SENSITIVITY ANALYSIS OF NANO-NEWTON CMOS-MEMS CAPACITIVE FORCE SENSOR FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

In this research, we investigated about sensitivity of a Nano-Newton CMOS-MEMS capacitive force sensor. Sensitivity analysis is an important factor to reach a more optimized structure for MEMS force sensors and improve their efficiency. The procedure is based on scaling rules of the electrodes. The most change of capacitance (increased capacitance + decreased capacitance) occurs in ℓ=2/3. By this ℓ, gap, w (thickness of metals) and L (the length of comb fingers) become 2 (μm), 0.46 (μm) and 66.67 (μm) respectively. In this case, sensitivity of increased capacitance and decreased capacitance are 0.0585 fF/nN (8.33% increase) and 0.09 fF/nN (2.27% increase) respectively. By combining all the results, it can be obtained to increase w and L and decrease gap (g) simultaneously which consequently leads to 1.2×w, 1.2×L and 2/3×gap. Such results show sensitivity for increased capacitance is 0.19 fF/nN (251.85% increase) and for decreased capacitance is 0.3 fF/nN (240.9% increase).. by these selections, length (L), thickness of metal (w) and gap become 120 (μm), 0.828 (μm) and 2 (μm) respectively.

KEYWORDS

Sensitivity, Nano-Newton, CMOS-MEMS, Capacitive, Force Sensor

1. INTRODUCTION

MEMS Force sensing devices play a pivotal role in sensitive application such as living cell manipulation and minimally invasive surgery (MIS) because of vulnerability of biological cells and tissues. Providing that the tissues are damaged, the health of patient may be threatened in MIS. Most MEMS force sensors (represented in the literature [1 and 2]) use in-plane sensing mechanism which has some problems such as pull-in effect and complicated electrical isolation [3]. Also, a 6-DOF force and torque sensor applied for micro-manipulation applications was proposed by P. Estevez and et al. in 2012 [4]. The sensor has the capability of detecting forces and torques in μN range. However, Surgeons face nano-newton forces in minimally invasive surgery and living cell manipulation. Different kinds of MEMS force sensors include piezoresistive [5], piezoelectric [6], optical and capacitive [7]. The most important characteristics of capacitive force sensors are relatively high sensitivity and low temperature dependence [7]. The capacitive MEMS force sensor developed in [3] has utilized out-of-plane sensing mechanism with high accuracy and reliability. Also, CMOS-MEMS technology causes better integration of a force sensor and manipulation. This method was used for fabrication accelerometers such as the accelerometer developed by Xie and Fedder [8]. Later, a CMOS-MEMS accelerometer with tri-axis sensing electrodes Arrays was proposed by Tsai and et al. in 2010 [9]. Also, Xie and Fedder developed a CMOS-MEMS sensing-actuating system equipped with vertical capacitive comb fingers [10].

One of the biggest challenges in designing MEMS force sensors is the sensitivity issue. Since this issue is directly affected by structural parameters of the sensor, the efficient design of these devices provide more opportunity to be applied in a wide range of medical and scientific

applications. Determining more optimal dimensions of the comb fingers of a capacitive force sensor along with the gap between them are critical points for designing the force sensor. Also, determining the thickness of metals of these comb fingers is very important in CMOS-MEMS technology. This paper presents sensitivity analysis of capacitive force sensor designed in [3]. By sensitivity analysis, the more optimal magnitudes of the fingers dimensions, the gap between them and the metals thicknesses these comb fingers can be calculated. It means the change of displacement should cause larger change of capacitance.

2. Mathematical Modeling and Formulation

2.1. Structure of the Force Sensor

Figure 1 depicts a CAD model of the sensing and actuating elements of the force sensor developed in [3]. In the proposed mechanism, a micro probe is attached to the proof mass to convert the effect of applied vertical external force at the tip to relative displacement between the rotor (movable) and stator (fixed) comb fingers, and to capacitance changes take place during sensing. The force sensor has 76 pairs of sensing comb fingers. The length, width and thickness of these comb fingers are 100 (µm), 5 (µm) and 40 (µm) respectively. The gap between them is 3 (µm). Actuating comb fingers are for controlling disturbance [3].

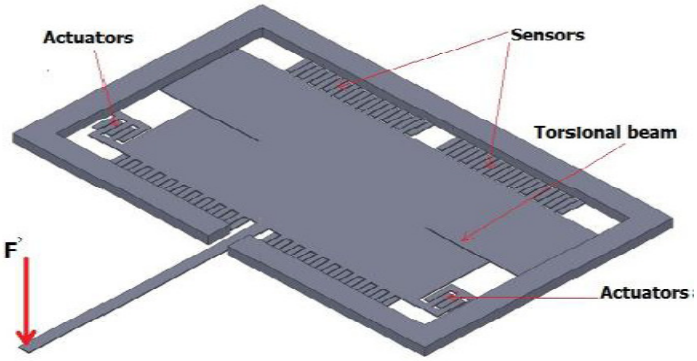

Figure 1. A CAD model of the CMOS-MEMS Nano-Newton force sensor used in this research

2.2. Sensitivity analysis

The sensitivity of a capacitive force sensor is equal to the change in the capacitance value, C, over the change in the force, F, or displacement, D. The equation. (1) is applied for sensitivity analysis this Nano-Newton capacitive force sensor [7].

$$\text{Sensitivity} = \frac{\partial C}{\partial F} = \frac{\partial C}{\partial D} \tag{1}$$

Where capacitance value (C) is equal to the equation (2):

$$C = \frac{\varepsilon \times w \times L}{g} \tag{2}$$

Consequently, the capacitance value is inversely related to the initial gap distance (P) and directly related to the effective area (w×L). For increasing sensitivity, change of displacement should cause larger change of capacitance. It means that larger trend of changes of capacitance ascribing to displacement causes larger sensitivity.

For sensitivity analysis of the sensor's structure without changing the properties of comb fingers of the sensor, ℓ (linear scale of the electrodes) is defined [11]. Equations (3) and (4) are gained based on formula 2.

$$\varepsilon \propto \ell^0 \tag{3}$$

$$w, L \text{ and } g \propto \ell^1 \tag{4}$$

We assume that the length, width and thickness of the frame of the sensor should be fixed because the sensor has to be in scale of MEMS. It means that dimensions have to be lower than 1 (mm) in MEMS. So, the length of comb fingers (L), the thickness of Metals (w) and gap between comb fingers (g) are our factors for sensitivity analysis. Our constraints for sensitivity analysis are listed in table 1.

Table 1. Constraints of Sensitivity Analysis.

Parameter	**Magnitude**	**Description**
Length, Width and Thickness of the sensor's frame	Fix	Dimensions have to be lower than 1 (mm) in MEMS.
Length of comb fingers, Thickness of Metals and Gap	Changeable	For sensitivity analysis
Minimum of acceptable amount of gap for ℓ < 1	1.5 (μm)	Gap < 1 (μm) causes Nano problems and it is not desired. 1.5 (μm) is trustable for being in MEMS scale.
Size of step for decreasing of ℓ	0.5 (μm) (Gap = 3 , 2.5 , 2 , 1.5)	This magnitude is related to limitations of fabrication of sensor.
Size of step for increasing of ℓ	(5/100) ×A	This magnitude is related to limitations of fabrication of sensor.
Minimum of acceptable amount of w	(12/10) × A	This magnitude is related to limitations of AMI 0.5 (μm) which is a technology for fabrication of CMOS-MEMS devices.

For selecting linear scale of the electrodes (ℓ) can be considered in two ranges mentioned in table 2.

Table 2. Ranges of ℓ.

Linear Scale	ℓ < 1	1- Effect of decrease of gap 2- Increase of the number of fingers
Linear Scale	ℓ >1	1- Effect of increase of A = L ×W 2- Decrease of substrate 3- Decrease of the number of fingers

By calculating the total capacitance of the sensor based on figure 2, the changes of the capacitance for different displacements were obtained illustrated in figures 3. The maximum amount of the displacement of the probe for a force of 1000 (nN) which is the acceptable maximum force for this force sensor is 0.6 μm.

Figure 2 shows a pair of comb finger including a rotor and a stator fingers for part B. The red areas illustrated in this figure, indicate metal layers used to construct electrodes. The green areas indicate oxide layers used between metals in sensor structure, and the blue one indicates substrate material. Furthermore, the equivalent electrical circuit for a pair of comb fingers is presented in this figure. Capacitance changes corresponding to relative displacement of the fingers can be calculated using the equivalent electrical circuits illustrated in figure 2.

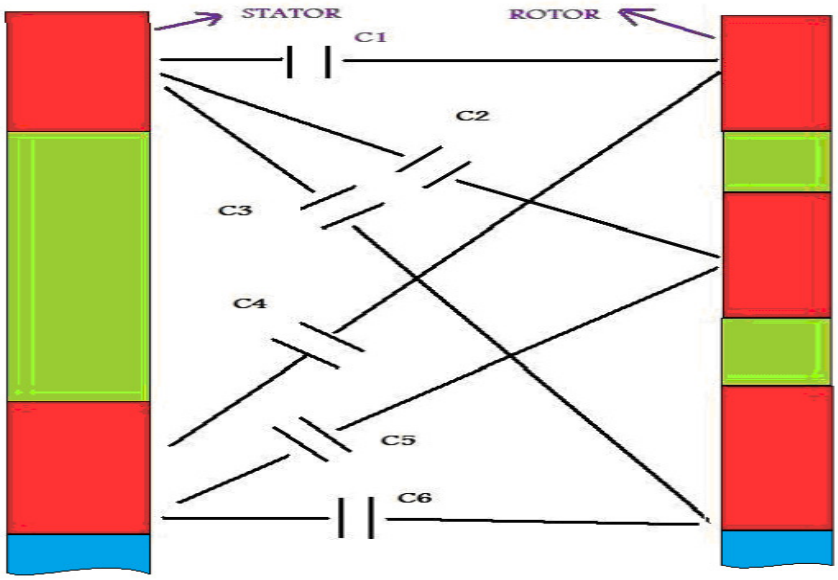

Figure 2. Capacitors between stator and rotor fingers.

Then we can calculate the equivalent capacitance changes for whole of the sensor. As shown in figure 2, there are six capacitors between a stator and a rotor comb finger. After applying an external force and moving the rotor finger toward down, C1, C2 and C3 are decreased and C4, C5 and C6 are increased.

Based on the capacitance value given in the formula 2, these parameters are changed linearly with respect to linear scale of the electrode. In the proposed sensitivity analysis scheme, the value of the scale factor is deviated from its nominal value by an appropriate step size and its effect on the sensitivity is calculated till the maximum sensitivity and corresponding dimensions of the sensor

are obtained. Sensitivity for increased capacitance is 0.057 (fF/nN) and for decreased capacitance is 0.084 (fF/n).

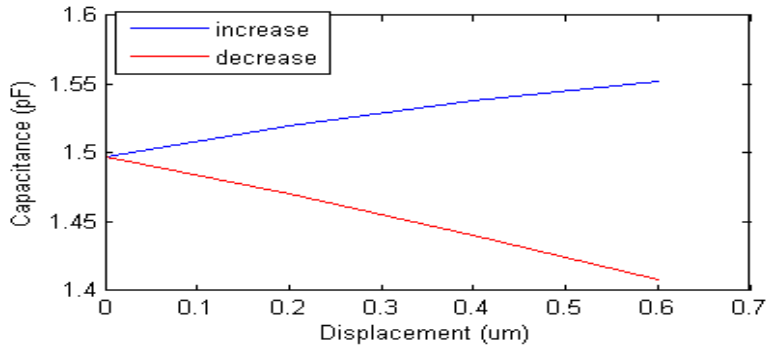

Figure 3. Increase and decrease of capacitance of the sensor for different displacement

3. Result and Discussion

At first, for Sensitivity analysis of the sensor, ℓ=5/6 is selected (It is better that gap decreases 0.5 (μm) in every step from aspect of fabrication. It means that gap can be 3, 2.5, 2, and 1.5 (μm)). As shown in table 1, constrain of the select of ℓ < 1 is minimum of acceptable amount of gap, and we assume it is 1.5 (μm) because lower than it causes our MEMS problem to convert to Nano problem. By selecting ℓ > 1, we can consider the effect of the decrease of gap. Figure 4 illustrates the result of this selection. This decrease of gap causes of to add four new set of comb fingers to the sensor. Based on this figure, sensitivity for increased capacitance is 0.058 (fF/n) and for decreased capacitance is 0.089 (fF/n).

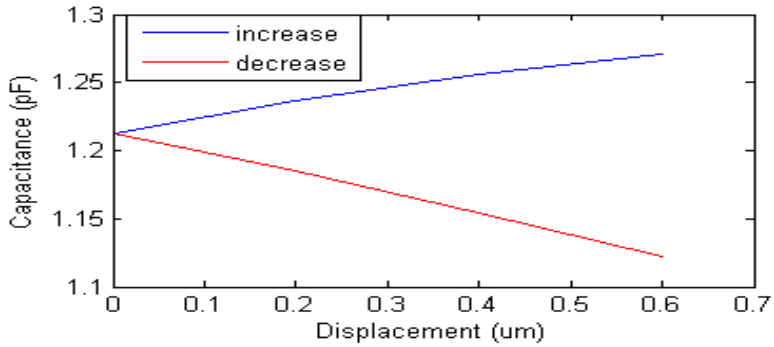

Figure 4. Increase and decrease of capacitance of the sensor when ℓ =5/6

Then ℓ=2/3 is selected. Figure 5(a) illustrates the result of this selection. This decrease of gap causes of to add eight new set of comb fingers to the sensor. Based on this figure, sensitivity for increased capacitance is 0.0585 (fF/nN), and for decreased capacitance is 0.09 (fF/nN). Figure 5(b) show the result for ℓ=1/2. This decrease of gap causes of to add 12 new set of comb fingers to the sensor. Based on this figure, sensitivity for increased capacitance is 0.052 (fF/nN) and for decreased capacitance is 0.0855 (fF/nN). The reason for the decrease of sensitivity for this ℓ is a large decrease of effective area (A). ℓ=1/2 causes the acceptable minimum for gap and ℓ cannot be lower than it.

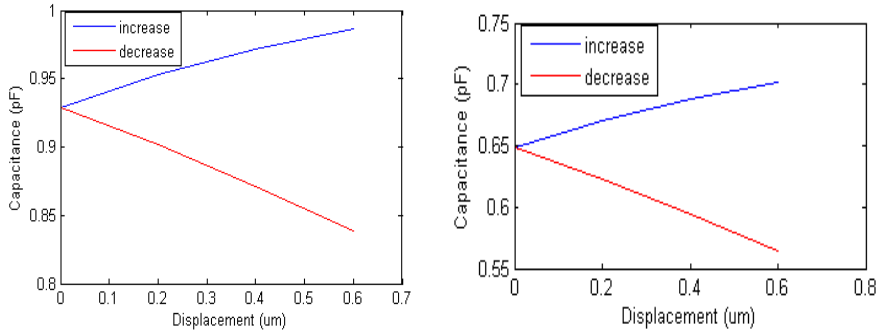

Figure 5. a) Increase and decrease of capacitance of the sensor when ℓ =2/3. b) Increase and decrease of capacitance of the sensor when ℓ =1/2.

Then ℓ=105/100 is selected. Constrain of selecting of ℓ > 1 is limitation related to AMI 0.5 (μm) which is a technology for CMOS-MEMS fabrication and it cannot be larger than (12/10) × A as shown in table 1. By selecting ℓ > 1, we can investigate the effect of increase of A = L ×W. This increase causes the decrease of the substrate and the decrease of the number of fingers. The size of step for the increase of ℓ is (5/100) ×A. This magnitude is related to limitations of fabrication of the sensor. Figure 6(a) illustrates the result of this selection. Based on this figure, sensitivity for increased capacitance is 0.053 (fF/nN) and for decreased capacitance is 0.091 (fF/nN).

Figures 6(b) illustrates the result of the selection of ℓ=110/100. This increase of gap causes of to be obliged to remove a set of comb fingers available in the sensor. Based on these figures, sensitivity for increased capacitance is 0.052 (fF/nN) and for decreased capacitance is 0.0875 (fF/nN). Figures 7(a) shows the result for ℓ=115/100. This increase of gap does not cause of to remove another set of comb fingers of the sensor. Based on this figure, sensitivity for increased capacitance is 0.052 (fF/nN) and for decreased capacitance is 0.087 (fF/nN).

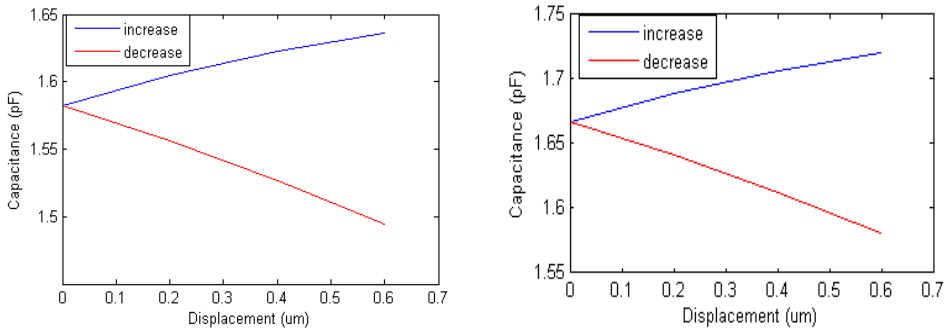

Figure 6. a) Increase and decrease of capacitance of the sensor when ℓ =105/100. b) Increase and decrease of capacitance of the sensor when ℓ =110/100.

Finally, ℓ=120/100 is selected. Figure 7(b) illustrates the result of this selection. Based on these figures, sensitivity for increased capacitance is 0.051 (fF/nN) and for decreased capacitance is 0.085 (fF/nN). This increase of gap causes of to remove two sets of comb fingers available in the sensor and it decreases sensitivity.

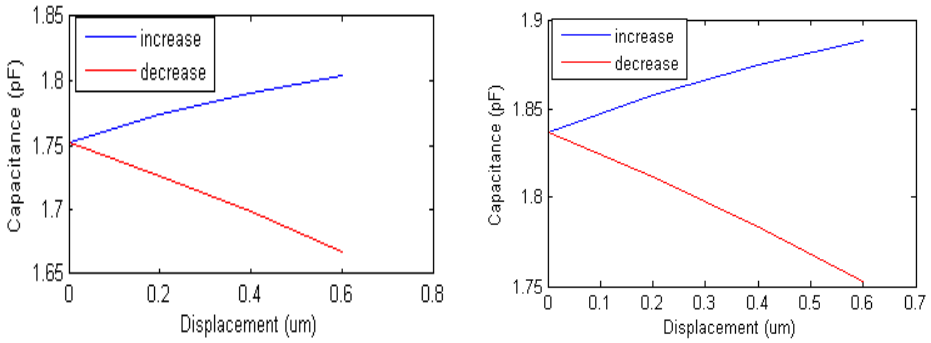

Figure 7. a) Increase and decrease of capacitance of the sensor when ℓ =115/100. b) Increase and decrease of capacitance of the sensor when ℓ =120/100.

Figures 8(a) and (b) show increased capacitance and decreased capacitance for different ℓ. The most increase of capacitance occurs in ℓ=2/3 and the most decrease of capacitance occurs in ℓ=105/100.

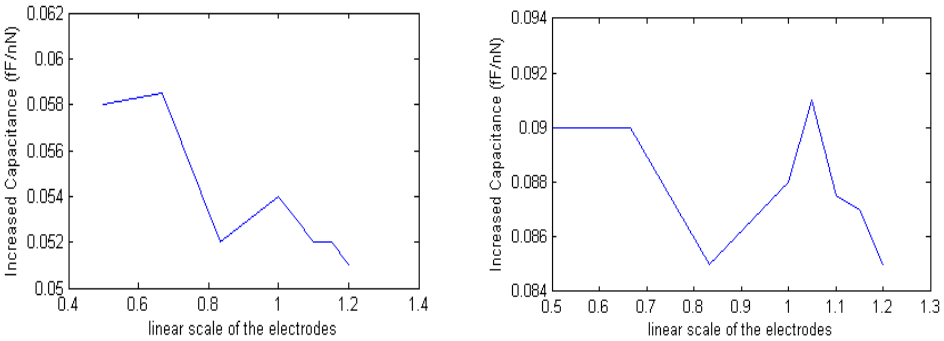

Figure 8. a) Sensitivity for increased of capacitance with different ℓ. b) Sensitivity for decrease of capacitance with different ℓ.

Based on figures 8 (a) and (b), the most change of capacitance (increased capacitance + decreased capacitance) occurs in ℓ=2/3. With this ℓ, gap becomes 2 (µm), w (thickness of metals) becomes 0.46 (µm) and L (the length of comb fingers) becomes 66.67 (µm). Sensitivity for increased capacitance increases 8.33% and sensitivity for decreased capacitance increases 2.27%.

By combining the results of ℓ>1 and ℓ<1, we can apply to increase w and L and decrease gap (g) together. Figure 9 shows results for 1.2×w, 1.2×L and 2/3×gap. Based on these figures, sensitivity for increased capacitance is 0.19 (fF/nN) and for decreased capacitance is 0.3 (fF/nN). So, sensitivity increases 251.85% and 240.9% for increased capacitance and decreased capacitance respectively. With this selection, L becomes 120 (µm), w becomes .828 (µm) and gap becomes 2 (µm).

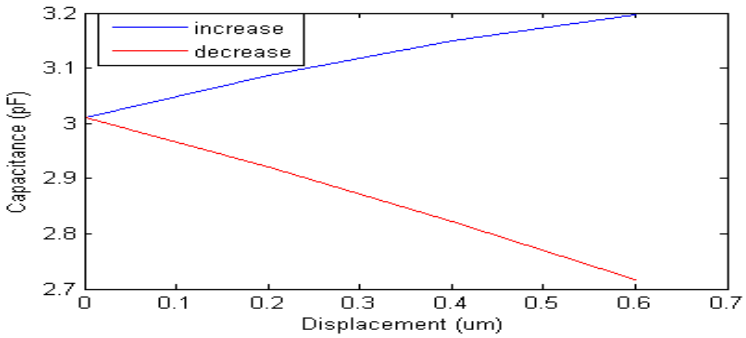

Figure 9. changes of capacitance of the sensor for 1.2×w, 1.2×L and 2/3×gap.

4. Conclusion

This paper reported sensitivity analysis of a Nano-Newton CMOS-MEMS capacitive force sensor based on linear scale of the electrodes. Sensitivity analysis is an important factor to reach to a more optimized structure for MEMS force sensors and improve their efficiency. The most change of capacitance (increased capacitance + decreased capacitance) occurs in ℓ=2/3. By this ℓ, gap, w (thickness of metals) and L (the length of comb fingers) become 2 (µm), 0.46 (µm) and 66.67 (µm) respectively. In this case, sensitivity for increased capacitance and decreased capacitance are 0.0585 fF/nN (8.33% increase) and 0.09 fF/nN (2.27% increase). The proposed method provides useful guidelines to increase the sensitivity of the sensor under investigation by 250%. It means we can simultaneously apply to increase w and L and decrease gap (g). The results for 1.2×w, 1.2×L and 2/3×gap show sensitivity for increased capacitance is 0.19 (fF/nN) and for decreased capacitance is 0.3 (fF/nN). So, sensitivity increases 251.85% for increased capacitance and 240.9% for decreased capacitance increases. With this selection, length (L), thickness of metal (w) and gap become 120 (µm), 0.828 (µm) and 2 (µm) respectively.

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