

Suppression of Unwanted Harmonics in Piezoelectric Transducers Using Phononic Crystals: Modeling and Simulation

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Abstract

Piezoelectric resonators are fundamental components in ultrasonic transducers, playing a crucial role in determining the overall performance of these devices across a wide range of applications, including medical imaging, therapeutic physiotherapy, and underwater sensing. The mechanical vibration modes of piezoelectric resonators at their resonant frequencies are particularly significant, as they directly influence the efficiency, sensitivity, and signal clarity of ultrasonic transducers. The resonator's geometry such as its thickness, diameter, shape and its dimensional parameters govern the oscillatory behavior at specific frequencies. This behavior arises mainly from the coupling and interaction of various contour vibration modes, including thickness, radial, and shear modes. However, unwanted vibrational modes, especially shear and radial modes, can interfere with the desired piston-like vibration, reducing the transducer's acoustic efficiency and degrading signal quality. To address these challenges, phononic crystals have emerged as a promising solution. Phononic crystals are artificially engineered periodic structures designed to manipulate elastic wave propagation through mechanisms like scattering and interference. In this study, a phononic crystal structure is developed by creating a periodic array of circular holes arranged in a triangular lattice along the resonant polarization axis of the piezoelectric resonator. This modification of the resonator's internal structure effectively alters wave propagation, resulting in a piston-like vibration pattern that suppresses undesirable shear modes while enhancing vibrations in the thickness direction. This selective mode filtering significantly expands the mechanical vibration domain, and improves the acoustic output of the transducer. The proposed model has been developed using Finite Element Method (FEM) simulations, which validate that the phononic crystal structure promotes efficient piston-like wave propagation while significantly minimizing unwanted harmonic distortions. These results suggest that fabricating an experimental prototype based on this design could play a crucial role in

advancing high-performance piezoelectric transducers for therapeutic physiotherapy, where precise and controlled ultrasonic wave emission is essential for effective treatment.

Keywords: phononic crystals; piezoelectric transducers; physiotherapy; FEM.

1. Introduction

Piezoelectric transducers with superior performance are widely used as sensors and actuators in various vibration control applications. Among piezoelectric materials, polycrystalline ceramics such as lead zirconate titanate (PZT) have attracted considerable research interest due to their relatively easy fabrication and strong electromechanical coupling.

A notable feature of these devices is their operation in either narrow-band or broadband resonance modes, making them suitable for detection and imaging applications. Designing such systems requires careful consideration of transmission mechanisms and complex geometries.

Ultrasound devices operate by generating ultrasonic waves, and advancements in technology have enabled these devices to achieve very high resolution. Ultrasound imaging employs different modes such as amplitude mode, brightness mode, blood flow mode, constant range mode, and motion mode.

Several factors negatively impact treatment efficacy, including total acoustic intensity, beam intensity, transducer size, session duration, and frequency. High-resolution imaging demands high frequencies, which can cause interference among different frequency modes and degrade performance. Researchers have proposed various solutions to address these challenges, among which the use of phononic crystals periodic structures composed of materials with contrasting mechanical impedances has emerged as a promising approach [1].

Conventional physiotherapy devices typically use a piezoceramic disc covered with a metal layer in direct contact with the body. The dimensions and geometry of the piezoceramic resonator govern its oscillation characteristics at specific frequencies.

The standard operating frequency is typically 1 MHz but may vary depending on factors such as tissue characteristics, signal type, and acoustic pressure; these must be considered when selecting a transducer frequency. The key active component of a transducer is the piezoceramic disk, where the thickness-to-diameter ratio determines resonance frequencies and vibration modes. For piston-like ultrasound transducers, the lateral dimensions of the resonator should be significantly larger or smaller than its thickness [2].

In the 1980s, piezocomposite structures were introduced alongside other interface designs aimed at improving transfer efficiency [3]. The most effective piezocomposite design involves a square pattern of grooves along the thickness, controlling the placement of cut pieces, lateral intensifications, and vibration phase coherence [4].

The relationship between intensity and pressure distribution in the emission medium, as a function of frequency and domain size, aligns with wave diffraction theory [5].

This study focuses on designing homogeneous transducers exhibiting uniform vibration phases across their surfaces. Traditional designs face limitations due to converter boundary constraints and the presence of disturbing modes caused by transverse (shear) resonances, which interfere with the primary thickness mode [6].

Research into phononic materials has garnered significant interest for their ability to precisely manipulate sound and elastic waves [6]. A key property of phononic materials is the creation of band gaps that inhibit wave propagation within specific frequency ranges via scattering and interference effects. Wave propagation in phononic crystals is commonly analyzed using Bloch theorem approaches [7-11].

One earlier method to mitigate radial effects involved modifying the metal coatings on the capsules [7]. Another approach utilizes phononic band gaps to suppress radial modes and enhance thickness vibrations [1].

A challenge in applying Bloch theory to piezoelectric materials lies in the coupled variability of wave propagation with the material's elastic parameters, a complexity addressed through numerical simulations. One proposed solution involves creating a periodic array of hollow cylindrical holes within the piezoelectric element and investigating the resulting acoustic wave behavior [8].

The phononic crystal in this study consists of a triangular array of air holes characterized by lattice parameter (a), hole radius (r), and filling factor Eq. (1):

$$f = \frac{\pi r^2}{\frac{\sqrt{3}}{4} a^2} \quad (1)$$

Generally, all displayed formulas should Considering the periodicity of the holes to be approximately half the wavelength ($a = \lambda/2$) according to the Langevin modulus, this configuration yields a piston-like piezoelectric transducer with a desirable vibration pattern [1,8].

The physiotherapy piezoceramic transducer comprises two components: a disk and a metal capsule. The drilling patterns of the phononic structure need to be evaluated on one or both components. Research indicates that phononic crystals achieve optimal performance when holes are introduced in both parts [9].

In this study, the operating frequency is set at 1 MHz. Due to the differing speeds of sound in the two materials, the lattice parameter must be selected accordingly. To determine the hole radius (r), the relation ($\pi = r^2/a^2$) is applied, which based on experimental findings [1,9], yields effective results at 1 MHz when ($a = 2.3$ mm) and the filling factor is approximately 57%. Consequently, holes with a diameter of 1.3 mm were chosen.

2. Material and methods

Finite element model

Piezoelectric converters were simulated using the finite element method (FEM) in COMSOL Multiphysics 6.3 software. Material properties for aluminum and PZT4 were obtained from the software library. For piezoceramics, isotropic mechanical damping with a complex damping coefficient ($\eta = 1 + 2 \times 10^{-2} i$) was applied. The lower surface of the piezo disk was grounded with a potential $V_0 = 0$, and the upper surface was excited with a 1 V electrical potential. Due to the symmetry of the hole pattern and the piezoelectric disk, the computational domain was reduced to one-quarter of the full model.

Effects of asymmetric spacing between the edge holes and the disk boundary were neglected. Mesh elements of 0.15 mm were used near the holes, and 0.5 mm elements were applied elsewhere in the domain.

In the model, the disk center aligns with the center of the triangular hole pattern. Various vibration modes were investigated, as shown in Table 1, along with component dimensions and simulation results.

Table 1 presents various parameters of the piezoelectric components, with the center of the triangular array located at the middle of the disk. The values from Table 1 are used sequentially in the models shown in Fig 1 to 4.

Table 1. Different parameters of piezoelectric components considering the middle of the triangular array in the middle of the disk.

	hole in the piece	PZT4 piece height (mm)	Al piece height (mm)	Holes diameter inside PZT4 (mm)	Holes diameter inside Al (mm)	Resonant frequency (KHz)	Electrical impedance (Ω)
1	-	2	-	-	-	999	10.3
2	-		-	-	-	1023	8.76
3	Al		3.2	-	1.3	1060	53.3
4	both				1.3	992	34.65

Fig. 1. presents the resonant frequency at 999 kHz, electrical impedance, and phase ($^{\circ}$) diagrams for the PZT-4 piezoceramic as functions of disk height and diameter. The interference caused by vibrations in the radial direction of the disk has introduced noise into the electrical impedance diagram.

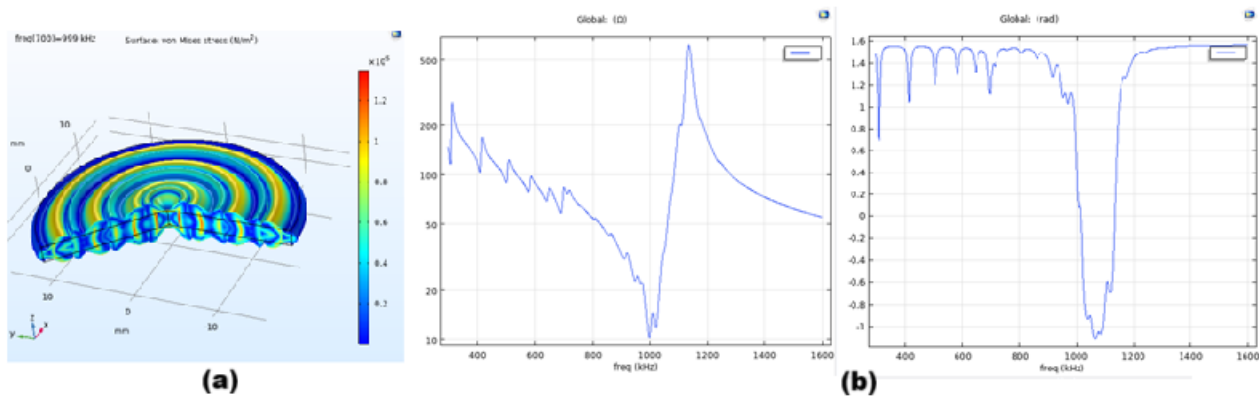


Figure 1. piezoceramic PZT-4; (a) acoustic pressure at 999 (KHz), (b) Electrical impedance module diagram $|Z|$ (Ω) and Diagrams of the values of phase ($^{\circ}$).

In Fig. 2, attaching the Aluminum piece to the disk results in a frequency shift compared to Fig. 1. This shift is caused by the different sound propagation speeds in the materials. In this model, the noise level is as high as in the single piezo sample.

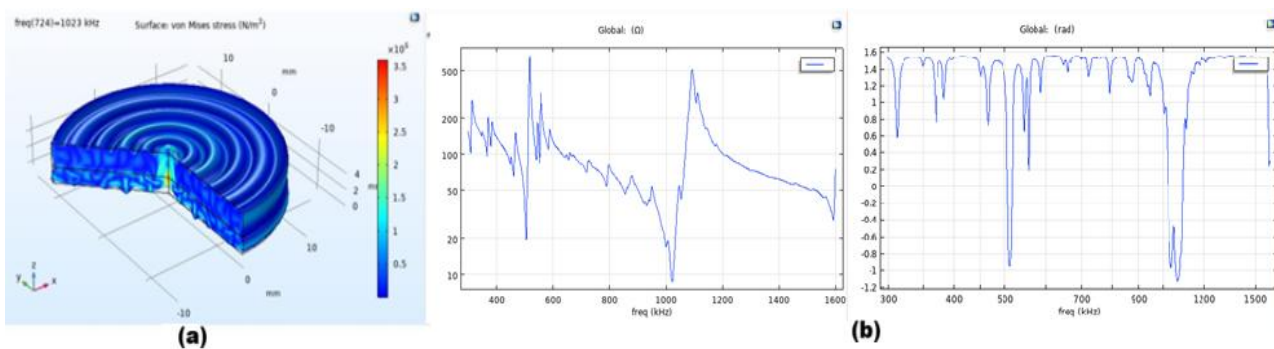


Figure 2. PZT4-Al piece ; (a) acoustic pressure at 1023(KHz), (b) Electrical impedance module diagram $|Z|$ (Ω) and Diagrams of the values of phase ($^{\circ}$).

Fig. 3 shows the aluminum structure of PZT-4 with a triangular array of cavities, each having a radius of 0.65 mm, within the aluminum. The electrical admittance and phase (degree) plots, compared to Fig. 2, indicate that noise caused by radial vibrations has been largely eliminated.

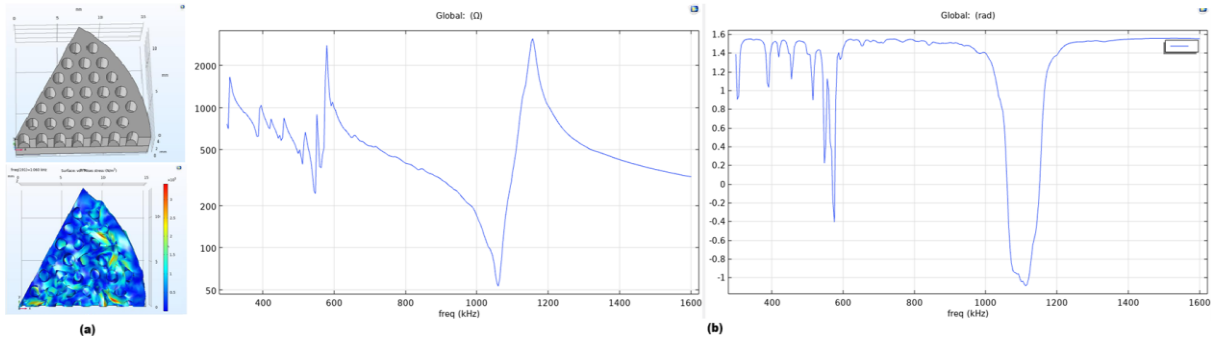


Figure 3. The structure of the PZT 4-Al Pieces by creating a triangular array of holes with a radius of 0.65(mm) inside Aluminum. (a) Acoustic pressure at 1060(KHz), (b) Diagrams of the values of Electrical admittance diagram and phase ($^{\circ}$).

Fig. 4 is similar to Fig. 2 and 3 but includes holes with a radius of 0.65 mm arranged in a triangular pattern. In this sample, both the piezoceramic and aluminum are perforated. As shown in the electrical impedance diagram in Fig. 4, the presence of holes in both structures significantly reduces vibration-induced noise in the radial direction.

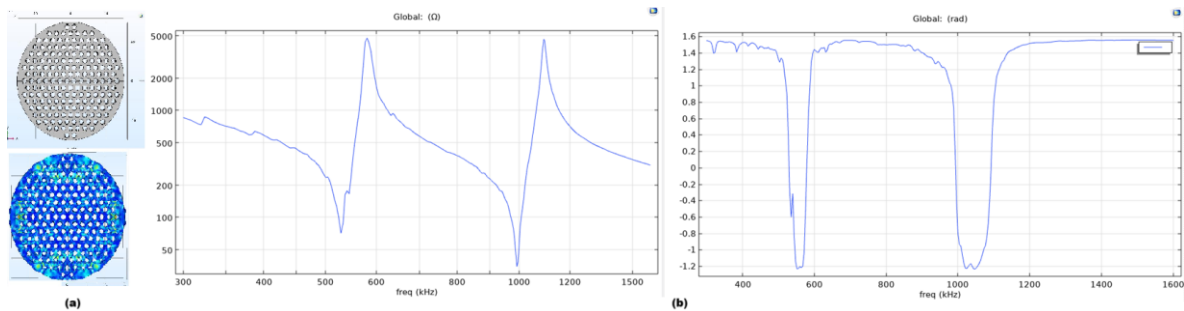


Figure 4. The structure of the PZT 4-Al Pieces by creating a triangular array of holes with a radius of 0.65(mm) inside both parts. (a) Acoustic pressure at 992(KHz), (b) Diagrams of the values of Electrical admittance diagram and phase ($^{\circ}$).

3. conclusion

The best performance was observed when both the aluminum capsule and piezoceramic disk featured phononic structures (i.e., both contained holes). The minimum disturbance levels were achieved with holes of 1.3 mm diameter, effectively suppressing vibrations induced by radial modes. Modeling the piezoelectric disk with a repeated array of cylindrical holes demonstrated that the configuration shown in Fig. 4. is the most efficient.

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