# Optimizing Helmholtz oscillator-based sonic crystals for noise reduction

Abhinav M[a], Himangshu B Baskey[b], Prashant S Alegaonkar[a,*]

[a]*Department of Physics, Central University of Punjab, Bathinda, 151401, Punjab, India*
[b]*Directorate of Strategic Materials, DMSRDE (DRDO), G.T Road, Kanpur-208013, India*

**Abstract**

Acoustic metamaterials, also known as sonic crystals, have the ability to manipulate sound waves in unique ways. In this communication, we present the design and simulation of a rectangular Helmholtz oscillator-based sonic crystal operating in the frequency range of 1000 - 3000 Hz for noise reduction in industrial and environmental applications. By studying the effect of slit width, scaling factor, and lattice spacing on the shift in resonance frequency of the oscillators, we tune these materials for effective noise reduction in the desired frequency range. The sonic crystals exhibit variable band gaps from 1400 - 3500 Hz, with maximum insertion loss of 13dB. The use of multi-slitted and concentric geometries for oscillators, resulted in improvements in performance. Multi-slit geometry gave 18% increase in insertion loss over the single slit design. Our study provides a comprehensive analysis of the performance of Helmholtz oscillator-based sonic crystals and their potential for suppressing industrial and environmental noise, and represents a novel approach to the optimization of these materials.



## 1. Introduction

Noise pollution is a significant issue that affects various settings, including industrial plants, transportation systems, and residential areas. The health effects of noise exposure have been extensively studied by researchers, with evidence showing that progression of hearing loss at frequencies of 500, 1,000, 2,000, and 3,000 Hz eventually leads to impaired hearing [1]. This is due to the fact that the range of 600 - 4,000 Hz is considered to be the most important for intelligibility with 1,000 - 4,000 Hz being the most sensitive range of hearing [2]. Prolonged exposure to noises in these frequency ranges have been shown to have detrimental impacts on human health and well-being, including sleep disturbances, hypertension, noise-induced annoyance [3], fatigue, lack of concentration, and complications in autonomic functions [4]. The developing world is filled with noise sources such as construction equipment, industrial machinery, and traffic noise. Noise pollution from Industries (such as metal industry, wood processing shipping), Construction and Road noise have significant sound levels in the frequency range of 1000 - 3000 Hz [5][6] [7]. Attenuating these frequencies is the main objective of this work. Acoustic metamaterials, also known as sonic crystals, have garnered significant attention in recent years for noise reduction applications due to their ability to manipulate sound waves in unique ways. These materials exhibit bandgaps, which are frequency ranges in which sound waves are effectively attenuated, making them good sound attenuators [9] [10] [11]. One approach to designing sonic crystals for noise reduction is to use resonance of Helmholtz oscillators and the Bragg diffraction [12] [13] [14]. Helmholtz oscillators are resonators that consist of a rigid wall with a small opening, or neck, and a volume of air behind it. The resonance frequency of a general Helmholtz oscillator can be calculated using the equation:

*Corresponding author.
*Email address:* prashant.alegaonkar@cup.edu.in (Prashant S Alegaonkar)

$$f_0 = \frac{c}{2l}\sqrt{\frac{A}{V}}$$

where $f_0$ is the resonance frequency, $c$ is the speed of sound in the medium, $l$ is the neck length of the oscillator, $A$ is the cross-sectional area of the neck, and $V$ is the volume of the resonator chamber [15]. By optimizing the parameters of these oscillators, it is possible to tune the resonance frequency and, in turn, the bandgaps of the sonic crystal. The Bragg diffraction is a phenomenon that occurs when sound waves are reflected by a periodic structure, such as a lattice of Helmholtz oscillators. The Bragg diffraction condition for a periodic structure can be calculated using a using the Bragg equation :

$$2d\sin\theta = n\lambda$$

The center frequency of the bandgap ($f_{bg}$) in a periodic structure of sonic scatterers can be derived from the Bragg condition by considering the case of normal incidence. In this case, we obtain:

$$f_{bg} = \frac{c}{2a}$$

where $c$ is the speed of sound in the medium and $a$ is the lattice spacing. By satisfying this condition, it is possible to produce bandgaps in the frequency spectrum of sound waves.[8]

Other techniques have also been explored for producing bandgaps in sonic crystals, such as the use of negative stiffness or non-linearity [16]. These techniques can offer additional flexibility in the design of sonic crystals, but may also introduce additional complexity and challenges. However, in this research, we focused on the use of resonance of Helmholtz oscillators and the Bragg diffraction as the main mechanisms for producing bandgaps in our sonic crystals, as we aimed to study the effect of different parameters on the performance of these materials and identify new geometries that maximize insertion loss for better attenuation.

The insertion loss of a sonic crystal can be calculated using a the equation:

$$IL = 10.\log\frac{P_1}{P_0}$$

where $P_0$ is the sound pressure level without the presence of the sonic crystal and $P_1$ is the sound pressure level with the sonic crystal in place. This can provide a useful framework for understanding the performance of sonic crystals and identifying design strategies that maximize their effectiveness for noise reduction.

One key aspect of designing sonic crystals for noise reduction is the ability to accurately predict their performance using computational techniques . Finite element method (FEM) is a commonly used approach for this purpose. FEM works by dividing the domain of the partial differential equation into small pieces called elements with a mesh and using these elements to approximate the solution to the equation. It allows for the simulation of complex geometries and boundary conditions. In this research, we used FEM with the commercial COMSOL Acoustics software to conduct our simulations, which allowed us to study the effect of different parameters on the performance of the sonic crystal and identify new geometries that maximize insertion loss for better attenuation. Another important consideration in the design of sonic crystals is the size of the unit cells, which are the basic repeating units of the periodic structure. In this research, we studied the effect of unit cell size on the performance of the sonic crystal and identified a range of sizes that provide good performance.

The results of our simulations, showed that the proposed sonic crystals exhibit good band gaps, providing effective noise reduction in a wide range of frequencies. The design and simulation methodology presented in this paper can be applied to the optimization of other acoustic metamaterial configurations, adding to the understanding of their use for noise reduction in a variety of settings.

## 2. Methods

The design and simulation of the rectangular Helmholtz oscillator-based sonic crystal has been carried out using commercially available COMSOL simulation software. The target frequency range for noise reduction in this study was 1000

- 3000 Hz, and simulations were conducted over the broader range of 500 - 6000 Hz with steps of 50Hz.

A monopole point source was used as the sound source, placed 25 cm away from the center of the sonic crystal (SC). The receiver was an array of 5 microphones, spaced equally at 55 cm away from the center of the SC as shown in Figure 1. The final reading for the insertion loss was obtained by averaging the readings from the 5 microphones.

In COMSOL Acoustics, the finite element method (FEM) was used to solve the Helmholtz equation and the wave equation in the frequency domain in 2D. These equations are used to describe the behavior of sound waves as they propagate through a medium and can be applied to a wide range of acoustic phenomena.

The Helmholtz equation is given by:

$$\nabla^2 p + k^2 p = 0$$

where $p$ is the pressure field, $k$ is the wavenumber.

The wave equation is given by:

$$\frac{\partial^2 p}{\partial t^2} - c^2 \nabla^2 p = 0$$

where $p$ is the pressure field, $c$ is the speed of sound in the medium, and $t$ is the time coordinate, respectively. In our study, a fine mesh was used in the regions occupied by the SCs, with physics controlled meshing. A free triangular mesh was used for the remaining areas of the computational domain.

In order to study the effect of different parameters on the performance of the sonic crystals and identify new geometries that maximize insertion loss for better attenuation, we varied the slit width, volume, and lattice spacing of the oscillators. Plane wave boundary conditions were applied to the 2.5x2.5 m anechoic chamber in which the simulations were conducted, while acoustic hard boundary was applied to the scatterers.

To evaluate the performance of the sonic crystals, we calculated the insertion loss (IL), which allowed us to quantify the amount of noise reduction achieved by the sonic crystals at different frequencies.

To optimize the sonic crystals for noise reduction, we iteratively varied the design parameters and unit cell size and reran the simulations until we identified the configurations that provided the best performance. The results of our optimization process showed that the proposed sonic crystals exhibit excellent band gaps and are tunable across a wide range of frequencies, providing effective noise reduction in various settings.

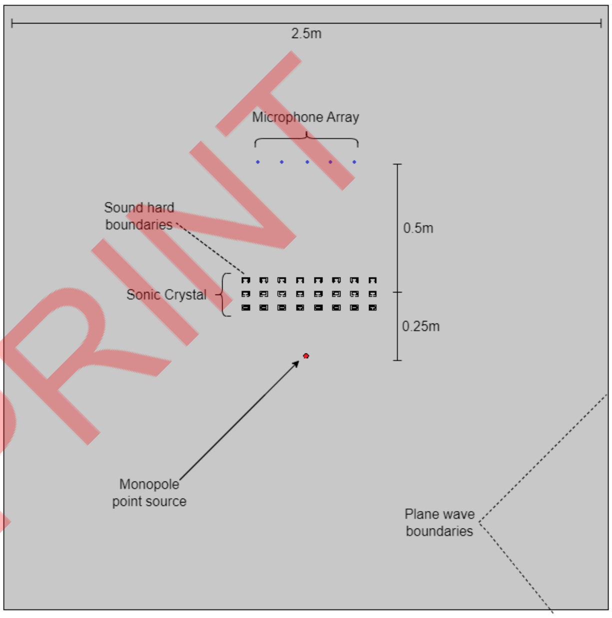


Figure 1: Computational domain and boundary conditions.(top view)

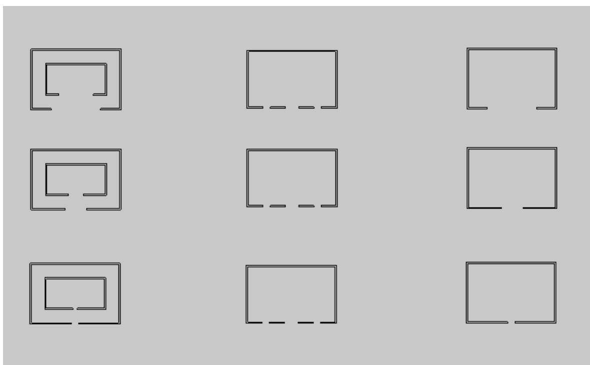

Figure 2: Geometry of different Helmholtz oscillators : Concentric, Multi-slit and single-slit.(top view)

During the design process, we noticed from the simulation results that each slit width corresponded to attenuation of the corresponding resonance frequency for the normal single slit resonator. Based on this insight, we developed the multi-slit resonators to provide improved attenuation across a wider range of frequencies. We also found that better attenuation may be achieved by increasing the surface area for sound dissipation or reflection, leading to the design of concentric rectangular oscillators.

In this study, three types of sonic crystals were investigated: concentric, multi-slit, and single-slit, these are represented in Figure 2. All S.C. designs consisted of 3 rows of 8 elements each. The material chosen for the scatterers was aluminium and the thickness of the walls are 1mm.

The concentric sonic crystals had inner and outer rectangles measuring 2 cm by 3 cm and 1 cm by 2 cm, respectively. The outer slits had widths of 2.5, 7.5, and 1.7 mm, while the inner slits had widths of 1.5, 5, and 1.2 mm row-wise. The lattice constant for these concentric sonic crystals was 5.73 cm.

The multi-slit sonic crystals also had a cross-section of 2 cm by 3 cm. The smaller slits had widths of 2.5 mm, while the center slits had widths of 4.5 mm. The lattice constant for these multi-slit sonic crystals was 6.85 cm.

Finally, the single-slit sonic crystals consisted of 3 rows of 8 elements each, with a cross-section of 2 cm by 3 cm. The slit widths for each row were 2.5, 7.5, and 1.7 mm, and the lattice constant for these single-slit sonic crystals was 5.73 cm.

These dimensions and measurements were arrived upon by analyzing factors such as the resonance frequency of Helmholtz oscillators, target attenuation frequency range, Bragg condition and practicality of design. The results of these analyses and simulations will be presented in a later section of the paper.

The methodology presented in this paper represents a novel approach to the optimization of Helmholtz oscillator-based sonic crystals for noise reduction, building upon and advancing previous research in the field. The design and simulation techniques described can be applied to the optimization of other acoustic metamaterial configurations, deepening our understanding of their use for noise reduction in a variety of settings.

## 3. Results

The results of the simulations of the proposed rectangular Helmholtz oscillator-based sonic crystals are presented in this section.

First, we examined the effect of slit width on the resonant frequency of the oscillators. As shown in Figure 3, an increase in slit width resulted in a corresponding increase in the resonant frequency of the oscillator.

Next, we investigated the effect of scaling on the resonant frequency of the oscillators. As shown in Figure 4, an increase in the scale of the oscillators resulted in a corresponding decrease in their resonant frequency.

We also examined the insertion loss at resonant frequencies as a function of frequency. As shown in Figure 5, the optimal scaling of the oscillators resulted in the best insertion loss at the resonant frequencies. We then compared the performance of the multi-slit, concentric, and plain lattice configurations. The multi-slit configuration showed the best results, with a bandgap from 1700 - 2900 Hz and a broad plateau of attenuation within the bandgap, as shown in Figure 6. The concentric configuration had a bandgap from 1400 - 2200 Hz with sharp drops in insertion loss and

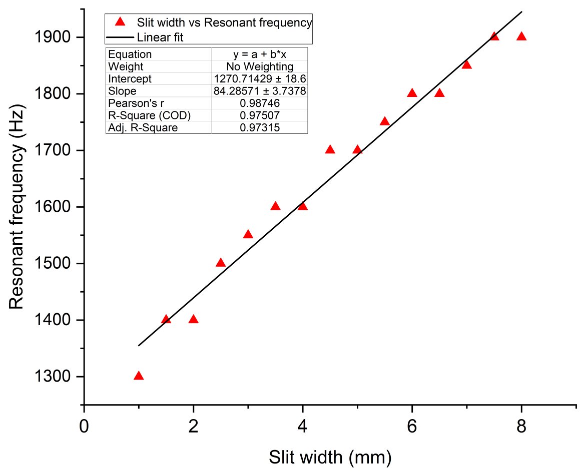


Figure 3: Slit-width vs resonant frequency

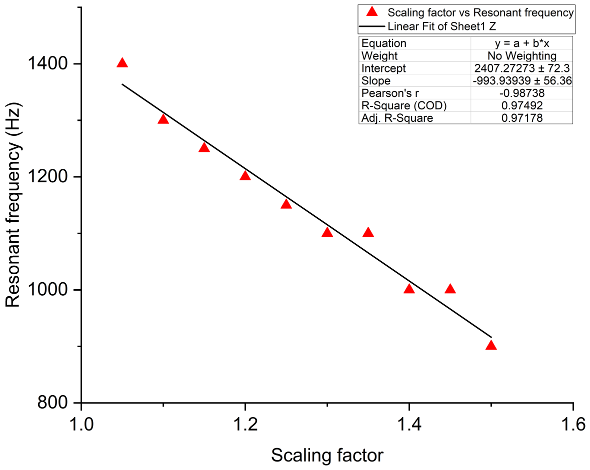


Figure 4: Scaling factor vs resonant frequency for slit-width 1.5mm

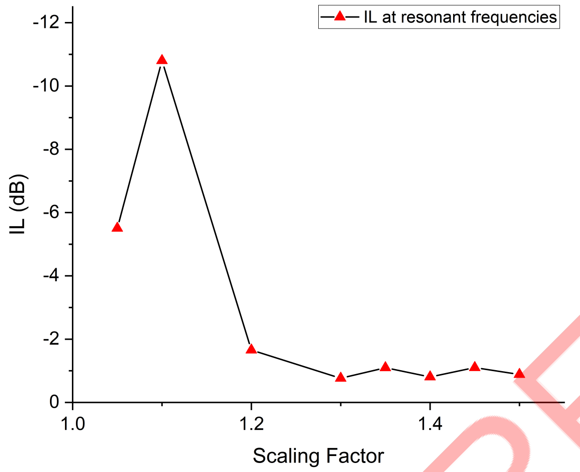


Figure 5: IL vs scaling factor at resonant frequencies of Helmholtz resonators.

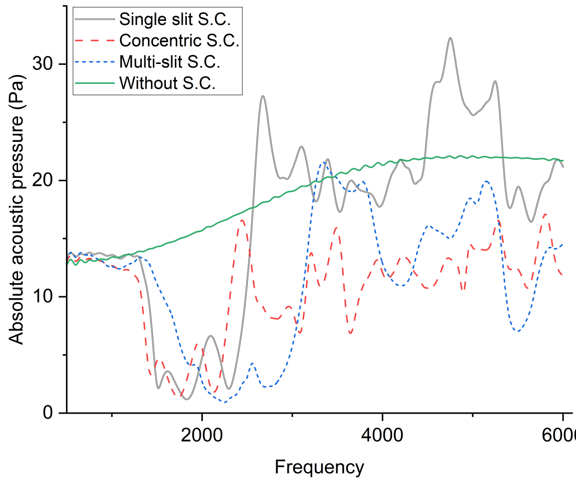


Figure 6: Performance comparison

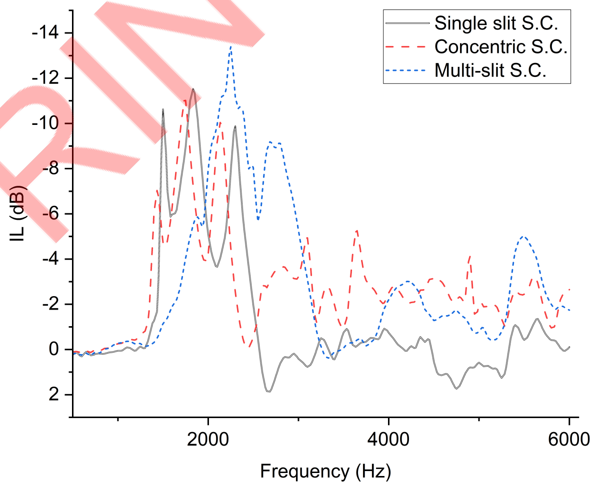


Figure 7: IL performance comparison

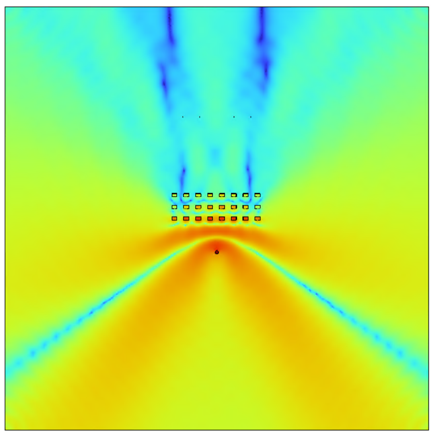

Figure 8: Performance at 2150 Hz for Multi-slit design. (Three rows, top view)

a few small peaks, as shown in Figure 5. Among the three, it showed the best attenuation at higher frequencies. The plain configuration also showed good results, similar to the concentric configuration but performance was worse at high frequencies.

We also analyzed the IL for the three types of lattices, as shown in Figure 7. Single slit SC gave good insertion loss in the range of 1400 - 2400 Hz. Multi-slit SC gave highest insertion loss of 13.5 dB at around 2400 Hz. These results provide further insights into the performance of the proposed sonic crystals and can inform the optimization of future designs.

These results give insight into the effectiveness of rectangular Helmholtz oscillator-based sonic crystals in suppressing noise over tunable range of frequencies.

## 4. Discussion

The results of this study show that the proposed rectangular Helmholtz oscillator-based sonic crystals can effectively reduce noise across a wide range of frequencies. By varying the design parameters of the oscillators, such as the slit width, volume, and lattice spacing, we were able to identify configurations that provided good band gaps and tunability.

Based on the finding that each slit width corresponded to attenuation of the corresponding resonance frequency, we developed the multi-slit resonators to provide improved attenuation across a wider range of frequencies. The results show that the multi-slit resonators had the best performance, with a bandgap from 1700 - 2900 Hz and a broad plateau region.

In addition, we found that increasing the volume of the oscillators can lead to improved attenuation. This is likely due to the increased surface area available for sound dissipation or reflection. Based on this insight, we designed the concentric rectangular oscillators, which showed a bandgap from 1400 - 2200 Hz with sharp drops and a few small peaks. The plain oscillators also showed good results, similar to those of the concentric oscillators as seen in Figure 6.

The results of this study demonstrate the effectiveness of the proposed sonic crystals for noise reduction. The design and simulation techniques described in this paper can be applied to the optimization of other acoustic metamaterial configurations, deepening our understanding of their use for noise reduction in industrial and environmental noise reduction settings.

## 5. Conclusion

In conclusion, our study has demonstrated the effectiveness of Helmholtz oscillator-based sonic crystals in reducing noise across a wide range of frequencies. By investigating the influence of various design parameters, we have identified optimal configurations for noise reduction, including the use of multi-slit resonators and concentric rectangular oscillators. Our optimization process, which utilized the finite element method and COMSOL Acoustics software, has provided valuable insights into the behavior of these acoustic metamaterials and can be applied to the optimization of other configurations.

Overall, this work represents a novel approach to the optimization of sonic crystals for noise reduction, building upon and advancing previous research in the field. Our work builds upon and advances previous research in the field, and provides valuable insight into the potential of Helmholtz oscillator-based sonic crystals for noise reduction in a variety of settings. The results of this study have practical implications for the design of noise control systems in a variety of settings, including transportation, industrial, and architectural contexts. Further research could explore the potential of these materials for noise reduction in three-dimensional settings and investigate their robustness and durability under real-world conditions. Exploring new resonator designs with complex internal geometries could also be interesting.




## Acknowledgements

The authors would like to express their gratitude to [insert names of funding agencies, colleagues, professors, etc. who helped with the research and writing process]. The support and guidance provided by [these individuals/organizations] was invaluable in the completion of this work.

The authors would also like to thank the reviewers for their insightful comments and suggestions, which helped improve the quality of the paper.

Finally, the authors would like to acknowledge the use of [any software or tools used in the research process]. Without the availability of these resources, the research presented in this paper would not have been possible.

## References


[1] Johnson, D.L., Papadopoulos, P., Watfa, N. Takala, J. 2001. Exposure Criteria, Occupational Exposure Levels. In: Occupational exposure to noise: evaluation, prevention and control. Ed: Goelzer, B., Hansen, C.H., Sehrndt, A.G.

[2] Salvendy, G. 2012. Handbook of Human Factors and Ergonomics. John Wiley Sons, New Jersey, 1752 pp

[3] Alves-Pereira, M. Castelo Branco, N.A.A. 2007. Vibroacoustic disease: Biological effects of infrasound and low-frequency noise explained by mechanotransduction cellular signaling. Prog. Biophys. and Mol. Biol. 93, 256–279.

[4] Muzet, A. 2007. Environmental noise, sleep and health. Sleep Medic. Rev. 11, 135–142. NAL (National Acoustics Laboratories). 2007. Series 153 – Ergotec - Variphone Personally Moulded Earplug. Hearing Protector Attenuation Testing. (January 19, 2014)

[5] K. Reinhold (2014) "Exposure to high or low frequency noise at workplaces: differences between assessment, health complaints and implementation of adequate personal protective equipment ," Agronomy Research, 12(3), pp. 895–906.

[6] Ballesteros, M. J., Fernández, M. D., Quintana, S., Ballesteros, J. A., González, I. (2010). Noise emission evolution on construction sites. Measurement for controlling and assessing its impact on the people and on the environment. Building and Environment, 45(3), 711–717. doi:10.1016/j.buildenv.2009.08.011

[7] Sandberg U (2003) The multi-coincidence peak around 1000 Hz in tyre/road noise spectra. In: Euronoise 2003, 5th European conference on noise control and AIA 2003, volume 498, Naples, Italy, 19–21 May 2003, pp. 1–8. Stuttgart: S. Hirzel Verlag.

[8] Lee HM, Lim KM, Lee HP. Environmental and sound divergence effects on the performance of rectangular sonic crystals with Helmholtz resonators. Journal of Vibration and Control. 2018;24(12):2483-2493. doi:10.1177/1077546316688422

[9] Dowling J (1992) Sonic band-structure in fluids with periodic density variations. Journal of the Acoustical Society of America 91(5): 2539–2543.

[10] Sanchez–Perez J, Caballero D, Martinez–Sala R, et al. (1998) Sound attenuation by a two dimensional array of rigid cylinders. Physical Review Letters 80(24): 5325–5328

[11] Kushwaha M (1997) Stop-bands for periodic metallic rods: Sculptures that can filter the noise. Applied Physics Letters 70(24): 3218–3220.

[12] Krynkin A, Umnova O, Chong A, et al. (2010) Sonic crystal noise barriers made of resonant elements. In: Proceedings of 20th international congress on acoustics, Sydney, Australia, 23–27 August 2010, pp. 1–6. New York: Curran Associates, Inc.

[13] Koussa F, Defrance J, Jean P, et al. (2012) Transport noise reduction by low height sonic crystal noise barriers. In: d'coustique SF (ed.) Acoustics 2012. Nantes: Australian Acoustical Society.

[14] Castineira–Ibanez S, Rubio C and Vicente Sanchez–Perez J (2015) Environmental noise control during its transmission phase to protect buildings. Design model for acoustic barriers based on arrays of isolated scatterers. Building and Environment 93(2): 179–185

[15] Everest FA and Pohlmann KC (2009) Master Handbook of Acoustics, 1st edition. New York: McGraw Hill.

[16] Hamham EM, Jimenez N, Pico R, et al. (2015) Nonlinear self-collimated sound beams in sonic crystals. Physical Review B 92(054302): 1–6.