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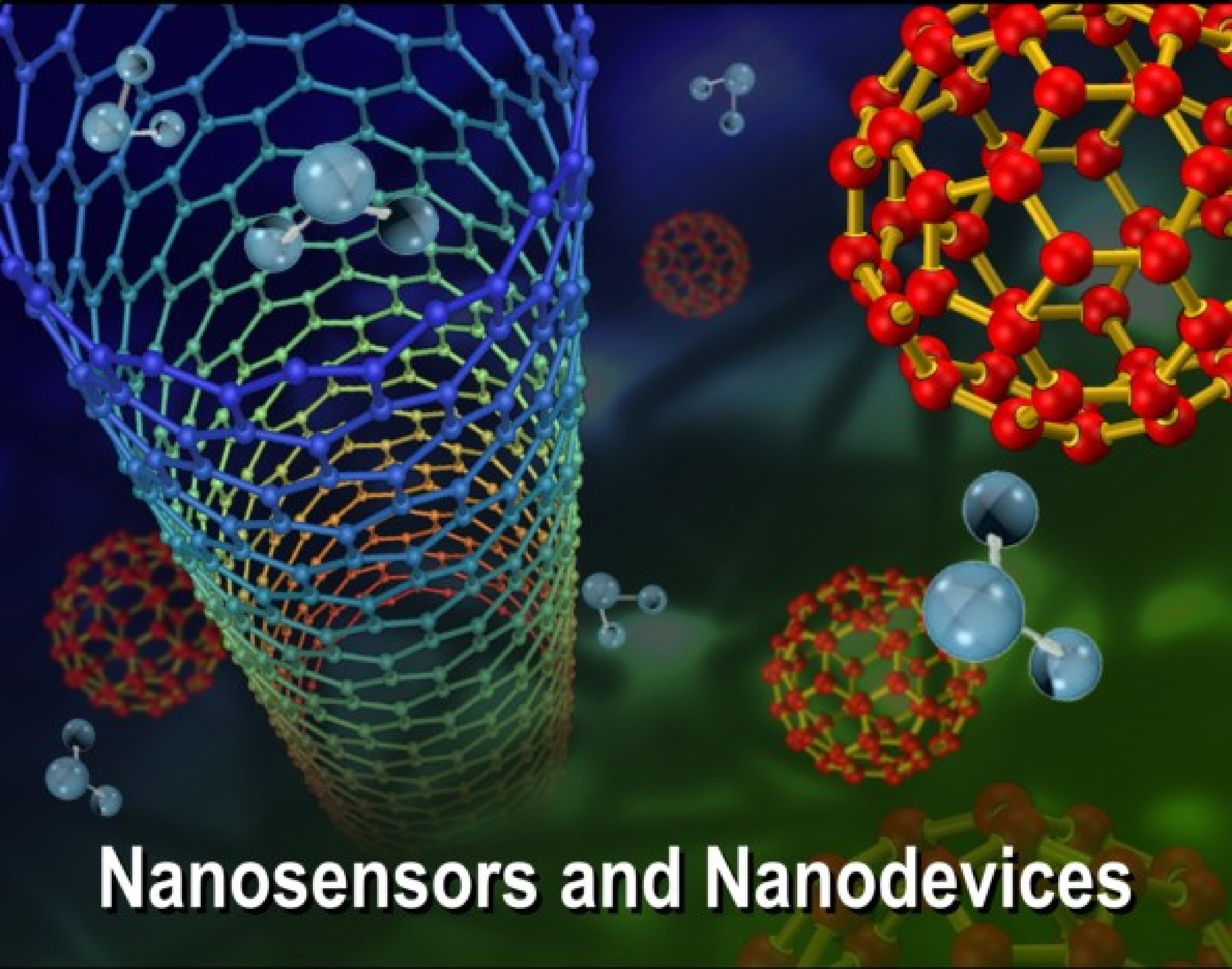

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On the Modeling of an Open Channel MEMS Based Capacitive Flow Sensor

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Abstract: In this paper an open channel MEMS capacitive flow sensor has been designed based on a microplate deflection measuring. Proposed flow sensor consists with two separate units, one for sensing the static fluid pressure and the other for sensing the fluid static and dynamic pressure. The governing equation whose solution holds the answer to all our questions about the sensor's characteristics is a nonlinear elasto-electrostatic equation. Sensor's static response and mechanical behavior of the sensing elements in a channel have been simulated numerically by using of Step by Step Linearization Method**.** The sensor stability has been examined and the stable region of the sensor has been studied. The effect of fluid velocity and static pressure on stability limit of the sensor has been investigated and the effect of bias voltage on sensor sensitivity has been studied. *Copyright © 2008 IFSA.*

Keywords: MEMS, Open channel, Flow sensor, Microplate, Capacitive

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1. Introduction

Open channel flow is defined as flow in any channel where the liquid flows with a free surface. Open channel flow is not under pressure; gravity is the only force that can cause flow in open channels and a progressive decline in water surface elevation always occurs as the flow moves downstream [1], so measuring of flow is so important for us. One of methods to know discharge is finding velocity in an open channel. In addition to measure flow, velocity helps us to find specific energy. Specific energy, E, is defined as the energy head relative to channel bottom. If the channel is not too steep (slope less than 10%) and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy become the sum of the depth and velocity head [2, 3]. The actual distribution of flow velocity is generally quite complex. Open channel flow is often laminar or near-laminar, with the different layers moving at different velocities. Flow velocity at the contact point with the channel boundary is low [4]. Typically, the highest velocity flow is located in the center of the flow channel and slightly below the water surface [1]. A general knowledge of velocity distributions is extremely important in evaluating and selecting a method of flow measurement. Sites with irregular or complicated channel geometries, such as meanders or riffle areas, can cause a decrease in measurement accuracy when using methods that rely on velocity measurements to calculate discharge. There are several methods to measure velocity in an open channel for instance: using Floats, Pitot tube, Dye Method and etc [4]. In measuring by Floats the average flow velocity in an open channel can be estimated by measuring the speed of a floating object on the surface of the water. This can be done by marking uniform distances along the channel and using a watch to measure the elapsed time location to respective downstream locations .This is not a good method, because, for example, the wind can affect the velocity of float, changing the relationship between surface velocity and average flow velocity [4]. In measuring by Pitot Tube, one end of the tube is pointed into the flow, and the other end is pointed up vertically out of the water-both ends are open. This method is best applied for higher flow velocities because it is difficult to read the head differential at low velocities, in which large errors in the estimation of velocity can result [4]. The Dye method or color-velocity method can be used to measure the flow velocity, similar to the float method. Nowadays, this method is not used to measure velocity [4].

There are other methods to measure velocity. Gradually, the use Micro-Electromechanical Systems (MEMS) has been replaced primitive methods. The advent of MEMS has revolutionized numerous branches of science and industry. The ability to accurately measure fluid velocity and flows impacts a broad application spectrum that ranges from fundamental scientific research to industrial process control, biomedical applications, etc. MEMS are often used to combine electronics with micro-size mechanical devices in the design of various types of microscopic machinery. The rapidly developing field of micro/nano-electro-mechanical systems (MEMS/NEMS) promises even more radical changes. MEMS and NEMS devices have therefore become key components of many systems, such as accelerometers [5], micropumps [6], optical switches [7], microgrippers [8], chemical sensors [9] and so on. The MEMS community has produced a variety of sensors, that, it is typically achieved by employing a floating element balance.

The goal of the present work is application of MEMS capacitive flow sensor to measure flow in an open channel. The proposed flow sensor is designed based on a microplate deflection measuring. Sensor's static response and mechanical behavior of the sensing elements in a channel have been simulated numerically by using of Step by Step Linearization Method**.** The sensor stability has been examined and the stable region of the sensor has been studied. The effect of fluid velocity and static pressure on stability limit of the sensor has been investigated and the effect of bias voltage on sensor sensitivity has been studied.

2. Model Description and Assumptions

The major component of Nano electromechanical systems (NEMS) and MEMS is generally comprised of two major parts: 1) an element which is affected by changes or mechanical part, 2) associated electronics.

The proposed device is shown in Fig. 1. It consists with two separate sensing units, one for sensing the static fluid pressure and the other for sensing the fluid flow. The upper parts of both units consist of a thin deformable elastic circular plate with thickness *t*, diameter *2R* and isotropic with Young's modulus *E* that is held fixed along its boundary and the lower part that is entitled ground plate, attached to a rigid and insensitive to electrostatic pressure changes substrate. The space between these plates is filled with a dielectric material like air.

All the structural elements of the device are assumed to be made of polycrystalline silicon. A sputtered film of aluminum is placed over the inner surface of the flexible microplates and the corresponding areas of the fixed part to create equipotential surfaces which are crucial to achieve two independent capacitors.

When the voltage between these plates and/or uniform hydrostatic or dynamic pressure (*P*) over flexible plate is applied the flexible plate is deflected toward the ground plate.

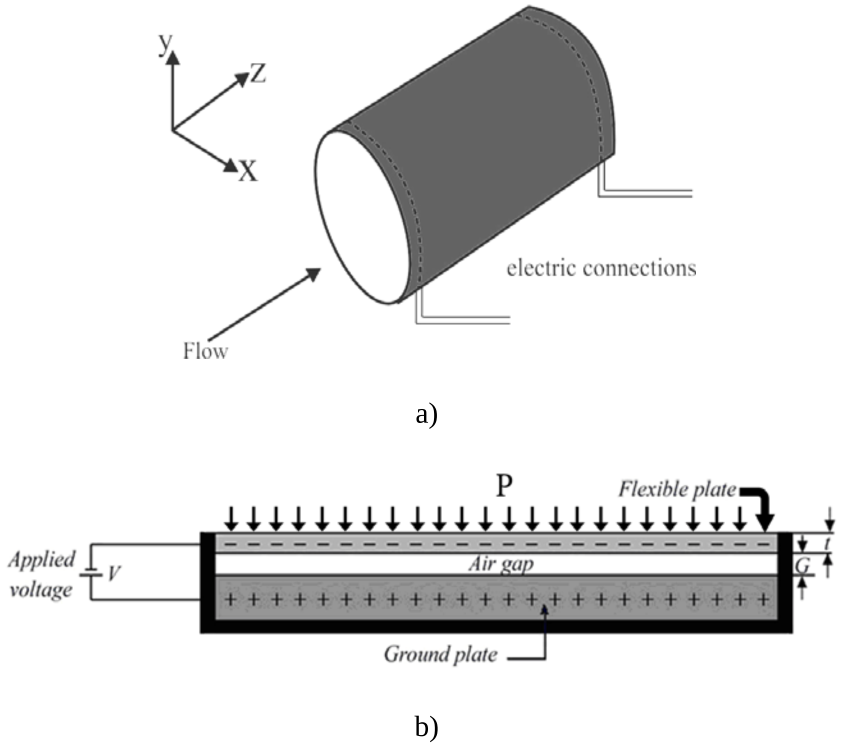


Fig. 1. A Schematic view of the device: (a) A device with two separate units, one for sensing the static fluid pressure and the other for sensing the fluid flow; (b) A cross sectional schematic of the sensing unit.

3. Mathematical Model

The bending properties of a plate depend greatly on its thickness as compared with its other dimensions. When the thickness-to-length ratio of a plate is less than 0.05 that is conventionally called thin. We should distinguish between three kinds of plates: 1) thin plates with small deflections, 2) thin plates with large deflections and 3) thick plates. The first type is of great engineering importance and the relating satisfactory approximate theory can be developed by making the following assumptions [10]:

1. Deflections w of the middle plane of the plate are small in comparison with its thickness t.
2. There is no deformation in the middle plane of the plate. This plane remains neutral during bending. It must be noted that the stretching or hardening of the micro plate due to clamped boundary conditions in our model is neglected.
3. Points of the plate lying initially on a normal-to-the-middle plane of the plate remain on the normal-to-the-middle surface of the plate after bending.
4. The normal stresses in the direction transverse to the plate can be disregarded.

Using these assumptions (Kirchhoff assumptions), all stress components can be expressed by deflection w of the plate, which is a function of the one coordinate in the plane of the plate.

For a circular plate in the case axisymmetric loading deflection w of the plate is a function of the radius.

This function has to satisfy a partial differential equation, which together with the boundary conditions, completely defines w. Depending on how the plate is loaded, the partial differential equation might be linear or nonlinear. As discussed in reference [11] the governing partial differential equation can be obtained as follows:

$$D\nabla^4(w) = D\left(\frac{d^4w}{dr^4} + \frac{2}{r}\frac{d^3w}{dr^3} - \frac{1}{r^2}\frac{d^2w}{dr^2} + \frac{1}{r^3}\frac{dw}{dr}\right) = P(r, w, V, P_s, P_d) \qquad 0 \prec r \prec R \tag{1}$$

where $w(r)$ is the mid plane deflection of the plate in distance r from the center of the micro plate P is the sum of the electrostatic, hydrostatic and dynamic pressures and D is the flexural rigidity which can be expressed as:

$$D = \frac{Et^3}{12(1-\nu^2)}, \tag{2}$$

where ν is the Poisson's ratio. In Eq. (1) P includes the uniform fluid and electrostatic pressures. The intensity of the continuously distributed electrostatic load may be expressed as:

$$P_e = \frac{\varepsilon_0 V^2}{2(G - w(r))^2}, \tag{3}$$

where ε_0 is the permittivity of air, V is the applied voltage and G is the initial gap between the two conductive aluminum films in each unit of the sensor [11]. The fluid pressure consists of two separate parts: uniform static pressure P_s and uniform dynamic pressure P_d. The dynamic fluid pressure is defined as:

$$P_d = \frac{1}{2}\rho u^2 \tag{4}$$

In this equation ρ is the density of water and u is the velocity of the fluid at 0.6 depth of the fluid at the channel or for more accuracy u is the velocity of the fluid at 0.2 and 0.8 depths of the fluid at the channel. Since P in Eq. (1) is the intensity of the total load, it can be written as:

$$P = P_e + P_s + P_d = \frac{\varepsilon_0 V^2}{2(G - w(r))^2} + P_s + \frac{1}{2}\rho u^2 \tag{5}$$

The needed boundary conditions are determined from the requirement that the circular micro plate are clamped along its boundary i.e. zero displacement and zero slope surrounding the plate. Hence the boundary conditions are:

$$(\frac{dw}{dr})\Big|_{r=\pm R}=0, \qquad w\Big|_{r=\pm R}=0 \tag{6}$$

4. Numerical Solution

Substituting Eq. (5) in Eq. (1), we will obtain a nonlinear ODE for which that is not easy to find any analytical or even numerical solution without linearization. So this ODE is first linearized and then solved numerically. The linearization method employed is a step-by-step procedure called "Step-by-Step Linearization Method (SSLM)" [11, 12, 13]. The linearized governing ODE with considering the boundary conditions can be solved using any numerical method.

Due to the nonlinearity in the electrostatic pressure, an analytical solution is impractical to obtain and a numerical solution is sought. The solution of the electrostatic deflections problems by numerical techniques currently produces cost effective design and analysis for a variety of problems. Choice of the numerical technique as well as choice of difference operators plays a major role in solution accuracy. An account of the way out of a difficulty of nonlinearity was utilized linearization method for changing governing equation into a linear equation. Because of considerable value of *w* respect to initial gap especially when the applied voltage or static and dynamic pressure increasing, the linearizing respect to *w*, may causes to appear some considerable errors. Therefore, to minimize the value of errors, the method of step by step increasing the applied voltage and hydrostatic and dynamic pressure is proposed and the governing equation was linearized at the each step [12].

Assuming that w^i is the deflection of the microbeam due to applied voltage V^i, hydrostatic pressure P_s^i and dynamic pressure P_d^i, applied voltage, hydrostatic and dynamic pressure is then increased to:

$$V^{i+1}\to V^i+\delta V \quad P_s^{i+1}\to P_s^i+\delta P_s \quad P_d^{i+1}\to P_d^i+\delta P_d \tag{7}$$

We have:

$$w^{i+1}\to w^i+\delta w=w^i+\psi(r) \tag{8}$$

Substituting Eq. (8) into Eq. (1), we have:

$$D\nabla^4(w^{i+1})=P^{i+1}\left(r,w^{i+1},V^{i+1},P_s^{i+1},P_d^{i+1}\right) \tag{9}$$

Using the calculus of variation theory and Taylor's series expansion P^{i+1} can be expressed as follow:

$$P^{i+1}=P^i+\left(\frac{\partial Q}{\partial w}\right)^i\delta w+\left(\frac{\partial P}{\partial V}\right)^i\delta V+\left(\frac{\partial P}{\partial P_s}\right)^i\delta P_s+\left(\frac{\partial P}{\partial P_d}\right)^i\delta P_d+O(2) \tag{10}$$

The higher order of the Taylor's series can be neglected to linearize the total pressure due to the next step of the applied voltage and the hydrostatic pressure increase. Thus, the linear total pressure can be written as:

$$P^{i+1}\left(r, w^{i+1}, V^{i+1}, P_s^{i+1}, P_d^{i+1}\right) = \frac{\varepsilon_0 V^i}{2\left(G - w^i(r)\right)^2} + \frac{\varepsilon_0\left(2V^i \delta V\right)}{2\left(G - w^i(r)\right)^2} + \frac{\varepsilon_0\left(V^i\right)^2}{\left(G - w^i(r)\right)^3}\psi(r) + P_s^i + P_d^i + \delta P_s + \delta P_d \qquad (11)$$

Substituting the Eq. (11) into Eq. (9), and using of Eq. (1) at the *i*-th step, the following equation to calculate the ψ can be expressed as:

$$D\nabla^4\left(\psi(r)\right) - \frac{\varepsilon_0\left(V^i\right)^2}{\left(G - w^i(r)\right)^3}\psi(r) = \frac{\varepsilon_0\left(2V^i \delta V\right)}{2\left(G - w^i(r)\right)^2} + \delta P_s + \delta P_d \qquad (12)$$

The nonlinear Eq. (1) is converted to the linear Eq. (12), therefore using of any numerical method and imposing the boundary conditions, the Eq. (12) may be discretized into N nodes and then by solving linear system of algebraic equations, the $\psi(r)$ can be obtained at the each step of applied voltage and hydrostatic and dynamic pressures.

5. Numerical Results and Discussion

5.1. Verifying and Convergency of the Method

In this section, it is tried, first of all, to find the best step size for application of voltage and hydrostatic or dynamic pressure and the number of grid points for the finite difference method to show the convergency of the used method. The geometrical and material properties from [14] are listed in Table 1 as:

Table 1. Geometrical and material properties of the micro plate.

Radius	250 µm
Thickness	20 µm
Young’s modulus	169 (GPa)
Poisson’s ratio	0.3
(Initial gap) G	1 µm
(Dielectric of air) ε_0	8.8541878×10^{-12} (F/m)

In order to find the best step size for hydrostatic pressure and application of voltage and the number of grid points for the finite difference method, some sample grid points with step size for the hydrostatic pressure and voltage are used. The results are listed in Tables 2, 3.

Table 2. The obtained pull-in voltages with 500 grid points for different step sizes of applied voltages $(P_s = P_d = 0)$.

δV (V)	3	1	0.1	0.05	0.025
V_{pi} (V)	321.00	316.00	313.80	313.70	313.70

Table 3. The obtained pull-in voltages with 0.05 volt step size of applied voltages for different number of grid points $(P_s = P_d = 0)$.

Number of grid points	20	100	200	400	500
V_{pi} (V)	287.40	308.50	312.00	313.70	313.70

As they were presented in tables 2 and 3, the obtained pull-in voltage (313.7) is in well agreement with pull-in voltage presented by [14]. Also, the best results can be obtained for 0.05 (V) and 400 grid points for step size of applied voltage and finite difference method, respectively.

5.2. Numerical Results

Calculations have been accomplished for water as a sample fluid. In this case to ascertain that the sensor is placed within the channel, it must be placed at a distance of 0.6 depth of water.

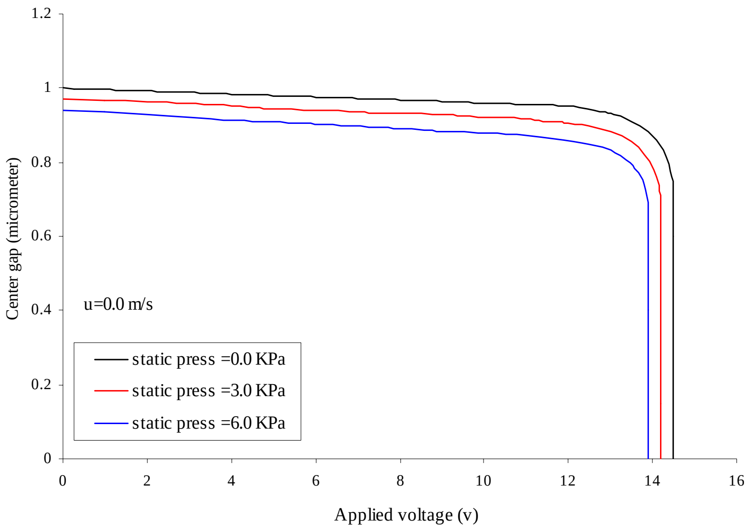
Geometrical and material properties of the sensing elements and other required data are listed in Table 4.

Table 4. Geometrical and material properties of the sensing elements and other required data.

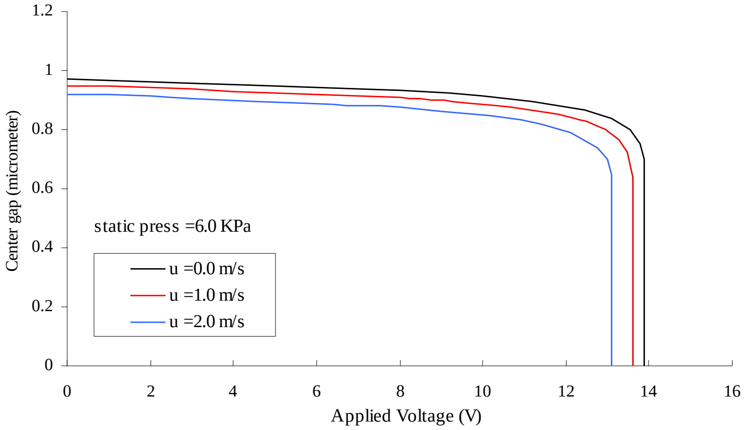
Radius	200 µm
Thickness	2 µm
Young's modulus	169 (GPa)
Poisson's ratio	0.3
(Initial gap) G	1 µm
(Dielectric of air) ε_0	8.8541878×10^{-12} (F/m)
Depth of water in the channel	1*m*
Water Density	$1000\, {}^{kg}\!/_{m^3}$

The maximum voltage that can be applied to the capacitors is limited by their minimum pull-in voltage [11, 15-16]. Fig. 2 indicates the mechanical behavior of the flexible microplate in the flow sensing unit and its pull-in voltage under different conditions. The vertical axes in this figure show the minimum aperture between the flexible microplate and the fixed part in the flow sensing unit (centre gap). According to this figure it may be found out that the closer the applied voltage gets to the pull-in voltage, the more sensitive the sensor becomes. This can be better explored from Fig. 5.

When the sensor is placed within the channel, its flexible microplates are exposed to fluid pressure. In addition, an electrostatic force is also generated on the flexible microplate in each unit of the sensor by applying a DC voltage between the two conductive aluminum films in that unit. Since these forces are known, we can determine the deflection of the microplates and consequently the corresponding variation in capacitance. Having determined different capacitance values under various loading conditions, we can readily discern the load and the fluid velocity it connotes in new measurements. Capacitance in the flow sensing unit depends on the fluid velocity, fluid type, the electrostatic, and the static fluid pressures. Static fluid pressure P_s can be determined using the diagram shown in Fig. 3.



(a) Mechanical behavior at different static fluid pressures.



b) Mechanical behavior at different free stream velocities.

Fig. 2. Mechanical behavior of the flow sensing element and its stability limits.

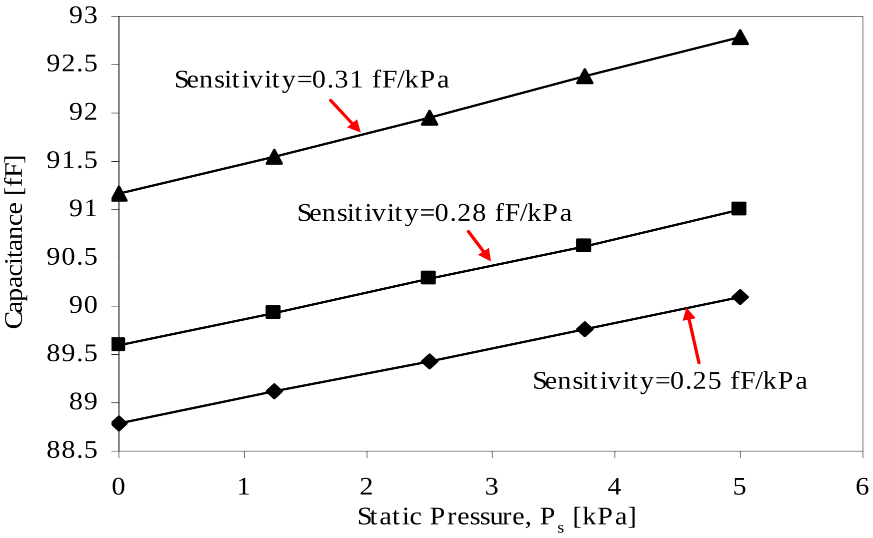


Fig. 3. Capacitance-static pressure diagram at three different sensor's sensitivities.

Capacitance changes in the flow sensing unit of the device with different flow velocities are demonstrated in Fig. 4.

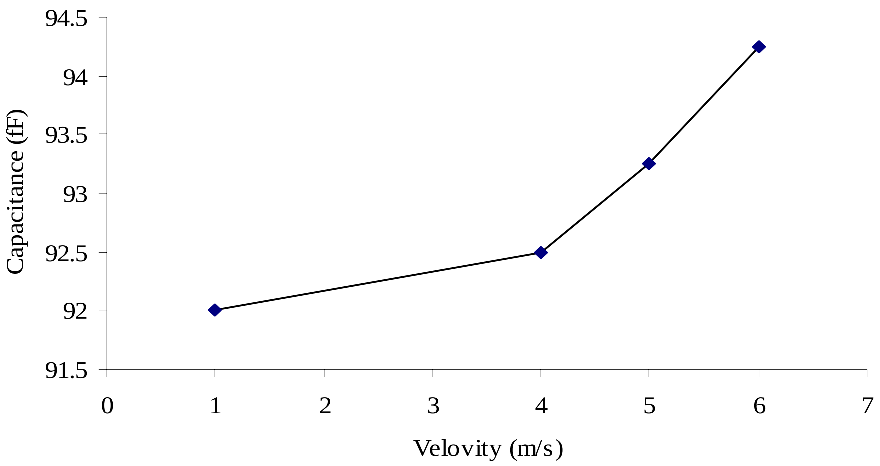


Fig. 4. Capacitance in the flow sensing unit of the sensor vs flow velocities.

Corresponding to capacitance changes in the front and rear sensing unit the static pressure and the fluid velocity can be determined.

Sensitivity is another item to be defined. Imagine that the sensing microplates are under no pressure except the electrostatic force. The corresponding capacitance in this case is denoted by C_1. If a uniformly distributed load of 1 kPa is added to the electrostatic pressure, the flexible microplates will deflect and the capacitance will increase to C_2. The amount of change in capacitance caused by this added load, namely $C_2 - C_1$, is referred to as the sensor's sensitivity and is expressed in terms of fF/kPa and is shown in the Fig. 5.

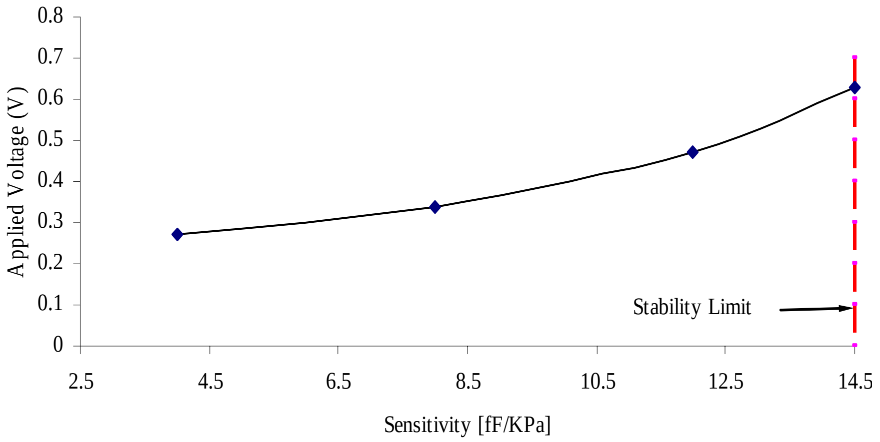


Fig. 5. Sensor's sensitivity vs applied voltage.

5. Conclusions

A novel MEMS capacitive flow sensor for implementation in open channels based on a microplate deflection was developed. Nonlinear governing differential equation of the microplate due to its nonlinearity was solved using Step by Step Linearization method. The stable region of the sensor was determined and effect of bias voltage on sensor sensitivity was studied. The result showed that the static pressure and fluid velocity decrease the voltage that leads sensor to an unstable position. Also was showed that with increasing bias voltage sensor sensitivity due to decreasing equivalent stiffness, sensor sensitivity raises, but the measurable rang of the static or dynamic pressure reduces.

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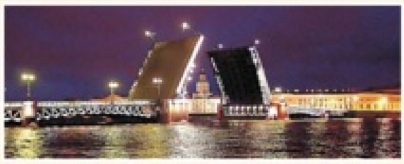

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Contacts

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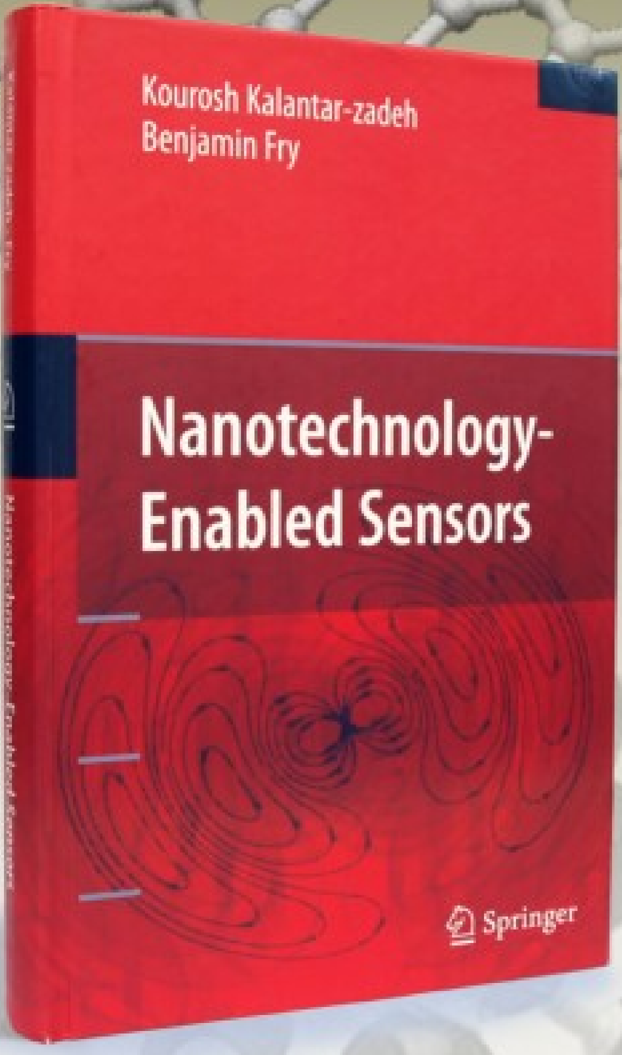
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