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

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Abstract: This work presents a novel, highly sensitive, and directional piezoelectric cantilever-based micro-electro-mechanical system (MEMS) device realized by a biomimetic approach of the fish lateral line system for marine sensing robotics. The device will consist of twelve cantilevers with different lengths in a cross-shape configuration made by 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 a finite element method to design, model, and simulate our device in COMSOL software. Cantilever microstructures have been simulated with lengths ranging from 100 to 1000 mm. The results show that PZT has the best performance in these materials. Maximum potential voltage was shown as 1.9 mV by 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 these mechanoreceptors with various structures to acquire information from their surroundings and convert it into important biological signals for their lives [3,4]. A fish's lateral line system, for example, helps it 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 for researchers due to Micro-Electro-Mechanical Systems (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 [6–8].

An advancement in underwater acoustic sensors has been made using MEMS cantilevers for marine sensing robotics [9]. A directional hydrophone is formed by these MEMS cantilevers that detect the direction from which the incoming signal is coming [10,11]. Due to their micrometer size and lightweight, 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 [11,12]. Furthermore, this Vector Hydrophone will aid in developing submarine communication systems, sonobuoys, SONARs, fish tracking, oceanographic surveys, and marine life surveys [12].

During the past two decades, microelectromechanical systems (MEMS) have attracted many researchers, especially microsensors and actuators. Among them, pressure sensors are essential [13]. 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 [14,15]. 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 [16,17]. 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 [17].

The piezoelectric hydrophone is an acoustics device used to detect underwater noise and signals; therefore, it has great importance in marine sensing robotics [18,19]. Different mechanoreceptors designs have been exploited for biomimetic MEMS flow sensors [20–22]. A piezoelectric directional hydrophone inspired by a fish lateral line system based on the AlN functional layer has been reported to find the acoustic source direction in the ultrasonic frequency range [10], and a novel directivity pattern was introduced [11].

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

2. Bionic and Vibration Picking Principle

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

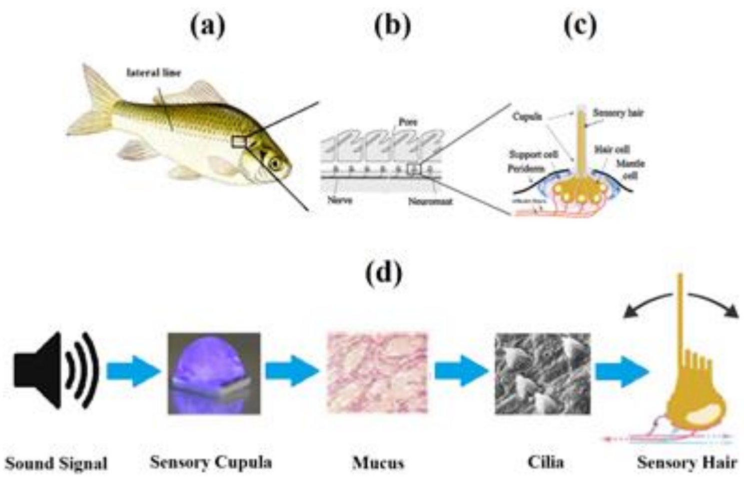

Figure 1. (**a**) Fish lateral line organ. (**b**) Structure of the canal. (**c**) a schematic of neuromast [22]. (**d**) vibration picking principle of the lateral line system.

3. Device Design and Modeling

The simulation has been 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 [10,11] in the stress-charge form:

$$T = s^E S - e^T E \quad (1)$$

$$D = e S + \varepsilon E \quad (2)$$

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 [23]

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

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 module.

Assuming a thin piezoelectric layer on a thick elastic substrate and without the external force or moment [24], the relationship between the cantilever tip displacement and the corresponding voltage is written as

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

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

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

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

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

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 displacement response and potential voltage response, as shown in Figure 2. The simulated results showed that microcantilevers with PZT have maximum displacement among these piezoelectric materials, while $BaTiO_3$ showed the lowest displacement. Similarly, the potential voltage response of these microcantilevers was shown maximum by PZT material.

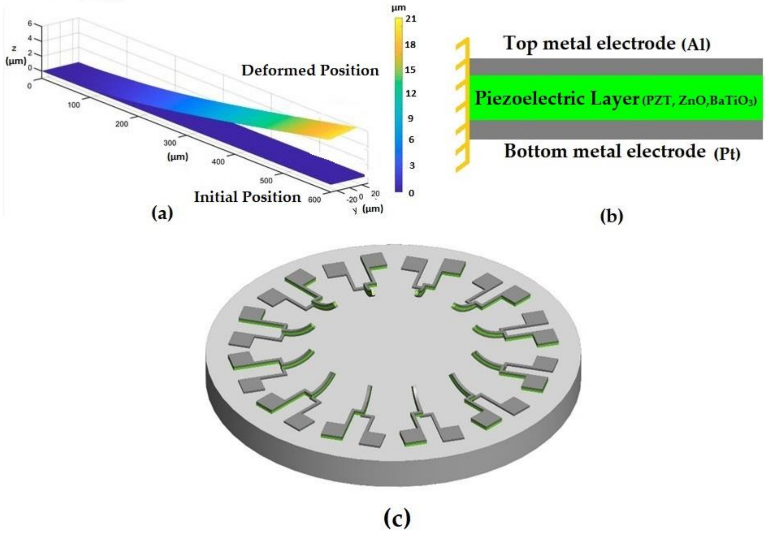

Figure 2. (**a**) Simulated microcantilever with the deformed position. (**b**) Side view of microcantilevers (**c**) Face-to-face configuration of the microcantilever.

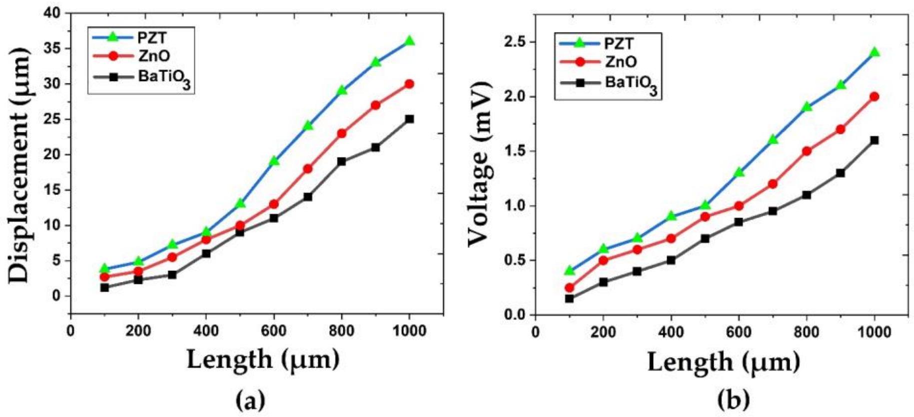

Figure 2. (**a**) Microcantilevers displacement vs. length with different piezoelectric materials (**b**) Microcantilever Voltage response vs. length with different piezoelectric materials.

5. Conclusions

This work designs and models MEMS cantilevers on COMSOL (Multiphysics). COMSOL built-in material properties, thickness, and governing equations are provided for analyzing the MEMS piezoelectric cantilevers. Simulations setup and parameters are defined. Based on simulation results, PZT performs best in these piezoelectric materials. Simulations can provide guidelines for designing and optimizing piezoelectric micro-cantilever pressure sensors based on comparative analysis. Therefore, MEMS piezoelectric cantilevers can be used as hydrophones for measuring underwater acoustics 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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