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Open noise barriers based on sonic crystals. Advances in noise control in transport infrastructures.

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Abstract

Noise control is an environmental problem of first magnitude nowadays. In this work, we present a new concept of acoustic screen designed to control the specific noise generated by transport infrastructures, based on new materials called sonic crystals. These materials are formed by arrangements of acoustic scatterers in air, and provide a new and different mechanism in the fight against noise from those of the classical screens. This mechanism is usually called multiple scattering and is due to their structuring in addition to their physical properties. Due to the separation between scatterers, these barriers are transparent to air and water allowing a reduction on their foundations. Tests carried out in a wind tunnel show a reduction of 42% in the overturning momentum compared to classical barriers. The acoustical performance of these barriers is shown in this work, explaining the new characteristics provided in the control of noise. Finally, an example of these barriers is presented and classified according to acoustic standardization tests. The acoustic barrier reported in this work provides a high technological solution in the field of noise control.

1. Introduction

Environmental noise, defined as an unpleasant outdoor sound generated by transport, industry and human activities in general, is one of the main environmental problems of the industrialized countries (EC Directive, 2002).

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Furthermore, this noise problem is linked with some health problems such as stress, fatigue, sleep disturbance, cardiovascular disorders or hearing loss (Kotzen and English, 1999; Platon and Hionis, 2014). Cities are considered as critical places where this problem is magnified and where conflict of interests appear, because high noise levels are created due to human activities and where low noise levels are necessary to enable people to rest. Schafer introduced the concept of urban soundscape as the complete range of sounds that characterize a city (Schafer, 1977). The main contribution to this urban soundscape is supplied by noise transport.

According to UE, more than 55 dBA in night hours and 65 dBA in day should not be excessed. However, the EU-Eurostat says that higher noise levels are suffered during the day by 20% of EU citizens and during the night by 30%. These noise problems can involve important sanitary cost of around 0.35% of UE PIB.

Generally, noise control can be carried out in one of the three phases of noise propagation: (i) at noise source; (ii) at transmission phase; (iii) at noise reception.

The main solution to reduce noise levels in its transmission is the use of acoustic barriers (ABs) (Harris 1991). These barriers are built between the source of noise and the receiver. The transmitted noise travels from the source to the receiver in a straight line, and it is interrupted by the AB placed between them, which reduces the noise level by means of different acoustic mechanisms. These classic ABs are made by a continuum rigid material with a minimum superficial density of 20 kg/m^2 (Department of Transportation, FHWA U.S.A., 2001). The acoustic effect of ABs can be explained as follows: They reflect or scatter back towards the source a portion of the transmitted acoustical energy and other portion of the noise energy is absorbed by the material of the barrier. Other portion is transmitted through the barrier or diffracted from the barrier's edge (Fig. 1a). This diffraction can be considered as one of the main factors that decreases the effectiveness of the barriers (Harris, 1991; Kotzen and English, 1999). In fact, this is one of the main research lines in the field of classical ABs, focused on reducing this diffraction effect over the top edge, by designing new profiles far away from the simple edge of the classical ones in order to increase their efficiency. (Mak and Leung, 2013; Okubo and Fujiwara, 1999; Watts, 1996; Watts et al., 2004)

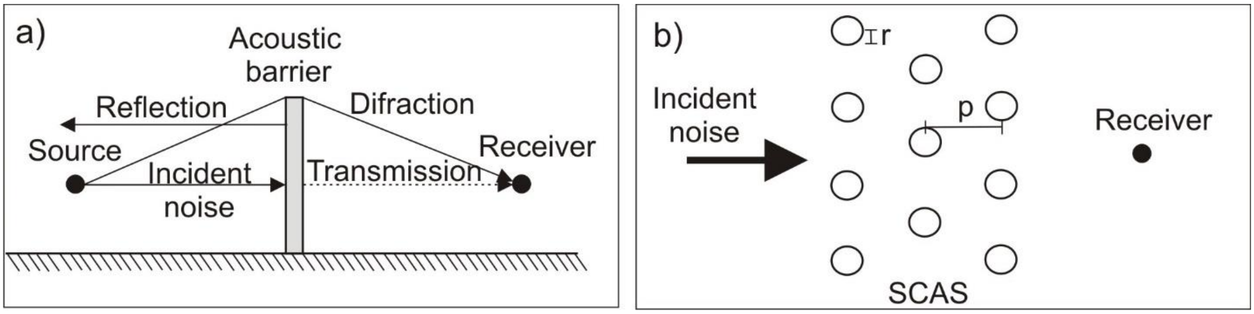

Fig. 1. (a) Scheme of a classical acoustic barrier; (b) Plan view of a Sonic Crystal Acoustic Screen.

However, the use of ABs involves some disadvantages. First, the state of technology in the field of ABs nowadays does not guarantee a specific protection for each noise problem. There are not ABs which be able to distinguish the noise which have to be controlled. For that reason the same screen is used to protect different noises, it does not matter if it is a truck noise or an ambulance siren warning. Second, the placement of continuous walls presents two kinds of problems. On the one hand, classical ABs are not permeable to wind or water, as a consequence, a large volume of foundations is needed to support the heavy efforts produced, especially for large barrier heights. The heavy wind load can also produce some structural problems in viaducts with ABs installed in the case of a high speed trains, as Luo and Yang demonstrated in 2010. On the other hand, these continuous walls in cities present aesthetic and communication problems due to the existence of a solid and continuous barrier (FHWA U.S.A., 2011) related to both breakdown of the cityscape and the physical isolation of the acoustically protected areas.

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Thus, the placement of classical barriers in certain places can involve high costs from technical and economical points of view. For all these drawbacks, installation of classical ABs could be inappropriate in urban areas for transport infrastructures noise control.

In the last decade, the discovery of new materials has enabled the development of new devices to noise control. Sonic Crystals (SC) can be defined as periodic arrays of cylindrical acoustic scatterers with radius r separated by a predetermined lattice constant p, and embedded in air (Martínez-Sala et al., 1995) as can be seen at figure 1b. SC add a new noise control mechanism based on the well-known Bragg interferences due to a multiple scattering (MS) process (Chen and Ye, 2001), different from those previously known. As a consequence, there are frequency ranges, related to the periodicity of the medium, where the propagation of the waves is forbidden through the crystal, (Sigalas, 1992; Sánchez-Pérez et al., 1998). These ranges of frequencies are called band gaps (BG).

The acoustic barriers based on SC are usually called Sonic Crystals Acoustic Screens (SCAS), and the first prototype was designed and constructed by Sánchez-Pérez et al. (2002).

The goal of this work is to explain the working of SCAS, as well as the design and development of an advanced barrier based on these materials explaining the advantages on its use compared to the classical ABS. The paper is organized as follows: In section 2 we develop a brief introduction of SCAS, explaining their development and their noise control properties. The standardization tests for road traffic noise of the constructed prototype and its behavior in a wind tunnel are developed in section 3. Section 4 shows advantages of SCAS compared to ABs. Finally, section 5 summarizes the main results of the work.

2. Description of first and second generation of Sonic Crystals Acoustic Screens.

The first SCAS was theoretically proposed by Kushwaha in 1997, and the first prototype was designed and constructed by Sánchez-Pérez et al. (2002). These devices were designed using the existence of Bragg interferences as the unique attenuation mechanism, and were formed by a set of rigid scatterers embedded in air (Figure 2a).

The distance between the scatterers, the diameter of the cylinders or the angle of incidence of the wave on the structure, among other parameters, determine the size and the position of the BG in the range of frequencies. However, the mere use of BG as the unique mechanism to avoid the transmission of waves, is not enough to ensure a good performance of a SCAS.

To improve the noise control capabilities of SCAS, other noise control features was proposed by Romero-García et al. (2011a). Thus, resonances or absorption mechanisms are used in the design of the scatterers, resulting in multi-physical phenomena scatterers. These scatterers are formed by a core made of rigid cylinders with a slot along its entire length, and wrapped in a layer of absorbent material. Its inner acts as an acoustic resonant cavity because the core can be considered acoustically rigid and contribute to the multiple scattering (MS) phenomenon. Its external part, with absorbent material, gives a baseline of noise attenuation. Also the resonant cavities produce attenuation peaks due to the resonances. Thus, three noise control mechanisms are involved in the design of the multi-physical scatterers: BG, absorption and resonances. SCAS that use other noise control mechanisms apart from the BG, as the exposed previously, are called SCAS of 2nd generation, and provide high technological procedures to the industrial field of ABs.

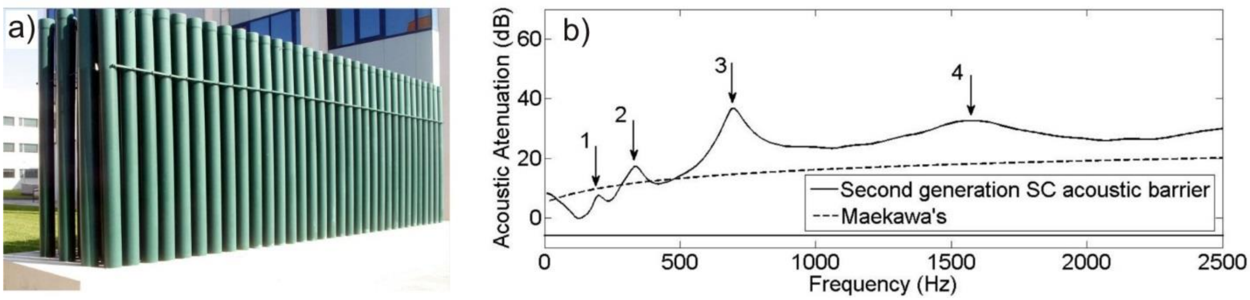

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Fig. 2. (a) Example of first generation SCAS; (b) Simulated attenuation spectrum of the SCAS.

An example of the attenuation performance of the second generation SCAS can be seen in the numerical simulation presented in Figure 2b. One can observe the attenuation peaks due to the different mechanisms named before: (i) the attenuation peaks due to the resonant cavity (1) (2), which position in the frequency range depends on the volume of the resonators. We have used in the design cylinders with two different diameters for adding two resonance peaks placed at different frequencies of the spectrum; (ii) the attenuation peaks due to the periodicity of the array correspond to the BG of the array (3) (4); (iii) the threshold of attenuation due to the effect of the absorbent used in every cylinder of the structure appears from 500 Hz onwards. Also in this figure the theoretical attenuation level for a classical AB with the same height and width using the Maekawa's method (Maekawa, 1968) can be observed, in order to compare the acoustic response of both kind of barriers. An increasing of the attenuation in most of the analyzed frequencies can be seen. In fact, this new generation allows the design of specific ABs for specific noise problems acting in the position of these peaks in the range of frequencies, as it will be explained in the following section.

This design of a second generation of SCAS is protected under Spanish patents (Sánchez-Pérez et al., 2003; Sánchez-Pérez et al., 2009)

3. Acoustic standardization and determination of the structural efforts in a wind tunnel

3.1. Acoustic standardization

We have applied to SCAS the acoustical standardization tests that determine the level of protection against noise. These tests are the only ones available in the European Standards to evaluate ABs. All tests have been carried out in a laboratory approved for this type of testing.

In order to characterize acoustically the second generation of SCAS, two acoustics tests have been carried out in a laboratory approved. The standards EN 1793:1997 relative to road traffic noise reducing devices, test method for determining the acoustic performance has been used to characterize our barrier: (i) EN 1793-1:1997 Intrinsic characteristics of sound absorption; (ii) EN 1793-2:1997 Intrinsic characteristics of airborne sound insulation. These two first standards define the performed tests related with the noise absorption and their behaviour with regard to the spread or airborne noise. Finally (iii) EN 1793-3:1997 Normalized traffic noise spectrum, is used as a reference to obtain a ranking of barriers on the basis of their acoustic characteristics. Although these tests are not designed to evaluate this kind of barriers, the obtained results were promising.

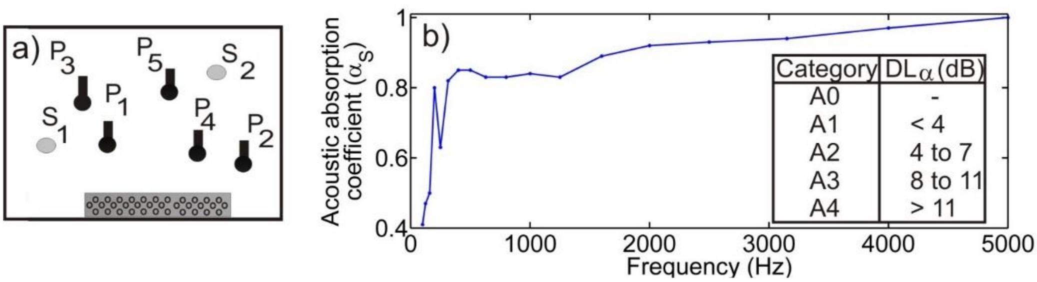

Fig. 3. (a) Scheme of arrangement of the instrumental used (two sources and five microphones) in the test given by EN 1793-1:1997 norm. ; (b) Variation of α_S as a function of the frequency.

To carry out the first test, five microphones have been placed at points P1, P2, P3, P4 and P5 faced the device, and two omnidirectional sound sources are used placed in the positions S1 and S2 as can be seen in Figure 3a and as this standard specifies.

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The goal of this test is to classify the barrier with regard to its acoustic absorption characteristics through experimental measurements in a reverberant chamber, obtaining the evaluation index of the acoustic absorption (DL_{α}):

$$DL_{\propto} = -10\, log \left| \frac{\sum_{i=1}^{18} \propto_{s_i} 10^{0,1L_i}}{\sum_{i=1}^{18} 10^{0,1L_i}} \right| \; (dB) \qquad (1)$$

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_{α}=8dB, which corresponds to the A3 category; it was almost the highest category, regarding its acoustic absorption characteristics as it can be seen at figure 3b.

The second test were carried out in a transmission chamber, and the sample was installed in the same way as it will be used in practice, as can be seen at figure 4a.

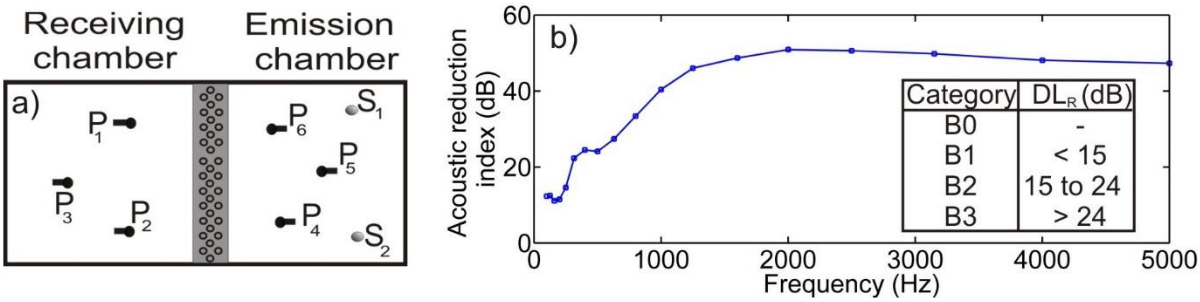

Fig. 4. (a) Scheme of arrangement of the experimental set up used (two sources and five microphones) in the test given by EN 1793-2:1997; (b) Experimental values of the index R.

This test checks the intrinsic characteristics of the barrier relative to the airborne sound insulation, which is defined by the evaluation index of the airborne sound insulation according to the standard EN-ISO 10140:2011 (ISO, 2010) DL_R (dB). The value of this index enables us to classify the capability of airborne sound insulation of the barrier using the following expression:

$$DL_R = -10\, log \left| \frac{\sum_{i=1}^{18} 10^{0,1L_i} 10^{0,1\, R_i}}{\sum_{i=1}^{18} 10^{0,1L_i}} \right| \; (dB) \qquad (2)$$

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_R=22dB, which corresponds to the category B2, almost the highest category (Figure 4b). This is the value that allows us to classify the capability of airborne sound insulation of the checked barrier.

Then we conclude that, under the acoustical point of view, these open noise barriers based on sonic crystals can compete with the traditional ones formed by continuous walls. In any case, the constructive interaction of the different mechanisms of sound attenuation involved in SCAS makes possible to select the range of frequencies where each one of the different mechanism mainly contributes.

3.2. Determination of the structural effort in a wind tunnel

Several laboratory experiments in a wind tunnel have been carried out to estimate the values of wind efforts in SCAS and to compare them with corresponding to a classical AB formed by a wall (figure 5a). This test could give

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information about the size of their foundations or the efforts transmitted to the ground, because it depends basically on this kind of load. (Castiñeira-Ibáñez, et al., 2015)

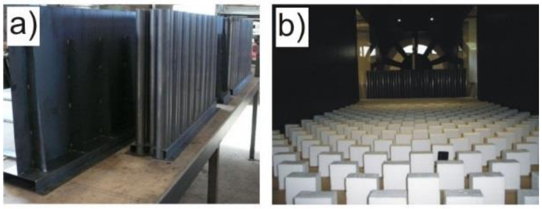

Fig. 5. Partial view of the scale model of both classical AB and SCAS; (b) View of the arrangement of obstacles inside the wind tunnel

We have to consider the action of the wind on both ABs and SCAS as it was generated by the atmospheric pressure field. According to the Spanish Technical Building Code (SMD, 2006), we have considered here a ground roughness corresponding to urban or industrial areas as can be seen at figure 5b. Thus, we have simulated typical flow conditions, assuming an area with uniform buildings.

We have used a precision balance AMTI MC36 to measure the wind efforts on both barriers. This balance allows the measurement of forces in the three directions of the space. In this test we measured both the force in the wind direction and the corresponding overturning momentum on the bases of the barriers. To determinate the size of the foundations is necessary know the variations of these efforts with the wind speed.

Thus, we obtained the efforts on the model in a real-time conditions, and applying criteria of similarity and scale, the values of the actions on the model.

Taking into account the obtained results we can conclude that SCAS supports smaller efforts than the classical AB. In fact, there is an average around 42% of reduction for both the drag efforts and the overturning momentum.

This is an important structural factor since the placement of acoustic barriers in certain places is restricted by the huge efforts transmitted to the structure, allowing the use of SCAS in situations where until now it was not possible the use of classical AB due to structural problems, such as viaducts. And also this characteristic can lead to significant foundation reduction in this kind of devices compared to classical ABs.

4. Advantages of SCAS

The SCAS of 2nd generation are based on a more advanced design of multiphenomena scatterers, in which three different noise control mechanisms are involved. On the one hand, the use of resonators allows the existence of two different resonance peaks, which position in the range of frequencies can be shifted by changing the geometry of the resonators. On the other hand, the distance between scatterers in the array used allows the existence of BG, which location in the range of frequencies can be again determined by changing the geometrical characteristics of the array. Finally, the absorption level depends on the volume of the absorbent material used (Romero-García et al., 2011b). All these peaks and the acoustical characteristics of the 2nd generation of SCAS designed can be seen in Fig 2b. Note that this kind of barriers allows the inclusion in their acoustic design of different noise control mechanisms separately and their design can be shifted according to the type of noise that is needed to be controlled. Thus, the designer can choose the frequency range in which each of the noise control mechanisms must act, allowing the design of customized SCAS for each type of noise. This tunability of the attenuation capabilities of the SCAS makes them highly competitive respect to the classical ABs and it makes possible to construct barriers on demand.

Moreover, SCAS are formed by periodically distributing multi-physical phenomena scatterers, and the separation between the scatterers allows the wind to pass through decreasing the efforts that are transmitted. This characteristic makes possible the reduction on the foundations of the device. Furthermore, this characteristic can solve some structural problems when classical ABs are placed, due to the heavy wind load supported by the structure.

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Another advantage is the constructive possibilities of these barriers, which allows creating barriers with important aesthetic components. In fact, the first idea of use SC technology for SCAS is given by a minimalist sculpture by Eusebio Sempere made of steel cylinders in air (Martínez-Sala et al., 1995). Thus, the aesthetic aspects are improved giving visual continuity to the urban landscape and reducing the physical isolation of the protected areas.

5. Conclusions

In this paper, we present new open noise barriers based on sonic crystal called “Sonic Crystal Acoustics Screens” (SCAS). At SCAS, there are three noise control mechanisms BG, absorption and resonances. These new SCAS introduce an important technological procedure in the field of the acoustic barriers.

These new devices have shown a very good acoustical response, in view of the standardization results obtained, showing that they can compete acoustically with classical ABs.

For that reason SCAS can be used in noise control to reduce the most important type of noise that appears in cities: the transport noise. The sculpture origin, its open design and its versatile to be projected for specific noises are aesthetic and technological advantages for this kind of barriers. For that reason, we conclude that a new generation of AB has already appeared on the noise control market because of all advantages that this SCAS offers.

One example of the use of SCAS can be seen in Eindhoven A2 ring road by Van Campen Industries (2009), where a semi-SCAS have installed following the new technology presented in this paper. Nowadays their use is at an intermediate point between the basic research of its physical properties and its widespread use as noise control devices.

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