Transport noise reduction by low height sonic crystal noise barriers

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Noise barriers along roads and railways are one of the existing solutions to protect inhabitants from noise. In this research we attempt to create quiet areas in cities using sonic crystal noise barriers. For aesthetic and security aspects, such protections do not exceed a size of 1 m×1 m in a vertical section. Cylindrical scatterers with added acoustical properties of resonance and absorption are used in this work to improve the acoustic performance of low height sonic crystal barriers. Numerical simulations, using a 2D Boundary Element Method (BEM), are carried out to evaluate their acoustic properties in terms of insertion loss. Our results show that the effectiveness of low height sonic crystal noises barriers is significant for road and tramway noise over the entire frequency range of study.

1 Introduction

Sonic crystals (SC) are inhomogeneous materials made of regular arrays of scatterers embedded in a fluid medium. An interesting property of these materials is the occurrence of ranges of frequencies where no propagating modes are supported by the periodic structure. These ranges are known as band gaps (BG). The physical mechanism that explains this phenomenon is the destructive Bragg interference. The center frequency of the band gap f_{BG} is determined by the lattice constant α which presents the distance between adjacent scatterers:

$$f_{BG} = \frac{c}{2\alpha} \tag{1}$$

where c is the speed of sound in air.

A growing number of studies and applications has been presented in the last two decades analyzing the propagation of acouctic waves inside sonic crystals [1-11]. Rigid scatterers like wood or aluminum have been used to study the physical behavior of sonic crystals when the reflection of acoustic waves becomes the mechanism of the band gap creation. In addition, sonic crystals with mixed rigid and absorbent materials have been used to study the double effect of reflection and absorption on the frequency response of the sonic crystal. Indeed, the use of soft cylinders is an alternative to solve the problem of the angular dependence of the acoustic attenuation. Resonant cylinders allow the sound to penetrate inside the elements of the periodic structure and as a consequence new acoustical properties can appear. In this paper, we are interested in low height sonic crystal noise barriers. Indeed, in urban areas pedestrians and cyclists are located very close to road traffic or tramway noise sources. It is easy to protect them using small devices which do not exceed a size of 1 m×1 m in a vertical section. Engineering methods cannot lead to accurate values for the acoustic attenuation of such barriers. Here, it is proposed to use numerical simulations to evaluate the acoustic performance of sonic crystal noise barriers. The Boundary Element Method is used in this research study. This paper is organized in four parts: firstly, a brief description of the boundary element method is presented; secondly, there is a description of the sonic crystal design; then the numerical simulations and the geometrical configurations are presented; and lastly the results are detailed.

2 Boundary element method

The boundary element method is a technique developed in the early sixties and is based on the integral equation theory [12,13]. This method appears more appropriate in an infinite space than the finite element method because only the surface of the domain boundary must be discretized. Its main advantage is that it allows any kind of shape and impedance condition values on the surfaces to be accounted for in a homogeneous atmosphere. Two families of boundary element methods can be distinguished: direct and indirect formulations. The direct formulation relies on the use of the Helmholtz integral equation where the unknown functions are pressure and velocity, while the indirect one is based on an integral formulation assuming that the sound field scattered by a boundary can be represented by a linear combination of a distribution of monopoles (a simple-layer potential) and a distribution of dipoles (a double-layer potential). The numerical code, MICADO [14], which we propose to use in this work is based on the direct integral equation formulation. It uses a more complex approach based on a variational formalism leading to a functional. The minimum of this functional also leads to a square symmetric matrix system. This approach provides a solution numerically more stable and the order of the singularities is reduced. Boundaries are meshed at each frequency automatically according to a criteria of minimum number of elements per wavelength and per segment, which greatly reduces computation times. The Hankel functions used to compute the elementary Green's terms are tabulated and interpolated when needed, which reduces the computation time required to compute the matrix by a factor of more than 20. The elementary integrations are done quite classically using Gauss integrations. In MICADO, the number of Gauss points may vary depending on the distance between points. These aspects make MICADO a specially optimized software in time computation. In this work study, we use a 2D version of MICADO because of time consuming calculations. The geometry of the problem is bi-dimensional: the sources are infinite linear coherent sources and all the obstacles remain unchanged and infinite along a direction perpendicular to the vertical section plane (see figure 1).

Preliminary calculations are carried out to ensure convergence of BEM calculations. A compromise on the number of frequencies per third octave and the number of elements for each segment of the geometry is found leading to accurate results with reasonable calculation times. It is chosen also to achieve calculations within the frequency range 100-2500 Hz. This assumption is acceptable since it corresponds to the frequencies where the transport noise is the highest in energy [15].

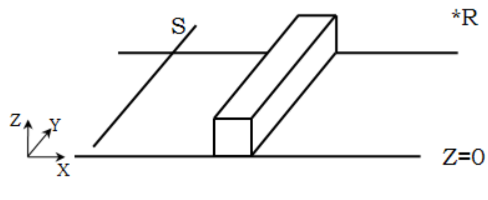


Figure 1: Geometrical configuration for bi-dimensional BEM calculations.

3 Low height sonic crystal noise barrier design

The geometry of the studied low height sonic crystal noise barrier is given in figure 2. We have developed a 2D arrangement made of scatterers inside a 1 m high and 1 m wide parallelepiped. It consists of two periodic bands and a last row of joined cylinders. The first periodic band of scatterers BS1 extend from x=0 m to x=0.30 m with lattice constant a_1=0.085 m. The scatterers used have a diameter of d_1=0.05 m. The second periodic band BS2 extend from x=0.30 m to x=0.80 m with lattice constant a_2=0.17 m. The diameter of the scatterers is d_2=0.14 m. The last row of joined cylinders extend from x=0.80 m to x=1 m. The diameter of the cylinders is d_3=0.20 m. The design of the sonic crystal has been proposed to overcome the two major drawbacks of sonic crystals: the angular dependence of the acoustic attenuation and the fact that the necessary space to put the sonic crystal is larger than in the case of conventional acoustic protections. Indeed, because of the last row of joined cylinders, the transmitted ray is more attenuated than the diffracted one over the entire frequency range. The first band of the sonic crystal is constituted by a rectangular periodic distribution of small scatterers. It increases the absorption and reflection loss effect when the wavelength is larger than the sizes of the scatterers. Using Eq. (1), the band gap of the first band will be created around 2000 Hz. The cylinders of the second band are larger than those of the first band. They are used to attenuate a frequency band around 1000 Hz which present the main energy in A-weighted traffic noise.

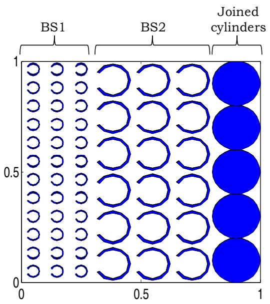


Figure 2: Scatterers arrangement in the low height sonic crystal noise barrier.

4 Numerical simulations

In this section, the acoustic performance of sonic crystal noise barriers for road traffic and tramway noises is studied. For road traffic noise (figure 3), the width of each traffic lane is 4 m, both the street surface and pavement are modeled as rigid. Four sources are considered: two located at a height of 0.01 m (S2 and S4, representing light vehicle rolling noise emission) and two located 0.3 m above the road (S1 and S3, representing light vehicle engine noise emission). The noise sources are located in the middle of the road lanes. To calculate the global insertion loss in dB(A), the A-weighted road traffic noise spectra (for rolling and engine noises) calculated with weights according to the European Harmonoise model [15] are used. For tramway noise (figure 4), the wheel-rail rolling contact is described by two sources located at a height of 0.05 m. Because of its considerable dimensions, the tramway body is modeled by a reflective surface (2.45 $m \times 3.20$ m). For both road traffic and tramway noises, one region of receivers is defined behind the low height noise barrier. It extends 40 m behind the protection, at a height between 1 m and 2 m. It is representative of pedestrians and cyclists. The results are expressed as the average insertion loss per third octave band in the two regions of receivers. A homogenous and windless atmosphere is assumed since the receivers' area is close to the barrier.

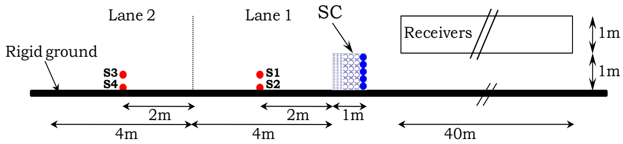


Figure 3: Geometrical configuration for road traffic noise.

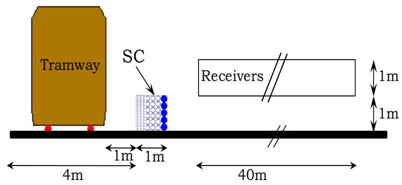


Figure 4: Geometrical configuration for tramway noise.

The reference case for all tests is a rigid noise barrier (RB). It have a size of 1 $m \times 1$ m in a vertical section. In this work, we investigate two various sonic crystal barriers with different properties. The scatterers of the two periodic bands are resonant cavities and absorbent cavities for sonic crystal barriers SC1 and SC2, respectively. The absorbent material used to cover the interior of cavities in the sonic crystal barrier (SC2) is a glass wool. It is characterized by a flow resistivity of σ=30 cgs and is described using the one-parameter Delany and Bazley model [16]. The last row for the two sonic crystal barriers is constituted of joined rigid cylinders. Sonic crystal barriers are proposed to add new acoustic effects different from those generated by the periodicity phenomenon (destructive Bragg interference).

5 Numerical results

In this section we present numerical results of sonic crystal noise barrier's insertion loss in real road traffic and tramway noise situations. This insertion loss is the difference in received sound pressure level between the situations without and with the barrier, for the same source-receiver configuration. It indicates the true noise barrier benefit at the receivers' zones, it is given for each third octave band by:

$$IL_{\Delta f} = 10 \log_{10} \left(\left| \frac{P_{ref}(\Delta f)}{P_{nb}(\Delta f)} \right|^2 \right) \tag{2}$$

where $P_{ref}(\Delta f)$ is the acoustic pressure for the reference configuration without the noise protection in the third octave band Δf and $P_{nb}(\Delta f)$ is the acoustic pressure for the configuration with the noise barrier in the third octave band Δf.

The insertion loss spectra (IL) of the reference rigid barrier and the two sonic crystal noise barriers SC1 and SC2 for road traffic and tramway noises, are given in figure 5 and figure 6, respectively. For road traffic configuration, the improvement due to sonic crystal SC1, in comparison to the reference rigid barrier RB, is weak and the maximum of improvement does not exceed 1.5 dB(A). Its insertion loss spectrum presents some improvements for some third octave bands (1000 Hz, 2000 Hz). They correspond to the band gaps created by the first and second periodic bands of scatterers due to the periodicity phenomenon. For sonic crystal barrier SC2, we take advantage of the absorbent properties of the glass wool to improve the acoustic properties of the resonant cavities. Figure 5 shows an increase in insertion loss at medium and high frequencies when we combine resonant cavities with absorbent material. The global improvement due to sonic crystal SC2 can reach 2.5 dB(A).

For tramway noise configuration, the improvement due to sonic crystals SC1 and SC2 is significant almost over the entire frequency range. Indeed, a complex distrubtion of resonant or absorbent cavities near the tramway body reduces the effect of multiple reflections between the noise barrier and the reflecting tramway surface. This can lead to a strong absorption of the acoustic energy allowing a reduction of noise levels in the region of receivers. The global improvements due to sonic crystals SC1 and SC2, in comparison to the reference rigid barrier, reach 4 dB(A) and 8 dB(A), respectively.

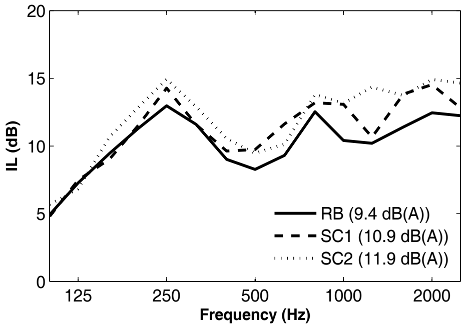


Figure 5: Insertion loss of rigid and sonic crystal noise barriers as a function of frequency: road traffic noise. RB (solid line), SC1 (dashed line) and SC2 (dotted line).

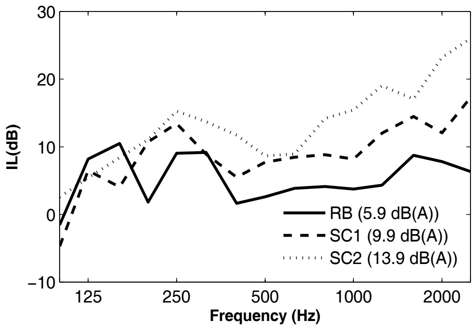


Figure 6: Insertion loss of rigid and sonic crystal noise barriers as a function of frequency: tramway noise. RB (solid line), SC1 (dashed line) and SC2 (dotted line).

Figure 5 and figure 6 show significant values of insertion loss of sonic crystal noise barriers compared to the reference rigid protection. However, The number of scatterers used in the design of the sonic crystal is high causing a difficult implementation of these kinds of noise barriers. Therefore, the aim is to reduce the number of scatteres of the sonic crystal without radically degrading its insertion loss.

The initial structure of the sonic crystal contains two periodic bands of scatterers (six rows) and a last row of joined cylinders making a total of 59 scatterers. In this study, we set n orders, in each order a cylinder in each row of the two periodic bands is removed randomly. Six scatterers are removed then in each order. For each order a calculation of the insertion loss is made to show the effect of the number of removed cylinders and the created vacancies on the acoustic performance of the sonic crystal. The number n of orders chosen then is a number for which a maximum of degradation, equal in our case to 1.5 dB(A), is a limit for the last order. The insertion loss results for road traffic and tramway noises, are given in figure 8 and figure 9, respectively. From these results, the number of orders obtained is $n = 4$ for all cases. Therefore, for the fourth order, the total number of scatterers obtained in the sonic crystal is 35 (figure 7).

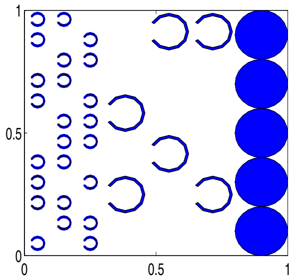
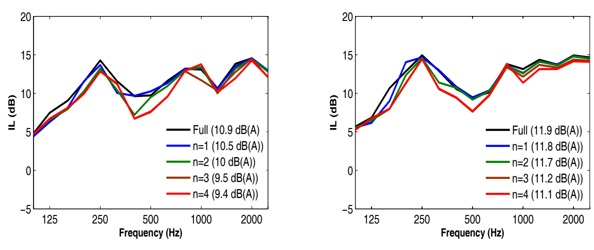


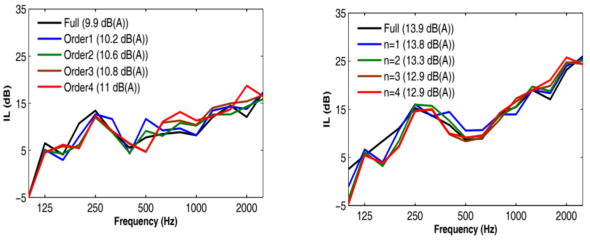
Figure 7: Sonic crystal barrier obtained for the fourth order of scatterers number reduction.

For road traffic noise configuration, the degradation is weak for sonic crystals SC1 and SC2 and do not exceed 1.5 dB(A) for the last order when 24 scatterers are removed. For tramway noise configuration, the degradation is weak for sonic crystal SC2 and do not exceed 1.2 dB(A). For sonic crystal SC1, we do not observe any degradation, on the contrary some improvement for some third octave bands is observed fot each order. This leads to a global improvement of the acoustic performance of the sonic crystal of 1.1 dB(A) for the last order. This is explained by the effect of the vacancies inside the sonic crystal by adding attenuation peaks in ranges of frequencies independent on the geometry of the starting sonic crystal. These results allow to use a low number of scatterers in the implementation of low height sonic crystal barriers with conserving high values of shielding for both road traffic and tramway noises.



(a) (b)

Figure 8: Insertion loss of sonic crystals SC1 (a) and SC2 (b) for the different orders of scatterers number reduction (IL_{RB}=9.4 dB(A)): road traffic noise.



(a) (b)

Figure 9: Insertion loss of sonic crystals SC1 (a) and SC2 (b) for the different orders of scatterers number reduction (IL_{RB}=5.9 dB(A)): tramway noise.

6 Conclusion

Low height sonic crystal noise barriers (1 m×1 m in a vertical section), with added properties of resonance and absorption, inserted in urban areas as efficient solutions for reduction of transport noise, have shown interesting results. Numerical simulations carried out using a 2D Boundary Element Method (BEM) have shown a significant efficiency of these kinds of noise barriers. The global insertion loss of a sonic crystal barrier made of rigid resonant cavities can reach 9.5 dB(A) and 9 dB(A) for road traffic noise and tramway noise, respectively. When the interior of the cavities is covered by an absorbent material the global insertion loss values increase and reach 11.9 dB(A) and 13.9 dB(A). To facilitate the implementation of sonic crystal barriers, a random removal of some scatterers has shown a negligible effect on the degradation of their acoustical efficiency. This may lead on the contrary to an improvement of the effectiveness because of the creation of some resonant vacancies inside the noise barrier. Numerical results show that low height sonic crystal noise barriers can be used as effective noise barriers for both road traffic and tramway noises. Its implementation do not need any fundation and there are wide choices of existing material of construction. For improving the efficiency of low height sonic crystal barriers, work is still in progress to complete this study with a systematic method to obtain the best sonic crystal design. This will be done using a new approach based on a coupling of the numerical boundary element method with an optimization method.

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