Sonic Crystal Acoustic Attenuation Applied to Exhaust Air Systems

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1 Introduction

Air quality is a critical aspect of maintaining comfort and good health inside homes or in transportation vehicles. According to the Government of Canada's health website, Canadians spend on average 90% their time indoors. Thus, it is necessary to develop air filtration systems to reduce humidity and impurities caused by stagnant air. The commonly used mechanical ventilation systems in Canada can be noisy and cause discomfort. This study focuses on reducing the noise from these systems.

To solve the noise problem, one approach is to prevent the noise from escaping the system. Another option is to design a more acoustically efficient fan. This study focuses on the former method. Sonic crystals [1] can effectively block ventilation noise while allowing uninterrupted airflow. These crystals can be designed with various geometries, permeability, and thickness. The objective is to create a method to determine the transmission loss of a sonic crystal lattice that is both fast in computation time and simple in design in order to then optimize certain parameters efficiently.

The proposed approach using transfer matrices will be applied to circular sonic crystals subjected to a plane wave at normal incidence. Thermo-viscous losses will be incorporated by assigning effective properties to the air between the crystals. The effective density and bulk modulus will be calculated using the Johnson-Champoux-Allard (JCA) [2] equivalent fluid model. The predictions obtained from this approach will be validated by comparing them to normal-incidence transmission loss measurements in an acoustic tube and finite element simulations conducted in previous studies. A correction in tortuosity is also applied due to the proposed method not seeing changes in inertia due to the changes in geometry brought by the sonic crystals.

2 Methods

2.1 Materials

The solution proposed in this paper is a periodic structure comprised of N rows of sonic crystals, arranged so that the acoustic waves hit the sides of the cylinders. Each periodic unit cell (PUC) can be separated into two segmented crystals of different diameters. This allows us to build the transfer matrix of each diameter separately, and reconstruct the transfer matrix of the PUC using the parallel transfer matrix method (PTMM). Once done, the PUC is periodized in a linear array using the classical TMM to reconstruct the entire crystal network. Figure 1 shows the general methodology.

All crystal segments simplify into a single uniform solid cylinder inside a rectangular cube of air, its PUC can be represented in a 2D plane. The 2D parameters of a global PUC, composed of the parallel assembly of two individual cells, are shown in Figure 1. They are D_i and h_i, the diameter and height of individual cell i, where $i = 1$ or 2, and H_x, H_z, the width and depth of the cell.

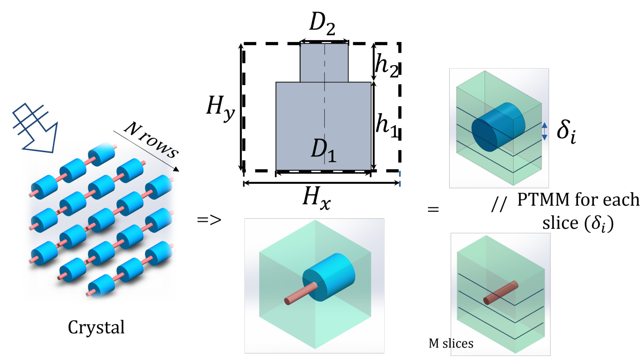

Figure 1 – Periodic unit cell (PUC) of the studied sonic crystal : Side view of the parallel assembly of two different sized crystals to form the global PUC.

The experimental samples tested in an impedance tube were made from resin with a SLA 3D printer, and their dimensions are shown in table 1. The parameter h represents the total height of the sonic crystal, also written as H_y.

Table 1 – Parameter values for each sonic crystals samples

Sample set ID	H_x (mm)	H_y & H_z (mm)	h_1 (mm)	h_2 (mm)	D_1 (mm)	D_2 (mm)
A	60	38	h	0	31.5	0
B	60	38	$\frac{2}{3}h$	$\frac{1}{3}h$	31.5	9.5

2.2 Discretized PTMM

To model the geometries of the sonic crystals, a discrete transfer matrix (DTMM) approach is proposed. The air domain between crystals is discretized to accommodate their intricate shapes. Each element of width δ_i in the domain will have a transfer matrix that considers local thermo-viscous losses. These element transfer matrices will be combined into a global transfer matrix using the PTMM [3] alongside the surface ratio of air for each element and the classical serial transfer matrix method (TMM) as shown in Figure 1. By applying the proposed approach and Bragg's law to sonic crystals, the sound transmission loss of the crystal network, exhibiting "stop-bands," can be predicted.

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3 Results & Discussion

3.1 Sample set A & tortuosity

Figure 2 shows the transmission loss (TL) for sample set A (Table 1) with three 31.5 mm diameter crystals in series distance from each other by 60 mm in reference to their centers. A stop-band appears around a central frequency of 2830 Hz, with a transmission loss peak of 34 ± 1 dB. All methods yield similar TL curves with a variation of around ± 2 dB, except for a small frequency shift observed with the DTMM without correction. This shift is due to the fixed tortuosity of each discrete element, and can be recentered with a correction to the previous tortuosity as the TMM does not consider the inertia from contraction and expansion between elements. This corrected tortuosity, hereby called geometric tortuosity (α_g), is established using the number of discretizations of a single PUC (M) as well as the formula defining the distance between the surface of a crystal and the opposing face of the PUC ($a(x)$). It can then be applied as a corrected thickness written as : $\delta'_i = \delta_i.\alpha_g$. With this correction applied, the DTMM with correction better represents the experimental and numerical models

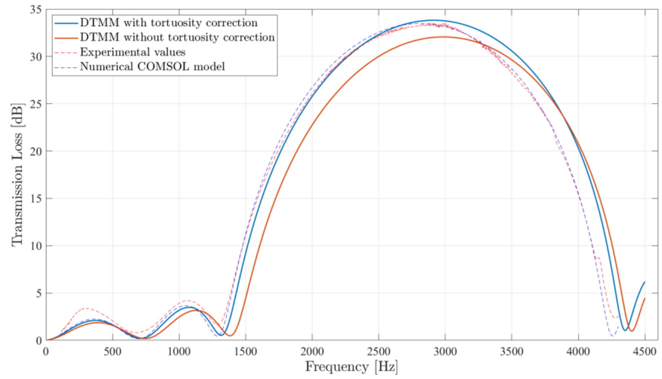

FIGURE 2 – Sound transmission loss obtained with sample set A. Comparison between transfer matrix methods, experimental method and numerical method.

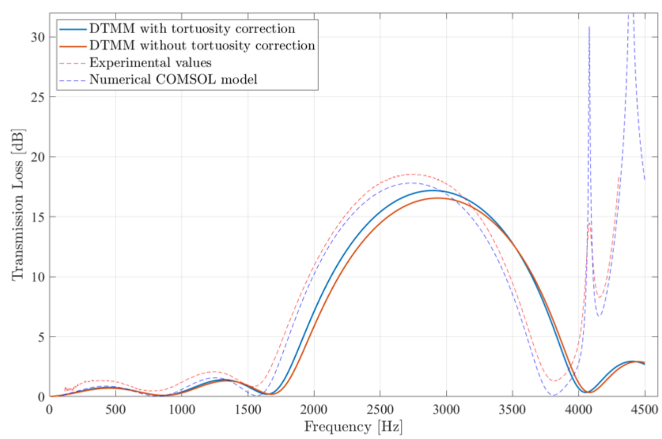

FIGURE 3 – Sound transmission loss obtained with sample set B. Comparison between transfer matrix methods, experimental method and numerical method.

3.2 Sample set B & tortuosity

Figure 3 shows the transmission loss for sample set B (Table 1) made up of the parallel assembly of two diameters (9.5 mm and 31.5 mm). As the distance between the crystals remains unchanged compared to sample set A, the central frequency remains the same, and the level of TL is slightly above half the one of set sample A. The same trend is observed with the DTMM without correction. However when applying the corrected tortuosity, the shift in frequencies is not sufficient enough to be validated by the experimental and numerical models. The authors think this is due to the the corrected tortuosity only considering corrections in a 2D plane and not a 3D one, which is justified for sample set A, but not B. Further research needs to be conducted to implement a more robust corrected tortuosity.

Conclusion

A discrete transfer matrix method (DTMM) has been developed to model a periodic linear array of complex-shaped sonic crystals (SC). The method discretizes the air domain between the crystals into rectangular elements. Each element is characterized by a transfer matrix that accounts for thermoviscous losses. Two different crystals arranged in parallel are combined into a global transfer matrix using the parallel transfer matrix method (PTMM) applied to each element individually. The linear N-periodic lattice of the sonic crystal parallel assembly is constructed using the classical serial transfer matrix method. The transfer matrix of the linear array is then used to predict the transmission loss under normal incidence. This functional method answers the established objective of being both simple, using only 2X2 matrices, and fast in computation time.

However, the tortuosity remains difficult to determine for each element. Even with a global tortuosity correction this is only sufficient for sonic crystals with no variations in diameter along its axis, and further study is needed. An optimization method is underway in order to create the best lattice possible for a given sonic crystal exterior geometry.

Acknowledgments

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