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The transmission spectrum of sound through a phononic crystal subjected to liquid flow

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The influence of liquid-flow up to 7 mm/s is examined on transmission spectra of phononic crystals, revealing a potential use for slow liquid-flow measurement techniques. It is known that transmission of ultrasound through a phononic crystal is determined by its periodicity and depends on the material characteristics of the crystal’s constituents. Here, the crystal consists of metal rods with the space in between filled with water. Previous studies have assumed still water in the crystal, and here, we consider flowing liquid. First, the crystal bandgaps are investigated in still water, and the results of transmission experiments are compared with theoretical band structures obtained with the finite element method. Then, changes in transmission spectra are investigated for different speeds of liquid flow. Two situations are investigated: a crystal is placed with a principal symmetry axis in the flow direction (ΓX) and then at an angle (ΓM). The good stability of the bandgap structure of the transmission spectrum for both directions is observed, which may be of importance for the application of phononic crystals as acoustic filters in an environment of flowing liquid. Minor transmission amplitude changes on the other hand reveal a possibility for slow liquid flow measurements. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5017168>

Phononic crystals (PCs) are generally formed by a periodic arrangement of materials (scatterers) with elastic properties different from those of the homogeneous matrix in between the scatterers, typically scaled at the wavelengths of interest and giving rise to the emergence of transmission bandgaps. The concept was studied by Yablonovitch¹ in optics for a photonic crystal in the ultraviolet microwave regime, where he shows that bandgaps in the spectrum exist as a result of interferences between direct and reverberated paths of waves. A similar behavior of acoustic waves in phononic crystals (PCs) has been observed. Additionally, ultrasonic waves in a periodic structure are used for sensing purposes, such as acoustic waveguides and acoustic lenses, to control, direct, and manipulate sound.^{2,3} The reported experiments are as follows: ultrasound is emitted by a transducer, and it travels through the PC, thereby probing its acoustic properties (density, viscosity, speed of sound, ..., speed of water flow). A specific transmission spectrum, including bandgaps, emerges, and its specific characteristics are determined by the physical properties of the PC. Over the last decade, PCs have been introduced as a platform for (still) liquid sensing purposes,^{4–9} based on significant spectral changes induced by composition changes of the liquid mixture.¹⁰ Many works discuss the application of PCs for fluid characterization such as viscosity, density, and concentration measurement of liquid solutions. However, no study of possible flow-speed influence on PC filter characteristics has been reported. For the case in which fluid-flow measurements without the presence of a PC is considered, we can cite, for example, Nishimura *et al.*,¹¹ for measuring the small open

channel fluid flow using pulse-echo signals scattered from the particles in a pipe. From the slope of the correlation peak amplitude with the variation in pulse-echo excitation time, the authors estimate the flow-speed of the medium, for speeds much higher than what is studied in the current paper. Here, we study the band structure and its stability and explore minor effects in actual transmission amplitudes to the flow-speed. The low speeds involved are comparable to what one may expect on a large scale in tidal water currents for example. The phononic crystal under study consists of a square lattice arrangement of 169 steel rods, each having a diameter of 1.2 mm and a length of 150 mm. A photograph of the crystal is shown in Fig. 1(a). The rods were aligned using two supporting plates that had been machined to have periodic arrays of holes, and Fig. 1(b) shows the square lattice pattern of the cylinders and the directions of the highest symmetry, referred to as ΓX and ΓM . The lattice constant, being the distance between the centers of any two adjacent rods, was measured: $a = 2.52$ mm. The crystal made of cylinders is submerged in water, such that the water in between the cylinders acts as the crystal matrix. Assuming a sound speed in water of 1480 m/s, incident ultrasound with a wavelength corresponding to the lattice constant would have a frequency on the order of

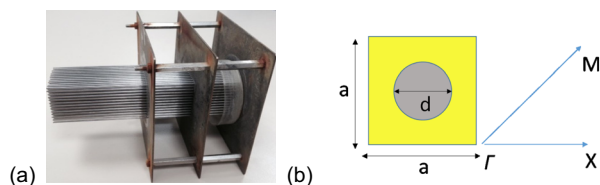


FIG. 1. (a) Photography of the sample and (b) schematic view of the PC in a rectangular lattice: $d = 1.2$ mm and $a = 2.52$ mm.

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1 MHz. Steel (rods) and water (host medium) were chosen here as the constituent materials of the crystal due to the large contrast in their densities and elastic constants, as this has been shown to be an effective approach for the formation of bandgaps in other studies on phononic crystals.^{12–14} To study effects of liquid flow on the transmission spectrum, that spectrum was first determined using through-transmission experiments using an emitting and a receiving transducer, namely, two Valpey-Fisher IS0104GP transducers with a nominal center frequency of and a beamwidth of approximately 10 mm. Two types of experiments have been performed on the crystal: through-transmission measurements in the ΓX direction and in the ΓM direction; the results are shown in Fig. 2.

First, the transducers were mounted, with the aid of the transducer mounting fork that was part of the polar C-scan equipment, at normal incidence on opposite sides of the crystal as shown in Fig. 2(a) and then at 45° from the crystal as shown in Fig. 2(b). A photograph is shown in Fig. 3 (left). The distance between each transducer face and the crystal surfaces is 6 cm. The through-transmission measurements were taken for the region of the crystal between the two support plates to better guarantee the periodicity of the cylinders of the crystal. To generate the pulsed ultrasound, the transducers were connected to the polar/C-scan equipment with the integrated JSR pulser/receiver. The pulser/receiver was triggered by Winspect software that was installed on the computer and integrated with the system. First, the measurement is done in the absence of the crystal. The frequency spectrum obtained from pulsed transmission between the transducer pair in still water is shown in Fig. 3(bottom). This spectrum was obtained from time-waveforms that were averaged over 100 received waveforms.

Then, the measurement was done using the crystal in both directions ΓX and ΓM for still water. The normalized frequency spectra obtained from pulsed transmission between the transducer pair and through the crystal water, averaged over 100 received waveforms, are shown in Fig. 4 for both cases. The bandgaps are shown in shadow dashed areas.

A lack of transmission can be observed in the spectra of the PC in the ΓX direction for frequencies between 0.2 MHz and 0.3 MHz, 0.5 MHz and 0.67 MHz, 0.74 MHz and 0.83 MHz, and 1.16 MHz and 1.26 MHz. Drops in transmission also occur for frequencies between 1.5 MHz and 1.65 MHz and for those just above 1.77 MHz. These ranges of reduced transmission are all defined by dotted lines and shaded regions in Fig. 4. For the ΓM direction, we obtain less drops in transmission compared to the ΓX direction, which is due probably to

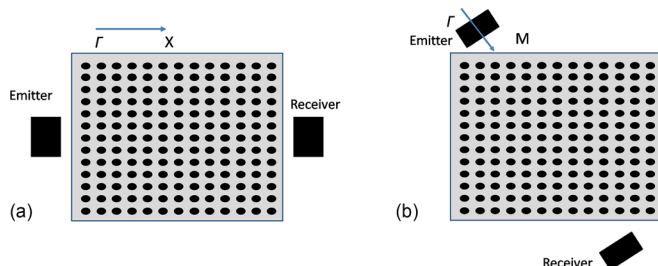


FIG. 2. Position of the transducers and the crystal in (a) the ΓX direction and (b) the ΓM direction.

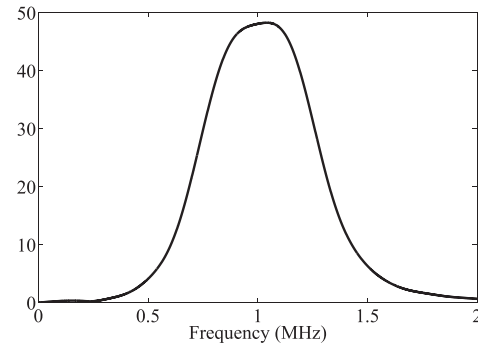
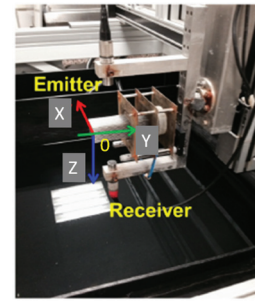


FIG. 3. (Top) Photograph of through-transmission underwater the experimental setup using Polar/C-scan equipment configured for pulsed ultrasound. XYZ are the axes of motion of the polar scan robot. Both the transducers and the sample move in the X direction of the robot fork which starts from the origin “O.” (bottom) Frequency spectra of pulsed transmission between the transducer pair of 1 MHz central frequency.

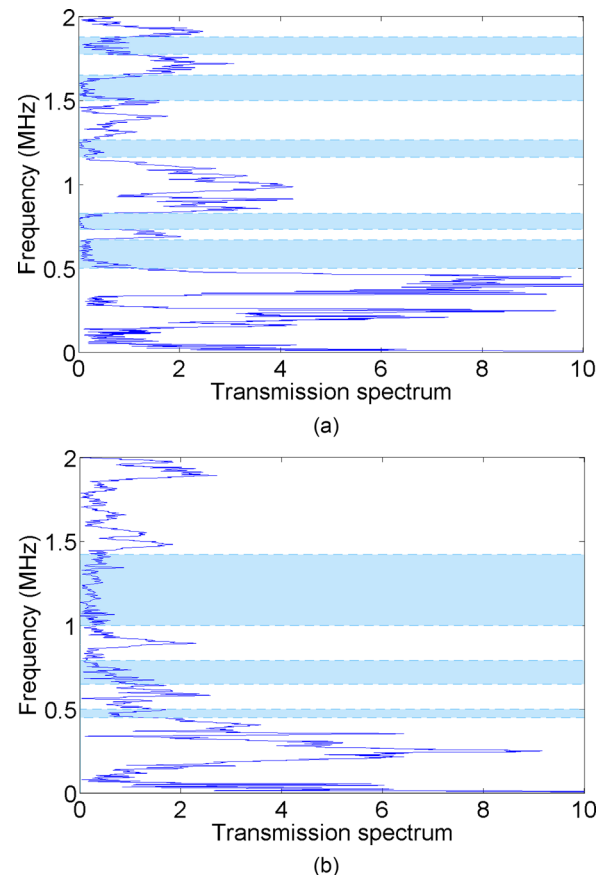


FIG. 4. Through-transmission spectra results from pulsed ultrasound in the (a) ΓX and (b) ΓM directions using the FFT in still water.

the lattice constant which is relatively larger than in the ΓX direction, and therefore, the filling fraction (i.e., $\pi d^2/4a^2$) becomes quite small. The band structure of the phononic crystal is calculated using the finite element method for ΓX and ΓM in the reduced Brillouin zone using Comsol Multiphysics software. Steel parameters taken for computations are $\rho = 7850 \text{ kg/m}^3$, Young modulus $E = 205 \text{ GPa}$, and Poisson ratio $= 0.28$. Figure 5 shows the band structure for the infinite PC composed of periodic steel rods in the water matrix with a square lattice in both directions ΓX and ΓM , respectively, irrespective of whether shear is included or not.

The material parameters of the PCs are the density $\rho = 7850 \text{ kg/m}^3$ and the sound speed of the longitudinal wave as 6100 m/s for steel; $\rho = 1.25 \text{ kg/m}^3$ and $V = 1480 \text{ m/s}$ for water. The geometrical parameters are the lattice constant $(a) = 2.52 \text{ mm}$ for the ΓX direction and a $\sqrt{2}$ for the ΓM direction, and the rod width $d = 1.2 \text{ mm}$. Blue lines indicate the deaf modes (modes that do not contribute to the transmission of the waves through the crystal) which are not excited here. One can observe that there are 7 bands in the frequency range of 0–2 MHz for the ΓX direction, which correlates with the experimental result shown in Fig. 4(a), and only 2 bandgaps for the second direction which correlates with the experimental result shown in Fig. 4(b).

After the crystal bandgap characterization, the influence of flow speed changes in the spectrum is investigated. The flow-speed is actually the relative speed of still water with respect to the moving PC and transducers and is controlled by the controller motion of the scanner, i.e., the whole PC with transducers is placed in relative motion to the water (X axis in Fig. 3), therefore creating a water flow through the PC. A series of measurements are done every 5 mm along (1) the perpendicular and (2) oblique directions (as shown in Fig. 2) to the rod orientation, for a full length of 100 mm. Different temporal waveforms are then obtained and recorded while gradually changing the water velocity ranging from 0.3 mm/s to 7.2 mm/s. To ensure measuring in a stable situation and to avoid transient effects, we have chosen the averaged 14 waveforms at the middle points of the scan at around 35 mm–70 mm from the position indicated by “O” in Fig. 3. First, to have a reference dependent velocity and to check the repeatability, the measurements are done without the PC and with moving water. In Fig. 6, the FFT spectrum for the low and high velocities is plotted.

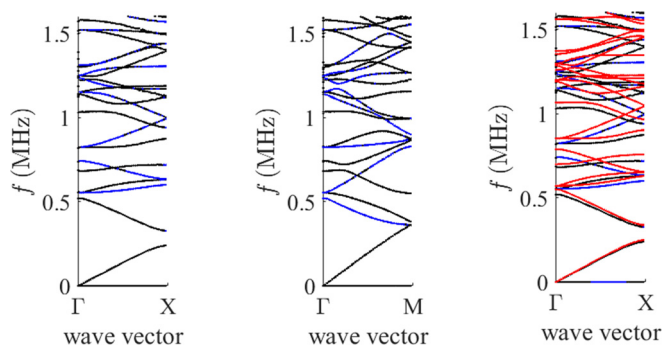


FIG. 5. Band structure of the two-dimension PC along the ΓX and ΓM directions, respectively. Blue lines indicated the deaf modes which are not excited, and red lines indicate when shear is included.

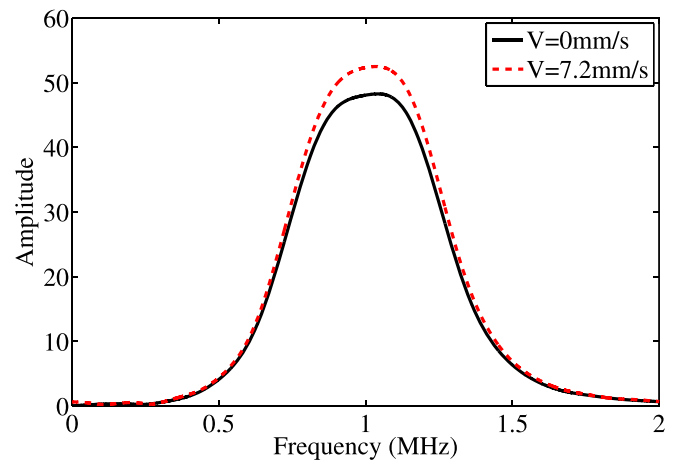
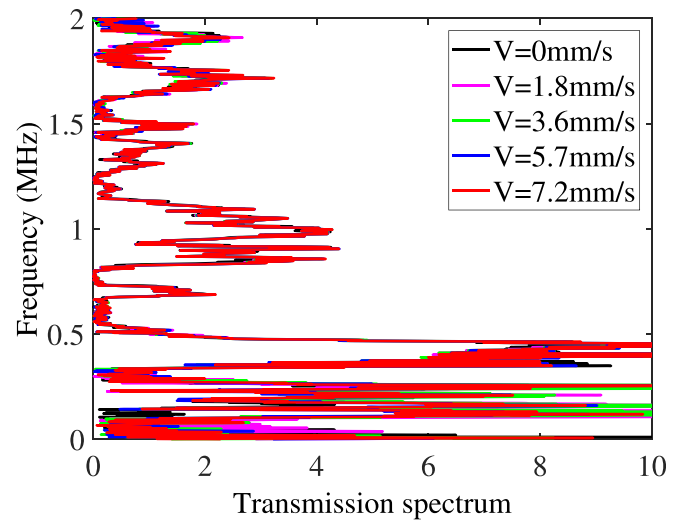
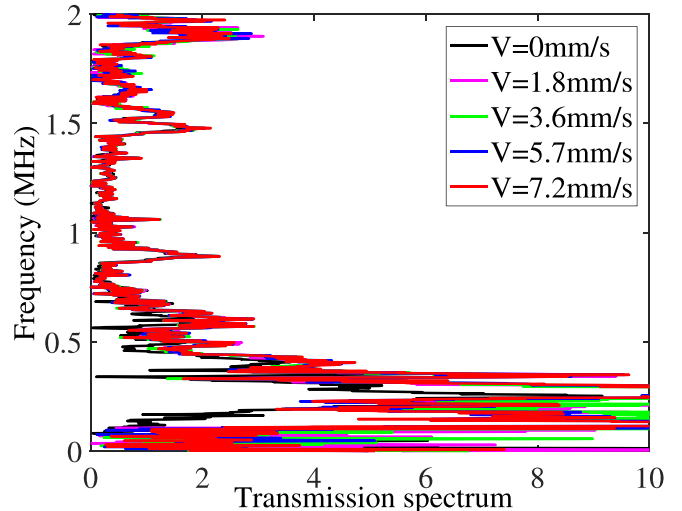


FIG. 6. Frequency spectra of pulsed transmission between the transducer pair of 1 MHz central frequency in still water (solid line) and in moving water (dashed line).

The results show that for measurements at velocities $V = 0 \text{ mm/s}$ and $V = 7.2 \text{ mm/s}$, the same results are found in amplitude and phase. As a matter of fact, the results represent the transducer characteristics and appear uninfluenced



(a)



(b)

FIG. 7. FFT of measured signals using PC in (a) ΓX and (b) ΓM directions for 5 flow speeds.

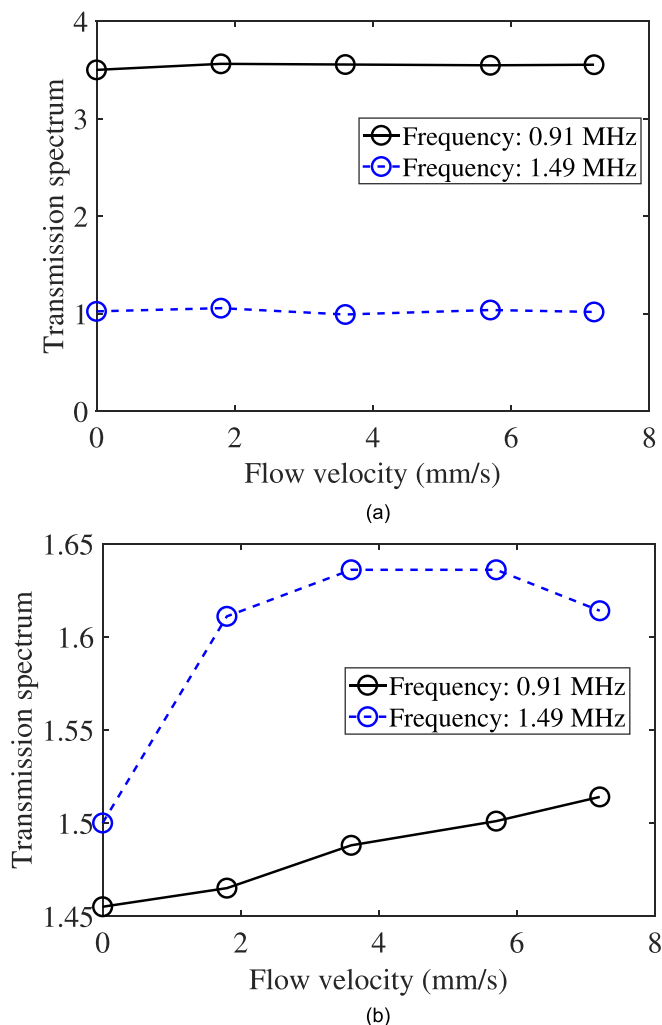


FIG. 8. FFT of measured signals using PC in (a) ΓX and (b) ΓM directions for 0.91 MHz and 1.49 MHz, respectively.

by the low speeds of water. The question is now if a similar conclusion is possible in the case of PCs. The answer is not automatically obvious as sound waves scatter inside the PC and may therefore represent a larger propagation path which may have a cumulative effect even in cases where a Doppler shift is not immediately expected, resulting in direction changes of the sound waves and therefore perhaps in changes of the through transmitted spectrum of the PC. Therefore, next, the PC is placed in between the two transducers, and the experiments are repeated for both ΓX and ΓM directions. The normalized FFT for both cases is plotted for 5 velocities in Fig. 7(a) for ΓX and Fig. 7(b) for ΓM directions, respectively. The spectrum is represented between approximately 0.5 MHz and 1.6 MHz which corresponds to the spectrum of the used transducers.

For more clarity, we plotted the spectrum vs the flow velocity at 0.91 MHz and 1.49 MHz frequencies for both directions (see Fig. 8).

The results indicate first, as expected, that the phononic crystal influences the transmission of sound and gives rise to

significant spectral changes when compared to the reference case. Second, the observed spectrum for the ΓX direction is not visibly influenced by the fluid flow-speed, whereas that in the ΓM direction is moderately. The band structure appears stable. Third, at selected transmitted frequencies, a clear influence caused by the studied low flow speeds appears, as can be seen in Fig. 8.

The observation that the flow velocity alters the amplitude very slightly in the spectrum can probably be understood by flow pattern changes within the PC as a function of speed or by minor acoustic ray bending effects that are exaggerated by internal scattering within the PC, particularly for the ΓM direction and influencing the constructive and destructive spectral interference patterns within the crystal which are so deterministic for the “Bragg mechanism,” leading to a spectrum as in Fig. 4.

The actual bandgap structure does not appear to alter as the effect caused by the liquid flow is not drastic, which makes the PC filter properties stable. Minor changes in transmission amplitude are correlated with liquid speed and can possibly be exploited as a speed measurement mechanism. It is beyond the scope of this report, which presents a short proof of concept on what may change in the transmission spectra through phononic crystals, to try to explain the entire physical process combining fluid dynamics and acoustics. The contribution of fluid flow patterns is expected to have a non-scalable effect on the observed phenomena that may give rise to the use of multiple phononic crystals with different periodicities for the accurate liquid flow measurement. Such investigations may be performed in future long-term projects and might therefore be of further interest not only to acousticians but also to researchers in fluid dynamics.

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