Piezoelectric MEMS sensor for fish-like underwater sensing

Mohsen Asadnia[1*], Ajay Giri prakash Kottapalli[1,2], Jianmin Miao[1,2], and Michael Triantafyllou[2,3]

[1]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

[2]Singapore-MIT Alliance for Research and Technology (SMART), Singapore

[3]Department of Mechanical Engineering, Massachusetts Institute of Technology, Massachusetts, USA

[*] (Tel: +65-6790 4264; E-mail: asadnia@ntu.edu.sg)

Abstract

Introduction

Continuous sensing of flows and flow generated pressures around the bodies of surface ships and submarines gives a plethora of information which can greatly benefit the maneuverability and object avoidance strategies of the ocean going vehicles [1,2]. Fish that live in a similar environment utilize dense arrays of biological pressure and flow sensors to attain energy efficient maneuvering and to generate a hydrodynamic image of its surroundings thereby creating an artificial vision [3]. In spite of being blind, the Mexican blind cave fish is capable of swimming at high speeds without colliding with any underwater objects just by relying on its velocity and pressure sensors [4]. Trout can detect patterns in turbulent flow just by utilizing its lateral-line. It is believed that the detection of strong vortex structures shed by a vehicle during maneuvering could be utilized to either increase vehicle maneuverability, or decrease the drag associated with rapid maneuvers [5]. Using arrays of micro-pressure sensors it is possible to actively sense the flows around the surface of the vehicle effectively benefiting the maneuverability of the vehicle. This work presents the design fabrication and testing of surface mountable flexible arrays of micro-sized pressure sensors that are fabricated using micro electro mechanical systems (MEMS) technology. The pressure sensors developed in this work are very tiny in size (a foot-print of 1.8 mm × 1.8 mm), inexpensive and can be batch fabricated. In comparison to other MEMS pressure sensors developed in the past [6,7], these piezoelectric pressure sensors are self-powered and therefore do not need any external power supply for them to operate thereby reducing the need for any power supply on the weight constrained AUV body. Although many commercial off-the-shelf sensors were used in the past, these sensors do not meet the requirements of the MEMS pressure sensors designed and fabricated in out clean rooms. The fabricated flexible MEMS pressure sensor arrays are tested on two different platforms to demonstrate two major applications of the sensors. Firstly, the array of sensors was tested on a kayak in a water reservoir to demonstrate the pressure sensing abilities around the body of the vehicle. Secondly the sensors were mounted on an artificial robotic stingray (fabricated in our lab) to determine the frequency of flapping wings which could help in maneuvering the stingray.

Sensor development

The device fabrication scheme employed to develop the piezoelectric sensors, combines MEMS microfabrication technology and the sol-gel method for growth of thin film PZT. The key fabrication process is composed of six main steps, which are shown in figure 1. A thin layer of Ti/Pt (30/300 nm) is sputtered as bottom electrode on the top side of a 4 inch <1 0 0> SOI wafer as shown in figure 1(a). After that, a 3 µm layer of Pb (Zr0.52 Ti 0.48) O_3 (PZT) solution is spincoated on the Pt by sol-gel method, as shown in figure 1(b). In the third step, a thin layer of Cr/Au (20nm/400 nm) is sputtered on top of the PZT layer to form the top electrode. Later on, the top side metal layer is patterned by the lift-off process to form the spiral electrode pattern as shown in Figure 1(c). In order to form the backside through-hole etching, a 10 µm thick patterned photoresist is used as the masking layer. Deep reactive ion etching (DRIE) is performed to release the sensing membrane while the intermediate SiO_2 layer acts as an etch-stop layer to the DRIE process.

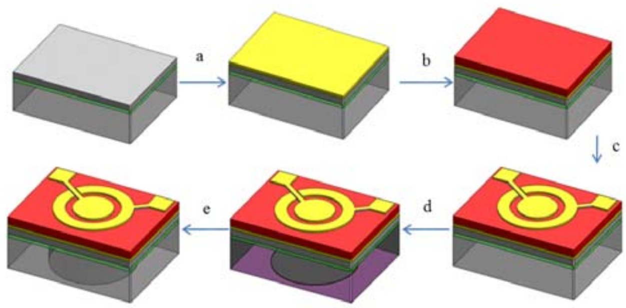

Fig. 1.Fabrication process of piezoelectric pressure sensor. (a) SOI wafer sputtered with Ti/Pt as bottom electrode (b) Sol-gel PZT deposition (c) Cr/Au is deposited as top electrode by sputtering and lift-off patterned (d) Photoresist patterning on the bottom side (e) Backside through-hole DRIE etching.

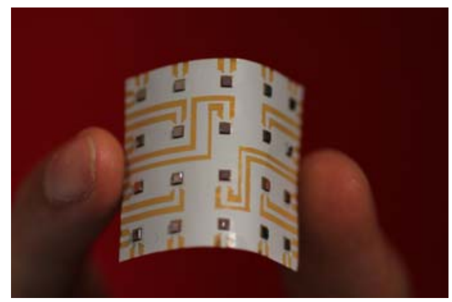

Fig. 2. A photograph of a flexible self-powered array of 20 (5×4) sensors

Sensor testing

A. Testing on kayak

Two arrays of proposed sensor are mounted on two sides of the kayak bow using silicone adhesive and tape. Figure 3 show the arrays of sensor after mounting on the kayak during the real-time experiment in the swimming pool. Wires are extended out from sensors to the data acquisition card, which is mounted in the kayak along with a computer installed with LABVIEW software to employed collecting data.

The kayak is manually pushed up and down about 10 cm in water while data from all 8 sensors of the array are simultaneously recorded. The results of up-and-down test are shown in figure 4. Sensors are found to provide excellent baselines and outputs for all tests without using any filtration or amplification. Variation in peak magnitude between channels could be attributed to a slight difference in depth below the kayak waterline as a result of waves during the motion. Similar experiments are performed for the case of pitch and yaw, each result matches expectations.

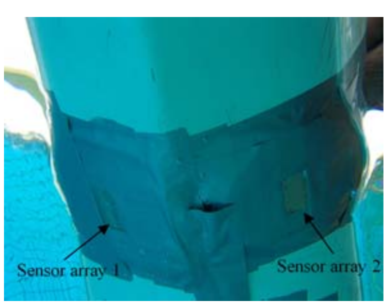

Fig. 3. Sensors are mounted on two sides of a kayak hull

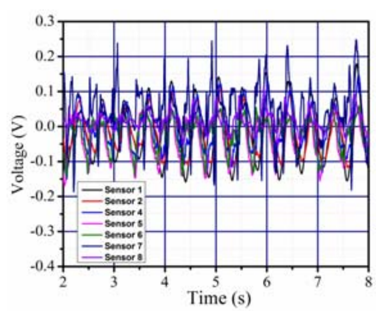

Fig. 4. Testing results from all 8 sensors of an array

B. Testing on stingray

Two sensors are mounted one each on the flaps of the stingray as shown in figure 5. When the motor controlled fins flap up and down in water, the sensors can sense the exact flapping frequency, phase different between individual fin flapping and the amplitude of flapping.

Fig. 5. Sensors are mounted on two fins of a robotic stingray

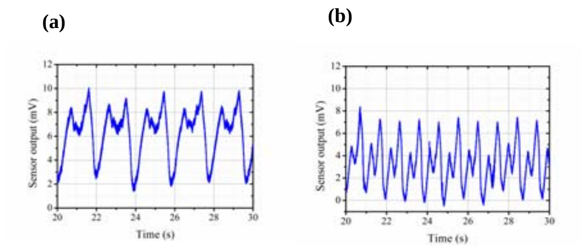

Fig. 6. Testing results of flapping of the fins at (a) 0.5 Hz and (b) 1 Hz

Conclusion

Arrays of flexible miniatured self-powered MEMS sensors are developed for flow sensing around the bodies of underwater vehicles. The sensors developed are tested for two different applications (on bodies of kayaks and a robotic stingray) and shown to have performed extremely well.

Number of words (excluding references): 1000

References

[1] V. I. Fernandez et. al., "Lateral-line inspired sensor arrays for navigation and object identification," *J. Marine Tech. Soc.*, vol. 45, pp. 130-146, 2011.

[2] V. I. Fernandez, S. M. Hou, F. S. Hover, J. H. Lang and M. S. Triantafyllou "Lateral-line inspire MEMS-array pressure sensing for passive underwater navigation parts I and II," in *Proc. 15th International Symposium on Unmanned Untethered Submersible Technology* New Hampshire, August 19-22, 2007.

[3] J. C. Montgomery, S. Coombs, and M Halstead, "Biology of the mechanosensory lateral line in fishes," *Rev. Fish Biol. Fisher.*, vol. 5, pp. 399-416, 1995.

[4] J. C. Montgomery, S. Coombs, and C. F. Baker, "The mechanosensory lateral line system of the hypogean form of *Astyanax fasciatus*," *Evol. Biol. Fish.*, vol. 62, pp. 87-96, 2001.

[5] V. Fernandez, J. Dusek, J. Schulmeister, A. Maertens, S. Hou, K. Srivatsa, J. Lang and M. S. Triantafyllou "Pressure sensor arrays to optimize the high speed performance of ocean vehicles" *11th Int. Conf. on Fast Sea Transportation (July) pp 1–8*, 2011

[6] S. Peleshanko et.al., "Hydrogel-encapsulated microfabricated haircells mimicking fish cupula neuromast," *Adv. Mater.*, vol. 19, pp. 2903-2909, 2007.

[7] N. Chen, C. Tucker, J. M. Enge, Y. C. Yang, S. Pandya and C. liu "Design and characterization of artificial haircel sensor for flow sensing with ultrahigh velocity and angular sensitivity,", *J. Microelectromech. Syst.* Vol. 16, pp. 999-1014, 2007