Modelling and analysis of SU8/CB nanocomposite polymer flow sensor

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Abstract. This paper studies the effect of diaphragm size and stylus design on flow measurement characteristics of a polymer flow sensor. The sensor is made of two piezoresistive SU8/CB nanocomposite polymer cantilevers integrated with diaphragm carrying a free standing stylus its centre. The fluid flow drag force deflects the stylus which in turn deforms the anchoring cantilevers and changes their electrical resistivity. Finite element analysis software ANSYS Multiphysics used to determine the deflection, stress and sensitivity characteristics of the flow sensor at different velocities. Results show that sensitivity of flow sensor decreases with increase in diaphragm size and square stylus has better sensitivity.

1. Introduction

Flow sensors are devices used to determine flow properties of fluid like velocity, volume flow rate, flow profile and flow discontinuity. These sensors are commonly used in flow metering systems to measure discharge rate and volume. The objective of present study is to design a low velocity fluid flow sensor that can detect water flow of the order of few cm/s. Polymers are natural candidate to be used as such sensing application due to their flexible and broad spectrum of customizable properties. Though polymers generally behave as electrical insulator, but they can also be tailored to be electrical conducting. Conducting polymers are a class of polymers that conduct electricity. Electrically non-conducting polymers can be made conducting by inserting conductive fillers, like carbon black (CB), CNT, graphite, Au and Ag in a concentration beyond their conduction threshold limit inside the non-conducting polymer matrix than can be SU8, PDMS, ABS, PMMA etc. In general, conducting polymers can be classified into four categories: conducting filled polymers, ionic conducting polymers, charge transfer polymers and conjugate conductively filled polymers [1]. Some examples of filler based conducting polymers include SU8/Au [2], SU8/Ag [3], SU8/CB [4], PDMS/CB [5].

Conductive polymers show piezoresistivity phenomena wherein their electrical resistivity changes when these are compressed. This behaviour can be used to design novel sensors including strain sensor [6], gas sensor [7], biosensor [8] and humidity sensor [9]. Micro-electro-mechanical systems (MEMS) flow sensors use different principles to detect air flow. Hot-wire anemometry is the most common type wherein the rate of cooling due to flowing air is used to determine flow rate [10]. Shear-stress sensors can also be used to determine fluid flow and its viscosity [11]. These sensors are normally made of silicon and are fabricated using standard silicon microfabrication technologies. Polymer flow sensors can be a substitute to these because of their inherent advantages like low cost, disposable, easy to fabricate and biocompatible.

The objective of present work is to design a polymer flow sensor employing two SU8/CB-based piezoresistive nanocomposite anchoring cantilevers. The stylus and its supporting diaphragm is made of SU8. A commercial finite element analysis software ANSYS Multi physics is used to determine flow properties in terms of drag force exerted by the flowing water on one face of the stylus. The
deflection, stress and resistance change, i.e., sensitivity of the flow sensors is studied by varying the diaphragm size and the stylus shape under different water flow rates.

2. Design and Simulation
Flow sensor based on the concept of drag force which is applied normal to surfaces normal to flow direction. Drag is a mechanical force. It is generated by the interaction and contact of a solid body with a fluid (liquid or gas). For drag to be produced, the solid body should be in contact with the fluid. Drag force can be given as: \( F_D = \rho C_D A V^2 / 2 \), where, \( C_D \) is the drag coefficient, \( A \) is projected area the object facing the fluid, and \( \rho \) is the density of the fluid. The value of drag coefficient is 1.5 for rectangular and 1.4 for square stylus. Figure 1 shows the schematic design of two different types of flow sensor. One has square cross-section stylus and the other has rectangular one. The cantilevers have three-layered structure with 100 \( \mu \)m thick SU8 bottom substrate layer, 20 \( \mu \)m thick conducting middle layer with 8% volume concentration of carbon black, and 5 \( \mu \)m thick SU8 top substrate layer. The diaphragm is single structure which is attached with two micro-cantilevers at two edges. These two micro-cantilevers have been arranged only in one direction from i.e., \( y \)-direction. A free standing stylus of different shapes has been taken. The material properties for two different materials are elastic modulus for SU8 is taken as 6 GPa and for middle layer SU8/CB modulus is 6.72 GPa [Mahak]. Poisson’s ratio for both the material is about 0.22.

![Figure 1. Schematic and finite element models of polymer flow sensor with square and rectangular stylus. Meshing, load and boundary conditions are also indicated.](image-url)
Figure 2. Geometric dimensions of square (left) and rectangular (right) stylus flow sensor designs.

Figure 2 shows the detailed geometric design of the two flow sensors shown earlier in figure 1. The stylus size is fixed as 1250×1250×5000 μm for square and 1250×500×5000 μm for rectangular. The size of the square diaphragm was changed as 1750 μm, 2750 μm and 3750 μm for both cases. The total thickness of diaphragm is fixed as 125 μm. The sensing characteristics of the sensor were determined using commercial finite element analysis software ANSYS Multiphysics v.12. Deflection, stress and resistance change, i.e., sensitivity, results were determined for the two sensor designs at three different fluid velocities. Finite element model was meshed by using solid brick 8-node SOLID45 element. Hexahedral elements of size 25 μm are chosen for meshing. Mesh convergence was performed before setting the final element size. All the boundary conditions and load have been applied. The total average longitudinal elastic strain in two piezoresistors is determined and is multiplied with gauge factor to calculate relative change in resistance using relation, ΔR/R = Kε, where K is a gauge factor ε is average longitudinal strain induces in piezoresistor. The gauge factor, K = 90 [12].

3. Results and Discussion

Table 1 presents the numerical results for the effect of diaphragm size on maximum deflection, maximum stress and resistance change, i.e., sensitivity, of square and rectangular flow sensor designs for flow velocity of 500 mm. As can be seen in the table, deflection values decrease with increase in diaphragm size for both sensor types. This can be attributed to larger torsional stiffness offered by the diaphragm to stylus rotation. Rectangular design is showing higher deflection values of more than 50% than square. Maximum stresses induced in the sensor are also presented the table. The stress values decrease with increase in diaphragm size for square designs, but the trend is reversed in case of rectangular case. The sensitivity results show a decrease when the diaphragm size is increased, and the square design is showing about 15% higher sensitivity than rectangular.

| Diaphragm size (μm) | Square Deflection (μm) | Rectangular Deflection (μm) | Square Maximum stress (MPa) | Rectangular Maximum stress (MPa) | Square Sensitivity, ΔR/R (%) | Rectangular Sensitivity, ΔR/R (%) |
|---------------------|------------------------|-----------------------------|-----------------------------|---------------------------------|-----------------------------|---------------------------------|
| 1750                | 2.65                   | 4.35                        | 0.576                       | 0.674                           | 0.124                       | 0.119                           |
| 2750                | 2.63                   | 4.08                        | 0.564                       | 0.727                           | 0.061                       | 0.058                           |
| 3750                | 2.61                   | 3.90                        | 0.518                       | 0.792                           | 0.023                       | 0.020                           |

Figure 3 shows the deflection, stress and SU8/CB piezoresistor element longitudinal strain distribution in diaphragm size 3750 μm when exposed to water flow of 500 mm/s. The strain values are multiplied with gauge factor to determine the resistance change and therefore the sensitivity of the flow sensor to the water flow velocity. A theoretical model to predict deflection can be found in [9].
Table 2 shows the effect of velocity of deflection, stress and sensitivity characteristics of the square and rectangular flow sensors for diaphragm size 1750 μm. The deflection values increase in a proportional of the flow velocity squared. Similar correlation also observed in case of stress and sensitivity. Since the maximum stress induced is less than failure strength of SB8 34 MPa [10], the designs studied here are safe from fracture failure.
Table 2. Comparison between deflection, stress and sensitivity results of polymer flow sensor at different water flow velocities and diaphragm size 1750 μm.

| Flow rate (mm/s) | Deflection (μm) | Maximum stress (MPa) | Sensitivity, ΔR/R (%) |
|------------------|-----------------|----------------------|-----------------------|
|                  | Square          | Rectangular          | Square                | Rectangular          | Square                | Rectangular          |
| 5                | 2.65×10⁻⁴       | 4.35×10⁻⁴            | 5.76×10⁻⁵            | 6.74×10⁻⁵            | 1.24×10⁻⁵            | 1.20×10⁻⁵            |
| 10               | 1.06×10⁻³       | 1.74×10⁻³            | 2.30×10⁻⁴            | 2.70×10⁻⁴            | 4.97×10⁻⁵            | 4.78×10⁻⁵            |
| 50               | 0.027           | 0.043                | 5.76×10⁻³            | 6.74×10⁻⁵            | 1.24×10⁻³            | 1.20×10⁻³            |
| 100              | 0.106           | 0.174                | 0.023                | 0.027                | 4.97×10⁻³            | 4.78×10⁻³            |
| 500              | 2.65            | 4.35                 | 0.576                | 0.674                | 0.124                | 0.119                |

4. Conclusions

This study investigated numerically the effect of diaphragm size and stylus design on mechanical characteristics of polymer flow sensor in terms of deflection, stress and sensitivity under different flow rates. The sensor was made of SU8 with two anchoring SU8/CB piezoresistive cantilevers. Results showed that for given flow velocity the rectangular design is showing deflection values of more than 50% than square. The sensitivity results showed a decrease with diaphragm size, and the square design is showing about 15% higher sensitivity than rectangular. In addition, sensitivity results increased with fluid velocity squared. Thus, based on the results we can conclude that flow sensor 1750 μm diaphragm size and square stylus design is the most sensitive flow sensor design.

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