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Numerical and Experimental Study of a Phononic-Fluidic Sensor Using a Cubic Unit Cell with Spherical Void

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Abstract—This paper presents a design study of a phononic-fluidic cavity sensor to measure volumetric properties of different liquids. A 3D finite element model shows that the sensor performance drastically depends on the lattice constant of a phononic crystal unit cell. As a result, the numerical model predicts the quality factor up to 200. As proof of concept, we fabricated several sensors using microstereolithography printing, and performed their experimental characterization. We achieved a good match of resonance frequency in the numerical model and experiments. Our experimental results displays a quality factor up to 55, and clearly separated resonance frequencies for different liquids in the cavity, with frequency shifts corresponding to differences in density and speed of sound.

Index Terms—3D phononic crystals, 3D printed phononic-fluidic cavity sensor, finite element method, additive manufacturing.

I. INTRODUCTION

A phononic crystal (PnC) is a periodic arrangement of scattering centers in a surrounding matrix with a large acoustic mismatch [1]. The most appealing feature of this material is a strong band gap (BG), which prohibits acoustic and elastic wave propagation in certain frequency ranges [2]. Bands gaps in PnCs appear due to Bragg scattering and local resonances. Moreover, the existence of BGs opens for PnCs a variety of applications, e.g. as vibration and noise insulators [3,4], acoustic filters [5], waveguides [6] and sensors [7].

Over the last twenty five years, a wide variety of 1D and 2D PnCs have been studied and experimentally realized. Nowadays, with the help of additive manufacturing techniques, complex three-dimensional PnCs can be rapidly fabricated [8], achieving extraordinary band gaps [9].

Our sensor is a combination of a fluidic cavity resonator with phononic layers around it. The phononic structures around the cavity effectively improve the boundary conditions of the cavity resonance, drastically increasing quality factor and resolution. This concept was demonstrated in one- and two-dimensional arrangements [10-15]. Additionally, this concept was implemented in three-dimensional arrangements [16-17]. Recently, we have shown [18] that a change in design parameters of a phononic-fluidic sensor has strong influence on its performance. In this work, with the help of numerical simulations and experimental characterization, we investigated the influence of a PnC lattice constant on the characteristics of a sensor.

II. SENSOR CONCEPT, DESIGN AND FINITE ELEMENT MODEL

A. Design of phononic unit cell and sensor element

The PnC used in this work is based on a simple cubic unit cell with a spherical cutout (Fig. 1a). As the design parameters for a single unit cell, we consider the lattice constant $a$ and the diameter of a spherical cutout $d$. In this study, we defined $d = 1.3a$. In order to build a sensor element, we structured the PnC (green colour) around a rectangular cavity (orange colour) with thin solid walls on all sides except the top as it is shown in Fig. 1b.

The cavity can be characterized by its width $w$ and the wall thickness. The cavity wall thickness can be expressed through the lattice constant $a$ and the cavity width $w$ as $(a - w)/2$.

The main goal of this research is to investigate how a PnC with different lattice constant will influence the performance of a phononic-fluidic cavity sensor. By performance we understand the quality factor of a cavity resonance peak and its frequency shift between liquids with different speeds of sound.
B. Numerical Analysis

To carry out this study, we established a coupled acoustic-mechanical finite element (FE) model using commercially available software COMSOL Multiphysics 5.6. In order to compare numerical and experimental results, we have to consider a finite structural model, which represents the actual sensor element. Since the full 3D multiphysical FE model with a long frequency sweep is computationally demanding, we decided to take advantage of mirror symmetry and cut a quarter model. However, we compared this quarter model with a half-model and found only minor differences.

For our numerical experiments we analyzed two models with $a = 5 \text{ mm}$ and $w = 4.5 \text{ mm}$ (Fig. 2a), as well as $a = 1.5 \text{ mm}$ and $w = 1.1 \text{ mm}$ (Fig. 2b).

Our model evaluates the transmission through a sensor cell. Here, under transmission we assume the ratio between surface averaged velocity amplitudes at receiver and emitter respectively. Contact with the emitter and receiver to excite and detect transmitted waves is modelled as a low-reflection impedance boundary condition with the effective transducer surface impedance.

The model is meshed finely enough to capture the minimum wavelength encountered in this study. As a rule of thumb, this required eight elements per lattice constant ($a$). Thus, the maximum element size is set as $a/8$.

We model the solid domains of the sensor as an acrylic plastic based on the 3D-printed resin material used in our experiments. As liquids we used DI-water and 2-propanol. All material properties are summarized in Table I.

In addition, we applied an isotropic loss factor for acryl to account for material losses and viscoelastic effects. For the fluid domain we utilize a viscous model taking into account dynamic and bulk viscosity. Our results are shown in Fig. 3.

As our model demonstrates, there are two clearly separated peaks from each other. The resonance peaks are sensitive to changes in speed of sound ($\Delta f_r \sim \Delta v/2w$) of the liquid inside the cavity. The quality factor ($Q$) of resonance peaks can be calculated as $Q = f_r/\delta f$, where $\delta f$ is the full width at half maximum of a resonance peak. Viscosity of a liquid is a key factor, which influences on a $Q$-factor. Since the bulk viscosity has almost the same values for DI-water and 2-propanol, we observe the same $Q$-factors for those liquids. Two designs display different $Q$-factors. For a lattice constant of 5 mm the $Q$-factor is approximately 35. However, for a lattice constant of 1.5 mm the $Q$-factor is 200. This drastic mismatch between two quality factors appeared for several reasons: smaller total transmission path of the sensor, smaller cavity volume, thinner cavity walls, and larger PnC lattice in perpendicular directions.

III. Fabrication and Measurements

We fabricated all sensor cells (Fig. 4) with a high-resolution microstereolithography printer (Asiga MAX-X35UV), using an acrylic polymer resin (FusionGRAY v.2).

After fabrication, the sensor cells were carefully rinsed and dried. As a final step, they were placed in an ultraviolet chamber, in order to fully cure the samples and increase their hardness.
We measured the transmission between two wide-band longitudinal ultrasonic transducers (Olympus V-101-RM) with a center frequency of 500 kHz. The sensor element is clamped between the transducers using a coupling gel. Moreover, the transducer are placed on XYZ alignment stages as it is depicted in Fig. 5.

We performed measurements with a high-precision lock-in amplifier (MFLI, Zurich Instruments AG, Switzerland), connecting the transducers as emitter to the output signal and as receiver to the lock-in input. The emitter is driven with an amplitude of 200 mV. We sweep the reference frequency and measure the amplitude at the receiver. We defined the transmission as a ratio of voltage amplitudes at receiver and emitter. A frequency step for all measurements is set at 200 Hz.

Our measured transmission spectra (Fig. 6) are in a good agreement with the simulated ones. The small deviation of resonance frequencies appeared because of minor differences of material parameters and the influence of clamping forces. The sensor with a PnC lattice constant of 1.5 mm shows the Q-factor of 35 for 2-propanol and DI-water. For 50% vol. 2-propanol aqueous solution the Q-factor is 40. For the sensor with a PnC lattice constant of 5 mm, the quality factor is 55 for 2-propanol and 40 for the other liquids.

As we expected, the frequency shift between water, 2-propanol, and its 50% vol. aqueous solution is proportional to the difference between the speed of sounds of those three liquids [20].

The resonance frequency of 50% vol. 2-propanol solution is closer to the resonance frequency of DI-water for both sensors because of the speed of sound in 50% solution is 1427 m/s. Thereby, for both sensors between DI-water and 50% vol. 2-propanol solution we observe the relative frequency shift of 3.8%, and 32% between DI-water and 2-propanol.

However, we can observe significant difference between the quality factors of resonance peaks in Fig. 6a. We assume that this mismatch can be caused by curved cavity walls and some fabrication aspects such as a change of the thickness of cavity walls. Moreover, another reason of this divergence is that in our numerical model we did not take into account losses on the coupling between transducers and a sensor element. Thereby, this problem requires extra investigation such as improving the fabrication process, in order to minimize the curvature of cavity walls. In addition, we are planning to include the losses on coupling in our numerical model, using measured data from the characterization of transducers.

Furthermore, to reduce the volume of a liquid sample, the lattice constant $a$ and the cavity width $w$ can be decreased, while increasing the interrogating frequency. However, fabrication and experimental characterization of smaller sensor cells might be a challenge due to the limits of our 3D-printer.

**IV. CONCLUSIONS**

We have presented selected results from our systematic study of the lattice constant influence on the performance of a phononic-fluidic cavity sensor. The dependence of the fluid cavity resonance frequency on speed of sound was demonstrated theoretically and experimentally. Moreover, as we have shown, even variation of a single parameter, a lattice constant, can change a quality factor of a resonance peak drastically. As a result of our study, we numerically obtained a quality factor of 200 and experimentally up to 55. However, mismatch between our experimental and computed results requires additional investigation. Besides continuation of the systematic design study, our future work will be focus on structural and topology optimization of phononic-fluidic sensors, in order to enhance their performance.
REFERENCES


