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Design, Manufacture and Characterization of an Acoustic Barrier Made of Multi-Phenomena Cylindrical Scatterers Arranged in a Fractal-Based Geometry

Sergio CASTIÑEIRA-IBÁÑEZ(1), Constanza RUBIO(3), Vicent ROMERO-GARCÍA(2),
Juan Vicente SÁNCHEZ-PÉREZ(3), Luís Miguel GARCÍA-RAFFI(4)

(1) *Dpto. Física Aplicada, Universitat Politècnica de València*
València 46022, Spain; e-mail: sercasib@mat.upv.es

(2) *Instituto de Investigación para la Gestión Integrada de zonas Costeras, Universitat Politècnica de València*
Paranimf 1, 46730 Gandia, Spain; e-mail: virogar1@upvnet.upv.es

(3) *Centro de Tecnologías Físicas: Acústica, Materiales y Astrofísica, Universitat Politècnica de València*
València 46022, Spain; e-mail: crubiom@fis.upv.es

(4) *Instituto Universitario de Matemática Pura y Aplicada, Universitat Politècnica de València*
València 46022, Spain; e-mail: lmgarcia@mat.upv.es

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In this work we present the design and the manufacturing processes, as well as the acoustics standardization tests, of an acoustic barrier formed by a set of multi-phenomena cylindrical scatterers. Periodic arrangements of acoustic scatterers embedded in a fluid medium with different physical properties are usually called Sonic Crystals. The multiple scattering of waves inside these structures leads to attenuation bands related to the periodicity of the structure by means of Bragg scattering. In order to design the acoustic barrier, two strategies have been used: First, the arrangement of scatterers is based on fractal geometries to maximize the Bragg scattering; second, multi-phenomena scatterers with several noise control mechanisms, as resonances or absorption, are designed and used to construct the periodic array. The acoustic barrier reported in this work provides a high technological solution in the field of noise control.

Keywords: acoustic arrays, acoustic attenuation, acoustic wave absorption, acoustic wave scattering, phononic crystals, acoustic barrier, physical effect of sound.

1. Introduction

One of the main environmental problems of the industrialized countries is the noise, which can be defined as an unwanted or unpleasant outdoor sound generated by transport and industry. When it is not possible to reduce the emission of the noise acting on the source, it seems appropriated to reduce the noise levels in its transmission, using acoustic barriers (ABs) (Harris, 1991). A classic AB is in general a continuum rigid material which is interposed between the sound source and the receiver. In general, the materials used in their construction have to be rigid and with a minimum superficial density of 20 kg/m^2 (Department of Transportation, FHA U.S.A, 2001), according with the mass law. The acoustical effect of AB can be explained as follows: the transmitted noise travels from the source to the receiver in a straight line. This path is interrupted by the AB when it is placed between the source and the receiver. A portion of the transmitted acoustical energy is either reflected or scattered back towards the source, and other portion is transmitted through the barrier, diffracted from the barrier's edge or absorbed by the material of the barrier (see Fig. 1a).

The aim of this work is to present alternatives to the classical ABs based on arrangements of scatterers embedded in air, called by us Sonic Crystals Acoustic Barrier (SCAB). The design and manufacturing processes of this new type of barrier are both presented. To evaluate the attenuation capabilities of this bar-

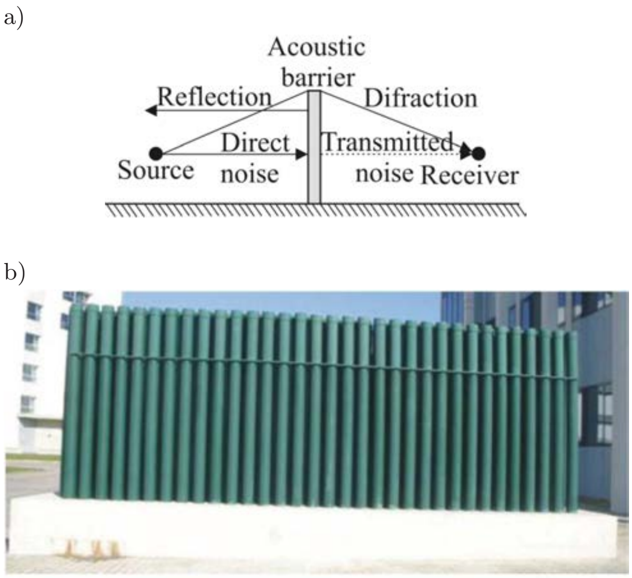


Fig. 1. a) Acoustical performance of an AB, b) example of a SCAB.

rier, we have first compared the numerical results with those obtained for a classical AB with the same size using the Maekawa's method. Moreover, we have applied to our barrier the acoustical standardization tests that determine the level of protection against noise of traditional ABs. It is worth noting that these tests are designed for AB and only evaluates the effect of the mass law, therefore it does not seem to be appropriated to our barrier due to the fact that other attenuation phenomena are introduced. However, this standardization process is the only one available in the European Standards to evaluate ABs. The results shown in this work are quite promising.

The work is organized as follows: In Sec. 2 we explain the transmission properties of SCs, and summarize the recent advances in the field considered in the design of the new type of barrier. Its design and the numerical results obtained for the barrier are presented in Sec. 3. Section 4 shows both its acoustical and constructive characteristics, including the experimental results used in the process. The acoustic standardization for traffic noise of the constructed prototype is developed in Sec. 5. Finally, Sec. 6 summarizes the main results of the work.

2. Sonic Crystals as acoustic barriers

SC can be defined as a heterogeneous medium consisting of a periodic array of acoustic scatterers embedded in air (Martinez-Sala *et al.*, 1995). These systems present an interesting property that allows their use as ABs: the existence of ranges of frequencies in which the sound is not transmitted through the crystal. These ranges are called band gaps (BG), and the underlying physical mechanism is the destructive Bragg interference due to a Multiple Scattering (MS) process (Chen, Ye, 2001), related to the periodicity of the system. One of the first examples of SC is given by a minimalist sculpture made of steel cylinders in air (Martinez-Sala *et al.*, 1995), which experimentally showed the existence of BG. Both the position and the size of these BG depend on several factors (Kushwaha, 1997) as: (i) the spatial distribution of the scatterers, (ii) the separation between the scatterers, (iii) the densities and the contrast of propagation velocities between the air and the scatterers, and (iv) the number of scatterers per unit area. The existence of the BG allows the use of SC as ABs. In this sense, Sánchez-Pérez *et al.* (2002) designed and constructed the first SCAB. The devices designed in this way, i.e. being the existence of Bragg interferences the unique attenuation mechanism, can be named as first generation SCABs (see Fig. 1b).

However, the existence of Bragg reflections as the unique mechanism to avoid the transmission of waves is not sufficient to ensure a good performance of an SCAB. In this sense, an improvement of the size of the attenuation band and the addition of more attenuation mechanisms in the designed devices seem necessary. Two research lines have been developed to increase the acoustical performance of SCABs: (i) add new noise control mechanisms such as absorption and resonance in the design of the scatterers and (ii) maximize the size of the attenuation band designing new arrangements of scatterers.

Concerning the design of scatterers, several works have been developed. Umnova *et al.* (2006) proposed cylindrical scatterers consisting of a rigid core surrounded by porous absorbent material, in such a way the noise control mechanisms used are the existence of BG and absorption. Another proposed design is based on the use of rigid materials that present resonant properties (Movchan, Guenneau, 2004; Hu, Chan, 2005). In these scatterers the position in frequency of the resonance peaks can be modulated by varying the geometrical characteristics of the resonators. Here the mechanisms involved are the existence of BG and resonance. A more advanced design of multiphenomena scatterers is based on the use of elastic scatterers in which two resonance peaks appear due to different physical phenomena (Romero-García *et al.*, 2011b). In this case, the position of the resonance peaks can be modulated within a certain range of frequencies by changing the geometry of the resonator and/or the material that forms the scatterer. One of the most advanced designs has been presented by Romero-García *et al.* (2011a) who proposed multiphenomena scatterers with three noise control mechanisms involved: BG, absorption and resonance. These scatterers are composed by a rigid core that forms a resonance cavity and an absorbent layer covering the core. This design is considered here both to design and to construct our barrier.

The second research line followed to increase the acoustical performance of SCAB is to maximize the size of the attenuation band. Several procedures have been followed, such as optimization algorithms (Romero-García *et al.*, 2009) and the redistribution of the elements of the SC based on fractal geometries (Mandelbrot, 1983). Here, an arrangement of scatterers based on the Sierpinski triangle (Castiñeira-Ibañez *et al.,* 2010) has been used instead of the classical crystalline arrangements used until now. The use of this arrangement allows increasing the attenuation band, since fractal distribution embeds several periodicities, and therefore the resulting attenuation band is the sum of Bragg peaks of each one of these periodicities.

The SCABs which include some other attenuation mechanisms in addition to the existence of an attenuation band due to the Bragg reflections, are called by us second generation SCABs. The most important feature in their implementation consists of the possibilities offered to reduce the noise at several ranges of frequencies using different noise control mechanisms. On one hand, the position of the peaks of attenuation due to the existence of BG depends basically on some geometrical aspects of the SCAB. On the other hand, the position of the resonance peaks depends on the geometry of the resonator. Finally the acoustic attenuation due to the absorption level depends on the volume of absorbent material used. It has been shown (Romero-García *et al.*, 2011b) that the effects of noise control mechanisms involved overlap constructively, increasing the overall capacity of the acoustic attenuation over a wide range of frequencies. This procedure provides a high technological procedure in the design of SCABs, because these devices can be developed in such a way one can choose the ranges of desired attenuated frequencies.

Thus, taking advantage of the research done, we have designed a new prototype of AB based on SC that maximize the Bragg reflections in order to increase attenuation band using arrangements based on fractal geometries, and also includes other attenuation mechanisms in addition. The barriers designed in this way are called by us Fractal-based Sonic Crystal Acoustic Barriers (FSCAB).

3. Theoretical design of second generation SC acoustic barriers using fractal arrangements

Finite Elements Method (FEM) has been used to design the FSCAB by means of COMSOL Multiphysics 3.5. Due to the several physical mechanisms involved and the geometrical shape of scatterers, this numerical procedure is a good theoretical tool to design this kind of ABs. Using FEM and considering temporal harmonic dependence we have to solve the propagation of sound described by the equation:

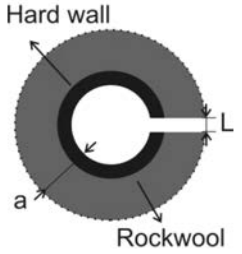
$$\frac{1}{\rho c^2}\frac{\partial^2 p}{\partial t^2} = \nabla\left(\frac{1}{\rho}\nabla p\right). \tag{1}$$

For the FEM calculations a point source has been considered. The solution domain has been discretized using 8.1×10^5 elements.

To simulate the characteristics of our problem, we have considered that no waves are reflected from infinity, i.e. the wave propagation is performed in free space conditions (unbounded acoustic domain). This assumption is known as the Sommerfeld condition. Solving these kinds of problems using FEM is only possible by applying some artificial boundaries in the numerical domain. We have used here the perfectly matched layers (PML). This method was presented by Berenger (1994) and is useful to emulate the Sommerfeld condition in the numerical solution of scattering and wave radiation problems. Basically, the PML method consists of a coordinate transformation (Liu, 1999). This transformation is a scaling to complex coordinates so that the new medium becomes selectively dissipative in the direction perpendicular to the interface between the PML and the physical domain.

Although the external boundary of the PML produces artificial reflections in practice because the PML have to be truncated at a finite distance of the domain of interest, under the theoretical point of view these reflections have minor importance due to the exponential decay of the acoustic waves inside the PML. As an example, it has been proven that, for Helmholtz-type scattering problems, the approximate solution obtained using the PML method exponentially converges to the exact solution in the computational domain as the thickness of the layer goes to infinity (Lassas, Somersalo, 1998).

Using FEM we have designed a FSCAB which main characteristics, both acoustic and geometric, can be seen in Fig. 2. FSCAB is formed by three types of scatterers. On one hand, multi-phenomena scatterers which section is shown in Fig. 2a. These scatterers are formed by a resonant cavity wrapped by rock wool as absorbent material. Thus, the attenuation mechanisms involved are resonance and absorption. Two different diameters are designed in order to induce two resonance peaks. On the other hand, simple scatterers formed only by rigid materials whose mission is the reinforcement of the Bragg reflections by multiple scattering are designed. Also, to maximize the Bragg mechanism the scatterers are arranged following a pattern based on fractal geometries, specifically the Sierpinski triangle, as one can see in the inset of Fig. 2b. An example of the attenuation performance of the proposed FSCAB can be seen in the numerical simulation a)



b)

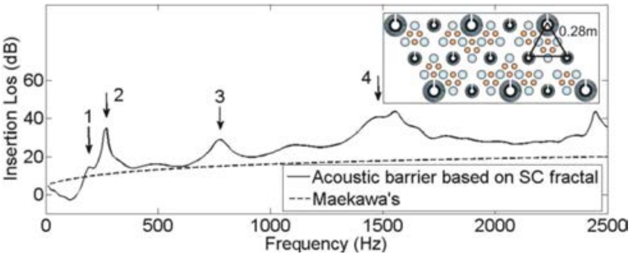


Fig. 2. a) Transversal view of the designed scatterer; b) attenuation spectrum of the FSCAB simulated by means of FEM. One can see the comparison for the case of a classical AB with the same size of the FSCAB calculated using the Maekawa's method. The inset shows a transversal cut of the FSCAB proposed where one can see the fractal arrangement used and the position of each one of the three types of the scatterers designed.

of the Fig. 2b. Throughout this work we have used the Insertion Loss (IL) as the index to determine the attenuation properties of the ABs. It can be defined as the difference between the sound level recorded in the same point with and without the sample, and is given by:

$$\mathrm{IL} = 20 \log_{10} \frac{|P_{\text{direct}}|}{|P_{\text{interferred}}|}. \tag{2}$$

In Fig. 2b one can observe the existence of several attenuation peaks due to the different considered mechanisms. Thus, the attenuation peaks (1) and (2) below 500 Hz are due to the two resonances corresponding to the two different sizes of the multi-physical scatterers that contain a resonance cavity. Note that the peak located at 310 Hz is more intense than the other located at 220 Hz due to the number of scatterers that produce this resonance is double (see the inset of Fig. 2b). The attenuation peaks (3) and (4) correspond to the MS effect due to the periodicity of the array. Finally, the threshold of attenuation that appears from 500 Hz corresponds to the effect of the absorbent. To check the acoustic response of the designed FSCAB, we have included in Fig. 2b the theoretical attenuation level for a classical AB with the same size of the FSCAB using the Maekawa's method (Maekawa, 1968). A higher level in the acoustic attenuation can be seen in the case of FSCAB in most of the analyzed range of frequencies.

4. Construction of the device and materials

We have constructed the proposed FSCAB following the design shown in the inset of Fig. 2b. The construction of the prototype to standardize its acoustical response has been carried out taking into account the appropriate choice, under the acoustical point of view, of the materials that form the scatterers. These scatterers can be classified in two categories, depending on its acoustic response.

Simple scatterers: The role of these elements is to increase the MS phenomenon. The chosen material is iron because it presents the appropriate reflecting properties to participate in the MS process throughout the fractal geometry of the arrangement used. For the designed device, 252 cylinders with 3 m height are used (1.5 mm wall thickness) with two external diameters: 0.15 m (126 cylinders) and 0.30 m (126 cylinders).

Multi-phenomena scatterers: These scatterers are bigger than the exposed above and they have two roles: constructively they have to act as structural elements, and acoustically they have to introduce the selected noise control mechanisms: resonance, absorption and MS. In order to comply with these premises, the scatterers are formed of three parts: core, cover and perforated sheet. The core is an iron cylinder with a slot (L = 20 mm) along its entire length (3 m). It serves as the structural support of the scatterers. Acoustically, its interior acts as an acoustic resonant cavity and its exterior contribute to the MS phenomenon. 14 cylinders with external diameter 165 mm and 4.85 mm thickness; and 28 with external diameter 114, 3 mm and 4.5 mm thickness are used for the designed device. These geometrical characteristics lead to two cavity dimensions, so two resonance peaks appear at 220 Hz and 310 Hz. Next part is the cover, formed of a rock wool layer (ρ = 100 kg/m^3 and 40 mm thickness) which covers the core. It has a double function: acoustically introduces the mechanism of the absorption increasing the attenuation produced by the device and, constructively, it protects the core of the deterioration due to outdoor conditions. Last part is an iron perforated plate (1 mm thickness and perforations of 5 mm of diameter) that contributes to protect the rock wool having a minimum influence in the MS process.

To manufacture this device, an iron rectangular platform (3 mm thickness) with size 4.00 × 0.76 × 0.15 m^3, has been fabricated to place the different scatterers. This platform consists of two sheets separated 0.20 m and tied by additional iron bars to prevent deformations due to the weight of the cylinders. Both sheets have different circular perforations (see Fig. 3a) where the cylinders must be installed, so that they cross both sheet in order to remain them in a vertical position (see Fig. 3b). The top of the different cylinders are joining by means of a few plates and strips of iron, as it can be seen in Fig. 3c.

Fig. 3. Different details of the FSCAB used in the standardization process; a) placement of the scatterers in the fastening system; b) detail of the hard core of the cylinders used; c) constructive detail of the system showing the assembly among the top of the scatterers; d) IL spectra of the different materials and combinations that form the multi-phenomena scatterers obtained in anechoic chamber.

Figure 3d shows the acoustical response of the different elements that form the multi-phenomena scatterers. One can see that the perforated plate has not acoustical influence, acting only as a protective element of the scatterer. Also the acoustic performance of the core and the core plus the absorbent can be seen. Note in the inset the existence of the resonance peak of the core at 300 Hz and the change of the position in the resonance peak when the core plus the absorbent is considered. Note that the difference in the position of the resonance peak in both cases is due to the change in the length of the neck when the absorbent is added.

5. Acoustic standardization

Two tests have been carried out in order to characterize acoustically the designed FSCAB. Selected tests are used to characterize conventional ABs for traffic noise according to the European standard. In particular, the standards EN 1793: 1997 relative to road traffic noise reducing devices, test method for determining the acoustic performance: Part 1: Intrinsic characteristics of sound absorption (EN 1793-1: 1997), Part 2: Intrinsic characteristics of airborne sound insulation (EN 1793-2: 1997), and Part 3: Normalized traffic noise spectrum (EN 1793-3: 1997), are used to characterize our barrier. The first two standards define the performed test, related with the noise absorption and their behaviour with regard to the spread of airborne noise, while the third defines the normalized traffic noise spectrum, which is used as a reference to obtain a ranking of the barriers on the basis of their acoustic characteristics. The tests have been carried out in a laboratory approved for this type of testing. In the following we briefly develop these standards, as well as the results obtained by the FSCAB in each of the tests.

5.1. Test 1: Intrinsic characteristics of sound absorption: EN-1793-1:1997

The aim of this test is to measure the acoustic absorption coefficient (α_S) in a reverberation chamber and to evaluate the results according to the standards used. These are EN ISO 354:2004 (ISO, 2003), to determine the test procedure, and EN ISO 11654:1997 (ISO, 1997) to evaluate the results and to classify the performance of the barrier.

Standard 1793-1:1997 specifies the situation of the device (it must be located next to one of the walls of the reverberation chamber), and the method of fixation and assembly must be the same as it is used in practice. Pink noise is used throughout the test. Faced the device, five microphones have been placed at points P1, P2, P3, P4 and P5 (see Fig. 4a). Two omnidirectional sound sources are used throughout the measurements, placed in the positions S1 and S2, as one can see in the scheme showed in Fig. 4a.

The reverberation times as a function of the frequency are obtained for each third octave band in the range from 100 Hz to 5000 Hz. Then, the equivalent

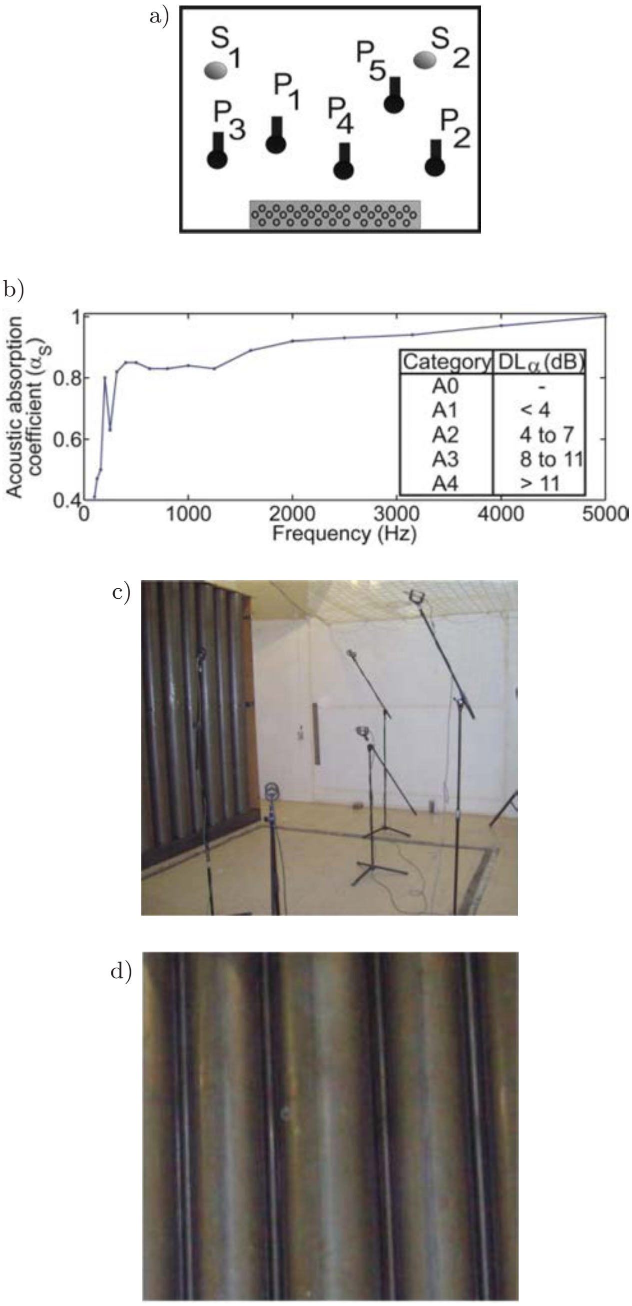


Fig. 4. a) Measurement points (P_1 to P_5) and sources position (S_1 and S_2) scheme; b) variation of α_S as a function of the frequency in octave bands. Noise barriers' classification, as a function of DL_α, can be seen in the inset; c) details of the arrangements of microphones and sources and of the position of the sample in the reverberant chamber; d) detail of the FSCAB where one can observe the existence of the two types of scatterers: multi-phenomena (high diameter and perforated plate) and simple (low diameter).

absorption area (A_T) for each third octave band is calculated by using Sabine's equation:

$$A_T = A_2 - A_1 = 55.3V\left(\frac{1}{c_2T_2} - \frac{1}{c_1T_1}\right) - 4V(m_2 - m_1), \qquad (3)$$

where c_i is the sound propagation velocities in air for the temperature t; V is the volume of the empty reverberation chamber; T_i is the reverberation time of the chamber that varies with the frequency and m is the sound absorption coefficient for the reverberation chamber, calculated according to the standard ISO 9613-1 (ISO, 1993) taking into account the climatic conditions of the chamber during the measurements. Subindexes 1 and 2 correspond to the situation with and without the device, respectively.

According with the expression the sound absorption coefficient (α_S) is then obtained:

$$\alpha_S = A_T/S, \qquad (4)$$

where S is the surface of the barrier. This parameter also depends on the frequency.

In order to classify the barrier with regard to its acoustic absorption characteristics, the evaluation index of the acoustic absorption, DL_α, must be calculated. Following the standard EN-1793-1:1998:

$$DL_\alpha = -10\log\left|1 - \frac{\sum\limits_{i=1}^{18} \alpha_{S_i} 10^{0.1L_i}}{\sum\limits_{i=1}^{18} 10^{0.1L_i}}\right| \quad \text{[dB]}, \qquad (5)$$

where L_i is the noise level for each third octave band of the normalized traffic noise spectrum (dB) given by the standard EN-1793-3 1997. In our case, $DL_\alpha = 8$ dB, that corresponds to the A3 category. Figure 4b also shows the variation of α_S as a function of the frequency and in the inset one can see the classification of the barriers under the absorption point of view, which appears in the standard used.

5.2. Test 2: Intrinsic characteristics of airborne sound insulation: EN 1793-2: 1997

This test checks the intrinsic characteristics of the barrier relative to airborne sound insulation. Test procedures for these measurements are indicated in the standard EN 1793-2:1997, and the evaluation index of the airborne sound insulation DL_R (dB) is calculated according to the standard EN-ISO 10140:2011 (ISO, 2010). Measures are carried out in a transmission chamber, and the sample must be installed in the same way as it is used in practice. The AB analyzed is located in the middle of the chamber, dividing it in two parts. Some details of the experimental set up used are shown in Figs. 5a and 5b. In the emission chamber (one of the two parts of the chamber) a pressure sound level is generated so in the receiving chamber (the other part of the chamber) the sound level is 15 dB higher than the background noise in every frequency band analyzed (from 110 Hz to 5000 Hz). A scheme of the experimental set up used is shown in Fig. 5c. With these conditions, the sound pressure level (dB) is measured both, in the emission (L_1) and in the receiving

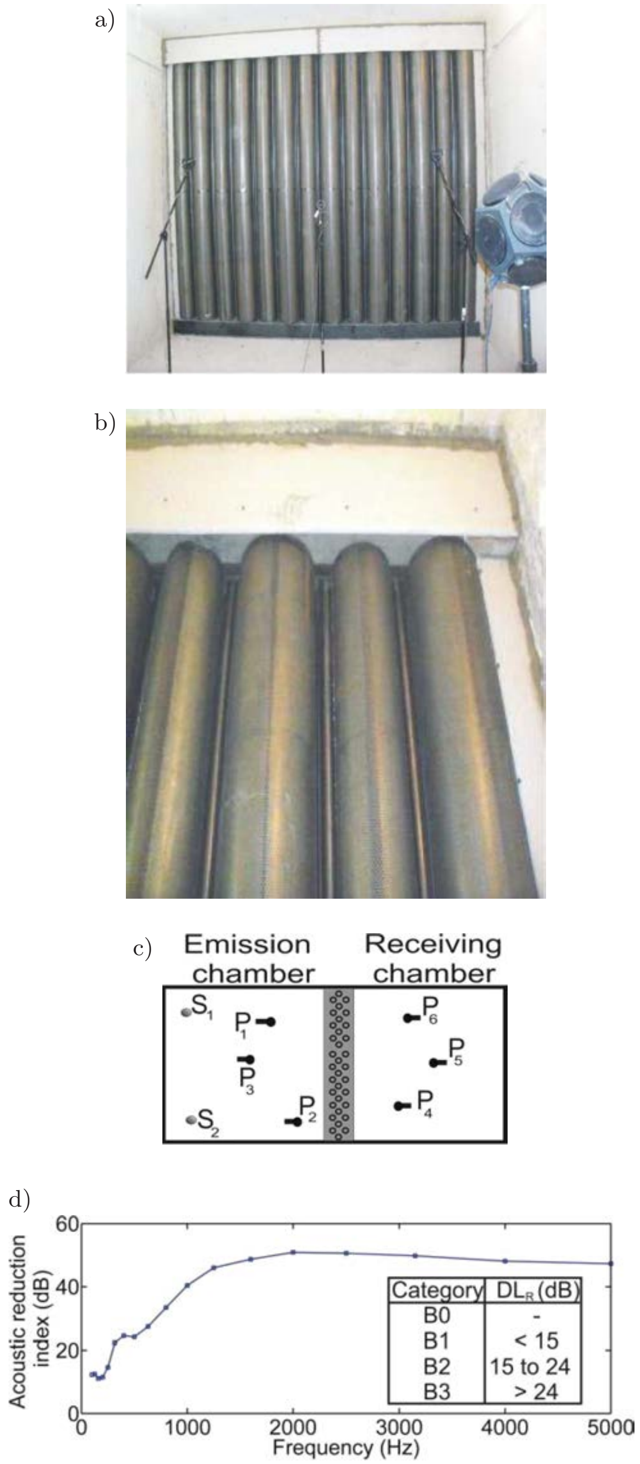


Fig. 5. a) and b) some details of the experimental set up; c) scheme of the experimental set up used in the transmission chamber; d) experimental values of the index R.

chambers (L_2), for three positions of the microphones. From these two averaged levels, the difference (D) can be achieved:

$$D = L_1 - L_2. \tag{6}$$

D must be corrected using a factor that depends on the reverberation time (T), on the volume of the reception chamber (V) an on the common surface of separation between the two chambers, i.e. the surface of the sample (S). Thus, the acoustic reduction index R is:

$$R = L_1 - L_2 + 10 \log \left(\frac{ST}{0.163V} \right). \tag{7}$$

The variation of R as a function of the frequency in the analyzed case can be seen in Fig. 5d.

Finally, DL_R is calculated using the following expression:

$$DL_R = -10 \log \left| \frac{\sum\limits_{i=1}^{18} 10^{0.1L_i} 10^{0.1R_i}}{\sum\limits_{i=1}^{18} 10^{0.1L_i}} \right| \quad [\text{dB}], \tag{8}$$

where L_i represents the noise 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, $DL_R = 22$ dB that correspond to the category B2 specified in the standard EN 1793-2: 1997.

6. Conclusions

In this work, we present new structures called by us Fractal-based Sonic Crystal Acoustic Barrier (FSCAB) that show a good acoustical response due to the constructive overlapping of several physical mechanisms as the increasing of Bragg reflections due to the use of an arrangement based on fractal geometries, and both the resonance and the absorption included in the design of the scatterers. Due to the separation between the scatterers these barriers are transparent to air and water being possible a reduction on their foundations. On the other hand, and under the technological point of view, it is possible to construct barriers on demand by selecting the characteristics of the materials used and the geometry of both the scatterers and the arrangement of these scatterers. In order to compare these structures with the classical ABs, we present the conclusions of the standardization by means of the perceptive tests. These shows that FSCABs can compete acoustically, in view of the standardization results obtained, with classical ABs and their use can be better sometimes. Finally, the constructive possibilities of these barriers allow creating barriers with important aesthetic components. As a conclusion, a high technological design can be introduced in the field of acoustic barriers with this kind of barriers, considering them as a complement to the classical ones for certain cases. That is the case of the structural problems in viaducts that appear when classical ABs are placed, due to the heavy wind load supported by the structure. In this case, the use of FSCAB (discontinuous medium that allow the passage of the wind) instead of the classical AB can reduce this load.

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