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Fish-inspired self-powered microelectromechanical flow sensor with biomimetic hydrogel cupula

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Flow sensors inspired from lateral line neuromasts of cavefish have been widely investigated over decades to develop artificial sensors. The design and function of these natural sensors have been mimicked using microelectromechanical systems (MEMS) based sensors. However, there is more to the overall function and performance of these natural sensors. Mimicking the morphology and material properties of specialized structures like a cupula would significantly help to improve the existing designs. Toward this goal, the paper reports development of a canal neuromast inspired piezoelectric sensor and investigates the role of a biomimetic cupula in influencing the performance of the sensor. The sensor was developed using microfabrication technology and tested for the detection of the steady-state and oscillatory flows. An artificial cupula was synthesized using a soft hydrogel material and characterized for morphology and mechanical properties. Results show that the artificial cupula had a porous structure and high mechanical strength similar to the biological canal neuromast. Experimental results show the ability of these sensors to measure the steady-state flows accurately, and for oscillatory flows, an increase in the sensor output was detected in the presence of the cupula structure. This is the first time a MEMS based piezoelectric sensor is demonstrated to detect steady-state flows using the principle of vortex-induced vibrations. The bioinspired sensor developed in this work would be investigated further to understand the role of the cupula structure in biological flow sensing mechanisms, thus contributing toward the design of highly sensitive and efficient sensors for various applications such as underwater robotics, microfluidics, and biomedical devices. https://doi.org/10.1063/1.5009128

Nature's designs inspire solutions for many engineering problems.[1,2] Biological flow sensors of aquatics, that help in survival under challenging environments, are very small and have excellent sensing abilities.[3] Targeting the high sensitivity and performance of natural sensors, artificial sensors have been developed for various applications. The mechanosensory lateral line system (LLS) of cavefish [Fig. 1(a)] has been widely investigated for the development of bioinspired devices. Lateral line neuromasts are located on the skin (superficial neuromasts, SNs) or inside fluid filled canals (canal neuromasts, CNs).[4] Figure 1(b) shows different parts of a neuromast. SNs and CNs are sensitive to flow velocity and acceleration, respectively.[5] SNs interact with water flow directly while CNs communicate through a series of equidistant pores on the skin with one neuromast arranged between every two pores [Fig. 1(c)]. Figure 1(d) shows a photograph of the sensor developed in this work which is inspired from CNs and has a dome shaped structure similar to a cupula.

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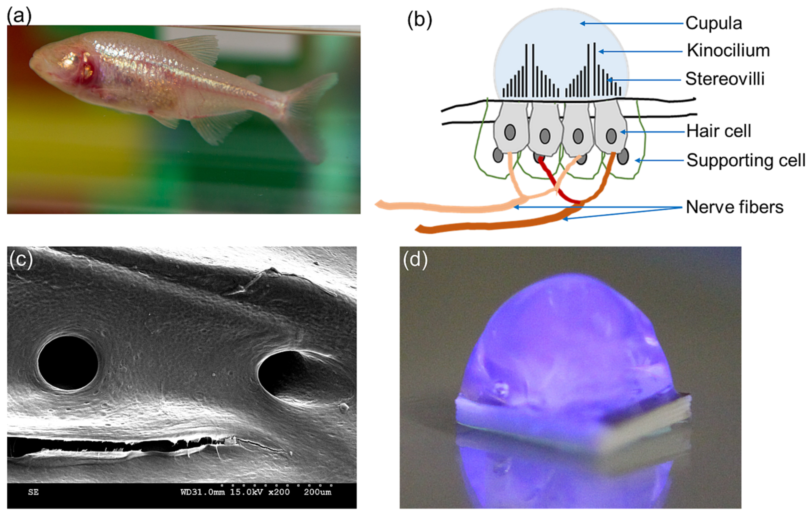

FIG. 1. Bioinspiration. (a) Photograph of a blind cavefish *Astyanax fasciatus*. (b) Schematic of a CN. (c) Scanning electron microscope (SEM) image of a piece of skin with two canal pores. (d) Our biomimetic sensor with a dome shaped biomimetic cupula.

The cupula of a lateral line neuromast significantly contributes to the mechanotransduction process. It couples the water flow with sensory hair cells through viscous forces. It maximizes the drag of neuromasts enhancing the absorption of fluid motion by stereovilli and transmission of flow stimulus to the hair cells.[6,7] Hair cells convert the mechanical stimulus to electrical signals that are transmitted to brain via nerve fibers generating appropriate responses.[8] The cupulae of SNs have an elliptical shape and their size varies along the length of the body.[3] A SN contains tens of hair bundles which get deflected if the neuromast is exposed to water flow demonstrating a bending mechanism of flow detection. Cupulae of SNs are softer with a Young's modulus (E′) of ∼21 Pa.[3,9] The cupulae of CNs are hemispherical in shape and their size remains same throughout the canal.[3] A CN contains thousands of hair bundles that demonstrate the sliding mechanism of flow detection. Cupulae of CNs are stiffer with an E′ of ∼10 kPa.[3,7]

SNs and CNs have inspired development of several microelectromechanical systems (MEMS) based flow sensors.[10–13] Recently, microfabrication technologies exploring biomimetic materials are gaining interest. MEMS sensors featuring the specialized microstructure cupula of the LLS were investigated to improve the sensing performance and various factors contributing toward the increase in sensitivity of SN-inspired sensors were proposed.[7,14–16] It would be interesting to evaluate how these factors (morphology, structure, and material properties of a cupula) affect the performance of a CN-inspired sensor. However, earlier studies were limited to piezoresistive sensing membranes while a piezoelectric membrane would be ideal to develop a CN-inspired sensor as CNs detect high frequency oscillations of pressure difference across canal pores. CNs are sensitive to high frequency alternating current (AC) flows and are known to act as high-pass filters.[17] They generally respond best to a frequency range of 30–150 Hz,[18] but in some fishes, the CNs are sensitive up to 450 Hz.[18]

Here, we report the development, characterization, and hydrodynamic testing of a self-powered MEMS flow sensor inspired from CNs and equipped with a biomimetic hydrogel cupula. A piezoelectric material, $Pb(Zr_{0.52}Ti_{0.48})O_3$ (lead zirconium titanate, PZT), was used as the sensing membrane to mimic the sensory hair cells of CNs. A natural polymer, hyaluronic acid (HA), hydrogel was used to develop the artificial cupula and optimized to mimic the mechanical properties of the rigid cupula of a CN. The shape of this artificial cupula was also maintained similar to that of CNs by optimizing the drop casting process. The naked hair cell sensor (without a hydrogel cupula) was tested for vortex-induced vibration (VIV) based detection of steady-state flows. Further, the sensor with and without the hydrogel cupula was tested for detecting oscillatory flows under water.

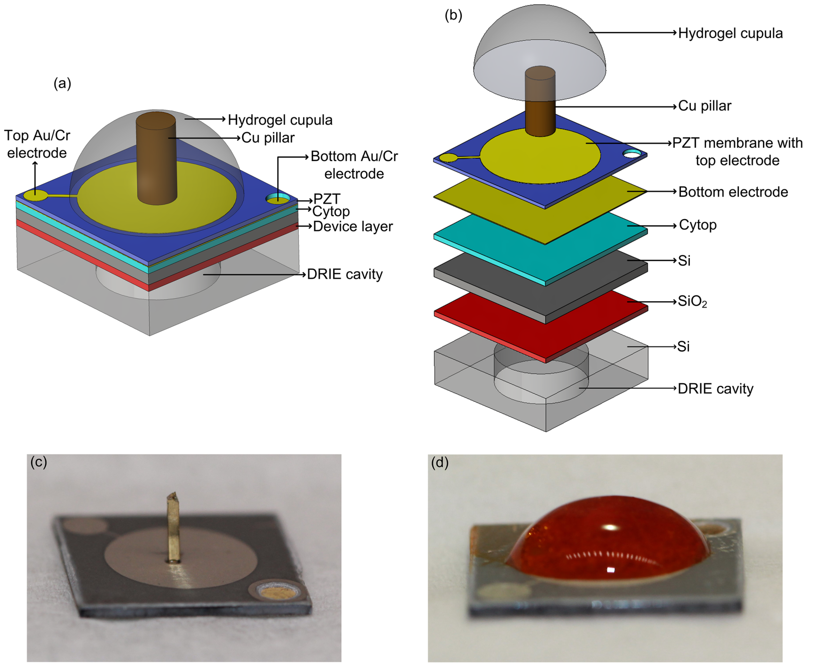

FIG. 2. (a) Biomimetic flow sensor with an artificial cupula. (b) Exploded view of the sensor showing the individual fabrication layers. (c) Photograph of the PZT sensor with the Cu pillar. (d) Photograph of the PZT sensor equipped with a hydrogel cupula (hydrogel is colored with rhodamine dye).

The CN-inspired MEMS sensor was fabricated through microfabrication technology. It consists of three main components: a PZT piezoelectric membrane, a rigid cylindrical pillar of copper (Cu), and a hydrogel cupula. Figure 2(a) shows a schematic of the sensor, and Fig. 2(b) shows an exploded view of all the components used for fabrication. A PZT membrane serves as the principle sensing element and the high aspect ratio pillar mounted at the center of the membrane acts as a structural element that interacts with flow. The pillar detects disturbances in fluid motion and transmits flow stimulus to the PZT membrane. If exposed to water flow, the pillar bends causing a displacement of the sensing membrane. This mechanical deflection of pillar is converted into an electrical signal due to the charges generated by displacement of the PZT membrane. These charges are collected as voltage signals through the top and bottom electrodes of the sensing base. The sensor with the PZT membrane and Cu pillar is referred to as the naked hair cell sensor. For the fabrication of a sensor equipped with a cupula, methacrylic anhydride (MA) modified HA hydrogel (HA-MA) was drop cast over the Cu pillar. Figures 2(c) and 2(d) show photographs of the naked hair cell sensor and the sensor with the hydrogel cupula, respectively.

The HA-MA hydrogel was characterized for morphology, network structure, and mechanical properties. Figures 3(a) and 3(b) show photographs of the HA-MA hydrogel after crosslinking and swelling in water, respectively. The swollen gel had a smooth surface and was transparent. Figures 3(c) and 3(d) are SEM images showing pores in the cross section and on the surface of the hydrogel, respectively. The porous network indicates the ability of these gels to absorb and retain water within its polymer chains upon swelling. The hydrogel was subjected to dynamic oscillatory shear tests to evaluate its mechanical strength. An amplitude sweep test was conducted to obtain storage modulus (G') as a function of varying strain rate percent (δ) as shown in Fig. 3(e). From this plot, a fixed δ value was selected to conduct a frequency sweep in which G' and the complex viscosity (η^*) were recorded simultaneously. Figure 3(f) shows that the HA-MA hydrogel has considerably high stiffness across all frequencies tested from 0.1 to 10 Hz. At 1 Hz, G' was $\sim$3.6 kPa corresponding to an E' of $\sim$10 kPa using the relationship $G' = 3 \times E'$.[9] η^* gradually declined with the increase in frequency [Fig. 3(g)] demonstrating the shear thinning behavior of hydrogel wherein the polymer chains under strain mobilize from the entangled network aligning themselves along the direction of strain.

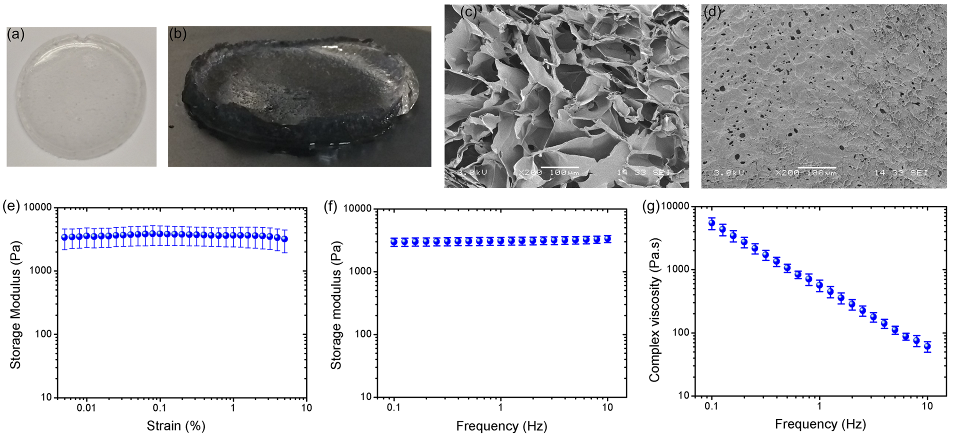

FIG. 3. Characterization of HA-MA hydrogel. [(a) and (b)] Photographs of a crosslinked and water swollen hydrogel, respectively. [(c) and (d)] SEM of cross section and surface of hydrogel showing a porous network, respectively. (e) Amplitude sweep plot showing constant G′ independent of strain rates. [(f) and (g)] Frequency sweep plots showing high stiffness across the entire range of frequency and decrease in η* with increase in frequency, typical of shear thinning behavior, respectively.

Next, the sensor was characterized to evaluate its performance in steady-state and oscillatory flows [Fig. 4(a)]. All piezoelectric flow sensors investigated so far could only sense oscillatory flows due to the inherent disadvantage of electron discharging associated with piezoelectric materials when subjected to static forces. Here, for the first time, we proposed an innovative method through which a piezoelectric MEMS sensor was used to accurately measure steady-state flows. VIV generated on the cylindrical pillar caused vibrations of the PZT membrane, which was used to measure the incident flow velocity (U). When a cylindrical pillar was subjected to a steady-state flow (Reynolds number, $R_e > 50$), periodic vortices were shed at the back of the cylinder from either side. These pressure irregularities formed in the flow induced motion on the cylinder making it to vibrate at the same frequency as that of the vortices shed. This VIV frequency (f_{VIV}) is related to R_e and thereby depends on U, diameter of cylinder (d), and viscosity of fluid (ν). Since these parameters are known, U can be determined if f_{VIV} of the cylinder is detected. In our sensor, the VIV induced on the Cu pillar caused the PZT membrane to vibrate at the same frequency. Analyzing the frequency content of the sensor output will therefore reveal the steady-state U experienced by the pillar. The f_{VIV} of the pillar can be calculated as

$$S_t = \frac{f_{VIV}\, d}{U},$$

where S_t is the Strouhal number (approximated to 0.2 for a cylindrical structure). For steady-state flow sensing experiment, the sensor was tested in a water tunnel with a wide range of U (0-0.7 m/s). The sensor was positioned such that the direction of flow was perpendicular to the length axis of the pillar. The sensor output showed a distinct peak at a frequency in good agreement to the theoretically estimated f_{VIV} [Fig. 4(b)]. Figure 4(c) shows the VIV-induced sensor output for a steady-state U of 0.625 m/s. The dominating frequency component in the sensor output matches closely with the theoretically predicted f_{VIV}.

Biological CN sense flows of higher frequencies and accelerations.[5,6] In order to mimic a biologically relevant scenario, the water movements generated by a vibrating sphere (dipole) were used to test the sensor for oscillatory flows. The dipole was vibrated in a plane perpendicular to the long axis of the Cu pillar of the sensor and was driven with a sinusoidal signal of desired frequency and amplitude. The vibration of dipole sets water flow oscillations at the vicinity of the sensor. Drag force induced on the pillar caused it to vibrate at the same frequency as that of the dipole. Figure 4(d) shows the outputs acquired from the sensor at different vibration frequencies. The sensor output followed the frequencies of dipole stimulus very well. Minor variations in the amplitude of the sensor output could be attributed to the backflows due to the reflections from the walls of the container.

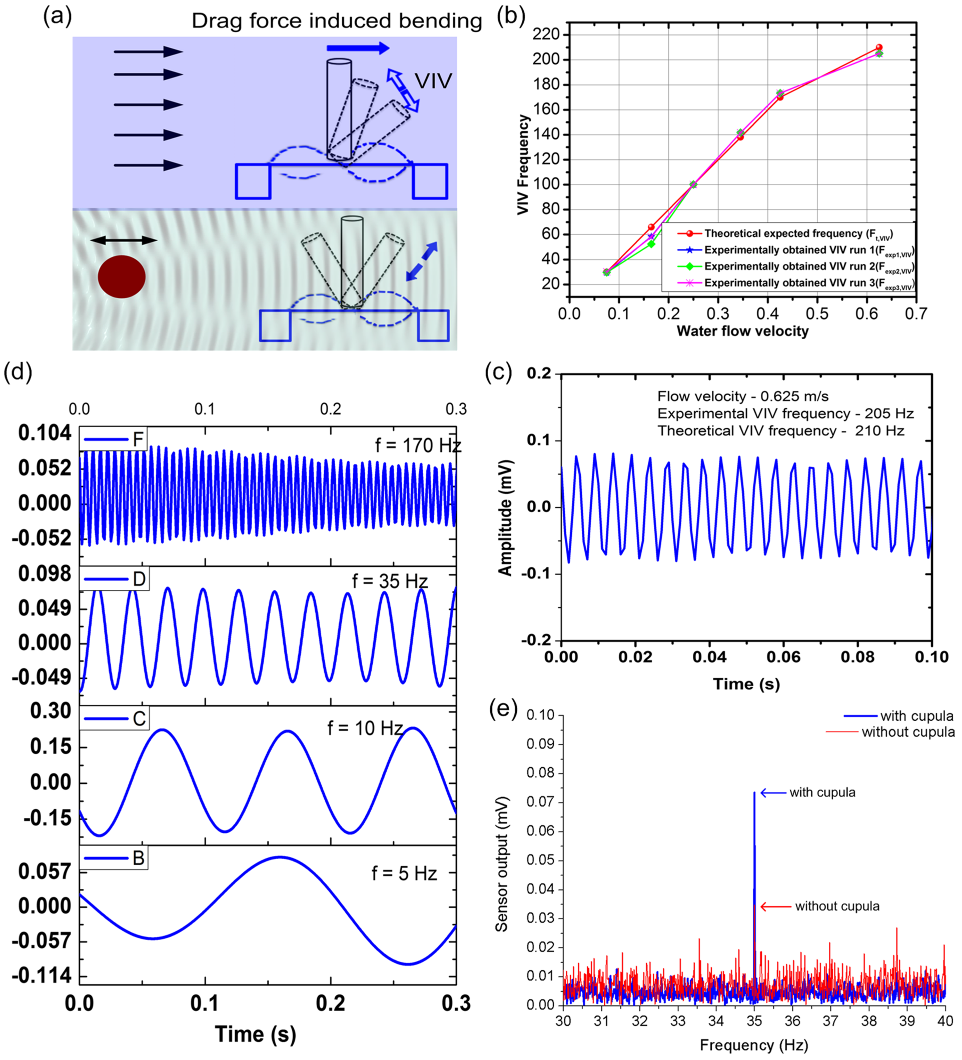

FIG. 4. Hydrodynamic characterization of a bioinspired sensor. (a) Schematic showing sensing mechanism of steady-state and oscillatory flow stimuli. (b) Steady-state flow sensing using flow generated VIV. (c) VIV-induced sensor output for a steady-state U of 0.625 m/s. (d) Dipolar flow fields of various frequencies. (e) The response of a sensor without (red) and with a cupula (blue). Note the increase in the sensor output for the sensor that was equipped with a cupula.

In order to predict the enhancement in sensing performance due to the addition of a biomimetic hydrogel cupula, a comparative experimental analysis of the output of the cupula-dressed and naked hair cell sensor was conducted. The outputs of both sensors were simultaneously recorded as a dipole (positioned equidistant from sensors) was vibrated at a frequency of 35 Hz. Figure 4(e) shows the Fast Fourier Transform of the outputs. The hydrogel cupula enhanced the sensor output by ~2.1 times as it increases surface area exposed to the flow and facilitates the viscous coupling of water to the sensing membrane.[7,16] Other material factors such as porous microstructure, permeability, and hydrophilicity also contribute to the increased sensitivity.[19] Additional data on repeatability of the sensitivity enhancement due to the presence of the hydrogel cupula are provided in Fig. S1 of the supplementary material.

Neuromast inspired artificial sensors, investigated so far, feature the cylindrical pillar and piezoresistive membranes. Going a step further, in this work, we developed and tested a hydrogel cupula-dressed PZT MEMS sensor that mimics the design, function, and performance of CNs. The HA-MA hydrogel mimicked the morphology, material composition, and structure of a natural cupula. The hydrogel was optimized to exhibit a porous network with high stiffness similar to the cupula of

CNs. The naked hair cell sensor accurately detected steady-state flows based on VIV. For oscillatory flows, the sensor output was enhanced by two times due to the hydrogel cupula. To the best of our knowledge, this is the first report of steady-state flow detection by a piezoelectric MEMS sensor. The bioinspired sensor developed in this work will guide design and fabrication of artificial flow sensors for robotics applications and biomedical devices. The hydrogel cupula-dressed PZT sensor will be further evaluated for the role of cupular properties in detecting flow stimuli to get more insights into the mechanosensory system.

See supplementary material for experimental details of hydrogel synthesis and characterization, sensor fabrication, and testing.

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