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Virtual Fabrication, 3D Electromechanical Simulation and System Level Modeling of MEMS Capacitive Pressure Sensor for Tire Pressure Monitoring System

Anurekha Sharma, Munju Mittal, Deepika Saini
Electronic Science Department, Kurukshetra University, Kurukshetra, 136119, India
Tel.: 91-1744-238410 ext. 2823, 91-1744-238023
E-mail: anurekhasharma@kuk.ac.in

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Abstract: Tire pressure monitoring system (TPMS) plays an important role in automobile safety. One of the important components of TPMS is a MEMS pressure sensor. This paper presents the virtual prototyping of TPMS which involves design, virtual fabrication and system level modelling of a square as well as acircular diaphragm based capacitive pressure sensor for a given stroke length. Intellisuite® MEMS design tool is used for obtaining the virtual prototype. The analytical expression for the sensitivity of square diaphragm in small deflection regime is derived and comparison of calculated results with simulated is presented. *Copyright © 2012 IFSA.*

Keywords: TPMS, MEMS, Intellisuite, Capacitive pressure sensor.

1. Introduction

MEMS stand for Micro Electro Mechanical Systems. It is a process technology used to create tiny integrated devices that combine mechanical and electrical components [1]. MEMS have been identified as one of the most promising technology for the 21st century and have the capability to reform both industrial and consumer products based microelectronics [2]. MEMS find application in automotive, medical, consumer, industrial, and aerospace sectors etc. The automotive sector has been a long growth market for MEMS sensors. Leading markets are ESP gyroscopes ($ 272 million), airbags ($ 260 million), followed by pressure with MAP and BAP (total $ 192 million), side airbags and TPMS [3]. Tire pressure monitoring system (TPMS) is one of the biggest automotive safety equipment required for safety on the road. Tire pressure monitoring systems (TPMS) are a way of warning a driver that the tire is incorrectly inflated, which will decrease the safety and performance of the vehicle, and increase the risk of an accident [2]. TPMS includes sensors for measuring pressure and temperature inside the tire, sensors to detect wheel speed and/or direction of rotation, controller with time base for periodic measurements, means to identify which tire is providing the data, data output to the vehicle chassis, command input for diagnostics and wake up and power source [5]. 99 % of direct TPM systems currently use MEMS pressure sensors. TPMS pressure sensor is expected to reach \$183M in 2012 from \$168M in 2007[4]. The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) has mandated that all vehicles sold in the United States must be equipped with TPMS from the year 2012 [6]. The MEMS pressure sensors can either be piezoresistive or capacitive. Capacitive pressure sensor has less power consumption, insensitivity to environmental (temp.) effect, high sensitivity near linear region in comparison with piezoresistive pressure sensor. It can also be easily be scaled down as there is no need to have resistor membrane [7]. This paper presents the virtual prototyping of TPMS which involves design, virtual fabrication and system level modelling of a square and circular diaphragm based capacitive pressure sensor for a given stroke length. Intellisuite® MEMS design tool is used for obtaining the virtual prototype. The analytical expression for sensitivity of a square diaphragm based pressure sensor is also derived, as the literature survey revealed that the expression for the same has not been reported. The capacitance is also calculated numerically using Mathematica and by finite element modelling.

2. Sensor Design Concept

A capacitive pressure sensor is composed of two plates which serve as top and bottom electrodes and a sealed cavity in the middle as shown in Fig. 1. The bottom electrode is fixed while the top electrode is composed of a deformable diaphragm. The deformation of the top diaphragm due to applied load pressure results in the variation or change in the capacitance, which can be measured with an interface circuit. The deformable diaphragm can either be circular or square or rectangular. This paper focuses on circular and square diaphragms. According to the theory of diaphragm bending, the deflection of diaphragm/plate may fall in small deflection regime and large deflection regime depending upon whether the strain in the middle plane can be neglected or not. The deflection regime is chosen as small as the deflection varies linearly in this case. The performance of capacitive pressure sensor is given by two important parameter named as sensitivity and non-linearity. The analytical expression for sensitivity, non-linearity and deflection in small regime is discussed below for both geometries.

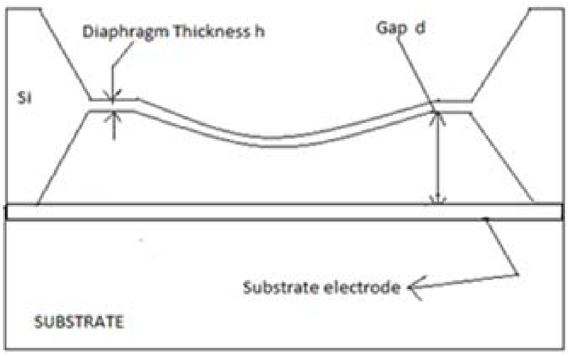

Fig. 1. Capacitive pressure sensor.

2.1. Circular Diaphragm

For circular diaphragm deflection in the small deflection regime at any point is given by [8]:

$$w(r) = \frac{Pa^4}{64D} \times \left[1 - \left(\frac{r}{a}\right)^2\right]^2, \tag{1}$$

where a is the radius of the diaphragm and r is the distance of the point from the center, and D is the flexural rigidity of the plate/diaphragm and is given by:

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

where E is the Young's modulus, υ is the Poisson's ratio and h is the thickness of the diaphragm. The maximum deflection occurs at the center (r=0) and is given by:

$$w_0 = \frac{0.17Pa^4}{Eh^3} \tag{3}$$

and the capacitance is given by

$$C = \iint \frac{\varepsilon dxdy}{d - w(x,y)} \tag{4}$$

sensitivity for circular diaphragm is given by [9]:

$$S_A = \frac{\varepsilon 12(1-v^2)r^6}{49Ed^2h^3} \tag{5}$$

2.2. Square Diaphragm

For square diaphragm small deflection at any point (x, y) is given by [9]:

$$w(x,y) = \frac{49Pa^4(x^2-a^2)(y^2-a^2)}{2304D} \tag{6}$$

Here a is the half side length and maximum deflection occurs at the center (x=0, y=0) is given by

$$w_0 = \frac{0.216Pa^4}{Eh^3} \tag{7}$$

and the capacitance given as

$$\mathrm{C} = \iint \frac{\varepsilon \mathrm{dxdy}}{\mathrm{d-w(x,y)}} \tag{8}$$

Eq. (8) is solved numerically using Mathematica®. For ***small deflection*** analytical expression of capacitance can be derived by expanding the denominator of equation (8) by using Taylor series expansion as given below:

$$C = \frac{\varepsilon}{d}\iint\left\{1 + \frac{w(x,y)}{d} + \frac{w^2(x,y)}{2d^2}\right\}dxdy \tag{9}$$

Since it is small deflection case so higher order terms can be neglected. Then equation becomes:

$$C = \frac{\varepsilon}{d}\iint\left\{1 + \frac{w(x,y)}{d}\right\}dxdy \tag{10}$$

Integrating the equation (10) by substituting w(x, y) from Eq. (6), one gets

$$C = C_0\left(1 + \frac{12.5Pa^4}{2025dD}\right), \tag{11}$$

where C_0 is the zero pressure capacitance and given by

$$C_0 = \frac{\varepsilon 4a^2}{d}$$

Sensitivity is given as

$$S_A = \frac{dC}{dP} \tag{12}$$

Sensitivity can be calculated by differentiating equation (11) w.r.t to pressure P and is given as

$$S_A = \frac{49\varepsilon a^6}{2025d^2D} \tag{13}$$

Non-linearity is given by

$$\frac{\Delta C_+ - \Delta C_-}{2(C_{\max} - C_{\min})}100\% \tag{14}$$

where $\Delta C+$ and ΔC are the maximum and minimum deviation from the straight line characteristics, respectively and C_{max} and C_{min} are the maximum and minimum capacitances in the operation range, respectively.

2.3. Von -Mises Stress

In circular diaphragm the maximum stresses are at the edges and are given as [11]:

$$T_r(a) = \frac{3a^2P}{4h^2} = \sigma_1; T_t(a) = \nu T_r(a) = \sigma_2; \sigma_3=0\ , \tag{15}$$

where r and t are the radial and tangential directions respectively.

In square diaphragm the maximum stresses are at the center of edges and are given as

$$T_{xx} = \frac{1.02\pi a^2P}{h^2} = \sigma_1; T_{yy} = \nu T_{xx} = \sigma_2;\ \sigma_3 = 0 \tag{16}$$

The Von Mises Stress provides a measure of the shear, or distortional, stress in the material. This type of stress tends to cause yielding in metals. Von-Mises stress is given by the following equation

$$\sigma_{vm} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}{2}} \tag{17}$$

Virtual Prototyping involves following steps:

1. Calculation of the structural parameters for a given stroke length and determination of sensitivity and non-linearity for a given pressure range;
2. Virtual Fabrication of the structure using Intellifab®;
3. Thermo-electromechanical simulation to analyze the behavior of the pressure sensor;
4. Macromodel Extraction and capacitance to voltage conversion using SNYPLE®.

2.4. Calculation of Structural Parameters

The two parameters sensitivity and non-linearity are influenced by structural properties, material properties and the stroke length, where as stroke length is decided by the gap d. The stroke length is chosen because it decides the pressure range that can be traversed by the diaphragm. The gap d is the critical parameter in both surface micromachining and bulk micromachining devices, as it is decided by the thickness of sacrificial layer in surface micromachining and by etch stop in bulk micromachining [11]. The choice of material is also important. Si (E=130 GPa, υ=0.3) is chosen as the device material here. Depending upon the choice of material and micromachining process gap d is taken as 5 µm. The maximum pressure to be measured by the pressure sensor is equal to standard tire pressure of car i.e. 35 psi or 241.29 kPa. We have considered three different stroke lengths:

Case I: maximum stroke length is 1/3 of the gap.
Case II: maximum stroke length is 1/2 of the gap.
Case III: maximum stroke length is 3/4 of the gap.

Since the maximum deflection is always limited to one third of thickness, therefore, stroke length gives the following relation between h and d:

Case I: thickness of diaphragm is equal to the gap.
Case II: thickness of diaphragm is 1.6 times of gap.
Case III: thickness of diaphragm is 2.6 times of gap.

The other parameter is side length. The side length can be calculated either by deflection formula as given in (3 and 5) sensitivity formula as given in (7 and 13). The structural parameters and calculated sensitivity for three cases are given in Tables 1-2.

Table 1. Structural parameters for three cases.

Case	Stroke length (µm)	D (µm)	h (µm)	Square (a) (mm)	Circular (r) (mm)
I.	1.5	5	5	0.146	0.156
II.	2.5		8.3	0.244	0.259
III.	3.75		12.5	0.367	0.390

Table 2. Calculated sensitivity for the three cases.

Case	Stroke length (μm)	Sensitivity for circular (pF/kPa)	Sensitivity for square (pF/kPa)
I.	1.5	0.000065	0.000069
II.	2.5	0.00026	0.00032
III.	3.75	0.0009	0.0012

3. Virtual Fabrication Process

In MEMS electronic component are fabricated using IC fabrication technique and mechanical component are fabricated using Micromachining [6]. Micromachining has become the fundamental technology for the fabrication of MEMS devices and in particular miniaturized sensors and actuators. For the virtual fabrication of capacitive pressure sensor IntelliFab is used. This paper includes the virtual fabrication steps of normal mode CPS using bulk micromachining. To fabricate the pressure sensor using bulk micromachining one needs to utilize bonding to create a sealed cavity. The creation of a permanent or temporary connection between two or more wafers / substrates is known as bonding. Two types of bonding techniques are used in fabrication of pressure sensor.

- Anodic bonding
- Si-Si fusion bonding

The Fig. 2 gives the process flow of capacitive pressure sensor of dimensions a=0.146 mm, h=5 μm, d=5 μm in IntelliFab for the square diaphragm. The same has been done for all the three case of circular as well as square diaphragm, but, for the purpose of brevity, only one case has been discussed. Fig. 3 shows the process flow for virtual fabrication. Figs. 4 and 5 show the results of simulation for structure constructed using IntelliFab.

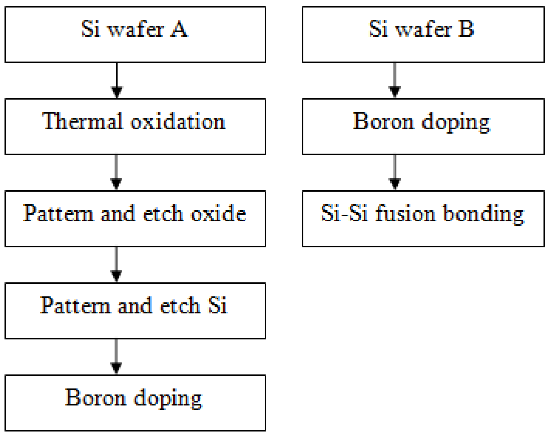

Fig. 2. Process flow chart of fusion bonding.

4. 3D Electromechanical Simulation Using Intellisuite

Virtually fabricated sensor is analyzed using TEM module and the results of simulation are shown in Table 3, 4 and 5. Figs. 6 and 7 give the comparison between calculated and simulated results for deflection and capacitance of square diaphragm. Fig. 7 also shows the curve fitting for obtaining the sensitivity. Figs. 8 and 9 compare the deflection and capacitance respectively of square and circular diaphragms. Figs. 10 and 11 give the comparison between the deflection as well as capacitance for all the three cases for square diaphragm. Figs. 12 and 13 show the simulation results for Von Mises stress for circular and square diaphragm.

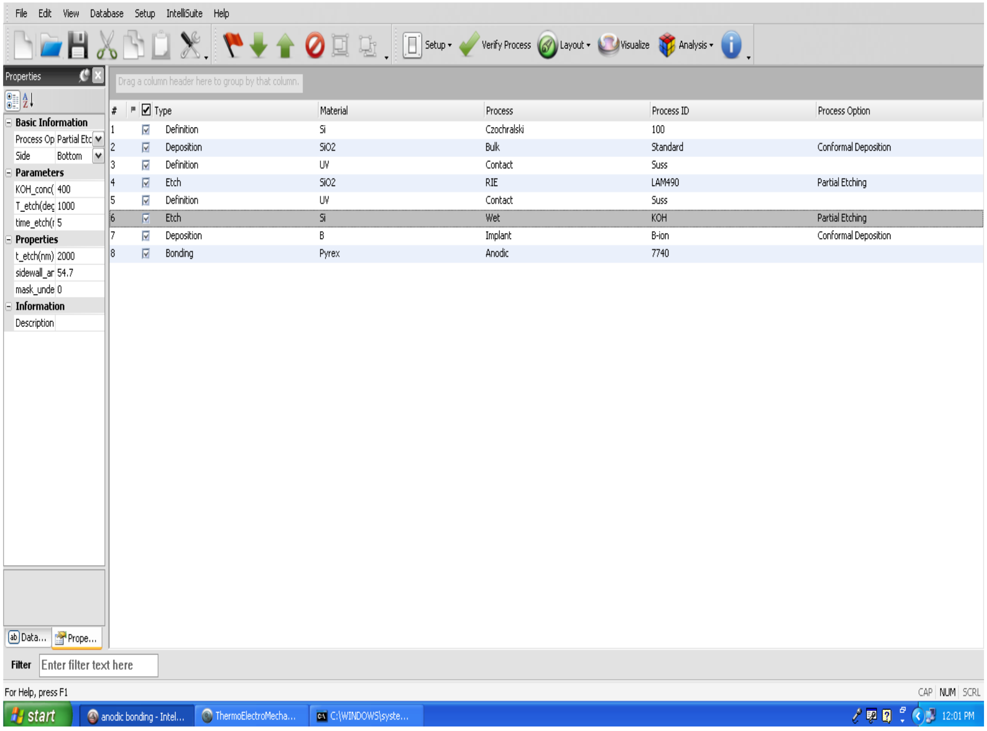

Fig. 3. Process flow of fusion bonding in Intellifab.

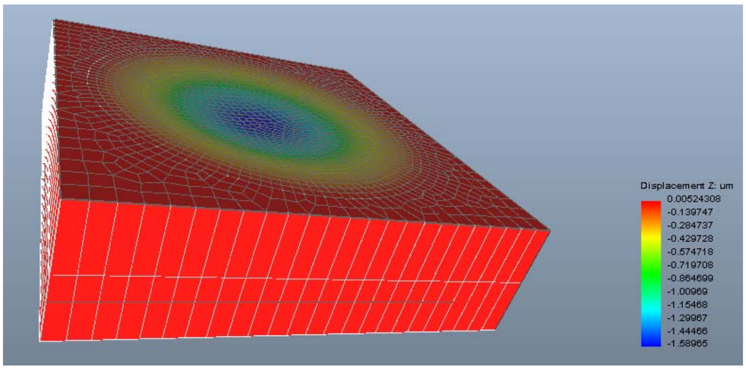

Fig. 4. Simulation deflection of a circular diaphragm.

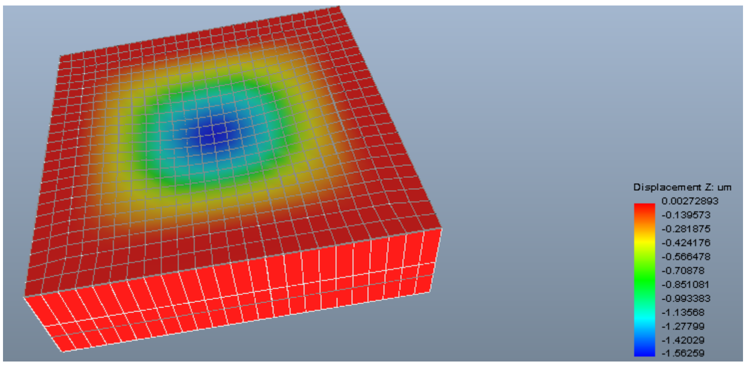

Fig. 5. Simulated Deflection of square diaphragm.

Table 3. Deflection and capacitance variation with applied load for case I.

Pressure (kPa)	Circular w_0 (µm)	Circular Cap (pF)	Square w_0 (µm)	Square Cap (pF)
0	0	0.1401	0	0.1675
20	0.118	0.1411	0.1295	0.1687
40	0.236	0.1422	0.2591	0.17
60	0.354	0.1433	0.388	0.1713
80	0.472	0.1445	0.518	0.1727
100	0.590	0.1456	0.647	0.1741
120	0.708	0.1468	0.775	0.1755
140	0.826	0.1480	0.907	0.177
160	0.945	0.1493	1.036	0.1786
180	1.063	0.1506	1.166	0.1802
200	1.181	0.1519	1.295	0.1819
220	1.299	0.1532	1.425	0.1836
240	**1.417**	**0.1546**	**1.55**	**0.1855**

Table 4. Simulated results for small deflections.

Case	Circular S_a(pF/kPa)	Circular Non-Linearity	Square S_a(pF/kPa)	Square Non-Linearity
I.	0.00006	1.8 %	0.00007	2.4 %
II.	0.0003	3.6 %	0.0004	3.7 %
III.	0.0015	6.9 %	0.0015	6.8 %

Table 5. Comparison of simulated Von Mises stress with calculated values.

Circular		Square	
Cal. (MPa)	Sim (MPa)	Cal. (MPa)	Sim (MPa)
155	145	175	186

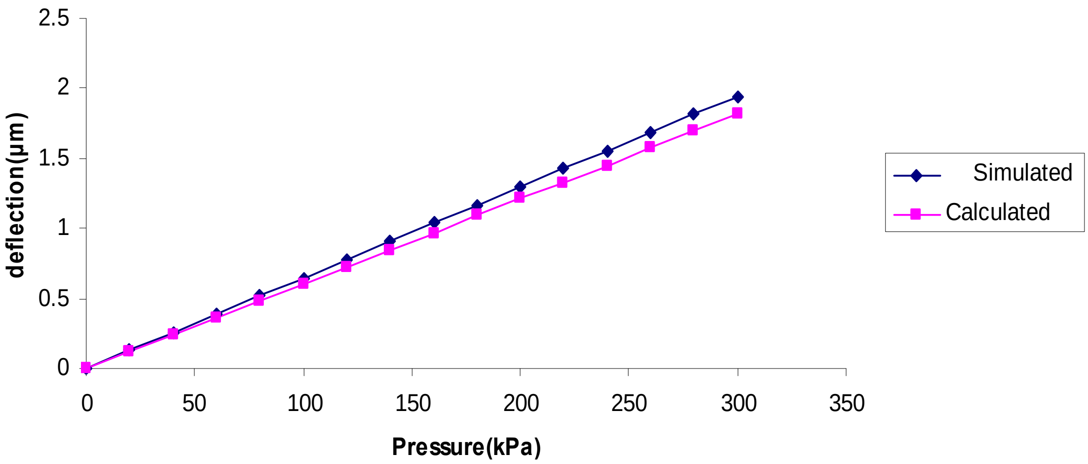

Fig. 6. Displacement of Square diaphragm with change in pressure.

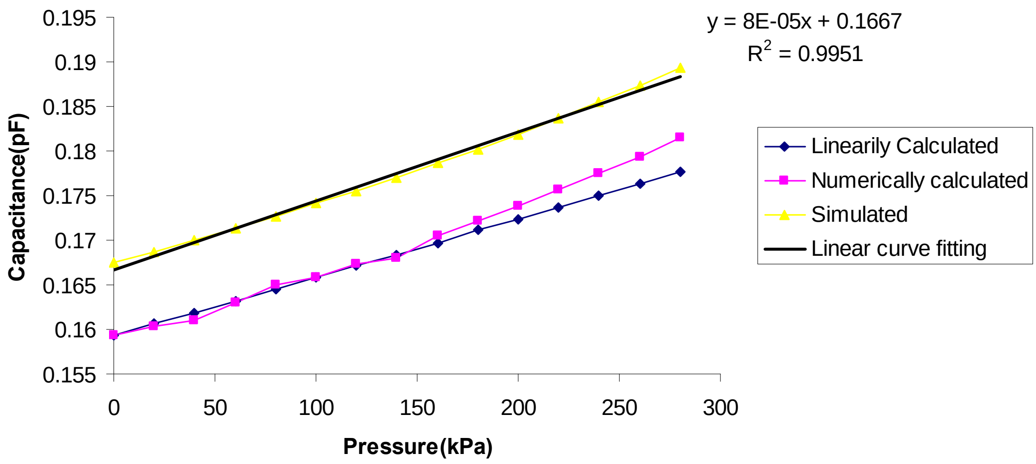

Fig. 7. Capacitance variations of square diaphragm with change in pressure.

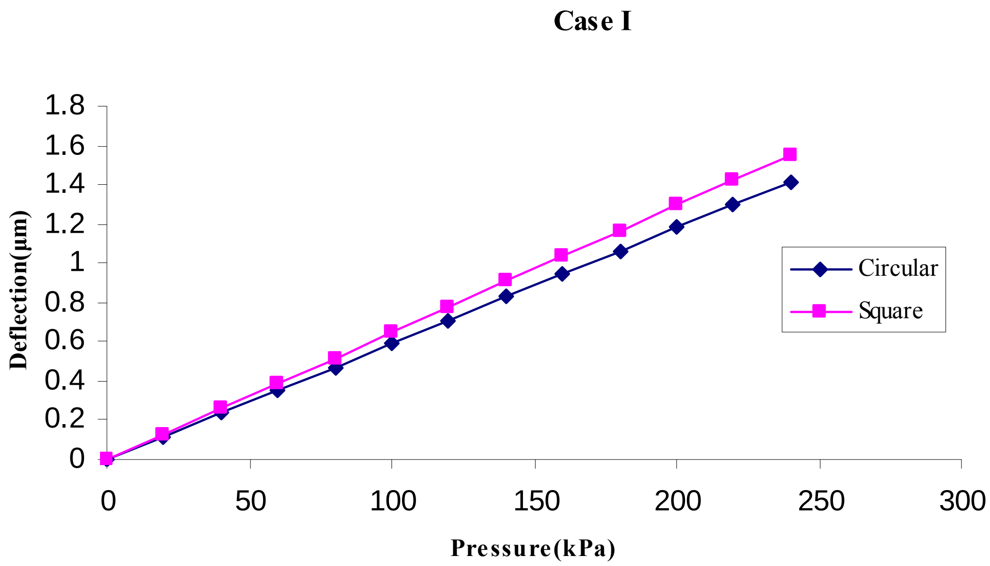

Fig. 8. Deflection v/s pressure for case I.

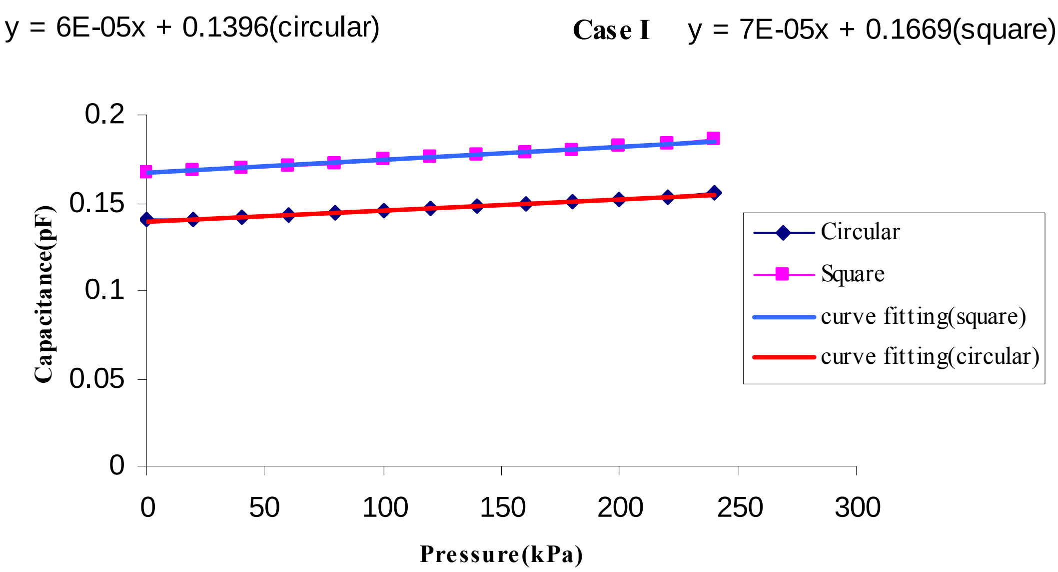

Fig. 9. Capacitance v/s pressure for case I.

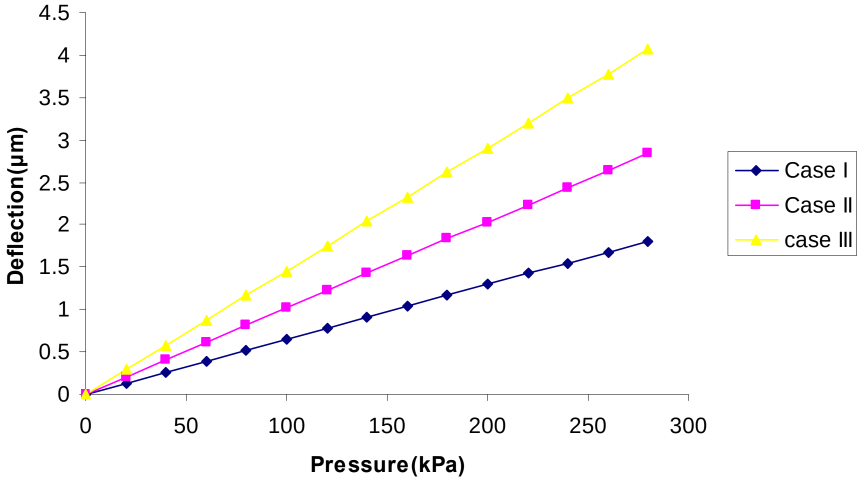

Fig. 10. Combined graph for small deflection variation due to applied pressure for a square diaphragm.

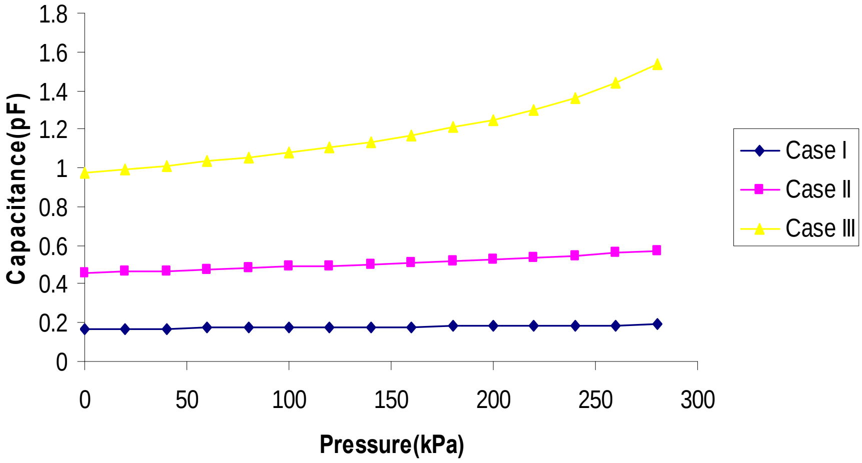

Fig. 11. Combined graph for capacitance variation due to applied pressure for all three cases.

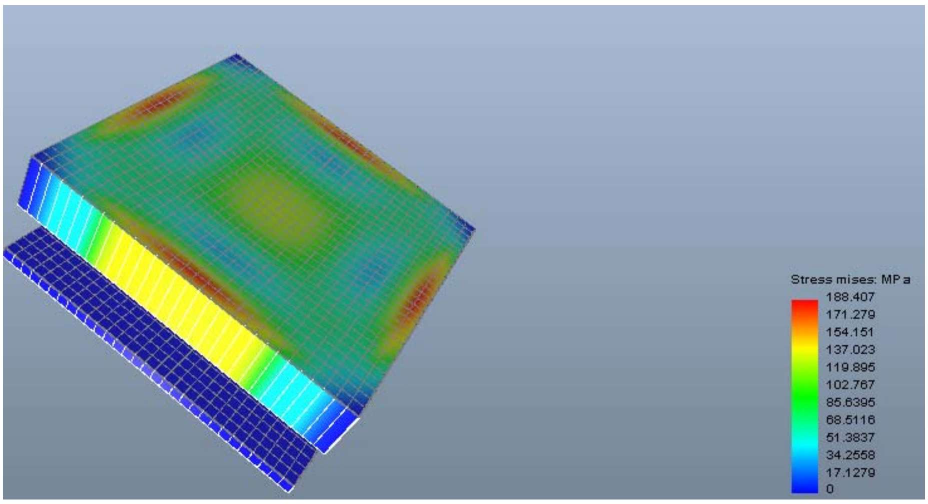

Fig. 12. Von Mises stress in square diaphragm.

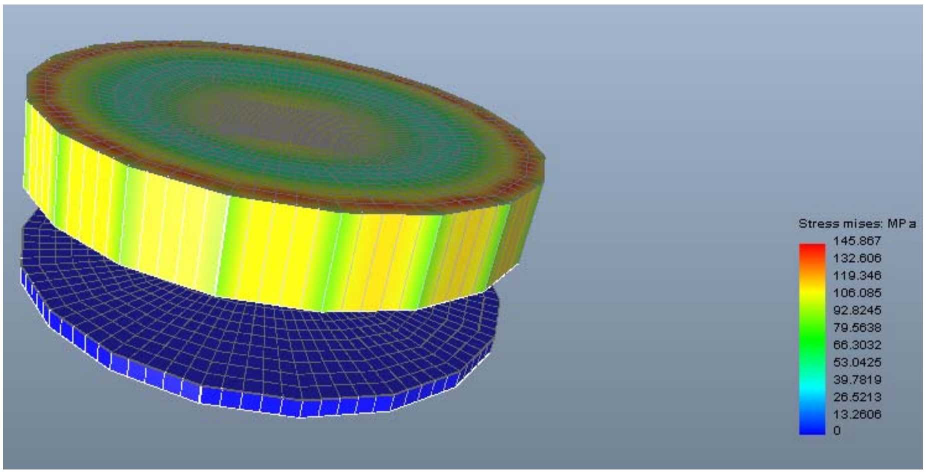

Fig. 13. Von Mises stress in circular diaphargm.

5. System Level Modeling

System-level modeling is that approach of simulation, where analytical or semi-analytical models of device components are placed and connected in a schematic of the device and the whole device is simulated. This approach allows the straightforward coupling of many different physical domains, including control circuitry, but is limited by the availability and/or accuracy of component models [12]. System Model Extraction is a three dimensional model of multi conductor electromechanical device. It can be converted into analytical macromodel that can be inserted as a black-box element mixed with signal circuit simulation. This process is based on energy method which constructs analytical model for each energy domain of the system. To extract the macro model, Intellsuite software has an important module named as SYNPLE. SYNPLE is also known as a circuit-simulator. SYNPLE is used for circuit analysis as well as modified nodal analysis [10]. System model extraction is done by following three steps in TEM module.

- Modal contribution analysis is done to determine the mode contribution for deformed state.
- Strain energy vs. modal amplitudes analysis is done to determine strain energy for selected mode.
- Mutual capacitance vs. Modal amplitudes analysis is done to determine the capacitance for selected mode.

After constructing the model in TEM, analysis is done using SYNPLE. The Fig. 14 shows the schematic for dc analysis. A force load equivalent of pressure is applied in Macromodel Extraction. This force is calculated by the formula

$$F = \frac{K_f}{K_p} P \quad , \tag{18}$$

where K_f is the slope given by the force v/s displacement curve and K_P is the slope given by the pressure v/s displacement curve.

6. Capacitance Measurement Circuit

In the capacitive pressure sensor whenever pressure is applied at the electrode which is free to move, there is change in gap between the electrodes leading to change in the capacitance. Capacitive Pressure sensor converts the diaphragm deformation, corresponding to pressure, into a change of capacitance and which is finally converted output electrical signal. To convert the capacitance into voltage, capacitance measurement circuit is used. There are various methods for the measurement of capacitance [11]. These range from measurement of capacitance using a capacitance bridge to excitation of the unknown capacitance by modulating it using a waveform and demodulating it. One of the commonly used capacitance to voltage converter is charge amplifier, which has been used here for illustration of virtual prototyping. The schematic of the charge amplifier is shown in Fig. 15 and the output voltage variation is shown in Fig. 16. Voltage sensitivity obtained is -0.00003 V/kPa, which is very poor for any practical use and there is a need to use better alternatives.

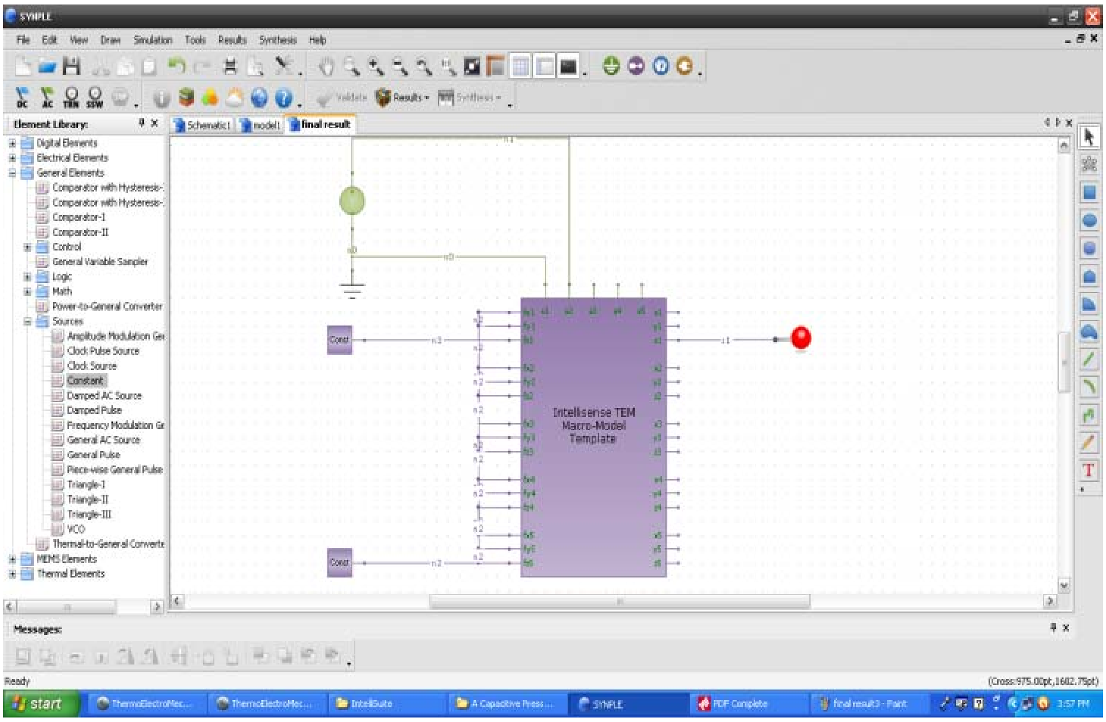

Fig. 14. DC analysis schematic.

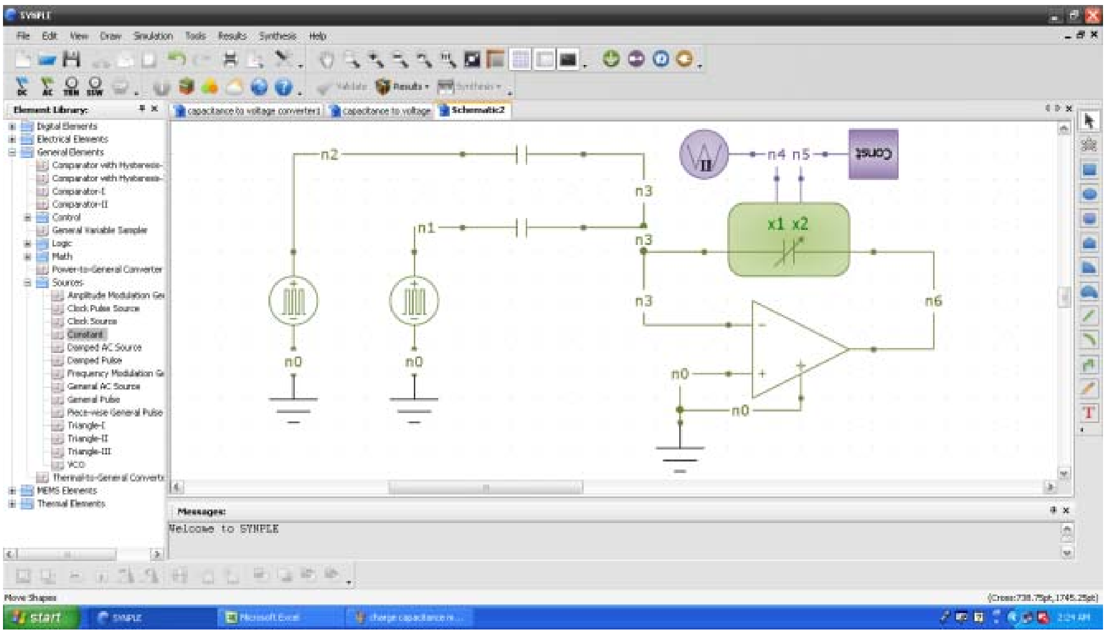

Fig. 15. Capacitance measurement circuit.

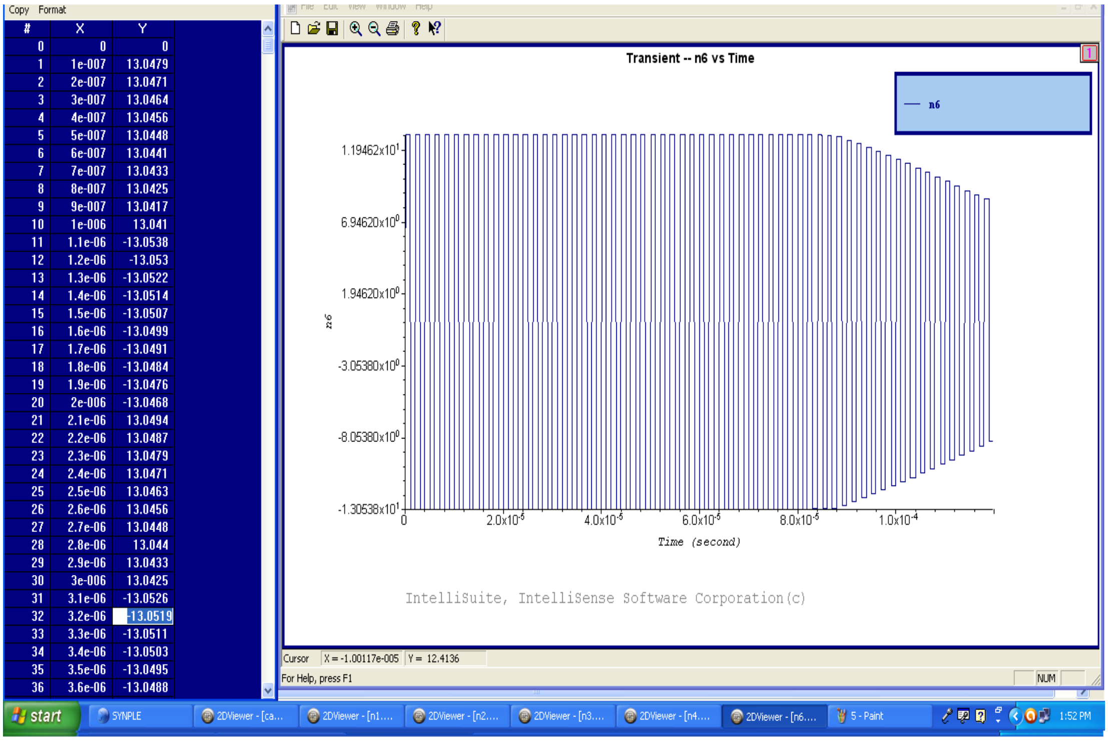

Fig. 16. Output voltage.

7. Results and Discussions

Capacitive pressure sensor with square and circular diaphragm was designed for small deflection by taking three different stroke lengths and two performance parameters sensitivity and non-linearity were obtained from simulation and as well as calculations. The results obtained are summarized as follows:

- The expression for sensitivity was obtained for case of small deflection only and is given by

$$S_A = \frac{49 \in a^6}{2025 d^2 D}$$

- For a given gap, as the stroke length increases, the side length as well as thickness also increases by almost the same ratio.
- Sensitivity and non-linearity increases as stroke length increases
- The calculated and simulated values were found to be in good agreement for the capacitance as well as deflection.
- The virtual prototyping of pressure sensor was successfully done

The explanation for the above results is as follows:

- For the small deflection case since the condition is w≤0.3 h and we have chosen maximum deflection to be limited to w=0.3 h therefore, restricting the stroke length means restricting the value of thickness h. Now according to the expression given in equation (2) it can be seen that the maximum deflection varies linearly as fourth power of side length, and inversely as third power of thickness. As the stroke length is increased, the side length increased by almost the same ratio as the increase in thickness.
- As the stroke length increases for a given pressure range, the deflection at given pressure as well as the change in deflection also increases. This in turn increases the change in capacitance and thereby

sensitivity. However, capacitance variations are non-linear with gap, therefore as the stroke length increases the non-linearity increases.
- To obtain a given sensitivity for a given gap and given stroke length, the diameter of circular diaphragm is more than the side length of square diaphragm. However, the area of the square diaphragm is more than the circular, therefore, higher capacitance as well as higher stress is obtained in the case of square diaphragm. These facts govern the choice of the geometry. Circular diaphragms are preferred if size is at premium whereas if parasitic are to be minimized then square geometry is preferred.

The limitations of this paper are summarized as:
- The paper discusses only the small deflection of the diaphragm.
- The structural material always has inherent residual stress present in it and same has to be taken into account while simulating the device.
- The effect of temperature on the performance of device has not been studied.

Acknowledgement

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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