Towards the development of a software to design acoustic barriers based on Sonic Crystals: An overlapping model

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Summary

The use of Sonic Crystals as acoustic screens, usually called SCAS (Sonic Crystal Acoustic Screens) has meant a qualitative jump in the field of environmental noise protection. This technological achievement, developed over the last decade, has been accomplished in two steps: the discovery of the basic knowledge about physical principles underlying in the behaviour of these periodic systems and the development of technological procedures for designing and constructing this kind of acoustic screens in such a way that be competitive, under the acoustic point of view, with respect to the classical barriers. In this sense, among all the fields where these periodic systems can be applied, the one referred to acoustic screens has been the first where a device has been designed, patented, constructed and standardized with fairly good results. However, the development of specific software to design these devices in a professional way is a pending subject to introduce them successfully in the market. Following this line, in this paper we present an overlapping comprehensive model to easily design SCAS. The model has been implemented using the Finite Elements method and is based on the tunability concept, which establish that all the acoustic effects, involved in the design, act independently one from each other, and furthermore work constructively. This fact allows the design of barriers for specific purposes, assigning to each acoustic effect a predetermined range of frequencies where it has to work. An example in the use of this model is applied to the case of the reduction of diffraction at the upper edge of a SCAS.

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1. Introduction

The possibility of controlling the transmission of acoustic waves using a kind of composite material called Sonic Crystals (SC) was proposed at the end of the last century [1]. These materials are formed by periodic arrays of solid scatterers embedded in a fluid, and one of their best-known features is the existence of band gaps (BG), defined as ranges of frequencies where the wave propagation is forbidden due to a Bragg scattering process [2]. A great effort, both theoretical and experimental, has been made to understand the underlying physics involved in these composites, and several applications have been proposed, including waveguides [3], acoustic filters [4], acoustic convergent lenses [5], Fabry-Perot interferometers [6] or environmental noise screens [7, 8].

As a result of this research, several mathematical techniques have been developed or applied to the analysis of these materials. Thus, the Multiple Scattering Theory (MST) [9, 10], the Plane Wave Expansion (PWE) [11], the Finite Difference Time Domain (FDTD) [12] or the Finite Elements Method (FEM) [13] represent different theoretical approaches to characterize the acoustic behavior of SC.

However, these models are not really useful to be used in the design of real devices based on SC. Some of them, especially the numerical ones, employ high computational time in the simulations. In some analytical methods the consideration of infinite arrays or the assumption of scatterers with infinite length are taken into account, allowing the simplification of the problem by means of transforming a three-dimensional (3D) case into a two-dimensional (2D) one, far away from real situations. But the development of theoretical models that can reflect the real performance of SC seems necessary to design acoustic devices that can compete with the current ones under the acoustic point of view. These models should consider all the acoustic phenomena involved in the analysed problem, which means that the supposition of the real 3D case should be taken into account.

On the other hand, the use of SC as acoustic screens, usually called Sonic Crystal Acoustic Screens (SCAS), is one of the most celebrated applications of these periodic structures. One of the research lines followed in this field consist on the increasing of the attenuation properties of SC using multi-phenomena cylindrical scatterers including BG, absorption and resonance phenomena, showing the tunability of the attenuation capabilities in the final design [8].

In this paper we present a handy comprehensive model, developed using FEM, to design real SCAS [14] based on multi-phenomena scatterers with a dual purpose. First, introducing new acoustic effects, such as the diffraction at the upper edge of the SCAS, that converts the analysis in a real 3D case. Second, reducing the computational cost involved in the analysis of 3D devices. Moreover, and as an example of the versatility of the developed model, we also present a solution based on the location of rigid cylindrical scatterers at the top of the SCAS to reduce the diffraction pattern by means of destructive interference of waves. We provide numerical predictions obtained with the model, which are validated with experimental results. Taking into account the obtained results, we conclude that the developed model is a step forward in the technological development of SCAS in the fight against noise.

2. Experimental characterization

To validate the numerical results obtained by means of our model, a set of experiments have been performed in controlled conditions. A sound source emitting continuous white noise, and located 1m behind the considered SCAS in order to simulate plane waves, has been used in the experiments. A SCAS made of 16 (4columns×4rows) multi-phenomena scatterers arranged in a square array with lattice constant p=0.22m is considered (Figure 1a). The multi-phenomena scatterers with length h=1,20m, are formed by PVC cylindrical resonant cavities with inner radius r_0=0.095m, thickness of the rigid wall e_1=0.005m, and a slot along its length with aperture d=0.02m. These rigid cylinders are wrapped by a layer of rockwool as absorbent material, with thickness e=0.04m and with the same slot than the PVC cylinders. Geometrical details of these scatterers are shown in the inset of Figure 1a. The first Bragg's frequency of the resultant crystal at ΓX direction (0º incidence), appears at a frequency f=515Hz, as can be seen in the band structures shown in the inset of Figure 1b.

On the other hand, and with the idea of reducing the diffraction at the upper edge of the cylinders that form the SCAS, a set of 4 empty PVC cylindrical scatterers with radius r_1=0.05m and wall thickness e_1=0.005m are arranged with a separation among them equal to the lattice constant of the SCAS, p=0.22m, being located at h_1=0.33m height on the top of the sample, as can be seen in Figure 1a. Finally, a photograph of the device can be seen in Figure 1b.

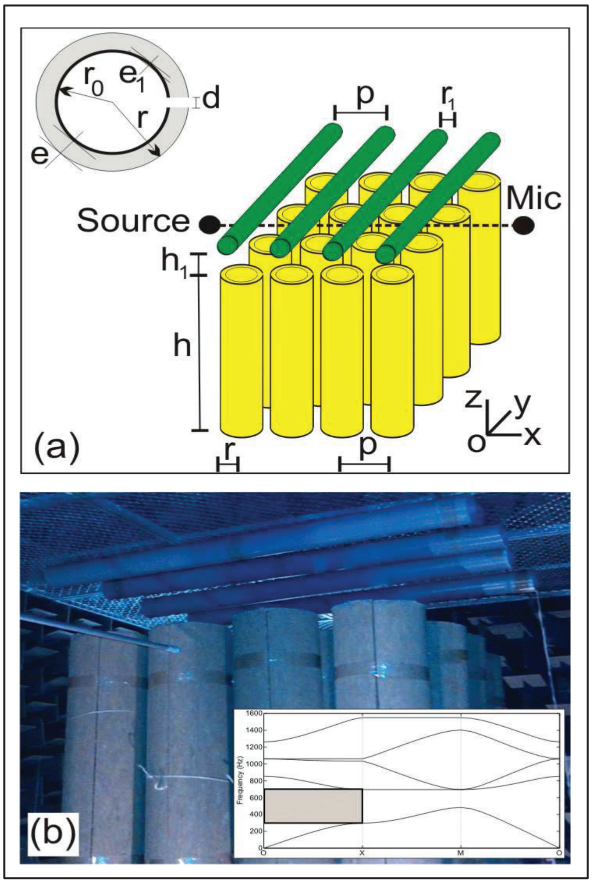

Figure 1. (a) Scheme of the experimental set-up used; (b) A picture of the sample made of multi-phenomena cylindrical scatterers. A partial view of the cylinders used to reduce diffraction at the upper edge of the sample is also shown. In the inset, one can see the band structures of the SACS calculated using the PWE method with the following parameters: $\rho_{cylinders}$=2700kg/m^3; ρ_{air}=1.3 kg/m^3; $c_{cylinders}$=6400m/s; c_{air}=340m/s, and with 961 plane waves.

3. Numerical comprehensive model

The use of numerical methods represents a good choice to solve problems related to the interaction of waves with scatterers. In our case, to model a real SCAS, the finite size of the cylinders has to be considered and, as a consequence, diffraction on the upper edge of the device appears. This real 3D problem has been modelled by us superimposing 2D models, one which takes into account the physics involved in the interaction between the incident plane wave and the multi-phenomena scatterers (BG, absorption and resonances), and another which evaluates the diffraction on the upper edge of the considered SCAS. This method implies some advantages such as the use of simplified models to explain the physical reality with good results and with a low computational cost. In the development of the model we have use as an example the SCAS defined in the experimental section. A detailed cross section of the multi-phenomena scatterer designed can be seen in the inset of Figure 2b.

The 2D model related to the array of multi-phenomena scatterers (MP-model) is shown in Figure 2a. The 2D domain (OXY plane) is formed by 4 multi-phenomena cylinders separated by the lattice constant of the array, p=0.33m, and confined between two completely reflected lateral lines also separated by the lattice constant, p. The direction of these reflected lines is parallel to the propagation direction of the incident plane wave travelling from left to right. With this geometry, the incident plane wave, which is not reflected by the lateral lines, impinges on the cylinders, and the resultant scattered waves are reflected by the lateral lines, reproducing the effect of a semi-infinite SCAS formed by 4 rows of cylinders arranged in a square array. This geometry allows the decreasing of the computational cost using a reduced surface domain. To simulate the Sommerfeld radiation conditions in the final boundary of the domain, behind the array of scatterers, we have used a Perfectly Matched Layer (PML) [15]. In the case of the multi-phenomena scatterers, the Neumann boundary condition (zero sound velocity) is applied to their rigid surfaces and the Delany-Bazley model has been used to model the porous layer (Flow resistivity 23000 kg/m³s).

Moreover, the 2D model simulating the diffraction effect (DIF-model) is reproduced by a multilayer, as we show in Figure 2b. In this case four rectangles are designed with the same height and width as height and diameter of the multi-phenomena cylinders respectively. The 2D selected domain (OXZ plane) is surrounded by PML on three boundaries, and by the impedance condition and a partial PML at the bottom boundary. The multi-phenomena scatterers are simulated as in the previous case.

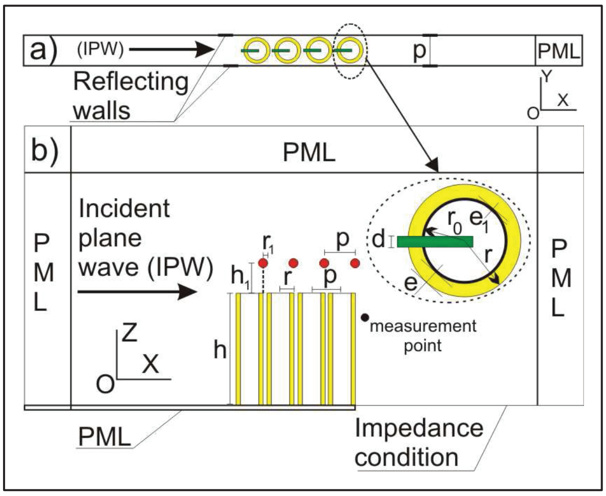

Figure 2. Comprehensive model where the real 3D problem is replaced by two 2D cases; (a) MP-model (OXY), which includes BG, resonances and absorption phenomena; (b) DIF-model (OXZ) with the main geometrical parameters of the problem considered. The PMLs and the impedance condition defined at the boundaries are also indicated in the figure. In the inset, one can see the main geometrical parameters of the multi-phenomena cylindrical scatterers.

In the design of the solution to reduce the diffraction at the upper edge of the considered SCAS, 4 empty rigid cylinders with radius r_1 and wall thickness e_1 are included in the model, arranged near the back boundary of each multi-phenomena cylindrical scatterer in order to reduce diffraction at the upper edge of each one that forms the SCAS (see Figure 2b). These cylinders are strategically located to create destructive interferences with the diffracted wave at a predetermined range of frequencies and, as a consequence, achieving a decreasing of the diffraction pressure behind the SCAS. This set of rigid cylinders is called "tuned solution" by us. As an example, the distance h_1 between each one of these cylinders and the corresponding multi-phenomena cylindrical scatterers has been chosen to decrease diffraction at a frequency f = 515Hz, which is the Bragg's frequency of the first band gap at ΓX (0º) direction of the crystal. As they are considered acoustically rigid, the Neumann boundary condition is applied to their surfaces. To develop the model and to obtain the numerical predictions, the commercial software COMSOL Multiphysics has been used throughout this study.

The acoustic attenuation is given by the Insertion loss (IL) parameter, defined as the difference between the sound level at a point recorded with and without the corresponding sample. In our case, the expression can be written as:

$$IL = 20\log_{10}\left|\frac{P_{direct}}{P_{interferred}}\right| = 20\log_{10}\left|\frac{P_0}{P_{MP\text{-}model} + P_{DIF\text{-}model}}\right| \quad (1)$$

where P_0 represents the incident complex pressure and $P_{MP\text{-}model}$ and $P_{DIF\text{-}model}$ represent the complex pressures obtained at each one of the 2D models.

4. Results and discussion

We have calculated the IL spectra using our model with and without the tuned solution by means of the expression (1) at a point located behind the device, with coordinates (0.11, 0, −0.30)m from the back edge of the last cylinder of the SCAS. The results can be seen in Figure 3a.

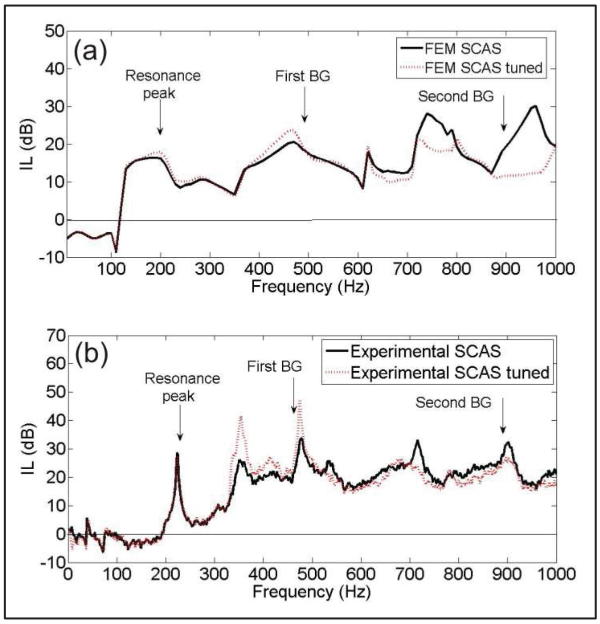

Figure 3. Attenuation results calculated behind the considered SCAS. (a) Numerical and (b) Experimental IL spectra respectively at the tested point with (red dotted line) and without (black continuous line) the tuned solution proposed to reduce diffraction at the upper edge of the device. The real value of the total pressure, Re(P), is plotted in both cases.

Some details of the resultant spectra have to be explained: (i) One can see some attenuation effects in both spectra (with and without the tuned solution). Thus, a resonance peak around 200Hz corresponding to the resonator designed and two BG peaks corresponding to the first and the second BG at 0º incidence, around 515Hz and 1030Hz respectively, appear. Moreover, an IL effect due to the porous layer (absorption) appears connecting the different attenuation peaks named before from 400 Hz. These IL spectra confirm the good performance of the developed model. (ii) On the other hand, it can be seen an extra IL in the first BG range when the tuned solution adopted to reduce the diffraction is applied. Here, $4.37 \cdot 10^5$ elements with $7.89 \cdot 10^5$ degrees of freedom for the MP-model, and $5.1 \cdot 10^5$ elements with $3.02 \cdot 10^5$ degrees of freedom for the DIF-model have been used to solve the problem. These numerical results are experimentally checked, as we show in Figure 3b.

5. Conclusions

A numerical comprehensive model to design real SCAS formed by cylindrical multi-phenomena scatterers embedded in air is presented in this paper. Basically, the model allows the study of the 3D problem as an overlap of two 2D cases. The MP-model includes BG, resonances and absorption mechanisms. The DIF-model, which evaluates the diffraction at the upper edge of the cylinders, was tuned by adding rigid cylinders above the last edge of each of the multi-phenomena scatterers that forms the SCAS. The model allows the analysis of each one of the acoustic mechanisms involved independently and, at the same time, allows the research of the best solution for each one of the acoustic phenomena involved. This versatility allows the inclusion of any desired acoustic mechanism, with the only caution of introducing it into the appropriate 2D model in which the complete 3D model has been split. The versatility of the model, the low computational cost and the successful obtained results can allow the design of technologically advanced SCAS to control acoustic waves.

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