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NOVEL AND LOW-COST TEMPERATURE COMPENSATION TECHNIQUE FOR PIEZORESISTIVE PRESSURE SENSORS

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Abstract – This paper proposes a low-cost technique to compensate for the temperature dependence of piezoresistive pressure sensors configured in a Wheatstone bridge. The sensor is treated as a resistive circuit and three equivalent resistances are measured by setting appropriately the bridge terminals. One of these equivalent resistances depends on temperature but not on pressure and, hence, it can be used to compensate for the temperature dependence of the output parameter. In such a way, neither data of a previous temperature calibration nor additional components are required to compensate for the temperature dependence. The proposed technique is applied to a commercial pressure sensor, which is measured by means of a direct sensor-to-microcontroller interface circuit. Experimental results show that temperature effects on the pressure measurement decrease more than ten times when the proposed technique is applied.

Keywords: pressure sensor, piezoresistive sensor, temperature compensation, sensor electronic interface, microcontroller.

1. NOMENCLATURE

P	Pressure applied to the sensor
P_{atm}	Atmospheric pressure
T	Actual temperature
T_0	Reference temperature defined by the sensor manufacturer
T_0'	Reference temperature defined by the sensor user
R_1-R_4	The four piezoresistors of the bridge sensor
R_n	Nominal value of the piezoresistors at $P = 0$
R_0	Resistance value of R_n at $T = T_0$
R_0'	Resistance value of R_n at $T = T_0'$
α_R	Temperature coefficient of R_n using T_0 as a reference
α_R'	Temperature coefficient of R_n using T_0' as a reference
S	Piezoresistive sensitivity
S_0	Piezoresistive sensitivity at $T = T_0$
α_S	Temperature coefficient of S using T_0 as a reference
M	Output parameter that combines the measurement of the equivalent resistances without compensation
M^*	Output parameter that combines the measurement of the equivalent resistances with compensation

2. INTRODUCTION

Semiconductor sensors are widely used in current measurement systems because of their low cost, small size and easy integration with electronic circuits [1]. In the automotive industry, for example, mechanical semiconductor sensors have become very widespread, especially those intended for the measurement of pressure and acceleration [2]. Such mechanical sensors generally rely on either piezoresistances or capacitances.

Semiconductor pressure sensors based on piezoresistances are usually configured in a Wheatstone bridge with four active arms, as shown in Fig. 1. In the event of a pressure change, two piezoresistors (R_1 and R_4) undergo a resistance change that is equal but opposite to that of the other two piezoresistors (R_2 and R_3). In such a way, the sensitivity of the bridge is higher than in bridges with only one or two active arms [3].

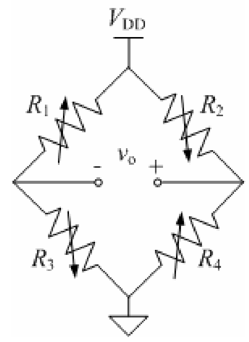

Figure 1. Piezoresistive pressure sensor in a Wheatstone-bridge configuration.

A remarkable drawback of piezoresistive pressure sensors is their temperature dependence [1] and, for this reason, several temperature compensation techniques have been proposed. Generally, these techniques involve additional components [4] (e.g. a thermistor) that increase the effective voltage applied to the bridge when the temperature increases so that the loss of sensitivity is compensated [5]. The temperature dependence can also be compensated by measuring the sensor temperature by means of the sensor itself. For example, references [6, 7] propose a relaxation oscillator in which the frequency of the output signal carries information about the bridge unbalance whereas the duty cycle carries information about the bridge resistance and, hence, the temperature. Reference [8] proposes (for metallic strain gages, not for semiconductor ones) a technique based on two current sources and two differential voltage measurements, one with information about the mechanical stress and the other with information about the temperature.

This paper proposes a novel technique to compensate for the temperature dependence of piezoresistive pressure sensors by using a simple and low-cost microcontroller-based interface circuit. The proposed technique uses the same pressure sensor to measure the temperature and, hence, it does not require either data of a previous temperature calibration or additional components.

3. TEMPERATURE DEPENDENCE

The four piezoresistors of the pressure sensor (Fig. 1) can be modelled by [9]

$$R_1 = R_4 = R_n\left[1 + S \cdot P\right] \tag{1a}$$

$$R_2 = R_3 = R_n\left[1 - S \cdot P\right], \tag{1b}$$

in which both R_n and S depend on temperature. Consequently, if we assume a first-order temperature dependence and the same temperature coefficients for the four piezoresistors, these can be modelled by

$$R_1 = R_4 = R_0\left[1 + \alpha_R\left(T - T_0\right)\right]\left[1 + S_0\left(1 + \alpha_S\left(T - T_0\right)\right)P\right] \tag{2a}$$

$$R_2 = R_3 = R_0\left[1 + \alpha_R\left(T - T_0\right)\right]\left[1 - S_0\left(1 + \alpha_S\left(T - T_0\right)\right)P\right]. \tag{2b}$$

According to [1], α_R is a positive temperature coefficient (i.e. $\alpha_R > 0$) whereas α_S is a negative temperature coefficient (i.e. $\alpha_S < 0$). Data sheets of commercial pressure sensors usually specify α_R and α_S by means of the “temperature coefficient of input resistance” and the “temperature coefficient of span”, respectively. These coefficients depend on the temperature used as a reference by the manufacturer (T_0 according to our nomenclature).

If a constant supply voltage (V_{DD}) is applied to the bridge sensor and then the differential output voltage (v_o) is read, as shown in Fig. 1, the measurement result is

$$v_o = V_{DD} S_0\left(1 + \alpha_S\left(T - T_0\right)\right)P, \tag{3}$$

which depends on pressure but also on temperature. Since $\alpha_S < 0$, for a given value of P, the value of v_o decreases with temperature. Generally, this temperature dependence is compensated by using additional components that increase the effective voltage applied to the bridge when the temperature increases [4, 5].

Bridge sensors can also be measured by determining three equivalent resistances of the bridge [10]. To do so, the bridge terminals are appropriately set to ground or in high-impedance state (HZ), as shown in Fig. 2, and the resulting equivalent resistances are:

$$R_{eq,A} = \frac{R_4\left(R_1 + R_2 + R_3\right)}{R_1 + R_2 + R_3 + R_4} \tag{4a}$$

$$R_{eq,B} = \frac{\left(R_1 + R_2\right)\left(R_3 + R_4\right)}{R_1 + R_2 + R_3 + R_4} \tag{4b}$$

$$R_{eq,C} = \frac{R_2\left(R_1 + R_3 + R_4\right)}{R_1 + R_2 + R_3 + R_4}. \tag{4c}$$

Replacing (2) in (4) yields

$$R_{eq,A} \approx \frac{R_0}{4}\left[1 + \alpha_R\left(T - T_0\right)\right]\left[3 + 2S_0\left(1 + \alpha_S\left(T - T_0\right)\right)P\right] \tag{5a}$$

$$R_{eq,B} = R_0\left[1 + \alpha_R\left(T - T_0\right)\right] \tag{5b}$$

$$R_{eq,C} \approx \frac{R_0}{4}\left[1 + \alpha_R\left(T - T_0\right)\right]\left[3 - 2S_0\left(1 + \alpha_S\left(T - T_0\right)\right)P\right]. \tag{5c}$$

Then, the measurand can be estimated by calculating the parameter M that combines the measurement of the equivalent resistances as follows [10]:

$$M = \frac{R_{eq,A} - R_{eq,C}}{R_{eq,B}}. \tag{6}$$

Replacing now (5) in (6) yields

$$M = S_0\left(1 + \alpha_S\left(T - T_0\right)\right)P, \tag{7}$$

which, the same as in (3), depends on pressure but also on temperature. Therefore, since $\alpha_S < 0$, for a given value of P, the value of M also decreases with temperature.

4. COMPENSATION TECHNIQUE

To compensate for the temperature dependence shown in (7), we propose to estimate the sensor temperature by means of the sensor itself. This can be done by using appropriately the measurement of $R_{eq,B}$, which just depends on temperature, as shown in (5b). Then, in order to achieve an output independent of temperature (i.e. $M^* = S_0P$), we could calculate the following parameter:

$$M^* = \frac{M}{1 + \frac{\alpha_S}{\alpha_R}\left(\frac{R_{eq,B}}{R_0} - 1\right)}, \tag{8}$$

where M is calculated by (6), α_S and α_R are specified by the sensor manufacturer, $R_{eq,B}$ is the measured equivalent resistance at a given temperature T, and R_0 is the value of $R_{eq,B}$ at $T = T_0$. Regrettably, the tolerance of R_0 is either very large (say, 20 % or higher) or not specified at all in sensor data sheets. Of course, R_0 could be measured at $T = T_0$, but this involves time and specific temperature-calibration instrumentation.

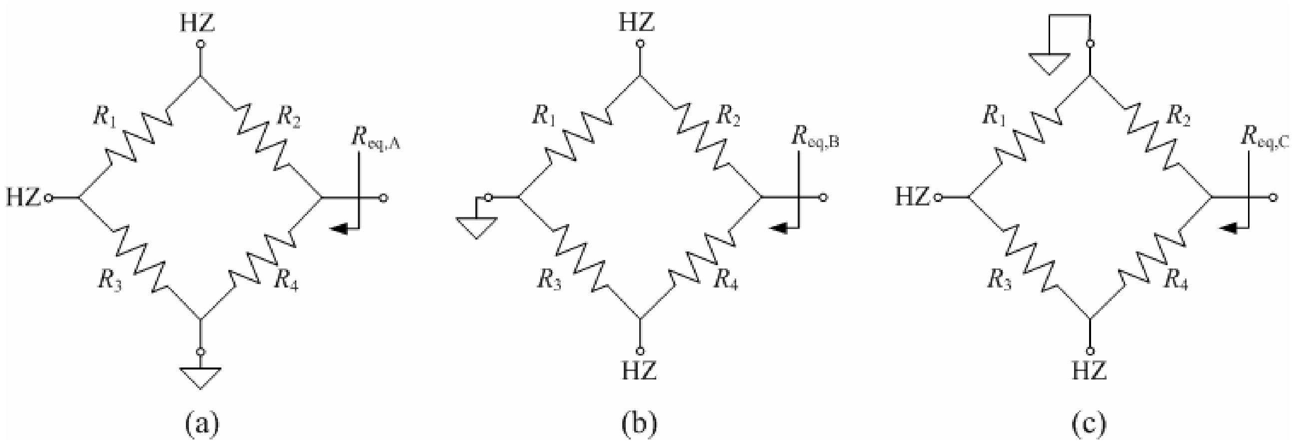

Figure 2. Bridge sensor treated as a resistive circuit and measurement of the equivalent resistances (a) $R_{eq,A}$, (b) $R_{eq,B}$ and (c) $R_{eq,C}$.

To avoid the previous limitations, we propose to use T_0' as a reference instead of T_0; T_0' can be, for example, room temperature whenever it does not differ significantly from T_0. In such conditions, we can assume $\alpha_R' \approx \alpha_R$ and, hence, $R_{eq,B}$ can be expressed and approximated to

$$R_{eq,B} = R_0'\left[1+\alpha_R'\left(T-T_0'\right)\right] \approx R_0'\left[1+\alpha_R\left(T-T_0'\right)\right]. \quad (9)$$

Then, instead of (8), we propose to calculate M^* as follows:

$$M^* = \frac{M}{1+\frac{\alpha_S}{\alpha_R}\left(\frac{R_{eq,B}}{R_0'}-1\right)}, \quad (10)$$

where R_0' is the value of $R_{eq,B}$ registered at $T = T_0'$. Replacing now (7) in (10) yields

$$M^* \approx S_0\left(1+\alpha_S\left(T_0'-T_0\right)\right)P. \quad (11)$$

which just depends on pressure because the term ($T_0' - T_0$) is constant.

This compensation technique can also be applied to conventional conditioning circuits based on the measurement of the differential output voltage (Fig. 1). If the circuit is able to measure both v_o and $R_{eq,B}$, then the information provided by the latter can be used to compensate for the temperature dependence of the former (see (3)).

5. MATERIALS AND METHOD

The proposed temperature compensation technique has been applied to a commercial pressure sensor (SX15AD2, SensorTechnics), which is intended for absolute pressure measurements. This sensor is internally configured in a Wheatstone bridge with four active arms (Fig. 1) and does not include either compensation electronics or conditioning circuits inside. Table I summarises the main features of this sensor.

Table 1. Features of the SX15AD2 sensor.

Feature	Value
Operating pressure range	[0, 103] kPa
Sensitivity	214 µV/V/kPa (typ)
Operating temperature range	[-40, +85] ºC
Temperature coefficient of input resistance (α_R) using T_0 = 25 ºC (not 100 % tested)	+690 ppm/ºC (min) +750 ppm/ºC (typ) +810 ppm/ºC (max)
Temperature coefficient of span (α_S) using T_0 = 25 ºC (not 100 % tested)	-2550 ppm/ºC (min) -2150 ppm/ºC (typ) -1900 ppm/ºC (max)

The sensor was subjected to atmospheric pressure, which was equal to 101 kPa according to the Croatian national meteorological institute. The temperature applied to the sensor was controlled by a climatic chamber (Weiss Technik 125 SB) from -40 ºC to 70 ºC. For each test condition, the three equivalent resistances (Fig. 2) were measured using the direct sensor-to-microcontroller interface circuit proposed in [10], which was controlled by the dsPIC30F3012 microcontroller (Microchip). For the temperature compensation, we used $T_0' \approx 26$ ºC as a reference, which is near to $T_0 = 25$ ºC.

6. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 (solid line and crosses) shows the normalized value of M versus temperature at $P = P_{atm}$ when the compensation technique was not applied (Eq. (6)). The parameter M clearly depended on temperature, to be precise, the temperature coefficient was -2700 ppm/ºC. As predicted by (7), the temperature coefficient of M is negative, however its (absolute) value is slightly higher than the maximum one expected (-2550 ppm/ºC according to Table 1). In the worst case (i.e. for $T \approx$ -40 ºC), the relative error in M (and, hence, in the pressure measurement) due to temperature was about 17 %.

Fig. 3 (dashed line and squares) also shows the normalized value of M^* versus temperature at $P = P_{atm}$ when the compensation technique was applied (Eq. (10)). The parameter M^* was more insensitive to temperature, as predicted by (11). The use of the typical values of α_R and α_S in (10) and/or the temperature dependence of the interface circuit can explain why the response in Fig. 3 is not completely flat. Even so, in the worst case (i.e. for $T \approx 70$ ºC), the relative error due to temperature was about 1.6 %, which is more than ten times smaller than that obtained when the compensation technique was not applied.

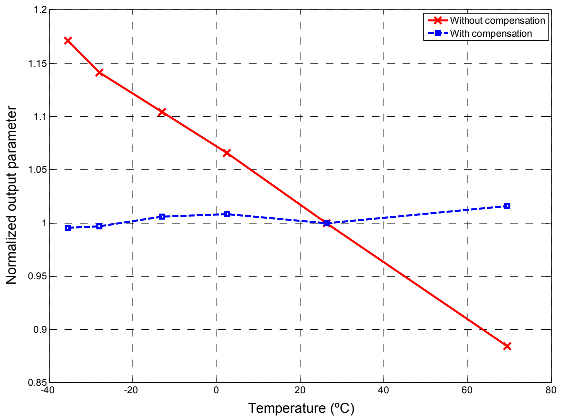

Figure 3. Temperature dependence of the output parameter at $P = P_{atm} = 101$ kPa.

7. CONCLUSIONS

A novel and low-cost technique to compensate for the temperature dependence of piezoresistive pressure sensors has been proposed. This compensation technique relies on estimating the temperature of the sensor by means of the sensor itself, without using any additional component. Once the temperature is known, the output parameter can easily be corrected. This idea has been tested in a commercial pressure sensor and the experimental results agree with the theoretical predictions. Other semiconductor sensors (such as acceleration sensors and magnetoresistive sensors) can also benefit from the results of this work.

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