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Designing Novel MEMS Cantilevers for Marine Sensing Robots Using COMSOL Modeling and Different Piezoelectric Materials †

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Abstract: The present work presents an innovative marine sensing robotics device based on piezoelectric cantilever-integrated micro-electro-mechanical systems (MEMS) modeled on the approach of fish lateral lines. The device comprises 12 cantilevers of different sizes and shapes in a cross-shaped configuration, embedded between molybdenum (Mo) as electrodes in a piezoelectric thin film ($PbTiO_3$, $GaPO_4$). It has the advantage of directional response due to the unique design of the circular cantilevers. In COMSOL software, we designed, modeled, and simulated a piezoelectric device based on a comparative study of these piezoelectric materials. Simulations were performed on cantilever microstructures ranging in length from 100 um to 500 um. These materials perform best when lead titanate ($PbTiO_3$) is used. A maximum voltage of 4.9 mV was obtained with the $PbTiO_3$ material cantilever with a displacement of 37 um. A laser-Doppler vibrometer was used to measure resonance frequency mode and displacement. Simulations and experiments were in good agreement. Its performance and compactness make us envision its employment in underwater acoustics for monitoring marine cetaceans and ultrasound communications. In conclusion, MEMS piezoelectric transducers can be used as hydrophones to sense underwater acoustic pulses.

Keywords: piezoelectric; COMSOL multiphysics; MEMS; $PbTiO_3$; sensitivity

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1. Introduction

Human scientific advancements have always been inspired by nature. The ability of living organisms to encourage the creation of their counterparts has been applied to various sectors by humans [1,2]. Animals obtain information from their environments through these mechanoreceptors and translate it into significant biological signals for survival [3,4]. As an example, the lateral line system of a fish aids it in recognizing external stimuli and responding accordingly. Artificial hair-like sensors in water, such as hydrophones, can be developed by mimicking these natural cilia. Researchers have been investigating biomimetic cilia-based devices using Micro-Electro-Mechanical Systems (MEMS). A piezoelectric hydrophone is an acoustic device that detects underwater sounds and signals; therefore, it is essential in marine resources exploration and sonar systems [6–8].

MEMS cantilevers for underwater acoustic sensors have been demonstrated for marine sensing robotics [9]. This MEMS cantilever forms a directional hydrophone that detects the direction [10–15].

Many researchers have been interested in microelectromechanical systems (MEMS) over the past two decades, particularly in microsensors and actuators. A pressure sensor is one of the most essential among them [16,17]. Nanoscale and microscale devices can be developed efficiently with piezoelectric thin films because of their electromechanical couplings and micromachinability [18,19]. PZT, BaTiO3, ZnO, and PZT thin films are used as surface acoustic wave (SAW) filters, bulk acoustic wave (BAW) resonators, and actuators in MEMS/NEMS systems [20,21]. An acoustic device, the piezoelectric hydrophone, detects underwater noises and signals and is helpful in marine sensors and robotics [22,23]. MEMS flow sensors based on biomimetic mechanoreceptors have been developed [24,25].

COMSOL was used to study the displacement and voltage response of MEMS cantilevers made from $PbTiO_3$ and $GaPO_4$, two piezoelectric materials. Miniaturization, sensitivity, and bandwidth are all critical components of the proposed research.

2. Principles of Bionics and Vibration Picking

In fish, the lateral line contains neuromasts and cilia-based mechanoreceptors. Each of these cilia is covered by a jelly-like cupola located along the body canals or on the surface of the fish. Fig. 1a, 1b, and 1c show bionic representations of fish lateral lines, while Fig. 1d shows schematics of sensing mechanisms.

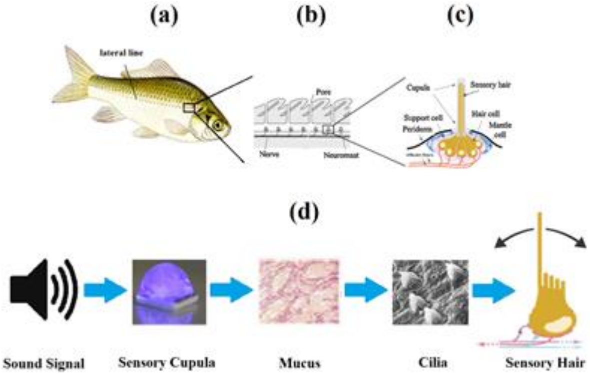


Figure 1. (**a**) Fish' lateral line organ (**b**) Canal structure. (**c**) Neuromast schematic (**d**) Lateral line vibration picking principle.

3. Device Design and Modeling

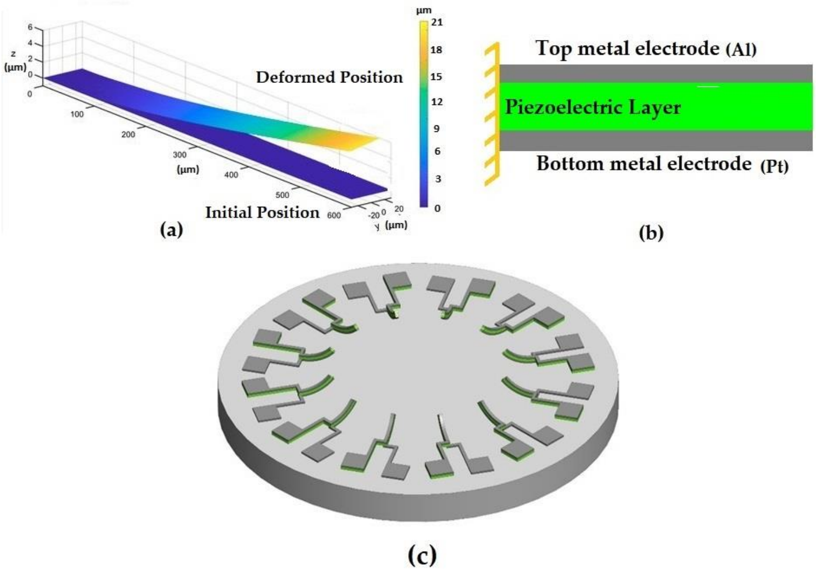
The simulations were carried out using the COMSOL Multiphysics FEM software, implementing the constitutive equations of piezoelectricity. An electrical and mechanical property can be coupled through piezoelectricity. Piezoelectric materials produce electrical charges upon mechanical deformation and vice versa. A stress-charge form of the piezoelectric constitutive equations, also known as "coupled equations," can be found below [10,11].

$$T = s^E\, S - e^T E \tag{1}$$

$$D = e\, S + \varepsilon\, E \tag{2}$$

where S is the strain tensor, s^E is the elasticity matrix, T is the stress tensor, e is the piezoelectric coupling matrix, D is the tensor of electric displacement, ε is the electrical permittivity, and E is the electric field.

$PbTiO_3$ and $GaPO_4$ are used to simulate and compare different piezoelectric materials to determine the best material to use for MEMS cantilevers. We simulate cantilever microstructures between 100 and 500 μm in order to investigate how length affects displacement and voltage response. The behavior of microcantilevers is studied using solid mechanics, electrostatics, and pressure acoustics. Additionally, one end of the cantilever is constrained and the other is free. Static equilibrium exists in each cantilever layer. Each cantilever has a fixed width of 50 μm. There are metal electrodes with a thickness of 200 nm and a piezoelectric thin film of 1 μm on microcantilevers.



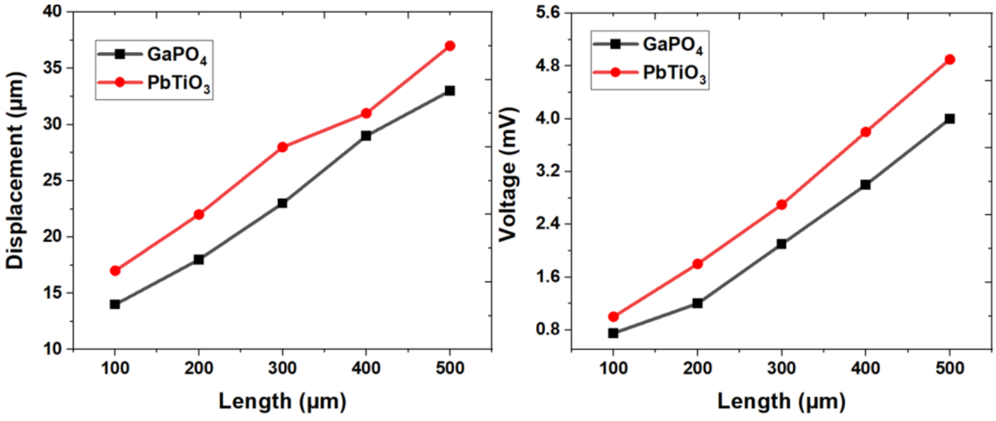
(a) (b)

(c)

Figure 2. (**a**) Simulated microcantilever with the deformed position. (**b**) Side view of microcantilevers. (**c**) Face-to-face configuration.

4. Results

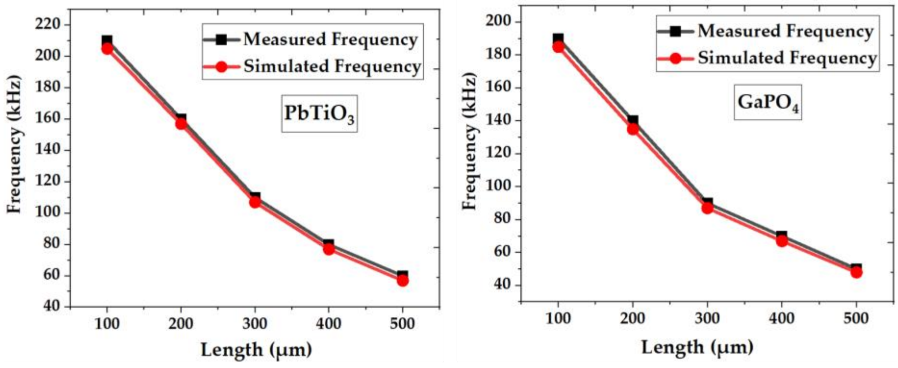
According to the results in Fig. 3, we used COMSOL Multiphysics to determine displacements and potential voltage responses of microcantilevers of different lengths between 100 μm and 500 μm. Simulated results showed that microcantilevers with $PbTiO_3$ had the largest displacements, whereas those with $GaPO_4$ showed the smallest displacements. Further, these microcantilevers showed the most significant potential voltage responses when made from $PbTiO_3$ material.



(**a**) (**b**)

Figure 3. MEMS Piezo-material cantilevers (**a**). Length vs. Displacement (**b**). Length vs. Potential Voltage.

Figure 4 illustrates the measured and simulated frequency response of MEMS cantilevers. It showed that the microcantilvers fabricated with both materials are in good agreement.



(a) **(b)**

Figure 4. MEMS Piezo-material cantilevers, Length vs Frequency (**a**). $PbTiO_3$ (**b**). $GaPO_4$.

5. Conclusions

This work presents the design and modeling of MEMS cantilevers using COMSOL (Multiphysics). In COMSOL, MEMS piezoelectric cantilevers are analyzed using built-in materials properties, thickness, and motion equations. The setup and parameters for the simulation are defined. Based on simulations, $PbTiO_3$ performs best in these piezoelectric materials. The design and optimization of piezoelectric micro-cantilever pressure sensors can be guided by comparative analysis. The amplitude and direction of underwater acoustic pulses can be measured using MEMS piezoelectric cantilevers. In addition to cantilever lengths, cross-configurations are useful for identifying acoustic wave directions.

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Conflicts of Interest: The authors declare no conflict of interest.

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