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EXPERIMENTAL AND NUMERICAL ANALYSIS OF SONIC CRYSTAL NOISE BARRIERS WITH HYBRID SCATTERERS

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ABSTRACT

Sonic crystals (SC) have emerged as a promising alternative to solid noise barriers, offering comparable attenuation properties with improved design flexibility. This study presents the design and analysis of a sonic crystal noise barrier covered with absorbing material to reduce urban traffic noise. The scatterers are designed to meet urban aesthetic requirements, with a maximum height of 1 m and a diameter of 8 cm.

Numerical simulations and experimental work were conducted to evaluate the sound absorption and insertion loss of the barrier. The results highlight the distinct roles of the rigid core and absorbing material layer, showing significant noise attenuation across a wide frequency range.

This research demonstrates the potential of combining absorbing material with rigid structures to develop effective noise barriers for urban environments. Furthermore, it details nonstandard methods to test the attenuation of the barrier. The findings contribute to advancing the practical application of sonic crystals in addressing traffic noise challenges while maintaining aesthetic and functional considerations

Keywords: Sonic crystal, urban noise, porous material, FEM, alpha cabin

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1. INTRODUCTION

Acoustic waves have been the focus of research for decades. Brillouin's classical work opened the field's possibilities with concepts like band gaps or the Brillouin zone, which can also be used in electromagnetic waves [1]. In 1987, the photonic crystal concept was first proposed to evaluate light's propagation inside a periodic structure [2]. Taking that work as inspiration, the concept of phononic crystal (PC) was born, with acoustic waves propagating inside periodic structures as well.

Phononic crystals are man-made composite materials consisting of periodically distributed scatterers in a matrix (fluid) with a high impedance, mass, and elastic moduli contrast to the host fluid, which can give rise to acoustic dispersions and band structures due to Bragg scattering [3]. Phononic crystals are mainly organized in three different distributions: one, two, and three dimensions (1D, 2D, 3D). The dimensions refer to the number of directions in which the crystal is periodic. Each of these tackles either pure or mixed transversal and longitudinal waves. [4]

The infinite repetition of the same unit cell or pattern constitutes a periodic system. This means that, at any location or portion of the system, the behavior is the same and is independent of its vicinity. The specific pattern that will be infinitely repeated is called a lattice. The space between individual unit cells in a lattice is called the *lattice constant* and is generally abbreviated with the symbol a. This is one of the most important things to consider when designing the SC. a will, in theory, determine the first Bragg band gap (BG) [5]. This means that the spacing between unit cells in rigid sonic crystals will establish the frequency range where acoustic waves are not able to propagate. a and the frequency relate to each other in the equation:

$$f_c = \frac{c}{2a} \tag{1}$$

where f_c is the central frequency of the first Bragg-BG, and c is the speed of sound in the propagating medium.

Another important geometric parameter is the *filling fraction*, abbreviated with ff. This value is the amount of volume the scatterers occupy relative to the total volume of the sonic crystal. For a 2D sonic crystal with a rectangular lattice pattern, it can be calculated as:

$$ff = \frac{\pi r^2}{a^2} \tag{2}$$

where r is the radius of the scatterers, with a constant lattice constant a. If the filling fraction increases, it means that the scatterers occupy more of the total volume. As shown in equations 1 and 2, the effective frequency range that the noise barrier (NB) will attenuate is governed by the geometric parameters. Bevilacqua and her team [6] performed a study campaign to see the change in the insertion loss of a wooden SC when the radius and spacing of the unit cells are changed. They demonstrated that thinner scatterers shift the sound attenuation to higher frequencies. If the aim is to attenuate low frequencies in the unit cells, a larger diameter size should be considered.

While rigid sonic crystals offer promising noise reduction capabilities, further advancements can be achieved by incorporating additional functionalities into their design. There have been works that focus on changing the shape of the scatterer, like the one made by [7]. They found that by doing this, they have more versatility in changing the band gap without having to modify a or ff. Another option to enhance the acoustic response of the scatterers is to take advantage of its resonance. This means not only improving the spacing or the geometry of the inclusions but also taking advantage of another property. [8,9] used a split ring resonator to enhance the properties of the sonic crystal. When the opening is carefully selected to have a resonance under or over the Bragg BG, the barrier in theory will have a wider bandgap. Another approach is to coat the scatterer with a porous material. Umnova et al. [10] Their findings show that covering the cylinders with a porous material makes the array insertion loss more uniform in frequency.

What these researchers can tell is that SC is an effective technique to combat railway and traffic noises. They are more aesthetically pleasing than solid NB and require less material to build. However, to have good attenuation properties in a wide frequency range using rigid scatterers is not enough. Early improvements to SC focused on geometric parameters, that are effective in some applications. For traffic use, it is necessary to combine multiple strategies in one inclusion in a way that guarantees the necessary properties.

This study focuses on the design and evaluation of a sonic crystal (SC) enhanced with an absorbing material to improve its performance against traffic noise. Given the intended outdoor application, porous concrete was selected as the preferred material due to its sound absorption properties and durability. To assess the effectiveness of the proposed configuration, a nonstandard experimental approach was employed. The methodology utilizes an alpha cabin as a controlled noise source, with the SC noise barrier mounted at the cabin door. An array of microphones is used to measure the attenuation induced by the scatterers, with focus on insertion loss. In addition to the experimental campaign, numerical models of the SC array are developed to compare with the measured results, providing further insight into the barrier's acoustic performance and the impact of the hybrid material composition.

The paper from this point forward is distributed as: Sec. 2 introduces the dimensions of the SC, materials used, and how they were characterized numerically and experimentally. Sec. 3 explains the experimental method to test the SC with the alpha cabin. Sec. 4 details the how the array was modeled using FEM. The experimental and numerical results are presented in sec. 5. Finally, sec.6 discusses the results.

2. SONIC CRYSTAL DESIGN AND MATERIAL CHARACTERIZATION

2.1 Sonic crystal unit cell and array dimensions

In this study, a square lattice sonic crystal (SC) was designed with scatterers consisting of a PVC pipe core (6 cm diameter) surrounded by a 1 cm thick polyester fiber absorbing layer, resulting in a total scatterer diameter of 8 cm. While the final SC design will use rigid and porous concrete, the polyester fiber layer was chosen for experimental testing in the alpha cabin as a proof of concept. Numerical simulations compare the acoustic behavior of both materials to assess their performance. In Fig. 1 the diagram of the scatterer is represented. In Tab. 1 the acoustic parameters of the configuration are given. The chosen lattice constant is because for traffic noise the most critical frequencies are close to 1000 [Hz], and to the geometric constraints of the experimental setup.

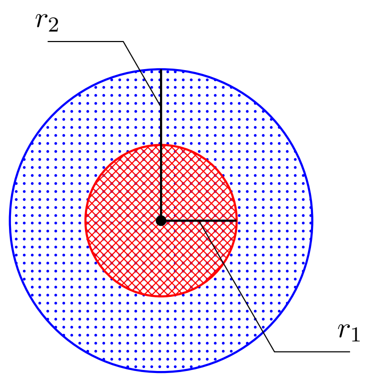

Figure 1: Top view of the scatterer

Table 1: Array geometric and acoustic parameters

Parameter	Value	Description
r_1	3 [cm]	radius rigid inner core
r_2	4 [cm]	radius complete scatterer (core + absorbing layer)
a	15 [cm]	lattice constant
f_c	1143 [Hz]	central Bragg frequency
ff	1.4	filling factor

2.2 Experimental material characterization

The characterization of the absorbing material was conducted in the Alpha cabin following ISO 354:2003 [11]. This standard specifies the use of a reverberation room and a 12 m² sample to determine a material's sound absorption coefficient (α) based on its reverberation time. Although the standard requires a large test sample, the polyester fiber layer was characterized inside the Alpha cabin, which also generates a diffuse sound field, ensuring the validity of the method. In this case, the sample size was reduced to 1.2 [m^2].

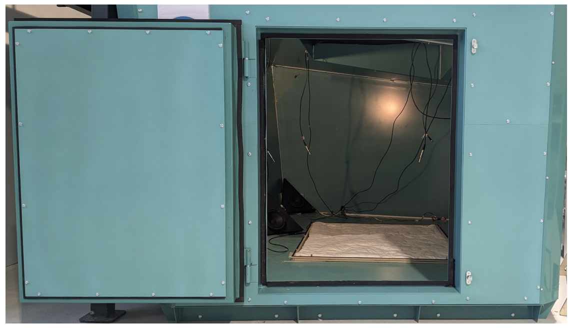

Figure 2: Polyester fiber sound absorption coefficient measures in an Alpha cabin using ISO 354:2003 standard.

To calculate α, two measurements were performed. First, the reverberation time was measured inside the empty Alpha cabin. Then, the test was repeated with the material inside. By comparing the reverberation times from both cases and applying Sabine's formula (Eq. 3), the absorption coefficient was determined.

$$TR_{60} = \frac{0.161 \times V}{S \times \alpha}. \tag{3}$$

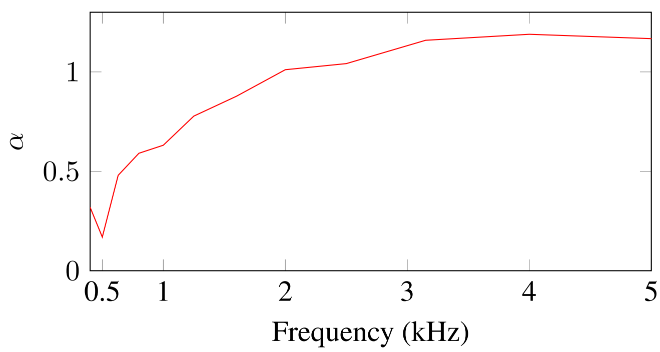

Figure 3: Polyester fiber sound absorption coefficient results obtained in an Alpha cabin using ISO 354:2003 standard.

2.3 Miki Equivalent fluid models

Miki's equivalent fluid model [12] are empirical relationships that estimate the characteristic impedance and propagation constant of porous materials. Those depend on porosity, tortuosity, and a pore shape factor.

Miki proposes to use the following expressions for the wave number (k) and characteristic impedance (Z_c):

$$Z_c = \rho_0 c_0 \left(1 + 5.5(\times 3 \left(\frac{f}{\sigma}\right)^{-0.632} - i8.43(\times 3 \left(\frac{f}{\sigma}\right)^{-0.632}\right) \quad (4)$$

$$k = \frac{\omega}{c_0} \left(1 + 7.81(\times 10^3 \left(\frac{f}{\sigma}\right)^{-0.618} - \mathrm{i}11.41(\times 10^3 \left(\frac{f}{\sigma}\right)^{-0.618}\right) \quad (5)$$

The selected absorbing material can be accurately represented using this model.

3. EXPERIMENTAL METHOD

Noise barriers are typically tested *in situ* following the ISO 10847:1997 standard. However, since the current design is still under development, performing full-scale tests for every iteration would be impractical. Instead, a non-conventional method is proposed to obtain reliable data on noise attenuation rapidly. The key component, besides the sonic crystal (SC), is an Alpha cabin, whose characteristics are summarized in the following table and visible in Fig. 4.

Table 2: Alpha cabin characteristics

Parameter	Value
Internal volume	9 m^3
Maximum SPL	115 dB
Frequency range	400–10,000 Hz

To assess the effectiveness of the sonic crystal, insertion loss (IL) is selected as the performance metric, defined by:

$$IL = SPL_{\text{without}} - SPL_{\text{with}} \quad [\text{dB}] \quad (6)$$

This requires measuring the sound pressure level (SPL) in two configurations: (i) with the SC mounted on the Alpha cabin door and (ii) without it. The SPL is recorded using an array of seven PCB Piezotronics 130F20 microphones, positioned 60 cm from the outermost scatterer of the SC.

The system is controlled via a DEWESoft Sirius XHS LV, which generates a white noise signal for the speakers and processes input from the microphone array.

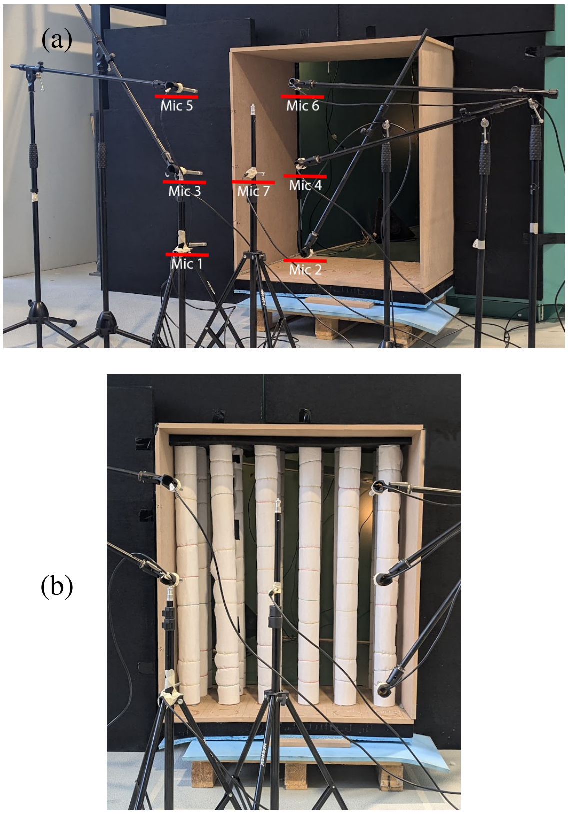

Figure 4: IL experimental setup: (a) Empty Alpha cabin with SC frame; (b) SC covered with polyester fiber absorbing material.

4. NUMERICAL MODELING

To validate and understand the behavior of 2D sonic crystals two-dimensional FEM simulations were employed. By using this technique, it is possible to test parameter changes quickly. The simulation setting for this section is relatively simple and is used with some adaptions for the studied cases.

Fig. 1 shows the geometries for the simulation. r_1 is the radius of the rigid cavity inside the scatterer, and r_2 is the radius of the full scatterer (core + absorbing material). Likewise, as with the experimental method, the analysis parameter to assess the barrier's performance is Insertion Loss (IL).

The modeled geometry is three scatterers in a row with infinite periodic conditions to the sides. The system is excited by a plane wave coming from the bottom edge of the model.

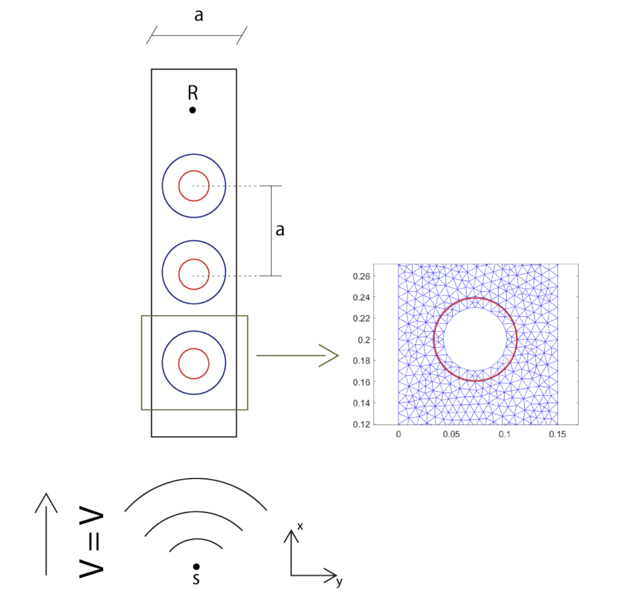

Figure 5: FEM model example for the numerical analysis.

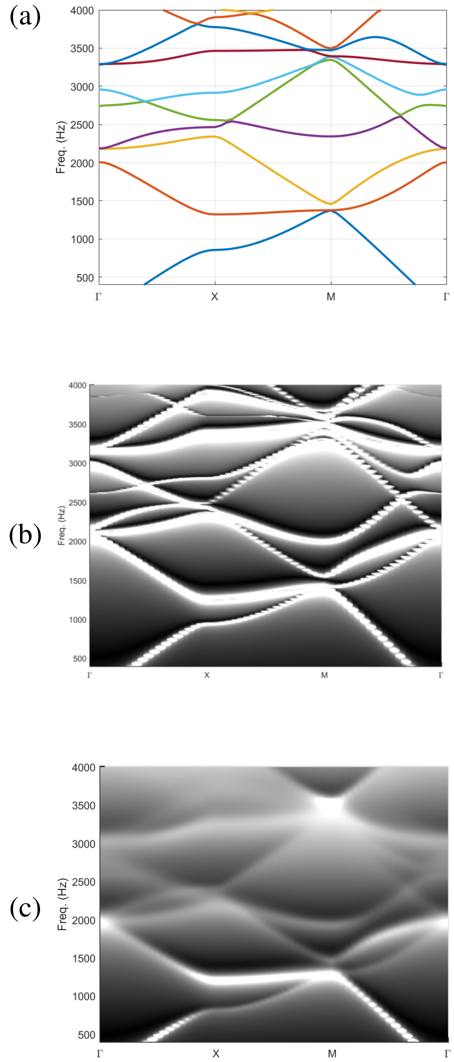

Figure 6: Dispersion relation curves for the different configurations: (a) normal eigen frequency analysis for a 8 cm rigid scatterer SC; (b) fine band analysis of a 8 cm rigid scatterer SC; (c) fine band analysis of a 6 cm rigid scatterer SC covered with 1 cm thick polyester layer.

5. RESULTS

Dispersion relation curves were obtained for both the rigid and porous cases to understand the wave propagation characteristics of the sonic crystal (SC) and identify the expected frequency range of the band gap. The rigid case was analyzed using eigenfrequency analysis, providing a direct calculation of the dispersion curves. In contrast, the porous case required a frequency-dependent approach, where each frequency was evaluated separately, and the contribution of the modes was analyzed independently.

Figure 6 presents the dispersion relation curves for both configurations. The results highlight differences in wave propagation characteristics between the two cases, with the introduction of porous material influencing the modal contributions, making them weaker. By this behavior, it is possible to expect a considerable energy reduction starting around 600-700 Hz. These findings provide insight into the type of acoustic response expected from the SC and indicate the frequency range where attenuation effects should be most pronounced.

Experimental tests were conducted to measure the SC's acoustic attenuation performance. Figure 7 presents an overview of the microphone measurements collected during the experimental setup.

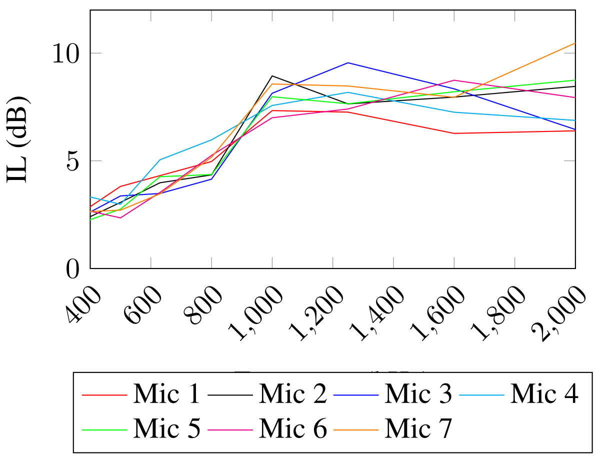

Figure 7: IL results per microphone for the absorbing layer configuration SC.

With these results, it is possible to see the contribution from both the Bragg scattering and the absorbing layer. As predicted, there is a peak of absorption between the 1000 to 1200 Hz 1/3 octave band, this is thanks to the interference caused by the rigid core. After the bandgap, the attenuation stagnates with a high value, which is approximately the same behavior as the experimental sound absorption coefficient curve visible in Fig. 3.

The IL experiments are then correlated with a FEM analysis. The results of the comparison are visible in Fig. 8

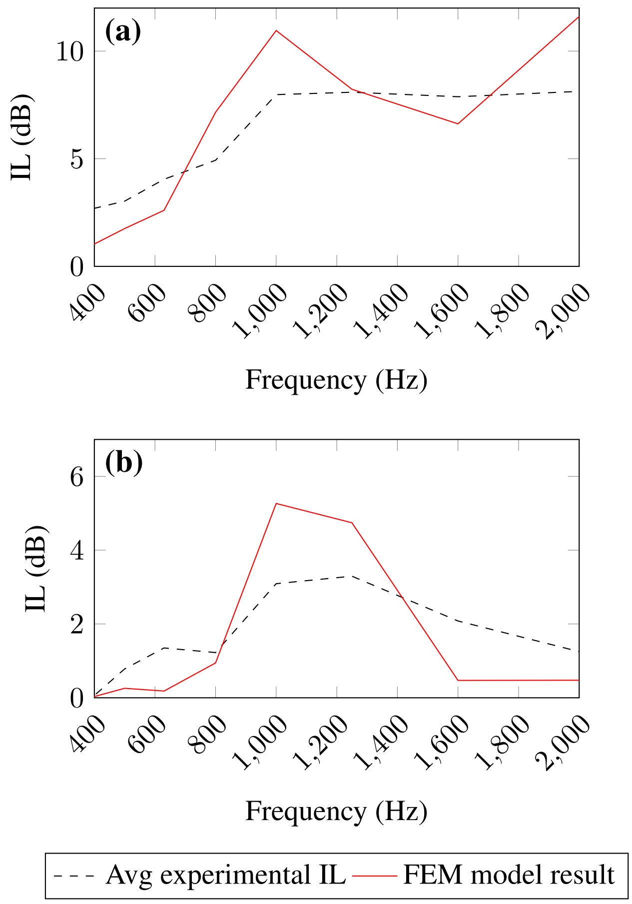

Figure 8: Average experimental IL results compared with numerical FEM results for the configurations: (a) 6 cm rigid core scatterer covered with 1 cm polyester fiber, and (b) 6 cm rigid scatterer.

The numerical results align with the experimental findings and the dispersion relation predictions, confirming the role of the porous material in enhancing sound attenuation. The simulations provide a detailed understanding of the SC's acoustic behavior, reinforcing the observed improvements in noise reduction.

The experimental results reveal key differences in insertion loss between the two cases, demonstrating the impact of the porous material on acoustic attenuation. The presence of the absorbing layer enhances attenuation, shifting and broadening the band gap, as anticipated from the dispersion analysis. These observations provide strong experimental support for the effectiveness of integrating porous materials into the SC design.

6. FINAL REMARKS

The numerical results align closely with both the experimental findings and the dispersion relation predictions, confirming the role of the porous material in enhancing sound attenuation. The consistency of these results underscores the potential of combining porous materials with sonic crystal structures for effective noise control solutions. The simulations contribute to a detailed understanding of the SC's acoustic behavior, suggesting that this design approach could be a viable strategy for mitigating urban noise pollution, particularly from traffic sources.

7. ACKNOWLEDGMENTS

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