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Short communication

Planar modes free piezoelectric resonators using a phononic crystal with holes

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ABSTRACT

By using the principles behind phononic crystals, a periodic array of circular holes made along the polarization thickness direction of piezoceramic resonators are used to stop the planar resonances around the thickness mode band. In this way, a piezoceramic resonator adequate for operation in the thickness mode with an in phase vibration surface is obtained, independently of its lateral shape. Laser vibrometry, electric impedance tests and finite element models are used to corroborate the performances of different resonators made with this procedure. This method can be useful in power ultrasonic devices, physiotherapy and other external medical power ultrasound applications where piston-like vibration in a narrow band is required.

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1. Introduction

Piezoceramic resonators are the basic component of most ultrasonic transducers and its mechanical vibration profile at the resonance frequency constitutes an important issue in many applications. The dimensions and shape of a piezoceramic resonator define the vibration profile at a certain frequency due to the coupling of the contour waves. In the case of a disk polarized along the thickness direction, the plane wave traveling along the thickness and the wave coming from the cylindrical boundary are the two coupled wave fields. The thickness to diameter aspect ratio governs the resonance frequencies and the vibration profile. Thus if a piston-like vibration surface is required, for either piezoelectric material characterization or ultrasonic transducer design, the lateral dimensions of a resonator should be many times smaller, or larger, than the thickness one [1]. This is the case of transducers used in power ultrasonic, where a tall cylindrical shape, working at the first and lowest longitudinal mode, must be used to avoid the coupling with resonances related with the cylindrical shape. When planar are coupled with the thickness mode, a non-flat vibration emission surface is generated, producing a non-efficient transducer in terms of vibration or ultrasonic field emission. Consequently, filtering or canceling the planar resonance modes is an important issue in many applications. Albeit, as it has been already mentioned, this can be done by an adequate control of the geometry of the resonators, it would be desirable to find a way to achieve this regardless the geometry and dimensions of the resonator. Piezocomposite structures have been proposed since the 80s to solve this problem together with other issues related with the transduction efficiency to water-like media [2]. The most successful piezocomposite design is the dice of a piezoceramic resonator along its thickness, forming a square pattern with grooves filled with a polymer. By controlling the width and pitch of the dice, lateral resonances in the planar direction are strongly attenuated and the surface vibrates in-phase. Furthermore, triangular-cut piezocomposites have been designed for unimodal operation [3]. Piezocomposites are the best option for ultrasonic imaging applications where low acoustic power and large frequency bandwidth is required, but they are not useful for ultrasonic high power at a narrow frequency band, which is our main interest in this work. Indeed, running away from the geometric condition were the spacing of the bars is one half the wavelength is the basic requirement of the piezocomposites design. This is exactly the opposite of the present approach, where the strict Bragg condition is required. Consequently, we show that by using the principles of a phononic crystal, the radial modes of a piezoceramic resonator can be stopped independently of its lateral shape, producing, at certain frequency, a resonator with a regular and in-phase vibration surface capable to deliver high elastic and acoustic intensity.

Photonic and phononic materials are composite materials made of periodic distributions of embedded inclusions and the name phononic material or phononic crystal is used to refer materials for control phonons, sound and other mechanical waves. Research

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on phononic materials is active and of great interest since recently new materials capable to manipulate sound and elastic waves with high precision have been developed (see Ref. [4] and references therein). Phononic materials prevent propagation of waves in certain frequency ranges by making use of the fundamental properties of waves, such as scattering and interference, which can lead to the formation of band gaps, that is, a range of frequencies within which waves cannot propagate through the structure. The main idea is then to modify the dispersion relation of the radial waves by making a periodic array of holes in a piezoelectric resonator through which radial waves cannot propagate. The Floquet-Bloch theorem is the standard tool for the theory of formation of band gaps by a periodic array and the propagation of sound and elastic waves in phononic crystals has been extensively studied both experimentally and theoretically [5–9]. In the case a piezoelectric material as the one described here, the theory faces the problem that the elastic parameters of the material change as the wave propagates. For this reason, the properties of the proposed phononic crystals by itself are beyond the purposes of this work but as we will see, simple rules and numerical and experimental testing lead to an optimal result in terms of the applications we are interested in. This approach also provides clear indications that the band gap around the Bragg diffraction frequency is indeed the reason why radial waves cannot propagate.

Phononic crystals where the periodic array consists of piezoelectric elements embedded on a substrate were first studied [10–12]. A different approach consisting of a piezoelectric material with a periodic repetition of hollow cylinders was used to study surface acoustic waves in this piezoelectric phononic crystals [13]. One of the advantages of working with piezoelectrics is that, contrary to usual materials where an external source of waves is required and the attenuation or phase shift is measured with Gain-Phase analyzer or other techniques, in phononic crystals built from piezoelectric materials, as proposed here, the propagating waves are originated by direct electric excitation of the material itself and no external sources of incoming waves is required. Even more, the direct piezoelectric effect also simplifies the detection of the different elastic effects since the pressure waves are a source of electric charge variations that are translated into electric signal, which can be easily analyzed.

Here, we use a phononic crystal design as in Ref. [13], consisting of a periodic array of cylindrical voids drilled along the poling direction of a piezoceramic resonator, to stop the propagation of waves along the plane perpendicular to the poling direction. This produces a resonator capable of vibrating at its resonance frequency with a piston-like vibration surface, independently on its shape and dimensions. As mentioned above, the properties of the phononic crystal by itself are not studied here but it is enough to take into account some general experimental results [5]. In a phononic crystal consisting of a square array of air holes, the lattice parameter or periodicity of the perforations must be around half the wavelength of the wave to be diffracted and the band-gap width is proportional to the so-called filling factor $\pi(r^2/a^2)$, where a is the lattice parameter and r is the radius of the perforation.

2. Materials and methods

The material used to prepare the samples was PZT-5A. A set of five metallized disks with 10 mm radius and 2 mm thickness, polarized along the thickness direction were fabricated. Periodic arrays of circular holes with radius r were worked on the piezoelectric samples using high speed drilling at the vertices of a square array with lattice parameter $a = 2$ mm (see Fig. 1). Five disks were prepared: the disk without perforation and perforated disks with $r = 0.2$, 0.3, 0.5 and 0.7 mm holes, respectively. Given the theoretical complexity of the velocity wave dispersion in piezoceramic plates and the well-known softening effect in perforated piezoceramics (decreasing the resonance frequency), the lattice parameter was chosen by a semi empirical procedure as follows. The vibrating surface of the disk without holes was scanned at 800 kHz (see below) by laser interferometry, measuring the spatial wave length observed with the nodal circles. Then the lattice parameter a was set to a half the measured wave length at the scanned frequency: $\lambda/2 = 0.002$ m. Notice that taking into account a and r (0.2, 0.3, 0.5 and 0.7 mm) the approximated filling factors are 3%, 7%, 19% and 38%, respectively.

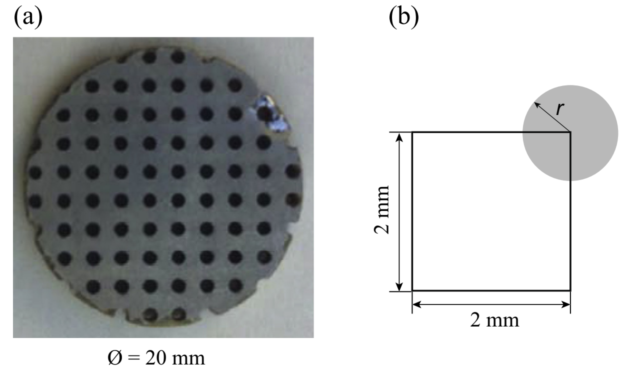

Fig. 1. (a) Experimental PZT-5A disk with 10 mm radius, 2 mm thickness and perforated with $r = 0.7$ mm holes. (b) Unit cell geometry and dimensions.

3. Results

Since we are dealing with a piezoelectric material, the mechanical displacements of the propagating waves produce electrical information at the electrodes and at the same time, by the inverse piezoelectric effect, the resonators themselves can produce the propagating waves if an electric signal with the studied frequency is applied at the electrodes. Consequently, if the electric impedance of the resonators is measured with a standard electric impedance analyzer (Agilent 4294A), the signature of the resonator shows all the required information in order to verify if the planar resonances are indeed stopped and the frequency range where this occurs. In Fig. 2, the absolute value of the admittance of the five disks is shown. Three samples were fabricated for each resonator type but the mechanical drilling process introduced differences affecting the reproducibility in some cases. However at least two samples in each case allowed to verify the reproducibility of the results shown in Fig. 2.

In Fig. 2(a) the measured admittance of the disk with and without perforations is compared. From this it is concluded that with $r = 0.7$ mm, the planar resonances are completely filtered from 300 kHz up to 1 MHz, cleaning the frequency spectrum in this frequency window. Notice that the thickness resonance now appears below the resonance frequency of the resonator disk without holes (1 MHz); this effect was expected as the material was softened by the perforations. For this reason, the lattice parameter was calculated at 800 kHz.

In Fig. 2(b) the evolution of the filter strength as a function of r is shown. The lowest frequency filtered (that is, the last planar unstopped mode appearing in the admittance spectrum) decreases from 700 kHz for $r = 0.2$ mm to 300 kHz for $r = 0.7$ mm. Also in Fig. 2(b) it is observed that the first resonance appearing after the thickness resonance is around 1 MHz and it is more noticeable for lower values of r. From this, it can be concluded that the attenuation bandwidth related to the stop band increases from 300 kHz to 700 kHz as a function of the filling factor.