SOUND DIFFUSION PROVIDED BY SONIC CRYSTAL STRUCTURES - EXPERIMENTAL AND NUMERICAL RESULTS

Paulo Amado Mendes[1], Luís Godinho[1], Pedro Gil Santos[1], Ricardo Patraquim[1], Tony Almeida[2]

[1] ISISE, Dep. Civil Engineering, University of Coimbra, Coimbra, Portugal
{ pamendes@dec.uc.pt; lgodinho@dec.uc.pt; gils@sapo.pt; rpatraquim@gmail.com }
[2] Dep. Civil Engineering, University of Coimbra, Coimbra, Portugal
{ 26tonyalmeida26@gmail.com }

Abstract

The metamaterials are interesting structures, with peculiar physical properties, which have been studied comparatively to more traditional materials in recent decades. One particular case of acoustic metamaterials is the case of sonic crystals; they are periodically arranged structures, with individual scatterers regularly spaced, and they present a certain behavior, revealing high levels of sound attenuation in a range of frequencies known as the band-gap. However, in this work, a different acoustic feature of the sonic crystal structures is explored, namely its ability to work as a sound diffuser in comparison to a flat surface. An experimental study has been performed, using a simplified semi-anechoic space at the Department of Civil Engineering of the University of Coimbra, with different configurations of reduced-scale sonic crystals being analyzed for the diffusion coefficient along the frequency range. Additionally, a meshless numerical model, based on the Method of Fundamental Solutions (MFS), has been developed in order to simulate the diffusivity of those sets of periodically distributed cylindrical scatterers defining the sonic crystal structures. The obtained results highlight the effects of the presence of the sonic crystals on the diffusion coefficient when compared to a flat surface.

Keywords: Sound diffusion, sonic crystal, numerical modelling, experimental evaluation.

PACS no. 43.55.Br, 43.55.Ka, 43.35.Gk

1 Introduction

Acoustic diffusers are generally adopted in conditioning of spaces with higher acoustic requirements (such as studios, theaters, concert halls, etc.), acting mainly to ensure a proper sound field without excessive sound absorption and spreading the sound evenly around the room, while eliminating acoustic defects such as echoes or "shadow" zones [1]. For sound diffusion, we can shape the surfaces of the room, use surface ornamentation or mount dedicated elements, such as acoustic diffusers. Much of the existing diffusers on the market correspond to Schroeder-type solutions (and their numerous variants), also known as QRD (quadratic residue diffuser), with the depths of the elements/wells being defined by a given theoretical sequence of quadratic residues.

More recently, during the last decade, in the works by Redondo et al [2, 3] the use of new acoustic diffusers based on sonic crystals (with a flat panel backing) has been proposed and thoroughly investigated by an implemented two-dimensional Finite Difference Time Domain (FDTD) scheme. The use of regular crystals was analysed and the adoption of modified crystals (with mixed configurations/periods) revealed an increased performance. The authors concluded that this kind of structures could be an alternative to classical sound diffusers, specially in the low frequency range and with lower thickness than the conventional ones. Following those previous studies, the optimization of sonic crystals to act as acoustic diffusers over a large frequency range has been explored by Redondo et al [4]. They used optimization techniques, namely evolutionary multiobjective algorithms, that were combined with the FDTD scheme to predict and considerably enhance the performance of the sound diffusers based on sonic crystals.

On the other hand, Patraquim et al [5] also proposed an innovative solution for acoustic conditioning of spaces, consisting of mixed absorptive-diffusive panels, with alternate areas of absorptive and reflective surfaces. A set of different solutions was tested in reverberant and semi-anechoic conditions, and a numerical model based on the Boundary Elements Method was used to simulate the acoustic behaviour of the mixed panels.

The objective of the present preliminary study is to evaluate the sound diffusion coefficient of periodic structures, with rigid cylindrical scatterers regularly displaced in different spatial configurations. For this purpose, a laboratorial analysis of the sonic crystal structures is performed in a small-sized semi-anechoic room, with the diffusion coefficient being computed in accordance to the methodology described in the ISO 17497-2 standard [6], and some of the experimental data is compared with a numerical model based on the MFS (Method of Fundamental Solutions), in the frequency domain.

2 Experimental evaluation

The experimental analysis of the diffusive behaviour of sonic crystal structures was performed, in this work, by evaluating the spatial uniformity of the scattered energy by the sonic crystal and computing the diffusion coefficient of several configurations. The adopted measurement procedure followed the ISO 17497-2 standard [6], in a simplified semi-anechoic room so as to meet the free field required condition.

2.1 Laboratorial setup

An existing room in the Department of Civil Engineering at the University of Coimbra, with approximate dimensions of 5.0 x 4.3 x 2.7 m^3, was refurbished with the application of sound absorbent linings both in the walls and in the ceiling (the floor was kept with its reflective condition, as can be seen in Figure 1). The obtained semi-anechoic space thus approached the necessary free field acoustic conditions while presenting a very low background noise, and Pereira et al [7] performed a more detailed description of this space.

The layout for the measurement procedure (Figure 1) was defined considering the available space and the dimensions of the specimens to be tested. The microphones were placed facing the diffusive structures, in a semi-circle of radius 1.90 m, aligned with the frontal plane/row of the diffusing surface/sonic crystal. Since an angle of 5° was adopted between microphone locations, 37 measurement positions were used to get impulse responses between +90° and -90°. With this configuration, more than 90% of the receivers were located outside the specular zone, surpassing the requirement from the test standard. The sound source was located 3.00 m away from the specimen, in three possible positions: centered at 0º in relation to the normal direction of the diffuser structure and at angles +35º and -35º in relation to that direction. The measurements corresponded to the room impulse responses, using the Maximum Length Sequence (MLS) technique and *01dB's Symphonie unit & dBBati 32* software, with the maximum number of sequences given by 2^{14}-1 = 16383 and a total measuring time of 20.5 s.

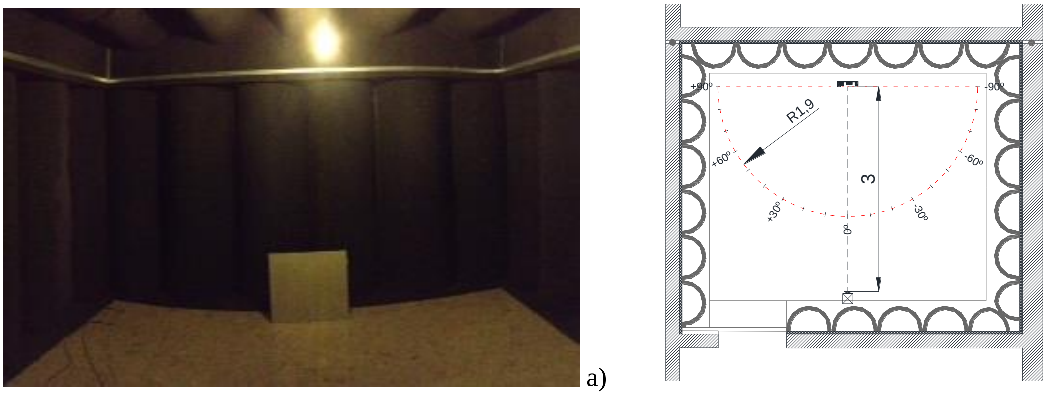


Figure 1 – Simplified semi-anechoic room: a) image of the interior, looking at the specimen's location; b) layout configuration for diffusion coefficient evaluation.

2.2 Analysed specimens and configurations

The tested specimens correspond to a set of sonic crystal structures, with individual scatterers regularly spaced and a similar look as a sonic crystal barrier. Several configurations were tried, essentially consisting of variants to the traditional rectangular and triangular lattices, with different numbers of rows and spacing between the cylindrical scatterers (see the schematic representations of some variants on Figure 2). The periodically arranged cylinders used to build the sonic crystal structures comprised a set of PVC hollow tubes with diameters of 20 mm and 600 mm height. They were glued directly to the floor of the room and a great effort was made so as to keep them in vertical positions as much as possible (with a thin horizontal board at the top). Both rectangular and triangular lattice configurations were tried, with spacing between cylinders of 2 and 3 times the tube diameter (referred as 2D and 3D), and the cylinders were organized in arrangements of 1, 2 and 3 rows, in succession. Additionally, a plane surface with dimensions of 60 x 60 cm^2, made of flat rigid stone, was also used as a reference plane surface for comparison of the diffusive behaviours.

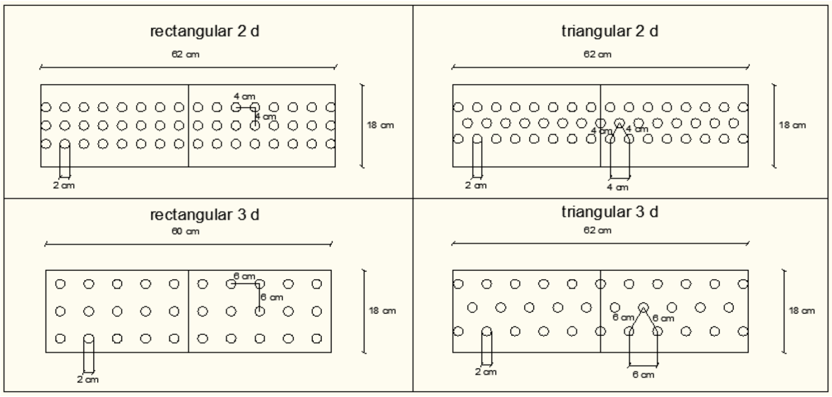


Figure 2 – Schematic representation of some of the sonic crystal structures tested.

2.3 Measurement procedure and data processing

The experimental evaluation of the diffusion coefficient requires the measurement of the reference impulse response with no diffusive structure inside the room ($h_2(t)$) and an analogous measurement with the diffusive specimen present in the room ($h_1(t)$). The diffuser response is then isolated by subtracting the response with the diffusive specimen to the response without the diffusive structure. To obtain the frequency domain responses, at each microphone position, a fast Fourier transformation (FFT) is applied to the impulse responses. The integration of those frequency responses in 1/3 octave band frequencies computes the polar diagrams with the corresponding sound intensities L_i, produced by the diffusive structure. At each frequency, with the polar responses and the use of an autocorrelation function, the directional diffusion coefficient is then computed by using the following equation

$$d_q = \frac{\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 - \sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}{\left(n-1\right)\sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}, \tag{1}$$

with θ representing the angle of incidence, L_i the sound pressure levels (in dB) taken from the polar response at receiver position i, and n the number of microphone positions (37, in the present study). On the other hand, the normalized diffusion coefficient can be evaluated, at each frequency, by the next expression, taking into account the reference results of a flat surface:

$$d_{\theta,n} = \frac{d_\theta - d_{\theta,r}}{1 - d_{\theta,r}}, \tag{2}$$

with d_θ corresponding to the diffusion coefficient of a test specimen while $d_{\theta,r}$ corresponds to the diffusion coefficient attained by a flat reference surface with the same size as the test specimen being analyzed.

3 Numerical method

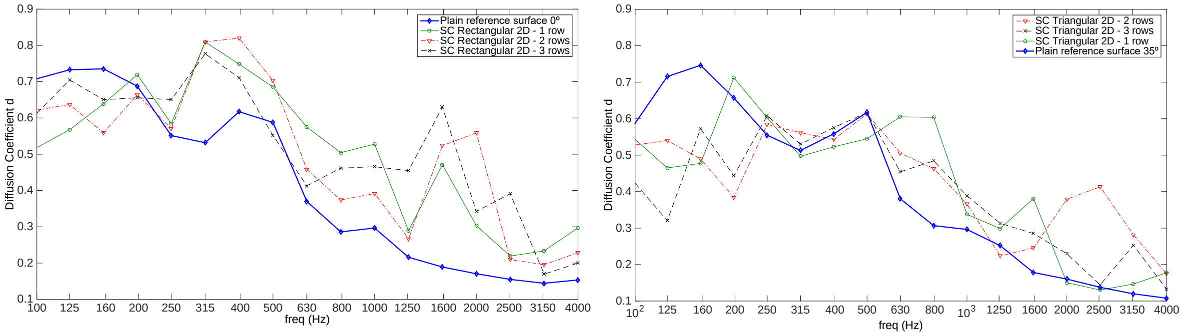
With the aim of analysing the validity of the experimental measurement procedure, and to develop an efficient tool to evaluate the diffusion coefficient and perform some initial simulations with sonic crystal specimens, a numerical model was set-up. In this model, the diffusive structure is considered to be infinite in the *z* direction and embedded in an unbounded air medium, excited by a cylindrical pressure source. For these two-dimensional simulations, the numerical model is based on the meshless Method of Fundamental Solutions (MFS), which leads to results with comparable level of accuracy of those obtained by the classical Finite Element Method (FEM) or the Boundary Elements Method (BEM) numerical methodologies, although requiring considerable less computational resources. The implemented strategy was previously described in the works by Martins et al. [8] and Santos et al. [9], and adapted in the scope of this work for the computation of the diffusion coefficient. The MFS is a meshless method, used here for analysing the propagation of sound in a two-dimensional space with scattering elements, in the frequency domain, which is represented by the Helmholtz equation. This method establishes an approximation of the solution of the problem, by linearly combining the fundamental solutions of a set of virtual sources located outside the propagation domain and of the real acoustic sources of the problem, and after prescribing the adequate boundary conditions. By postprocessing the numerical results corresponding to the scattered wave field in the acoustic domain, it is possible to evaluate the diffusion coefficient for each geometric configuration of the diffusive structures and to compare with data obtained in the laboratorial semi-anechoic room.

4 Sound diffusion results by sonic crystals

Using the experimental methodology previously described, the specimens were tested in the simplified semi-anechoic room, with the sound source being positioned 3.00 m away from the centre of the first row of the crystal and for incidence angles of 0º, 35º and -35º. The influence of the spatial distribution of the cylindrical scatterers was analysed in a parametric study involving more than twenty complete acoustic tests. The measured data was processed in order to obtain, for each specimen, the diffusion coefficient along a frequency range from 100 to 4000 Hz. At the same time, some of the tested configurations were also reproduced by the numerical method and the comparison of the experimental data and preliminary numerical results was envisaged.

4.1 Experimental data

Two sets of experimental results are presented in Figures 3a and 3b, illustrating the measured diffusion coefficient for different cases. In the first figure, the sonic crystals with rectangular lattice with 2D spacing were selected, with the sound source positioned perpendicularly to the diffusive structure (0º incidence angle). On the other hand, in Figure 3b, the presented results correspond to the triangular lattice with 2D spacing, for an incidence angle of 35º. In both cases, results for the reference plane surface cases are also shown, making it possible to identify the main differences in the diffusive behaviour of periodic structures to a plane rigid surface with similar dimensions. One may notice that, in the mid to high frequency range of interest, there seems to be an improved diffusive capacity of the sonic crystal structures, although this is not observed at low frequencies. Additionally, there is not a clear pattern regarding the evolution of the diffusive coefficient when comparing the periodic structures with 1, 2 or 3 rows, which may indicate that the lattice configurations can be further optimized.



a) b)

Figure 3 – Diffusion coefficient of periodic structures measured in semi-anechoic conditions:
a) rectangular lattice (2D) with 0º sound incidence; b) triangular lattice (2D) with 35º sound incidence.

4.2 Comparison with numerical results

One further comparison can be observed in Figure 4, where results for the case of a periodic structure, organized in a rectangular lattice with a 2D spacing between cylinders, are included. In this figure, the numerical results are compared with the data measured in laboratorial conditions. For comparison purposes, the diffusion coefficient measured with the plane surface is also plotted as a reference result. The geometric configuration of the sonic crystal has been implemented in the two-dimensional MFS model, with the rigid scatterers organized in 3 rows, and the experimental free field conditions being reproduced in the numerical formulation. The general trend of the diffusion coefficient along the frequency range is followed, despite some visible differences between the predicted numerical values and the measured data. The major disparities are observed in the low frequency range, and they may be justified by some inadequate experimental conditions due the dimensions of the simplified semi-anechoic room. Further improvements of the numerical results are presently being studied in order to attenuate the observed differences. However, with both methodologies, the improvement of the diffusion coefficient is registered, when the plane surface reference results are compared.

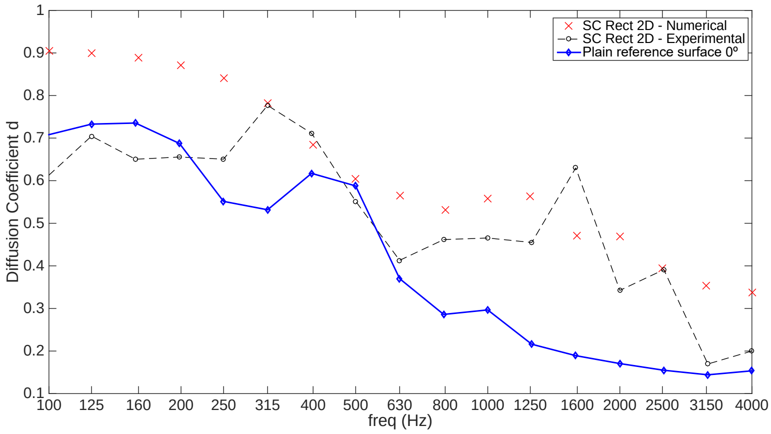


Figure 4 –Diffusion coefficient for a sonic crystal with rectangular lattice: comparison between measured data and computed results.

5 Conclusions

The results obtained in the scope of this preliminary study suggest that the periodic arrangement of rigid cylindrical scatterers, known as sonic crystal structures, can be used as sound diffusers, representing an improvement in comparison to a flat surface. Different periodic configurations were studied and their diffusion coefficient was evaluated in a simplified semi-anechoic room. The increase of the diffusion coefficient was mainly observed in the mid to high frequency range, and in the case of normal incidence to the sonic crystal structure (0º incidence angle). Some limitations were found on the use of the semi-anechoic room at low frequencies. The preliminary numerical simulations also corroborate the more diffusive behaviour of the sonic crystals when compared to a smooth flat surface. The adopted numerical methodology, adapted from previously used models for evaluating the insertion loss (IL) of periodic structures, has revealed to be an efficient tool, even with a large number of scatterers. In future works, the numerical model will be improved towards the optimization of the sonic crystal structures so as to better understand and further enhance the diffusive character of this kind of interesting structures.

Acknowledgements

This work was partly financed by FEDER funds through the Competitivity Factors Operational Programme - COMPETE and by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633.

References

[1] Cox, T.J.; D'Antonio, P. *Acoustic absorbers and diffusers: theory, design and application*, Spon Press, 2nd Edition, 2009.

[2] Redondo, J.; Sánchez-Morcillo, V.; Picó, R. The potential for phononic sound diffusers. *Proceedings of the International Symposium on Room Acoustics, ISRA 2010*, Melbourne, Austrália, 2010.

[3] Redondo, J.; Picó, R.; Sánchez-Morcillo, V. Sound diffusers based on sonic crystals. *Journal of the Acoustical Society of America*, 134(6), 2013, pp. 4412-4417.

[4] Redondo, J.; Sánchez-Perez, J.V.; Blasco, X.; Herrero, J.M.; Vorlander, M. Optimization of sound diffusers based on sonic crystals. *Proceedings of TecniAcustica 2015*, Valencia, 2015.

[5] Patraquim, R.; Santos, P.G.; Godinho, L.; Amado Mendes, P.; Mateus, D.; Pereira, A. Behaviour of mixed absorptive-diffusive panels based in pseudo-random sequences. *Proceedings of the 22nd International Congress on Sound and Vibration (ICSV22)*, Florence, Italy, july 12-16, IIAV, 2015.

[6] ISO 17497-2 Standard. Acoustics. Sound-scattering properties of surfaces. Part 2: Measurement of the directional diffusion coefficient in a free field, 2012.

[7] Pereira, A.; Gonçalves, H.; Mateus, D.; Godinho, L.; Branco, F. Assessment of the diffusion coefficient provided by wooden panels". *Proceedings of Forum Acusticum*, Kraków, 7 -12 September, 2014.

[8] Martins, M.; Godinho, L.; Santos, L. Numerical Evaluation of Sound Attenuation Provided by Periodic Structures". *Archives of Acoustics*, 38(4), 2013, pp. 503-516.

[9] Santos, P.G.; Carbajo, J.; Godinho L.; Ramis, J. Sound Propagation Analysis on Sonic Crystal Elastic Structures using the Method of Fundamental Solutions (MFS), *Computers, Materials and Continua*, 43(2), 2014, 109-136.