Fluidic based Multidirectional Flow Sensor Inspired from Artificial Cupula

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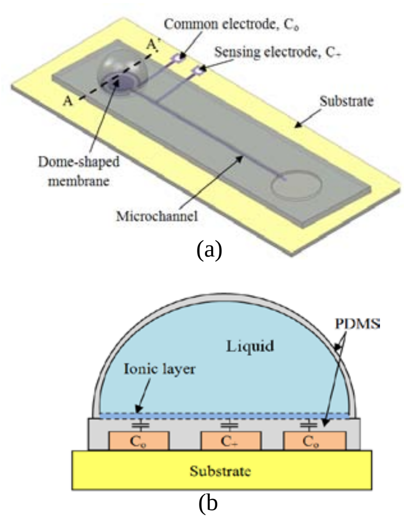
ABSTRACT
The fluidic based multidirectional flow sensor inspired from artificial cupula was presented in this paper. It is consists of dome-shaped membrane, microchannel and one-side electrode with implementation of electrical double layer capacitor as a sensing element. The PDMS with ratio 20:1 was selected as a material because it is suitable to be implemented as a membrane. The micro-stamping technique for fabrication of dome-shaped membrane was proposed where the uniform thickness of membrane can be achieved. The operating frequency of the sensor using methanol was 1.5 kHz. The flow measurement was done by using water channel which flow rate 10 to 40 cm/s was applied with the resolution of 5 cm/s. The directionality tests for flow direction and angle also were carried out and it is proved that the sensor was able to detect the flow in omnidirectional directions.

Keywords
cupula; flow sensor; PDMS; dome-shaped membrane; stamping; edlc.

1. INTRODUCTION
Flow sensor sensor has been implemented for underwater applications especially for localization and navigation [1]. Previously, the development of the flow sensor has focused on the piezoresistive and capacitive types of sensor where the suitable material to embed these types of sensing element is silicon. Enhancement of the silicon based sensor design is often realized with complex fabrication techniques and might compromise the robustness of the sensor. The fabrication of the silicon involves complex fabrication techniques such as deposition and sacrificial layer and it needs precise control because changes of geometry will change the mechanical properties of the sensor [2]. The fluidic system offers a simple sensing technique which requires a small amount of liquid to create a capacitance [3,4]. The commonly used material in microfluidic technologies is PDMS polymer where it is more compatible whereby it provides greater advantages, especially in mechanical yield strain than commonly used material such as silicon [5].

Biological inspiration such as the lateral line system in fish body has been a new alternative to improve the sensor structure and performance [6]. In this study, the mechanism of artificial cupula in lateral line system was studied where the gelatin cupula mediating the drags forces in the surrounding environment and transfers the movements into hair cells to induce the neuron signals. The proposed flow sensor consists of the one-side-electrode and dome-shaped membrane which integrated with the microchannel. In our work, we design, fabricate and characterize the flow sensor. The directionality test also has been carried out to test the capability of the sensor for multidirectional flow sensing.

2. SENSOR DESIGN
The sensor design for the flow sensor was based on artificial cupula mechanism, the dome-shaped membrane was proposed and integrated with the fluidic system. The liquid displacement inside microchannel will replace the function of biological hair cells, which induces the signal in capacitance due to the membrane deflection. The schematic of the proposed fluidic based flow sensor with electrode pattern is shown in Figure 1(a). It consists of a dome-shaped membrane, micrcochannel and electrodes. Unlike previous microfluidic based sensor that has pair electrodes inside microchannel [7], this sensor only has a single electrode and implements the electrical double layer capacitance (EDLC) principle to create a capacitance.The liquid such as methanol is used to fill in the cavity to form the ionic layer on the top of the PDMS insulator as shown in Figure 1(b). This ionic layer will behave as a conductor and create the capacitance.



(b

Figure 1. (a) Schematic of the sensor; (b) cross section A-A' for formation of ionic layer.

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When the flow rate was applied to the dome-shaped membrane, it gave displacement and subsequently pushed the liquid inside the microchannel (see Figure 2). The relationship between the capacitance changes, ΔC and liquid displacement, ΔL is given in equation below.

$$\Delta C = \frac{\varepsilon w(\Delta L)}{d} \tag{1}$$

where C_o, ε, w and d are the initial capacitance, dielectric constant of insulator, width of the microchannel and thickness of the insulator, respectively.

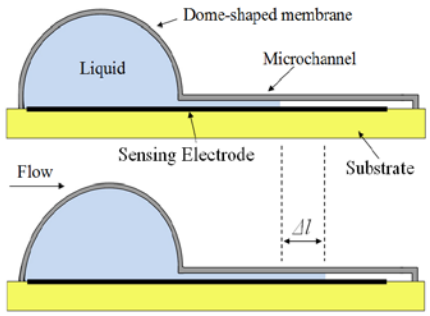


Figure 2. Sensor principle

3. MATERIALS AND METHODS

3.1 Fabrication Process

The fabrication process involves three major steps, including PDMS container, electrode fabrication, and the sealing process. The PDMS container consisted of dome-shaped membrane and microchannel. It has been fabricated by using the stamping techniques. Two molds which are top mold and bottom mold were designed using CAD software and fabricated using the Rapid Prototype machine. The PDMS base was mixed with its curing agent with ratio 1:20. The PDMS mixed was stirred and placed in the vacuum for 1 hour to completely remove the bubble. The mold was prepared and PDMS solvent was poured onto the bottom mold (see Figure 3 (a)).

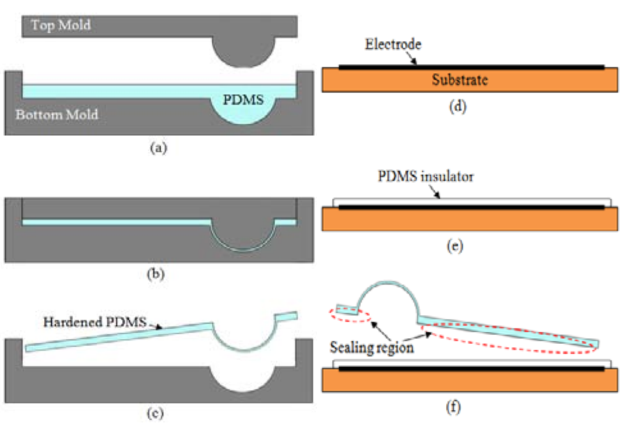


Figure 3. Process flow for sensor fabrication process.

Then, the top mold was pressed slowly and left for 1 day in temperature room (see Figure 3(b)). After curing process, the top mold was removed and PDMS container was peeled off from the bottom mold as shown in Figure 3(c). During the peeling process, it should be done carefully because the thick membrane is easily torn and broken. Next, the sealing process was started by fabricating the electrode using Printed Circuit Board (PCB) process, then the PDMS solvent was deposited (see Figure 3(d-e)). The spin coater was used to achieve the smallest and uniform thickness. For sealing process, Figure 3(f) shows that the hardened PDMS was sealed together with the electrode and we ensured that the electrode and microchannel was aligned

The advantage using a stamping technique is the uniform thickness can be achieved. The SEM dome-shaped membrane for fabricating membrane is shown Figure 4. From the figure, the thickness of the membrane was obtained about 220 µm (plus or minus 20 µm) and it seems the membrane has the thicker area. Also, given the radius of the dome, width and thickness of microchannel were 3.2 mm, 0.5 mm and 0.5 mm, respectively. To make the sensor robust to external force, a little PDMS solvent was applied to that area. The dome-shaped membrane does not break or fail during measurement because it deformable and flexible.

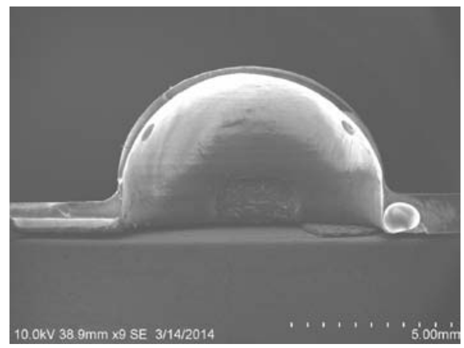


Figure 4. SEM image for fabricated membrane using stamping technique

3.2 Experimental Setup

For the sensor characterization, the output response was recorded in capacitance using LCR meter (GW Instek LCR-821) and connected to the computer. The flow sensor was tested by applying the water flow that was manually controlled in a water tunnel. It also has been monitored by conventional flow sensor as shown in Figure 5(a). To evaluate the capability of the sensor in multiple directions, the sensor was tested in different direction and angle using the rotating stage in Figure 5 (b).

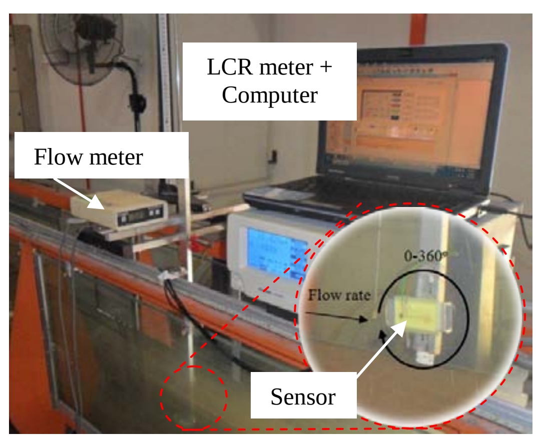


Figure 5. Water flow measurement setup and the stage for directionality test

4. RESULT AND DISCUSSION

4.1 Operating Frequency

The important factors to select the liquid are easy movement of the liquid and having a high dielectric constant. Water with a high dielectric constant, was not considered due to high surface tension resulted in difficult movement. The behavior of electrical double layer capacitance was evaluated by measuring the capacitance and frequency. The frequency was measured between 120 Hz and 200 kHz for the sensor and the output capacitance was recorded. Methanol, which has a high dielectric constant and low kinematic viscosity was selected to ionize the solution. Figure 6 shows the output response for variation of frequency for different mediums including air and methanol. As shown in the figure, the capacitance value for methanol was high compared to air medium and it decreased as the frequency became higher. In order to obtain the suitable operating frequency for the sensor, the capacitance of the sensor needs to be calculated by referring to the Eq. 2.

$$C = \frac{\varepsilon_{PDMS} A}{d_{PDMS}} \qquad (2)$$

where ε_{PDMS}, d_{PDMS}, and A are dielectric constant for PDMS, thickness PDMS and surface area of sensing electrode, respectively. The calculated capacitance of the sensor is 15 pF and from the graph the frequency about 1.5 kHz was obtained.

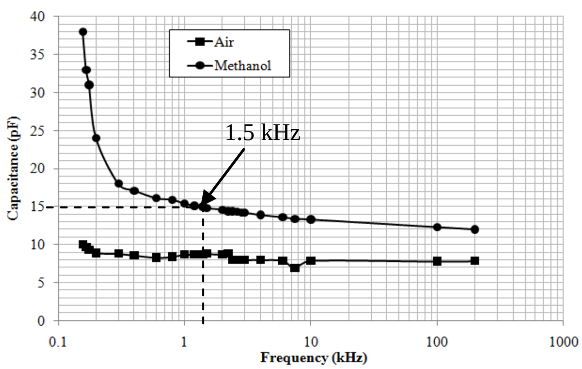


Figure 6. The response in capacitance for different operating frequency, comparison between air and methanol.

4.2 Water Flow Measurement

For the water flow measurement, the flow rate was varied starting from 10 to 40 cm/s where both of the flow direction and angle were fixed. Figure 7 shows the output sensor response in capacitance where the capacitance increased with the increasing of applied water flow. In this experiment, the standard deviation was also calculated to show the good measurement precision of the sensor. From the graph, the sensitivity of the sensor obtained was equal to 0.4 pF/cm^{-1} at 30 cm/s. The time response of the sensor was 0.35 s where it measured from minimum response time to 90% of maximum time. The sensor resolution is 5 cm/s where it was able to detect the flow rate as low as 10 cm/s.

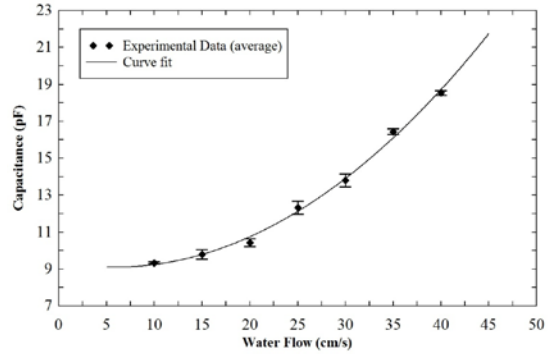


Figure 7. Sensor responses in capacitance. The experiment was repeated and error bars represent the standard deviation error

4.3 Directionality Test

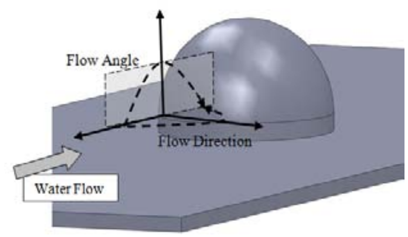
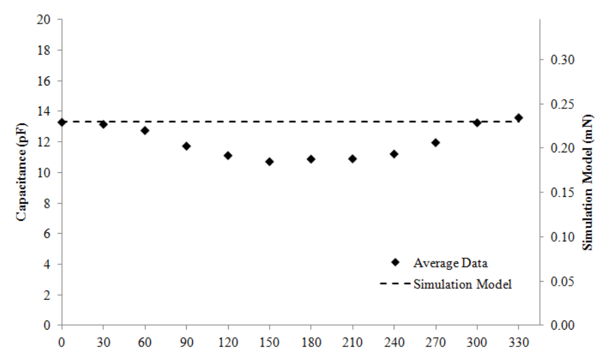
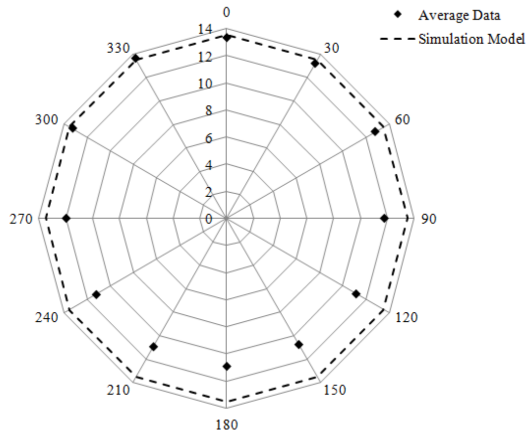


Figure 8. The axis for flow angle and flow direction acting on the dome structure

To test the capability of the sensor in multidirectional sensing, two parameters were varied, including flow direction and flow angle as shown in Figure 8. The water flow rate was fixed to 25 cm/s. The flow direction varied from 0 to 360^o while the flow angle was varied from 0 to 180^o. For the flow direction, Figure 9(a) shows the measurement data in linear plot while Figure 9(b) shows for the polar plot. It seems the measurement was non linear where it was reduced to 10.6 pF or equivalent to 20.2 cm/s at 180^o flow direction. The percentage error measurement obtained was below than 19%. The major factor that affected the sensor reading was the fabricated geometry of the sensor where the leading edge distance at 180^o was considerably due the existing of the microchannel. The increasing of the leading edge distance will reduce the drag force acting on the sensor and subsequently reduce the sensor response.



(a)



(b)

Figure 9. Output responses obtained for variation of water flow direction. (a) Linear plot. (b) Polar plot

For the variation of the flow angle, the water flow angle at 60 to 90^{o} (top surface of dome-shaped facing the flow) gave maximum response and increased about 7.2% compared to the initial value as shown in Figure 10. This increment of capacitance was due to the increasing of the drag force on the surface area of the dome-shaped structure. The graph obtained showed a good fit of average experimental data to the simulation model. It is proved that the dome shaped membrane that integrated with fluidic system has advantages in omnidirectional sensing compared to the flow sensor with embedded piezoresistive [8]. However, to determine the actual flow direction for the single fluid flow sensor was quite difficult and may be able to be solved in an array. As further work, the experimental on the sensors in an array will be carried out to test the capability of the sensors in localization especially for the moving object.

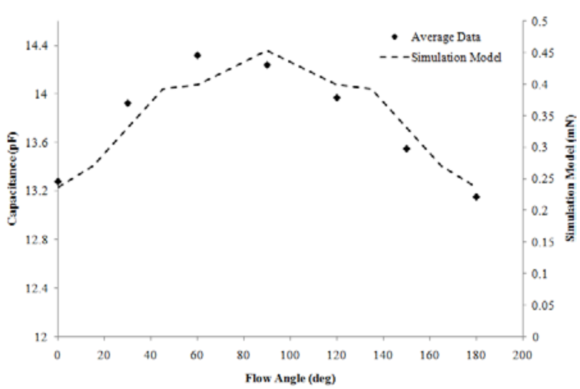


Figure 10. Output responses for variation water flow angle, linear plot

5. CONCLUSIONS

The fluidic based multidirectional flow sensor inspired from artificial cupula has been successfully designed and fabricated. The stamping technique was used to form the uniform thickness of the dome-shaped membrane. In experimental studies, the operating frequency of the sensor using methanol is 1.2 kHz. The sensor was capable to measure the water flow rate as low as 10cm/s in water with the resolution of 5 cm/s. Also, the directionality test proved that the sensor was able to measure the flow in omnidirectional especially for variation of flow direction and angle. However, the experimental result is not linear due to the sensor geometry, especially for the different flow directions. For sensor enhancement, the geometry of the sensor can improve by modifying the microchannel design such as spiraling around the dome, which make the leading edge at same distance in all directions.

6. ACKNOWLEDGMENTS

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