



EXPERIMENTAL AND NUMERICAL ANALYSIS OF SUSTAINABLE SONIC CRYSTAL BARRIERS BASED ON TIMBER LOGS

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Abstract

The acoustic attenuation properties of sonic crystals have been studied in the last decades in different fields of interest. Matching the so-called band gap, in which very high attenuation is obtained, with the dominant noise frequencies in order to obtain tailor-made solutions for certain applications is an appealing concept, which makes these structures an interesting alternative to existing ones. This work presents the results of the research performed at the Civil Eng. Dept. of the University of Coimbra in this field, developing the idea of sonic crystals as a traffic noise mitigation solution. The studied concept corresponds to a highly sustainable solution, in which the structural elements are made of timber logs obtained from forest thinning operations. Here, we summarize the main steps of the conducted researches, both experimental and numerical, and document the first results measured on an experimental site using a full-scale prototype, produced using the proposed solution.

Keywords: sonic crystal, timber, numerical modelling, real-scale prototype.

PACS no. 43.50.Lj, 43.28.Js

1 Introduction

In recent years, and mainly since the 1990's, the scientific community has become increasingly interested in the study of sound attenuation provided by sonic crystals. These structures, which can be seen as composite structures designed in periodic or quasi-periodic arrangements, seem to have quite an interesting acoustic behaviour, which can be useful in noise mitigation. Their presence in a host fluid medium, such as the outdoor environment, can lead to the formation of band gaps, corresponding to frequency ranges where the acoustic waves are not allowed to propagate, being scattered by the sonic crystal solid scatterers. The concept is, indeed, similar to that of photonic crystals and electronic band structures, in which the propagation of electromagnetic waves is significantly affected by a periodic arrangement of scatterers [1, 2].

A pioneering work by Martínez-Sala et al. [3] experimentally demonstrated the sound filtering capabilities in a real structure, when analysing the artistic sculpture by Eusebio Sempere with a periodic arrangement of steel tubes installed in the gardens of the Fundación Juan March, in Madrid. Those authors have shown that the periodic arrangement of the stainless steel tubes originates multiple interferences (constructive and destructive, similar to Bragg scattering/diffraction) between acoustic



waves. This was identified as a frequency dependent behaviour, which attenuated the sound spectra of the transmitted waves at certain frequencies (the forbidden bands or band gaps) while having minimal effect on others. In several studies, researchers have pointed out the effect on noise attenuation of this type of periodic structures, with different geometrical configurations and materials [4, 5]. The specific interest on the use of sonic crystals as a noise mitigation measure, when designing acoustic barriers with cylindrical scatterers, has also been demonstrated in different published works [6, 7]. Recent developments can be found in the literature, such as those regarding the adoption of sound absorbent cylinders [8], the use of a periodic array of trees or recycled materials [9, 10], and the combination of sonic crystal scatterers aligned parallel to the ground with a classic rigid noise barrier [11].

In most of the published works, the acoustic behaviour of sonic crystals is studied mainly from either a theoretical and/or an analytical point of view, or using experimental and laboratorial approaches. Different numerical techniques have been proposed for modelling acoustic wave propagation in the presence of these structures, mostly using two-dimensional (2D) approaches. It seems that only a limited number of publications address the full three-dimensional (3D) numerical modelling of wave scattering through sonic crystals, and mostly corresponding to proposed extensions of some of the mentioned methods. Although most of the prominent phenomena related to periodic structures are still observable in 2D analyses, the finite character of these structures in all three dimensions can only be captured in detail using 3D strategies. However, these strategies invariably lead to higher computational demands.

In the present paper, the main findings of a research project – project SCLog – developed at the University of Coimbra are described. Its aim was to define an innovative technological solution for traffic noise mitigation, based on timber logs forming sonic crystals. Here, the developed concepts and methodologies are described, regarding the development of adequate numerical methods, their laboratorial validation, and the construction and testing of a real sized prototype.

2 Description of the solution

When considering the technological use of sonic crystals, the development of acoustic barriers for traffic noise attenuation (see a conceptual preview in Figure 1a) is one of the most interesting and widely accepted applications. Traffic noise usually presents dominant frequencies that can therefore be used to adjust the prohibited frequencies or band gaps that are attenuated by the sonic crystal structures. From previous research and ongoing works it is possible to conclude that the sound reduction provided by periodic structures is mainly related to two mechanisms, namely the configuration of the structure (geometrical arrangement and distance between scatterers or lattice – Figure 1b) and the acoustic properties (geometry-dependent and sound absorption) of the individual elements. This type of barriers present practical advantages, since they are light and can be easily built, they can use less material and be cost competitive, they exhibit some level of transparency and low visual impact, and they can be adequately tuned by making the correct arrangement of scatterers, in order to control sound attenuation properties for different situations. For instance, when considering road traffic noise, the most important frequency range extends from 500 to 1500Hz, occurring, in most of the cases, the noise peak around 1000Hz.

A recent research project at the University of Coimbra focused on the development of a possible practical solution for reducing traffic noise, which had not yet been explored. The use of round timber elements, with small diameters, to build the sonic crystal acoustic barrier is here proposed and analysed. These elements are thoroughly available from forest thinning operations and require little processing to be incorporated in the acoustic barrier, giving rise to an interesting, sustainable and viable solution that needs to be characterized in detail.

The use of small diameter timber logs taken from forest thinning operations, in structural applications, such as in roofs, building frames, bridges, among others, has already been studied worldwide and,

specifically in Portugal, an extensive research work was performed in the characterization of small roundwood timber obtained from maritime pine (*pinus pinaster*) forest thinning operations. After assessing the mechanical behaviour as structural members, their mechanical properties were found to be similar or often higher than the ones obtained for wood available from other species, and to be significantly higher than that of other's, more processed, wood elements namely with rectangular cross section. Moreover, this species is the main softwood growth in Portugal, with an abundant number of trees being taken from thinning operations in the country that fulfil the main requirements for the barrier elements (e.g. the size and mechanical properties). However, the incorporation of this renewable material in periodic arrays to form acoustic barriers hasn't been tried yet, to the authors' knowledge. In terms of sustainability, the log trees that are being proposed for this solution only need low processing, such as lathe and a preservative treatment.

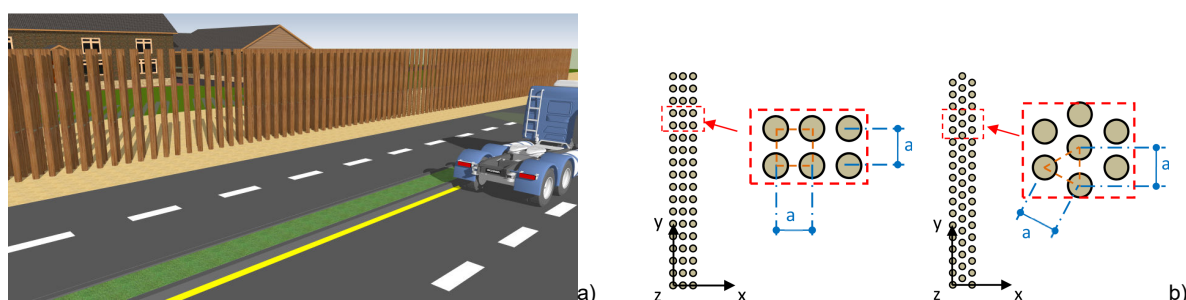


Figure 1 - a) Computer image of an implementation of the sonic crystal-type barrier with: b) schematic representation of element's placement on rectangular (left) and triangular (right) lattice distributions.

The construction of the acoustic barrier illustrated in Figure 1a can be performed with similar equipment that is used for the installation of utility poles for communication lines, by introducing the logs into the soil at a given depth. The proposed solution can thus be seen as a technologically simple and sustainable solution, with high potential in the mitigation of traffic noise.

3 Numerical modelling and laboratory testing

Special attention has been given to the evaluation of the acoustic behaviour of the sonic crystal-type barriers, in terms of insertion loss (noise attenuation) and acoustic dispersion, with the development of numerical models. As it was referred, different numerical methodologies are available to model the crystals, some of them more efficient and/or exhaustive than others. In the present research, three numerical models were implemented, based either on the Method of Fundamental Solutions (MFS) or on the Boundary Element Method (BEM), and allowing the analysis of these structures in 2D, 3D and 2.5D. The proposed approaches are quite general, and may allow interesting analysis of the sonic crystal structures from an engineering point of view.

3.1 2D Noise reduction / Insertion Loss assessment

For the 2D simulations, the numerical model is based on the MFS, leading to results with similar level of accuracy of those obtained by the classical FEM or BEM approaches, but requiring less computational resources. The implemented methodology was previously described in the works by Martins et al. [12] and Santos et al. [13]. The MFS is a meshless method, used here for analysing the propagation of sound in a two-dimensional space, in the frequency domain, which is represented by the Helmholtz equation. This method obtains an approximation of the solution of the problem, by

combining in a linear way the fundamental solutions of a set of virtual sources located outside the propagation domain and of the real acoustic sources of the problem, such that

$$p(X, k_f) = \sum_{j=1}^{NS} Q_j G(X, X_j, k_f) \quad (1)$$

where $p(X, k_f)$ is the acoustic pressure at a given domain point (X) for a given wavenumber (k_f), $G(X, X_j, k_f)$ is the Green's function representing the pressure originated by the virtual sound source located at X_j , and Q_j represents the amplitude (initially unknown) of that source. After applying the adequate boundary conditions, a system of equations is formed, whose solution leads to the unknown amplitude values.

The implemented numerical model was tested against experimental results obtained for reduced scale prototypes. The tested models correspond to 1:10 reduced scale models of a full-scale barrier and several configurations were tried out for the sonic crystal barrier, 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 on Figures 3a and 4a). The cylinders used to build the reduced scale barriers comprised a set of PVC hollow tubes with diameters of 20mm, which corresponds to 200mm cylindrical elements in full-scale acoustic barriers, as can be seen in Figure 2.



Figure 2 – a) Sample image of a 1:10 sonic-crystal prototype (from [14]); b) Image of the acoustic test.

The experimental setup was created to represent, as close as possible, the 2D sound propagation assumed in the numerical model. Having that in mind, the sonic crystal structures were tested on a previously prepared quasi-anechoic closed room, in order to avoid possible interferences generated by reflections in the vicinity of the crystals. The frequency range of interest in these validation tests ranges from 5000 to 15000 Hz, as it represents, at the 1:10 scale, the usual range for traffic noise for the real scale (typically 500-1500 Hz). The sound attenuation provided by the acoustic barrier, defined by the registered Insertion Loss (IL), was evaluated as the difference between the average Sound Pressure Levels (SPL) measured with and without the sonic crystal barrier, using the SPL registered at a square grid of 25 receiver/microphone points (see the schematic setup on Figures 3a and 4a).

An extensive comparison between the numerical results provided by the MFS model and the experimental results was performed for different configurations, initially defined considering simpler rectangular and triangular lattices (as illustrated on the selected examples of Figures 3a and 4a) and then varying the lattice parameters. For the two selected cases, the insertion loss was determined for a frequency range between 100 to 20000Hz, considering frequency bands with a width of 100Hz. In Figures 3b and 4b, the red lines represent the experimental results and the blue ones the numerical

results. In general, the computed results closely follow the experimental measurements, except for lower frequencies of up to 2500Hz. At these lower frequencies, it is possible that the observed differences are due to the modelling of the sound source (which predominantly makes use of the woofer component), and to a less efficient sound absorption provided by the lining materials on the room, which can disturb the response by introducing undesired reflections. The band gaps can be easily observed, with peak Insertion Loss results reaching almost 20dB, and a generalized sound attenuation is visible in the medium- to high-frequency range.

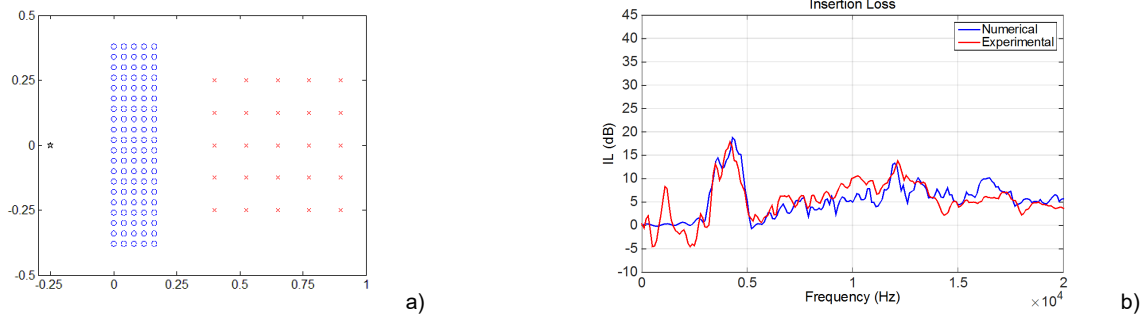


Figure 3 - Sonic crystal barrier with rectangular lattice: a) schematic representation; b) IL with rigid cylinders.

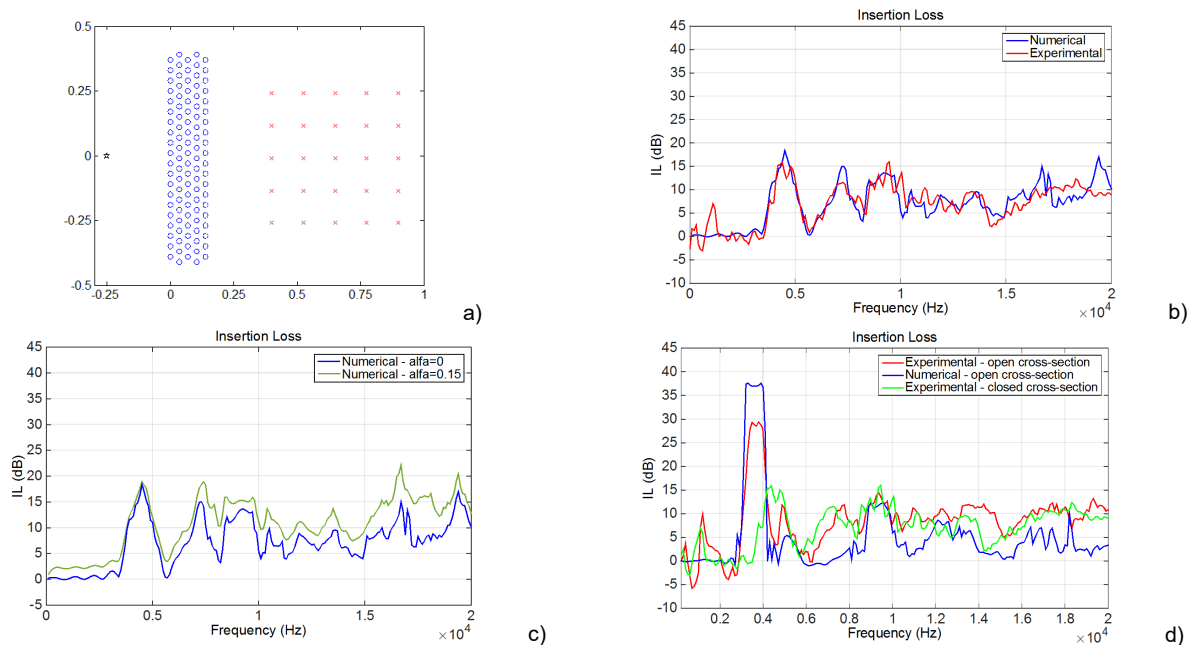


Figure 4 - Sonic crystal barrier with triangular lattice: a) schematic representation; b) IL with rigid cylinders; c) IL with superficial sound absorbent cylinders; d) IL with open cross-section cylinders.

For the same lattice configurations, the influence in the sound attenuation assuming a certain level of superficial sound absorption of the barrier elements is numerically assessed, since roundwood timber elements are likely to be more sound absorbent than hollow PVC tubes. As can be observed in Figure 4c, the use of that natural material as raw material for the barrier elements is expected to lead to visible improvements in the insertion loss levels provided by the barrier, particularly outside the first detected band gap.

Additionally, some preliminary (experimental and numerical) results are presented regarding the adoption of cylindrical elements with an open cross-section, which can lead to an increase to sound attenuation, not only at specific resonant frequencies but along the frequency range of interest (see Figure 4d).

3.2 3D Insertion Loss assessment

The 3D acoustic analysis of the proposed structures may highlight a number of features that are not seen in the simpler 2D simulations described above. Indeed, this kind of simulation, although numerically more demanding, allows accounting for specific aspects such as the real height of the barrier (including diffraction effects occurring on its top), or the positioning of the source and receivers at different heights from the ground. In our research, the 3D Boundary Element Method (BEM) was used in this simulation. The basic 3D direct BEM equation (CBIE) can be written as

$$C(\xi)p(\xi) = -i\rho\omega \int_{\Gamma} G(\xi, X) v_n(X) d\Gamma - \int_{\Gamma} \frac{G(\xi, X)}{\partial n} p(X) d\Gamma + \sum_{k=1}^{NS} Q_k G(\xi_k^f, \xi) \quad (2)$$

where Γ is the boundary surface, ρ is the density, $G(\xi_k^f, \xi)$ is the incident field regarding the acoustic pressure generated by the real source placed at position ξ_k^f ; $p(X)$ and $v_n(X)$ represent the acoustic pressure and the normal component of the particle velocity, respectively. The coefficient $C(\xi)$ depends on the boundary geometry at the source point, and equals $\frac{1}{2}$ for a point in a smooth boundary.

For the case of exterior problems, it is known that the previous method provides unstable solutions at certain frequencies. Strategies have thus been developed in order to avoid this significant drawback, namely by means of its combination with the so-called hypersingular boundary integral equation (HBIE). To obtain this second equation, the first derivative with respect to the normal direction at the source point must be considered, and the following equation arises:

$$-i\rho\omega \tilde{C}(\xi) v_n(\xi) = -i\rho\omega \int_{\Gamma} \frac{\partial G(\xi, X)}{\partial n_L} v_n(X) d\Gamma - \int_{\Gamma} \frac{\partial G(\xi, X)}{\partial n_L \partial n} p(X) d\Gamma + \sum_{k=1}^{NS} Q_k \frac{\partial G(\xi_k^f, \xi)}{\partial n_L} \quad (3)$$

As before, the coefficient $\tilde{C}(\xi)$ depends on the boundary geometry at the source point, and equals $\frac{1}{2}$ for a smooth boundary.

As proposed by Burton and Miller, the authors have used a combination of these two boundary integral equations in the form

$$CBIE + i/k HBIE = 0 \quad (4)$$

To allow tackling problems with large structures (usually a limitation of classic BEM implementations), an Adaptive-Cross-Approximation was used. Further details can be found in [15].

Some illustrative results, for a comparison of the 3D pressure fields computed in the presence of a conventional and a sonic crystal acoustic barrier can be observed in Figure 5. Although the sound pressure levels behind the barrier are not as low as obtained with the plane and opaque barrier, the sound attenuation and the 3D acoustic character can still be seen when comparing Figures 5a to 5b, and 5c to 5d.

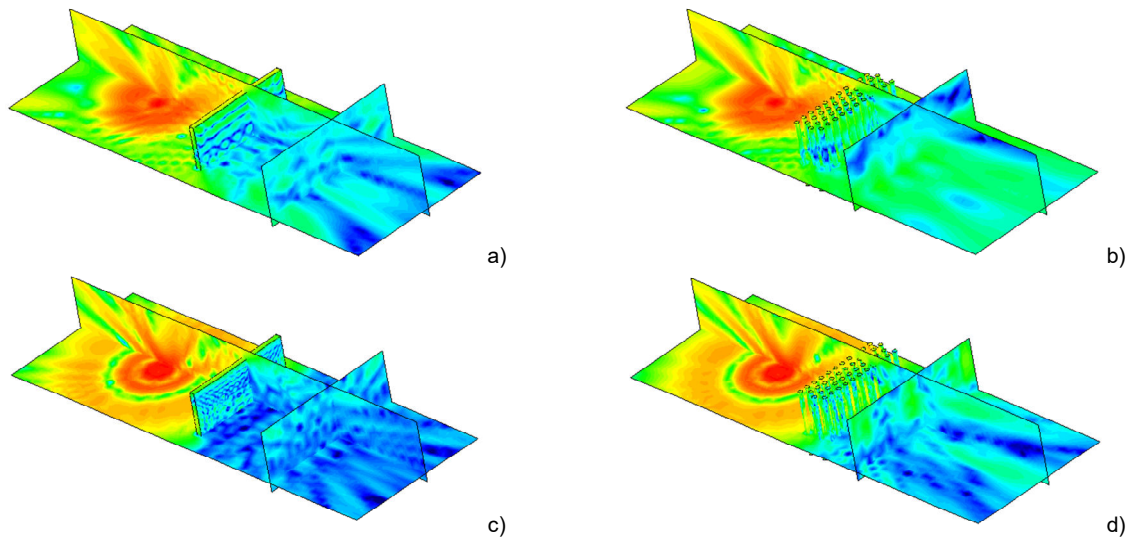


Figure 5 - 3D pressure field numerical modelling, comparison between conventional acoustic barriers and sonic crystal (SC) barriers: a) conventional, 500Hz; b) SC, 500Hz; c) conventional, 1000Hz; d) SC, 1000Hz.

3.3 2.5D modelling of SC structures

A high-performance 2.5D MFS model has also been developed, and seems to be an interesting approach to tackle the analysis of sonic crystals. A new strategy for the solution of 3D configurations of sonic crystals has been proposed, based on the use of the MFS formulated in the frequency domain, and considering that the 3D problem can be modelled using a 2.5D approach. To allow the solution of very large-scale problems, with a high number of scatterers, an Adaptive-Cross-Approximation (ACA) approach is proposed and incorporated in the MFS algorithm, rendering the calculation much faster and with very significant savings in terms of computational requirements. The proposed approach allowed drastically reducing the memory requirements of the problem, and thus modelling very large structures that previously were not viable to address. This numerical model is reported in [16]. An illustrative analysis is presented below in Figures 6 and 7. In this case, the IL curves clearly demonstrate the 3D character of the response, with distinct characters being observed for the three tested receiver heights.

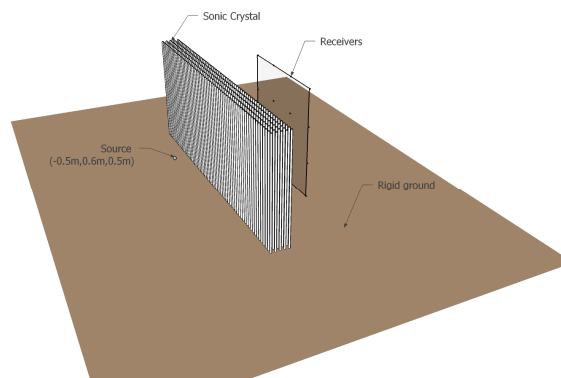


Figure 6 – Sample configuration of a vertical sonic crystal structure modelled using the 2.5D MFS approach.

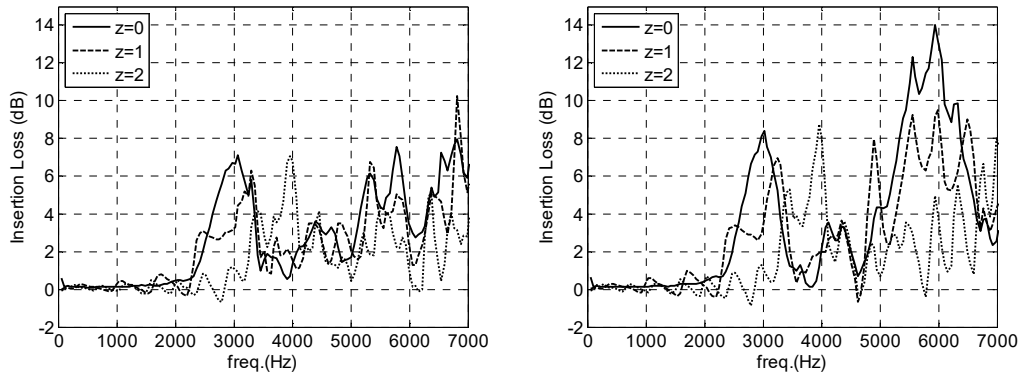


Figure 7 - Insertion loss (in dB) calculated for the rectangular (a) and triangular (b) lattices, and for different heights of the receivers.

4 Real scale prototype

A real-scale structure was constructed and analysed. The structure was built using maritime pine timber logs, and it was evaluated in terms of its acoustic efficiency and in terms of its vibrational behaviour. Figure 8 presents some images of the involved raw materials and of the prototype structure.



Figure 8 - Images of the timber logs and of the assembled prototype structure.

The implemented real-scale model corresponds to a barrier with four rows of circular scatterers, two rows with approximate diameter of 0.1m and the other two with about 0.2m, in both cases spaced by one diameter. The Insertion Loss of this structure has been estimated using the models from Section 3,

and is presented in Figure 9, where the red line represents the experimental result and the blue one the numerical result. This solution exhibits a peak of maximum attenuation around 1000Hz (reaching 15 dB), and still provides good Insertion Loss from 600Hz to 1500Hz. It is also interesting to note that the global trend of both curves is quite similar, as previously observed from the laboratorial tests.

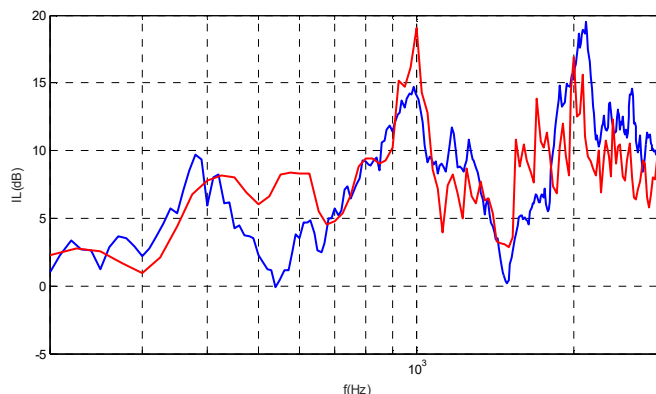


Figure 9 - Estimated and measured on site values of the Insertion Loss for the prototype test structure.

Vibration measurements with accelerometers were also performed, fixing the accelerometers directly at the timber logs, and thus evaluating their vibration when subject to the incidence of sound waves. The results indicate that the introduced sound field does not originate significant resonances of the poles, and thus has very little effect on the final behaviour and efficiency of the acoustic barrier (basically acting like a rigid set of periodic scatterers).

5 Conclusions

The present paper reports a set of results obtained in the scope of a research project developed at the University of Coimbra. These results refer to a highly sustainable sonic crystal noise barrier that can be used for traffic noise attenuation. A number of numerical models were implemented to evaluate the 2D, 3D and 2.5D barrier sound attenuation, showing an excellent agreement between experimental and numerical data for different configurations. The Insertion Loss values predicted by the numerical models, and confirmed on a series of reduced scale models (1:10), correspond to interesting levels of sound attenuation.

A real scale prototype has been built using the proposed technological solution, made of timber logs and making use of two different diameters. This structure was tested, confirming, in real-sized structure, the main findings from the laboratorial tests and from the numerical modelling. For this case, good agreement with numerical predictions was found.

Regardless of the positive results obtained so far, there seems to be space for further improvement and for optimization of the periodic arrangements and use of different log diameters.

Acknowledgements

The support of FCT (Fundação para a Ciência e a Tecnologia) and COMPETE, through research project PTDC/ECM-COM/1438/2012, is acknowledged. This work was also financed by FEDER funds through the Competitiveness 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.



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