Band structure and transmission of 3D chiral sonic crystals

R. Pico, V. Romero-Garcia, V. Sanchez-Morcillo, A. Cebrecos and L.M. Garcia-Raffi

Universidad Politecnica de Valencia, Paranimf 1, 46730 Gandia, Valencia, Spain, 46730 Gandia, Spain
rpico@fis.upv.es

Photonic crystal based on spiral elements posses' band gaps. The width of the band gaps and the shape of the gaps depend on the radius of the spiral. The sonic analogue has not been studied. We propose a 3D periodic structure based on a local geometry that breaks the mirror symmetry with respect to its centre. The unit cell is composed by three elbow elements connecting all the dimensions in a loop: x-y, y-z and z-x. By periodic translation in the three main directions, the complete structure is generated leading to quasi-spirals arranged in a hexagonal lattice interlaced with different rotation phase. We investigate the both the phononic band structure of our crystal and the transmission spectrum using the Finite Element Method.

1 Introduction

Sonic crystals (SCs) are periodic structures that can be used to manipulate acoustic waves. By suitably designing a SC it is possible to control the flow of waves, and use them for various wave-functional applications, such as the wave beaming [1,2], subwavelength imaging [3,4] and wave-guiding [5].

Most of the beam propagation effects like focalization, collimation or spatial filtering in Sonic Crystals have been addressed in two-dimensional (2D) periodic structures. The three-dimensional (3D) systems are more complicated not only for the experimental study but also in the numerical analysis, where the numerical methods are extremely time consuming. Moreover, the complete useful functionality of SCs like beamforming or waveguiding must be implemented in three-dimensional (3D) SCs.

One of the most known and used periodic media in 3D is the woodpile structure. Several authors have reported experimental observations of a well-collimated beam formation behind a 3D Photonic Crystals [6] and Sonic crystals [7] based on this design. Two crossed and interlaced scatters in a woodpilelike geometry form the unit cell of the crystal. For a particular direction, the subdiffractive propagation regime is achieved. When a beam propagates inside a 3D woopile crystal, it is strongly collimated in both directions perpendicular to the propagation direction.

Among the 3D crystals, a special attention must be pointed out on the spiral architecture. Photonic crystal based on a three dimensional spiral design have been shown to present interesting phenomena like paradoxical transmission [8] or polarization gaps [9]. Spiral photonic crystal is a type of three-dimensional (3D) chiral structures. Since the symmetry between the right-hand and left-hand circularly polarized waves is broken by chiral structures, the two polarizations travel with different speeds and one of the circular polarizations can potentially be blocked by the polarization gaps (or chiral Bragg gaps).

Here we propose an experimental study of three-dimensional periodic (3D) structures in air (Sonic Crystals SC) based on the composition of elbow elements. Acoustic waves in fluids like the air do not present several polarizations, but only one: longitudinal waves. For this reason, chirality is not an attribute of Sonic Crystals. Still, other phenomena observed in spiral crystals are explored. Realization of 3D Sonic Crystals based on this structure is of great simplicity

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2 Geometry of the Sonic Crystal

Three rotated elbows oriented in the three main directions of space compose the unit cell (see Figure 1a). As the unit cell is reproduced by periodicity, these elbows (see Figure 1b) connect all dimensions in a loop: x-y, y-z and z-x. The resulting Sonic Crystal is defined by an array of several quasi-spiral structures in the [1 1 1] direction.

The periodic structure generated by repetition in the space is identical in the x, y and z directions and presents several rotational symmetries as it is the case for the unit cell. It must be remarked that all the mirror symmetries in the main planes are broken in the unit cell.

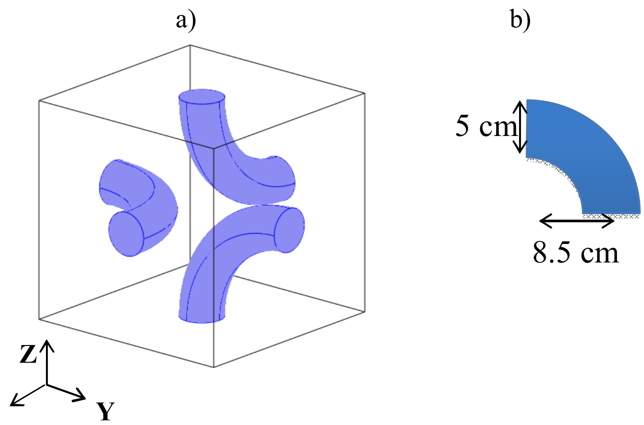


Figure 1 a) Unit cell and b) geometric dimensions of each elbow

X

Different views of the crystal are illustrated in Figure 2. Although the mirror symmetry is broken in the unit cell, the complete periodic structure presents several rotation symmetries. In this work, the direction represented in Figure 2a corresponding to [1 0 0], (and also by rotation symmetry [0 1 0] and [0 0 1]) has been both numerically and experimentally investigated.

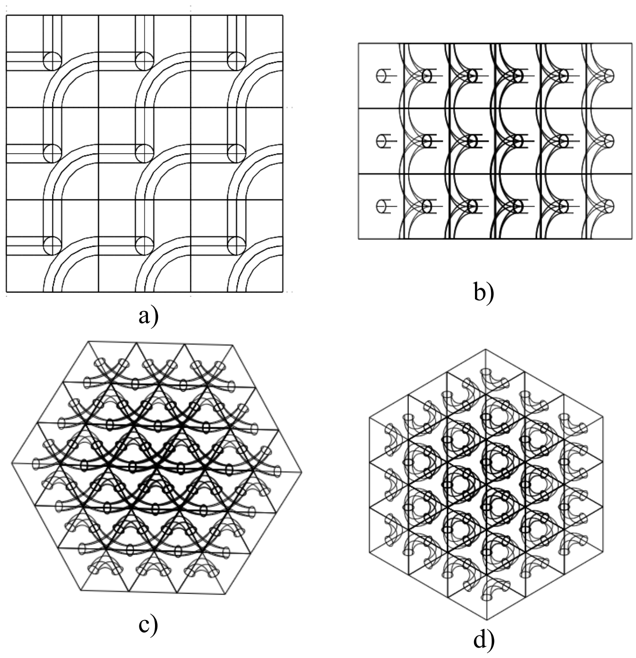


Figure 2 Different views of the Sonic crystal from directions a) [1 0 0], b) [1 1 0], c) [-1 1 1] and d) [1 1 1]

In Figure 3 the practical realization of the crystal is illustrated. The elbows are hollow and correspond to a specific variety of PVC plumbing fittings. The structure has built up by connecting by hand the elbows in the proper directions. The elbows at the bottom are glued to a sheet of wood in order to hold the whole structure. The sheet of wood has been covered by absorbent material in order to avoid unexpected reflections in the rigid surface. The periodic arrangement of the structure is achieved after several corrections in the rotation of the particular elbows. The visual alignment in several directions of the crystal is used to guide the optimal disposition of the elements constituting the Sonic Crystal in an iterative process.

The lattice period of the periodic structure in all directions x, y and z is a=17cm. The Bragg frequency for this period in the direction of propagation [1 0 0] is f_B=1000Hz. The unit cell is defined from three parts of a complete torus (three elbows). In this way, the volumetric filling fraction can be obtained as the ratio between three fourths of the volume of a complete torus of minor radius r and major radius R and the volume of the equivalent cube containing the unit cell of side two times R (see figure 1).

$$ff = \frac{3/4\cdot 2\pi^2 R\cdot r^2}{(2\cdot R)^3} = \frac{3}{16}\pi^2\left(\frac{r}{R}\right)^2 = 0.16. \qquad (1)$$

Let r be the radius of the circle being rotated, and let R be the distance from the center of the circle to the axis of rotation. Of course, equation (1) is only valid if r/R is small enough and the elbows don not intersect.

Figure 3 Illustrations of the Sonic Crystal at different views.

3 Experimental setup

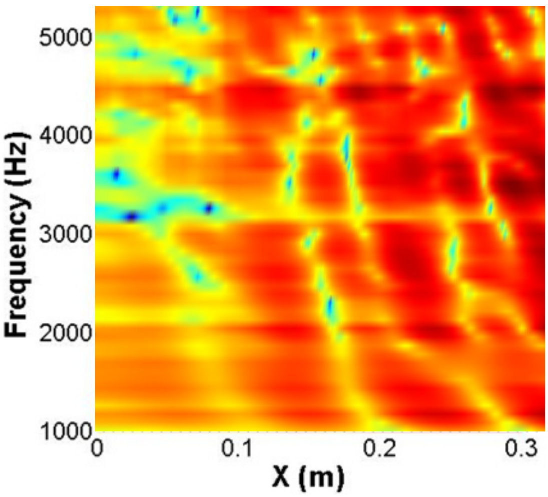
In this section, we describe the experimental set-up used to measure the propagation of acoustic waves inside and outside the Sonic Crystal. For this measurements a 3D computer-controlled automatic positioning system has been used together with an automatized acquisition system, called 3DReAMS (3D Robotized e-Acoustic Measurement System (see Figure 4).

Figure 4 Detail of the 3DReAMS robotized system

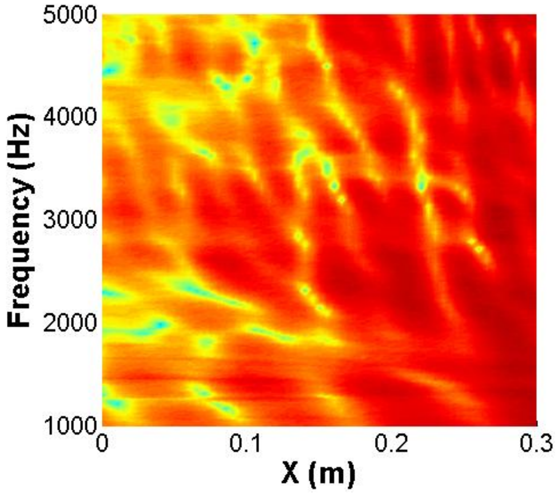
This system enables the pressure field in trajectories inside and outside the crystal to be measured. All the measurements are carried on in an acoustic chamber. It is assumed that the acoustic source used in the experiments emits plane waves and it is oriented in the [1 0 0] direction of the crystal.

4 Sound Field Measurements

The results for the sound field inside the crystal are illustrated in Figure 5, the experimental measurements (Figure 5a) and the numerical simulations with the Finite Element Method (Figure 5b). The sound source is placed at the position x=0.3m. Good agreement can be found by comparing both figures, specially for frequencies near the Bragg frequency(1kHz). The Sound Field is maximum at the entrance of the Sonic Crystal and the intensity is reduced though propagation. Local minima and maxima are present at different position for different frequencies because of the multiple scattering of acoustic waves inside the crystal.

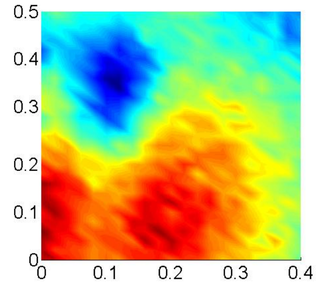


a)

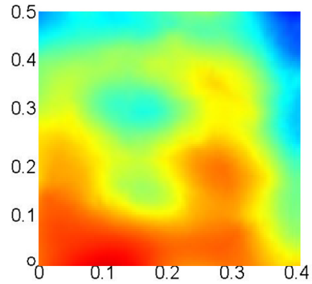


b)

Figure 5 Sound Field inside the crystal for a) experimental measurements and b) numerical simulations



a)



b)

Figure 6 Sound Pressure Level distribution in an horizontal plane behind the crystal at 1000Hz for a) experimental measurements and b) numeric simulations

The transmission of acoustic waves is measured in a horizontal plane behind the crystal. Results are shown in Figures 6a for the Sound Pressure Level behind the crystal in a map plot at 1000Hz. Very good agreement is found when maxima and minima of the field are compared for experimental measurements and numerical simulations in Figure 6b).

Measurements of a transverse cross section behind the crystal are illustrated in Figure 7 for different frequencies. The dotted line corresponds to the source alignment. For frequencies above the homogenization regime (higher than 1000Hz) and below 3kHz,, the sound field emitted from the soured is deflected and/or dispersed at different directions of the space. Although the Sonic Crystal is periodic, because of its complex geometry, the acoustic energy is spread in several directions. The main consequence of this is that the acoustic transmission in the range 1kHz-3kHz of the crystal is significantly because of dispersion of the waves. Remark that this mechanisms is different to the Band-gap attenuantion due to the Bragg dispersion.

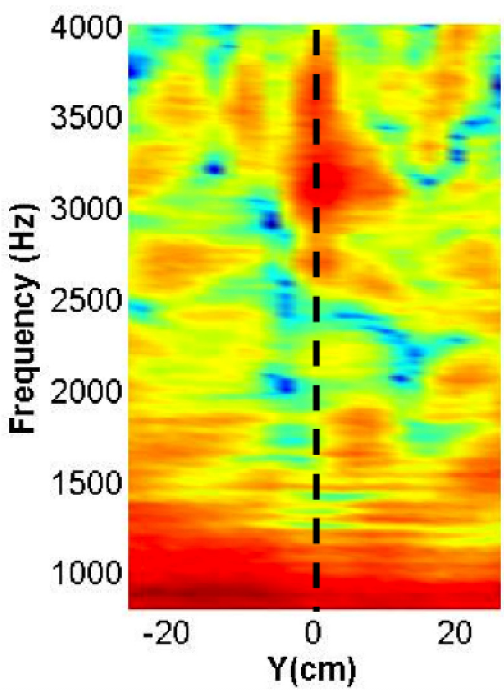


Figure 7 Experimental measurements for the transvers section of the beam profile behind the Sonic Crystal. The dotted line corresponds to the alignment of the source.

Dispersion of acoustic waves propagating through the [1 0 0] direction is also illustrated in Figure 8. The spectra of waves transmitted behind the crystal are represented at three different points in a transverse section behind the crystal. Except for very low frequency (homogenization limit), the Sound Field pattern is significantly different at the three positions. This result accounts for dispersion induced in waves by the Sonic Crystal.

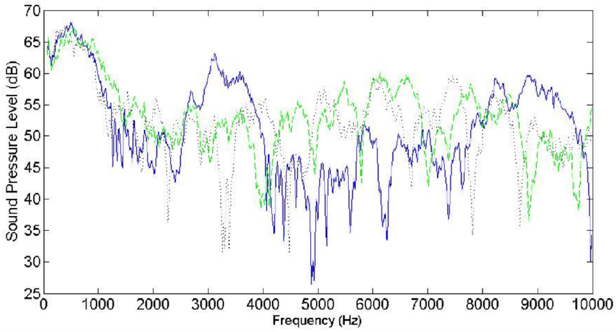


Figure 6 Sound Pressure Level spectra measured for three different positions behind the crystal in the transverse section y=-10cm (dotted), y=0cm (continuous, align with the source) and y=10cm (dashed).

5 Conclusion

A 3D sonic crystal has been designed based on a quasi-spiral architecture. This structure has rotational symmetry in the three directions of the space. An experimental realization of the crystal is based on the connection of multiple elbows. Acoustic measurements are carried on the [1 0 0] direction.The break of the mirror symmetry induces a dispersion of the transmitted field and the intensity of central diffraction order is significantly reduced for a large range of frequencies.

Acknowledgments

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