Performance improvement of IPMC flow sensors with a biologically-inspired cupula structure

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ABSTRACT

Ionic polymer-metal composites (IPMCs) have inherent underwater sensing and actuation properties. They can be used as sensors to collect flow information. Inspired by the hair-cell mediated receptor in the lateral line system of fish, the impact of a flexible, cupula-like structure on the performance of IPMC flow sensors is experimentally explored. The fabrication method to create a silicone-capped IPMC sensor is reported. Experiments are conducted to compare the sensing performance of the IPMC flow sensor before and after the PDMS coating under the periodic flow stimulus generated by a dipole source in still water and the laminar flow stimulus generated in a flow tank. Experimental results show that the performance of IPMC flow sensors is significantly improved under the stimulus of both periodic flow and laminar flow by the proposed silicone-capping.

Keywords: Ionic polymer-metal composite, IPMC sensor, cupula, bioinspiration, flow sensor, electroactive polymer

1. INTRODUCTION

The lateral line system is an important flow-sensing organ of fish and amphibians, and has been demonstrated to play a pronounced role in various biological behaviors, such as rheotaxis and energy-efficient swimming, predator detection, prey capture, and object avoidance. The lateral line is comprised of arrays of mechanoreceptive units called neuromasts, each of which consists of a bundle of sensory hair cells encapsulated in a gelatinous cupula,[1] as illustrated in Fig. 1. One of the two types of neuromast is the superficial neuromast, which stand external to the fish skin and tend to respond to flow velocity.[2] The response of the neuromasts, in the form of action potentials, is transmitted to the central nervous system for information processing.[3]

The lateral line system has inspired a number of efforts to create an engineering equivalent to facilitate the navigation, coordination and control of underwater robots and vehicles.[4] Such an artificial lateral line system offers the potential to introduce a novel and noiseless flow sensing modality for underwater applications, and to provide complementary information to traditional underwater vision sensors and sonar. Over the last decade, several research groups have reported hair cell-inspired flow sensors that to varying degrees have been motivated by fish neuromasts, exploiting micro-fabrication techniques at a micron scale,[5] optical transduction,[6] and novel sensing materials at milli- to centimeter scales such as ionic polymer-metal composites.[7–9]

Signal detection by a superficial neuromast depends on the mechanical properties of the cupula. It has been reported that cupula-inspired hydrogel-capping improves the sensitivity of a microfabricated artificial hair cell sensor by two orders of magnitude.[10] This improvement is likely the result of a high aspect-ratio structure, which increases the hydrodynamic drag on the structure and amplifies the flow stimulus. Generally, the shape and size

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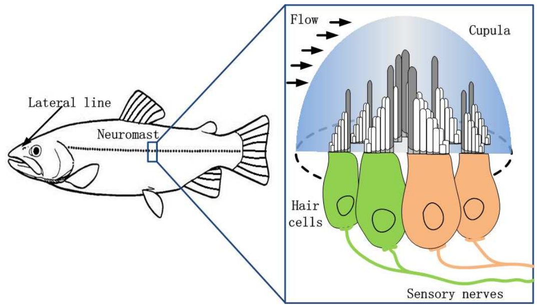


Figure 1. Illustration of the lateral line and the neuromast.

of the cupula affect both the fluid forces that may be generated by a stimulus and the structural resistance to these forces,[11] which then affects the sensitivity of the neuromast.

We previously described an artificial lateral line system based on IPMC flow sensors.[8,12,13] IPMCs are one important class of electroactive polymers (EAPs) with built-in sensing and actuation capabilities.[14,15] They have received significant interest over the past two decades due to their softness, inherent polarity, capability to work in water, high sensitivity, and direct mechanosensory property. IPMCs hold strong promise for versatile sensing applications in a large variety of engineering areas. They are also bio-compatible and amenable to microfabrication.[16–20] An IPMC sensor is typically fabricated by chemically plating a layer of noble metal (e.g., platinum) as electrodes on both surfaces of a thin ion-exchange membrane (e.g., Nafion).[16,21] Inside the polymer, only cations can move freely in the membrane while anions are covalently fixed to polymer chains. An applied force or deformation on an IPMC beam would redistribute the cations and accompanying solvent molecules inside the polymer, leading to the generation of a detectable electrical signal (typically open-circuit voltage or short-circuit current) across the electrodes. Recent studies on characterization, modeling, and applications of IPMCs can be found in the literature.[22–35] Potential applications of IPMC sensor span measurement of displacement,[36] flow,[12,37] shear loading,[38] curvature,[39] structural health monitoring,[40] and energy harvesting.[41–43]

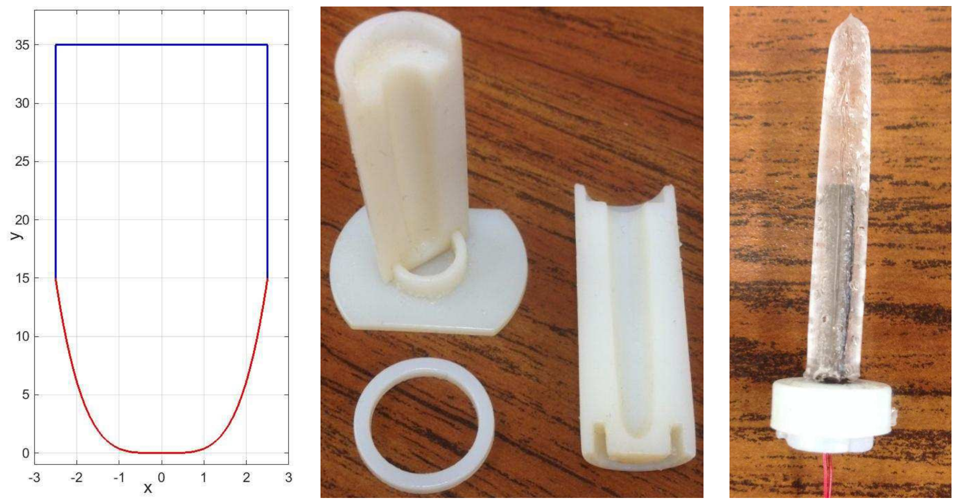
In this paper, inspired by the hair-cell mediated receptor in the lateral line system of fish, we experimentally explore the impact of a flexible, cupula-like structure on the performance of IPMC flow sensors. To create the desired cupula-like structure, a custom-designed mold is 3D-printed to hold the IPMC sensor and the Polydimethylsiloxane (PDMS) during the curing process. Experiments are conducted to compare the sensing performance (short-circuit current) of the IPMC flow sensor before and after the PDMS-capping. In particular, the signal amplitudes of IPMC sensors are tested under the periodic flow stimulus generated by a dipole source in the still water (AC stimulus), and the stand deviation of the IPMC sensor signals are compared under the laminar flow stimulus generated in a flow tank (DC stimulus). The experimental results demonstrate the enhanced sensitivity from the cupula-like structure, which is expected to increase the hydrodynamic drag and amplify the flow stimulus.

The remainder of the paper is organized as follows. The fabrication process of the cupula-like structure is first described. The experimental results with a dipole source are then presented, followed by the results in a flow tank. Finally, concluding remarks and future work are presented.

2. FABRICATION PROCESS

2.1 Fabrication of IPMC Flow Sensor

The IPMC fabrication follows the traditional impregnation-reduction ion-exchange process.[16] The Nafion film with a thickness of 254 microns (Nafion PFSA N 1110, DuPont) was first boiled in dilute hydrochloric acid (2 wt%) for 30 min to remove ions and impurities, and then boiled in deionized (DI) water for another 30 min to remove the acid and swell the film. After these pre-treatment steps, the Nafion film was immersed in a platinum complex solution ($[Pt(NH_3)_4]Cl_2$) for more than 4 h (usually overnight) to allow platinum ions to diffuse into the Nafion film completely through the ion-exchange process. After a rinse with DI water, the film was immersed in a water bath at 40 °C. After the temperature was raised up to 60 °C gradually, a sodium borohydride solution



(a) (b) (c)

Figure 2. Fabrication of cupula-like structure: (a) shape design; (b) 3D-printed mold parts; (c) IPMC sensor coated with cupula-like PDMS.

(5 wt% $NaBH_4$ aq) was added to the water bath as a reducing agent at a rate of 2 ml every 30 min. Once the platinum deposition was complete, those steps were repeated, from acid treatment to water-bath reduction, to depositing the platinum for the second time. The film was then cut into beam-shaped samples with the length of 20 mm and the width of 3 mm. Finally, an IPMC sensor was formed by soldering two electric wire connectors to the IPMC platinum electrodes. To further ensure the sensing consistency of the IPMC sensor, an additional step of parylene encapsulation was conducted with a parylene coating of 20 μm thickness and a following water drive-in process under 70°C for three days.[44]

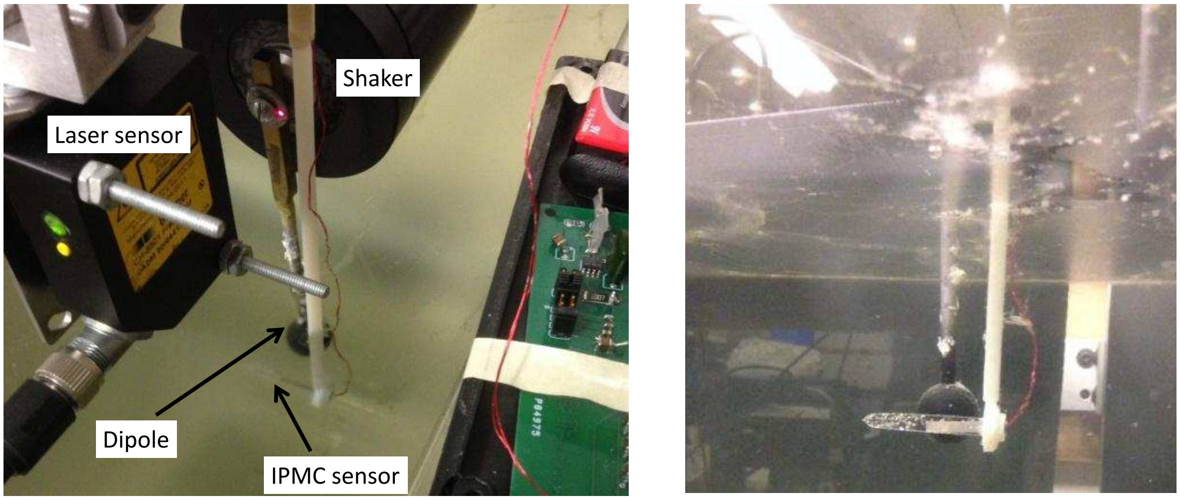
2.2 Fabrication of Cupula-like Structure

The cupula-like structure is created by curing a liquid silicone prepolymer, Polydimethylsiloxane (PDMS), within a custom-designed 3D-printed mold. The mold is designed in SolidWorks, a solid modeling computer-aided design (CAD) program, with controlled shape and size. For the first prototype, a smooth column shape is used for the PDMS cupula. Fig. 2 (a) shows the contours used to create the "cut-revolve" feature in SolidWorks. The lower curved part can be expressed as $y = 0.4x^4$, and upper flat part can be expressed as $x = \pm 2.5$ and $y = 35$. So the total length of the PDMS cupula is 35 mm and the diameter for the bottom part is 5 mm. The embedded IPMC sensor has the dimension of 20 mm by 3 mm by 0.3 mm. Once the design is finalized in SolidWorks, the mold parts are printed by a 3D printer (Objet Connex350, Stratasys Ltd.), as shown in Fig. 2 (b). An ultrasonic cleaning process and two layers of coating with acrylic lacquer and super seal are further needed for the mold parts to be used for PDMS curing.

The liquid PDMS is initially mixed with its curing agent at a ratio of 10:1 and injected into the mold. After that, the mold is baked in a oven under 70°C for 3 hours in order to achieve an estimated Young's modulus of 2 MPa for the PDMS. Fig. 2 (c) shows the fabricated cupula-like structure with the IPMC sensor embedded in the center of the PDMS sample. Some small bubbles still exist in the PDMS sample, which can be removed if a vaccum oven is used for curing. In this paper, one type of cupula-like structure is studied with fixed dimensions and stiffness, while both can be modified for the future work by changing the mold design and adjusting the ratio of PDMS to curing agent, respectively.

3. SENSOR PERFORMANCE IN AC FLOW

Experiments are first conducted under the periodic flow stimulus generated by a dipole source in the still water. To compare the sensing performance (the signal amplitudes of the short-circuit current) of the IPMC flow sensor



(a) (b)

Figure 3. Experimental setup with a dipole source: (a) top view; (b) side view.

before and after the PDMS-capping, the same IPMC is first tested, and then tested again under the same experimental conditions coated with the PDMS cupula-like structure.

3.1 Experimental Setup

Experiments were conducted in a water tank that measures $6 \times 2 \times 2$ ft^3, as shown in Fig. 3. A mini-shaker (Type 4810, Brüel & Kjær) is amounted on an aluminum frame above the tank, generating vibration stimulus (back and forth) on the horizontal plane from 5 to 15 Hz at a controlled amplitude. The dipole source used in this paper is a metallic sphere with diameter of 19.4 mm and excited by the mini-shaker. To meet the assumption that the generated flow is two-dimensional on the horizontal plane, the sphere was placed deep enough below the water surface. The IPMC sensor was fixed to a thin stick and extended to the same depth as the dipole source, as shown in Fig. 3. The sensor was placed with a distance of 30 mm from the sphere center and in a position where its tip bending direction is parallel to the sphere vibration direction. A laser displacement sensor (OADM 20I6441/S14F, Baumer Electric) was mounted above the water to measure the vibration displacement of the shaker as the input of the sensor. The mounting frame for the laser sensor was isolated from the frame where the mini-shaker is fixed. A two-tier four-channel amplification circuit was used to measure the short-circuit current generated by the IPMC sensor. Control signal generation, sensing data acquisition, and processing are all performed through a dSPACE system. Note that only the IPMC sensor with a cupula-like structure is shown in Fig. 3; the experimental conditions are exactly the same for the IPMC sensor before the PDMS-capping.

3.2 Results and Discussion

Fig. 4 shows the experimental results for the testing under the AC flow stimulus, including the gain enhancement and phase shift for the IPMC sensor before and after the PDMS-capping. At each stimulus frequency with each vibration amplitude, a frequency response of the IPMC sensor is collected with the laser sensor measurement as the input and the sensor signal as the output. Fast Fourier transform is used to extract the amplitudes and phases of both input and output at each testing, and then the amplitude gain and phase shift of each testing is calculated. Finally, as shown in Fig. 4, at each data point with particular frequency and vibration amplitude, the gain enhancement of the sensor performance after the PDMS-capping is obtained by taking the ratio of the amplitude gain of the IPMC sensor after the PDMS-capping to that of the sensor before the capping. Similarly, the phase shift at each data point in Fig. 4 is the difference of the phase shift of the IPMC sensor before and after the PDMS-capping.

As one can see from the experimental results in Fig. 4, generally there is significant improvement of the IPMC sensor performance in terms of the signal amplitude by the proposed silicone-capping. The results also indicate

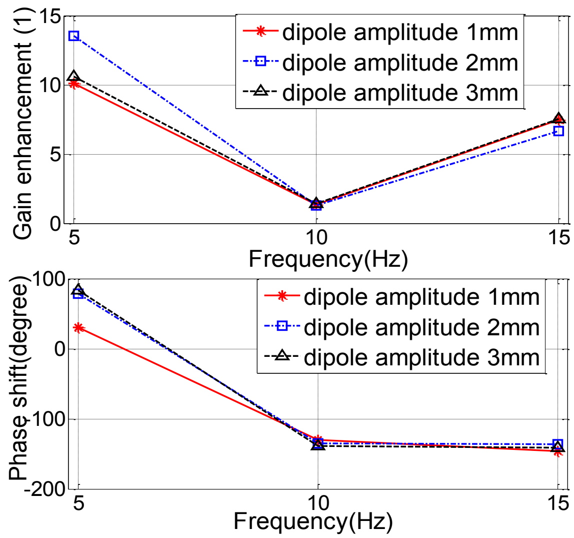
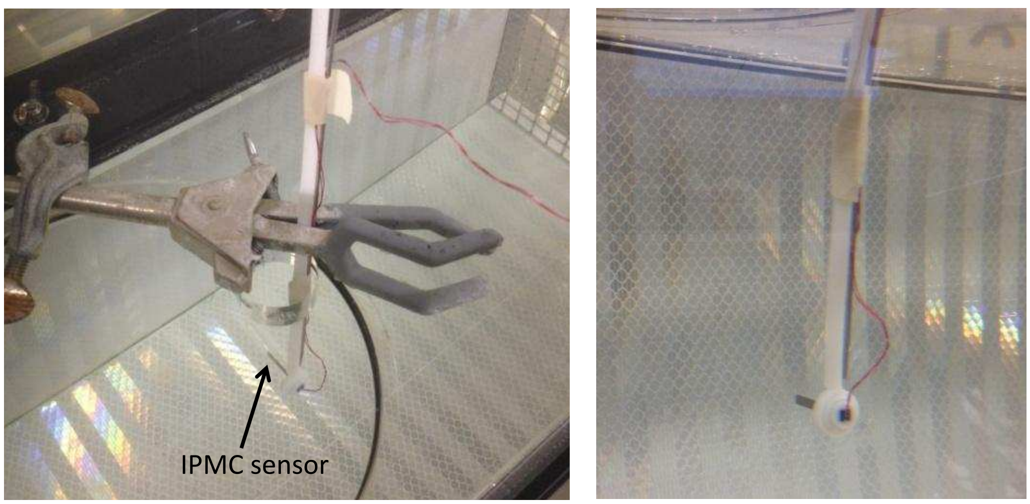


Figure 4. Experimental results for the improvement of sensor performance under periodic flow stimulus.



(a) (b)

Figure 5. Experimental setup in the flow tank: (a) top view; (b) side view.

that the cupula-like structure affects the phase property of the sensor significantly. Both the gain enhancement and the phase shift show considerable dependence on the frequency, which is likely due to the different dynamic properties of the mechanical structure between the IPMC itself and the PDMS cupula. In particular, the gain enhancement drops to its lowest value at 10 Hz, which can be explained by the assumption that the nature frequency of the IPMC sample itself in water is close to 10Hz, whereas the sample with PDMS structure is not. Compared with the frequency, the vibration amplitude appears not to have a significant effect on the sensor performance.

4. SENSOR PERFORMANCE IN DC FLOW

Experiments are also conducted under the laminar flows stimulus generated in a flow tank. Similarly, to compare the sensing performance, one IPMC sample is first tested in the flow tank, and then tested again under the same experimental condition coated with the PDMS cupula-like structure.

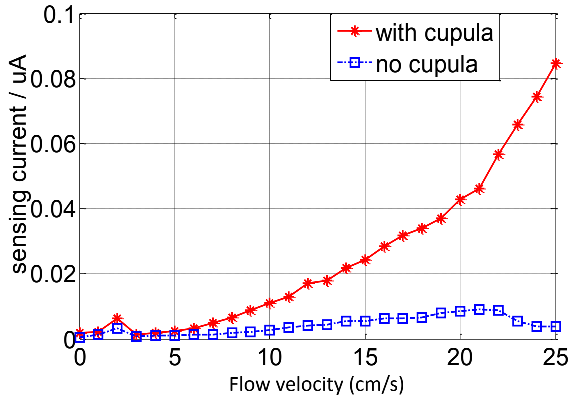


Figure 6. Experimental results for the improvement of sensor performance under periodic flow stimulus.

4.1 Experimental Setup

We generated a uniform flowfield in a swim tunnel (Loligo Systems) measuring $146 \times 68 \times 35\,\text{cm}^3$, with an enclosed test section of $65 \times 20 \times 20\,\text{cm}^3$. The flow velocity in the working section of this flow tank is controlled through adjusting the rotating speed of the motor, which is used to circulate the water in the tunnel. The IPMC sensor was mounted on a thin stick, which is fixed by a clamper and extends into the water flow with some depth in the test section as shown in Fig. 5. The same amplification circuit and dSPACE system as in Fig. 3 are used to measure the short-circuit current generated by the IPMC sensor, and to collect and process the data, respectively.

4.2 Results and Discussion

Unlike the experiments with an AC stimulus, laminar flow causes the IPMC sensor to produce a signal with a magnitude that is proportional to the amplitude of flow-induced vibration. The structural and electro-mechanical modeling of an IPMC sensor subjected to pressure distributions created by a moving fluid remains the subject of ongoing work. This study takes advantage of the experimental results[12] suggesting that the component of the flow normal to the sensor corresponds closely to the standard deviation of the magnitude of the IPMC measurement, which will be used in this study as the sensor performance.

Experimental results are shown in Fig. 6, where the standard deviation of the signal magnitude of the IPMC sensor before and after PDMS-capping are plotted as the flow velocity varies (corresponding to the motor speed in Fig. 6). One can easily tell that the sensor performance is significantly improved by the proposed cupula-like structure, especially when the flow velocity is higher. The improvement both in AC and DC flow is likely the result of an enlarged cross-section area, which increases the hydrodynamic drag on the structure and amplifies the flow stimulus.

5. CONCLUSION

This paper presents an experimental study on the performance improvement of IPMC flow sensors with a cupula-like structure, which is inspired by the hair-cell mediated receptor in the lateral line system of fish. The fabrication process has been presented for the IPMC and the cupula-like structure based on custom-designed mold and PDMS curing process. Experiments have been conducted to compare the sensing performance of the IPMC flow sensor before and after the PDMS-capping both under the periodic flow stimulus generated by a dipole source and the laminar flow stimulus generated in a circulating flow tank. The experimental results demonstrate the enhancement from the cupula-like structure, which is expected to increase the hydrodynamic drag and amplify the flow stimulus.

Future work will be devoted to the structural and electro-mechanical modeling of an IPMC sensor subjected to the flowfield created by the periodic flow or the uniform flow, as well as the same modeling work for an IPMC sensor with a cupula-like structure.

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