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Design of wideband attenuation devices based on Sonic Crystals made of multi-phenomena scatterers

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Sonic Crystals (SCs) are periodic structures of solid scatterers embedded in a fluid. Perhaps, the most celebrated property of SCs is the presence of ranges of frequencies, known as band gaps, where only evanescent modes are excited. As a consequence, in finite SCs the propagation of waves at these frequencies is attenuated. However the mere existence of these attenuation bands is not enough to design effective attenuation devices. In this work we report the theoretical and experimental design of multi-physical phenomena scatterers presenting resonances, absorption and scattering in the audible range. The design of the scatterers has been improved for its use outdoors. We use these scatterers to construct a periodic structure making use of the Bragg reflections, together with resonances and absorption, in order to combine the three phenomena working independently in different ranges of frequencies. Thus the overall effect is a wideband of attenuated frequencies. The resultant device has been acoustically standardized as traffic noise reducing device obtaining the expected results, following the norm EN 1793:1998. On the other hand, the structural efforts of these devices have been measured in an wind tunnel. The improvements with respect to the classical acoustic barriers are discussed in the work.

1 Introduction

Exploitation of propagation properties of periodic structures has shown an increasing interest in last years in several branches of fundamental science and technology. Photonic [1, 2] and phononic [3, 4] crystals are the examples in optics and acoustics respectively. In the case of phononics, there is a particular system, called Sonic Crystal (SC), [5] in which the solid inclusions are embedded in a fluid medium. Perhaps, the most celebrated property of all of these periodic systems is the presence of ranges of frequencies, known as band gaps (BGs), [6] where only evanescent modes are excited and waves cannot propagate through the structure. [7] The presence of the BG leads to several fundamental questions related with evanescence, [8] localization, [9] guiding [10] among other properties.

In last years, the possibility to manipulate the sound by means of SCs motivated the idea of using these periodic acoustic media as attenuation devices as, for example, an alternative to acoustic barriers. [11] However, from the acoustical point of view, the mere existence of the BGs is not sufficient to use SCs as acoustic barriers because both the size and position of these BGs depend on several factors such as the angle of incidence of the wave or the arrangement of the scatterers. To avoid these problems, some strategies have been developed in the last few years. First, some authors have studied new and more efficient arrangements of scatterers out of the classical crystalline ones, such as quasicrystals, [12] quasiordered structures [13, 14] or quasifractal [15] arrangements. Another strategy is the use of scatterers with additional properties motivated by the work of Liu *et al.* [16]. The use of local properties or scatterers can reduce the angular dependence of the attenuation achieved by the periodic arrangement and increases both the level and the range of the attenuated frequencies. In this sense, recent works have shown the possibility to design this kind of structures with multi-physical phenomena scatterers to be applied in the audible ranges of frequencies as efficient acoustic barriers. [17]

In this work we show the realization and the acoustical and structural characterization of a prototype of Sonic Crystal Acoustic Barrier (SCAB) (see Figure 1). We have acoustically characterized this SCAB in a laboratory approved for this purpose for its use as traffic noise reducing devices. To do that, we have followed the European Standards EN 1793:1997 [18] relative to the intrinsic characteristics of sound absorption (Part 1) and to the intrinsic characteristics of airborne sound insulation (Part 2). The structural characterization has been done in a wind tunnel evaluating the efforts produced by wind in these structures comparing the results with the ones obtained for a traditional acoustic barrier. In the following we briefly describe the acoustic standardization and the mechanical characterization of the prototype.

Figure 1: Different views of the SCAB prototype.

2 Multiphysical phenomena scatterers

The design and the experimental characterization of the building blocks of the prototype are discussed in this Section. Three different mechanisms have been considered to attenuate sound in the desired range of frequencies: resonances, absorption and scattering. Resonances in the low frequency range, absorption in the medium-high ranges of frequencies and scattering (making use of the periodicity of the structure, i.e., using the Bragg interference) in the medium-high frequencies.

2.1 Design of the multiphysics phenomena scatterers

The scatterer used in the prototype is based on the concept of split ring resonator (SRR) which is well-known in optics. [19] Figure 2 shows the transversal view of the scatterer, that is basically a two dimensional split ring resonator covered by an absorbing material. One can observe three parts. The inner one, which is a resonant cavity, the rigid wall and the absorbing cover. The rigid wall is made of iron and plays acoustical and structural roles. The absorbing cover is a sheet of porous material (rock wool) with density 100 kg/m^3.

The resonant behaviour of the scatterer is designed taking into account the aperture L of the scatterer, the interior radius r_{int} and the thickness of the aperture, $\Delta_a + \Delta_r$. [17] Two kind of scatterers with different areas of the resonant cavity have been designed in order to cover a wide band in the low range of frequencies (210 Hz and 300 Hz). The cover of porous material has a thickness $\Delta_a = 4$ cm and it is selected in order to attenuate both the medium and the high ranges frequencies. Finally, taking into account the outdoor application of the prototype, we have used a perforated plate to protect the rock wool to the environment.

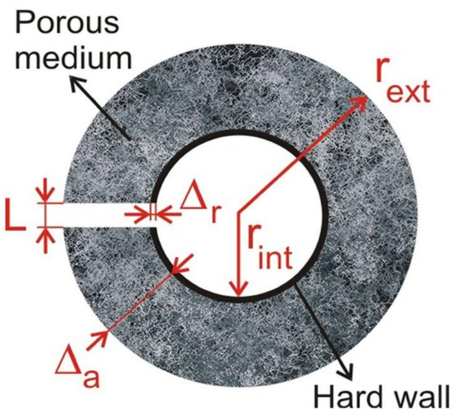

Figure 2: The transversal view of the multiphysical phenomena scatterer. r_{int} and r_{ext} are the inner and exterior radii respectively, L the aperture, Δ_r the rigid wall thickness and Δ_a the thickness of the absorbing cover.

2.2 Laboratory results

Before the acoustic standardization process we have characterized the acoustical response of a scatterer in our anechoic chamber. We used the Insertion Loss (IL), defined as the difference between the sound level recorded without and with the sample at the same point. In order to observe that the scatterer has the same acoustic response all along its symmetry axis (defined in this work in the vertical direction along the y axis), we measure the IL in several heights. IL measurements give the dependence of the attenuation properties of the scatterer on the frequency. The three parts of the scatterers used in the prototype can be seen in Figure 3a. One can observe the perforated plate, the absorbent cover and the inner resonator. We have analyzed the acoustical response of each part of the scatterer separately in order to observe the range of frequencies in which each part works.

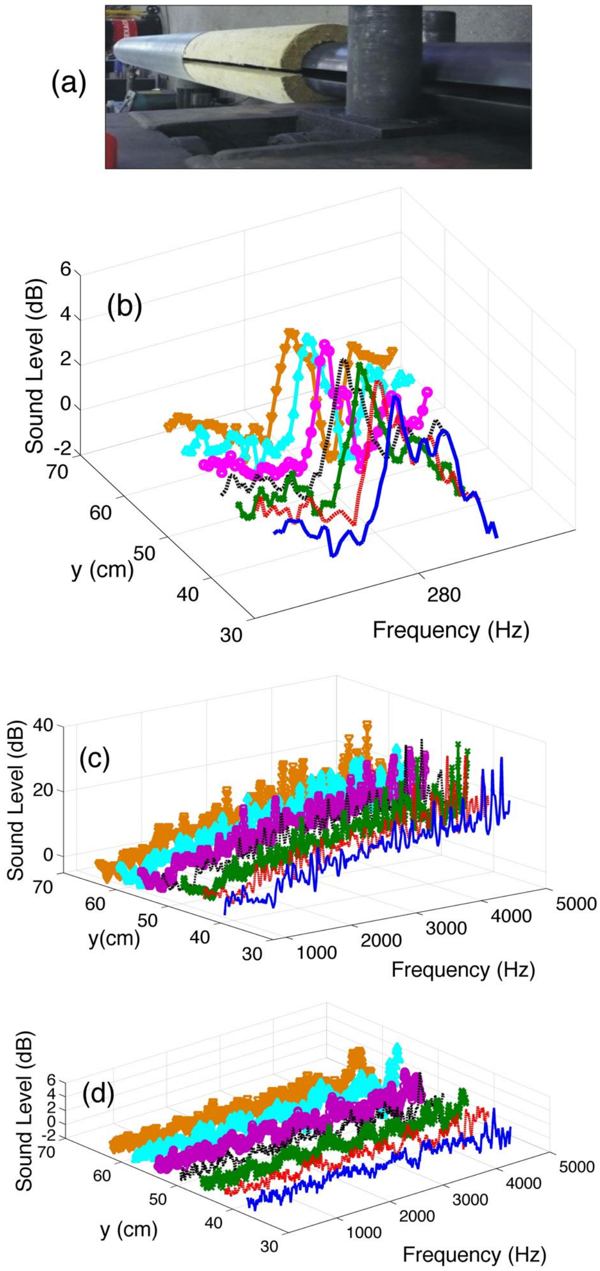

Figure 3: Characterization of the several parts of the multi-physical phenomena scatterer. (a) Picture of each part of the scatterer: Perforated cover, absorbing cover and inner resonator. IL measurements of the (b) inner resonator, (c) absorbing cover and (d) perforated plate. The measurements has been done at 25 cm from the scatterer at several points all along the symmetry axis (y-axis).

2.2.1 Resonators

The iron cylinders are slotted along its entire length with an aperture, L, equal to 2 cm. This forms the inner resonator. Figure 3b shows the IL for the inner resonator. The analyzed scatterer has an external diameter of 0.247 m, which produces a resonant peak around 210 Hz. One can observe that the resonance is practically constant all along the scatterer.

Notice that each scatterers attenuates, using resonances, around 6 dB.

2.2.2 Absorbent

The absorbent cover consists of a sheet of rock wool with a thickness of 4 cm. Porous materials work in the range of medium-high frequencies. Figure 4c shows IL measurements for the absorbent cover. One can observe that the response increases with the frequency and that the attenuation starts around 900 Hz. The average attenuation is similar for different heights all along the scatterer. Notice the difference of the IL values between the measurements of the absorbent covering and the resonators (see Figure 3b).

2.2.3 Perforated cover

The exterior cover of the scatterer is a perforated plate of 1 mm thickness and perforations of 5 mm of diameter. The role of the perforated cover is to protect the absorbent to the environment. Thus, it should be transparent to acoustic waves. Figure 3d shows the IL measurements of the perforated cover. One can see that it is transparent for the range of frequencies between 100 and 5000 Hz (traffic noise range of frequencies).

3 Periodic structure

The prototype consists of a two dimensional periodic array of multiphysics phenomena scatterers arranged following a triangular periodicity. The SCs are characterized by two parameters: the lattice constant a, separation between scatterers, and the filling fraction ff, the volume occupied by the scatterers with respect to the total volume occupied by the SC. For this periodicity, the main directions of symmetry are ΓX (0°) and ΓJ (30°). In this system, the inner part of the scatterer has a triple function. On one hand, it serves as structural support for the scatterers. On the other hand, the inner part acts as a resonator producing attenuation peaks in the low frequency range, as we have seen in the previous Section. However, the exterior part of the inner core (rigid resonator) contributes to increase the scattering inside the structure that leads to the phenomenon of the BG. The prototype has a lattice constant $a = 0.28$ m. For this lattice constant, the central frequency of the BG (Bragg's frequency) at ΓX direction is $f_{BG} = 600$ Hz.

4 Acoustic standardization

4.1 Sound absorption: EN-1793-1:1997

According to the standard EN 1793-1:1997, we have evaluated the sound absorption coefficient α_s in order to calculate the evaluation index of acoustic absorption DL_α. The value of this index is used to classify the barrier with regard to its acoustic absorption characteristics. In our case, DL_α=8 dB, that correspond to the A3 category. This result shows that a non continuous acoustic barrier formed by multiphysics phenomena cylinders can compete, from the acoustical point of view, with traditional acoustic barriers formed by continuous systems.

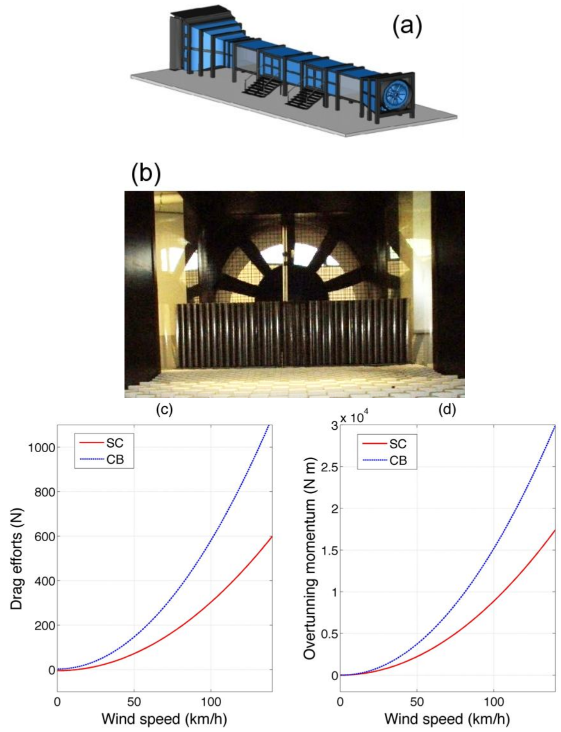

Figure 4: Wind tunnel characterization. (a) Scheme of the wind tunnel. (b) Picture of the scaled SCAB inside the tunnel. (c) and (d) show the dependence of the drag efforts an the overtunning momentum on the wind speed respectively.

4.2 Airborne sound insulation: EN 1793-2:1997

The test corresponding to the intrinsic characteristics of the barrier relative to the airborne sound insulation has been done following the recommendation of the Standard EN 1793-2:1998. To do that, the evaluation index of the airborne sound insulation DL_R (dB) is calculated according to the standard EN-ISO 10140:2011. The measurements take into account the sound level for each third octave band of the normalized traffic noise spectrum, given by the standard EN-1793-3 1997. The value of this index allows classifying the capability of airborne sound insulation of the checked barrier. In this case, DL_R=20 dB that correspond to the category B2.

5 Wind tunnel analysis: Structural efforts

Traditional acoustic barriers basically consist on a solid system interposed between the sound source and the receiver. Apart from the acoustical isolation, one of the main problems of these systems is the high transmission of the efforts produced by several systems of loads supported by the structure to the ground. For example, the transmitted efforts due to the wind are important, increasing with the height of the barrier, and as a consequence the volume of foundations and the product becomes technically and economically expensive. The prototype presented in this work is a SCAB which is formed by separated inclusions, and this fact allows the wind to pass through, decreasing the efforts that are transmitted to the ground. To estimate the values of these efforts in our barrier and to compare with those corresponding to a classical one, we have carried out some experiments in a wind tunnel with dimensions 2.14 m high, 1.8 m width and 12 m long (see Figure 4a). As a consequence two models in a scale 1:5 for both a classical barrier and a SCAB have been designed. Figure 4b shows the scaled SCAB inside the wind tunnel.

The results obtained in the laboratory are shown in Figures 4c-d. We have measured the drag effort and the overtunning momentum. Taking into account these results one can conclude that the SCAB produces efforts considerably smaller than the classical barrier, being this reduction in average around 42% in the case of the drag efforts in the wind direction and 37% in the case of the overturning momentum.

6 Conclusions

The attenuation properties of the SCAB analyzed in this work is characterized mainly by three acoustical properties: (*i*) a high attenuation baseline; (*ii*) the structure preserve the properties of the periodicity, that is, it preserves the BG although the absorbing covering is surrounding the scatterers; (*iii*) the resonances of each scatterer are also preserved in the structure. Then, Bragg interferences, resonances, and absorption coexist in the same structure without negative interplay between them. Thus, the frequency response of the system in the audible acoustic frequencies is similar to a wideband bandstop filter that allows the use of the system as traffic noise reducing device.

The acoustical properties of the SCAB have been tested by means of the European Standard for characterizing the acoustic barriers for traffic noise, the EN 1793:1997, obtaining an acoustic characterization comparable with traditional acoustic barriers. Moreover the flexibility on the control of the several mechanism involved in the attenuation process of the prototype, gives to these systems high design possibilities, being possible to construct SCAB on demand with the highest standards.

From the structural point of view, the results of the tests shown in this paper prove that the transmission of the efforts due to wind is considerably smaller than in the case of the traditional acoustic barriers. This fact could allow the installation of SCABs in places where until now it was not possible due to structural problems.

Recently, a British Standard, the CEN/TS 1793-5:2003 [20] describes a test method for determining the intrinsic characteristics of sound reflection and airborne sound isolation of traffic noise reducing devices. This Standard can be applied in situ, i.e., where the noise reducing devices are installed. The next step is to evaluate the attenuation properties of the SCAB analyzed in this work using this standard, in order to know if the attenuation properties are improved or not when the SCAB is placed outdoors and exposed to the environment.

Acknowledgments

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