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ATTENUATING AND DIFFUSERS DEVICES BASED ON SONIC CRYSTALS

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ABSTRACT.

Sonic Crystals are heterogeneous materials formed by arrays of scatterers embedded in a host material with different physical properties. Their particular properties in the control of acoustic waves lead the development of different devices, some of them highly evolved, as Sonic Crystals Acoustic Screens (SCAS) to attenuate environmental noise, or Sonic Crystals Acoustic Diffusers (SCAD) to spread sound in room acoustics. In this paper, we present the design of a new device that brings together both sound control mechanisms, attenuation and diffusion, avoiding the specular reflected noise produces in Classical acoustic barriers and improving their performance in environmental acoustics.

RESUMEN.

Los cristales de sonido se definen como materiales heterogéneos formados por redes de dispersores inmersos en otro material con diferentes propiedades físicas. Sus propiedades en el control de las ondas acústicas han permitido el desarrollo de distintos dispositivos, algunos muy evolucionados, como barreras acústicas basadas en cristales de sonido (SCAS) diseñadas para apantallas el ruido medioambiental, o difusores acústicos basados en cristales de sonido (SACD) para difundir el sonido en acústica de salas. En este trabajo, presentamos el diseño de un nuevo dispositivo que actúa como pantalla y como difusor, evitando la reflexión especular del ruido producido en las pantallas en general y aumentando su rendimiento como dispositivo de control en acústica medioambiental.

INTRODUCTION.

Transportation is one of the human activities necessary for the correct growth of the economy and the development of a country. The connection between cities is very important for people and goods transport. However, the construction of these large channels of communication also entails the generation of several problems. One of these problems is the environmental noise. When these channels of communications run through uninhabited areas the environmental noise is not a problem, however, conflict arises when these infrastructures run through urban areas. The acoustic comfort of these urban areas is reduced by the noise generated by transport. In fact, this is one of the main environmental problems of the industrialized countries (EC Directive, 2002). According to UE, more than 55 dBA in night hours and 65 dBA in day hours should not be excessed. However, the EU-Eurostat states that higher noise levels are suffered during the day by 20% of EU citizens and during the night by 30%. These high grades of exposure are linked with some health problems such as stress, fatigue, sleep disturbance, cardiovascular disorders or hearing loss (Kotzen and English, 1999; Platon and Hionis, 2014).

Generally speaking, noise can be controled in one of the three phases into which noise propagation may be divided: at noise source generation, at the transmission or at noise receiver. If the control has to be carried out in the noise transmission phase, the most common performance is placing acoustic barriers between the noise source and the noise reception. The traditional acoustic barriers (ABs) -usually made of continuous flat walls- use several noise control mechanisms, but the main one employed is the reflection of noise. Thus, a large portion of the noise is reflected back to the source specularly. Therefore, some new problems are created, because this reflected noise can increase the level on the protected areas, reducing the effectiveness of the ABs installed (Kotzen and English, 20 09).

To minimize such specular reflections, several solutions have been developed: the use of absorbent materials, tilt the screen or scatter the noise (Pigasse and Kragh, 2011). However, the application of the first two solutions presents some problems: the use of absorbing materials could be quite expensive and the use of tilted barriers may be more and even may be technically impossible for some sites.

Regarding to the solution based on scatter the noise, some proposals have been made in last years: on one hand, there were some advances in the state of technology in the field of acoustics, as the development of new devices to noise control, the Sonic Crystals Acoustics Screens (SCAS). Sonic crystals can be defined as arrays of acoustic scatterers embedded in air with different physical properties (Martínez-Sala et al., 1995). One of the most interesting features of Sonic Crystals is the existence of sonic bandgaps, defined as frequency ranges related to the periodicity of the medium, where the propagation of the waves through the crystal is forbidden (Sigalas, 1992, Sánchez-Pérez et al., 1998). The existence of bandgaps is the result of the interference of waves due to a Bragg scattering within the Sonic Crystal. These new barriers present aesthetic and technological advantages thanks to their open design and their versatility to be designed for specific noises. But these SCAS present the same problem as the traditional ABs: the specularly reflection of noise. On the other hand, to overcome the limitation of diffusers with the range of lowest frequencies, some devices based on sonic crystals have been proposed to work as diffusers in these ranges of frequencies without the need of extremely deep structures (Redondo et al., 2013). These devices, usually called Sonic Crystals Acoustic Diffusers (SCAD), avoid the specularly reflection of noise. In addition, the use of evolutionary algorithms to increase the performance of devices based on Sonic Crystals has been successful in last years. Specifically, an optimization technique based on Multiobjective Evolutionary Algorithms (Herrero et al., 2006) has been already used to increase the acoustic properties of both SCAS (Herrero et al. 2009) and SCAD (Redondo et al., 2016).

In this paper we propose the use of Multiobjective Evolutionary Algorithms to design devices based on Sonic Crystals that work simultaneously as SCAS and as SCAD. The goal is the design of devices that works as acoustic barriers but with a low level of specularly reflection. These devices will minimize the disturbance that appears when acoustic barriers are used to control transport noise. To do that, we have stablished a starting modulus of Sonic Crystals to be optimized. This modulus is prepared to obtain a device with high performance, at the same time, as SCAS and as SCAD in a predetermined range of frequencies. The devices obtained in this optimization process have been named Sonic Crystals Acoustic Screens and Diffusers (SCASAD) by us.

DESCRIPTION OF THE OPTIMIZATION PROCESS.

Due to we have to design devices that maximize two acoustic properties (insulation and diffusion), in the optimization process followed in this work we have chosen a Multiobjective evolutionary algorithm. This kind of algorithms obtains solutions that satisfy several conflicting objectives simultaneously. In some optimization problems involving two properties to be satisfied simultaneously, as the one studied here, improvements in one of them produce usually a degradation of the other. That means there is no unique solution in the optimization process, and a general way to solve the proposed problem is to localize a set of infinite optimal solutions, which is mapped as the Pareto front. This Pareto front shows the candidates who are the best in some sense according with the values of the objectives sought. Due to the difficulties to reach the exact Pareto front, we have used here an elitist multi-objective evolutionary algorithm based on the concept of e-dominance (Laumanns et al. 2002) named ev-MOGA (Herrero et al. 2009).

The starting point of the optimization process carried out in this work is a modulus of Sonic Crystal composed by 28 cylindrical rigid scatterers arranged in a square array of lattice constant p=0.17m. This modulus has the first band gap at 1000Hz, the most important frequency of the normalized noise spectrum according to the standard UNE 1793-3:1998. However, this starting modulus has not a high performance as a diffuser and its isolation properties can be largely improved in the optimization process carried out. To do that, we have to establish a gene codification. The candidates have been encoded by a set of genes that represents a set of 28 normalized cylinders radii. Thus, in our optimization process, the radii of the cylinders can take any value from 0 to 0.9. If the value is 0, the cylinder does not exist and, if the value is 0.9, the cylinder almost has the maximum possible radius. In this way, an individual θ of the optimization process can be represented by a genotype given by a vector of length 28, varying each element from 0 to 0.9.

Once the codification is determined, two are the steps to start an optimization process. First, the definition of the objectives to be optimized, usually called cost functions. Second, a simulation model that performs the necessary calculations to obtain the values of the cost functions for all the individuals involved in the optimization process. The simulation model adopted will be developed in the next section.

We have considered here two cost functions, the first one referred to the isolation capabilities of the candidates, given by the Insertion Loss (IL) index, defined as the difference of acoustic pressure in a point or area without and with the sample.

$$J_{IL}(\theta) = 10log\left|\frac{P_d}{P_{inter}}\right| \text{ (dB)} \qquad (1)$$

where p_d is the direct acoustic pressure (without device), and p_{inter} is the acoustic pressure interfered (with device), both calculated at the same point.

The second cost function is referred to the diffusion properties of the candidates. Here, we have defined a new index called Specular Reflection Sound (SRS). This index determines what part of the total sound pressure reflected by the device does so specularly, and is defined as:

$$J_{SRS}(\theta) = 10\log(1-\alpha) + 10\log(1-d) \text{ (dB)} \qquad (2)$$

where α is the absorption coefficient and d is the diffusion coefficient of each candidate.

Both cost functions, defined in this way, will determine the performance of the potential candidates both as SCAS and as SCAD in a predetermined range of frequencies stablished by us. In this work we have selected a range of frequencies formed by the octaves bands whose central frequencies are 500Hz, 1000Hz and 2000Hz, i.e. a range of frequencies from 355Hz to 2840Hz. We have selected this range taking into account the normalized spectral traffic noise defined in the norm UNE 1793-3:1998.

Finally, taking into account the characteristics of the ev-MOGA algorithm, which works minimizing cost functions, the final form of these will be –IL and SRS. That means that the insulation and diffusion are maximized.

SIMULATION MODEL.

The acoustic performance of the designed SCAS has been simulated with the numerical technique called Finite Difference Time Domain (FDTD). This technique has been used successfully to quantify the performance of Sonic Crystals, working together with the ev-MOGA optimization algorithm (Redondo et al., 2016). In this paper, we have developed the model shown in Figure 1.

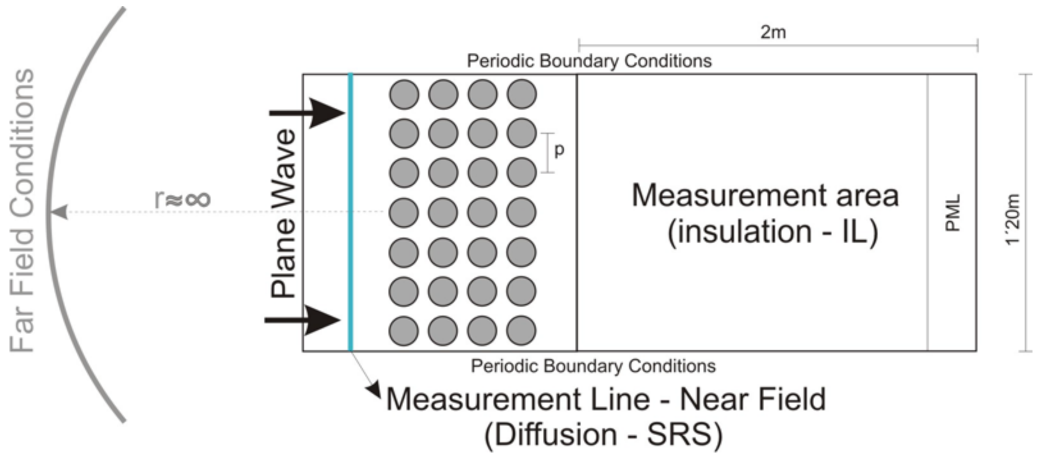

Figure 1: Numerical domain used for SCASAD simulations

A plane wave travelling from left to right impinge on the Sonic Crystal sample (individual). Part of this wave is transmitted through the device, and another part is reflected to the left. The insulation performance of each SCASAD candidate, given by the -IL cost function, is measured on the right area of the model ("measurement area"). We have calculated the acoustic pressure of insulation every 0.02m, with and without the sample. Then we have done the acoustic pressure average with and without the sample in all the points included in the "measurement area" before applying expression (1) to estimate the IL. On the other hand, to calculate the SRS index we have estimated the reflected pressure along the entire vertical blue line shown on the left in Figure 1 ("measurement line"). With these results, we have carried out a near field to far field transformation in order to estimate the value of the diffusion coefficient, d, in free field conditions according to the standard ISO 17497-2-2012. Finally, α has been calculated directly from the model.

RESULTS AND DISCUSSION.

The optimization process works using together ev-MOGA and the FDTD model developed. The first one leads the process (i) generating new SCASAD candidates by mixing, following the genetical rules, the genotypes of the individuals of an initial population generated by us; (ii) ordering the solutions in the objectives space according to the values of each one of the cost functions and (iii) stablishing the Pareto Front in the objectives space. On the other hand, FDTD evaluates the acoustic performance of each individual generated by ev-MOGA, calculating its values of the acoustic indexes defined in the previous section (-IL and SRS).

The results of the optimization process can be seen in Figure 2. This figure shows the objectives space of the optimization carried out. Black dots means the individuals of the initial population represented as a function of their values of the acoustic indexes considered, -IL and SRS (Abscissa and ordinate axes respectively). The best individuals obtained in the complete optimization process are represented in red color. These individuals form the Pareto Front, and are the best individuals, in some sense, according to their values of the -IL and SRS indexes.

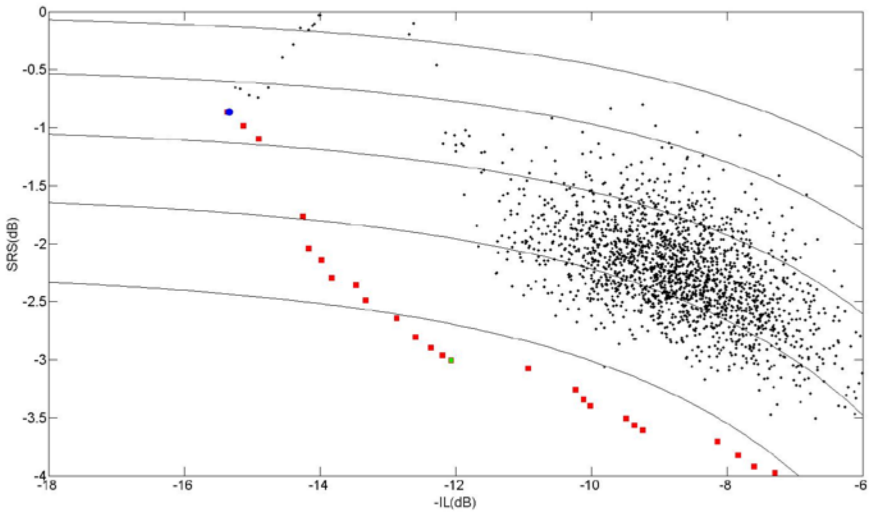

Figure 2: Objectives Space of the optimization done. The initial population (black dots), the Pareto Front (red dots), the most balanced individual selected (green point) and the reference individual (blue dot) are represented according their values of IL and SRS indexes.

Thus, red dots on the right of the figure represent some individuals who are the best in terms of their SRS (diffusion) values although their -IL (insulation) values are poor. On the other hand, red dots on the left of the Figure represent individuals whose -IL values are the best but their SRS values are poor.

The decision maker has to select the best individual obtained in the optimization process according to his preferences. The green dot represented in the figure is the individual whose -IL and SRS indexes take more balanced values. That is, its acoustic performance is quite good according to both indexes.

Finally, the blue dot in the figure 2 represents a Reference Sonic Crystal, formed by cylinders of equal radius with 80% filling fraction. That means that, due to the optimization has been performed by varying the radii of the cylinders this individual would represent a non-optimized Sonic Crystal. Note the high isolation performance of this individual but its low performance in terms of its diffusing properties. The position of this individual in the objectives space serves as a reference of the improvement achieved in the optimization process.

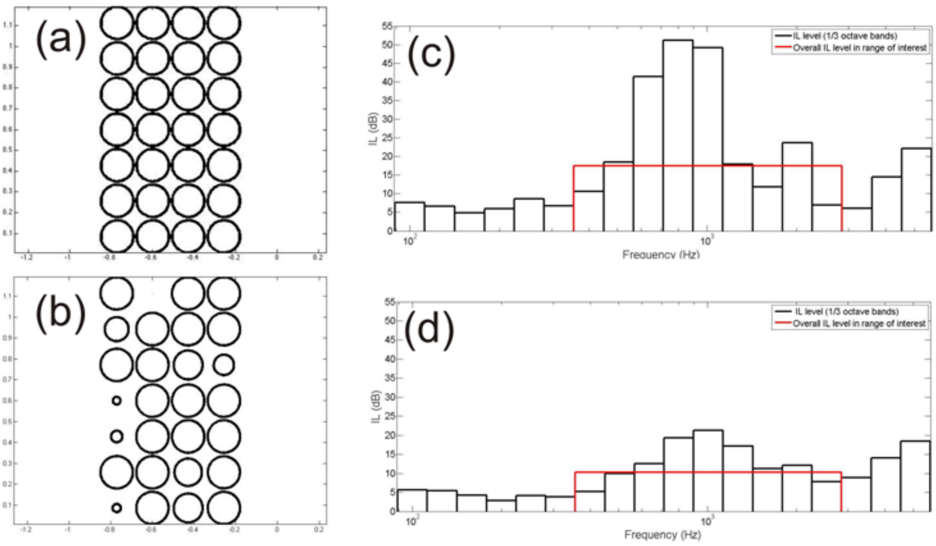

Figure 3: Scheme of the design of both (a) Reference Sonic Crystal and (b) Selected SCASAD (blue and green points in Figure 2, respectively); (c) and (d) Insulation properties of both individuals respectively

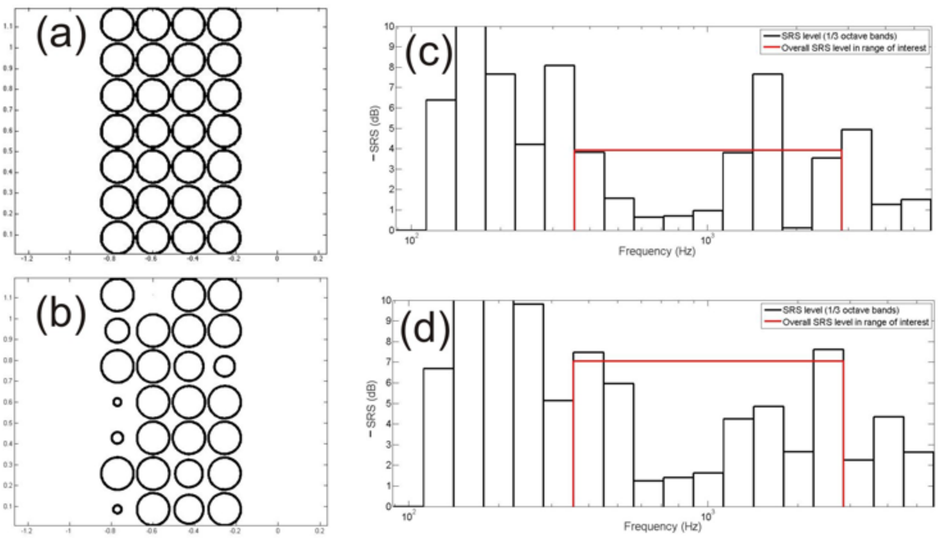

Figure 4: Scheme of the design of both (a) Reference Sonic Crystal and (b) Selected SCASAD (blue and green points in Figure 2, respectively); (c) and (d) Diffusion properties of both individuals respectively

In our case, comparing the positions of both the green dot -considered the most balanced individual of the optimization process-, and the blue one -the Reference Sonic Crystal- in the objective space in Figure 2, we can conclude that a relevant improvement of both -IL and

SRS indexes has been obtained. Therefore, we have obtained an individual (represented by the green dot) that could work as SCASAD with isolation and reflection properties improved.

Finally, in Figure 3 and Figure 4 we show the design of the SCASAD selected (green dot in Figure 2), the design of the Reference Sonic Crystal (blue dot in Figure 2) as well as their IL and -SRS spectra in the range of frequencies selected. Note the variability of the radii of the cylinders that form the selected SCASAD obtained in the optimization process.

CONCLUSIONS.

In this work we have used a Multiobjective evolutionary algorithm, called ev-MOGA, together with a simulation acoustic model based on the numerical technique called Finite Difference Time Domain (FDTD) in an optimization process. The optimization algorithm used is called ev-MOGA, which allows the obtaining of devices with high performance in some sense, according with the cost functions selected. In this case, we have optimized the insulation properties, given by –IL, and the diffusion, given by the SRS index. The main goal has been to obtain the design of a device based on Sonic Crystals that works as an acoustic barrier and as sound diffuser. The result has been called Sonic Crystal Acoustic Screen and Diffuser (SCASAD).

The need of the design of this SCASAD is given by the fact that the classical acoustic barriers, generally formed by straight walls, reflect the noise specularly. These reflections can produce disturbance in the opposite side of the place where the barriers are located. SCASAD acts as an acoustic screen, but the reflected noise is highly diffused, avoiding the disturbance that classical acoustic barriers present.

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