- and Quarter-wavelength Resonators

The devices called half- or Quarter-wavelength resonators are tubes that can have their ends open-open or open-close. The resonance frequencies can be deduced. The eigenfrequencies will be given, for the open-open case, by $f_n = nc/2L$, with n equal to the natural ones and, for the other, $f_n = nc/4L$, with n equal to the odd numbers [40]. Being c the speed of sound and L, the length of the tubes.

Field and Fricke [40] cites that one advantage is that these tubes can have their length changed easily after its construction with the insertion of a piston, while this other requires a design with greater accuracy. One of the disadvantages, however, of these devices is the long length of the tubes when dealing with low frequencies. There are comparative studies that demonstrate the performance of the mentioned acoustic devices [41]. There are also applications in pipe systems, according to Kim, Ih and Âbom [27]. The results are with at least a 5 dB decrease between 230 and 1000 Hz.

2.3 Coiling-up Resonators

The coiling of space [31-40,43-44] has been studied as a form of a complex waveguide, which can have the purpose of absorption [31-33, 35, 38-39, 43-44] or of near-perfect transmission [34, 36], which is useful to modulate a wave [35], to overcome obstacles that would usually cause dispersion, and also to design acoustic devices, that requiring extreme constitutive parameters, such as Hyperlens [33]. For the application discussed here, we are interested in the first case. An adaptation of the MPP cavities is possible when space coiling is done. This generates a rather complex geometry, which attempts to increase the size of an HR's neck by introducing coiled space.

Recently, Almeida et al [30] has shown the possibility of a block with the internal air cavity designed symmetrically, achieving perfect absorption peaks at frequencies between 100-600Hz. Chen et al [31] proposed a coiled waveguide, but at a specific point it is constricted, that is, an additional impedance mismatch is created to have new losses. This allowed for an absorption close to 80% between 76 and 112 Hz with the ratio of wavelength to total system thickness, which was 117.1 mm, of 1/38.5.

Li and Assour [34], in turn, proposed coplanar coiled chambers that compose a metasurface that achieves perfect absorption at 125 Hz, where the panel thickness to wavelength ratio equals 1/223. Because this ratio is quite high, the bandwidth also becomes narrow, as shown by Chen et al [31]. Donda et al [42] has improved the concepts and managed to achieve 0.99 of absorption coefficient at 50Hz having an ultra-thin panel (1.3 cm), which represented 1/527 in the ratio between its thickness and wavelength. Sousa et al [39] and Huang et al [43] proposed to make the coiling spiral-shaped. The first obtained, experimentally, a perfect absorption with peaks at 700 Hz and 800 Hz. The second, which had the opening embedded to the incident wave, provided, also experimentally, in its best case, a total absorption at 148.5 Hz.

Finally, Xia et al [38] brings the idea of applying the concept of fractals to the composition of the cells of metamaterials, in other words, a pattern is defined that arbitrarily repeats itself within the channels themselves, but in smaller scales. These geometries when applied to panels are potentially applicable to civil engineering, considering that acoustic treatments of rooms, studios, and residences are already common with acoustic material panels. However, it should still be noted that the manufacturing process of these models may still be one of the bottlenecks to overcome, because, as a large part depends on 3D printing, either this method becomes faster and more effective, which is certainly being studied, or other mechanisms, such as mechanical conformation in matrixes should be developed and tested since this has been a reasonable way to achieve low-frequency losses, which has been a challenge for a long time.

2.4 Locally Resonant Materials

In this section locally resonant materials are reviewed, as metamaterials models that can be applied in Civil Engineering and Construction, due to their physical principles. The locally resonant materials have their characteristics dependent on the dispersive properties of their cells [44], Kaina, Fink and Lerosey [45] proved, based on the transfer matrix, that the locally resonant metamaterials do not present interaction in the near field, suffering influence only from the Fano interference effect between the resonance of the unit cell and the continuity of propagation of plane waves in the medium. Thus, when this interaction generates destructive interference, the bandgap hybridization is obtained, as a result of the coupling between the incident wave and the local resonator [16, 47].

Melo Filho et al [12] presents a locally resonant metamaterial panel capable of attenuating the first acoustic mode of a cavity. More than that, it advocates the possibility of developing the metamaterial with low cost and large production scale, expanding the application horizons for thermoformed panel noise control. Other types of locally resonant metamaterials are periodic resonators/scatters and sonic crystals [11, 13-16]. They take advantage of the physical properties of interference to prevent acoustic transmission.

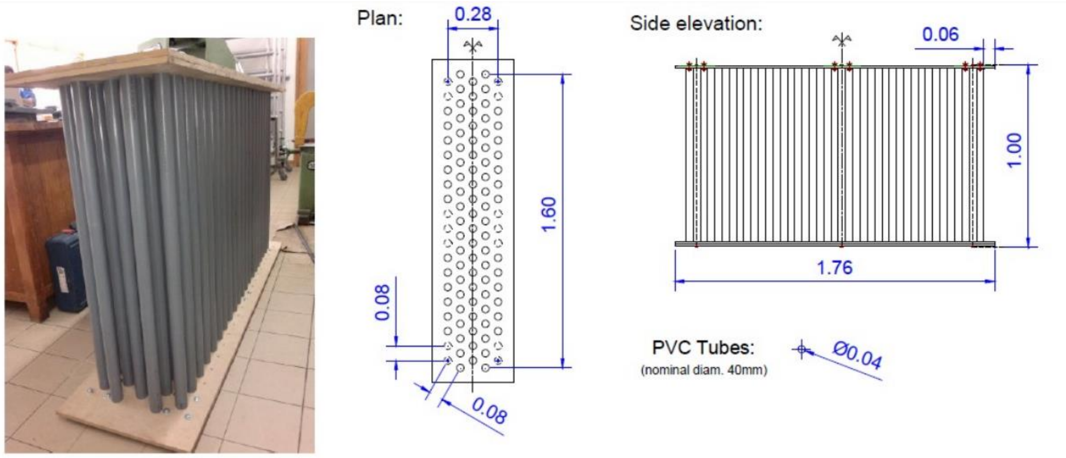

Figure 2: View of the first small-scale sonic-crystal prototype [11]

Amado-Mendes et al [11] citing [47] defines sonic crystals as structures that can be organized in a periodic or quasi-periodic manner, resulting in the appearence of band gaps, when present in the propagation of fluid. Lee et al [48] further explains, citing [49], that the destructive Bragg law was used to explain the phenomenon of band gaps. A well-known case for the physical application of this phenomenon was the sculpture developed by [50] experimentally presenting sound filtering capability.

2.5 Bragg Scattering

When it comes to applications for use in civil engineering and construction, [51] cites [52] when arguing about the effectiveness of the use of sonic crystals in controlling noise produced on highways and railroads. According to the authors, the fact of considering linear sources in roads compensates for the relevance of the relative position between source and receiver, which generates an Insertion Loss difference of up to 8dB [53]. Jean and Defrance [52] presents in **Erro! Fonte de referência não encontrada.** the periodic arrangement adopted along roads. In that article was found a peak of up to 6dB of sound attenuation with the use of cylindrical structures

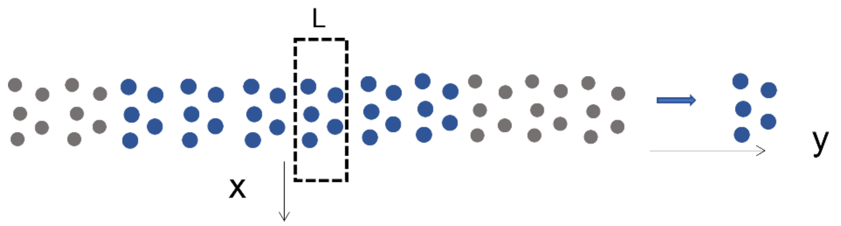

Figure 3: 2D periodic geometry of period L in the xy plane

with infinite height.

Amado – Mendes et al [11] proposes a barrier model with sonic crystals and performs an experimental validation both a reduced scale with PVC tubes in the laboratory and a full scale with timber logs arranged periodically as sustainable noise traffic barriers. With a configuration of 4 rows of circular scatterers, the experimental and simulated results exhibited very similar behavior with Insertion Loss peaks up to 15 dB for a frequency of 1000 Hz. The shape of these scatterers has been explored by different papers, with rectangular, circular, and triangular shapes being raised. The last one was identified by [54] as the geometry that allows the highest peak absorption for frequency bands above 2 kHz (industrial use), while elliptical shapes are more efficient in frequency bands of interest for road noise control.

Not only the shapes of the sonic crystals were diverse, but also the component materials of the periodic structure. It is presented an arrangement of trees with dense foliage with a transmission loss of up to 19 dB and variable band gaps **Erro! Fonte de referência não encontrada.** depending on the source of sound emission (which may be edge source or plane source) [55]. The benefits of a configuration with natural elements can be both acoustic and architectural, allowing greater thermal comfort in the surroundings [56].

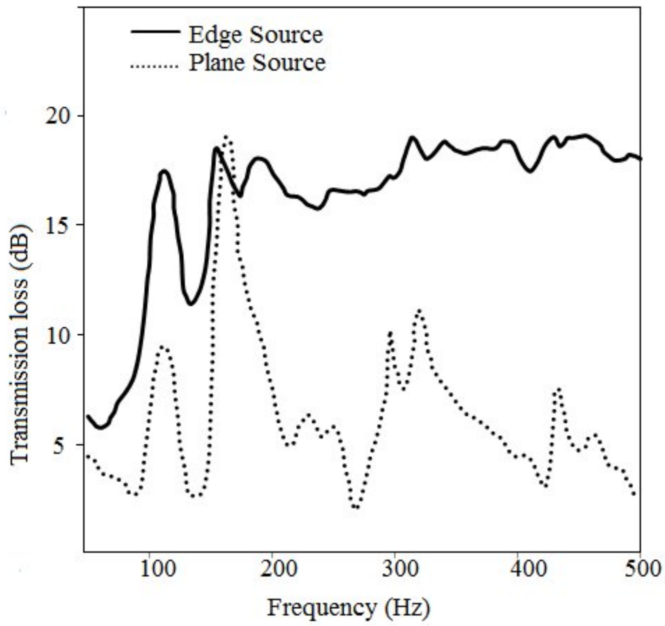

Figure 4: Trasmission loss results of an arrangement of trees [55]

Although they do not present wide bandgaps and require large occupation spaces to obtain peak attenuation in the ranges of interest to Civil Engineering, sonic crystals have great potential for application in specific situations, as in the case of highways, where they can already be part of the road design. As seen, they can even be formed by natural geometric periodicities, as in the use of trees and even living fences. In addition, it is worth further research on the use of periodic structures in the control of noise on construction sites.

3 Results and Discussion

In this section, the geometries, metamaterials, and discussions of the topics in the previous items are presented, to compile the. Possible applications in Civil Engineering are also be suggested. Helmholtz resonators, when applied together in perforated or micro-perforated panels (MPP) [17, 19, 21-23, 27], present relevant results for low-frequency absorption. A limitation is that this type of resonator acts only at narrow ranges.

This type of application also makes it possible to reduce the space required by isolated resonators, since this requires large volumes. Thus, the panels have been efficient not only in absorption but also by reducing weight and thickness. The Helmholtz resonator and the Half-quarter-wavelength are geometries that allow the inclusion of pistons, which can also be used for active noise control. The coiling-up space resonators are an adaptation of Helmholtz and half-quarter wavelength resonators that, when distributed in panels [32, 35, 38, 40, 43-44], show considerable improvement over the traditional resonators shown above. The construction of blocks with coiled cavities is also shown to be a possibility [30].

The viscous and thermal losses, as well as the increased wave path, make the panels thinner, lighter, and achieve low-frequency zones, which is desired. However, it is worth noting that these coilings can generate a large impedance mismatch between the incident medium and the internal medium of the resonator, a fact that can reverse the expected absorption effect by turning the resonator into a reflector.

Finally, it should be noted that because this resonator is still a new type, few experiments applied in realistic situations have been done, as well as the STL analysis that this geometry generates. The papers presented are mostly on the characterization of materials, i.e., laboratory conditions that do not occur in real situations.

As presented, local resonators and sonic crystals can be applied in specific noise control situations in Civil Engineering. Both for noise control during construction, and acoustic barriers accompanying highways. The applications of crystals on highways provide a sound attenuation of up to 15 dB at a given frequency [11], as well as studies that analyze the shapes and dimensions to be used, elliptical shapes being preferred, although they are not as common as circular shapes [51]. To acquire traffic noise mitigation, even natural elements such as trees can be used along highways, showing efficient results [55]. Some limitations are found in this model, such as the large spatial occupation of these barriers and the attenuation peaks in very narrow frequency ranges, which leads them not to be effective in other types of applications that require wider ranges of performance.

4 Conclusions

We conclude that this is a field to be explored intensively by researchers who intend to solve low-frequency noise problems cheaply and efficiently. With the analyses, a very promising path is seen in the use of acoustic panels as a substrate for resonators. Among resonators, it is suggested that for enclosures there may be a prioritization of studies that apply Helmholtz resonators or a variation of it, which are the Coiling-Up Space because they have shown relevant efficiency when combined in the panel structure. It should be noted that, at present, there is still a difficulty in manufacturing these metamaterials, because they are still based on complex geometries manufactured by 3D printing which is still a costly manufacturing process. Even though research on cheap manufacturing processes have been made, it is not sufficient to bring metamaterials closer to industrial reality, especially considering civil engineering.

Furthermore, it is important to highlight that for applications in roadways, there are studies for vibrational metamaterials with acoustic wave attenuation effects, presenting themselves as viable solutions that replace or corroborate existing rigid barriers. The use of trees as sonic crystals is an attractive point of this solution, for being the inclusion of natural elements with benefits for acoustic. For other types of applications, sonic crystals can become very limited and ineffective. Factors such as the manufacturing process or on-site construction of these structures were not taken into account in these analyses.

At last, it is suggested that studies be done for the application of metamaterial cells both in panels, as mentioned above, but also in building blocks, since this for projected spaces that already have estimated the main frequencies that will act, the device can be a constructive element and not applied later, as the panels. This could also have an important cheapening effect since it would not be necessary to use new materials, but a change in the extrusion matrix of the blocks.

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References

[1] A. P. O. Carvalho, J. A. Faria, and R. Buildings, "Conference in Building Acoustics ACOUSTIC REGULATIONS IN EUROPEAN UNION COUNTRIES," 1998.

[2] B. Rasmussen, "Building acoustic regulations in Europe – Brief history and actual situation Acoustic regulations Europe – Examples," *Bnam*, no. July, pp. 1–16, 2018.

[3] J. F. Pierrard and D. Akkerman, "Manual ProAcústica," p. 31, 2013.

[4] N. Brasileira, "ABNT NBR Edificações habitacionais-Desempenho Parte 1: Requisitos gerais Residential buildings-Performance Part 1: General requirements," 2013, [Online]. Available: www.abnt.org.br.

[5] V. G. Veselago, "The Electrodynamic of Substances with Simultaneous Negative Values of e and μ," *Soviet Physics Uspekhi*, vol. 10, no. 4. pp. 509–514, 1968.

[6] J. B. Pendry and J. Li, "An acoustic metafluid: Realizing a broadband acoustic cloak," *New J. Phys.*, vol. 10, no. October, 2008, doi: 10.1088/1367-2630/10/11/115032.

[7] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, "Metamaterials and negative refractive index," *Science (80-.).*, vol.

305, no. 5685, pp. 788–792, 2004, doi: 10.1126/science.1096796.
[8] S. H. Lee, C. M. Park, Y. M. Seo, Z. G. Wang, and C. K. Kim, "Composite acoustic medium with simultaneously negative density and modulus," *Phys. Rev. Lett.*, vol. 104, no. 5, pp. 1–4, 2010, doi: 10.1103/PhysRevLett.104.054301.
[9] M. Haberman, "Acoustic Metamaterials," *Acoust. Today*, vol. 12, no. 3, pp. 31–39, 2016, doi: 10.1557/mrs2008.202.
[10] X. I. Congreso *et al.*, "a Numerical Study on the Behavior of Partition Panels With Micro-Resonator-Type Metamaterials," 2018.
[11] P. Amado-Mendes, L. Godinho, P. G. Santos, A. G. Dias, and M. Martins, "Laboratory and full-scale experimental evaluation of the acoustic behaviour of sonic crystal noise barriers crystal noise barriers," *Int. Congr. Acoust.*, p. 10, 2016.
[12] N. G. R. de Melo Filho, C. Claeys, E. Deckers, and W. Desmet, "Realisation of a thermoformed vibro-acoustic metamaterial for increased STL in acoustic resonance driven environments," *Appl. Acoust.*, vol. 156, pp. 78–82, 2019, doi: 10.1016/j.apacoust.2019.07.007.
[13] L. Godinho, P. Amado-Mendes, A. Pereira, and D. Soares, "An Efficient MFS Formulation for the Analysis of Acoustic Scattering by Periodic Structures," *J. Theor. Comput. Acoust.*, vol. 26, no. 1, pp. 1–22, 2018, doi: 10.1142/S2591728518500032.
[14] P. Amado-Mendes, L. Godinho, J. Carbajo, and J. Ramis-Soriano, "Numerical modelling of finite periodic arrays of acoustic resonators using an efficient 3D BEM model," *Eng. Anal. Bound. Elem.*, vol. 102, no. February, pp. 73–86, 2019, doi: 10.1016/j.enganabound.2019.02.012.
[15] L. Godinho, J. Redondo, and P. Amado-Mendes, "The method of fundamental solutions for the analysis of infinite 3D sonic crystals," *Eng. Anal. Bound. Elem.*, vol. 98, no. August 2018, pp. 172–183, 2019, doi: 10.1016/j.enganabound.2018.09.015.
[16] Z. Liu *et al.*, "Locally Resonant Sonic Materials Published by : American Association for the Advancement of Science Stable URL : http://www.jstor.org/stable/3077841 Locally Resonant Sonic Materials," vol. 289, no. 5485, pp. 1734–1736, 2017.
[17] J. Pan, J. Guo, and C. Ayres, "Improvement of sound absorption of honeycomb panels," *Annu. Conf. Aust. Acoust. Soc. 2005, Acoust. 2005 Acoust. a Chang. Environ.*, vol. 0, no. November, pp. 158–163, 2005.
[18] M. DAH-YOU, "Theory and Design of Microperforated Panel Sound-Absorbing Constructions," *Sci. Sin.*, vol. 18, no. 1, pp. 55–71, 1975, doi: 10.1360/ya1975-18-1-55.
[19] Y. Tang *et al.*, "Hybrid acoustic metamaterial as super absorber for broadband low-frequency sound," *Sci. Rep.*, vol. 7, no. July 2016, pp. 1–10, 2017, doi: 10.1038/srep43340.
[20] D. Ramos, P. Amado-mendes, and P. Mareze, "Experimental and numerical modelling of Helmholtz Resonator with angled neck aperture," no. September, 2020.
[21] N. Jiménez, V. Romero-García, V. Pagneux, and J. P. Groby, "Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems," *Sci. Rep.*, vol. 7, no. 1, pp. 1–12, 2017, doi: 10.1038/s41598-017-13706-4.
[22] A. Hall, G. Dodd, and G. Schmid, "Mass-Air-Mass resonance cavity suppression using Helmholtz Resonators," *Acoust. 2019, Sound Decis. Mov. Forw. with Acoust. - Proc. Annu. Conf. Aust. Acoust. Soc.*, pp. 1–11, 2020.
[23] T. Yamamoto, "Acoustic metamaterial plate embedded with Helmholtz resonators for extraordinary sound transmission loss," *J. Appl. Phys.*, vol. 123, no. 21, 2018, doi: 10.1063/1.5025570.
[24] A. W. Guess, "Calculation of perforated plate liner parameters from specified acoustic resistance and reactance," *J. Sound Vib.*, vol. 40, no. 1, pp. 119–137, 1975, doi: 10.1016/S0022-460X(75)80234-3.
[25] J. M. Mason and F. J. Fahy, "The use of acoustically tuned resonators to improve the sound transmission loss of double-panel partitions," *J. Sound Vib.*, vol. 124, no. 2, pp. 367–379, 1988, doi: 10.1016/S0022-460X(88)80194-9.
[26] U. Ingard, "On the Theory and Design of Acoustic Resonators The Journal of the Acoustical Society of America," *J. Acoust. Soc. Am.*, vol. 25, no. 6, pp. 1037–1061, 1953, [Online]. Available: http://asa.scitation.org/toc/jas/80/S1.
[27] D. Y. Kim, J. G. Ih, and M. Åbom, "Virtual Herschel-Quincke tube using the multiple small resonators and acoustic metamaterials," *J. Sound Vib.*, vol. 466, p. 115045, 2020, doi: 10.1016/j.jsv.2019.115045.
[28] C. J. Naify, C. M. Chang, G. McKnight, and S. Nutt, "Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials," *J. Appl. Phys.*, vol. 108, no. 11, 2010, doi: 10.1063/1.3514082.
[29] R. Ghaffarivardavagh, J. Nikolajczyk, S. Anderson, and X. Zhang, "Ultra-open acoustic metamaterial silencer based on Fano-like interference," *Phys. Rev. B*, vol. 99, no. 2, p. 024302, Jan. 2019, doi: 10.1103/PhysRevB.99.024302.
[30] G. do N. Almeida, E. F. Vergara, L. R. Barbosa, and R. Brum, "Low-frequency sound absorption of a metamaterial with symmetrical-coiled-up spaces," *Appl. Acoust.*, vol. 172, p. 107593, 2021, doi: 10.1016/j.apacoust.2020.107593.
[31] C. Chen, Z. Du, G. Hu, and J. Yang, "A low-frequency sound absorbing material with subwavelength thickness," *Appl. Phys. Lett.*, vol. 110, no. 22, 2017, doi: 10.1063/1.4984095.
[32] T. Frenzel, J. David Brehm, T. Bückmann, R. Schittny, M. Kadic, and M. Wegener, "Three-dimensional labyrinthine acoustic metamaterials," *Appl. Phys. Lett.*, vol. 103, no. 6, pp. 1–6, 2013, doi: 10.1063/1.4817934.
[33] Z. Liang and J. Li, "Extreme acoustic metamaterial by coiling up space," *Phys. Rev. Lett.*, vol. 108, no. 11, pp. 1–4, 2012, doi: 10.1103/PhysRevLett.108.114301.
[34] Y. Li and B. M. Assouar, "Acoustic metasurface-based perfect absorber with deep subwavelength thickness," *Appl. Phys. Lett.*, vol. 108, no. 6, 2016, doi: 10.1063/1.4941338.
[35] Y. Xie, W. Wang, H. Chen, A. Konneker, B. I. Popa, and S. A. Cummer, "Wavefront modulation and subwavelength diffractive acoustics with an acoustic metasurface," *Nat. Commun.*, vol. 5, pp. 1–5, 2014, doi: 10.1038/ncomms6553.
[36] A. O. Krushynska, F. Bosia, M. Miniaci, and N. M. Pugno, "Spider web-structured labyrinthine acoustic metamaterials for low-frequency sound control," *New J. Phys.*, vol. 19, no. 10, 2017, doi: 10.1088/1367-2630/aa83f3.
[37] H. Ryoo and W. Jeon, "Perfect sound absorption of ultra-thin metasurface based on hybrid resonance and space-coiling," *Appl. Phys. Lett.*, vol. 113, no. 12, 2018, doi: 10.1063/1.5049696.

[38] B. Xia, L. Li, J. Liu, and D. Yu, "Acoustic Metamaterial with Fractal Coiling Up Space for Sound Blocking in a Deep Subwavelength Scale," *J. Vib. Acoust. Trans. ASME*, vol. 140, no. 1, pp. 1–8, 2018, doi: 10.1115/1.4037514.

[39] A. Carvalho de Sousa, E. Deckers, C. Claeys, and W. Desmet, "On the assembly of Archimedean spiral cavities for sound absorption applications: Design, optimization and experimental validation," *Mech. Syst. Signal Process.*, vol. 147, p. 107102, 2021, doi: 10.1016/j.ymssp.2020.107102.

[40] C. D. Field and F. R. Fricke, "Theory and applications of quarter-wave resonators: A prelude to their use for attenuating noise entering buildings through ventilation openings," *Appl. Acoust.*, vol. 53, no. 1–3, pp. 117–132, 1998, doi: 10.1016/s0003-682x(97)00035-2.

[41] C. H. Lee, M. J. Han, T. W. Park, Y. S. Kim, and K. D. Shin, "A comparative study on the transmission loss of helmholtz resonator and quarter, half, conical half-wave resonator using acoustic analysis model," *Int. J. Mech. Eng. Robot. Res.*, vol. 9, no. 1, pp. 153–157, 2020, doi: 10.18178/ijmerr.9.1.153-157.

[42] K. Donda, Y. Zhu, S. W. Fan, L. Cao, Y. Li, and B. Assouar, "Extreme low-frequency ultrathin acoustic absorbing metasurface," *Appl. Phys. Lett.*, vol. 115, no. 17, 2019, doi: 10.1063/1.5122704.

[43] S. Huang, X. Fang, X. Wang, B. Assouar, Q. Cheng, and Y. Li, "Acoustic perfect absorbers via spiral metasurfaces with embedded apertures," *Appl. Phys. Lett.*, vol. 113, no. 23, pp. 14–19, 2018, doi: 10.1063/1.5063289.

[44] M. Rupin, F. Lemoult, G. Lerosey, and P. Roux, "Experimental demonstration of ordered and disordered multiresonant metamaterials for lamb waves," *Phys. Rev. Lett.*, vol. 112, no. 23, pp. 1–5, 2014, doi: 10.1103/PhysRevLett.112.234301.

[45] N. Kaina, M. Fink, and G. Lerosey, "Composite media mixing Bragg and local resonances for highly attenuating and broad bandgaps," *Sci. Rep.*, vol. 3, pp. 1–7, 2013, doi: 10.1038/srep03240.

[46] F. Lemoult, N. Kaina, M. Fink, and G. Lerosey, "Wave propagation control at the deep subwavelength scale in metamaterials," *Nat. Phys.*, vol. 9, no. 1, pp. 55–60, 2013, doi: 10.1038/nphys2480.

[47] P. A. Deymier, *Acoustic Metamaterials and Photonic Crystals*. 2013.

[48] H. M. Lee, L. Bin Tan, K. M. Lim, and H. P. Lee, "Acoustical performance of a sonic crystal window," *Int. J. Mech. Eng. Robot. Res.*, vol. 6, no. 1, pp. 6–10, 2017, doi: 10.18178/ijmerr.6.1.6-10.

[49] J. P. Dowling, "Sonic band structure in fluids with periodic density variations," *J. Acoust. Soc. Am.*, vol. 91, no. 5, pp. 2539–2543, 1992, doi: 10.1121/1.402990.

[50] R. Martínez-Sala, J. Sancho, J. V. Sánchez, V. Gómez, J. Llinares, and F. Meseguer, "Sound attenuation by sculpture," *Nature*, vol. 378, no. 6554, p. 241, 1995, doi: 10.1038/378241a0.

[51] L. Fredianelli, A. Del Pizzo, and G. Licitra, "Recent developments in sonic crystals as barriers for road traffic noise mitigation," *Environ. - MDPI*, vol. 6, no. 2, pp. 1–19, 2019, doi: 10.3390/environments6020014.

[52] P. Jean and J. Defrance, "Sound propagation in rows of cylinders of infinite extent: Application to sonic crystals and thickets along roads," *Acta Acust. united with Acust.*, vol. 101, no. 3, pp. 474–483, 2015, doi: 10.3813/AAA.918844.

[53] M. Martins, L. Godinho, and L. Picado-Santos, "Numerical evaluation of sound attenuation provided by periodic structures," *Arch. Acoust.*, vol. 38, no. 4, pp. 503–516, 2013, doi: 10.2478/aoa-2013-0060.

[54] Y. Chong, "Sonic Crystal Noise Barriers," 2012, doi: 10.21954/ou.ro.0000add6.

[55] P. Gulia and A. Gupta, "Traffic Noise Control by Periodically Arranged Trees," no. October, 2016.

[56] E. C. Thom, "The Discomfort Index," *Weatherwise*, vol. 12, no. 2, pp. 57–61, 1959, doi: 10.1080/00431672.1959.9926960.

[57] B. E. N. Metamateriales, "48º congreso español de acústica encuentro ibérico de acústica."