The Sonic Window Project - Meeting the Trio Challenges of Providing Natural Ventilation, Daylight and Noise Mitigation

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The paper is related to the study of sound attenuation in a sonic crystal in the form of periodic structures. The main aim of the study is to investigate the phenomenon of sound attenuation in sonic crystals using computer simulations and experiments as well as the design of a window incorporating sonic crystals for traffic noise mitigation. Bragg's law is one of the governing laws that are used to predict the center frequency of the band gap whereby sound is attenuated. The second phenomenon explored is the Helmholtz resonator. Finite Element Method (FEM) is also used to analyse two-dimensional (2D) and three-dimensional (3D) models as close to reality as possible. Noise measurement was carried out at Eusoff Hall, a residential student hostel within the National University of Singapore to determine the range of frequency that contributes to the highest amount of sound pressure level. Simulation was first carried out to understand the effects caused by the presence of sonic crystals. Different sonic crystal designs were then investigated to determine which design was able to attenuate sound significantly as well as attenuate a larger range of frequencies. Experiments were then carried out to determine the similarities and differences between experimental and simulation results.

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1. Introduction

Singapore is a highly built-up country with a well-established network of roads. Due to the limited amount of land, many people live in close proximity to major roads and expressways. Hence, traffic is one of the major contributors of noise to these residents. In recent decades, there has been increasing number of studies conducted on a sound barrier technology called sonic crystals [1]. Sonic crystals are periodic solid structures that scatter sound waves in a fluid medium to produce band gaps [2]. Band gaps are ranges of frequencies where sound waves cannot propagate through and hence result in an attenuation of the original sound source [3]. The level of attenuation depends on several factors such as geometry, arrangement and size of the crystals [1]. Recent studies have shown that it is possible to design a system of sonic crystals to specifically attenuate frequency bands in the human audible range [4]. In addition to scattering, resonance and absorption can be incorporated into the sonic crystal design to improve the level of sound attenuation.

In Singapore, many residents and office workers live and work in close proximity to major roads and expressway. Traffic is likely a significant contributor of noise. To address the noise problem, one apparent application of sonic crystals is to use them as sound barriers [5]. The sonic crystals can be designed as a replacement or compliment to conventional windows. Due to the open structure of sonic crystals, they offer additional benefits of ventilation, heat dissipation and perimeter security over traditional sound barriers [6].

This paper presents some preliminary results on the design of a sonic crystal windows for a typical student residential unit in a residential college located within the National University of Singapore.

1. Methodology

The presence of scatterers in a periodic arrangement scatter waves such that it causes the sound waves to interfere destructively. The result of destructive interference of sound waves is the presence of band gaps. A band gap is characterized by the center peak frequency and band gap. The center peak frequency is the mean frequency of a band gap and a band gap is a range of frequencies in which sound is attenuated. The band gap of a specific configuration can be determined using Bragg's Law which is given by:

$$2d\sin\theta = n\lambda \qquad (1)$$

where d is the distance between each scatterer, θ is the angle of incidence, n is an integer that determines the reflection order and λ is the wavelength Assuming that the wave is planar with angle of incidence of 90°, n = 1 and substituting $\lambda = c/f$, equation 1 can be rewritten to give:

$$fc = c/2d \qquad (2)$$

where fc is the center frequency, c (≈343 m/s) is the speed of sound in air and d = ax is the distance between the center of each scatterer in the direction of sound.

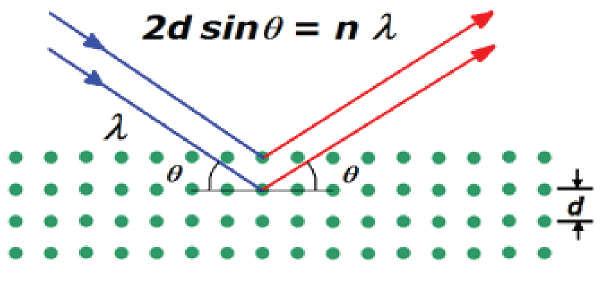

Figure 1

Helmholtz resonance is the phenomenon of air resonance in a cavity. A Helmholtz resonator is able to absorb and therefore attenuate sounds of a specific frequency depending on the geometry of the cavity. Any type of bottle with a cavity and neck can be a Helmholtz resonator [7]. The resonant frequency of a Helmholtz resonator is given by:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S}{V_o(L+0.9\sigma)}} \qquad (3)$$

where c is the speed of sound in air, S is the cross-sectional area of the opening, V_o is the volume of the cavity, L is the length of the neck and σ is the slit size.

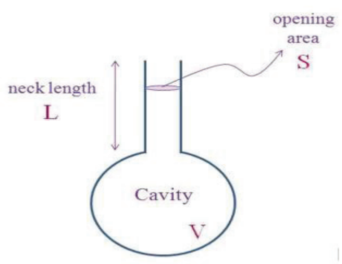

Figure 2

Finite element method (FEM) is used to create different models to simulate the effects of a sonic crystal as close as possible to reality. FEM was first used to understand how changing different variables will affect the results. Different possible window designs are then simulated in order to compare the results obtained from experiments and theoretical formulae. FEM is performed using both COMSOL Multiphysics 3.4 and Abaqus.

Before beginning to design window structures using sonic crystals for the hostels, the sound spectrum of the traffic noise is recorded. The sound spectrum is analysed to determine the range of frequencies that contributes to the highest amount of sound pressure level.
Recordings are done during three different time slots throughout the day (morning, noon and evening). For each of the time slots, five 2-minute samples are recorded. The sound spectrums of the recordings are then analyzed using the software SO Analyzer. The data is collected for each sample of recording and used to plot the average sound spectrum for the three locations. Based on the results, the range of frequency that is of the highest SPL between 300 Hz to 4000 Hz. The frequencies of sound that are selected to be attenuated are therefore targeted to be from 300 Hz to 3000 Hz.

2. Results and Discussion

A preliminary design was made with standard hollow Aluminium rectangular (63.5 mm x 31.75 mm) tubes, with wall thickness of 3mm and height of 1400 mm. There are a total of three columns of scatters, which each column of scatterer having a specific slit size. The first column of crystals has a slit of 0.003 m, the second with slit of 0.02 m and finally the last column has slits of 0.025 m. Based on equation 3, a slit size of 0.003 m, 0.020 m and 0.025 m is estimated to give a resonant frequency of about 992 Hz, 1334 Hz and 1354 Hz respectively. However, simulation done shows that the resonant frequencies achieved occur at about 800 Hz, 1100 Hz and 1200 Hz instead. This could be due to the equation used as it is known that the effective length $L_e = L+0.9\sigma$ is difficult to determine. The distance between each scatterer is ax = 0.1225 m, which will produced band gaps with center frequency of 1400 Hz for n = 1 and 2800 Hz for n = 2. The design is shown below.

Figure 3

The average maximum insertion loss attained using the experiment in an enclosed room is approximately 18 dB at 1100 Hz. The experiments show that there is insertion loss of more than 10 dB at about 800, 1100 and 2700 Hz. The experimental results show insertion loss at 800, 1100 and 1200 Hz and slight band gaps around 1400 and 2700 Hz as predicted using simulation. Certain regions of the results follow the same trend for results obtained using experiments and simulation. For example, between 1000 Hz to 1900 Hz and 2600 Hz to 3000 Hz, the experimental results follow the same trend as that of the simulation results. The experimental results however show significantly less insertion loss compared to the simulation results. There is also significant sound amplification at 2300 Hz of about 13 dB.
The differences in the results could be due to the conditions in which the experiment was done. It is not possible to achieve the exact same conditions simulated as in real life. For example, in the simulations, it is assumed that the waves are planar when they interact with the sonic crystal structure; however, it is probably not the case for the experiment as it is difficult to produce and ensure that the waves are planar when they interact. The sound amplification could be cause by the formation of standing waves in the room.
The sound level meter is also highly sensitive; this could have contributed to the fluctuations in the results collected and therefore affected experimental results. Also, the simulation was done for scatterers cut through the entire length of the

scatterer, however for the experimental setup, the scatterers were not cut all the way so as to ensure the scatterers does not become weak and buckle under its own weight. This could have also affected the results obtained.

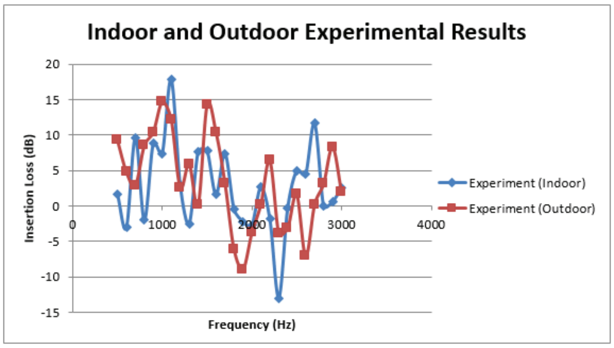

Figure 4

The results for the outdoor experiment show similar trends to the indoor experiments. Particularly, it follows the same trend between 500 to 600 Hz, 1500 to 1600 Hz, 1800 to 1900 Hz and 2300 to 2600 Hz. The outdoor results show slightly higher overall insertion loss between 500 and 1700 Hz but more significant sound amplification from 1800 – 2000 Hz.

The differences in the result are probably due to the difference in the surroundings. Also, for the outdoor experiment, there was irregular sound contribution from traffic noise and other disruptions. This could have led to the differences in the results as well.

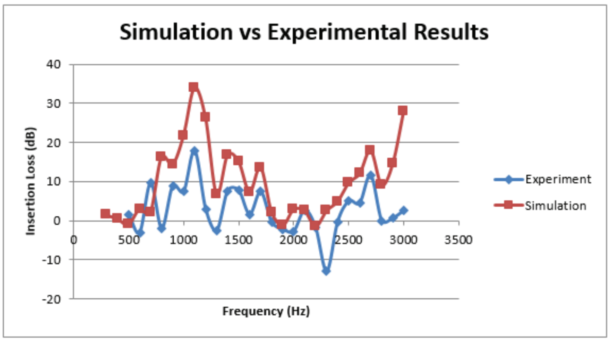

Figure 5

3. Conclusions

In conclusion, the phenomenon of sound attenuation in sonic crystals was studied using both simulations and experiments. Simulation was performed using FEM using both COMSOL and Abaqus. The window design that was selected has shown that it is possible to make use of Bragg's law and Helmholtz resonator to create a sonic crystal that is able to attenuate a much larger range of frequencies by incorporating the knowledge gained from preliminary studies. Although the results achieved from experiments and simulations follow a similar trend, the amount of insertion loss achieved experimentally was lower than simulated using FEM. More refined models will be constructed to have a closer match.

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