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Numerical Simulation Analysis of a Capacitive Pressure Sensor for Wearable Medical Devices †

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Abstract: Wearable sensor devices have found a great deal of application in medicine on account of their small size and high sensitivity, and flexible elastomer materials are essential for their practical use. In this study we undertake CAD-assisted design of a capacitive pressure sensor (CPS) using COMSOL-Multiphysics software (6.0) to investigate its medical capabilities. The CPS was constructed in the shape of a cylinder, where the dielectric layer consists of air sandwiched between a polysilicon base and polydimethylsiloxane (PDMS) membrane. Simulations show that the CPS has a capacitance of 1.28 pF and stores 0.644 pJ of energy under an electric field of 1 kPa. The pressure sensitivity of the CSP diminished with an increase in the forward pressure, indicating that there is a non-linear dependence of pressure on the capacitance. This nonlinearity was most pronounced at lower pressures, where for small changes in pressure, the capacitance changed more significantly in correlation due to minor changes to the diaphragm. Higher pressure, however, prevented differentiation due to the large amount of diaphragm bending and changes in the properties of the materials. Dielectric capacitance grew widely in respect to applied pressure, with a low capacitance growth rate exhibited under high steady-state pressure. As expected, the stored energy was directly proportional to the pressure increase, reflecting the characteristic quadratic dependence of a capacitor on pressure. Temperature differences from 22 to 40 °C were also logged. However, the change in the dielectric constant of air remained minimal and it was noted that a 10 °C rise in temperature caused a much greater capacitance increase of about 53.28% and an energy increase of about 52.38%. Validation of the numerical approach with respect to its analytical results showed high accuracy with a margin of error less than one percent, thus proving the model's reliability and usefulness in forecasting CPS performance under different conditions. The results of the simulations are encouraging for the further development of the CPS as it may be effectively integrated into the architecture of wearable devices for medical purposes, enhancing patient care and diagnostic processes.

Keywords: capacitive pressure sensor; dielectrics; wearable devices; sensitivity

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1. Introduction

Wearable sensor devices have helped improve modern medicine by providing additional means to apprehend and help manage diseases using minimal, yet very accurate technologies [1]. These are easily adoptable devices worn by the patients that offer real-time surveillance and data, key factors in preventing and controlling certain medical conditions [2]. The use of elastic functional materials in these devices has greatly enhanced the deployment of flattenable electronics by improving wearability, usability, and productivity [3]. The fast-evolving technology used in sensors for the healthcare sector is largely attributed to the technological developments in patients' independent sensors, which do not hinder the patients from engaging in their daily activities, yet enable real-time capturing of data [4]. These sensors are essential in the care of patients with chronic diseases, in continual observation of a patient's condition, and in care of patients from a distance. Advancements in materials science, particularly in the development and evolution of flexible and sensitive materials, have been essential for the development of sensors worn on the body [5]. Furthermore, elastomers including PDMS have become very popular in the biomedical field because of their excellent mechanical properties, chemical resistance, and biocompatibility [6,7]. Due to their sufficient sensitivity, low operating requirements and compatibility with different devices, CPSs are of great interest for wearable applications. Capacitive sensors work on the principle of capacitance measurement that varies depending on the shape of the sensor owing to the external force applied. It has been observed that when some force is exerted on the sensor, the distance between the plates of the capacitor can become deformed resulting in a variant value for capacitance [8]. This technique is pressure sensitive so it can be used in blood pressure monitors, respiratory monitors and other vital sign detection devices.

The aim of this research is to create a CPS model for a respiratory monitoring wearable device. Such an application requires the ongoing tracking of certain parameters like respiratory pace variation, blood pressure, and body movements. In this work, an FEM model of the CPS was modeled to evaluate breathing by monitoring the volume of chest movements and observing capacitance changes caused by mechanical breathing movements. These devices are particularly useful for patients with chronic obstruction pulmonary disease or sleep apnea, as they can detect rather minute pressure changes ranging between 0.05 and 5 KPa. The sensors are made from PDMS due to the provision of mechanical properties that help the sensor to mold to the body and because the sensors are worn continuously, they do not cause discomfort and still work accurately during bending and stretching. The sensor model was designed using Multiphysics software and the numerical results were compared with the analytical results.

2. Methodology

A cylindrically shaped compact pressure sensor was modeled using a numerical simulation software tool. The methodology includes sensor-governing equations, material selection, simulation model using COMSOL Multiphysics software (6.0), and the subsequent steps for validating the model using analytical equations.

2.1. Governing Equations

The capacitance of the CPS is given by Equation (1)

$$C = \frac{\epsilon_0 \epsilon_r A}{d} \tag{1}$$

where ϵ_0 is the permittivity of free space (8.854×10^{-12} F/m), ϵ_r is the relative permittivity of the dielectric material, A is contact area of the electrode, and d is the distance between the plates. For a CPS with a deformable diaphragm, d changes with applied pressure P. For small deformations, d can be approximated using Equation (2)

$$d(P) = d_0 - \Delta d(P) \tag{2}$$

where, d_0 is the initial gap between the plates, and $\Delta d(P)$ is the change in the gap due to applied pressure. The capacitance C' after applying pressure ΔP is given by Equation (3).

$$C' = \frac{\epsilon_0 \epsilon_r A}{d_0 - \Delta d(P)} \tag{3}$$

The change in the capacitance (ΔC) of nonlinear CPS is given by Equation (4).

$$\Delta C = C' - C = \frac{\epsilon_0 \epsilon_r A}{d_0 - \Delta d(P)} - \frac{\epsilon_0 \epsilon_r A}{d_0} \tag{4}$$

Simplifying Equation (4), gives Equation (5).

$$\Delta C = \epsilon_0 \epsilon_r A \left(\frac{1}{d_0 - \Delta d(P)} - \frac{1}{d_0} \right) \tag{5}$$

Combining the terms results in the following:

$$\Delta C = \epsilon_0 \epsilon_r A \left(\frac{d_0 - d_0 + \Delta d(P)}{d_0(d_0 - \Delta d(P))} \right) = \epsilon_0 \epsilon_r A \left(\frac{\Delta d(P)}{d_0^2 - d_0 \Delta d(P)} \right) \tag{6}$$

The energy (U) stored in a capacitor is given by Equation (7)

$$U = \frac{1}{2} \Delta C V^2 \tag{7}$$

where V is the applied voltage. The sensitivity (S) of the sensor is the change in capacitance per unit of pressure and can be expressed as Equation (8).

$$S = \frac{dC}{dP} \tag{8}$$

2.2. Materials and Properties

Polysilicon was chosen for its mechanical strength and PDMS for its flexibility and biocompatibility and air as the dielectric medium. The materials' properties are given in Table 1.

Table 1. Materials and material properties.

Materials	Dielectric Constant (ε)	Young's Modulus (E) [GPa]	Density (ϱ) [kg/m^3]	Poisson's Ratio (ν)	Reference
PDMS	2.7	0.75	970	0.5	[9]
Polysilicon	10.19	160	2330	0.22	[10,11]
Air	1	0 > E < 1	1.293	-	[12]

2.3. Numerical Approach

COMSOL Multiphysics software (6.0) was used for the design and analysis of the CPS. Figure 1a includes the schematic of the designed sensor model, whereas the physical parameters are presented in Figure 1b. A 3D model of the sensor was also prepared which included the polysilicon base and PDMS diaphragm along with the air gap, as shown in Figure 1c. Different components were defined according to the default materials selection. A relatively fine mesh was constructed in the models to avoid poor results, especially on highly stressed parts, as shown in Figure 1d. Only suitable boundary conditions were set to represent real pressure situations that can be expected inside and outside the diaphragm. Low pressure was applied uniformly to the PDMS diaphragm, while the lower side of the polysilicon base was restrained. The integration of the Electrostatics and Solid Mechanics modules allowed control of the programmable mechanical movement in the capacitive sensors. The amount of mechanical deformation of the PDMS diaphragm when applying pressure, causing variations in capacitance, was measured. Polysilicon was used for the base, due to mechanical and technological constraints. The PDMS diaphragm was selected for its elasticity and bioclinical compatibility with sustainable engineering in wearables. A very low dielectric constant was employed in the air dielectric medium for high sensitivity.

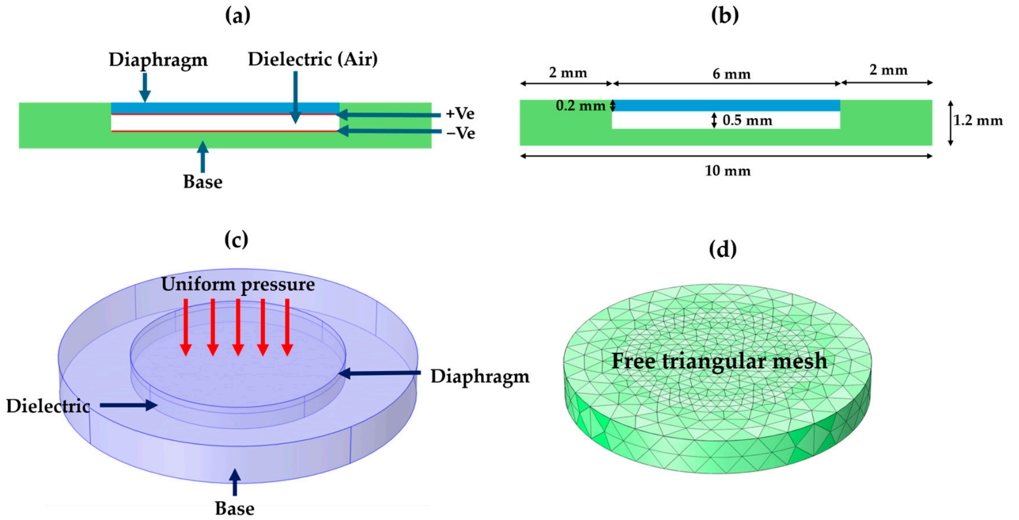

Figure 1. (**a**) Schematic diagram of the proposed sensor, (**b**) dimensions of the model, (**c**) simulation model of proposed sensor, and (**d**) meshing to the model.

3. Result and Discussion

To test the sensitivity of the CPS and to estimate the capacitance and energy storage efficiency, it is necessary to consider the diaphragm's displacement. To explain how the strain is transferred to the sensor when pressure is applied to the diaphragm, it is noted that the fixed edges allow maximum strain at the center. Here, a pressure range varying from 0 to 100 Pa was used to establish the performance of the CPS. At the reference temperature, a negligible deformation of 25×10^{-12} m was seen (Figure 2a). Figure 2b depicts diaphragm deflection at 100 Pa pressure. It can be observed that there is more deflection at the center of the diaphragm.

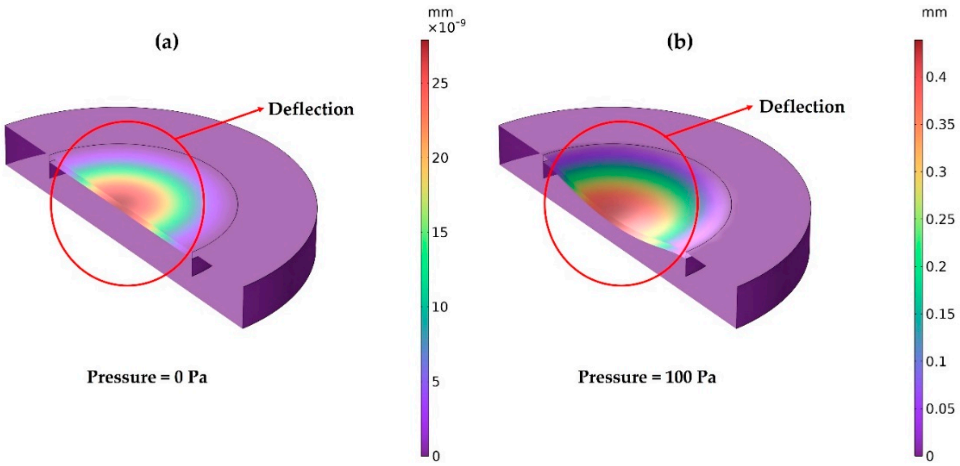

Figure 2. Displacement of diaphragm with respect to applied pressure (**a**) at zero pressure, (**b**) at a pressure of 100 Pa.

To investigate the electrical responses like capacitance and the energy storage capacity of the CPS, 1 Volt of potential difference was applied across the dielectric. Figure 3a,b show the side and top view of the CPS at 0 Pa pressure. The electric potential is uniformly distributed across the sensor when there is no pressure applied to it. Figure 3c,d show the side and top view of the CPS at 100 Pa pressure. The distribution of electric potential is no longer uniform. The application of pressure caused a significant change in the distribution of electric potential. The bottom of the sensor shows greater electric potential than the top. This indicates a pressure gradient across the sensor, which likely explains how the sensor detects pressure changes.

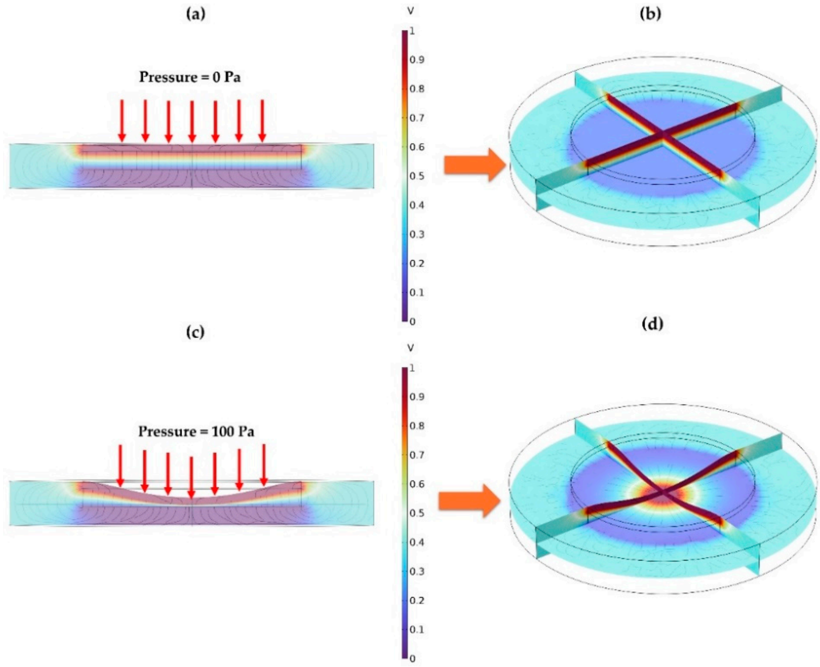

Figure 3. Distribution of electric potential with respect to applied pressure (**a**) side view of CPS at zero pressure, (**b**) top view of CPS at zero pressure, (**c**) side view of CPS at 100 Pa pressure, (**d**) top view of CPS at 100 Pa pressure.

As represented in Figure 4, the sensitivity tends to drop off as the applied pressure increases, which reinforces the presence of nonlinearity between pressure and capacitance. In this case, the sensor is more sensitive to low ranges of pressure where small changes in pressure lead to more significant changes in capacitance. This is because, in this study, there is an assumption of minimal structural deformation of the diaphragm. On the other hand, to substantiate the measurements under increased pressure, the diaphragm might deform to a greater extent, deviating from linearity. Furthermore, nonlinearity may also arise from the material properties of the diaphragm. This is due to the fact that, under compressive loads, the stiffness of the material may change, affecting its response. It should be mentioned that the sensitivity is highest at a pressure of 300 Pa. It can be observed that sensitivity plateaus at 12.5% under a higher pressure of 1 kPa compared to 100 Pa. Figure 5a demonstrates the pressure displacement response of the diaphragm. With the increase in pressure, the displacement increases and reaches its maximum in the central region of the diaphragm. This trend is dynamic, whereby the displacement profile peaks at low pressures and becomes flatter as the pressure increases. Figure 5b shows the capacity of the CPS vs. the pressure. When pressure rises, the rate of change of capacitance increases without a linear relation.

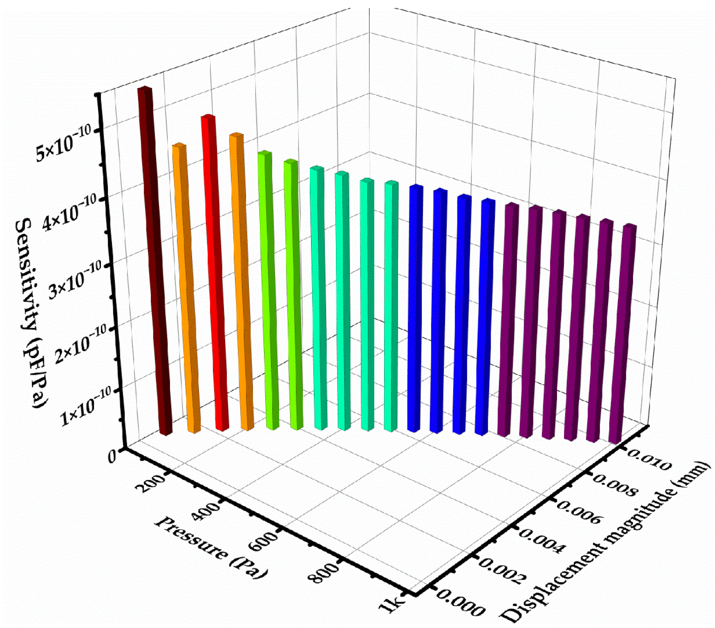

Figure 4. Plot showing sensitivity of CPS with respect to applied pressure and displacement of the diaphragm.

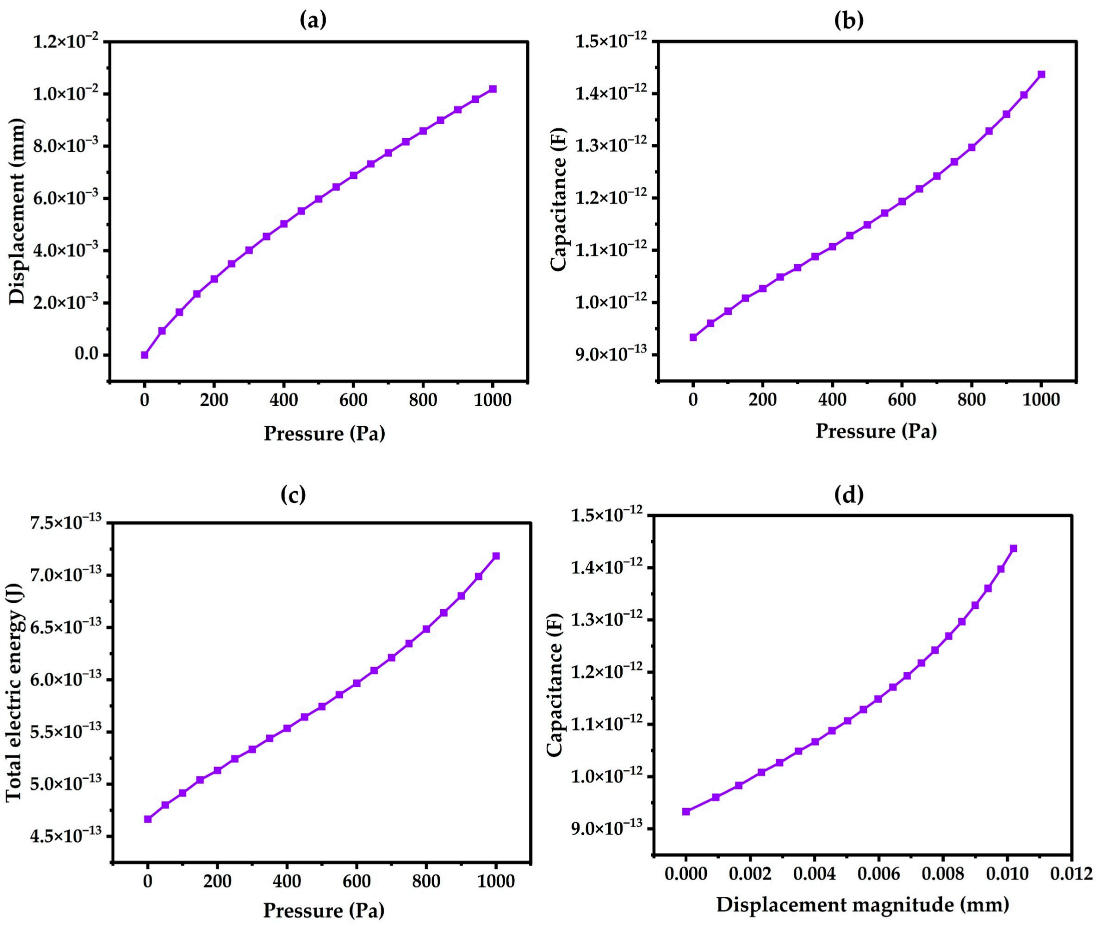

Figure 5. Result plots showing (**a**) displacement vs. pressure, (**b**) capacitance vs. pressure, (**c**) total electrical energy stored in the CPS vs. pressure and (**d**) the effect of temperature on CPS performance.

Initially, the capacitance increases rapidly, but as pressure continues to rise, the rate of change decreases. This diminishing rate of increase in capacitance with higher pressure indicates a nonlinear relationship, which is expected due to the nonlinear deformation behavior of the diaphragm under varying pressures.

Figure 5c shows the dependence of the total energy developed in the sensor with variation in pressure. The increase in energy seems to be quadratic, which means that although small ranges of pressure are increased, the amount of energy stored in the system increases in much larger amounts. This result is expected as the energy in a capacitor is proportional to the square of the voltage and is directly related to capacitance (Equation (7)). In Figure 5d, the relationship between the sensor's capacitance and the associated movement of diaphragm displacements is shown. This shows the similar action of capacitive-type sensors, where if the distance between the plates or diaphragm is decreased, the capacitance increases. Both the capacitance and the displacement show a non-linear increase. At first, the relationship was linear, with capacitance increasing with modest displacement changes. Typically, in such sensors, slight alterations in displacement lead to a significant rise in capacitance. There was an initial value of capacitance of 9.330×10^{-13} F and then it increased progressively to 1.436×10^{-12} F. Further, there was a linear increase in capacitance in curvilinear form with added displacement due to a decrease in volume change. In the initial state, the displacement was more than 3.348×10^{-10} m, but within a moment, a higher displacement of 9.242×10^{-4} m and an active increment up to 1.019×10^{-2} m were noted. This rapid increase in displacement in response to applied pressure indicates high sensitivity, especially at lower pressures.

3.1. Temperature Effect on the Sensor Performance

Investigation of temperature effect on the performance of the CPS is crucial to understanding real-time performance, so in this study, the operating temperature was varied from 22 to 40 °C. The dielectric constant of air is relatively stable and changes very little with temperature. However, at higher temperatures, there can be slight variations. The dielectric constant of air can be affected by temperature due to changes in density.

For temperature control, a variation of 10 °C from the reference temperature was applied in this study. Hence, it is accepted that dielectric constants of air are virtually unaffected under normal circumstances. Figure 6 shows an increase of 53.28% in capacitance due to a change in temperature from 22 °C to 40 °C. Similarly, the increase in energy was established to be 52.38%. Capacitance changes with temperature in the CPS are mainly caused by the thermal expansion of the PDMS diaphragm and the polysilicon base, which changes the distance between the capacitor plates. This effect is much more prominent than any change in the dielectric constant of the air.

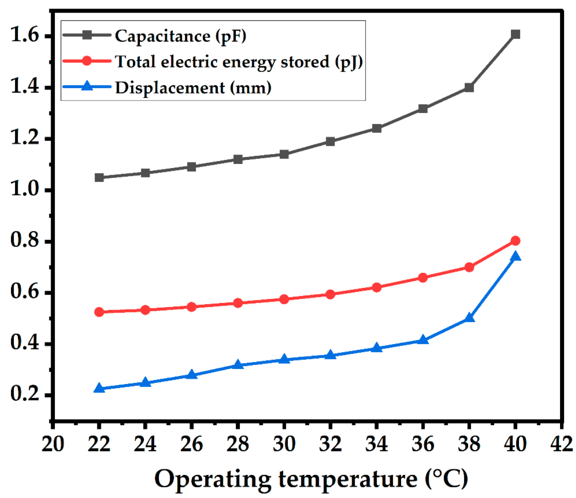

Figure 6. Temperature effect on the performance of CPS.

3.2. Comparison of Analytical and Numerical Analyses

Validation of the model is a crucial step in numerical analysis. In the present study, an analytical approach was used to validate the proposed numerical model. The value of capacitance was calculated using analytical Equation (6) and compared with the capacitance value obtained from the numerical method. The comparison plot is shown in the Figure 7.

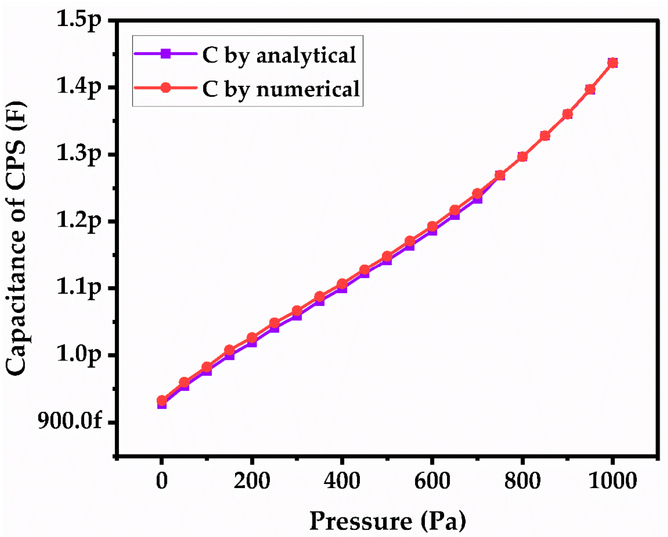

Figure 7. Comparison of analytical and numerical results.

Both the analytical and numerical methods show consistency. Numerical and analytical values are in close agreement, with small and consistent errors. The slight discrepancies can be attributed to the inherent differences in modeling assumptions, and numerical precision.

4. Conclusions

In this research, detailed analysis parameters like capacitance, energy storage capacity, sensitivity and the effects of temperature on the parameters of a capacitive sensor were discussed. The investigation was conducted over a pressure range from 0 to 100 Pa. At zero pressure on the sensor, the displacement of the diaphragm is negligible, which is attributed to the reference temperature, while at 100 Pa, a substantial displacement at the diaphragm's center is observed. The sensitivity plots show the decreasing sensitivity trend with increasing pressure, suggesting a nonlinear relationship between pressure and capacitance, and this nonlinear behavior is more pronounced at lower pressures. At higher pressures, significant deflection of the diaphragm and changes in its material stiffness contribute to this nonlinearity. The effect of temperature on CPS performance shows a 53.28% increase in capacitance and a 52.38% increase in energy for a temperature change from 22 to 40 °C. The validation of the numerical model using an analytical approach shows high consistency and errors generally below 1%, affirming the reliability of the numerical method. The present research validates the proposed model, demonstrating its efficacy in predicting CPS performance under varying pressures and temperatures, and underscores the importance of considering temperature effects when designing and optimizing capacitive pressure sensors.

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Abbreviations

CPS	Capacitive Pressure Sensor
PDMS	Polydimethylsiloxane

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