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Modeling and Simulation of Artificial Hair Cell Sensor for Underwater Applications

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This article uses finite volume and finite element methods for optimization of the artificial hair cell sensor. The performance of the sensor was investigated for different materials such as sicon and polysilicon and by varying hair cell dimensions including width and length. The silicon material which has low young modulus was proposed based on the simulation performance. The performance of the hair cell sensor was achieved by increasing the hair cell length while increasing the width did not significantly influence the performance. The performance of the sensor was studied for its viscous force, deflection, von mises stress and sensitivity. From the simulation, the hair cell with a length of 1600 μm and 80 μm width was suggested for the subsequent analysis. Another way to improve the performance was by modifying the hair cell geometry and it was proved that the modified hair cell was more sensitive, based on the deflection. The angle of flow that hit the hair cell also affected the deflection of the sensor where the zero angle flow which was parallel to the substrate was the most effective angle. The limitations of the performance of hair cell for various fluid velocity were also discussed in this paper.

Key words: Finite element method; silicon; polysilicon; viscous force; deflection; von mises stress; fluid viscosity; flow sensor

In the recent years, research on the flow sensor for underwater application has been carried out using various designs, materials, and sensing elements. The purpose is to optimize the dimension and to achieve high performance of the sensor. The conventional sensing method such as hot wire anemometry and the Doppler frequency shift have a limitation in terms of size where it is too large and not suitable to form an array especially for measuring the flow distribution (Fan *et al*. 2002). From nature, researchers found the new inspiration in designing the flow sensor based on the hair cells inside the lateral line system in the body of the fish where it is more simpler and can improve the performance. The Micro-electromechanical system (MEMS) fabrication technology also helped the researchers to miniaturize and to achieve high efficiency of the flow sensor. Most of the researchers used piezoresistive, strain gage and capacitor as a sensing element (Tao & Yu 2012). For underwater applications, an array of hair cell sensors helped vehicles to navigate and monitor and that which mimic the function of the lateral line system to form the hydrodynamic images for flow imaging for underwater environments (Coombs 2001).

A lateral line system that span the length in the body of the fish consists of two types of neuromast, that is superficial neuromast and canal neuromast. Superficial neuromast directly expose the flow and canal neuromast exists in subepidermal canals. Generally, fishes that live in distilled water tend to have many superficial neuromasts compared to canal neuromasts which are suitable for the fish to live in turbulent waters. Both neuromasts are composed or hair cells that are embedded in the gelatinous cupula. When the fluid passes the neuromast, it will cause a gelatinous cupula movement and the hair cell will induce neuron signals (Engelmann, Hanke & Bleckmann 2002). The general overview about hair cell is that it consists of a vertical cilium that is attached to a neuron, and this neuron is attached to the cilium stretchers. If the cilium of the hair cell is bent by the fluid flow, the displacement will induce output responses (Fan *et al*. 2002). In this paper, we focus on the modeling and simulation of a single hair cell to study its performance based on the effect of the material, dimension including width and length of the hair cell, geometry and the angle of flow to the sensor performance.

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APPROACH AND METHODS

As mention before, the biomimetic flow sensor was inspired from the hair cell that embedded in the gelatinous cupula as shown in Figure 1a. Generally, the mechanism of the hair cell is evident when the cupula gelatin move, it will deflect the hair cell and induce the neuron signal. By using the same principle, the artificial hair cell sensor was proposed. Figure 1b shows the structure of the artificial hair cell and we considered all the surface had a rectangular cross section. For the sensing principle, when external flow was applied onto the hair cell, it would give some deflection and induce strain at the base of the hair cell. The magnitude of the induced strain could be sensed by many means, for example, by using integrated piezoresistive sensors. The length, thickness and width of hair cell were *L, t,* and *w*, respectively.

Given the relationship between the relative change of resistances (sensitivity) and the flow rate in Equation 1. From the equation, we knew the sensitivity ($\Delta R/R$) of the hair cell was depended on the flow rate (u_o), density fluid (ρ), young's modulus (E), thickness (t), length (L) and the boundary-layer thickness (δ) (Equation 1).

$$\frac{\Delta R}{R} = \frac{3GwC_D\rho u_{o2}\left(\frac{L^4}{\delta^2}+\frac{L^6}{6\delta^4}-\frac{4L^5}{5\delta^3}\right)}{Et^2} \quad (1)$$

C_D is the drag coefficient and it is depended on the Reynolds number. We assumed the flow was laminar and Reynolds number is given as:

$$Re = \frac{u_o x}{\upsilon} \quad (2)$$

where, x is the hair cell location from the leading edge and υ is the kinematic viscosity. For the simulation, the biomimetic hair cell was modeled using computer-aided engineering software ANSYS (<http://www.ansys.com>). This software help researchers to analyze the model for the drag force acting on the hair cell, deflection of the hair cell, the distribution of stress and the sensitivity of the sensor. The parameters that were considered in this simulation are the material, width and length of hair cell, and also the angle of flow facing the hair cell. In ANSYS, two tools were used: ANSYS FLUENT and ANSYS Mechanical APDL. Recently, the same method of simulation in the setup was done and compared with the experimental result (Nawi *et al*. 2012). Therefore, the same method was used for this simulation.

When related to the fluid, we need to study the drag force acting on the hair cell. The FLUENT is a finite volume based software that runs a numerical simulation using Navier-Stokes equation. The Gambit software inside the FLUENT was used to model and generated the mesh. In mesh generation, the Tet/Hybrid element was chosen due to design geometry and 1228146 mesh volume was generated. Figure 2 shows the geometry model for hair cell it boundary condition. The hair cell is located *x* mm from the leading edge where in this simulation the leading edge of 3 mm was fixed. The inlet was set to velocity inlet for several of the velocity to apply to the hair cell. Meanwhile the top and outlet was set to the pressure outlet. For the hair cell and the bottom of the hair cell, the boundary was set to the wall. The iteration for simulation was stopped at 250 because it had already met the criterion, and it was limited to 1E-5 for convergence criterion. To study the performance of sensor for deflection and stress to the applied velocity, the result from the ANSYS FLUENT was transferred to the ANSYS Mechanical APDL. Modeling in Mechanical APDL began by choosing an element type, and entering the material properties. The list of property materials such

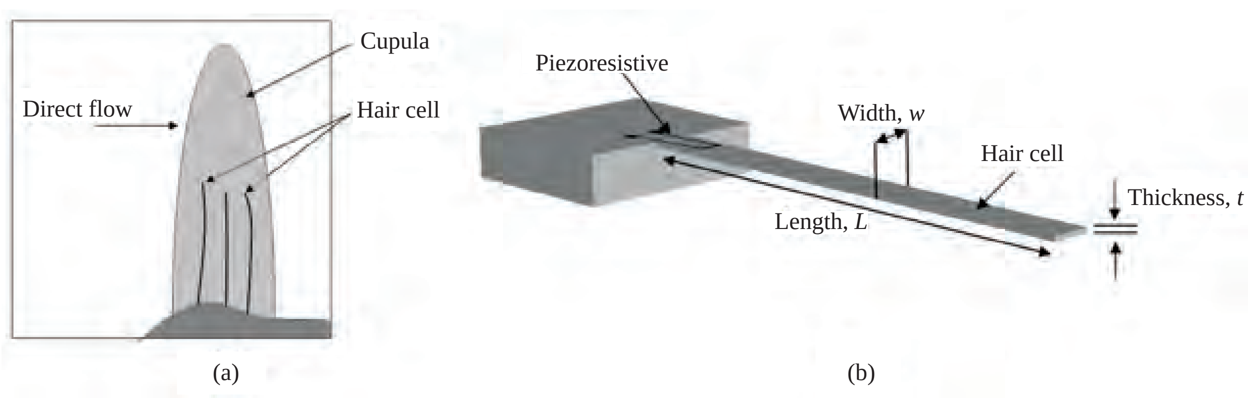

Figure 1 (a) Hair cell embedded in gelatinous cupula; (b) Artificial hair cell.

as Young's Modulus and Poisson's ratio are shown in Table 1. The model was then meshed and applied (the load) to the hair cell. The hair cell structure was fixed at one end, and applied load, at the other. The deflection of the hair cell would induce the value to the piezoresistive and sensitivity could be obtained.

RESULTS AND DISCUSSION

In this section, we discuss the effect of hair cell to a certain parameter as mentioned before, that is the material, width and length of the hair cell, geometry and also the angle of flow facing the hair cell. Figure 4 shows a comparison between PolySi and Si hair cell using the same dimension and velocity applied based on deflection. It was clearly shown that Si provided higher displacement over PolySi for the same applied load making Si more suitable to be used as a highly sensitive flow sensor. Therefore, for the next simulation process we used silicon as the material. Then we simulated for different hair cell dimension including the width between 120 µm to 640 µm and length 800 µm to 1600 µm. By assuming that the flow was laminar, the fluid velocity 1m/s which parallel the substrate was applied to the hair cell. From the ANSYS, the three parameters including viscous drag force, deflection and von mises stress could be observed as shown in Figure 5. For the viscous drag force acting on the hair cell, it depended on the surface area of hair cell facing the flow where the drag force increased as a surface area increased. It was proven when we saw the maximum drag force which was 616 µN for the largest surface area of hair cell measuring 640 µm × 1600 µm. It was different for deflection and stress of the sensor where the only highest length gave the maximum value for deflection which was 65.6 µm and for mises stress it was 64.9 MPa. The width of the hair cell did not contribute to the major effort of the performance of the sensor. The same was also true for sensitivity of the sensor where the maximum sensitivity was 0.045E-6 for the hair cell with a length of 1600 µm and a width of 80 µm. However, the effects of hair cell thickness was not investigated. Next, the hair cell with a modification of geometry was simulated to study its effect on the performance of the hair cell sensor.

The modification of the hair cell was by removing a certain area in order to improve the performance of the sensor. The 20 µm deep segment in the left and right was removed at the bottom of the hair cell sensor to reduce the moment inertia at that area as shown in Figure 6. The contour bars represent the stress value where the different colours indicated different values of stress. The red colour for the maximum miss stress value acted on the hair cell. As we can see, the mises stress for original geometry had a uniform stress distributed along the hair cell and

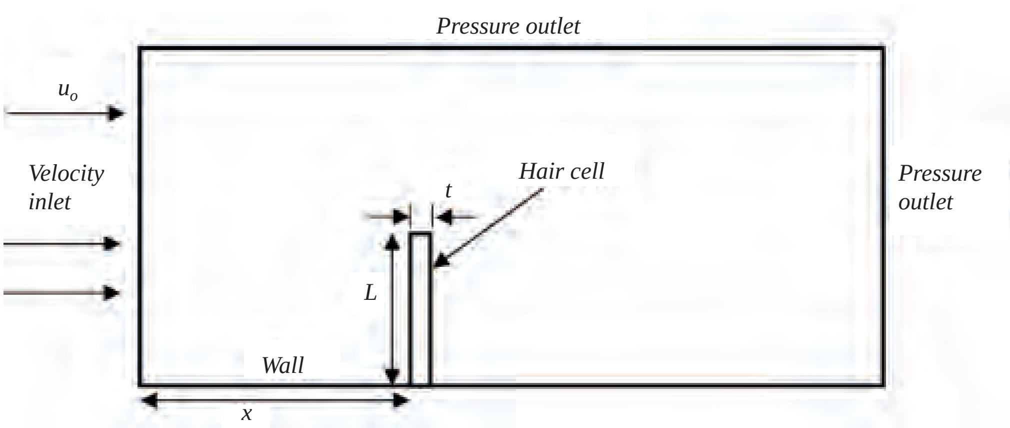

Figure 2. The geometry of the computational domain in FLUENT.

Table 2. Material properties of silicon.

Parameter	Silicon	Polysilicon
Young's Modulus (GPa)	130.1	169
Poisson's Ratio	0.278	0.22
Piezoresistive coefficient (MPa^{-1})	$\Pi_{11} = 6.6 \times 10^{-5}$ $\Pi_{12} = -1.1 \times 10^{-5}$ $\Pi_{44} = 1.381 \times 10^{-3}$	

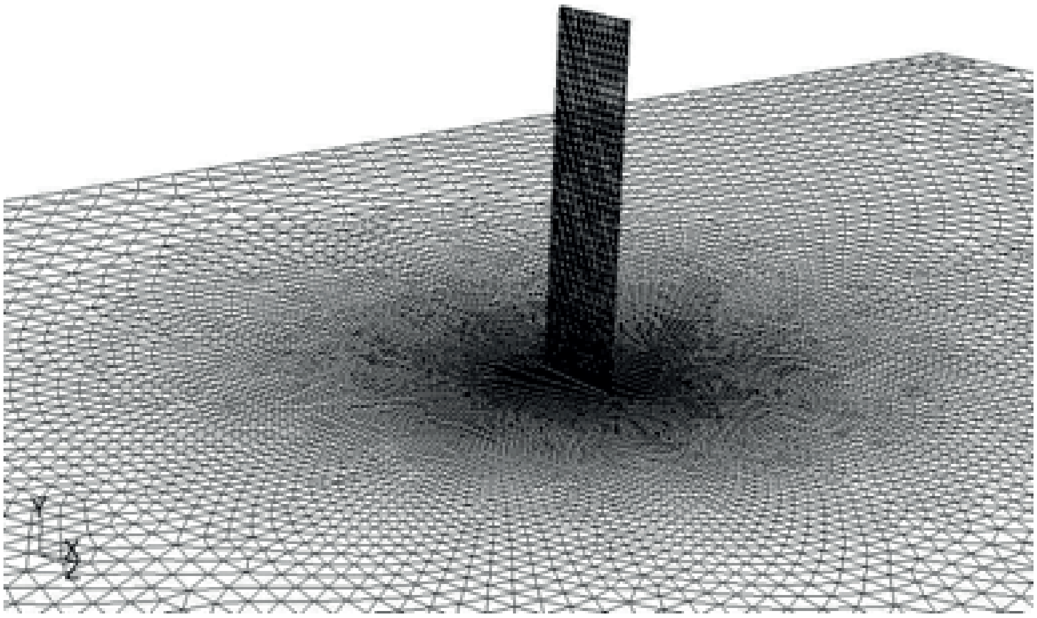

Figure 3. The meshing for the hair cell and the bottom surface.

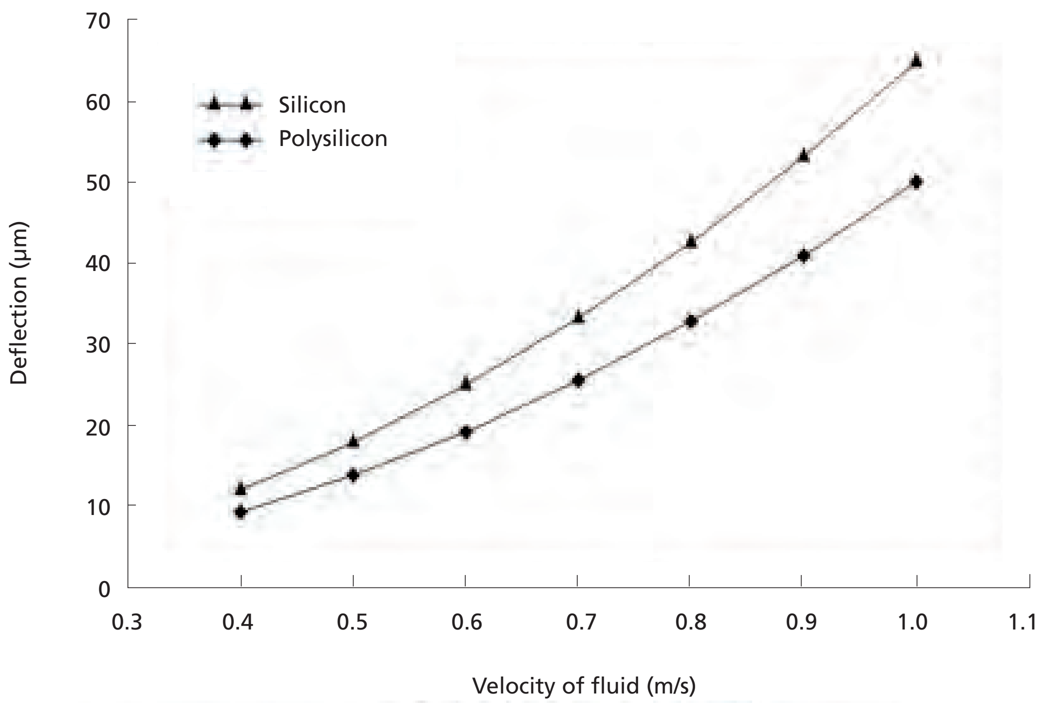

Figure 4. The deflection comparison between PolySi and Si material for the same applied velocity of fluid.

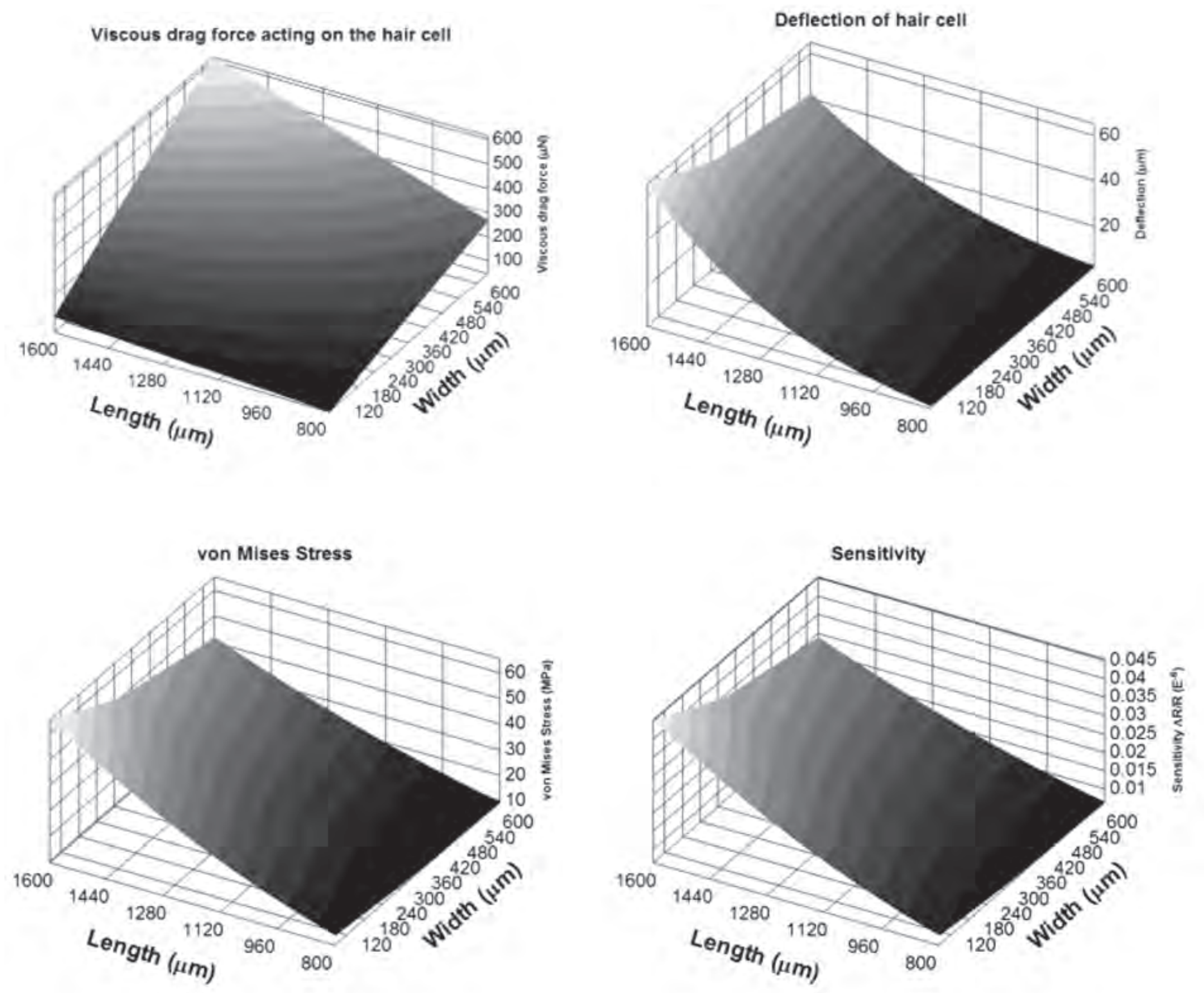

Figure 5. The sensor performance based on the viscous drag force, deflection, von mises stress and sensitivity of hair cell.

the maximum mises stress was 65 MPa. It was different with modified hair cell where the stress was concentrated on the smallest area and the mises stress value was 139 MPa and it was higher than the original geometry. The modified model was simulated for different velocities and we could observe the performance for the deflection and von mises stress as shown in Figure 7. From the figure, we could see the improvement in the modified hair cell where the deflection of the modified hair cell was higher than the original hair cell for the same applied velocity of fluid at 1 m/s. The maximum deflection for the modified original hair cell was 78 µm and 65 µm, respectively. Meanwhile, the maximum mises stress for the modified hair cell was 139 MPa which meant that the hair cell at that condition could not be broken during measurement. Each hair cell geometry had a limitation at certain applied velocity and that limitation would be discussed later.

The other parameter that affected the performance of the hair cell was the angle of the applied velocity of flow. Figure 8 shows the deflection for the original and modified geometry of the hair cell for different angles of flow. The 0º angle which was parallel to the substrate give the maximum deflection to the hair cell. As we could see, the deflection decreased as the angle of flow increased because of the decreasing area that faced the flow. It is recommended to take the measurement in a single direction which flowed parallel to the substrate in order to obtain the maximum performance. Finally, in designing the sensor it was most important to know the limitations of the sensor based on the applied input velocity. The limitation of the hair cell was investigated by applying higher fluid velocity starting at 1 m/s and above. The hair cell could break or fail when the mises stress value exceed the yield strength of the used material. For this sensor, we were using the silicon and its value was 7 GPa. Figure 9 shows the mises stress for hair cell length at 1600 µm and 80 µm width for both original and modified geometry. It showed that the original geometry would break when the velocity of fluid higher than 10 m/s and was different with the modified hair cell

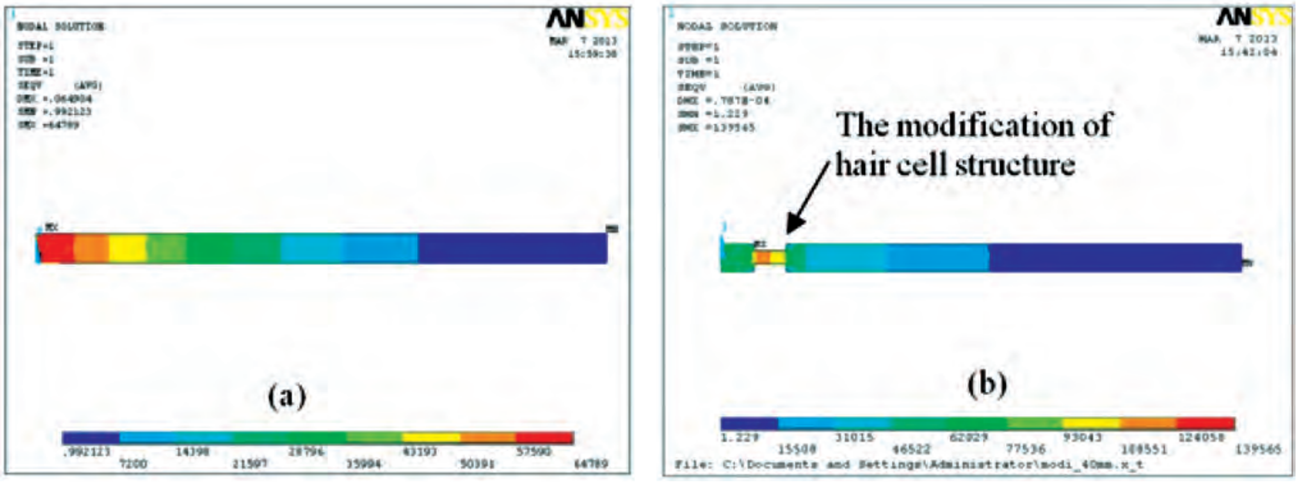

Figure 6. The stress distribution of hair cell in the same applied velocity: (a) The original shape; (b) The modified shape.

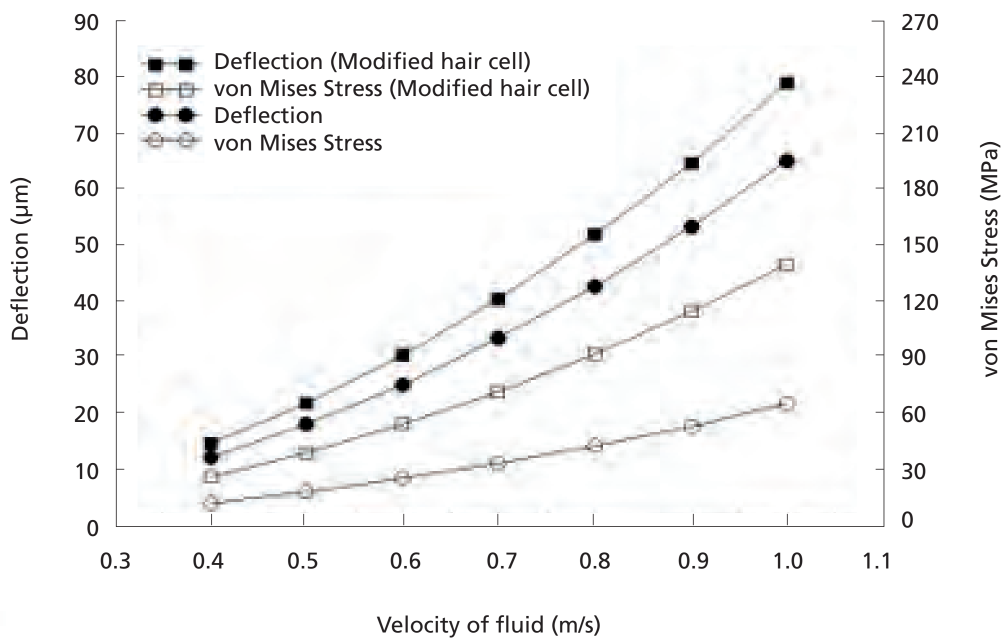

Figure 7. The comparison of deflection and mises stress for original and modified shape for the same applied fluid velocity.

where it only could survive for the 7 m/s velocity. In this paper, we focused on low velocity applications ranging from 0.1 m/s to 1 m/s of velocity. Therefore, the modified hair cell cannot be broken or fail during measurement.

CONCLUSION

The artificial hair cell was successfully simulated using finite volume and finite element methods that solved and analyzed problems that involve fluid flows. Various parameters such as material, width, length, geometry and angle of flow were thoroughly investigated. From the simulation, the silicon-based hair cell with a length and width of 1600 μm and 80 μm respectively, was proposed due to the maximum deflection, mises stress and sensitivity of the hair cell for the same applied fluid velocity. The modification of the hair cell geometry gave the best performance in terms of deflection. The flow that parallel to the substrate means zero angle gave the

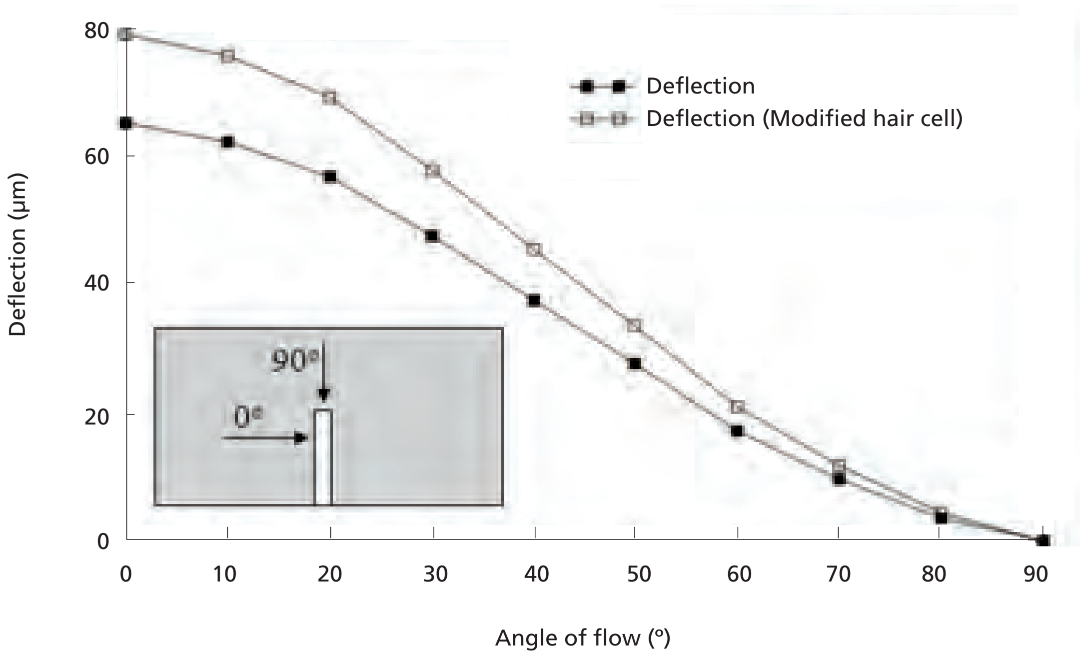

Figure 8. The deflection for different angles of flow applied to the hair cell.

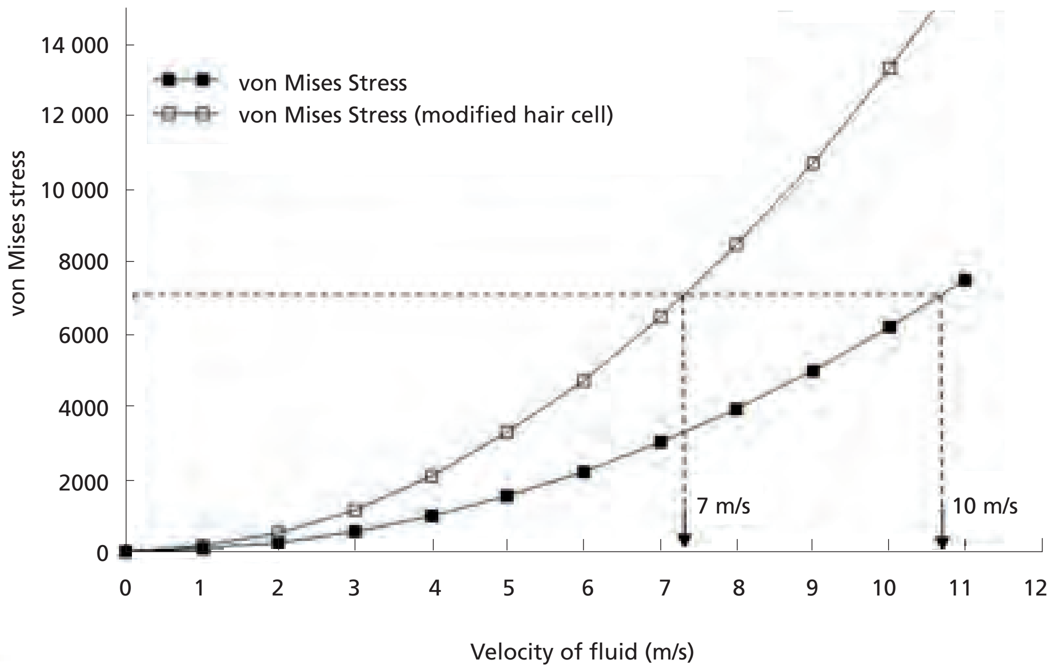

Figure 9. The limitation of the hair cell for the same applied velocity of fluid.

maximum deflection which meant the control of angle was an important parameter for future work. The limitation of the deflection of hair cell was obtained from the mises stress value and the hair cell could not be a failure during measurement when as long as the value of the stress was less than 7 GPa. For future fabrications, the hair cell with modification geometry was proposed to achieve higher sensitivity of the sensor.

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