Design and Simulation of Cantilever Array for Fluid Flow Sensing Applications

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Abstract: The biological hair-cell is a modular building block of a rich variety of biological sensors. These sensors are responsive to various mechanical properties like vibration, touch, gravitational forces, etc., especially flow.This study aims at the design and simulation of an artificial hair-cell sensor using MEMS module of COMSOL Multiphysics 4.2a. The design consists of an array of Silicon beams fixed at one end and the corresponding out-of-plane beams attached to the distal end of the horizontal beams were designed to be made of PMMA.The physics used to simulate the working condition of the sensor was Fluid Structure Interaction. By this study, parameters that are influenced by the flow rate of the fluid, such as displacement, pressure, stress-strain, etc were evaluated. A comparison between the efficiencies of this design and conventional cantilever beams has also been made in this study.

Keywords: Cantilever array sensor, hair cell sensor, Fluid flow sensing,and pressure sensor.

1. Introduction

A mechanical sensor consists of a fixed and a movable part. Such structures are referred to a cantilever where the movable part can be a thin film, plate or a beam. A cantilever is regarded as a micro fabricated rectangular bar shaped structure that is longer than its width and its thickness is smaller than its length or width.

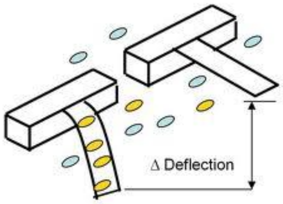

Figure 1: Cantilever based detection

Microcantilevers were first designed andfabricated for use as force sensors, possessing anextremely high force sensitivity, in the Piconewton (pN) range also. Availability ofinexpensive, mass-produced cantilevers alsotriggered applications other than imaging, wherecantilevers act as physical, chemical, andbiological sensors. These early observations laterlead to the development of a unique family ofmechanical sensors with numerous newapplications in physical, chemical and biologicalsensing. The deflection of a cantilever can be dueto number of processes such as fluid flow, thermal effects, electric and magneticfields, and molecular adsorption.

1.1 Biological hair cells

Sensors found in animals are sensitive, have a wide dynamic range, can function in a noisy environment and are often mechanically robust. They are known as hair cell sensors, a special class of mechanical cantilever sensors. Haircell sensors transfer mechanical stimuli into neuronal signals. The functions of these sensors include acoustic sensing, balance (gravitational) sensing, vibration sensing, flow sensing and joint angle sensing (for insects).

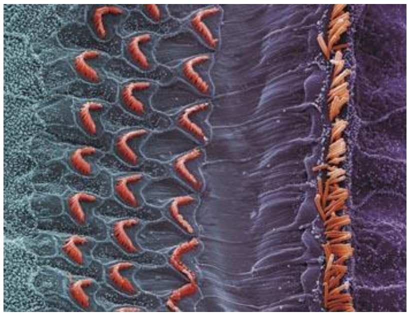

Figure 2: Scanning electron microscopy image of the mammalian cochlea. Hair cells are arranged in 3 rows of outer hair cells (to the left) and 1 row of inner hair cells (to the right). Each hair cell contains a bundle of stereocilia (orange) at the apical surface that form the mechanically sensitive organelle of the cell.

1.2Artificial Hair Cell Sensors

There are several incentives for building man made artificial haircells. First, the development of man-made haircells will provide a validation platform for studying the biological haircells themselves.

Secondly, the building of artificial haircells will increase the interest of studying biology, as the task of bioinspired engineering will demand answers to some unanswered questions in biology. This will push the frontier of biological studies.

Thirdly and most importantly, the artificial haircell will increase the engineering ability of sensor building and potentially reduce the cost of sensors. Integrated sensors are used widely today, from accelerometers in an automotive airbag deployment system to pressure sensors in patient-monitoring and microfluidic devices.

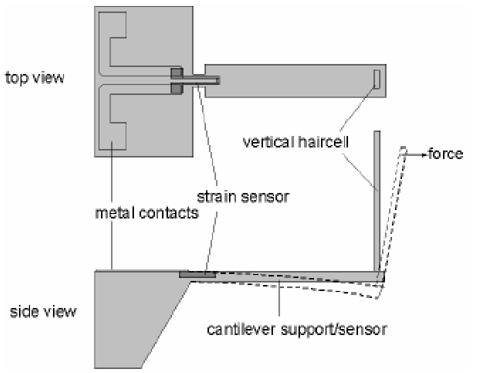

Figure 3: Schematic diagram of a single artificial haircell sensor consisting of a horizontal cantilever with a vertical polymer attached at the free end. The bending of the polymer is sensed using the strain sensor located at the base of the horizontal cantilever.

Various types of flow sensors, acoustic sensors, pressure sensors and vibration sensors have been developed using both conventional machining and micromachining technologies based on the concept of hair cell. They are based on a variety of materials (including semiconductor, oxide and polymers) depending on the application.

1.3Cantilever Array Sensors

The artificial hair cell constructed as an array has higher sensitivity.

1.4 Applications – Micro fluidics

AHC sensors can be used as flow sensors for;

a) Underwater hydrodynamic imaging and vehicle maneuvering (threat detection/tracking)

b) Environmental issues for air and water quality detection.

c) The development of medical diagnostic tools for a large number of genetic tests that are performed with small amounts of single donor-blood or body-fluid samples

d)Energy harvesting applications

2. Theory and Principle

Each sensor consists of an in plane cantilever with a vertical artificial cilium attached at the distal, free end. External flow parallel to the sensor substrate imparts friction drag and pressure drag upon the vertical cilium. Due to a rigid connection between the in-plane cantilever and the vertical cilium, a mechanicalbending moment is transferred to the horizontal cantileverbeam, inducing longitudinal strain at the base of the cantileverbeam. The magnitude of the induced strain can be sensed bymany means, for example by using integrated piezoresistivesensors, which change resistance upon deformation. It can be interrogatedby the resistance change by passing a known current through the piezoresistor and monitoring the voltage drop.The piezoresistor can be made by selectively doping regionsof the silicon semiconductor substrate. It should be notedthat though neurons are used in biology for both sensing andsignal conditioning, an engineering equivalent of the neuronis not available, so that signal processing downstream of thesensor is the primary way to reduce noise or extract relevantinformation from specific aspects of the sensor output.

3. Use of COMSOL Multiphysics

The MEMS based Hair cell array and conventional cantilever for flow sensing was modeled and simulated usingCOMSOL Multiphysics 4.2a - MEMS module.

Materials: Theconventional cantilever was made of silicon as fixed end and PMMA/Si as movable end, whereas the cantilever hair cell array was made ofSilicon, Poly Si and PMMA. The block encapsulating the geometry represented the fluid (Water) flow.

Geometry: The geometry involves the usage of rectangular vertical thin barsin case of conventional cantilevers supported by a horizontal bar.

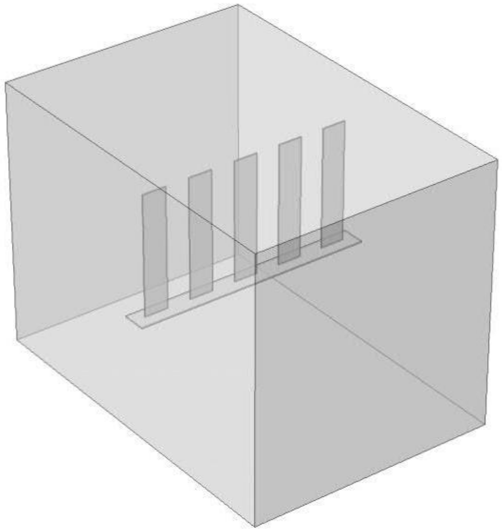

Figure 4: Conventional cantilever

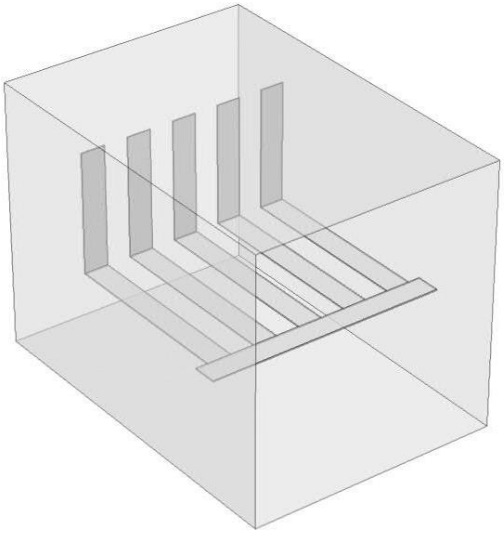

Figure 5: Cantilever Hair cell geometry

In case of Hair cell array, the hairy mimic is vertically placed rectangular bars on the cantilevers.

Physics Used: The Fluid structure interaction (FSI) physics was used to apply a fluid flow. The force corresponding to the pressure exerted on the vertical beams due to the fluid flow tends to create a specific displacement.

5. Equations

When an external force is applied to the vertical beam, through the drag force from fluid flow (flow Sensing), the beam will deflect and cause the beam to stretch or compress. The silicon strips are treated as beingrigidly(comparable to polymer strips) attached to the substrate, while the polymer strips are free.

Themagnitude of the induced strain (ε) is largest at the base, wherethe PMMA is located,

$$\varepsilon = \frac{M t_{PMMA}}{2EI}$$

Where M is the moment experienced at the base, $t_{\mathrm{PMMA},}$ the PMMA thickness and E and$I$ are the modulus of elasticity and the moment of inertia of PMMA,respectively.

6. Results and discussions

The simulation results for both the conventional and hair cell design was obtained as shown:

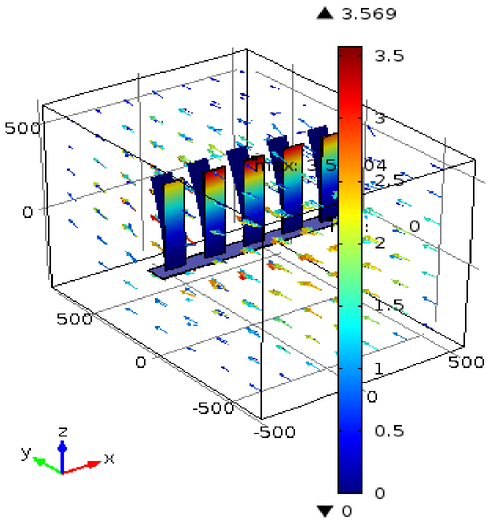

Figure 6: A conventional cantilever sensorwith lower deflection efficiency of only 3.569 µm displacement.

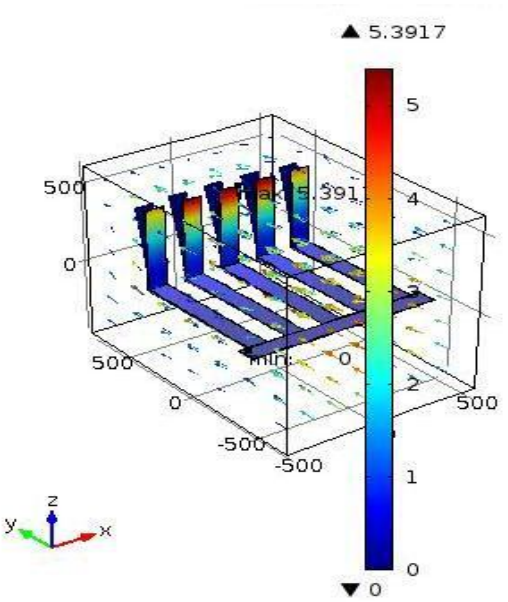

Figure 7: A cantilever hair cell sensor with higher deflection efficiency of 5.3917 µm displacement.

COMPARISON WITH SI(C)

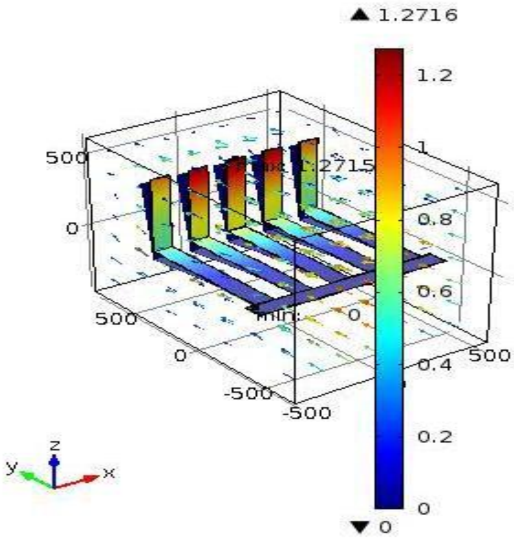

Figure 8: Simulation of sensor based on Silicon cilium, Frontal fluid flow (Smaller displacement).

DIFFERENT DIRECTION SENSING

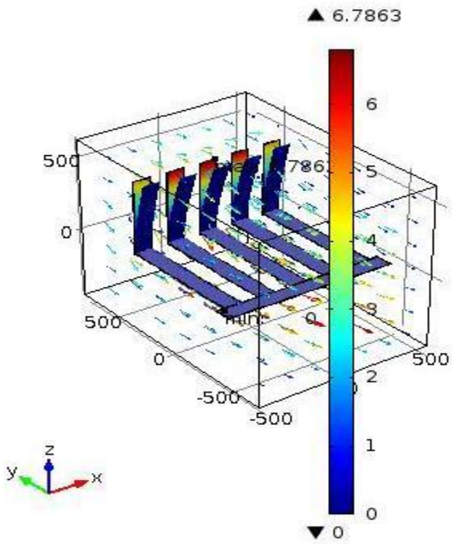

Figure 9: Simulation of the sensor based on PMMA polymer cilium, Backward fluid flow (Larger displacement).

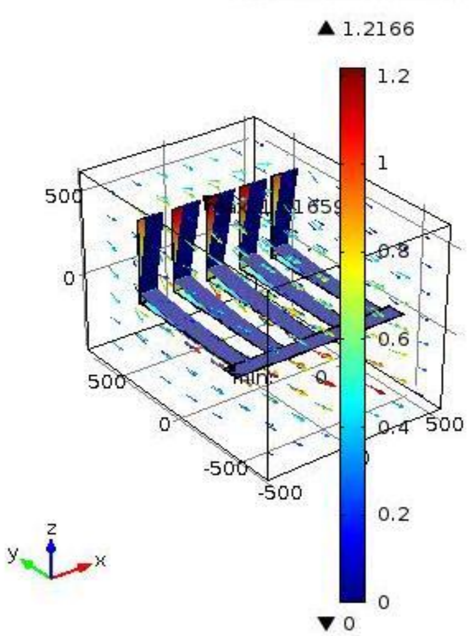

Figure 10: Simulation of sensor based on Silicon cilium, Backward fluid flow (Smaller displacement).

PARAMETRIC SWEEP

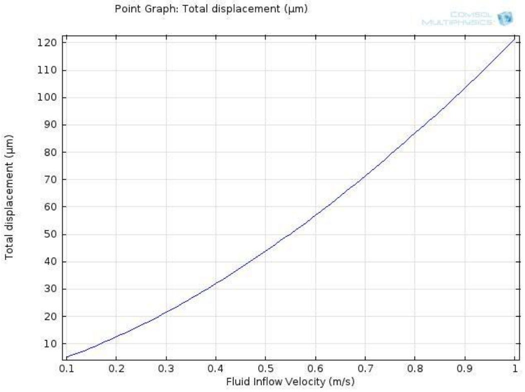

Figure 11: Graph showing the change in displacement when fluid flow was increased from 0.1 to 1ms^{-1}.

ENERGY HARVESTING

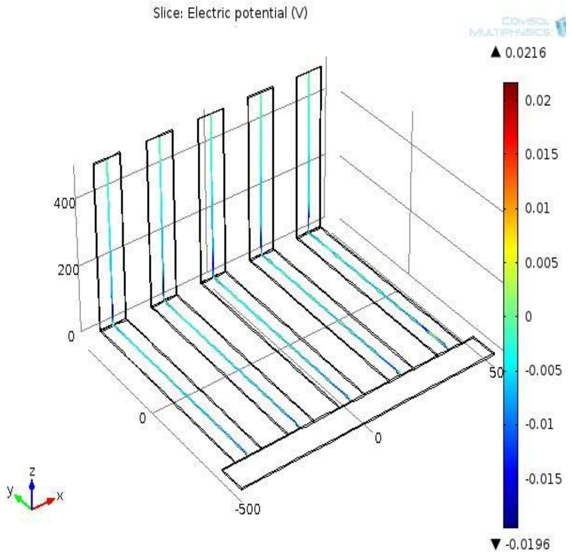

Figure 12: Potential slice plot indicating the output voltage obtained due to bending of the beam, when PZT was used as a material

7. Conclusions

The mathematical model of a MEMS based cantilever Hair cell sensor was designed and the Finite Element Analysis simulation completed.
The displacement in case of PMMA cilium in forward and backward fluid flow was found out to be 5.3917µm and 6.7863 µm respectively. The displacement in case of Si cilium in forward and backward fluid flow was found out to be 1.2716 µm and 1.2166 µm respectively.
This represents the higher sensitivity of PMMA polymer based cilium than Si based. Further, it was proved that efficiency of hair cell cantilever is more than a conventional cantilever with the displacement to be 5.3917 µm and 3.569 µm respectively. Also, if a piezoelectric material such as (PZT) is used; a detection scheme is achieved as a voltage output. When an array of cantilevers is used, the deflection of the beam in just one of the beams can be taken for detection while the output from the other beams can be stored thus paving way for an energy harvesting application. This harvested energy can be therefore power the microfluidic device.

Twomajorconclusions can be drawn from this design:
(1) The response of each sensor is bidirectional—i.e. the sensor response changes signs depending on the directionof the applied flow.
(2) The response sensitivity is a function of the presence of the PMMA hair.
(3) A self-powered microfluidic device is a possibility.

8. References

1) Chang Liu, Micromachined biomimetic artificial haircell sensors, *Bioinspiration&biomimetics*, Volume 2, S162–S169, 2011