The analysis of temperature compensation of the transient piezoresistive ultra-high pressure sensor

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Abstract. The ultra-high pressure piezoresistive sensor works with the Wheatstone half bridge theory. Because of the electric resistance temperature coefficient difference and the four electric resistances value of bridge arm are different in the manufacturing, zero drift and zero temperature drift generally exist in practical application of the ultra-high pressure piezoresistive sensor, which leads to loss of measuring accuracy of sensor. It requires a normalized polynomial fitting algorithm to achieve null balance and compensate zero drift simultaneously. According to model analysis and deduction as well as experiments, statistics obtained through normalized polynomial fitting algorithm is the same as experiments and shows higher accuracy, better compensation effect. The ultra-high pressure piezoresistive sensor compensated by the software method can be widely used in pressure testing and research on interior ballistics, especially the high pressure gun under the high temperature, high pressure, and high impact environment.

1. Introduction
With the development of high pressure gun technology development at home and aboard, it puts forward higher requirements on high pressure testing. The ultra-high pressure piezoresistive sensor has advantages of high sensitivity, good dynamic response, reliable performance and high precision, which can be used in 0 ~ 800MPa dynamic pressure testing in the high chamber pressure gun and closed bomb. It works with the Wheatstone half bridge theory, because of the electric resistance temperature coefficient difference and the four electric resistance resistivity of bridge arm are different in the manufacturing, zero drift and zero temperature drift generally exist in practical application of the ultra-high pressure piezoresistive sensors, which leads to loss of measuring accuracy of sensors. It provides a normalized polynomial fitting algorithm to achieve null balance and compensate zero drift simultaneously.

2. The temperature drift mechanism
The work principle of piezoresistive pressure sensor is shown in figure 1. Four electric resistances which have the same resistance value were linked into Wheatstone bridge. $R_1$ is piezoresistive pressure sensor, $R_2$ is temperature compensating resistance, $R_3$, $R_4$ is fixed resistance, and $V_B$ is applied voltage.
The working principle of piezoresistive pressure sensor.

The output voltage of the Wheatstone bridge is:

\[ V_0 = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} V_B \]  

(1)

When the sensor is working without any force, the resistance satisfies with the relation of \( R_1 R_3 = R_2 R_4 \). The output voltage of the Wheatstone bridge is zero, therefore, \( R_1 = R_3 = R_2 = R_4 = R \) is requested in the design, which is named equilateral arm bridge, and to make the bridge balance.

Which has the relation with \( R_1 R_3 \neq R_2 R_4 \), the sensor is working without any force, the Wheatstone bridge is out of balance, the output voltage is that:

\[ V_{oc} = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} V_B \]  

(2)

This is the zero output, when normal temperature, if \( R_1 R_3 > R_2 R_4 \), the zero output voltage is positive; if \( R_1 R_3 < R_2 R_4 \) the zero output voltage is negative.

The output voltage has close relationship with temperature, when the temperature changes, the output voltage changes at the same time, the output voltage is that:

\[ V_{oct} = \frac{R_1 R_3 - R_2 R_4}{(R_3 + R_2)(R_3 + R_4)} V_B \]  

(3)

This is the temperature drift of the zero output, which called zero temperature drift for short. If \( R_1 R_3 > R_2 R_4 \), the zero temperature drift is positive; if \( R_1 R_3 < R_2 R_4 \) the zero temperature drift is negative.

The causes of zero temperature drift are: on the one hand, because of the electric resistance temperature coefficient difference and the four electric resistance resistivity of bridge arm are different in the manufacturing, zero drift and zero temperature drift generally exist in practical application of the ultra-high pressure piezoresistive sensors. On the other hand, the electric resistance produces joule heat when working hot, the thermal expansion stress cause the zero temperature drift, at last the reverse leakage current should not be ignored.

### 3. The zero temperature compensation

Usually, there are two types of temperature compensation, one is hardware compensation, and another is software compensation. The hardware compensation includes the bridge arm thermistor compensation, double bridge compensation and so on, which the problem are complex circuits, difficulty of debugging, lower precision, high cost and so on, therefore it is unsuitable to be used for the real projects. The hardware compensation is easy to realize, has better compensation effect,
which is an important way to improve the testing accuracy of the pressure sensor. The software compensation adopts related software to deal with the data collected by pressure sensor. In this paper, we adopt a normalized polynomial fitting algorithm to achieve null balance and compensate zero drift simultaneously.

3.1. A normalized polynomial fitting algorithm of the nonlinear function

The circuit outputs voltage is the nonlinear function of temperature, that is
\[ V = V_0 + \alpha_1 \Delta T + \alpha_2 (\Delta T)^2 + \cdots + \alpha_n (\Delta T)^n \]

At this time, the solution of coefficient becomes the key. Usually, N=4, which can express approximately the single value relationship, that is:
\[ V - V_0 = \alpha_1 \Delta T + \alpha_2 (\Delta T)^2 + \alpha_3 (\Delta T)^3 + \alpha_4 (\Delta T)^4 + \varepsilon \]

It is a very small amount \( \varepsilon \), the solution expression need four group value of voltage and temperature

To be given the \( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \), we have to solve the algebraic equation (6)

\[
\begin{bmatrix}
V_1 - V_0 \\
V_2 - V_0 \\
V_3 - V_0 \\
V_4 - V_0 \\
\end{bmatrix} =
\begin{bmatrix}
(\Delta T_1)^2 & (\Delta T_1)^3 & (\Delta T_1)^4 \\
(\Delta T_2)^2 & (\Delta T_2)^3 & (\Delta T_2)^4 \\
(\Delta T_3)^2 & (\Delta T_3)^3 & (\Delta T_3)^4 \\
(\Delta T_4)^2 & (\Delta T_4)^3 & (\Delta T_4)^4 \\
\end{bmatrix}
\begin{bmatrix}
\alpha_1 \\
\alpha_2 \\
\alpha_3 \\
\alpha_4 \\
\end{bmatrix}
\]

\[
\begin{bmatrix}
\alpha_1 \\
\alpha_2 \\
\alpha_3 \\
\alpha_4 \\
\end{bmatrix} =
\begin{bmatrix}
(\Delta T_1)^2 & (\Delta T_1)^3 & (\Delta T_1)^4 \\
(\Delta T_2)^2 & (\Delta T_2)^3 & (\Delta T_2)^4 \\
(\Delta T_3)^2 & (\Delta T_3)^3 & (\Delta T_3)^4 \\
(\Delta T_4)^2 & (\Delta T_4)^3 & (\Delta T_4)^4 \\
\end{bmatrix}^{-1}
\begin{bmatrix}
V_1 - V_0 \\
V_2 - V_0 \\
V_3 - V_0 \\
V_4 - V_0 \\
\end{bmatrix} = \left(\chi_j^i\right)^{-1}
\begin{bmatrix}
\Delta V_1 \\
\Delta V_2 \\
\Delta V_3 \\
\Delta V_4 \\
\end{bmatrix}
\]

In which: the tensor \( \chi_j^i \) on the top right is , and lower right corner is the index of the column, we can not use a standardized method to solve \( \chi_j^i \) because of the power series polynomial is no orthogonality, it is not only computationally tedious but also conducive to implementation. It provides a normalized method. Make \( \chi_j^i \) and \( \left(\chi_j^i\right)^{-1} \) to convert normalized isomorphic matrix and corresponding inverse matrix each other.

Taking N+1 test points, the input is temperature \( i=0, 1, 2, \ldots, N \), the corresponding output is voltage \( V_i \) \( (i = 0, 1, 2, \ldots, N) \), making \( T_N - T_0 = N(T_i - T_0) \), when \( N=4, T_{\text{max}} = T_4 \) , \( T_i - T_0 = (T_{\text{max}} - T_0)/4 \), \( T_i - T_0 \) is abscissa scale, the temperature range from \( T_0 \) to \( T_4 \) is divided into four equal parts, we can get the normalized isomorphic matrix \( \left(N_{ij}^j\right) \) and corresponding inverse matrix \( \left(N_{ij}^j\right)^{-1} \).
\[
\begin{bmatrix}
1 & 1 & 1 & 1 \\
2 & 2^2 & 2^3 & 2^4 \\
3 & 3^2 & 3^3 & 3^4 \\
4 & 4^2 & 4^3 & 4^4 \\
\end{bmatrix} \quad \text{and} \quad \begin{bmatrix}
1 & 1 & 1 & 1 \\
2 & 2^2 & 2^3 & 2^4 \\
3 & 3^2 & 3^3 & 3^4 \\
4 & 4^2 & 4^3 & 4^4 \\
\end{bmatrix}
\]
\]

With \( (N^i_{ij})(N^j_{ij})^{-1} = 1 \), we can get the normalized polynomial related with the formula (4), that is:
\[
V - V_0 = aN + bN^2 + cN^3 + dN^4
\]

In which \( a = \alpha_1 (T_i - T_0) \), \( b = \alpha_2 (T_i - T_0)^2 \), \( c = \alpha_3 (T_i - T_0)^3 \), \( d = \alpha_4 (T_i - T_0)^4 \), the result of solving the inverse matrix is:
\[
(N^i_{ij})^{-1} = \begin{bmatrix}
1 & 1 & 1 & 1 \\
2 & 2^2 & 2^3 & 2^4 \\
3 & 3^2 & 3^3 & 3^4 \\
4 & 4^2 & 4^3 & 4^4 \\
\end{bmatrix}^{-1} = \begin{bmatrix}
4.0000 & -3.0000 & 1.3333 & -0.2500 \\
-4.3333 & 4.7500 & -2.3333 & 0.4583 \\
1.500 & -2.0000 & 1.1667 & -0.2500 \\
-0.1667 & 0.2500 & -0.1667 & 0.0417 \\
\end{bmatrix}
\]

Therefore, we can get the expression (11):
\[
\begin{bmatrix}
a \\
b \\
c \\
d \\
\end{bmatrix} = (N^i_{ij})^{-1} \begin{bmatrix}
V_1 - V_0 \\
V_2 - V_0 \\
V_3 - V_0 \\
V_4 - V_0 \\
\end{bmatrix}
\]
\[
= \begin{bmatrix}
4.0000\Delta V_1 - 3.0000\Delta V_2 + 1.3333\Delta V_3 - 0.2500\Delta V_4 \\
-4.3333\Delta V_1 + 4.7500\Delta V_2 - 2.3333\Delta V_3 + 0.4583\Delta V_4 \\
1.500\Delta V_1 - 2.0000\Delta V_2 + 1.1667\Delta V_3 - 0.2500\Delta V_4 \\
-0.1667\Delta V_1 + 0.2500\Delta V_2 - 0.1667\Delta V_3 + 0.0417\Delta V_4 \\
\end{bmatrix}
\]

We can get the polynomial function expression by plugging the coefficient of the nonlinear function \( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \) into the expression (5).

3.2 Experiment and result analysis

Obtain the effect of temperature change on the voltage output of the ultra-high pressure piezoresistive sensor, calculate the temperature drift and get the error analysis by the input-output data pairs of the ultra-high pressure piezoresistive sensor under the different temperature.

Experiment materials: the standard pressure gauge, temperature gauge and the ultra-high pressure piezoresistive sensor. Putting the sensor and temperature gauge into thermostatic bath, the temperature gauge is used for monitoring the temperature of thermostatic bath. Temperature range is from 10°C to 50°C, from which select 5 equally distributed points to record the voltage output of the ultra-high pressure piezoresistive sensor, that is shown in table 1.

| Table 1. Results of experiment. |
|---------------------------------|
| temperature /°C | 10 | 20 | 30 | 40 | 50 |
| voltage output /mV | -4.5 | -3.2 | -2 | -1.2 | -0.4 |
Plugging measured value in the expression fitted by normalized polynomial fitting algorithm, that is:

\[ V = -4.5 + 0.107489 \times (T - 10) + 0.42 \times 10^{-2} \times (T - 10)^2 \\
-0.22489 \times 10^{-3} \times (T - 10)^3 + 0.02915 \times 10^{-4} \times (T - 10)^4 \]  \hspace{1cm} (12)

The output voltage value fitted contrast with the measured value, the fitted curve correspond well with the measured curve, which have higher accuracy, better compensation effect.

**Table 2.** The comparative data.

| temperature/℃ | 10  | 20  | 30  | 40  | 50  |
|---------------|-----|-----|-----|-----|-----|
| measured value /mV | -4.5 | -3.2 | -2.0 | -1.2 | -0.4 |
| Fitted value /mV   | -4.5000 | -3.20085 | -2.00295 | -1.20621 | -0.4011 |

![Figure 2. Voltage-time curve.](image)

**4. Conclusion**

The temperature drift mechanism of ultra-high pressure piezoresistive sensor are stated, which introduced the method of temperature drift compensation, it provides a normalized polynomial fitting algorithm to achieve null balance and compensate zero drift simultaneously. Which have better compensation effect, low cost and easy to promote in the project. The accuracy of the compensate is related to the smooth degree of the nonlinear function, variety of rise and fall size and intensity of equal diversion points, the points is the more, the precision is the higher.

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