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Combining COMSOL Modeling with Different Piezoelectric Materials to Design MEMS Cantilevers for Marine Sensing Robotics †

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Abstract: This work presents a novel, highly sensitive, and directional piezoelectric cantilever-based micro-electro-mechanical system (MEMS) device conceived using a biomimetic approach of a fish's lateral line system for marine sensing robotics. The device will consist of twelve cantilevers with different lengths in a cross-shaped configuration made with a piezoelectric thin film (PZT, ZnO, $BaTiO_3$) embedded between the top and bottom metals, Platinum (Pt) and Aluminum (Al), used as electrodes. This unique design of cantilevers in circular shapes has the advantage of directional response. A comparative study of these piezoelectric materials was performed analytically through the finite element method to design, model, and simulate our device in COMSOL software. Cantilever microstructures were simulated with lengths ranging from 100 to 1000 mm. The results show that PZT has the best performance with these materials. The maximum potential voltage was shown as 1.9 mV using the PZT material cantilever with 29 µm displacement.

Keywords: MEMS; piezoelectric; vector hydrophone; sensitivity; PZT; COMSOL Multiphysics

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1. Introduction

Nature has always been an inspiration for human scientific advancements. Some of the vital abilities of living organisms can serve as a rich source of inspiration for humans to create their counterparts, allowing for various applications in different sectors [1,2]. Animals use mechanoreceptors with various structures to acquire information from their surroundings and convert them into important biological signals for their survival [3,4]. A fish's lateral line system, for example, helps it to recognize external stimuli and respond accordingly. Mimicking these natural cilia offers different techniques to design advanced and innovative artificial hair-like sensors as hydrophones in water. Biomimetic cilia-based devices have attracted significant attention from researchers due to the micro-electro-mechanical system (MEMS) technology. The piezoelectric hydrophone is an acoustics device used to detect underwater noise and signals; therefore, it has great importance in marine resource exploration, sonar systems, submarine, and marine sensing robotics [5–8].

An advancement in underwater acoustic sensors was made using MEMS cantilevers for marine sensing robotics [6]. A directional hydrophone was formed with these MEMS cantilevers that detect the direction from which the incoming signal is coming [9,10]. Due to their micrometer size and light weight, these hydrophones can be mounted in autonomous underwater vehicles such as AUVs and ROVs. We can locate enemy submarines, underwater drones, and warships through this microsensor, thus improving our defense [10,11].

Furthermore, this Vector Hydrophone will aid in developing submarine communication systems, sonobuoys, SONARs, fish tracking, oceanographic surveys, and marine life surveys [11].

During the past two decades, micro-electro-mechanical systems (MEMS) have interested many researchers, especially with microsensors and actuators. Among them, pressure sensors are essential [12]. Different types of pressure sensors exist based on various physical properties, such as piezoresistive, piezoelectric, capacitive, magnetic, and electrostatic. Due to their electromechanical coupling and their ability to be micromachined, piezoelectric thin films assist in developing nanoscale and microscale devices [13,14]. The thin films of piezoelectric materials, Barium titanate ($BaTiO_3$), Zinc Oxide (ZnO), and Lead zirconate titanate (PZT), are used in MEMS/NEMS systems as actuators, sensors, surface acoustic wave (SAW) filters, and bulk acoustic wave (BAW) resonators [15,16]. PZT is a promising active material among piezoelectric polycrystalline films due to its interesting properties. It can be easily engineered in shape and geometry, exploiting conventional microfabrication techniques [16].

The piezoelectric hydrophone is an acoustics device used to detect underwater noise and signals; therefore, it has great importance in marine sensing robotics [17,18]. Different mechanoreceptor designs were exploited for biomimetic MEMS flow sensors [19–21]. A piezoelectric directional hydrophone inspired by a fish's lateral line system and based on the AlN functional layer was reported to find the acoustic source direction in the ultrasonic frequency range [10], and a novel directivity pattern was introduced [10].

In this work, we used COMSOL to study the displacement and voltage response of MEMS cantilevers with different piezoelectric materials: Barium titanate ($BaTiO_3$), Zinc Oxide (ZnO), and Lead zirconate titanate (PZT). The proposed work has significant importance in miniaturization, sensitivity, and bandwidth.

2. Bionic and Vibration Picking Principle

A fish's lateral line is a particular sensory organ consisting of cilia-based mechanoreceptors called neuromasts. A jelly-like cupula covers these cilia that are situated in the canals along the body or on the fish's skin. Figure 1a–c illustrate the bionic representation of a fish's lateral line system, while Figure 1d shows a schematic path of the sensing mechanism.

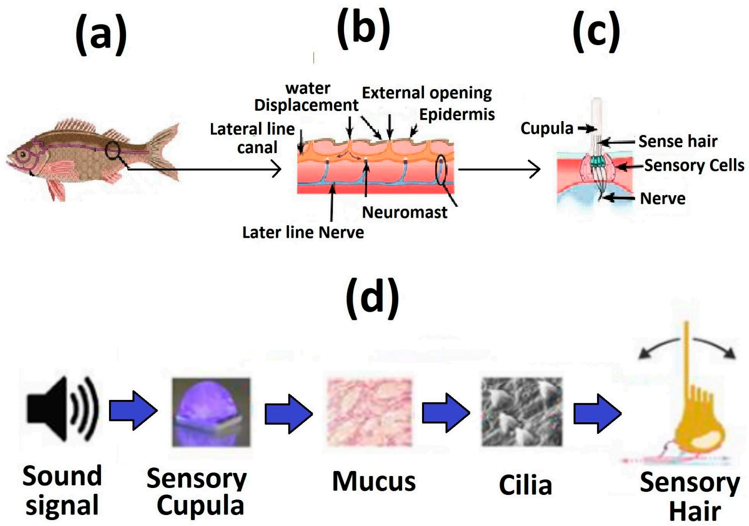

Figure 1. (**a**) Fish's lateral line organ. (**b**) Structure of the canal. (**c**) A schematic of a neuromast [21]. (**d**) Vibration picking principle of the lateral line system.

3. Device Design and Modeling

The simulation was performed using COMSOL Multiphysics FEM software, implementing the piezoelectric constitutive equations. Piezoelectricity is a coupling mechanism relating a material's mechanical and electrical properties. An electrical charge is produced when the piezoelectric material is mechanically deformed and vice versa. The piezoelectric constitutive equations, also known as "coupled equations", are given below [9,10] in the stress-charge form:

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

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

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.

Piezoelectric materials deform when strained by an external force, producing an electrical charge on opposing surfaces [6]. This is because these materials have permanent dipoles. In the presence of differential surface stress on the tip of a cantilever, the displacement z can be expressed as follows [22]

$$Z = \frac{3(1-v)L^2}{T^2 E}\sigma s \tag{3}$$

where L is the length of the cantilever, T is the overall cantilever thickness, ν is the Poisson ratio, S is the differential surface stress, and E is Young's modulus.

Assuming a thin piezoelectric layer is on a thick elastic substrate without external force or movement [23], the relationship between the cantilever tip displacement and the corresponding voltage is written as

$$V = \frac{T^2 E_e}{3d_{31} L^2 E_p} Z \tag{4}$$

Rearrange Equation (4) using Equation (3) and write as

$$V = \frac{E_e(1-v)}{d_{31} E_p E}\sigma s \tag{5}$$

where V is the potential voltage generated with microcantilevers, E_p is Young's modulus of elasticity for the piezoelectric, E_e is Young's modulus and d_{31} is the piezoelectric constant of the piezoelectric material.

Different piezoelectric materials like $BaTiO_3$, ZnO, and PZT were simulated and compared to find the best suitable functional material for MEMS cantilevers. In this design, simulations of cantilever microstructures between 100 and 1000 m were performed to study the effect of length on displacement (Figure 2a) and voltage response. In order to study the behavior of microcantilevers, solid mechanics, electrostatics, and pressure acoustics were used. Furthermore, the following conditions were applied: the cantilever was constrained at one end and free at the other. Each layer of the cantilever was in static equilibrium. All layers were in the form of a solid rectangular shape with equal Length, L, and width, W (Figure 2b). The width of each cantilever was fixed at 50 μm. Microcantilevers have a piezoelectric thin film of 1 μm and metal electrodes of 200 nm thickness. The acoustic–structure interaction and piezoelectric effect of each cantilever were simulated to find the displacement and voltage response of the MEMS cantilevers (Figure 2c). The mesh was composed of 202,168 to 253,278 elements, using free quad and free tetrahedral finite elements.

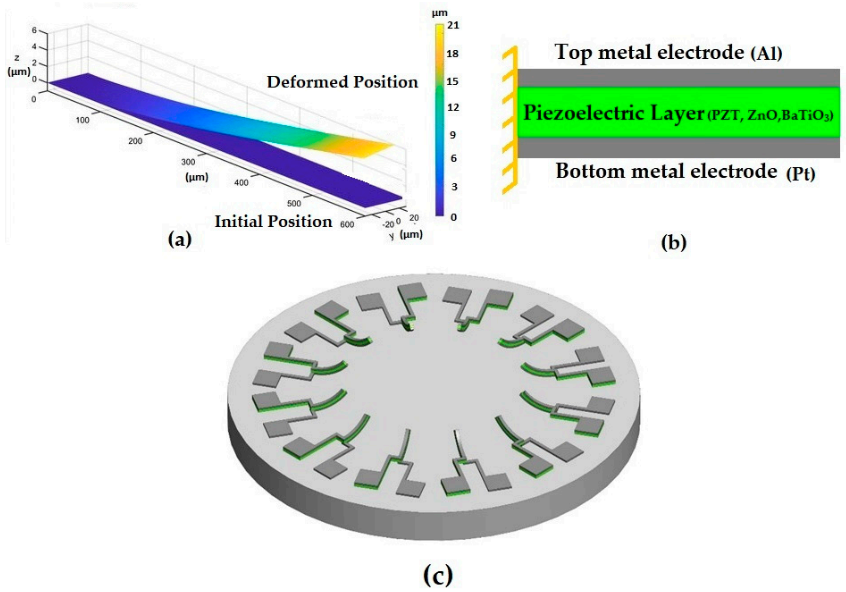

Figure 2. (**a**) Simulated microcantilever with the deformed position. (**b**) Side view of microcantilevers. (**c**) Facet–to–face configuration of the microcantilever.

4. Results

COMSOL Multiphysics was used to analyze the designed 3-D model of microcantilevers with different lengths (100 m to 1000 m) to determine the displacement response and potential voltage response, as shown in Figure 3. The simulated results showed that microcantilevers with PZT had maximum displacement among these piezoelectric materials, while $BaTiO_3$ showed the lowest displacement. Similarly, the potential voltage response of these microcantilevers reached its maximum using PZT material.

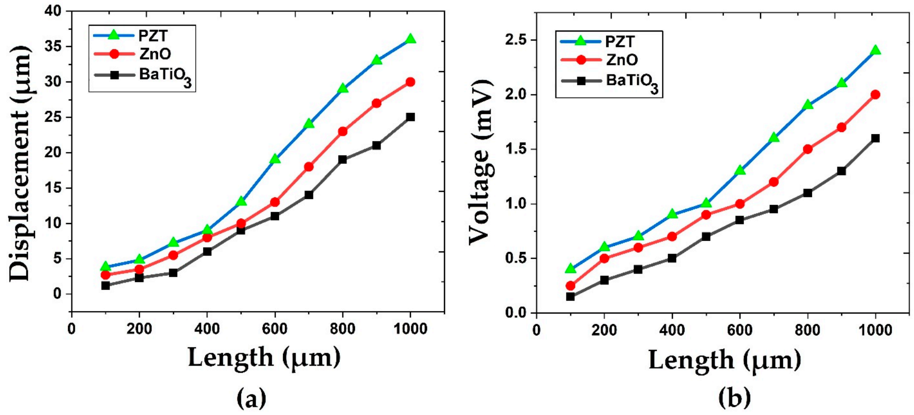

Figure 3. (**a**) Microcantilevers displacement vs. length with different piezoelectric materials. (**b**) Microcantilever voltage response vs. length with different piezoelectric materials.

5. Conclusions

This work designs and models MEMS cantilevers on COMSOL Multiphysics. The COMSOL built-in material properties, thickness, and governing equations were provided for analyzing the MEMS piezoelectric cantilevers. The simulation setups and parameters were defined. Based on the simulation results, PZT performs best in these piezoelectric materials. Simulations can provide guidelines for designing and optimizing piezoelectric microcantilever pressure sensors based on comparative analysis. Therefore, MEMS piezoelectric cantilevers can be used as hydrophones for measuring underwater acoustics for pulse amplitudes and directions. It is possible to identify the direction of acoustic waves via cross-configurations with different cantilever lengths.

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