Simulation and Experimental Characterizations of a Thin Touch Mode Capacitive Pressure Sensor

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Abstract: This study describes a thin and low-cost capacitive pressure sensor and a model elaborated by the finite element method (FEM) in touch mode for monitoring fluid pressure from 0 to 40kPa in a perfusion chamber with Luer fittings for medical applications. The touch mode is expected to provide good linearity, large measuring range and large overload protection [1]. The choice of a thin polymer membrane as sensitive element with a printed circular electrode reduces drastically the thickness and fabrication costs in comparison to standard microfabrication processes. A set of assumptions were successfully applied to reduce the computation time of the model which was validated by comparison with experiments. The principle, characteristics and a methodology of FEM model for a specific touch mode capacitive-type pressure sensor are illustrated in the report.

Keywords: Capacitive-type pressure sensor, FEM model, diaphragm bending, large deformation, capacitor, model coupling, Comsol multiphysics.

1. Introduction

The response of capacitive-type pressure sensors is intrinsically non-linear as it relies on the bending properties of a diaphragm; the latter is the transducer element. The deformation of the diaphragm highly depends on its thickness. Diaphragms deformation types are usually classified in two categories: 1) thin diaphragm with small deflections, 2) thin diaphragm with large deflections. There is, for the first type, a theory which can predict with a sufficient approximation the diaphragm behavior under loads application. However, for the second type, the theory is much more complicated as one must deal with nonlinear differential equations with unknown solution for the general case [4].

The two main fabrication methods for capacitive-type pressure sensors, silicon technology and thick film technology, offer a wide range of diaphragm tailoring possibilities to satisfy the specifications required by specific application. However, regardless of the technology used, the sensor in the parallel plate configuration can be designed to operate in normal mode or in touched mode as shown in Fig. 1. a) and b) respectively. In the normal mode, the diaphragm's maximum deflection is smaller than the distance separating the plates. The normal mode belongs to the category one of diaphragm's type. When the diaphragm is allowed to touch mechanically the opposite electrode, which is protected by a dielectric layer, the sensor is in touch mode. The touched mode belongs to the category two of diaphragm deflection type.

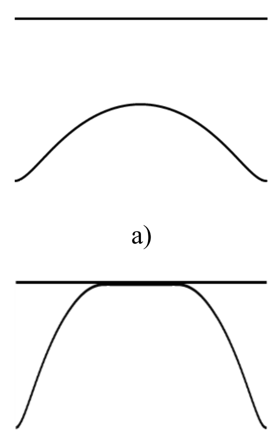


Fig. 1. a) Normal mode. b) Touch mode.

As the sensitivity depends on the distance separating the electrodes with a square root law

[2] and the dielectric constant, the main contribution to the output response is the capacitance of the touched area. Fortunately, according to [3] the touched area in function of the pressure may be well approximated by a linear function. Thus, the sensor can be tailored to have a linear C-P characteristic in the target measuring range.

The finite element method (FEM) advantageously provides a formalism that can replace such a problem described by complicated differential equation to a simpler one. This paper presents the elaboration of a FEM model done with COMSOL multiphysics for a low-cost and disposable capacitive pressure sensor in touch mode for monitoring fluid pressure from 0 to 40kPa in fluidic chambers with Luer fittings for medical applications, as well as an experimental validation process.

3. FEM model

The chosen sensor geometry is composed of a circular open capacitor in copper, covered with a dielectric layer, which faces two pad printed half moon electrodes, with a silver based ink, on a polyester membrane. The special electrode configuration is presented Fig. 2. a), with its equivalent circuit in figure Fig. 2. b). The dimensions of the sensor are given in Fig. 2. c).

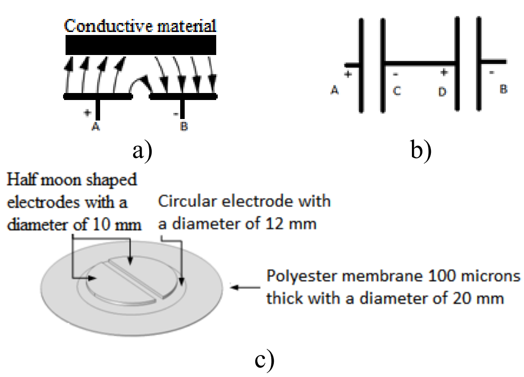


Fig. 2. a) Electrode configuration. b) Equivalent circuit. c) Geometry of the model; the distance between the plates is 500µm.

This electrode configuration was designed to have a flat sensor in direct contact with the fluid and to optimize a future production of a monolithic device in terms of production and heat sealing assembling processes.

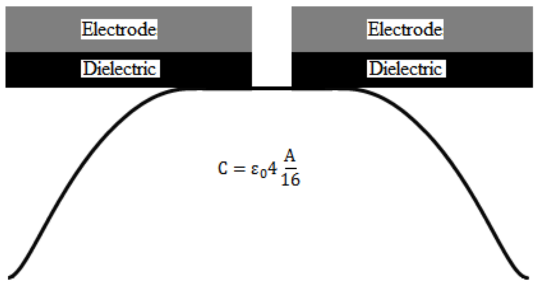
The potential in the conductive material shown in Fig. 2. a), is floating and unknown. The floating potential is handled in comsol with electrostatics interface. In this case, it is assumed that no charge are on the surface of the circular pad.
The drawback of the chosen configuration is an output response that is divided by two. Indeed, with $C_{AC} = C_{DB} = C$, d the distance between the parallel plates and A the surface area of one electrode, it follows that $C_{AB} = \frac{C}{2}$.

For comparison purpose, one may calculate the capacity in the simple case of null pressure. The dielectric is negligible here, because the gap between the electrodes is 500um and the thickness of the dielectric is 16 um. Thus, the capacity is:

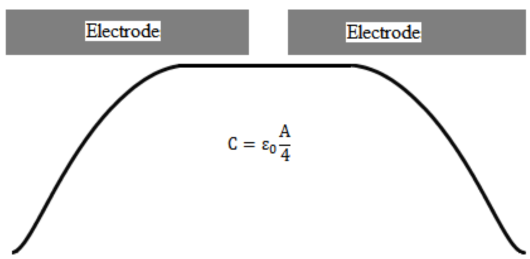
$$C_{AB} = \frac{\epsilon_0 A}{2\,d} \cong 0.33\ [\mathrm{pF}] \qquad (1)$$

3.1 Modeling assumptions

Due to the geometry high aspect ratio 200:1, the following assumptions were chosen to reduce the computational time while keeping a good approximation of the solution of the physical problem. The fluid is laminar and its pressure was applied to the membrane as uniform load acting on the diaphragm surface, i.e. the fluid itself was not modeled. The edges of the membrane are immovable. To have a better chance of getting a satisfactory approximation of the sensor behavior, special care must be taken to the discretization of the domain of the circular pad. As the 6µm thick circular silver layer on the diaphragm is largely smaller than the diaphragm's thickness, its contribution to the diaphragm bending is neglected. Thus, the circular silver layer is modeled as surface with electrical silver properties. The capacitance of the real system composed by the open capacitor covered with a 16µm dielectric layer and the diaphragm, represented in Fig. 3. a), was assumed to be equivalent to a simpler system in terms of modeling without dielectric material, represented in Fig. 3. b). This solution avoids adding unnecessary complexity due to mechanical contacts of a flexible body and a rigid body as well as dielectric changes.



a)



b)

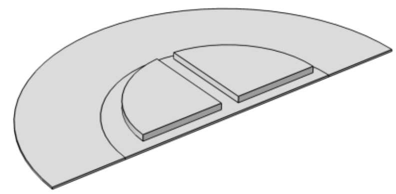
Fig. 3. a) Physical system. b) Equivalent circuit used for modeling, the diaphragm deflection is physically constraint 5µm before the collision occurs with the opposite electrodes.

The physical configuration afforded by the sensor geometry, i.e. the axisymmetry of the membrane and the symmetry of the half-moon electrodes provide a substantial advantage to reduce the computational cost. To take profit of the physical configuration two models were coupled. A 2D-axisymmetric model shown in Fig. 4. a), took care of the solution of the diaphragm deformation in touch mode while a 3D model was made to compute the sensor response, i.e. the capacity in function of the load pressure.
Furthermore, due to the geometrical configuration of the sensor, only the half is modeled as in Fig. 4. b).

3.1 Diaphragm model

The deformation of the diaphragm is large; this includes large strain and displacement. A consequence of large deformation is that the stress-strain relationship becomes nonlinear. So, in this situation it is necessary to distinguish the deformed area from the undeformed area to clarify which one is used to compute the stress.

a)



b)

Fig. 4. a) 2D axisymmetric model's geometry. b) 3D model's geometry with use of symmetry.

In the structural mechanics interface, the true stress, **σ,** is computed via the second Piola-Kirchoff stress tensor, **S**, as follow:

$$\boldsymbol{\sigma} = \frac{1}{j}\mathbf{FSF}^{\mathbf{T}} \qquad (2)$$

where, **F** is the deformation gradient, j is equal to det(**F**) and **S** the second Piola Kirchoff stress tensor. The second Piola-Kirchoff stress tensor, **S,** uses the undeformed area to compute the stress and is equal to the true stress for infinitesimal deformation. The constitutive relation from which the second Piola-Kirchoff stress tensor is obtained is the derivative of the strain energy density **W**:

$$\mathbf{S} = \frac{\partial \mathbf{W(E)}}{\partial \mathbf{E}} = \mathbf{D}:\mathbf{E} \qquad (3)$$

where **W** is the strain density energy, **E** is the Lagrangian strain, **D** is the fourth-order constitutive tensor for isotropic material.
More detailed discussions on nonlinear finite element analysis can found in many textbook such as [5].

3.2 Capacitive pressure model

The coupling of the 2D-aximetric model of the diaphragm to the 3D model is done with general coupling operator. The 2D model acts as the source domain while the 3D model is the destination domain. An intermediate mesh is necessary for the mapping. The source domain maps its mesh on the intermediate mesh. Then, the mapping on the destination domain is achieved by evaluating the operator on the intermediate mesh.

To be able to compute the capacitance with the electrostatics interface, the mesh of the diaphragm should move with the deformation. This is achieved with the moving mesh interface, which implements the arbitrary Lagrangian method.

The electrostatics interface is in charge to compute the capacitance with respect to the diaphragm deformation. The Basic equation to solve is:

$$\mathbf{C} = \boldsymbol{\varepsilon_0}\boldsymbol{\varepsilon}\frac{\mathbf{A}}{\mathbf{d}} \qquad (4)$$

where $\boldsymbol{\varepsilon_0}$ is permittivity of vacuum , $\boldsymbol{\varepsilon}$ is dielectric constant, A is the area and d the distance between the parallel plate. For that purpose, one has to solve:

$$\mathbf{E} = -\nabla\mathbf{V} \qquad (5)$$

where $\mathbf{E}$ is the electric field $\mathbf{V}$ the electric potential and Gauss's law:

$$\nabla.\mathbf{D} = \boldsymbol{\rho} \qquad (6)$$

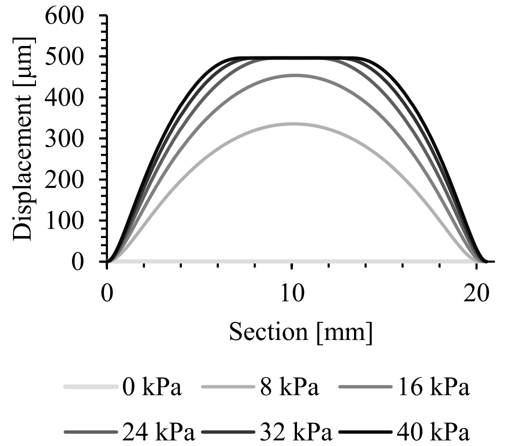
where $\nabla.\mathbf{D}$ is the divergence of the electric flux density and $\boldsymbol{\rho}$ is the total electric charge density. The constitutive relation for **D** is:

$$\mathbf{D} = \boldsymbol{\varepsilon_0}\mathbf{E} + \mathbf{P} \qquad (7)$$

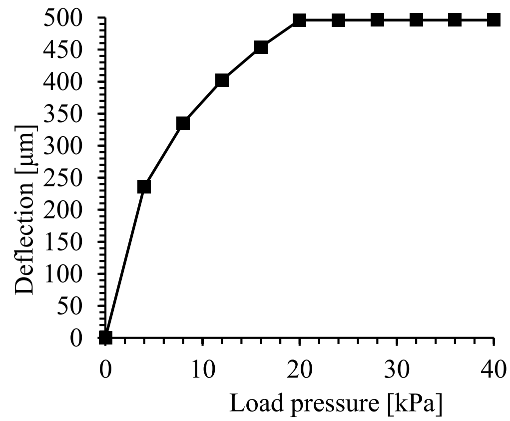
where **P** is the electric polarization vector. The aim is to get the function which expresses the capacitance in function of the applied pressure through a parametric analysis.

3.3 Simulation

The first step of the simulation process is the modeling of the diaphragm deformation in touched mode within the pressure range of 0 to 40kPa with the solid mechanics interface in 2D. A parametric study leads to the results presented in Fig. 5. a). From these results, one notes that the diaphragm enters in mechanical contact at a pressure closed to 20kPa. This is confirmed by Fig. 5. b) which shows the displacement of the point in the middle of the diaphragm in function of the applied load pressure.



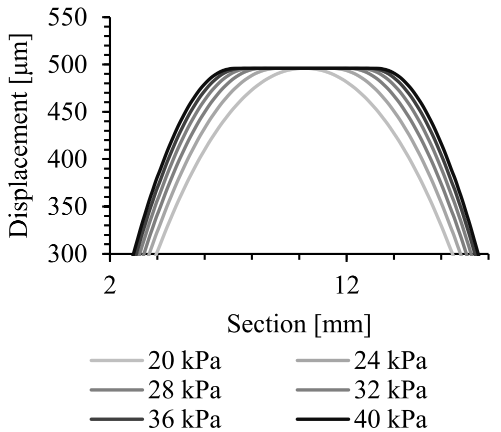
a)



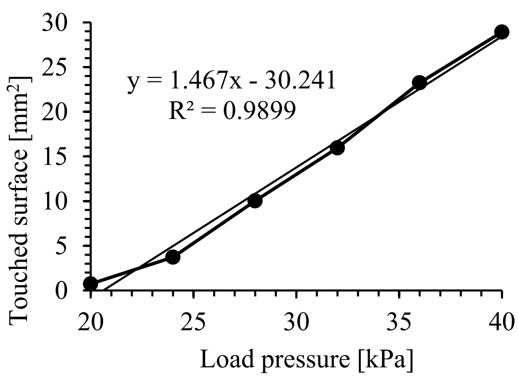
b)

Fig. 5. a) Diaphragm displacement in touch mode, within the pressure range of 0 to 40kPa. b) Membrane's maximum deflection in function of the applied load pressure.

A complementary study was performed to verify the result presented in [3], of the supposed linear function of the touched surface with respect to the pressure for the sensor configuration under study. For that purpose a finer parametric study was performed within the pressure range of 20 to 40kPa, these results are presented in Fig. 6. a). From this graph the touched area is extracted and plotted with respect to the load pressure in Fig. 6. b). As expected, a satisfactory linear function is obtained. From these results, one can expect a linear response of the sensor within the pressure range of 20 to 40kPa.



a)



b)

Fig. 6. a) Diaphragm displacement in touch mode, within the pressure range of 20 to 40kPa. b) Relation between touched surface and applied pressure.

The results shown in Fig. 6. b) confirms the results in [3], i.e. there is a satisfactory linear dependency between touched surface and load pressure. The last step is realised with the 3D-model which outputs the capacity with respect to the pressure sensor with moving mesh and the electrostatics interfaces. The C-P characteristics is presented in Fig. 7. Interestingly one can notice that the linearity range starts at 10kPa.

4. Validation process

To verify and validate predictions of the simulation provided by the Comsol model, two experimental tests were performed.

The first test was the verification of the membrane deformation in normal mode. A reverse engineering process was used for that purpose. The diaphragm with a circular pad printed electrode, shown in Fig. 8. a) is mounted on fluidic chamber as is the Fig. 8. b). A control pressure sensor, the SMC PSE563-01 pressure sensor from SMC pneumatics, was linked to the fluidic chamber with a Luer system. The pressure was applied with a Harvard syringe pump. The diaphragm deformation was measured with an Atos 3D scanner from Gom, which delivers three-dimensional data of the object under study. The scanner is presented in Fig. 8. c). Prior to the 3D scanning the diaphragm must be covered with an opaque layer as in Fig. 8. d). The Fig. 9. a) and b) shows an example of the scanned surface of the diaphragm. Image treatment with the Gom inspect software enables the extraction of diaphragm sections. Thus, the membrane deformation is compared to the model simulation. The experimental and simulation are compared in Fig. 9. c). Analysis of previous figure shows that the simulation differs in average, less than 10% with respect to the experimental data.

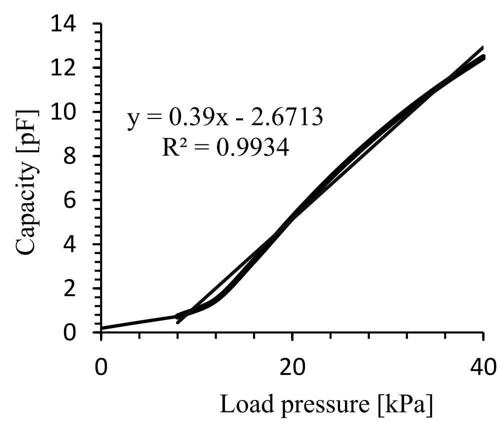


Fig. 7. C-P characteristics of a capacitive pressure sensor.

In the second experimental test the sensor response is analyzed. The same diaphragm with pad printed electrode was used. A PCB with two half moon electrodes, presented in Fig. 10. a), was designed and fabricated externally. The parts were stacked together with a rigid membrane of 500 um in between and placed on a fluidic chamber in direct contact with a fluid. The PCB was designed such that the open capacitor could

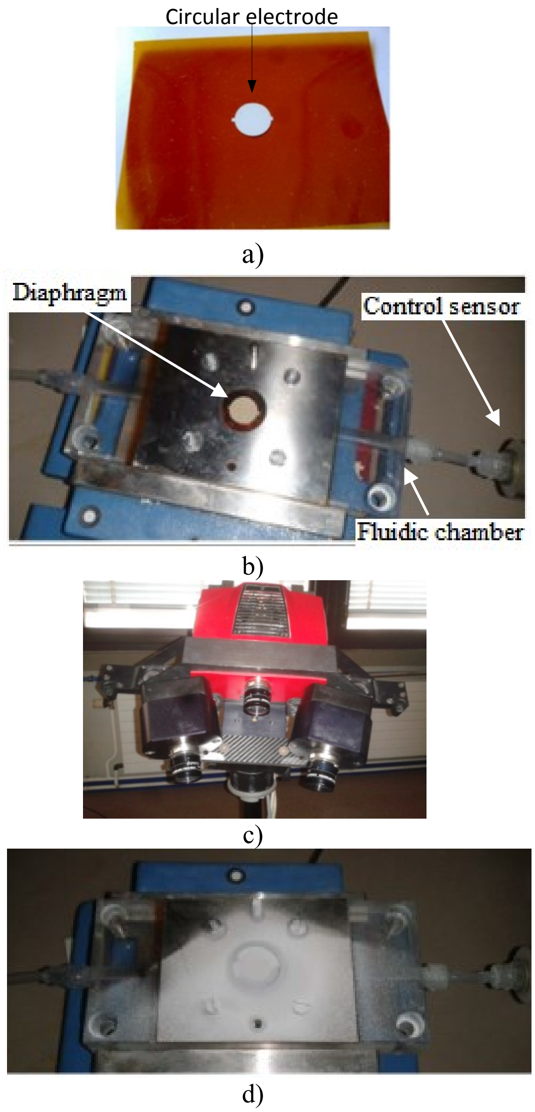
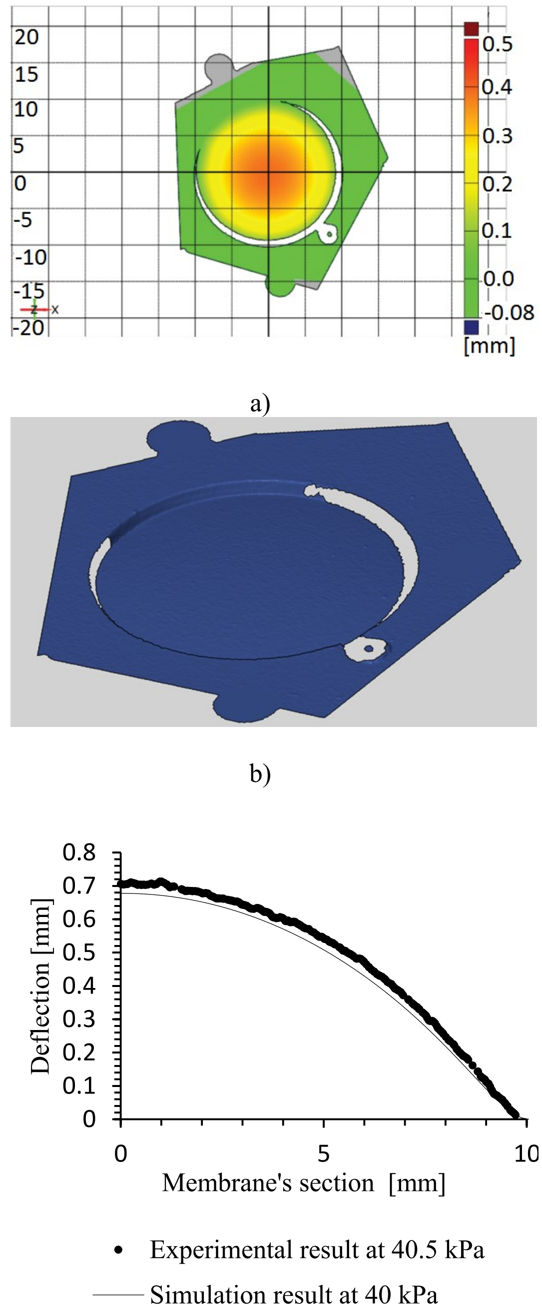


Fig. 8. a) Example of printed circular electrode. b) Experimental setup to measure the membrane deflection with the ATOS scanner from Gom optical measuring techniques for 3D measurement and inspection. c) 3D scanner. d) A thin opaque layer is sputtered on the membrane to enable optical measurements.

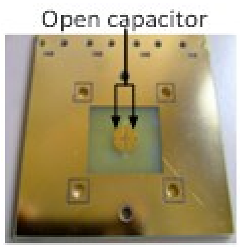
be directly mounted on the BNC connectors of the 4263A LCR-meter from HP LCR-meter. The measurements of the capacity in function of the load pressure were done with the four point technique to measure the impedance with more precision. A control pressure sensor was again linked the fluidic chamber with a Luer system. The whole test bench setup is presented in Fig. 10. b). The sensor's response presented in Fig. 11. is



c)

Fig. 9. a) Acquired data scan of the diaphragm deformation. b) 3D model of the data scan. c) Physical system and simulated diaphragm deformation.

characterized by a 12pF near-linear measuring range and by a 2kPa linearity error.The regression line within the near-linear range gives a slope of 0.397 and 0.390 for the sensor and the model respectively. The standard deviations of y-residuals with the sensor regression line are 0.53pF and 0.56pF for the sensor and the model respectively. The experimental value of the capacity at zero pressure is 0.38pF which is closed to the value of 0.33pF computed with equation (1).



a)

b)

Fig. 10. a) PCB with the open capacitor b) Experimental setup for Capacity measurements in function of the applied pressure.

5. Conclusions

The design, fabrication and verification of touch mode capacitive-type pressure for monitoring fluid pressure from 0 to 40kPa in fluidic chambers with Luer fittings for medical applications are reported. In this paper, it was demonstrated that a capacitive-type pressure sensor in touch mode characterized by near linear response within the range of 10 to 40kPa could be realised with a pad printed electrode on a polymer membrane. This sensor has the advantage of large overload ability, low production cost together with a promising heat sealing compatibility for polymer membranes assembling and a thin structure.

The model was validated by comparison with experimental data. It couples two models, two physics and the moving mesh method. Hypotheses have permitted to drastically simplify the real problem complexity and the response provides reliable predictions. The model may now be exploited for optimization purposes in terms of size and sensitivity. The design as well as the simulation may be useful for other transduction systems and polymer materials.

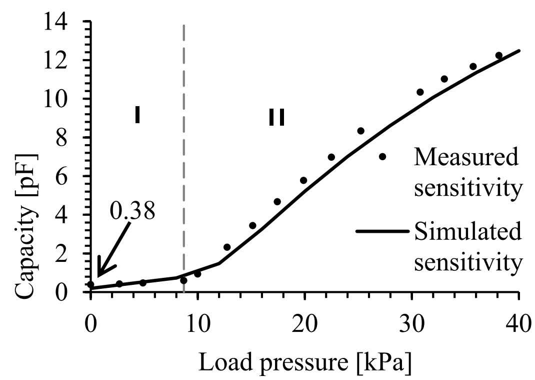


Fig. 11. C-P characteristics comparison of a capacitive pressure sensor and model. Both characteristics contain two region, I is the normal region and II is the near linear region.

6. References

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