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IMPROVEMENT OF PRESSURE MEASUREMENT ACCURACY AND SENSOR ERROR COMPENSATION IN INDUSTRIAL TECHNOLOGICAL PROCESSES

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Abstract. This study focuses on improving pressure measurement accuracy and enhancing sensor error compensation methods in industrial technological processes. Particular attention is given to piezoresistive pressure sensors, whose measurement accuracy can be affected by temperature variations, zero-point drift, sensitivity changes, nonlinearity, and thermal hysteresis. Experimental calibration was performed at different pressure and temperature values under both heating and cooling conditions. A polynomial compensation model was developed to establish the relationship between sensor output, pressure, and temperature. The obtained results demonstrate that incorporating temperature into the calibration procedure provides a more accurate representation of sensor characteristics under variable thermal conditions. The combined consideration of heating and cooling data enables more effective characterization of thermal hysteresis and compensation of temperature-dependent measurement errors. The proposed method can be implemented in digital processing units or microcontrollers for continuous correction of pressure measurements, thereby improving the stability and accuracy of pressure measurement systems in industrial technological processes.
Keywords: pressure measurement; measurement accuracy; piezoresistive pressure sensor; sensor error compensation; temperature compensation; thermal hysteresis.

Introduction

Pressure measurement plays an important role in the operation and control of modern industrial technological systems. In many production processes, pressure is continuously monitored to maintain stable operating conditions, improve process efficiency, and prevent undesirable changes in equipment performance. For this reason, the reliability of pressure measurement directly affects the quality of monitoring and control systems. Piezoresistive pressure sensors are widely used for this purpose because of their high sensitivity, compact design, and suitability for electronic measurement systems.

At the same time, obtaining accurate pressure data under real operating conditions remains a challenging task. The output signal of a pressure sensor can be influenced by temperature changes, zero-point instability, sensitivity variation, nonlinear characteristics, and other sources of measurement error. Temperature is particularly significant because changes in temperature can alter the electrical properties of the sensing elements and affect the output characteristics of the sensor. In silicon piezoresistive sensors, temperature-dependent changes in resistance and piezoresistive properties may lead to noticeable deviations between the actual pressure and the measured value.

The problem becomes more complicated when the sensor operates under changing thermal conditions. During heating and cooling, the same pressure value may produce different sensor outputs even when the temperature returns to a similar level. This behavior is associated with temperature hysteresis and differences in the thermal response of the sensor's structural components.

Experimental studies have shown that rapid temperature variations can cause additional output deviations and reduce the stability of pressure measurements.

Different methods have been developed to reduce these errors. They include hardware-based compensation, software correction, calibration methods, polynomial approximation, and intelligent computational algorithms. Among these approaches, software-based compensation is of particular interest because the correction procedure can be incorporated into a microcontroller or other digital measurement unit without substantially changing the construction of the sensing element. Previous research has demonstrated that temperature compensation can considerably improve pressure measurement accuracy and reduce thermal drift.

An important stage in the development of an effective compensation method is the formation of an appropriate calibration model. A sensor can be calibrated at several pressure and temperature points, after which the relationship between the sensor output, pressure, and temperature can be mathematically described. Polynomial models provide one possible approach because they allow nonlinear characteristics of the sensor to be represented while also considering the dependence of model coefficients on temperature. However, calibration based only on one temperature-change direction may not fully reflect the behavior of a sensor during actual operation. Combining calibration information obtained during heating and cooling can provide additional information about thermal hysteresis and improve the compensation process.

In this study, an improved method for increasing pressure measurement accuracy and compensating sensor errors in industrial technological processes is considered. The proposed approach focuses on reducing the influence of temperature-dependent errors and improving the stability of the measured pressure signal. The relationship between sensor output, pressure, and temperature is considered in the formation of the compensation model, while calibration data obtained under different thermal conditions are used to determine the correction parameters. The effectiveness of the proposed method can be evaluated using quantitative indicators such as measurement error, full-scale error, and root-mean-square error, which are also used in previous experimental investigations of pressure-sensor compensation.

Materials and Methods

The study focused on improving pressure measurement accuracy and compensating sensor errors under variable temperature conditions. The measurement system consisted of a pressure sensor, temperature sensor, signal-conditioning unit, data acquisition system, and digital processing unit. Calibration measurements were performed at different pressure and temperature values under both heating and cooling conditions to determine the influence of temperature drift and hysteresis on the sensor output.

The relationship between the sensor output signal, temperature, and reference pressure was described using a polynomial compensation model:

$$P=a_0+a_1U+a_2U_2+\cdots+a_NU^N$$

where P is the reference pressure, U is the sensor output signal, and ai are calibration coefficients. Since these coefficients depend on temperature, they were represented as functions of temperature:

$$a_i(T)=b_{0i}+b_{1i}T+b_{2i}T+\cdots+b_{Mi}T^M$$

Thus, the compensated pressure can generally be expressed as:

$$\hat{P}=\sum_{i=0}^{N}\sum_{j=0}^{M}b_{ji}T^jU^i$$

where $\hat{P}$ is the compensated pressure and T is the sensor temperature. The coefficients b_{ji} are determined from the experimental calibration data using curve fitting. This approach allows the nonlinear dependence of the sensor output on pressure and temperature to be considered simultaneously.

The effectiveness of the compensation method was evaluated by comparing the corrected pressure with the reference value. The full-scale measurement error was determined as:

$$\gamma = \frac{|P_s - P_o|}{P_{FS}} \cdot 100\%$$

where P_s is the measured steady-state pressure, P_0 is the reference pressure, and PFS is the full-scale pressure. The root-mean-square error (RMSE) was calculated using:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - P_0)^2}$$

where Pi represents the measured pressure values and n is the number of measurements.

The proposed compensation model is suitable for implementation in a digital processing unit or microcontroller, enabling continuous correction of the measured pressure based on the sensor response and current temperature conditions.

Results and Discussion

The experimental results demonstrate that temperature variation is an important factor affecting the performance of the pressure measurement system. As shown in Figure 1, the temperature changes considerably during the initial stage of the experiment and subsequently decreases more gradually until reaching a relatively stable level. The stabilization of temperature indicates that the thermal state of the measurement system becomes more uniform with time. Such temperature transitions are important because pressure sensor characteristics can vary with changes in the surrounding thermal conditions.

The observed temperature response confirms that the sensor output should not be considered independently of temperature when high measurement accuracy is required. Temperature changes may influence the electrical characteristics of the sensing element and consequently cause variations in the output signal. In silicon piezoresistive pressure sensors, thermal effects can contribute to zero-point drift, sensitivity changes, nonlinearity, and hysteresis. These effects may become particularly noticeable when the sensor operates under continuously changing environmental or process conditions.

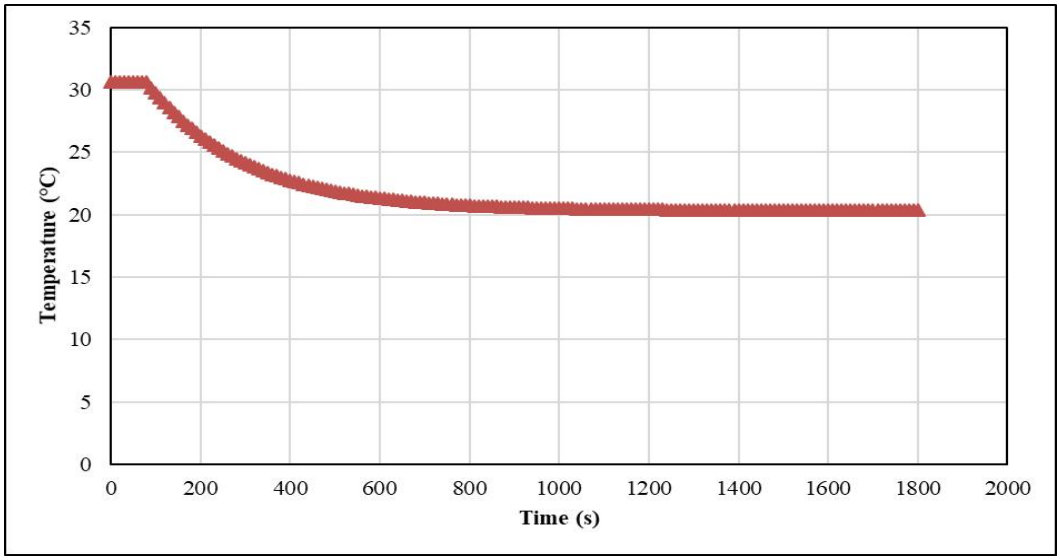


Figure 1. Temperature variation of the pressure measurement system during the experimental period.

A conventional pressure calibration generally establishes the relationship between the reference pressure and sensor output. However, this relationship may change when the operating temperature varies. Therefore, incorporating temperature into the calibration procedure provides additional information about the actual operating state of the sensor. The developed compensation approach uses both the sensor output and temperature data to describe the pressure response more accurately. This makes it possible to compensate for temperature-dependent deviations that cannot be adequately represented by a pressure-only calibration model.

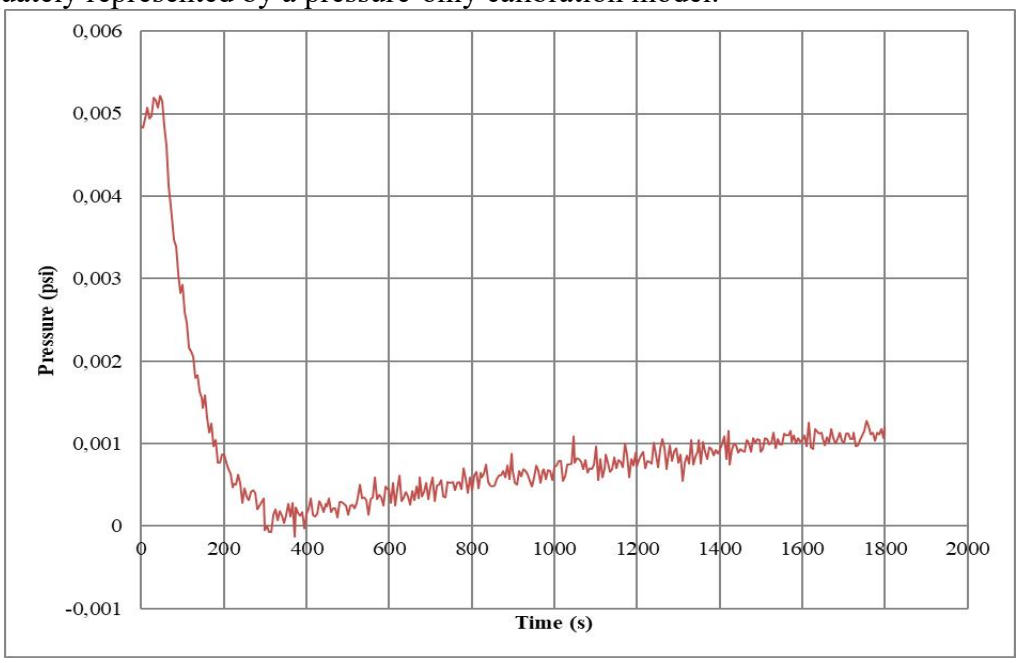


Figure 2. Pressure response of the measurement system during the experimental period.

Figure 2 illustrates the variation in the measured pressure signal over the experimental period. The pressure response changes significantly during the initial stage and subsequently approaches a relatively stable range. The observed variation indicates that the sensor output is affected by the

transient conditions of the measurement process. The polynomial compensation model provides a flexible mathematical representation of the relationship between pressure, sensor output, and temperature. By allowing the model coefficients to vary with temperature, the compensation procedure can account for both the nonlinear characteristics of the sensor and the influence of thermal conditions. Similar pressure–temperature calibration approaches have been used to characterize and compensate silicon piezoresistive pressure sensors under different temperature conditions.

Another important aspect of the obtained results is the consideration of both heating and cooling behavior. The sensor response during temperature increase may differ from its response during temperature decrease because of thermal hysteresis and differences in the thermal behavior of the sensor structure. Therefore, calibration data obtained from only one temperature direction may not fully describe the sensor response during actual operation. A combined calibration procedure provides a broader representation of the sensor characteristics under changing thermal conditions. The combined calibration results obtained during the cooling and heating processes are presented in Table 1. The table summarizes the sensor output voltage (U1) measured at different pressure levels and temperatures ranging from 10 to 60 °C. The observed changes in the output signal with increasing temperature confirm the temperature dependence of the sensor characteristics. These calibration data provide the basis for establishing the pressure–temperature relationship and determining the compensation coefficients used in the proposed model.

Table 1. Combined calibration data, cooling from 10–20 °c and heating from 30–60 °c

T1 /°C	U1/mV								
	-2.5psi	-1.875 psi	-1.25psi	-0.625 psi	0psi	0.625psi	1.25psi	1.875 psi	2.5 psi
10	-77.663	-55.796	-33.934	-12.101	9.713	31.478	53.206	74.894	96.529
20	-76.974	-55.535	-34.107	-12.700	8.682	30.023	51.331	72.591	93.805
30	-76.131	-55.105	-34.077	-13.069	7.910	28.865	49.783	70.646	91.463
40	-75.304	-54.644	-33.998	-13.384	7.209	27.770	48.294	68.776	89.209
50	-74.391	-54.105	-33.836	-13.582	6.643	26.841	47.007	67.123	87.197
60	-73.446	-53.514	-33.606	-13.709	6.169	26.010	45.823	65.583	85.311

From a practical perspective, the compensation model can be implemented in a digital processing unit or microcontroller. During operation, the current sensor output and temperature are

used as input parameters, and the compensated pressure value is calculated using the previously determined model coefficients. This approach allows the correction procedure to be performed continuously without requiring manual recalibration for every individual temperature condition. Software-based compensation is also consistent with established approaches involving polynomial models, lookup tables, and other computational techniques for reducing temperature-induced errors in pressure sensors.

Conclusion

The results of the study demonstrate that temperature variation has a significant influence on the accuracy of pressure measurements. Changes in temperature can cause zero-point drift, sensitivity variation, nonlinearity, and hysteresis in pressure sensors. The experimental results showed that both temperature and pressure signals changed considerably during the initial stage and gradually approached a relatively stable state. Therefore, for accurate pressure measurement, it is important to consider temperature effects during the calibration and compensation process rather than relying solely on the sensor output signal.

The proposed polynomial compensation model provides an effective approach for describing the relationship between sensor output, pressure, and temperature. Combining calibration data obtained under both heating and cooling conditions allows the thermal hysteresis of the sensor to be considered more comprehensively and helps reduce temperature-dependent measurement errors. The model can be implemented in a microcontroller or digital processing unit to continuously compensate the measured pressure according to the current sensor output and temperature. Thus, the proposed software-based compensation approach can improve the stability and accuracy of pressure measurements in industrial technological processes.

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