HARBOR SEAL INSPIRED MEMS ARTIFICIAL MICRO-WHISKER SENSOR

A.G.P. Kottapalli[1*], *M. Asadnia*[1], *H. Hans*[1], *J.M. Miao*[1], *and M.S. Triantafyllou*[2]
[1] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
[2] Department of Mechanical Engineering, Massachusetts Institute of Technology, Massachusetts, USA

ABSTRACT

Harbor seal whiskers possess a unique geometry along the length of the whisker which is believed to suppress vortex induced vibrations (VIV) in frontal flows. This paper presents the design, fabrication and experimental underwater characterization of a MEMS artificial whisker sensor. A bio-inspired artificial whisker fabricated by stereolithography is installed on a piezoelectric MEMS sensing membrane. Experimental results demonstrate that the whisker sensor is able to detect minute disturbances underwater with a velocity detection limit as low as 193μm/s.

INTRODUCTION

Unmanned underwater vehicles (UUVs) employ a plethora of sensors to achieve various purposes of control and feedback while maneuvering underwater. A major topic of research in the past few decades in this area is to develop sensors and sensory systems that could equip the UUV with an ability to intelligently assess its environment [1]. Most UUVs are space-constrained with limited inner volume and highly limited payload energy with utmost need to maintain neutral buoyancy. Therefore, there is a high demand for sensors that are light in weight, inexpensive, low-powered and small in size and could envision flows around the bodies of the vehicles and identify the underwater surroundings and thereby generate artificial vision. Sonar and optical methods have been used in the past to meet this purpose, but they suffer from serious disadvantages. They work fundamentally based on an active sensing principle and are large sized and heavy-weight systems, which often suffer poor resolution of detection in certain murky underwater conditions [2].

Some of the biological sensors found in nature portray the best designs with incomprehensible features. It has been found that even when visual and auditory senses are blocked, some pinnpeds are capable of tracking minute water movements such as those left in the wake of a fish [3]. Blind cave fishes demonstrate an exceptionally skilful ability of being able to swim at high speeds without colliding any surrounding underwater obstacles [4]. Relying on the lateral-line of pressure-gradient sensors, they are able to constantly monitor their surroundings and achieve energy-efficient maneuverability [5]. Some underwater animals like dolphins and tooth-whales use echolocation. Harbor seals neither have lateral-lines nor do they use echolocation, but they operate under similar conditions by depending on their highly sensitive whiskers (vibrissae) to track their surrounding objects [6]. While swimming, using their whiskers, harbor seals are able to detect water disturbances and perform hydrodynamic trail following [6]. More interestingly, the harbor seal whiskers possess a unique geometry along the length of the whisker (Figure 1) which is believed to suppress vortex induced vibrations (VIV) in frontal flows [6]. Figure 1 shows the photographs of the real seal whisker and the artificial whisker fabricated in this work.

Figure 1: Optical photograph of the real seal whisker (center) and the artificial whisker (left and right) fabricated in this work.

Owing to their small size, light weight, low power consumption, bio-inspired arrays of MEMS flow sensors could be an ineluctable alternative to existing sensing technologies used on UUVs. In the past, a number of ultrasensitive flow sensors have been developed that are inspired by the superficial neuromast flow sensors present on the blind cave fish [7-10]. Most of these sensors feature a standing pillar structure (haircell) that extends into the surrounding flow [11]. The deflection in the haircell generated by an external disturbance is recorded as a voltage signal employing piezoresistors embedded at the base of the haircell. Such sensors employing cylindrical standing pillars that protrude into the flow experience noise generated by the VIV of the pillar. However, despite its significance, a MEMS flow sensor employing an artificial micro-whisker has never been developed before. In this work, we present the design, fabrication and characterization of a self-powered MEMS micro-whisker sensor that is inspired by the harbor seal whisker. Micro-whiskers that feature undulations similar to those present on the real harbor seal whiskers are developed.

BIO-INSPIRED MEMS WHISKER SENSOR DESIGN

The structure of the MEMS whisker sensor developed in this work consists of two major parts – the artificial micro-whisker fabricated by stereolithography (SLA) and the piezoelectric $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT) MEMS sensing base fabricated by conventional microfabrication technologies. A schematic of the sensor structure is illustrated in figure 2. The artificial whisker mounted at the center of the PZT membrane extends into the external flow and responds to disturbances in water. Any flow disturbances or variations in the vicinity of the whisker cause the whisker to bend in response, which inturn causes the membrane at the base to buckle. Any displacement in the PZT membrane generates charges that are acquired by tapping voltage signal from the top and bottom electrodes of the PZT layer.

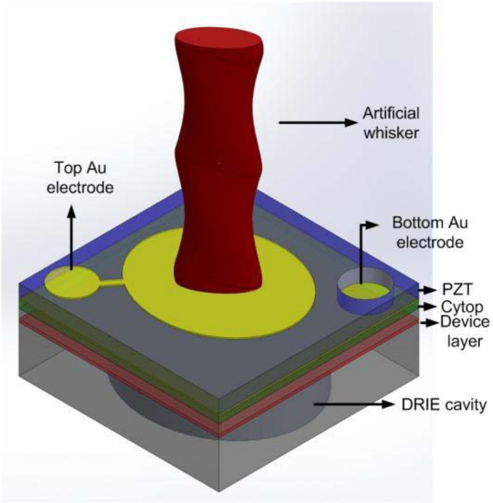

Figure 2: A schematic of the device structure of the artificial harbor seal whisker sensor developed in this work.

WHISKER SENSOR FABRICATION

The artificial micro-whisker and the PZT MEMS sensing base are fabricated separately and then assembled together. A polymer micro-whisker with dimensions similar to that of the real seal-whisker is fabricated by stereolithography (SLA) process. The whisker structure has a unique undulatory geometry which is almost impossible to fabricate using most conventional microfabrication technologies. It is extremely cumbersome to develop high-aspect SU-8 micro-structures that have continuously varying spatial features in the structural geometry. SLA is a very simple and promising technology to generate such structures with features varying along all the three dimensions. Three-dimensional models of a section of the seal whisker are created in Solid Works. The micro-pillar haircells are fabricated from Si60 polymer material on a built-in high resolution SLA VIPER machine. The designed 3D model is then sliced into a series of 2D layers of equal thicknesses which are executed to control an X-Y stage containing the UV curable Si60 solution. The high-aspect micro-pillars are formed by scanning a 355nm UV beam of spot size 0.01mm on the liquid monomer Si60 polycarbonate raisin, curing the raisin into a solid polymer structure layer by layer, and stacking all layers together.

The key fabrication steps for the piezoelectric sensing-base include a low-temperature bonding using Cytop, integration of the PZT layer on the silicon substrate, formation of the electrode interconnects and pads, chemical-mechanical-polishing, wet etching of the PZT layer and releasing the diaphragm structure by using the DRIE technique. The PZT sensing-base is fabricated by bonding an SOI wafer (with 20µm thick device layer) to a 300µm thick $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT) plate using a spin-on polymer (cytop) intermediate layer. After which, a 27µm thick PZT plate is formed by chemical mechanical polishing (CMP) of the 300µm thick PZT plate. The PZT plate is sandwiched between two Cr(10nm)/Au(300nm) metal electrodes that form the contact pads. A wet etching of PZT is performed alternatively in diluted HCI:HF and HNO_3 solutions with a photoresist mask to open a window to access the bottom electrode. A sensing membrane is defined by DRIE etching. The detailed fabrication of the PZT sensing base is presented in [12]. Figure 3 depicts a schematic that explains the various layers of the sensing membrane. Figure 4 shows the optical microscopic image of the fabricated device.

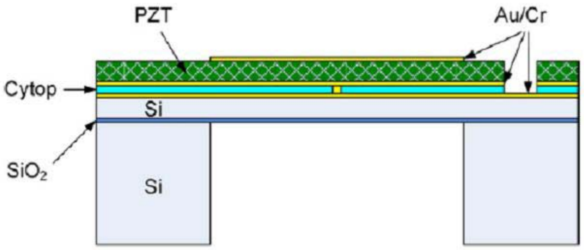

Figure 3: A schematic of the various layers in the sensing membrane formed during the device fabrication.

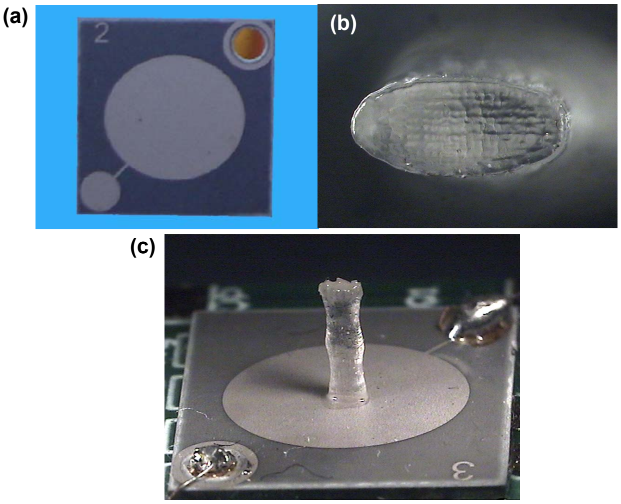

Figure 4: Optical images of (a)PZT membrane with two contact pads on top and bottom faces (b) flat end of the stereolithographically fabricated micro-whisker that is mounted at the center of the PZT membrane employing a precision XYZ control stage (c) PZT whisker sensor with contact pads wire-soldered for testing.

EXPERIMENTAL RESULTS

The goal of the experiments presented in this section is to evaluate the underwater sensing capabilities of the artificial micro-whisker sensor. The performance of the sensor in sensing minute underwater disturbances is evaluated using a vibrating sphere (dipole) stimulus [13].

A stainless steel sphere of 8mm diameter connected to a minishaker (model 4810, B & K, Norcross, GA) through a rod of diameter 2mm forms the dipole stimulus (source). The dipole can be driven from a function generator through a power amplifier and set to vibration of desired frequency and amplitude. The sensor, positioned underwater in the vicinity of the dipole at a distance of 30mm is observed to follow the dipole frequency and amplitude very well. The sensor's output is amplified by a gain of 500 using SRS560 low-noise preamplifier. Figure 5 shows a schematic of the experimental setup used. Figure 6 shows the output of the sensor for a dipole frequency of 10Hz, when the sensor is oriented at 0^0 and 90^0 with respect to the plane of vibration of the dipole.

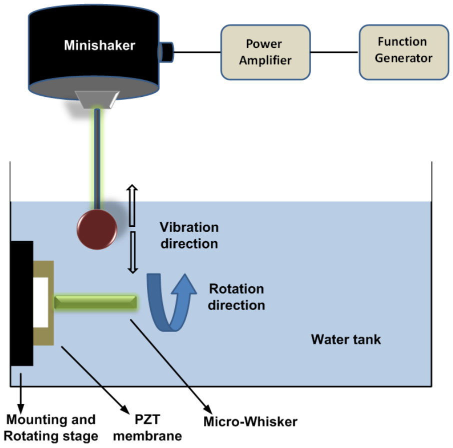

Figure 5: A schematic of the experimental setup used.

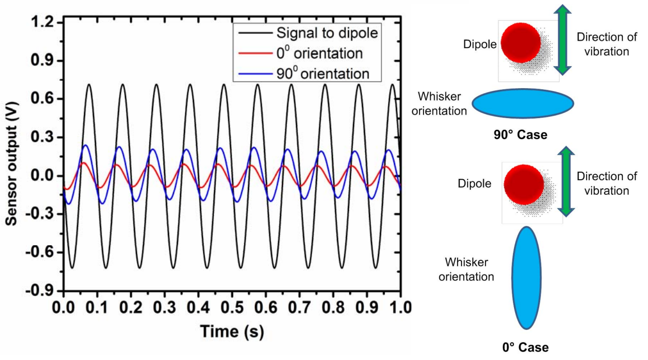

Figure 6 (a)Underwater response of the whisker sensor at 0^0 and 90^0 orientations to the dipole stimulus vibrating at 10 Hz (b)a schematic showing the top-view of the orientation of the whisker with respect to dipole.

In order to determine the resolution of directional sensing, we conducted an experiment where the stage on which the sensor is mounted is rotated in steps, which changes the orientation of the whisker with respect to the dipole. Since the whisker has an elliptical cross-section, at each angle the surface area it projects to the dipole changes and therefore the signal acquired from the PZT sensor changes. The results of this experiment are shown in figure 7.

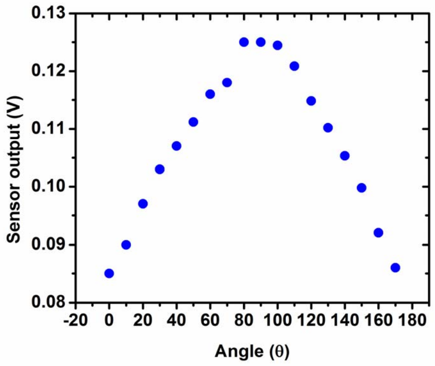

Figure 7: Experimental results showing the directional dependence of the output.

In order to determine the sensitivity and threshold velocity detection limit of the sensor, the velocity of the vibration of the dipole is varied from a very low velocity in the order of a few μm/s to a high velocity of 250mm/s by varying the amplitude of the sinusoidal signal supplied to the dipole. The sensors are mounted in such a way that the dipole moved perpendicular to the long axis of the whisker as described in the experimental setup shown in figure 5. The whisker sensors are tested for a dipole vibrating at constant frequency of 35Hz and varying sinusoidal source signal amplitudes. The signal from the dipole is collected at various velocities, and the peak-to-peak signal amplitude of the sensor output is plotted with respect to velocity in figure 8. The oscillatory flow velocity corresponding to a particular frequency and amplitude of vibration of the dipole is measured using a laser Doppler vibrometer (LDV).

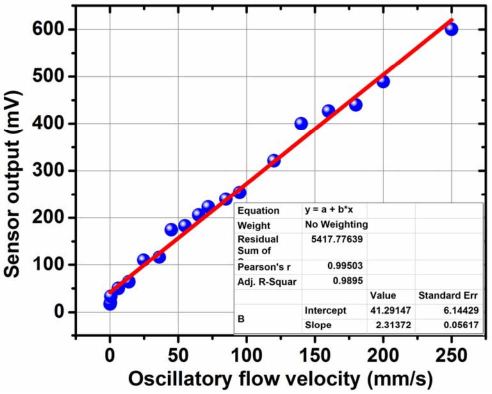

Figure 8: Oscillatory flow velocity sensing by the artificial MEMS whisker in water

The sensor demonstrates a linear response with a threshold velocity detection limit as low as 193μm/s (below which the sensor's output starts to become noisy) which rivals the abilities of the biological harbor seal whisker.

CONCLUSION

Most studies conducted in the literature, mainly focus on the theoretical fluid-dynamic analysis of the whisker geometry and fluid structure-interaction studies, but a functional seal-whisker inspired MEMS sensor has never been developed before. In this paper, the development of an artificial micro-whisker sensor that features a micro-whisker assembled on a MEMS PZT sensing membrane is presented. The three-dimensional simulation analysis conducted shows that the lift-coefficients are significantly higher (~43-times) in case of a cylinder as compared to a real seal-whisker. The underwater oscillatory flow sensing ability of the sensor is experimentally evaluated employing a dipole stimulus. More experiments are in progress to evaluate the VIV suppression abilities of a MEMS haircell sensor with whisker-like undulations on the haircell as compared to the conventional cylindrical haircell flow sensor.

ACKNOWLEDGEMENTS

This research was funded by the Singapore National Research Foundation (NRF) through the Singapore-MIT Alliance for Research and Technology (SMART) Centre, Center for Environmental Sensing and Modeling (CENSAM) IRG.

REFERENCES

[1] H. R. Beem and M. S. Triantafyllou, "Calibration and validation of a harbor seal whisker-inspired flow sensor," *Smart. Mater. Struct.,*vol. 22, p.014012, 2013.

[2] Y. C. Yang et.al., "Distant touch hydrodynamic imaging with an artificial lateral line," *Proc. Natl. Acad. Sci. USA,* vol.103, pp. 18891-18895, 2006.

[3] G. Dehnhardt, B. Mauck and H. Bleckmenn, "Seal whiskers detect water movements," *Nature,* vol. 394, pp. 235-236, 1998.

[4] 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.

[5] 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.

[6] W. Hanke et.al., "Harbor seal vibrissa morphology suppresses vortex-induced vibrations," *J. Exp. Biol.,* vol. 213, pp. 2665-2672, 2010

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

[8] A. G. P. Kottapalli, M. Asadnia, J. M. Miao, G. Barbastathis and M. Triantafyllou, " A flexible liquid crystal polymer MEMS pressure sensor array for fish-like underwater sensing," *Smart. Mater. Struct.*, vol. 21, p. 115030, 2012.

[9] J. Dusek, A.G.P. Kottapalli, M. E. Woo, M. Asadnia, J Miao, J H Lang and M S Triantafyllou, "Development and testing of bio-inspired microelectromechanical pressure sensor arrays for increased situational awareness for marine vehicles," *Smart. Mater. Struct.*, vol. 22, p. 014002, 2013.

[10] M. Asadnia, A.G.P. Kottapalli, Z. Shen, J. M. Miao, and M. Triantafyllou, "Flexible, and surface-mountable piezoelectric sensor arrays for underwater sensing in marine vehicles," *IEEE Sensors J.* vol. 13, pp. 3918-3925, 2013.

[11] A. G. P. Kottapalli, M. Asadnia, J. M. Miao, and M. Triantafyllou, "Electrospun nanofibrils encapsulatedin hydrogel cupula for biomimetic MEMS flow sensor development," in *Proc. IEEE MEMS'13 Conference,* Taipei, January 20-24, 2013, pp. 25-28.

[12] C. W. Tan, A. G. P. Kottapalli, Z. H. Wang, X. Ji J. M. Miao, G. Barbastathis and M. Triantafyllou, "Damping characteristics of a micromachined piezoelectric diaphragm-based pressure sensor for underwater applications," *in Proc. Transducers'11 Conference,* Beijing, June 5-9, 2011, pp. 72-75.

[13] M. Asadnia, A.G.P. Kottapalli, Z. Shen, J. M. Miao, G. Barbastathis and M. Triantafyllou, "Flexible, zero-powered, piezoelectric MEMS pressure sensor arrays for underwater sensing in marine vehicles," in *Proc. IEEE MEMS'13 Conference,* Taipei, January 26-24, 2013, pp. 126-129.

CONTACT

*A.G.P Kottapalli, tel: +65-67904264; School of Mechanical and Aerospace Engineering, Nanyang Technological University, kott0002@e.ntu.edu.sg