Modeling of Biomimetic Flow Sensor based on Artificial Hair Cell using CFD and FEM Approach

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Abstract— **This paper presents the modeling of biomimetic flow sensor based on artificial hair cell using the computational fluid dynamic and finite element method. The structure of the biomimetic flow sensor is consisted of single hair cell that perpendicular to substrate with leading edge was 31mm. The hair cell was integrated with general strain gage (Kyowa Type: KFG-1N-120-C1-11) and was connected to the Wheatstone bridge in order to measure the strain in voltage. The sensor performance was measured on the basis of drag force and strain. In order to study the performance of sensor, the hair cells with a length 1mm until 8mm and material such as copper, tungsten and silicon were simulated. The simulation result shows the high performance can be achieved by increasing the length of hair cell and using the low Young Modulus material. To validate the simulation, the experiment for the flow rate measurement was done for various flow rates 0.05m/s to 0.45m/s.**

Keywords-biomimetic flow sensor, computational fluid dynamic, finite element modeling

I. INTRODUCTION

Currently, the miniaturization and high performance of the sensor for the underwater applications are demanded. The problem with current conventional flow sensor is the size and it is not suitable to form an array [1]. Example of conventional flow sensor is thermal based hot wire anemometry and Doppler frequency shifts. The principle of the hot-wire anemometers is based on the anemometer principle where it measures the flow rate by sensing changes in heat transfer from a small electrically-heated hot-wire sensor and for the Doppler, it is measures the fluid velocity by transmit and receive a signal. The underwater flow sensor is become important to detect the flow rate and can be implemented as a navigation system for the underwater vehicle such as aqua robotic, glider and autonomous underwater vehicle (AUV). Nowadays, many researchers are trying to study a new alternative sensor design by investigating the function of organ, inspiration from the biological field. As an example, a development of hair cell that found in biological sensing for flow imaging on the fish body [2].

Fish depend on the mechanosensors along the body which appear as faint lines running lengthwise down each side to monitor the flow fields for maneuvering and survival under water. It is consisted of neuromast which is superficial neuromast and canal neuromast. Superficial neuromasts located in the skin in direct contact with the stream while canal neuromasts exist in the subepidermal canals connecting pore openings on the skin surface. Both canals and superficial are composed of hair cells with hair-like cilia projecting into a gelatinous cupula. When fluid passing the hair cell, it causes cupula displacement which will induce neuron signals [3]. In the recent years, many types of the underwater flow sensor based on artificial hair cell have been developed using different material and different types of sensing. The general structure of the flow sensor consists of single hair cell that perpendicular to the substrate and strain gage or piezoresistive was applied to measure the strain due to the deflection of the hair cell [4,5,6]. Flow visualization including velocity and pressure measurement is not a straight forward process. In other words, major of studies on the experimental computational fluid dynamic need to be considered for the applications such as for navigation, obstacle avoidance, underwater surveillance and monitoring of tsunami [7]. In this paper, the biomimetic flow sensor based artificial hair cell is design and modeled to study the performance of the sensor for the underwater sensing applications. The computational fluid dynamic (CFD) and finite element method (FEM) approach were used in modeling especially related to the flow parameter and the structural analysis.

II. THEORY AND METHODOLOGY

The schematic model for prototype of biomimetic flow sensor is shown in Fig. 1, the sensor consisted of hair cell perpendicular to the substrate and strain gage was used as a sensing element. The hair cells with different lengths and materials were simulated to study their effect to the sensor performance. The dimension of width and thickness of hair cell were fixed to 2000μm and 100 μm. The important properties such as Young's Modulus, E and Poisson ratio, v are listed in Table 1. External flow that parallel to the substrate imparted upon the hair cell gave the deflection and induces the strain. Strain gage will sense the strain of the hair cell and is converted to electrical signal by connecting with Wheatstone bridge. The Wheatstone bridge gives a result in output voltage, where voltage equal to zero when the bridge is balance.

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TABLE 1 LIST OF MATERIAL PROPERTIES

Material Properties	Young's Modulus , E (MPa)	Poisson's ratio, υ
Copper	128000	0.36
Tungsten	410000	0.28
Silicon	160000	0.22

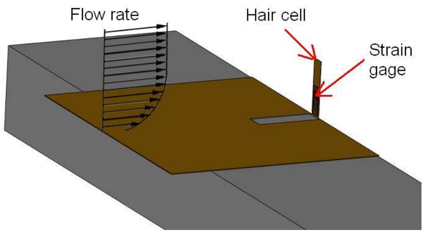

Figure 1. The schematic model of biomimetic flow sensor.

The flow rate is denoted as u_o and the overall length of hair cell is *L*. Beyond the boundary thickness the velocity is constant. The drag force acting on the hair cell and assumed that the flow velocity is parallel to the base

$$F_y = C_D\left(\frac{1}{2}\rho u_y^2 wdy\right) \tag{1}$$

where ρ and w are the fluid density and the width of the hair cell, respectively. The C_D is the drag coefficient and depends on the ratio of length and width of the hair cell. The velocity distribution along the vertical distance, u_y for the laminar flow was calculated

$$u_y = u_o\left(\frac{2y}{\delta} - \frac{y^2}{\delta^2}\right) \tag{2}$$

The magnitude of induced strain at the base of the cantilever beam was approximated as in (3)

$$\varepsilon = \frac{Mt}{2EI} \tag{3}$$

where E is the Young's modulus, t is the thickness of the cantilever, and I is the moment of inertia of the rectangular hair cell ($I = {wt^3}/{12}$). The moment was obtained by performing finite integration through the length of the hair cell

$$M = \int_{y=0}^{y=h} F_y y \tag{4}$$

By substituting (4) into (3), the equation for the strain was obtained

$$\varepsilon = \frac{3C_D\rho}{Et^2}\left(\frac{L^4}{\delta^2} - \frac{4L^5}{5\delta^3} + \frac{L^6}{4\delta^4}\right)u_o^2 \tag{5}$$

A. Numerical Approach

The numerical approach has been used in desired to understand the flow parameter and the performance of the sensor [8]. The common software that usually used in modeling related to fluid is the computational fluid dynamic (CFD) FLUENT software. The CFD FLUENT will analyze the velocity and drag force acting on the surface of hair cell structure. The whole FLUENT software package includes the FLUENT and the pre-processor Gambit. Gambit software was used to create the volume and generate the mesh. In mesh generation, the Tet/Hybrid element was selected due to the design of the geometry and 1198000 of mesh volumes were generated using this method. The bottom mesh is shown in Fig. 2. After an appropriate mesh is finished, Fluent is used for the simulation setup, the solving process and the post-processing of the results [9]. The numerical simulation solves the equation of the mass and momentum conservation equations in terms of primitive variables velocity and pressure for a constant property fluid [10].

$$\nabla \cdot U = 0 \tag{6}$$

$$\frac{\partial U}{\partial t} + U \cdot \nabla U = -\frac{1}{\rho}\nabla P + \upsilon \nabla^2 U \tag{7}$$

ρ and v are the density and kinematic viscosity of water, respectively. *U* is the vector velocity and *P* is the pressure. The result from the FLUENT is substituted into the model in Mechanical APDL Ansys for finite element method (FEM) solution. The purpose is to analyze the structure such as to simulate the maximum strain and displacement due to the flow rate. The performance of sensor is depending on the deflection of hair cell, where it induces the strain. ANSYS software is used as a tool for stress prediction in modeling and to predict stress distribution at certain cross sectional area. In modeling, it is important to develop the model with optimum dimension, and it would require some data such as properties of materials and types of sensing elements.

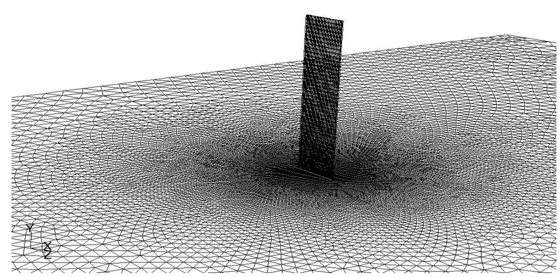

Figure 2. Mesh generation for bottom of hair cell

B. Measurement Setup

This biomimetic flow sensor with selected dimension will be tested using the titling flume channel and calibrated with conventional Vectrino Doppler by NORTEK Company. In order to measure the performance of sensor, the strain gage must be connected to the Wheatstone bridge which is capable to measure the minute changes of resistance corresponding to strain in voltage. The relationship of output voltage and the strain was defined in equation below

$$V = \frac{GE_o}{2}\varepsilon \tag{8}$$

where E_o, and G are bridge voltage and gage factor of strain gage. The analog output voltage of the Wheatstone bridge is in milivolts per volt input and was amplified using the low noise amplifier. The Analog-to-digital converter (ADC) was applied to convert the analog voltage to the decimal value to enable the data to display on computer using hyper terminal. The Fig. 3 shows the schematic for the experiment setup starting from the onsite testing, the system integration and the data was recorded on the computer.

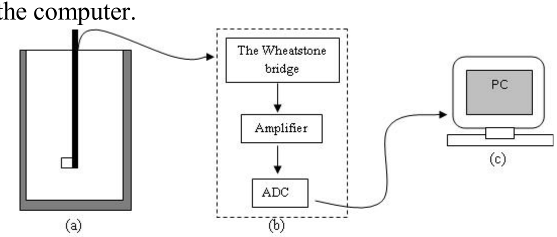

Figure 3. The simplified schematic of the measurement setup (a) Titling flume channel; (b) The system integration; (c) Computer.

III. RESULT AND DISCUSSION

The biomimetic flow sensor with 2000µm width, 100µm thickness and 8000µm length was simulated using the FLUENT software. The iteration for simulation was stopped at 150 because has already met the criterion, and it is limited to 1E-5 for convergence criterion. The Fig. 4 shows pressure coefficient contours for the front surface of the hair cell at velocity 0.1m/s. The side bar with different color represented the magnitude of the pressure. The front surface often a high pressure (P= 8.71Pa) compared to the other surface due to the maximum velocity drop. Pressure coefficient is not constant but varies as a function of speed, flow direction, object position, object size, fluid density and fluid viscosity. In terms of velocity, higher the velocity will give the higher pressure on the sensor surface. The velocity distribution in Fig. 5 shows the beginning of the velocity contours which have a leading effect and boundary layer. It occurred before reaching the hair cell, however, the flow led to the occurrence of turbulence in a certain region after passing the sensor.

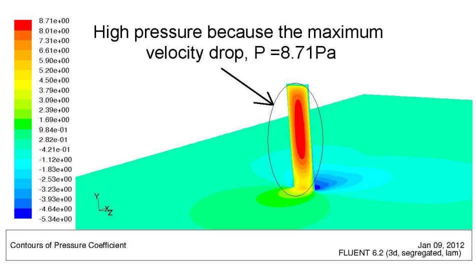

Figure 4. The pressure contour of the front surface for flow rate 0.1m/s.

The same phenomenon will occur if different height of hair cell is simulated. In this simulation, the different height of hair cell is chosen including 6000µm, 4000µm and 1000µm in order to investigate the effect of length to the performance of sensor. As mentioned before, FLUENT gave results for drag force and its depended on the size of the surface area of sensor. Fig. 6 shows the plotted graph for the drag force with different length of hair cell. . The drag force is increased as the length of hair cell increased. The 1000µm length of hair cell produced smallest drag force due to the small surface of the hair cell compared to others, while hair cell with length of 8000µm recorded the highest drag force. Thus, it indicated that as the length of hair cell increased, the drag force is increased.

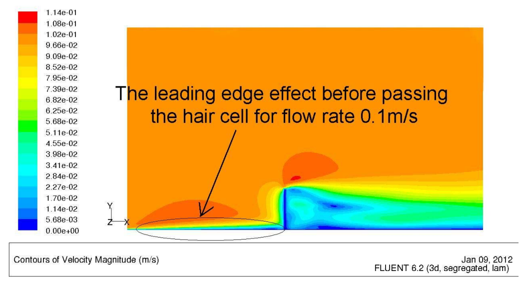

Figure 5. The velocity contour along the x-direction for flow rate 0.1 m/s.

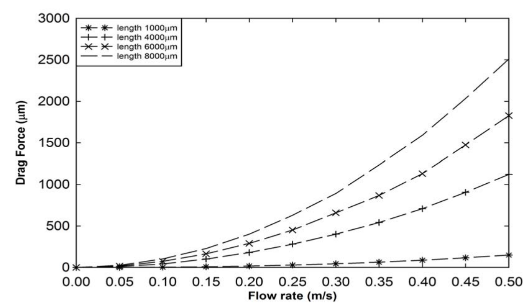

Figure 6. The drag force imposed to the hair cell with effect of different length of hair cell

For the strain measurement, ANSYS was used to analyze the strain distribution of the hair cell. Next, the hair cell with different materials was simulated. The different materials such copper, silicon and tungsten were selected to study the effect of different types materials to the performance of sensor where the length is fixed to 8000µm. As expected, material with low Young Modulus such as copper gave the maximum value of strain while, tungsten gave the lowest value of strain as shown in Fig. 7. Therefore, the effect of different types of materials should be considered during designing the sensor.

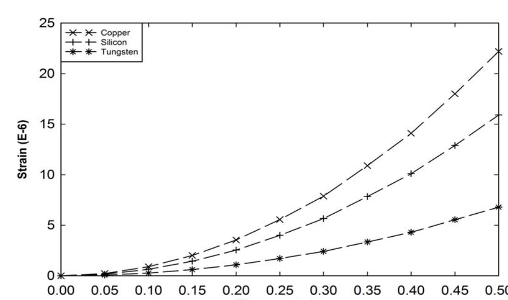

Figure 7. The measurement of strain for different types of materials.

The biomimetic flow senor with hair cell 8000um length, 2000um width and 100um thickness was fabricated using thin copper film because it gives the high strain compare with silicon and tungsten. The 100μm copper film was cutting using wire EDM (electrical discharge machining) process to form the cantilever. The strain gage was installs upper and lower of the cantilever which connected to the Wheatstone bridge. As mentioned in methodology, the output from the Wheatstone bridge will be amplified and display to the computer. For the measurement process, the sensor with one edge was polished to present a sharp profile facing the flow was attached to the rectangular bar and the position of the biomimetic flow sensor was totally merged in the water as shown in Fig. 8. The flow rate was manually controlled by using the titling flume channel where it produced the laminar flow. The flow range 0.15m/s until 0.45m/s was applied passing the sensor and the raw data was recorded in the HyperTerminal. The experiment was triplicates for each flow rate and the average value was taken to ensure the accuracy of data. The comparison between the experimental and simulation results is plotted in Fig. 9. The voltage for the simulation result is obtained using equation (8) by substituting the value of strain. In the real applications, the turbulence may be caused by many means including platform itself and the wall of channel.

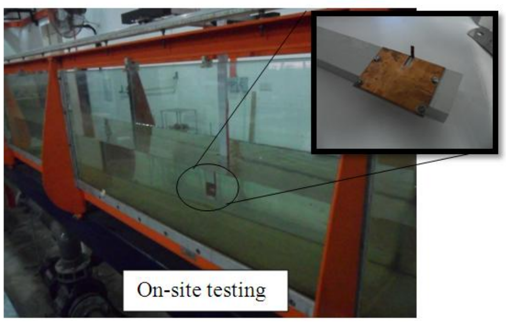

Figure 8. The biomimetic flow sensor fully merged in the water

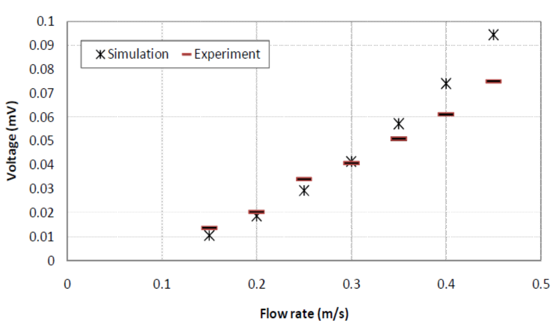

Figure 9. The comparative study between the simulation and experiment

This work can be extended from the individual to an array of biomimetic flow sensor to perform in underwater environment especially for monitoring or surveillance based artificial lateral line system. The system consist of an array of sensor will be able to localize the moving object, determine the distance and detection of wall.

IV. Conclusion

The biomimetic flow sensor with 8000μm length, 2000μm and 100μm of hair cell was successfully simulated and fabricated. This study using the computational fluid dynamic and finite element method proved that the different length and different types of materials of hair cell have significant effect to the strain distribution of hair cell. Highest performance of sensor was achieved by increasing the length of hair cell and using a low elastic modulus material. A comparative study was made between the simulation and experimental result according to the dimensions given.

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