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Sonic Crystals, Arts and Environments

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The article is discussing the sonic crystals, which are involved in artistic and environmental structures, from sculptures to sound barriers, from music to the auralization of sound fields.

A sonic crystal is a metamaterial which acts in the acoustic field. Generally, it is an assembly of many elements engineered to have a specific property concerning the sound propagation. The elements can be made of metal or plastic. They are usually arranged in repeating patterns, having scales of the order of the wavelengths of the phenomena that they are influencing [1-3]. Actually, the metamaterials derive their features not from the properties of the materials the elements are made of, but from their geometric arrangements. Among metamaterials, well-known are those which are acting on the electromagnetic waves, by blocking, absorbing, enhancing, or bending them [4,5]. Some of these metamaterials are "photonic crystals", that is, crystals acting on photons. Less known are the acoustic metamaterials, which exist to control, direct and manipulate the sound in the form of waves in gases, liquids and solids. Among these metamaterials, we have the "phononic crystals", which act on phonons, and the "sonic crystals" which act on the audible sounds.
As explained in [6] - a reference which is giving, besides a detailed review of literature, some theory of the related phenomena - the sonic crystals are artificial structures which are made by scatterers arranged in lattices with square or triangular configurations. “The scatterers are sound hard (i.e., having a high acoustic impedance) with respect to the medium in which they are placed". When the elements are plates arranged in a linear pile, we have a 1D sonic crystal. In the sonic crystals where the scatterers are cylinders arranged periodically we have 2D sonic crystals. When the scatterers are objects embedded in a 3D periodic arrangement, we have 3D sonic crystals.
Basically, the photonic (for light) or phononic (for sound) crystals "allow impinging waves to undergo destructive interference”, because the waves which have frequencies “that fall within a range known as the bandgap are prevented from propagating in the material" [7]. The physical phenomenon is the Bragg scattering of the waves. The period of the assembly must have the order of the involved wavelength. As a consequence, “to block sound for human hearing, the periods would be very large", and the structure needs being metre-sized.
Some readers could observe that meter-sized periodic structures are proposed in several modern art sculptures too, and that some of them resemble the metamaterials. Actually, a sculpture which is, in its physical features, linked to sonic crystals exists. It is the Eusebio Sempere's "Organo", which is on display at the Juan March Foundation in Madrid. Thanks to Google Earth in the Street View mode we see it as in the Figure 1. It is a real example of a sonic crystal, as demonstrated by the sound attenuation measurements [8]. This sculpture has been created by a structure having a bandgap at around 1.6 kHz. The structure is made of 3-centimetre-diameter metal rods arranged on a 10-cm-period lattice, fixed, as we can see from the Figure, on a circular platform of 4 metres diameter [7,8].
As told in [9], this modern minimalist sculpture has stimulated researchers to made screens of poles that "could cut road, aircraft or factory noise as well as unsightly solid sound barriers" [10]. As the Eusebio Sempere's work is damping sound waves within a particular frequency band, new sculptures made of pipes can be created to act as sonic crystals. The researchers in [10] used "hollow, lightweight PVC tubes 3 meters long and 16 centimetres across arranged in a honeycomb-like lattice six rows wide, creating a barrier 1.1 meters thick like a multi-layer picket fence" [9].

Figure 1: Eusebio Sempere's "Organo" (Courtesy Google Earth, Street View mode).

The experimental work in [10] is very interesting, as explained in [9]. This screen is able of reducing the white noise like the solid panelling along motorways can do. But, in the case of the sonic crystals, "over half of the space" in it is empty, and, remarkably, "at certain angles you can see straight through it" [9]. The researchers had also removed some rods to create a sub-lattice of additional gaps. This different sonic crystal has a further blocking band for low sound frequencies of around 500 Hertz.

For what concerns the environment, even an array of trees, arranged in a periodic lattice, could act as a sonic crystal, improving the sound attenuation from the mass of each tree [11,12]. The use of a belt of trees to reduce the noise pollution has received great interest, as shown by [13-16]. These living sonic crystals could be subjected to the practice of topiary, to add some of the art of the living sculptures to the sound attenuation features.

Actually, another way to block the sound exists and it is based on resonance. In this case, the related art we want to mention is the music. In [7], we read that in 1933 Marcel Minnaert published a paper entitled 'On musical air-bubbles and the sounds of running water' [17]. In this work, Minnaert deduced the basic theory about sound emitted by an air bubble formed in water. He noted that the bubbles undergo radial oscillations, the breathing modes, inside the fluid. In the Minnaert's model, the resonant frequency of the bubble turned out being dependent on the bulk modulus of the air, the density of the water and the radius of the bubble. For small bubbles, with a radius of the order of a millimetre, the low value of the bulk modulus of air gives a resonant frequency within the range of audible sound [7]. And here we find a mechanism for creating new sonic crystals. "If, instead of creating bubbles that emit sound, one has a liquid containing a host of randomly arranged bubbles" [7], the waves incident on the liquid, having the proper frequency that can set the bubbles into resonance, can be limited in propagation and have their energy absorbed.

"If one could make bubbles of uniform size and place them in a periodic array of the correct spacing", to the previously described mechanism of absorption we could add also the Bragg scattering of the waves, because of the periodic arrangement of the bubbles [7]. Of course, this is very hard to do in a fluid, but it is easier in an elastomer, as proposed in [18]. The researchers have used polydimethylsiloxane (PDMS) in place of the liquid. In this manner, they have created a remarkably simple method, which "paves the way for the development of more complex bubble-based phononic crystals" [7]. Actually, they have created new metamaterials which are using bubbly media displaying the Minnaert resonance [19]. To this family of sound metamaterials, we have also to add the "bubble metascreens", which are single layers of gas inclusions in a soft solid. By tuning the parameters of these metascreens, "acoustic superabsorption can be achieved over a broad frequency range" [20].

Arrays of resonators in water are very important for the environment too. Many human activities are generating underwater noise and this noise can have adverse effects on the underwater life, as explained in [21]. The researchers, in this article, propose the use of arrays of air-filled resonators to reduce underwater man-made noise.

As we have seen, the mainstream of the researches on metamaterials concerns the attenuation of sound. However, other topics involving sonic crystals can be investigated too. For instance, in [22], an illusion of proximity of a sound source, created by a sonic crystal placed between the source and a listener, has been investigated. This is a remarkable research involving some unexplored effects of sound. Let us conclude as in [22]: "Even when the singular acoustical properties of these periodic composite materials have been studied extensively, … the possible perceptual effects remain unexplored". It is possible, therefore, an art of sound illusions created by means of the sonic crystals, in the framework of the auralization of the sound fields [23,24]. That is, the sonic crystals are not only a potential form of noise barrier, but also “a form of sonic art aimed at enhancing perception of the surrounding acoustic environment” [25].

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