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The potential for Phononic Sound Diffusers (PSD)

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ABSTRACT

Although periodic structures theory gave rise to sound diffusers almost 40 years ago, it has been only in recent years when several authors regarded the possible application of a particular kind of periodic structures, phononic crystals, in the field on room acoustics. This paper explores the possible application of periodic structures used as sound diffusers in rooms. Preliminary simulations, carried out with FDTD, shows that due to the inherent time spreading provided by a periodic structure, they can be used to reduce, or even to eliminate, pernicious effects associated with the low frequency modes of the room.

INTRODUCTION

Recently, there has been growing interest in studying acoustic and elastic waves in periodic composite materials [1,2]. Due to the periodicity of the structure, there can be ranges of frequency in which waves cannot propagate, giving rise to sonic band gaps. They are analogous to photonic band gaps in photonic crystals. Such materials are called, by analogy, sonic or phononic crystals. Interest in sonic crystals comes from the rich physics of acoustic and elastic systems, where both the density and the velocity contrast affect wave scattering and propagation. These characteristics, together with the potential for developing accurate theoretical models, make sonic crystals promising for fundamental studies of wave properties in strongly scattering materials.

A sonic crystal is essentially made of inclusions arranged periodically in a propagating medium. For a two-dimensional sonic crystal, the inclusions are cylinders that can be arranged as in a square or triangular lattice for example. They need to be composed of a material different from the host material, which is usually a fluid. The key requirement is that the elastic wave scattering on these inclusions is very efficient. The concept of band gaps can be understood by considering the interference of waves multiply scattered within a sonic crystal. When a set of scatterers is positioned periodically, waves are strongly dispersed from one obstacle to the other, and end up filling all available space and propagating in every possible direction. They interfere constructively or destructively depending on the wave frequency and on the sonic crystal geometry. A band gap appears when the scattered waves interfere destructively in a given direction, such that their superposition decreases exponentially when traversing the crystal.

When the band gap exists for all propagation directions, it is called a complete band gap. A sonic crystal possessing a complete band gap would be a perfect mirror, reflecting back all incident waves. Indeed, the waves impinging on the sonic crystal could not possibly penetrate it. These properties are strictly true for the frequencies that fall within the complete band gap. For other frequencies, destructive interferences are balanced by constructive ones and waves are transmitted at least partially.

Roughly speaking, band gaps appear when the wave length (the period of spatial repetition of the wave) is of the order of the spatial period of the sonic crystal. Another essential point is that the principles of sonic crystals are expressed in the same manner whatever the scale chosen for their realization, though the operating frequencies change. The scale of the structure is then ruled by the wavelength of the sound wave, or more precisely by the sound frequencies in which we are interested to act.

Most of the previous work has explored the transmission properties of sonic crystals, searching for efficient sound barriers, or devices with the ability of manipulating sound diffraction (collimation, focusing, etc). Here we explore the potential of sonic crystals as efficient sound diffusers.

SOUND DIFFUSERS

It is now more than three decades since Schröeder proposed sound diffusers for the first time [3]. Sound striking a normal surface is reflected in the specular direction, i.e., the direction that fulfils the Snell law. On the contrary, a sound diffuser reflects the sound in several directions; in the ideal case, in all possible directions. It is well-known that sound diffusers can improve the acoustic performance of rooms in different ways, for instance an increase in sound field diffuseness, subjective impressions of 'spaciousness', and the removal of echoes, focalizations and coloration. However, the effectiveness of such structures strongly depends on the particular room in which they are installed. In other words, there are no models to predict how far a sound diffuser can improve in any sense the acoustic properties of a room.

Notwithstanding this problem, there are two main methods to quantitatively characterize sound diffusers:

The first, standardized by the AES [4], is based on the measurement of reflected sound over a range of angles. For this purpose an impulse response must be obtained. A microphone is moved along a semi-circumference (or over a hemisphere for full three dimensional evaluation), centred on the middle point of the test sample. Direct sound would be eliminated by appropriate windowing of the signal. The complete characterization of the diffuser is performed where the incidence angle is also varied from –90 to 90 degrees. Large anechoic environments are needed to ensure far field conditions. Scale models offer a simpler solution to this physical problem but the technique remains time consuming if several angles of incidence are considered. The parameter measured using this technique is known as the 'diffusion coefficient' and is defined as follows:

$$d = \frac{\left(\sum_{i=1}^{n} 10^{Li/10}\right)^2 - \sum_{i=1}^{n}\left(10^{Li/10}\right)^2}{(n-1)\sum_{i=1}^{n}\left(10^{Li/10}\right)^2} \quad (1)$$

were d is the diffusion coefficient, Li is the Sound Pressure Level of the reflected sound at the i-th measurement position, and n is the number of measurement positions.

The second kind of measurement has been recently standardized by the ISO [5]. This method allows the direct extraction of a parameter known as a 'scattering coefficient' under the assumption that scattered sound is non-coherent. The technique therefore exploits certain time features of the scattered sound. A test sample is introduced into a reverberant chamber, and impulse responses for different sample orientations are obtained. Using synchronous averaging of these impulse responses, the diffuse reflected sound is eliminated and a virtual impulse response is obtained. From that virtual impulse response a pseudo-absorption-coefficient can be obtained in an analogous way to the Sabine method. Finally, a scattering coefficient is obtained from this pseudo-absorption-coefficient.

SONIC CRYSTALS AS SOUND DIFFUSERS

The simplest sonic crystal for applications in Room acoustics is a 2D periodic structure of scatterers, i.e., a set of equally spaced cylinders, with a rigid backing. Applications of sonic crystals in other fields within acoustics, like noise barriers, do not have a rigid backing. Only in a closed space a rigid wall after the sound crystal is to be used.

In order to test the performance of that simplest crystal we have implemented a 2D Finite Difference Time Domain (FDTD) simulation of that structure following the AES standard for characterization of sound diffusers. The FDTD technique has been chosen since this solution offers an intrinsic time domain analysis of the method. This will allow us to investigate the 'time spreading' [6] effect produced by sonic crystals.

Figure 1 illustrates the test sample. Concerning the simulations with FDTD technique a small area around the test specimen has been simulated. All the calculations have been carried out in a mesh comprising approximately 400 by 700 elements, each with an approximate size of about 1 cm. In order to operate with a Courant number as close to 1 as possible, the sampling frequency is about 10 KHz. For frequencies above 10 KHz numerical dispersion should be significant enough to mask the reflected sound. The numerical scheme is excited by a line source placed at the right hand side of the integration area in which the test specimen is placed (see figure 1). The time domain signals corresponding to the pressure and to the particle velocity are recorded at the Near Field Far Field Transformation line in order to obtain the sound pressure at the 37 Far Field locations at a distance of 50 meters from the test specimen with angles between 90 and -90 degrees with a step of 5 degrees. As one of our purposes is to check the time spreading provided by sonic crystals, it is extremely important to use excitations signals as short in time as possible. We have used Ricker wavelets with central frequencies at 250 Hz and at 2 KHz, covering all the frequency bands of interest in diffuser characterization. Further details of the FDTD simulation can be found in [6]. In some of the particular cases developed for the present work the mesh size has been modified to better reproduce the geometries under investigation.

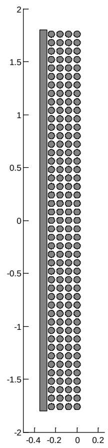

Figure 1. Test specimen. (Sample under analysis). Notice the flat panel backing.

The test sample is set of cylinders with a radius of 3cm, and a distance between the centers of each of them of 8cm. The lattice constant, i.e. the distance between elements, have been chosen small enough to have a band gap falling inside the typical range of interest in room acoustics. The band gap is expected to appear for frequencies having a wavelength two times the distance between elements. The radius of each element has been chosen large enough to obtain a filling ratio as large as possible to have a wide band gap. With these parameters the band gap is expected to appear around 2500 Hz. The test sample is backed with a rigid flat surface, given that we are exploring here it is possible application in room acoustics, and so, they are to be used covering flat surfaces. The distance between the last elements and the flat surface is half the distance between elements to ensure that the reflected sound sees a larger crystal without any discontinuity. The test sample is 3.6 meters wide to minimize edge effects. It is especially important to say that as the application investigated here is as sound diffusers, the total thickness of the test sample is limited. In particular we will consider only four periods (see figure 1) in the normal direction, so the total thickness is about 40cm. As reference of a conventional diffuser we will compare the results with those obtained in [6] for a QR sound diffuser whose operating range is between 550 Hz and 2000 Hz. The maximum depth of the sound diffuser wells is about 20 cm and the total width is 3.6m, exactly the same of the sonic crystal.

The first result is the polar patterns of the sound reflected by the sonic crystal. It is illustrated in figure 2. Notice that for frequencies around the band gap the sound is reflected mainly in three directions, the specular direction (0º) and ±50º. It must be pointed out that for frequencies around 800 Hz, which nearly corresponds to one third of the band gap frequency, two lateral lobes are observed close to the specular direction. (For comparison the results for a flat panel are shown in figure 3).

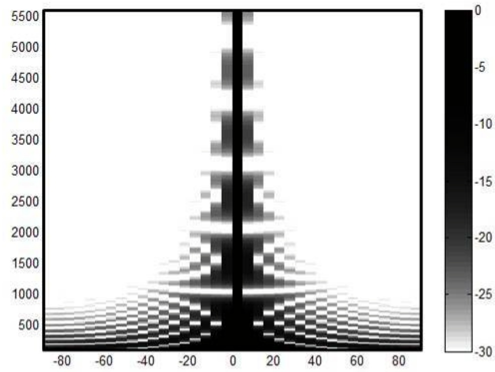

Figure 2. Flat surface (reference). The horizontal axis represents angle, the vertical axis is frequency. The gray scale corresponds to the relative intensity.

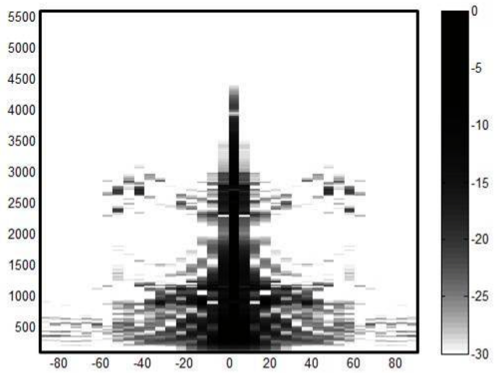

Figure 3. Sonic crystal. The horizontal axis represents angle, the vertical axis is frequency. The gray scale corresponds to the relative intensity.

Once the sound pressure has been obtained for each angle and frequency we can calculate the diffusion coefficient (see equation 1). In figure 4 the diffusion coefficient is plotted against frequency for both considered surfaces. This preliminary results shows that the sonic crystal is sightly efficient only for two small frequency ranges: the one corresponding to the band gap (2000Hz) and another one at one third of the band gap frequency (850Hz).

At first glance sonic crystals seem not to be a promising possibility especially if one considers that for the tests that we have done with smaller filling fractions the performance as sound diffusers is even poorer. However there are several possibilities that should be investigated, such as the use of chirped crystals, the combination with cavity resonators, and so on. In next section we investigate the fist one of these additional possibilities.

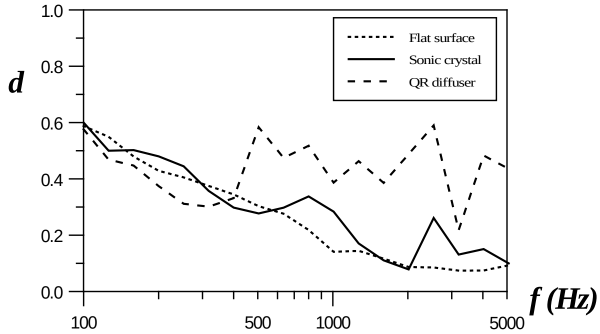

Figure 4. Diffusion coefficient versus frequency for a flat panel (dotted line), a sonic crystal with a flat surface backing (solid line) and a QR sound diffuser (dashed line). All surfaces are 3.6 m wide

CHIRPED CRISTALS

One of the possible modifications of the original design is to modify the crystal parameters by a modulation. Crystals in which the distance between elements is modified across one or more directions are known as chirped crystals. Chirped crystals are commonly used to obtain a progressive change of the effective acoustic impedance in order to optimize the transmission. However, as we are working with a few elements in the direction of incidence of the sound, it makes no sense to modified the lattice constant (distance between elements), in the *x* direction (direction normal to the wall). So we have modulated the distance between elements in the *y* direction following the expression:

$$a_{chirped} = a\left(1 + 0'1\sin\left(2\pi\, n\frac{y}{\max(y)}\right)\right) \tag{2}$$

After several attempts modifying the control parameter *n*, only for some values of n we have observed a weak increase of the diffusion coefficient at low frequencies. In a second modification we have tested a crystal in which the lattice constant abruptly changes between two extreme values, or in other words, the sinusoidal term in (2) is substituted by a square wave. This structure is illustrated in figure 5. For this particular case we have observed that with large values of the filling fraction a large increase of the diffusion coefficient at low frequencies can be observed (See figure 6).

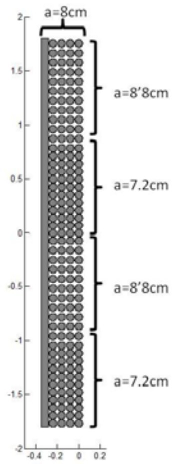

Figure 5. Second test specimen. The distance between elements in the *y* direction is abruptly changed from one zone to another.

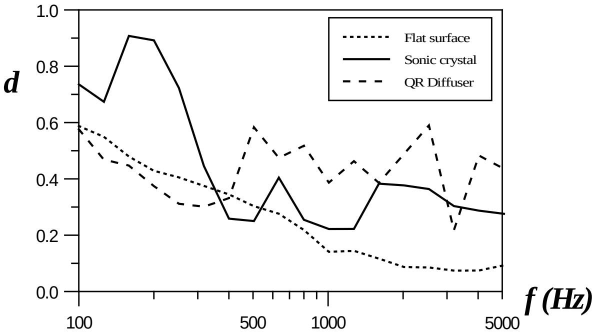

Figure 6. Diffusion coefficient versus frequency for a flat panel (dotted line), a sonic crystal with different distances between elements (solid line) and a QR sound diffuser (dashed line). All surfaces are 3.6 m wide

TIME SPREADING

It is well-known that the classic sound diffuser provides not only spatial but also time spreading of the reflected sound. The FDTD algorithm that has been used in order to obtain the diffusion coefficient, allows investigating the time spreading. Preliminary results and discussions are now presented.

Figure 6 illustrates the time spreading of the considered surfaces for a reflection direction of 0º (specular zone). In figure 7, in order to present a complete analysis of the results, we have performed a back-integration of the impulse responses (Schröeder integral [7]) to obtain characteristic decay times of the reflected signals. This is analogous to reverberation time in room acoustics.

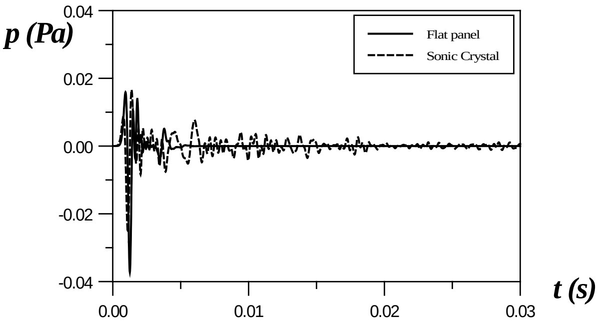

Figure 7. Sound pressure reflected at 0 degrees versus time: flat panel (continuous line), diffuser (dashed line)

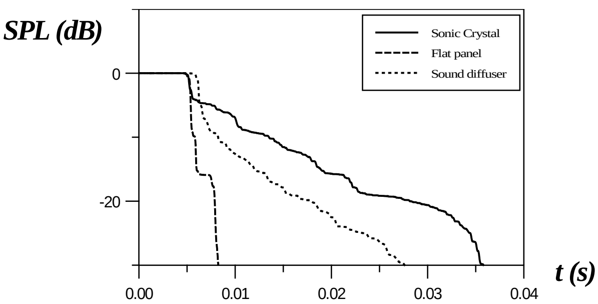

Figure 8. Normalized back-integrated time responses with Ricker wavelet excitation (only reflected sound) at 0 degrees versus time: Sonic Crystal (continuous line), flat panel (dashed line) and diffuser (dotted line).

An evaluation of results using the different surfaces considered before suggests that without considering spectral variations too closely, we may generally hold that sonic crystals provide a time spreading that is even larger than conventional sound diffusers. It is particularly interesting that for low frequencies the use of crystals in which the distance between elements is not constant the time spreading is extraordinary large. On the contrary crystals with a small filling fraction produce a poor time spreading.

It is still not clear which is the relationship between the time spreading provided by interior surfaces in a room and its acoustic characteristics. For instance the cross-correlation of signals measured at closely adjacent points in space might be expected to be modified by reflecting surfaces with complex space-time spreading characteristics. The inter-aural cross correlation coefficient (IACC) is known to be strongly associated with the subjective perception of ‘spaciousness’ [8-9]. It is even possible that modifications to the time-structure of decaying reverberant energy may have implications for the modulation transfer function and hence speech intelligibility can be strongly modified by the use of structures that causes a large time spreading of sound.

CONCLUSIONS

A Finite Difference scheme has been employed to evaluate the potential of sonic crystals as sound diffusers. It has been shown that using chirped crystals the performance of sonic crystals as sound diffusers can be improve especially at low frequencies. Additionally, preliminary results concerning the time domain features of the sound reflected by this kind of structures show that they can even provide a larger time spreading that conventional sound diffusers. However further research must be carried out in order to evaluate how much the time spreading provided by surfaces can improve the acoustic properties of a given space.

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