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**Original scientific paper** *

# MODELING A CAPACITIVE SENSOR WITH A SOFT FOAM POLYMER LAYER FOR SMALL FORCE MEASUREMENT

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**Abstract**. *Numerous types of sensors can be used in mechatronic systems. Flexible sensors have great potential for application in human-machine interfaces, human motion monitoring, artificial electronic skin, and wearable electronic devices. In the field of collaborative robots, sensitive force sensors made of flexible materials are frequently used for measuring very small forces. Finite element simulation is a very useful method for the cost-effective development of these sensors. This paper presents finite element simulation of a small force capacitive sensor. A soft foam polymer is used as the dielectric in the capacitor. A force applied to one electrode of the capacitor produces displacement of the polymer which in turn results in a variable capacitance of the capacitor. The total displacements of the soft foam polymer are presented, and the dependence between capacitance and force is introduced.*

**Key words**: *capacitive sensor, FEM simulation, soft polymer, hyperelastic material*

## 1. INTRODUCTION

Sensors play a significant role in mechatronic systems by providing the necessary environmental information to the controller of an automated system. Thus, engineers and scientists continuously develop different types of sensors and constantly improve them. There is a great interest in flexible sensors due to their great potential for application in human-machine interfaces, human motion monitoring, artificial electronic skin, and wearable electronic devices. Force (or pressure) sensors for very small forces, up to 1N with high sensitivity, can be very useful in the field of collaborative robots or wearable electronic devices. There are different sensing mechanisms and therefore existing flexible pressure sensors can be divided into piezoresistive, capacitive and piezoelectric [1].

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There are different methods for low-force sensor analysis and development. While some research studies are based only on simulation results, others have developed physical products and performed real evaluations, showing the high sensitivity of these sensors, regardless of the applied technique.

The development of flexible sensitive sensors for small forces can be a very expensive and time-consuming process. Over the last few years, the finite element method has been widely used as a powerful tool for analyzing engineering problems, providing faster and cost-effective sensor design.

Some authors have focused on the development of multi-axis force sensors [2-5]. The authors in paper [2] analyzed a multi-axis force/torque sensor based on a simply supported beam and optoelectronic technology that can customize mechanical structures for force/torque measurements in robotic systems. In [3] a six-axis capacitive force/torque sensor was developed by using the dielectric elastomer sensor technology. After the experiments, the authors demonstrated that the sensor could measure a force of 10N and a torque of 0.16Nm with a resolution of 0.5N and 0.02Nm. As a result, it should replace the existing six-axis torque sensors in industrial areas. In [4] the authors developed a miniature three-axis silicone sensor intended for the fingertip. Based on the obtained results, the differential capacitance of any possible capacitor combination can be determined. This is especially advantageous for sensors using differential capacitive principles. The flexible three-axial force sensor with a multilayered dielectric consisting of both the air gap and polydimethylsiloxane is given in [5]. The sensor exhibits a linear response to the three-axial forces, when operating in the range of 0–10N for three-axial loads.

Xu et al. [6] developed a fully soft capacitive omnidirectional tactile (ODT) sensor based on the multi-walled carbon nanotube (MWCNT)-coated micro-spines electrode and hemispheric dielectric structure. The applied tests confirmed a high sensitivity and a wide response range of the sensor.

In some studies, the focus is on the development of MEMS (Micro Electro-Mechanical Systems) sensors [7], while in others the COMSOL Multiphysics [8-9] is used for the development analysis. The authors in [7] created a bulk micromachined mass/beam system that has a MEMS device with an integrated capacitive transducer by wire. After detailed analysis, the results show the potential for an integrated platform of an extremely compact MEMS + ASIC gravimeter on the package level, or even a monolithically integrated CMOS in the MEMS device. Paper [8] designed, modeled, and simulated the development of a MEMS pressing sensor using different shapes and materials (InP, GaAs and Silicon) in COMSOL Multiphysics. The results show that the most sensitive is the pressure sensor with a circular membrane created from InP material. In [9] a MEMS based capacitive pressure sensor was analyzed using COMSOL Multiphysics. The paper presents the simulation of the deflection, stress, and Eigen frequency analysis of the capacitive pressure sensor.

Various research papers have focused on capacitive pressure sensors [10-14]. The authors in [10] presented the development of a capacitive pressure sensor with ceramic dielectric material - barium titanite fillers - in the dielectric layer to increase sensitivity. The strategy they implemented provided sensors with good performance such as high sensitivity at low pressure, low detection limit, short response time, and long-term cycle stability. In [11] the researchers performed the FEM simulation using the finite element method to calculate the capacity between two conductive plates. The results show that for small electrodes or those with a large distance between the plates, the thickness of the plates dramatically changes the value compared to an ideal capacitor. Cheng et al. [12] developed a polymer-based capacitive sensing array that consists of a micromachined PDMS structure and a flexible printed circuit board (FPCB), and which can be used for measuring normal and shear forces. A supersensitive capacitive pressure sensor was developed by combining porous CB/PDMS composites with a thin PET isolating layer [13]. After testing, the results show that highly sensitive and wearable capacitive sensors at low-cost and low-power consumption electronic systems can have various uses. In [14], the authors experimented with the reduction of the dielectric constant of PDMS achieved by the combination of treatment and washing with the ethanol-toluene buffer solution. The results show that this simple technique is effective and applicable for such sensors.

In the literature, some authors have focused on the piezoelectricity sensors [15,16]. The researchers in [15] developed a highly sensitive flexible sensor array based on piezoelectricity for dynamic tactile sensing. They used the core piezoelectric sensing micropillars, fabricated by straightforward and scalable nanoimprinting technology, which are positioned between a pair of cross-electrode arrays, to construct multiplexed sensor arrays, and got the good flexibility and robust stability of the sensor arrays that can be attached to curved surfaces for real-time tracking of dynamic force and imaging the force distribution. Paper [16] describes the development of a force transducer for small forces of up to 1N in the metrological field applicable to the EN AW-2007 aluminum alloy and transferable to the EN AW-2024 typically used for force transducers, validated as a very sensitive but stable behavior.

Pagoli et al. [17] created the tactile sensors for soft robotic applications using the cost-effective materials such as paper, silicone, conductive ink. The results validated this sensor capacity to detect simultaneous multi-touch points and to obtain their corresponding contact forces.

In this paper the finite element simulation of the small force capacitive sensor was performed. A soft foam polymer was used as a dielectric in the capacitor. The force of 1 N was applied to one electrode of the capacitor causing the displacement, which in turn resulted in the capacitance change of the capacitor.

## 2. PHYSICAL MODEL OF THE CAPACITIVE SENSOR

The flexible capacitive pressure sensor is a type of traditional parallel plate capacitor, which has a high stability due to its sandwich structure. Fig. 1 shows the cylindrical parallel plates capacitor whose electrodes are thin copper round plates with the diameter of 10 mm and the thickness of 0.5 mm. The dielectric between these two electrodes is a highly compressible soft foam polymer.

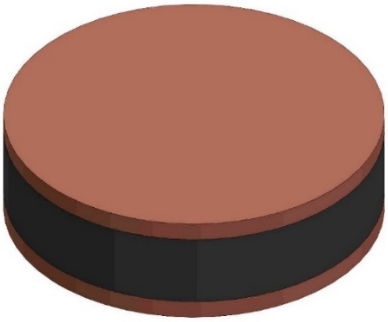

**Fig. 1** Model of the parallel plate capacitor

The capacitance $C$ of the parallel plate capacitor can be expressed as:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{1}$$

where $\varepsilon_0$ is the relative permittivity of the vacuum, $\varepsilon_r$ is the relative permittivity of the dielectric, $A$ is the area of the plate electrode and $d$ is the distance between the electrode plates. These parameters will change when an external force is applied to the capacitive flexible sensor. The result is a change in the force sensor capacitance, which is the key output of the sensor.

The dielectric properties of the highly compressible soft foam polymer are experimentally investigated in paper [18]. The researchers examined the electrical properties of polyurethane filled with graphene nanosheets, as well as pure polyurethane. The obtained results show that the relative dielectric permittivity, $\varepsilon_r$, of pure polyurethane foam varies between 4.5 and 5.5, thus, for this research the value of $\varepsilon_r = 5$ was adopted.

The mechanical properties of the highly compressible soft foam polymers can be described by the stretch-based model proposed by Storakers [19, 20]. This is the most utilized phenomenological hyperelasticity model for highly compressible foams. The strain energy density function for the Storakers material model is given by

$$W_s = \sum_{\mathrm{k}=1}^{\mathrm{N}} \frac{2\mu_k}{\alpha_k^2} \left( \lambda_1^{\alpha_k} + \lambda_2^{\alpha_k} + \lambda_3^{\alpha_k} - 3 + \frac{1}{\beta_k} \left( J_{el}^{-\alpha_k \beta_k - 1} \right) \right) \tag{2}$$

where $\lambda_1$, $\lambda_2$, and $\lambda_3$ are the principal stretches, $\alpha_k$, $\mu_k$, and $\beta_k$ are the Storakers material parameters, and $J_{el}$ is the elastic volume ratio which can be expresed as

$$J_{el} = \lambda_1 \lambda_2 \lambda_3 \,. \tag{3}$$

In a hyperelastic simulation, the Storakers material parameters need to be provided as an input. These parameters can be calculated by fitting experimental test data against analytical expressions representing stress or force versus stretch. In [20] the Storakers material parameters for specimens of polyurethane soft foam named SAF 6060 are obtained from a Swiss soft foam producer (Foam Partner Fritz Nauer AG). These Storakers material parameters, obtained by utilizing the uniaxial compression test, are given in Table 1 [20].

**Table 1** Storakers material parameters for polyurethane soft foam [20]

| Parameter | Value |
|---|---|
| $\alpha_1$ | 19.8 |
| $\mu_1$ [kPa] | 4.79 |
| $\beta_1$ | 0.0139 |
| $\alpha_2$ | 19.7 |
| $\mu_2$ [kPa] | 3.51 |
| $\beta_2$ | 0.00657 |

## 3. NUMERICAL MODEL OF THE CAPACITIVE FORCE SENSOR

Using the material properties described in the previous section of this paper, the coupled finite element method is performed in COMSOL Multiphysics. *Solid Mechani*cs and *Electrostatics* from COMSOL are used as coupled physics. The capacitor with two copper electrodes and soft polyurethane as the dielectric was loaded with the force in the range of 0.1÷1 N, with a 0.1 N increment. The force affects one electrode, while the other electrode is fixed. The electric potential of 1V is applied to one electrode, while the other electrode was grounded. The simulation was performed for three different thicknesses of the dielectric: 1 mm, 2 mm, and 3 mm. In the finite element analysis, the basic concept is to analyze the structure, which is an assemblage of discrete pieces called elements, connected at a finite number of points called nodes. A network of these elements is known as a mesh. For this analysis, the automatic mesh generating capabilities of COMSOL were used rather than defining the nodes individually. The number of generated elements in the mesh was 15748 for the dielectric of 1 mm, 17214 for the dielectric of 2mm, and 19909 for the dielectric of 3mm thick, as shown in Fig. 2.

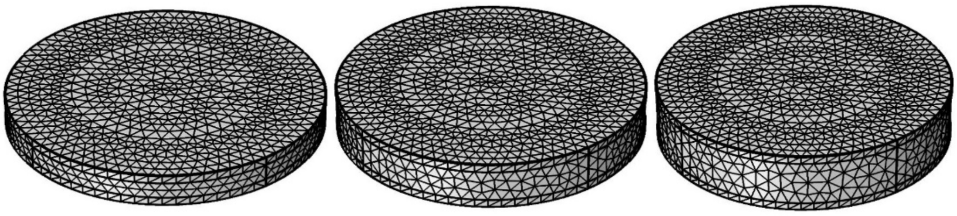

**Fig. 2** Mesh of the parallel plate capacitor

## 4. RESULTS

The displacement diagrams of the capacitive force sensor, with the soft polymer as the dielectric, for the three examined cases with the dielectric thicknesses of 1, 2, and 3 millimeters, respectively, are presented in Fig. 3, as results of the finite element simulation.

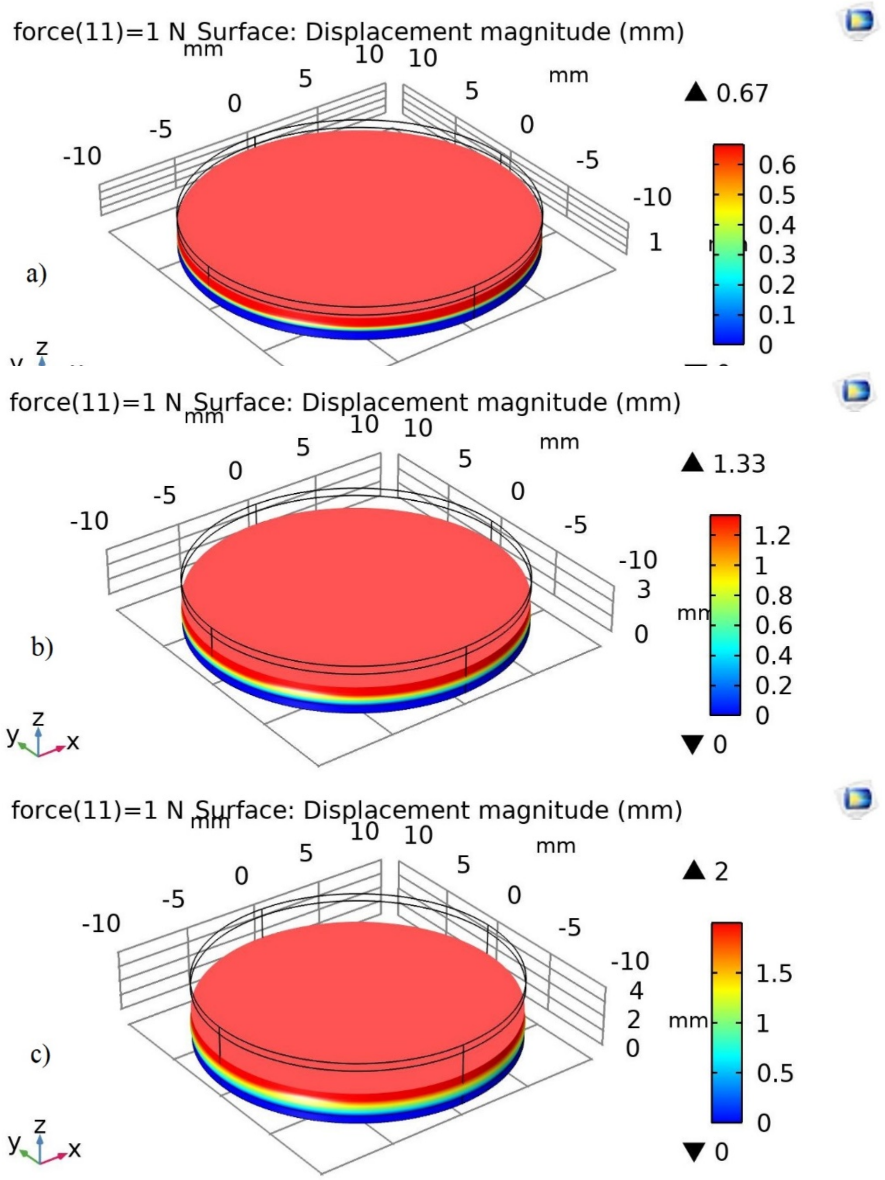

**Fig. 3** Displacement of the capacitive force sensor.
Initial thickness of the dielectric: a) 1mm, b) 2mm, c) 3mm.

The capacitance over applied force dependences is shown in Fig. 4. One can notice, comparing the obtained results, that the thicker soft polymer dielectric causes a larger change in the capacitance, for the applied force in the range 0.1 ÷ 1 N.

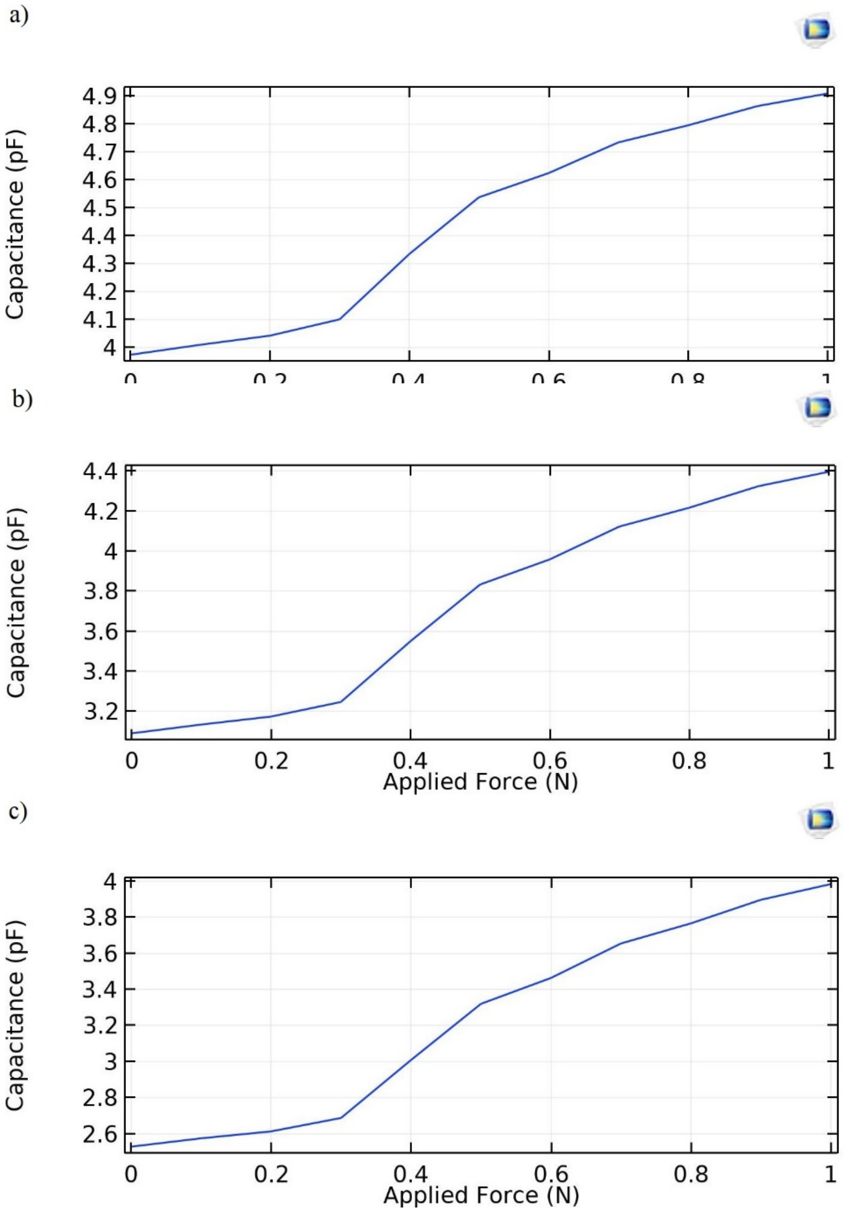

**Fig. 4** Capacitance-force dependence of the capacitive force sensor.
Initial thickness of the dielectric: a) 1 mm, b) 2 mm, c) 3 mm.

From Fig. 4, for the initial dielectric thickness of 1 mm (Fig. 4a), one can observe that with the increase in the force intensity from 0.1 ÷ 1 N, the capacitance increases from 4 to 4.9pF, or 22.5%. For the initial dielectric thickness of 2 mm (Fig. 4b), the capacitance changed in the range 3.2 ÷ 4.4pF, or 37.5%. Fig. 4c presents the variation of the capacitance with the dielectric thickness of 3 mm. The capacitance change is 53.8% (2.6 ÷ 4pF) for the same applied force. The obtained results show that by increasing the soft dielectric thickness, the capacitance change steadily increases.

## 5. CONCLUSION

This paper presents a capacitive sensor design intended for low intensity force measuring. Different dielectric thicknesses were examined, characterized and tested as candidate dielectric layers for such sensors. Based on the force vs. thickness relation of the dielectric, different capacitance and sensitivity sensors can be obtained. The scenario in which the sensor is to be used determines the selection of the appropriate sensor.

The capacitive sensors shown and tested in the FEM simulation are often repeatability and durability stable, and they can precisely measure the applied force at discreet points, even at very low force levels. Therefore, capacitive sensors are evaluated for many applications especially for wearable technology and products, medical equipment, electronic devices and robotics. The method presented in this paper shows the use of FEM simulation as an optimization method for designing soft capacitance sensors for small intensity force measurements.

The obtained results show that by increasing the soft dielectric thickness, the capacitance change also increases, but the initial capacitance values decrease significantly. This means that excessive values for the dielectric thickness lead to a significantly lower initial capacitance, which can hinder practical application.

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