CAPACITIVE BASED PURE BENDING STRAIN SENSOR FOR KNEE REPLACEMENT MONITORING

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ABSTRACT

MEMS (Microelectromechanical system) capacitive based pure bending strain sensor is presented for use in monitoring the progress in healing of the knee after injury or after knee replacement. The sensor is designed to monitor the progress in knee bending during physiotherapy. The sensor is designed and simulated in COMSOL multiphysics 4.4b software. The cantilever structure of sensor is composed of two parallel plates with narrow gap between them and conjoint end. The sensor is mounted on the cantilever, which responds to the strain. For simulation, two methods were used .First consists of simulating only the sensor by having the effect of cantilever displacement on it. Second, consists of simulating the cantilever and sensor as the two components in same model. The mechanism of sensing is based on the concept of change in capacitance due to change in gap between capacitor plates. Nine permutation of the design with different metal coverage area and gaps were simulated. The change in capacitance is simulated for different strain range. The simulation is done using electromechanics module and simulated results were compared with the analytic results. Different graph were plotted between capacitance v/s strains for different initial gap between plates of capacitor. Gauge factor for different design were compared. Different materials were used for the fabrication of sensor. This device is virtually fabricated in Intellisuite8.8 software. We have also compared the results of COMSOL with that of intellisuite.

Keywords: Cantilever structure, MEMS (microelectromechanical system), knee replacement monitoring, pure bending capacitive strain sensor.

1. INTRODUCTION

MEMS stand for Micro Electro Mechanical System. It is a technology used to create micro systems which possess mechanical and electronic components. MEMS find application in various fields like automobile, medical, biomechanics, industrial and aerospace sectors, etc. Now-a-days various types of MEMS sensors are used in orthopaedics which helps in monitoring of prosthetics devices. This helps in preventing any damage to prosthetics devices. The procedure of replacing patient’s knee joints affected by disease originated in the early 1970’s. Use of capacitive strain sensor for monitoring knee transplant helps in proper healing and settlement of prosthetic devices. It provides information to the patient about the strain produced (corresponds to the particular movement of the knee) in the prosthetic device so as to stop making that movements if the strain exceeds the safe limit. Capacitive based pure bending strain sensor (CBPBSS) can be used externally and it responds to the strain by change of its capacitance. CBPBSS possess high nominal capacitance due to small initial gap between the electrodes. The basic concept of capacitive strain sensor features a pair of metalized parallel plates with a dielectric gap. The sensing mechanism manifests itself in varying either the area of the plate, the gap between the plates [1], or the dielectric medium between the plates [2]. These sensors generally exhibit low nominal capacitance and sensitivity due to large air gap. In general, the change in gap between the parallel plates due to applied strain is very small. Therefore, to obtain high sensitivity, these changes need to be as large as possible with respect to unstrained gap. Designs that maximize the change in gap and minimize the unstrained gap are optimal. The major problem in designing a knee replacement for the Total Knee Arthroplasty (TKA) procedure lies in the fact that there is very little in vivo data on the load conditions available. The capacitive based pure bending strain sensor described in [3] is for the spinal fusion monitoring while we have modified it to be used for monitoring knee transplant.

2. REVIEW OF STRAIN SENSORS USED IN ORTHOPAEDICS

There are various types of strain sensors used in orthopaedics like metal foil strain gauge, piezoresistive and piezoelectric strain gauge, MEMS capacitive based strain gauge, MEMS double ended tuning fork strain gauge.

3. CAPACITIVE PURE BENDING SENSOR DESIGN

CBPBSS consists of variable gap configuration. It consists of two plates which were connected at one end and open at another end. The bottom plate was of silicon while top plate of borosilate glass. Bottom silicon plate was affixed to the cantilever bending test substrate. As the structure bends the bottom silicon plate bends along with the test substrate and moves away from the straight top plate. Due to this there was increase in gap takes place. This increase in gap results in change of capacitance of sensor. Three coverage configuration of the metal area as shown in fig. 2, with each having different initial gaps configurations were modelled to characterise the sensor response.

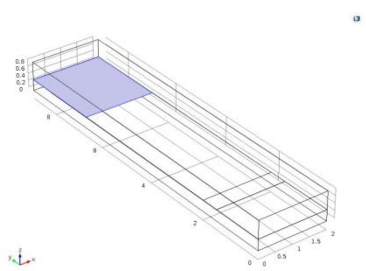


Fig.1 (33% metal coverage)

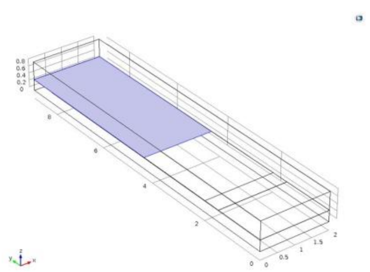


Fig.2 (67% metal coverage)

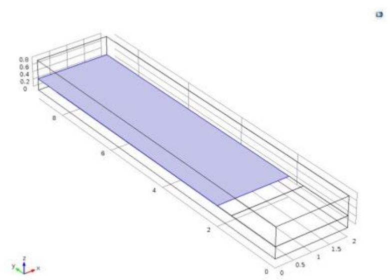


Fig.3 (100% metal coverage)

4. WORKING PRINCIPLE OF SENSOR

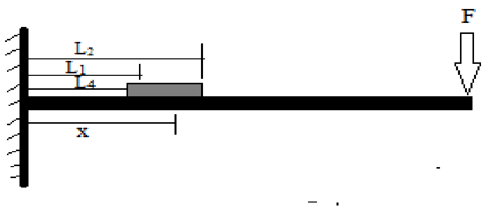


Fig.4 Sensor placed on cantilever test substrate

The capacitance from two parallel electrode plates is given by;

$C = \epsilon_0 \epsilon_r A/D$ (eq.1)

Where, A is the area, D the distance between two parallel plates, ϵ_0 is the permittivity of free space and ϵ_r is the dielectric constant of the material between the plates. In order to measure the strain magnitude, a cantilever test substrate is utilised. The sensor is affixed to the substrate. For a cantilever beam, the moment of inertia (I) is given by;

$$I = \frac{Wt^3}{12} \quad \text{(eq.2)}$$

Where, W is the width of beam and t is the thickness

The relation between strain and stress is given by;

$$\varepsilon = \frac{\sigma}{E} = \frac{Mc}{EI} = \frac{6\mathrm{Fd}}{\mathrm{EWt}^2} \quad \text{(eq.3)}$$

Where σ is the stress on the surface, E the Young's modulus of the steel test substrate, M is the bending moment, c the distance from the neutral axis to the surface, F the force applied at the free end of the beam and d is the sensor location from the free end of the beam.

The equations used for finding the total capacitance are with reference to [3].

The initial sensor capacitance is given by;

$$C_0 = \epsilon_0 \epsilon_r \frac{w_1(L_2 - M_1)}{D_0} \quad \text{(eq.4)}$$

Where, L_2 not only represents the boundary of the sensor but also the end of the metal layers on both the bottom and top electrode beams and therefore, $L_2 - M_1 = L_0$ the effective electrode length. With various designs, M_1 is a variable that represents the start of the metal layer on the top electrode beam, $w_1 (L_2 - M_1)$ represents the area of the overlapping metal plates, D_0 the initial spacing between the plates. The deflection of a cantilever beam and the attached sensor metal plate is given by;

$$V(x) = \frac{-Fx^2(3L - x)}{6EI} \quad \text{(eq.5)}$$

Where, the V(x) is the vertical displacement at position x on the beam.

The initially parallel plate remains straight and its position is represented by a line tangent to the deformed beam at the pivot point of the sensor. The tangent line is given by;

$$V_t(x) = \theta(x)x + b \quad \text{(eq.6)}$$

Where, θ(x) is the slope at x and b is a constant determined by a boundary condition.

The equation of tangent line from [3] is expressed as;

$$V_t(x) = \frac{-F}{2EI}(2LL_3 - L_3^2)x + \frac{F}{6EI}(3LL_3^2 - 2L_3^3) \quad \text{(eq.7)}$$

The increased gap between electrodes is given by;

$$D(x) = v_t(x) - v(x) \quad \text{(eq.8)}$$

The capacitance change is determined by calculating the average distance between the two metal plates of the strain sensor. The average displacement is given by;

$$D_1 = \frac{1}{L_2 - M_1} \int_{M_1}^{L_2} (v_t(x) - v(x))\,dx \quad \text{(eq.9)}$$

Where, M_1 is where the sensing portion of metal starts and L_2 where it ends.

Net capacitance is given by;

$C_f =$

$$\epsilon_0\epsilon_r \frac{w_1(L_2-M_1)}{D_0+\frac{(\epsilon\left(L\left(L_2{}^3-M_1{}^3\right)-\left(\frac{1}{4}\right)\left(L_2{}^4-M_1{}^4\right)+\left(3LL_3{}^2-2L_3{}^3\right)(L_2-M_1)+\left(\left(\frac{3}{2}\right)L_3{}^2-3LL_3\right)\left(L_2{}^2-M_1{}^2\right)\right)}{3dt(L_2-M_1)}}$$

(eq.10)

The sensitivity of three different strain sensor designs with three different initial gaps was calculated .The values of the initial gaps are 3m, 6m and 7.4m, determined by the fabricated sensors. The average sensitivity S_{1930}, in the range 0με to 1930με is given by;

$$S_{1930} = \frac{(C_0-C_{1930})/C_0}{1930} \quad \text{(eq.11)}$$

5. METHODOLOGY (Modelling and Simulation)

Sensor was modelled in two different ways in COMSOL multiphysics 4.4.

First method involves, using analytic function and giving prescribed displacement to the sensor. For this, first the analytic function was defined which represent the deflection of cantilever test substrate and its value was stored in a variable. This variable was used to give the prescribed displacement to a sensor which moves the lower electrode and hence change in capacitance takes place. The capacitance was noted for different strain value.

Second method involves, modelling of both sensor and cantilever test substrate together and load was applied at free end of the cantilever.

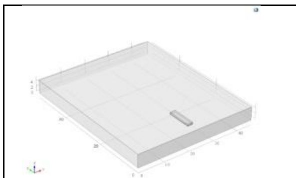
Sensitivity of sensor was simulated by changing the material of test substrate from steel 316L to silicon.

Use of electromechanics module was done. The stationary study was used for the simulation of sensor. The strain range was selected corresponding to the stress analysis of knee implant for an adult of 55kg. The simulated and calculated values of capacitance were compared for different strain. The sensitivity of sensor was also calculated. Different graphs were plotted between capacitance vs. strain for different design. The stress value at different knee angle is;

Weight(N)	10^0	30^0	50^0	90^0
540	8.90E+07	2.40E+08	2.93E+08	3.73E+08

- ✓ Table 1

Geometry of sensor and cantilever test substrate is:

	Length(mm)	Width(mm)	Height(mm)
Cantilever beam	56	46	5
Sensor Silicon base	9	2	.307, .304, .3026
Silicon anchor	1.5	2	.003, .006, .0074
Top Borosilate glass	9	2	.5

✓ Table 2
The values of sensor and cantilever test substrate used for simulation;

Sensor location(mm)	Value	Cantilever test bar(mm)	Value	Sensor parameter	Value
D	48.2	W	46	w_1 (mm)	2
L_0	7	T	5	ε_0 (F/m)	$8.854*10^{-12}$
L_1	5.3	L	56	ε_r	1
L_2	12.3	E[GPa](steel)	193	D_0(µm)	3,6,7.4
L_3	4.8	E[GPa](silicon)	178	Thickness(mm)	.810
L_4	3.3				

✓ Table 3
Design variables;

	Design 1	Design 2	Design 3
Electrode coverage	100%	67%	33%
Starting metal position	$M_1=L_1$	$M_1=L_1+(L_0/3)$	$M_1=L_1+(2L_0/3)$
Metal length	L_0	$2L_0/3$	$L_0/3$

✓ Simulated results for the displacement of sensor:

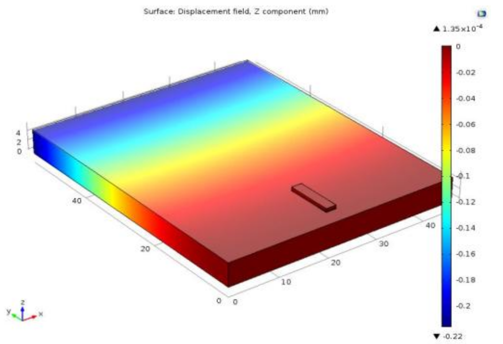


Fig. 5 Displacement produced in sensor placed on loaded beam (load (373.503N) corresponding to 1st strain at 100% metal coverage with 3µm initial gap is applied at free end).

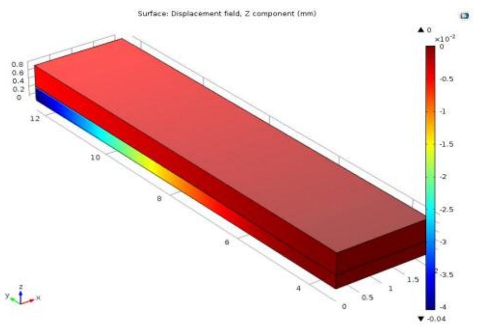


Fig. 6 Displacement produced in sensor as result of prescribed displacement when only sensor is modelled at same condition as that for Fig. 5

6. SENSOR FABRICATION

The sensor was virtually fabricated using Intellisuite 8.8. This was done by taking a silicon (100) substrate of thickness 310µm and deposited a SiO_2 layer by dry oxidation. The silicon was etched using RIE (Reactive Ion Etching). Thin layer of metal of thickness .2µm was sputtered on etched silicon. Glass was taken as another substrate of thickness .5µm and thin layer of metal was sputtered on glass. Both substrates were bonded using Pyrex bonding. Fig. below shows the fabrication steps.

Taking Si (100) substrate
⇩
Etching Si using RIE (Reactive Ion Etching) etch
⇩
Sputtering metal (gold) on etched Si
⇩
Taking glass substrate
⇩
Sputtering metal (gold) on glass
⇩
Bonding of both substrate using Pyrex bonding

Fig. 7 Process Flow

Fig.8 (a) Silicon substrate

Fig. 8 (b) Etching Si using RIE etch

Fig. 8 (c) Metal Sputtered on silicon

Fig. 8 (d) Glass substrate

Fig. 8 (e) Metal sputtered (Au) on glass

Fig. 8 (f) Bonding of both substrates using Pyrex bonding

Silicon

Borosilate Glass

Metal (gold)

7. OBSERVATION

- **When cantilever test substrate was of steel**

Table 4

Simulated and calculated capacitance at .003mm gap;

Strain	Simulated capacitance	Calculated capacitance(pF) at 100% metal coverage
0.00046114	21.8478	25.3206
0.00124	12.30252	15.309
0.00152	10.84614	13.403
0.00193	9.25172	11.338
Strain	**Simulated capacitance**	**Calculated capacitance(pF) at 67% metal coverage**
0.00046114	13.4658	14.532
0.00124	7.89202	8.082
0.00152	7.49563	6.97
0.00193	5.7831	5.801
Strain	**Simulated capacitance**	**Calculated capacitance(pF) at 33% metal coverage**
0.00046114	7.92322	6.069
0.00124	3.7379	3.121
0.00152	3.27722	2.657
0.00193	2.89575	2.182

Table 5

Simulated and calculated capacitance at .006mm gap;

Strain	Simulated capacitance	Calculated capacitance(pF) at 100% metal coverage
0.00046114	13.89426	15.61
0.00124	9.2022	11.17
0.00152	8.2525	10.121
0.00193	7.19041	8.896
Strain	**Simulated capacitance**	**Calculated capacitance(pF) at 67% metal coverage**
0.00046114	9.41913	9.513
0.00124	5.68022	6.249
0.00152	5.15206	5.563
0.00193	4.44838	4.792
Strain	**Simulated capacitance**	**Calculated capacitance(pF) at 33% metal coverage**
0.00046114	6.24684	4.213
0.00124	3.09522	2.544
0.00152	2.65338	2.227
0.00193	2.21659	1.884

Table 6

Simulated and calculated value for .0074 mm gap:

Strain	Simulated capacitance	Calculated capacitance(pF) at 100% metal coverage
0.00046114	11.96376	13.335
0.00124	8.33706	9.919
0.00152	7.51144	9.083
0.00193	6.58422	8.084
Strain	**Simulated capacitance**	**Calculated capacitance(pF) at 67% metal coverage**
0.00046114	8.16844	8.193
0.00124	5.20161	5.651
0.00152	4.64035	5.084
0.00193	4.1536	4.432
Strain	**Simulated capacitance**	**Calculated capacitance(pF) at 33% metal coverage**
0.00046114	5.13692	3.686
0.00124	2.96469	2.342
0.00152	2.52202	2.071
0.00193	2.10513	1.771

- **When cantilever test substrate was of silicon**

  Table 7

  The value of calculated and simulated capacitance for 3 designs;

Initial gap between electrode(mm)	%age of metal coverage	Capacitance(pF) for silicon substrate	Capacitance(pF) for steel substrate
	100	20.594	21.8478
0.003	67	12.835	13.4658
	33	7.376	7.92322
	100	13.56317	13.89426
0.006	67	9.17762	9.41913
	33	5.7471	6.24684
	100	11.70485	11.96376
0.0074	67	7.966	8.16844
	33	4.94562	5.13692

8. RESULT

Various sensor designs were investigated and the value of calculated capacitance is compared with the simulated one.

- The graph of capacitance vs. strain for .003mm gap between electrodes is shown in fig. 9;

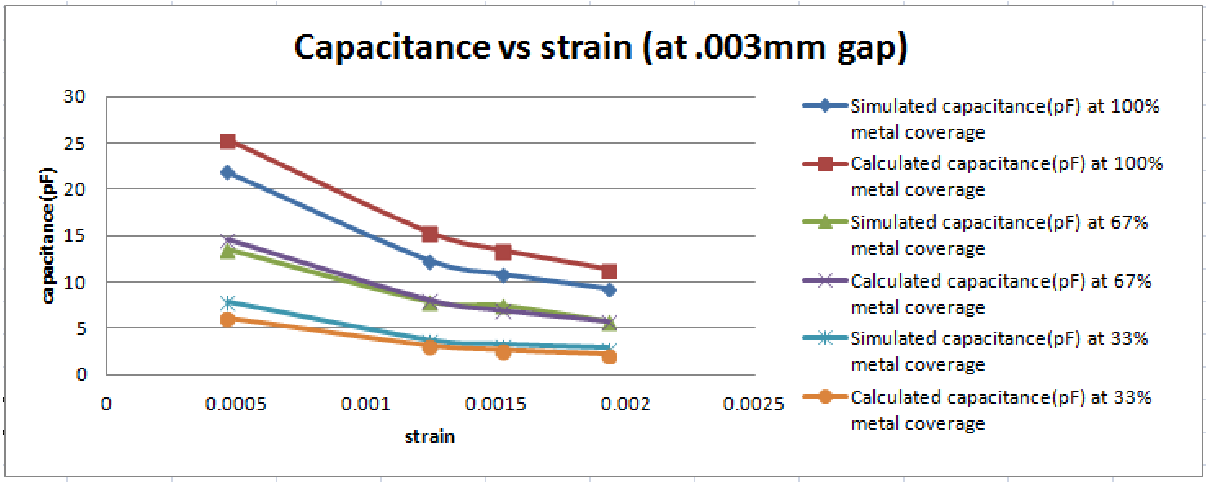


Fig. 9 Capacitance vs. Strain response with .003mm gap

- For .006mm gap, shown in fig. 10;

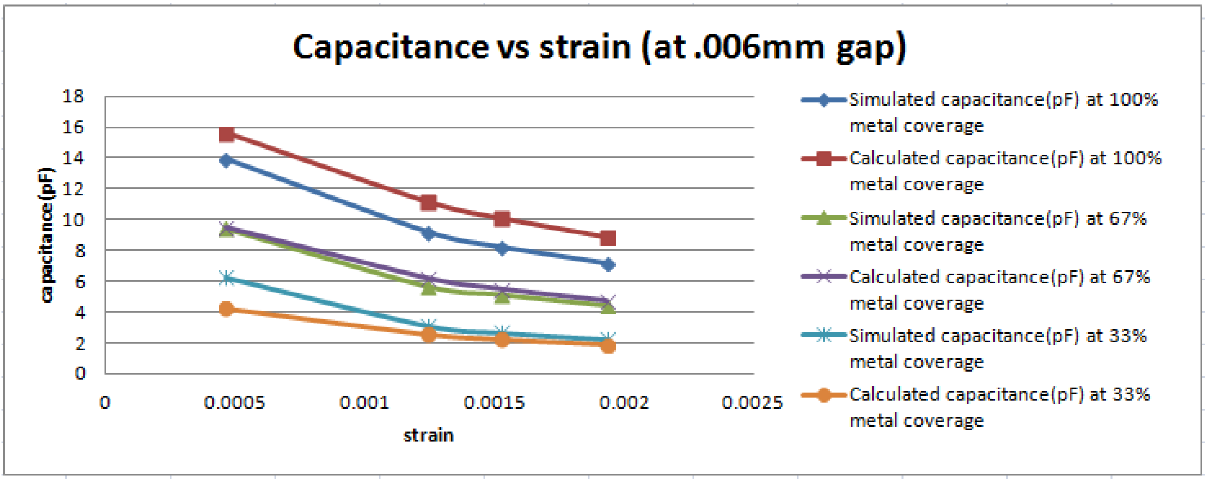


Fig. 10 Capacitance vs. Strain response with .006mm gap

- For .0074mm gap, shown in fig. 11;

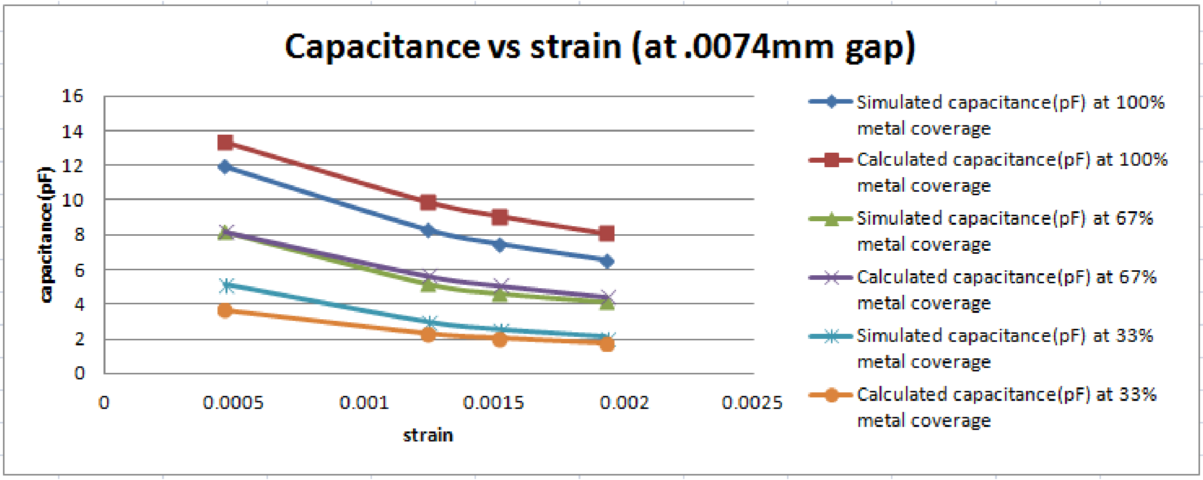


Fig. 11 Capacitance vs. Strain response with .0074mm gap

- Table 8

  Average sensitivity over the range of 1930με as defined in eq.11 for nine permutations is shown below;

Initial Gap	Result	Design no.1	Design no.2	Design no.3
3µm	Calculated	379.36	409.07	436.15
	Simulated	402.60	420.14	439.79
6µm	Calculated	295.14	338.08	376.66
	Simulated	338.56	367.37	398.20
7.4µm	Calculated	268.08	312.74	354.33
	Simulated	315.33	344.52	377.64

9. CONCLUSION

The small gap provides sufficient capacitance to avoid sensitivity losses due to parasitic capacitance. It is also clear from the observation that there is less difference between calculated and simulated values of capacitance. The design 3 (in which metal coverage is 33%) is proved to be most sensitive among three designs.

References

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