Auralisation of Finite Difference Time Domain Simulations of Sonic Crystal Noise Barriers in an Urban Environment

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Summary
Sonic crystals have been presented previously as both a potential type of noise barrier, and as a form of sonic art aimed at enhancing the perception of an urban soundscape. Most simulations of such structures are evaluated based on a measure of Insertion Loss - the spectral attenuation imparted on a sound source due to the insertion of the structure under investigation between source and receiver. Although this gives an indication as to the noise attenuation performance for a barrier, it gives little qualitative information as to how results might be perceived when considered in the context of the soundscape in which a sonic crystal might be placed. This is particularly important if the device, through its design, is intended to enhance a given soundscape, rather than mitigate against its negative, or noisy, aspects. This paper presents a finite difference time domain simulation of a 2-D periodic structure suitable for use as a sonic crystal noise barrier. The impulse responses obtained from these simulations are used to filter typical audio source material recorded from an urban environment resulting in a number of auralisations that can be used to evaluate the effects of such structures on a typical soundscape. A perceivable difference listening test is used to determine how effective these 2-D periodic structures are at making a significant change in the source material. Results confirm that there are significant perceivable differences imparted due to the sonic crystal structures used, under the assumed limitations of these evaluations having taken place under laboratory conditions and where the duration of the source material does not exceed that of the average auditory short-term memory. Further work will explore whether these differences are significant under more natural listening conditions.

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1. Introduction

Auralisation is most commonly used to predict and render soundfields generated by a source within an enclosed space, and is a method that is applied extensively in architectural acoustics, both in terms of research and industry practice [1]. More recently there has been a growing interest in the use of auralisation in the area of environmental acoustics, where it is beginning to take its place alongside more established methods such as predicted noise level exposure measures and sound level contour maps to quantify environmental impact. This is due to its ability to give a sense of subjective sound quality over time, rather than relying on single or multiple measures of sound quantity, as part of the design/planning process.

Sound barriers are often used to mitigate noise levels from planned for developments such as road or rail, and standardised prediction models exist [2] to enable them to be incorporated into environmental acoustic impact assessments. Although rarely used in practice to date, there has been some particular attention given to the use of sonic crystal structures as potential noise barriers through their ability to passively absorb sound while giving scope for more aesthetically pleasing interventions in the landscape (e.g. [3] [4] [5]). Prior work has been mostly based on the modelling, simulation and verification of various designs of periodic array in order to establish attenuation and absorption capabilities. This is usually defined by Insertion Loss - the spectral attenuation imparted to a sound source due to the insertion of the structure under investigation between source and receiver. Although this gives an indication as to the noise attenuation performance for a barrier, it gives little qualitative information as to how results might be perceived when considered in the context of the soundscape in which such a sonic crystal structure might be placed. This is particularly important if the device, through its design, is intended to enhance a given soundscape, rather than just mitigate against its negative, or noisy, aspects.

This paper presents an auralisation framework based on a finite-difference time domain simulation of a simple 2-D sonic crystal structure, combined with audio source material recorded from an urban environment, to test whether such sonic crystal noise barriers might be perceptually effective as a means of noise attenuation in a given soundscape. The paper is organised as follows: firstly the simulation methodology used to derive the transfer functions of the barriers is outlined; secondly it describes the process of auralisation using a combination of simulated data and classical noise barrier estimation methods; finally it presents the results of a listening test designed to investigate whether such a structure makes a subjective difference on how we hear a pre-recorded urban soundscape.

2. Finite Difference Time Domain Simulation

The simulation set-up for the sonic crystal array being considered is based on the experiments presented in [6], and used subsequently in e.g. [7], in which empirical results are obtained for an array of rigid cylindrical scatterers arranged in a square lattice configuration as presented in Figure 1. Note that although the sonic crystal structure is indeed 3-D, the lattice array used is actually only periodic in 2-D, and hence this is refered to as a 2-D sonic crystal. 3-D type structures have also been investigated in similar work (e.g. [8]).

The simulation domain, denoted by the bounding cubic boundary in Figure 1, is discretised using a uniform 3-D Cartesian grid of points, across which the 3-D linear wave equation is calculated using a second-order finite difference time domain (FDTD) numerical method. A perfectly matched layer (PML) is implemented at the boundaries of the domain to minimise reflections returning into the interior. A 4-by-4 array of cylindrical scattering elements is inserted into the simulation domain, and assumed to be acoustically hard such that they are totally reflective. Simulations are also performed without the scattering elements in place to enable comparison of the source signal before and after their insertion. A spatial sampling interval of 0.005m is used for the FDTD grid, allowing the cylinders to be approximated at an appropriate level of detail. Assuming that the speed of sound in air under normal atmospheric conditions, $c = 343$ m/s, from the Courant stability condition, the grid sampling rate, F_s, can be calculated such that $F_s = 118670$ Hz. The simulation domain therefore uses a grid 310x310x300, a total of 28.83 million spatial sampling points, with a PML 10 elements in depth. Numerical dispersion limits the effective sampling rate of the grid, and it has

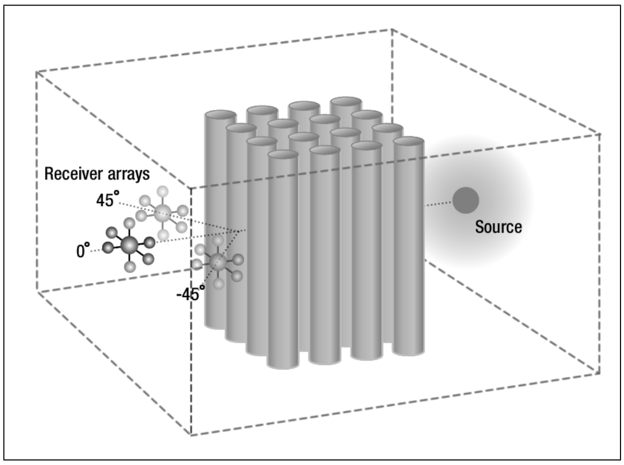

Figure 1. The FDTD simulation set-up used: a 4-by-4 sonic crystal array with a single sound source incident upon it and three receiver arrays, each consisting of seven adjacent grid points.

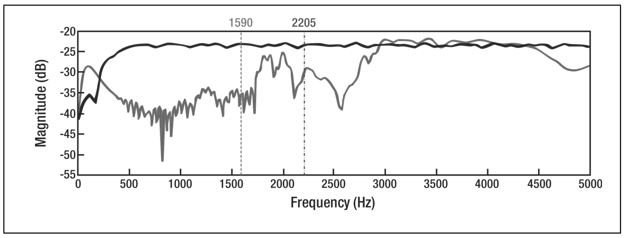

Figure 2. Frequency spectra of impulse responses obtained from a 3-D FDTD simulation of a 4-by-4 sonic crystal array. The black line is the spectra obtained from the simulation with no sonic crystal included for comparison. The vertical lines indicate the centre frequencies of the first theoretical band gaps associated with the first and second set of Bragg planes.

been demonstrated in [9] that this becomes perceivable above approximately 0.15 x F_s giving an effective bandwidth for this simulation of 17.8kHz which adequately covers the frequency range of interest.

Source excitation is from a Ricker wavelet signal applied at a single grid point on the opposite side of the cylinders to the receiver arrays, and then deconvolved from the signals obtained at these receiver points. It is possible to obtain 4-channel spatially encoded ambisonic B-format output from a FDTD simulation by measuring the sound pressure signal at seven adjacent grid points in a 3-D cross formation, and calculating the relevant pressure differential signals as detailed in [10]. This results in a set of four sonic crystal impulse responses corresponding to the four ambisonic B-format channels, for each of the three receiver arrays shown in Figure 1. The central point of each array gives the omni-directional W B-format channel impulse response, with the three subsequently derived figure-of-eight impulse responses X, Y, and Z, aligned along the Cartesian axes of the spatial sampling grid.

Figure 2 shows the frequency spectrum of the deconvolved impulse response captured at the central

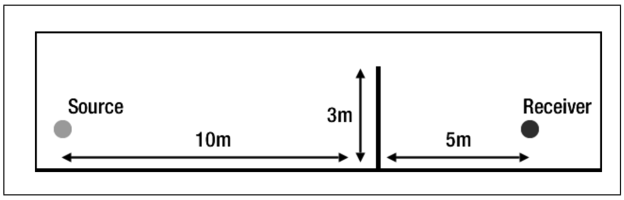

Figure 3. The source/receiver scheme of the virtual barrier. Note that the distances and barrier dimensions depicted in this example are arbitrary and can be adapted to a specific situation.

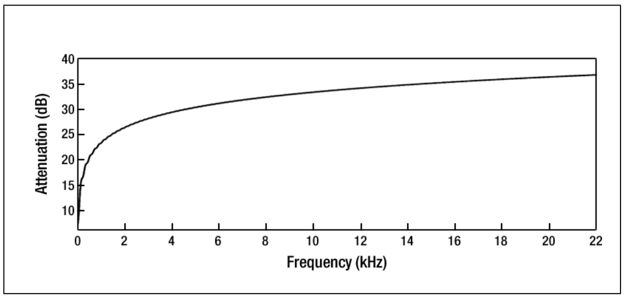

Figure 4. Frequency response of the amplitude envelope corresponding to a source and receiver on opposite sides of the thin rigid barrier pictured in Figure 3.

grid point of the 0° receiver array (from Figure 1). The spectrum has been depicted up to a maximum frequency of 5 kHz, being the main region of interest in terms of the sound cancelling properties of the sonic crystal structure. In general, these sound cancelling band gaps arise due to destructive Bragg interference determined by the distance between elements in the given (in this case) 2-D array, known as the lattice constant a (see e.g. [3]). For this simulation, $a = 0.11$cm such that the first band gap for the [1 0 0] set of planes (parallel to the axes of the sonic crystal array) is centred at approximately 1559 Hz, and for the [1 1 0] set of planes (diagonal to the axes of the array) is centred at 2205 Hz. These two predicted band gaps are also highlighted in Figure 2.

3. Sound Barrier Approximation

For the purpose of estimating the relative incident and diffracted signals reaching a receiver at a given location we consider the source-barrier-receiver geometry as if the sonic-crystal barrier were a thin rigid screen. When sound energy normally interacts with a barrier, four properties are noted: transmission, diffraction, reflection and absorption. The latter two can be neglected in this case since they are captured by the sonic crystal impulse response measurement. What remains to be established is the ratio of transmitted to diffracted energy at different frequency bands and under normal, free-field conditions. From [2] and [11] a frequency weighted amplitude envelope can be calculated that is then applied to a sound source incident on the barrier structure, resulting in an approximation of that reaching the receiver positions.

Figure 3 shows the particular source-barrier-receiver configuration that has been used to produce the result shown in Figure 4. This has been selected to reflect the soundscape used in the listening tests that follow - the proposed barrier is set 10m from the main sound source of interest, with the receiver/listener 5m away from the barrier, representing a typical person standing within this environment. Since the formula assumes the barrier has a smooth, reflective surface, the majority of the energy that reaches the receiver should be the result of diffraction around the barrier edges. The signal that results from this filtering process shall be referred to hereafter as the *diffracted signal*. The *incident signal* is therefore considered to be that which is removed by the filtering process - i.e. all the energy that was absorbed or reflected away from the barrier surface. This signal is obtained by filtering the original signal with the inverse of the filter that is used to obtain the diffracted signal.

4. Auralisation

Once both the incident signal and the diffracted signal have been derived, the next stage is the auralisation of a given sound source with the sonic crystal structure/filter. The impulse responses are first re-sampled to match the sampling rate of the recorded material that forms the sound source. The two signals (incident and diffracted) are recombined by addition, ignoring any phase differences which can be assumed to be a consequence of sound interacting with the barrier. Finally, the processed signal is mixed with unprocessed ambient sound wherein the source sound is either absent or heavily suppressed. The purpose of this step is to try to account for sound reaching the receiver from other directions and that has therefore not been in direct contact with the barrier. For clarification, this entire procedure is illustrated in Figure 5 and may be summarised as follows:

1. Obtain the transfer function of the sonic crystal structure using 3-D FDTD simulation.
2. Define filters to separate sound source used into diffracted and incident parts, approximating the sound a listener receives due to diffraction over and around a thin rigid barrier, and that which would be incident on the barrier's surface, respectively.
3. Apply incident sound filter from (2) to source recordings made at an equivalent distance from proposed barrier location according to Figure 3.
4. Convolution of the result from (3) with the sonic crystal IR from (1).
5. Apply the diffracted sound filter from (2) to recordings made at source position.
6. Sum outputs from (3) and (4) with the diffracted part of the signal (5) in time domain.

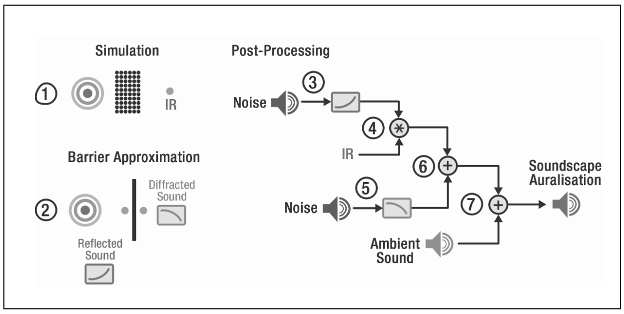

Figure 5. The step-by-step process used to auralise a sonic crystal barrier.

7. Sum output from (6) with ambient sound in which the sound source itself is absent or much reduced.

It is noted that the use of different recording positions can potentially create phase problems and other ambiguities when attempting to mix in the time domain. The method is therefore only considered viable in the case of complex or 'noisy' soundscapes wherein such ambiguities are less likely to be perceived. Source material is captured using an ambisonic B-format soundfield-type microphone, ensuring compatibility with the receivers used in the FDTD simulations.

5. Listening Tests

5.1. Test Protocol

Perceivable difference tests have been performed to determine: a) whether there are perceivable differences between the sonic crystal auralisation and the untreated soundscape; and b) whether any artefacts of the FDTD simulation are perceptually significant to the extent that the results of any kind of qualitative assessment would be compromised.

The test took the form of a category judgement test in which 13 experienced listeners with normal hearing were asked to compare pairs of sounds and rate their respective difference on a category scale according to a specified criterion. It was conducted in two parts, each associated with a different difference criterion, these being 'loudness' and 'timbre'. A 5-point Rohrmann category scale was used [12], with catergories defined as, 'not at all', 'slightly', 'moderately', 'very' and 'extremely'.

The audio source material consisted of 3-4s extracts of ambisonic B-format soundscape recordings made in an urban park in Leeds, UK. Two different extracts were used for each difference criterion. The first contained only continuous, broadband sounds, or, 'background ambiences', which are primarily wind and road traffic; the second contained a distinct sound object - in this case, police sirens - with an obvious tonal component. From each extract a total of 3 unique sound files were produced: the first uses an impulse response recorded in an 'empty' FDTD simulation; the second uses the filters derived from the 2-D sonic crystal array simulation as outlined previously; the third is used as a control and has no filter applied at all. Note that although both source material and simulations were rendered to ambisonic B-format, these listening tests were conducted in mono only, with the spatially rendered versions being used for a further study. As such only the W (omni-directional) channel was used and rendered similarly to two channels for calibrated headphone presentation to the test subjects.

The test interface was presented in a web page displayed on a desktop computer. The test interface allowed participants control over the order of playback and number of repetitions of each relative pair of sounds but they were not able to control the order in which the pairs were presented, this being randomised for each participant to distribute any bias in the data that might be linked to presentation order.

Using a category scale can incur bias if participants are inconsistent with their answers - an effect which can be exacerbated when successive pairs are opposite extremes. In order to identify participants who did not give consistent answers, the test was structured so that each phase in the test would be preceded by a training phase - an approach which has the added benefit of permitting a period of listener 'calibration'. If it was found that answers given in a training phase did not correlate well with the answers given in the relative test phase, the answers to questions in that phase would then be excluded from the results. A second form of 'quality control' involved the inclusion of anchors in the guise of identical pairs. Participants who consistently failed to identify the anchors as 'not at all' different would also be excluded from the results. In total, the test consisted of 50 stimuli pairs. 5 in the training phase associated with 'loudness', followed by a main set of 20 questions. This format was repeated for the 'timbre' section. Allowing a period of time for reading and instructions, the total length of the test was no longer than 30 minutes. Participants were allowed to complete the test in their own time, although they were advised beforehand of a reasonable length of time to spend on each question in order to prevent a longer total test duration and the possibility of listener fatigue.

5.2. Results

Figure 6 shows the rated differences between the auralisations with the empty FDTD grid (Emp) and sonic crystal filters (Cyl) applied, and with the unprocessed audio example (Ctrl). In this figure, each of the mean averages and their respective error bars represents the combined results of all extracts and criteria for each pair, with no outliers due to 'unreliable' subjects having been removed.

It can be seen from the results that the subjects hear a clear difference when the soundscape has been

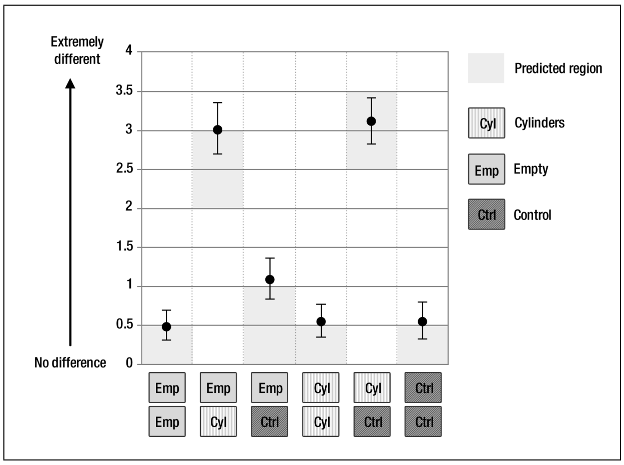

Figure 6. Results of paired perceivable difference test. *Ctrl* indicates the unprocessed soundscape material, *Emp* indicates the material was filtered with an impulse response obtained from an empty FDTD grid simulation, and *Cyl* indicates the material filtered with the sonic crystal cylindrical array.

processed using the sonic crystal cylindrical array (Emp-Cyl; Cyl-Ctrl). As anticipated, there is a slight perceivable difference between the control and empty grid auralisations (Emp-Ctrl) which is attributed to artefacts in the simulation (such as perceivable effects of dispersion error remaining, even after re-sampling, or non-perfect totally absorbing boundaries resulting in low level reflections). However, this is markedly smaller than the differences observed between the empty grid and sonic crystal cylindrical array (Emp-Cyl) auralisations. The perceivable differences for (Emp-Cyl) and (Cyl-Ctrl) are also very similar. It is also noted that the perceivable difference between identical pairs (Emp-Emp; Cyl-Cyl; Ctrl-Ctrl) is higher than anticipated, which suggests all ratings may be scaled to some small degree.

Figure 7 compares the perceived differences between the different audio extracts when assessed according to the different criteria of ‘loudness’ and ‘timbre’. The differences due to the filtering are more noticeable in extracts 1 and 4 which may be related to their predominantly broadband spectral content (extracts 2 and 3 each contained the police siren sound object).

While these results indicate that there are clear perceivable differences between the auralisations based on the sonic crystal cylindrical array and the unprocessed audio, this only applies directly to audio that is evaluated under laboratory conditions and where the duration of a sample does not exceed that of the average auditory short-term memory. The results of these tests cannot give any real indication as to whether these differences are significant under more natural listening conditions where the subject is not consciously seeking to compare one environment against another in rapid succession. However, these

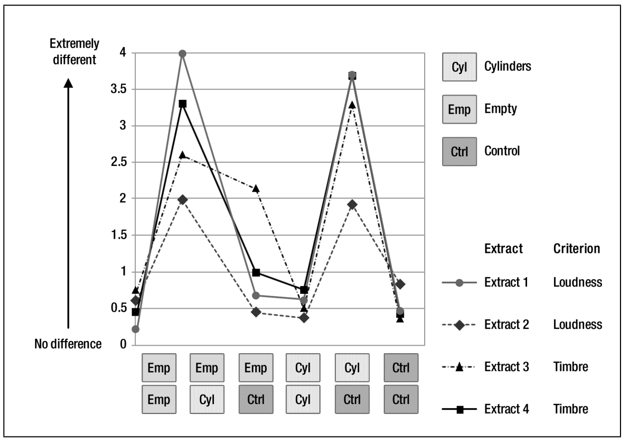

Figure 7. Comparison of average perceived differences using different audio extracts and difference criterion.

results have established a methodology for incorporating FDTD based simulations as part of a wider soundscape subjective evaluation, and demonstrated that any limitations of the simulation method itself do not impact negatively on results otherwise obtained. This test has also demonstrated that even with the simplest of sonic crystal noise barrier designs, a difference can be heard in terms of how it would be likely to filter sound incident upon it from the surrounding soundscape, for the scenario suggested here, being typical of a person placed within an urban park surrounded by busy roads. To enable a more meaningful qualitative assessment, this method and these results need to be extended to recreate a more natural listening environment, rendering the full soundscape using spatial audio techniques.

6. CONCLUSIONS

An experimental methodology has been presented in which spatial B-format impulse responses have been obtained from 3-D FDTD simulations and used to render auralisations of a simple sonic crystal cylindrical array noise barrier via convolution with B-Format soundscape recordings. It was also proposed that estimating frequency dependent attenuation due to a finite sized thin rigid barrier (according to [2] and [11]) could be used to weight the source signal prior to its convolution with the obtained impulse response, enabling directly incident and diffracted components to be dealt with separately, and thereby removing the need to simulate the entire soundscape environment being considered. While the 3-D FDTD simultation was arguably not necessary in the case of a 2-D periodic array, the method used permits the investigation of more complex structures, as well as enabling the direct measurement of B-Format impulse responses.

After auralisation, perceivable difference tests were performed to assess whether even such a simple sonic crystal array, with relatively limited sound attenuating abilities, could be used as the basis for a noise barrier that would impart a noticeably subjective change to a pre-recorded soundscape. It was shown that this was indeed the case, and that the measured difference was not directly impacted by the simulation method itself.

To ascertain whether or not these measured perceivable differences affect any change in the perceived sound quality of the soundscape, a more thorough, qualitative style assessment is needed where more natural listening conditions are used. It was for this purpose that the method outlined and implemented in this paper has been tested and it has since been applied in a more complete spatially rendered listening test based on a lab-based reproduction of a typical real-world soundwalk study and urban soundscape design problem. This is the subject of a forthcoming paper.

Acknowledgement

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