Numerical Modeling of Phononic Crystal-based Ventilated Noise Barrier for Traffic Noise Attenuation

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Abstract

Traffic noise pollution has represented a significant challenge for modern societies, requiring the development of innovative noise mitigation strategies. In the last decades, intensive research has been conducted into the design and novelty of noise barriers but there still lacks a simultaneous proper air ventilation for a comfortable environment and lower visual impact. This study presents a comprehensive numerical investigation into the design and performance of ventilated acoustic metamaterial noise barriers to mitigate urban noise while maintaining adequate ventilation. Considering the recent advancements in acoustic metamaterials and computational modeling techniques, a preliminary design proposed and numerically investigated the periodically arranged noise barriers in the open air which will also allow ventilation. To address this problem, COMSOL Multiphysics software is used to design and analyze the performance of noise barriers numerically. The approach involved modeling a unit cell of noise barriers placed periodically in outdoor environments to facilitate both noise attenuation and ventilation. The finite element approach was used to model the barrier unit cell design, focusing on the numerical calculation of the unit cell sound transmission loss (STL). In our work, the Pressure Acoustics Module is utilized to simulate and analyze the acoustic bandgap frequencies of the metamaterial barriers. Additionally, Narrow Region Acoustics is considered to model viscous and thermal boundary-layer-induced losses in channels and ducts of constant cross-section. COMSOL's built-in artificial domain Perfectly Matched Layers (PML) is used to simulate the effect of an infinite domain and absorb outgoing waves to prevent artificial reflections at the boundaries of the computational domain. Periodic boundary conditions (PBC) and Floquet periodicity are used to model unit cells as infinitely repeating structures. For performance analysis, a finite-element approach has been applied to model the design of the barrier, and the Sound Transmission Loss (STL) of the unit cell has been computed numerically. To validate STL and study bandgaps, dispersion curves have been generated for the unit cells with varying configurations. A parametric analysis is also carried out to investigate the effects of the unit cell's geometric size and the acoustic incident angle on the effectiveness of noise reduction. Sound waves have been attenuated within the 1000-2200 Hz frequencies without disturbing the airflow for ventilation. Finally, evaluating the effect of the finite size of the noise barrier on the STL, highlights how in-situ performance may vary as compared to the predicted performance in idealized infinite conditions.

Keywords: Ventilated Noise Barriers, Acoustic Metamaterials, Phononic Crystals, Numerical Modeling, Sound Transmission Loss, COMSOL Multiphysics

Introduction

An effective method for reducing noise is the use of sound barriers. A sound barrier is a structure between the source and the receiver that reduces the quantity of noise entering the protected area by reflecting and absorbing sound using the material's acoustic characteristics [1].

The materials commonly used to construct noise barriers include concrete, glass, and steel. Each of these materials offers different properties that can be adapted to specific noise control needs. Concrete is often used for its dense mass, which provides significant sound insulation. Glass, when treated or laminated, can provide both transparency and acoustic benefits, while steel can be made into perforated or composite shapes to improve sound absorption.

These traditional materials and methods form the basis of current noise mitigation strategies, although ongoing research seeks to develop more effective and sustainable solutions, including the use of advanced materials such as acoustic metamaterials and phononic crystals. The implementation of noise barriers in urban environments faces significant challenges due to structural and environmental constraints. To limit noise barrier height to 2-3 meters, engineers must contend with high wind loads that induce substantial rotational forces, potentially compromising structural integrity. Additionally, these barriers can obstruct airflow, affecting natural ventilation and creating high-pressure zones that hinder wind deflection as shown in Figure 1.

The bulky design required to withstand these forces not only increases material usage and costs but also imposes a high visual impact on the landscape, detracting from aesthetic and environmental considerations. These challenges underscore the need for innovative solutions that balance noise reduction with structural feasibility, ventilation, and visual impact.

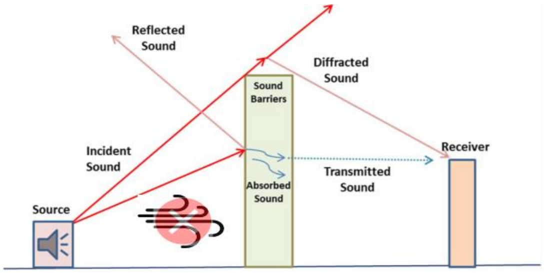

Figure 1: Schematics showing how traditional barriers have constraints [WWW.DUKEACRYLIC.COM]

The term "acoustic metamaterials" refers to artificial composite structures that have recently garnered much interest from researchers. These structures exhibit improved physical behaviors for attenuating noise [2]. These technologies can be implemented to attenuate noise but can face a challenge in maintaining airflow at the same time. Proposed metamaterial air-transparent soundproof solutions can be found in [3,4,5].

These metamaterials-based ventilated panels have been proposed that have high noise reduction properties in certain frequency bands while allowing ventilation but there is still a lack of acoustic metamaterials-based ventilated noise barriers for road traffic noise. This paper proposes a design of a road noise barrier and a numerical guideline for evaluating the performance of a ventilated noise barrier. As a first step, the design of a ventilated barrier is proposed then eigenfrequency analysis is conducted for stopband analysis.

Secondly, a numerical model is proposed to evaluate the Sound Transmission Loss (STL) for infinite and finite unit cells.

Finally, a numerical comparison between infinite and finite-size models highlights how in-situ performance may vary compared to the predicted performance in idealized infinite conditions.

Design and Methodology

Design

To address the challenges posed by traditional noise barriers, an innovative solution involves the use of metamaterial ventilated barriers, specifically Sonic Crystal-based noise barriers. Sonic Crystal-based barriers consist of periodic structures made up of regularly spaced unit cells. These cells are designed to interact with sound waves in a precise manner, allowing for the control of sound transmission and the achievement of sound insulation.

The structure manipulates wave behaviour through various mechanisms such as diffusion, interference, resonance, and absorption. These mechanisms enable the barriers to target specific frequency ranges, providing effective noise reduction adapted to environmental conditions. Unlike conventional noise barriers, which require significant material usage to achieve the desired noise attenuation, Sonic Crystal-based barriers can be designed to be more material-efficient. The precise construction of the unit cells allows significant noise reduction with less material, contributing to sustainability goals by reducing environmental impact.

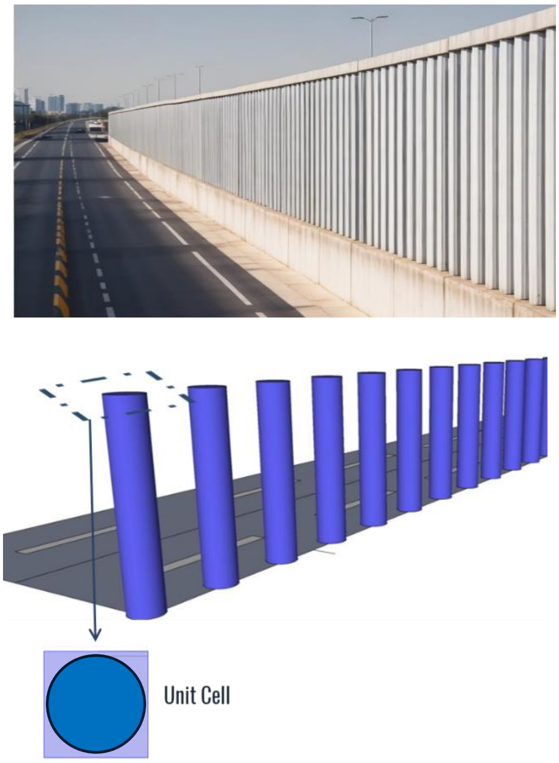

Figure 2: Animated View of proposed barriers installed on the highway

These barriers can be designed to maintain or even improve natural ventilation, thus avoiding the high-pressure zones associated with traditional solid barriers. In addition, their less bulky design can reduce the visual impact on the landscape, providing an aesthetically pleasing alternative to traditional noise barriers. The proposed design consists of a periodic arrangement of inclusions, so-called barriers. From Figure 2, one barrier represented as the unit cell is modeled to computed STL and then compared to the stopband calculated with the dispersion diagram.

The analyses that were conducted are the following:

1. The unit cell analysis for stopband prediction
2. Infinite modeling of unit cells (Idealized)
3. Finite modeling of unit cells (In situ)
4. Sound Pressure level

Acoustics Simulation Using COMSOL Multiphysics

In this study, COMSOL Multiphysics was employed to simulate the propagation of acoustic waves through a rigid medium using the Acoustics Module. The objective is to model the behavior of a plane wave incident on an infinitely rigid boundary, focusing on the frequency domain analysis.

The primary module used in this simulation was the Acoustics Module in COMSOL. Within this module, the Pressure Acoustics, Frequency Domain physics interface was selected to handle the acoustic pressure fields and solve the governing equations for wave propagation as shown in Figure 3.

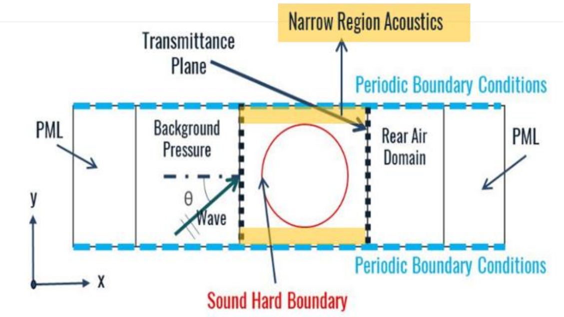

Figure 3: Conceptual Model for Unit Cell Modeling

This interface is well-suited for solving the Helmholtz equation, which governs sound wave behavior in a frequency-dependent manner.

Narrow Region Acoustics is considered to model viscous and thermal boundary-layer-induced losses in channels and ducts of constant cross-section. COMSOL's built-in artificial domain Perfectly Matched Layers (PML) is used to simulate the effect of an infinite domain and absorb outgoing waves to prevent artificial reflections at the boundaries of the computational domain. Periodic boundary conditions (PBC) and Floquet periodicity are used to model unit cells as infinitely repeating structures. For performance analysis, a finite-element approach has been applied to model the design of the barrier, and the Sound Transmission Loss (STL) of the unit cell has been computed numerically.

Mathematical Description of the Problem

The acoustic wave propagation is governed by the Helmholtz equation, which describes the spatial distribution of pressure p in a domain subject to harmonic time variation at angular frequency ω:

$$\nabla^2 p + k^2 p = 0 \qquad (1)$$

$$\omega = k\,c \qquad (2)$$

$$\omega = 2\,\pi f \qquad (3)$$

$$k = \frac{2\pi f}{c} \qquad (4)$$

where:

- p is the acoustic pressure (Pa),
- k is the wavenumber (1/m),
- c is the speed of sound in the medium (m/s),
- ω is the angular frequency (rad/s),
- f is the frequency of the incident wave (Hz).

The boundary condition for an infinitely rigid surface can be modeled as a Neumann boundary condition, where the normal derivative of the acoustic pressure is zero at the rigid surface. This boundary condition reflects the fact that no acoustic velocity penetrates the rigid boundary. A plane wave is assumed to be an incidence in the domain as:

$$p_{\mathrm{inc}}(x,t) = p_0 e^{i(k\cdot r-\omega t)} \qquad (5)$$

where p_0 is the amplitude of the incident wave, k is the wave vector, and r is the position vector.

Unit Cell Model

The modeling of the proposed design for the Sonic Crystal-based noise barrier involves the modeling and design of a unit cell that serves as the fundamental building block of the barrier. Considering there are an infinite number of these barriers installed along the highway, modeling one barrier as a unit cell will give global and local sound attenuation characteristics of all barriers, thanks to Floquet's periodic boundary conditions.

In simple 1D form, where the function is periodic in a domain of length L, the condition becomes:

$$u(x+L) = u(x)e^{ikL} \qquad (7)$$

The Floquet periodic boundary conditions allow for a reduction in computational effort while still capturing the essential physical behaviors, such as wave propagation and attenuation, across the entire array of barriers.

This is demonstrated by an array of 4x8 unit cells shown in Figure 4.

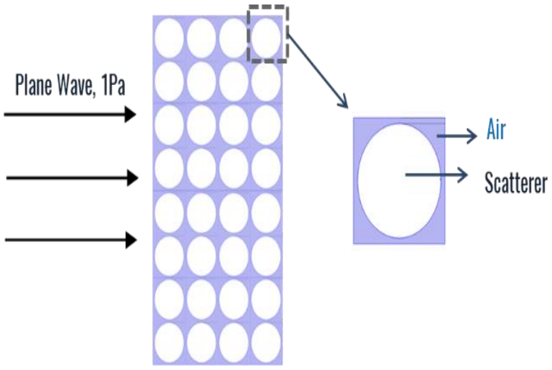

Figure 4: Proposed preliminary unit cell design

Infinite Unit Cell Model

This model integrates pressure acoustics and narrow region acoustics, considering thermo-viscous losses that can affect the barrier's performance. This comprehensive approach ensures that the model accurately captures the interaction between sound waves and the barrier structure. The interaction between sound waves and the barrier is modeled with a focus on the geometry and periodicity of the unit cells. This includes assessing how sound waves scatter, interfere, and are absorbed by the structure. In this idealized model, the barrier is assumed to be infinitely periodic, which simplifies the analysis and provides insight into the fundamental acoustic properties of the unit cell design.

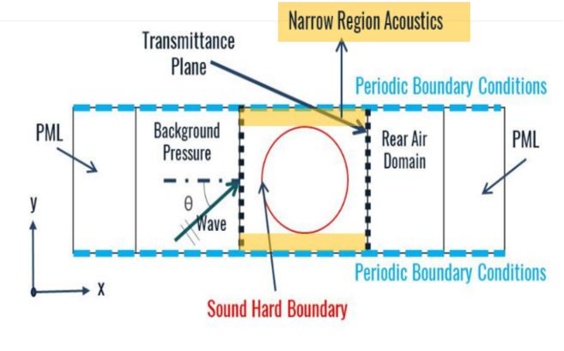

Figure 5: Conceptual Model for Infinite Unit Cell Modeling

Finite Unit Cell Model

The finite Unit Cell Model is a more realistic model that considers the barrier under actual conditions, including finite size height constraint, allowing for an accurate prediction of in-situ performance. The model is shown in Figure 6.

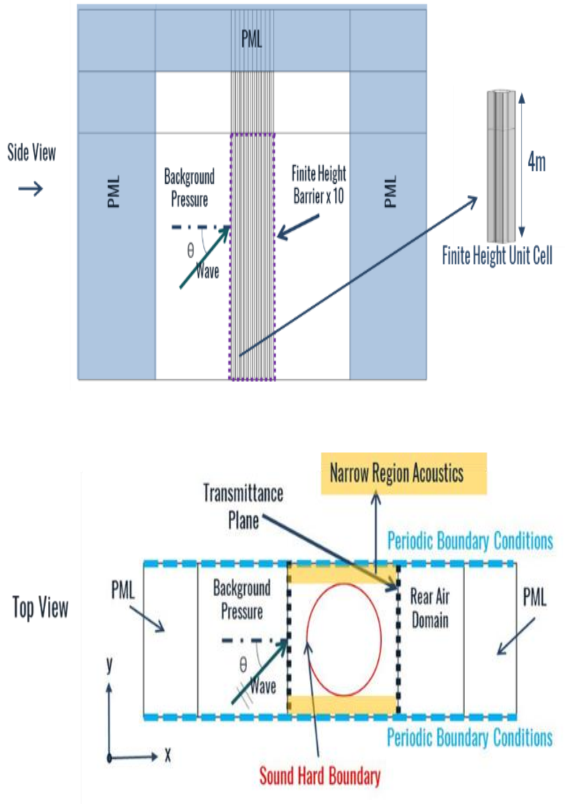

Figure 6: Conceptual Model for Finite Height Unit Cell

It also integrates pressure acoustics and narrow region acoustics, considering thermo-viscous losses that can affect the barrier's performance. The interaction between sound waves and the finite height barrier is modeled with a focus on the geometry and periodicity of the unit cells. This includes assessing how sound waves scatter, interfere, and especially are diffracted by the top of the structure.

Results

Stopband Analysis

The unit cell design is analyzed to identify stopbands—frequency ranges where no sound waves should pass. For this design, a stopband frequency range of 1250-2200 Hz has been identified as shown in Figure 7, which corresponds closely to the most prevalent frequencies found in traffic noise as shown in Figure 8 [6].

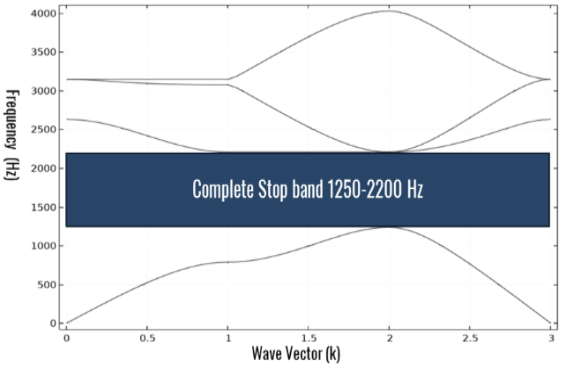

Figure 7: Stopband of the proposed unit cell

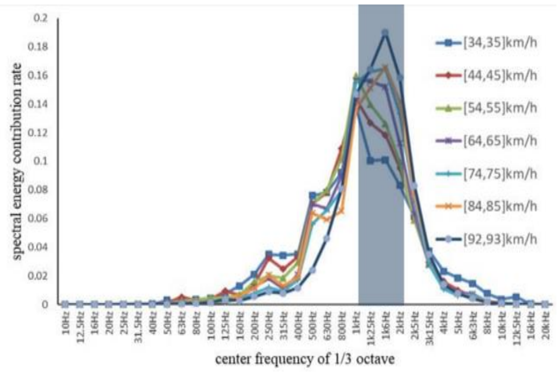

Figure 8: Road traffic noise spectrum [6]

Sound Transmission Loss Analysis for Infinite Unit Cell

In this study, the following hypotheses are considered:

- Periodic boundary conditions are assumed in the directions perpendicular to the wave incidence.
- Unit cells are assumed to extend infinitely in the vertical direction.
- The material is infinitely rigid.
- Thermo-viscous losses are accounted for in narrow regions.

The number of unit cells aligned along the direction of wave propagation significantly impacts the barrier's effectiveness. With fewer unit cells, there is a reduction in sound attenuation due to decreased opportunities for scattering of sound waves. This indicates that a minimum number of unit cells is necessary to achieve substantial noise reduction.

The spacing between unit cells can align with the wavelength of incoming sound waves, a condition that affects the frequency shift and can lead to constructive interference known as the Bragg Effect. This phenomenon occurs when the spacing between the unit cells coincides with the wavelength of the incident sound waves, resulting in enhanced reflection and scattering, thereby improving noise attenuation as shown in Figure 9.

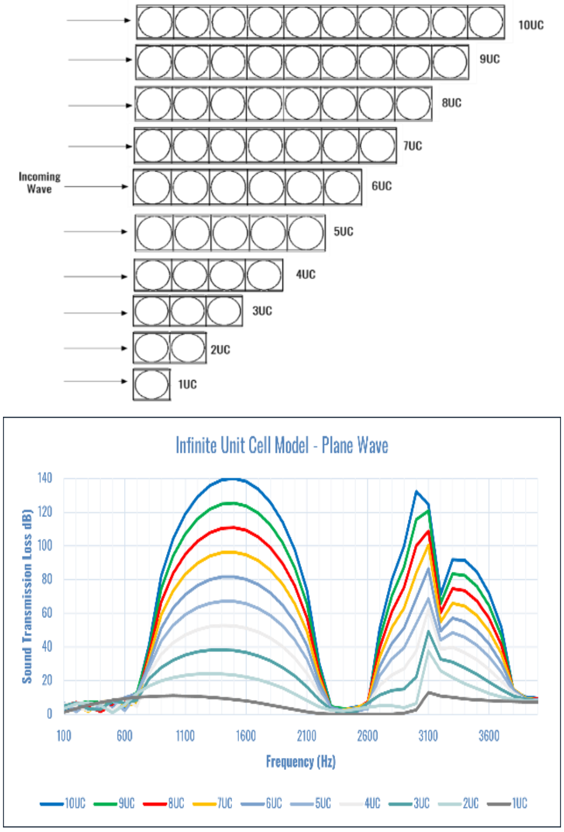

Figure 9: Sound Transmission Loss for 1 - 10 number of scatterers

For a configuration with 10 scatterers, a significant sound attenuation of around 140 dB was observed at the 1000-2000 Hz frequency range, indicating a high level of noise reduction. However, achieving such levels in practical scenarios may be challenging and warrants further investigation.

Sound Transmission Loss Analysis for Finite Unit Cell

The effectiveness of Sonic Crystal-based noise barriers is influenced significantly by their height, particularly when compared between idealized infinite height conditions and practical finite height implementations. When barriers are finite in height, they allow more sound waves to diffract over and around the structure. This diffraction leads to a reduction in the barrier's overall sound transmission loss (STL), as some portion of the sound energy bypasses the barrier instead of being scattered or absorbed by it. This is a critical factor that reduces the effectiveness of the barrier compared to an idealized infinite-height scenario.

In plane-wave behavior, the finite height of the barrier impacts the acoustic response, specifically leading to a decrease in STL as shown in Figure 9. This occurs because the finite height limits the physical extent to which the barrier can interact with the incident sound waves, reducing its capacity to attenuate sound across the entire wavefront.

These findings provide theoretical and practical insights into evaluating noise barrier effectiveness. Theoretical models often assume ideal conditions that maximize the noise attenuation potential. However, practical implementations must account for real-world factors such as finite barrier height, material limitations, and environmental conditions that can significantly impact performance.

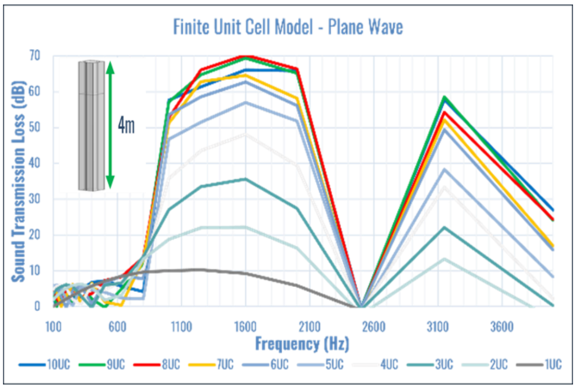

Figure 10: Sound Transmission Loss for 1 - 10 number of finite height scatterers

Figure 10 shows the sound transmission loss for varying numbers of unit cells (UCs) under plane wave conditions. The highest transmission loss is approximately 70 dB for 10-unit cells at the 1000-2000 Hz frequency range. When compared to the idealized case as in Figure 9, we observe a reduction in sound transmission loss for fewer unit cells. The following key points can be noted:

- The transmission loss increases significantly as the number of unit cells grows, particularly between 1000 Hz and 2000 Hz.
- The reduction factor in performance between the configurations is not uniform across different frequencies; larger discrepancies occur in the 500-1000 Hz range, where sound attenuation is most effective.

This indicates that while an idealized infinite array would theoretically perform better, the factor of reduction for real-world implementations of fewer unit cells varies with frequency. For instance, at certain frequencies, fewer UCs (e.g., 4 or 6) still achieve moderate attenuation, while in other ranges, the performance drop is more pronounced.

Sound Pressure Level vs Sound Transmission Loss Analysis

The study of Sonic Crystal-based noise barriers involves understanding how different configurations affect their performance, particularly through variations in the Sound Transmission Loss (STL) as shown in Figure 11. The observed differences in STL between idealized and practical scenarios highlight the impact of boundary effects and physical constraints on barrier performance. In practical implementations, the finite height of the unit cell introduces additional factors such as diffraction and edge effects. These boundary effects can reduce the STL, as sound waves are more likely to bypass the barrier or diffract around its edges, diminishing its effectiveness in sound attenuation.

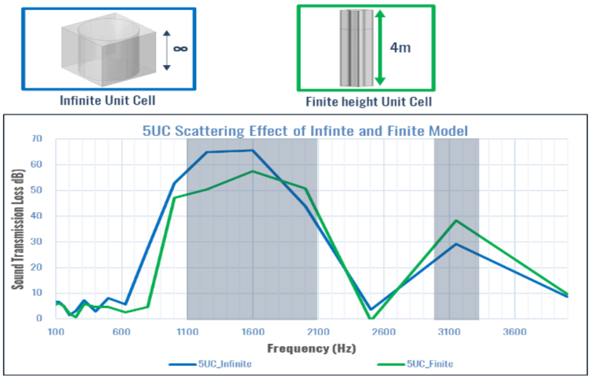

Figure 11: A comparison between STL for Infinite 5UC and Finite 5UC

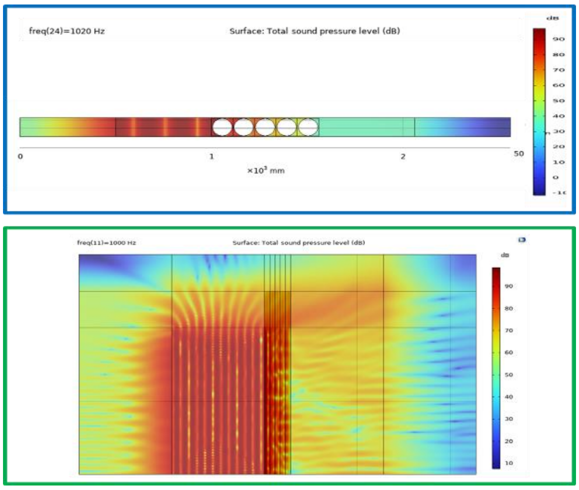

Figure 12: Sound Pressure Level for 5UC at 1000Hz for infinite and finite Model

Figure 12 illustrates the sound pressure level (SPL) distribution for 5 unit cells (UCs) at 1000 Hz, comparing the results between the infinite (blue) and finite (green) models. Key observations from the figure include:

- In the infinite unit cell model (blue), the sound pressure level appears more uniform, with a significant reduction in sound propagation, suggesting more effective sound attenuation.
- In contrast, the finite model (green) shows less uniformity in the pressure field, indicating weaker sound attenuation near the boundaries of the finite structure.
- The finite model also exhibits more pronounced interference patterns, especially near the edges, where the performance degrades as compared to the infinite model.

The comparison reveals that the finite unit cell model experiences more edge effects, resulting in decreased sound attenuation compared to the ideal infinite case. This difference emphasizes the importance of accounting for the finite nature of real-world implementations when designing Sonic Crystal-based noise barriers.

Conclusions

As preliminary, taking sonic crystals-based noise barrier design, modeling a unit cell, and computing sound transmission loss in both idealised and realistic boundary conditions to build a baseline.

By utilizing finite material properties and resonance elements, the acoustic performance of these structures will be further refined. Research progress will be achieved through rigorous numerical simulations and optimization, complemented by experimental validation to ensure applicability in practice.

The goal is a balanced and innovative approach to acoustic design. This comprehensive strategy not only improves our understanding of PC-based acoustic solutions but also aims to develop practical, market-ready products.

This paper shows an analysis of a Metamaterial ventilated barrier and a comparison between unit cell prediction and the semi-infinite arrangement of unit cells for STL prediction and in situ barrier.

Unit cell and STL prediction are in good agreement. There is a strong sensitivity on the STL peak due to the number of unit cells and geometric features. For a given design, for an in-situ STL analysis, it is important to consider the effect of the noise escaping from the top of the barrier that may lead to an STL reduction of up to 3dB.

From a future perspective, the model needs to incorporate air damping, which affects the propagation of sound waves and can reduce the effectiveness of the barrier. Applying finite rigid materials to the unit cells can alter their acoustic properties, potentially reducing or enhancing attenuation based on the material's characteristics. Real-world implementation requires consideration of the practical constraints, including material durability, weather resistance, and maintenance requirements.

As well, the effect of top configuration could be analyzed and explored further to optimize the performance of the Metamaterial ventilated barrier, and the impact of varying environmental conditions, on the barrier's effectiveness would provide valuable insights for real-world applications.

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Acknowledgments

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