Compensation of temperature errors in pressure piezoconverters

S V Emets and E A Khoroshavina

Ufa State Petroleum Technological University, 1, Kosmonavtov Street, Ufa, 450044, Russia

Abstract. Measuring pressure converters are one of the most popular control devices in technological processes. The most additional common error is temperature error. One of the causes of the additional temperature error is the uneven temperature field on the pressure converter measuring membrane surface that is determined by the nature of temperature impact. Constructive methods for reducing the stated error lie also in finding the topology of a resistance strain gage on the converter membrane that ensures minimum sensitivity to the uneven temperature field while retaining the pressure sensitivity. The effectiveness check of various topologies is hindered by different technical, technological and economic problems. The article proposes to run a check of topological solutions with the help of a mathematical model of the membrane temperature field that takes into account the temperature impact on the converter. The exponential function was chosen as a modelling function because it corresponded to the experimentally obtained temperature distribution data. This function allows virtually forming temperature field distributions on the membrane surface, characteristic of static, dynamic (thermal shock) and targeted temperature impact. This model will allow assessing without a physical experiment of additional temperature errors of various topological solutions. Additional temperature errors of the classic four resistance element topology and the topology proposed by the authors with component resistance strain gages are analysed as examples. The potential of topological solutions in minimizing of additional temperature errors in pressure converters is shown. The approach set forth in the article streamlines the search for constructive solutions for minimizing additional temperature errors in pressure converters by reducing physical simulation stage.

1. Introduction

Among many non-electrical physical values, pressure is one of the most common ones to be measured and this parameter is very important for ensuring normal operation of all technological processes. There are many pressure converters. The simplest in construction and the most reliable ones under the conditions of mechanic and heat impact are pressure piezoconverters. Their operation is based on the impact of the measured pressure on the tight membrane, the deformation of which is measured with piezoresistors placed on it and switched into the bridge connection.

The significant drawback of this type of converters is the additional temperature error [1-5]. One of its causes concerns technological difficulties in ensuring full symmetry of the values of resistance temperature coefficients (RTC) of piezoresistors and their dependence on temperature. The other cause is the uneven temperature field on the measuring membrane during a thermal shock [5, 6] and targeted temperature impact on the pressure converter. During a thermal shock on the membrane surface there is a short-term temperature gradient that causes a bridge imbalance. With a targeted static temperature filed, the temperature gradient and the corresponding bridge imbalance will be constant in time.
Today in order to correct the additional temperature error constructive, sheet-oriented and algorithmic methods are used [1-5]. The analysis of these methods showed that in order to achieve minimal temperature impact on the output sensor signal, the sensor control element construction must be optimized first of all.

A topology with minimum additional temperature errors may be found in various ways [7-11]:

- simulation of a temperature field that surrounds a converter and finding out its distribution patterns on the measuring membrane taking into account the construction of an individual converter;
- development of a simulation of a temperature distribution on a membrane that allows taking into account the possible variety of temperature effects on the sensor control element.

The second way seems more productive as it allows assessing more quickly the effectiveness of a topology or a technical solution for the construction of a sensor element from the point of view of its sensitivity to the temperature impact of various nature. Moreover, the second approach allows identifying trends and finding ways to reduce additional temperature errors.

2. Results and discussions

The present research proposed to simplify the task of checking the quality of a technical solution for the distribution configuration of piezoresistor system on the surface of the measuring membrane of the pressure converter by mathematic simulation of a temperature field on its surface and calculation of an additional output voltage of the bridge model caused by its temperature imbalance.

Based on the practical results of temperature distribution on the surface of the measuring membrane under difficult temperature effect [9] it was proposed to describe this distribution with the following exponential function

\[ y = b \cdot e^{-(ax)^2}, \]

where \( b \) - amplitude function value; \( a \) - form coefficient.

This function allows describing the axially symmetrical temperature field on the membrane surface that is close by its distribution patterns to the real corresponding symmetrical thermal shock, when the measured environment with the temperature that differs greatly from the current affects the measuring membrane. The present function allows comfortable simulation of the temperature distribution by changing its parameters as well as its lineal shift and the rotation of this distribution about the membrane axis. Based on a specific configuration of a membrane temperature field, it is possible to calculate individual values of piezoconverters temperature that are placed in different temperature zones of the membrane and then to find corresponding values of the output signal of a pressure piezoconverter that is determined by uneven temperature on the membrane surface.

In order to describe the temperature field a cylindrical coordination system (Figure 1, a) and its \( T \) axis matches the converter membrane axis, and \( r \) axis is in the membrane plane. Temperature change law on the membrane surface determines the surface, described in its vertical section by the following expression

\[ T = T_0 \cdot e^{-(ke)^2}, \]  \hspace{1cm} (1)

where \( T_0 \) – amplitude of the maximum of a temperature field; \( \varepsilon = r/R \) – relative distance from the maximum point of the temperature field to the analysed membrane point; \( r \) - current radial coordinate; \( R \) - radius with piezoresistors on it; \( k \) - temperature field form coefficient.

Figure 1.a shows a converter under the conditions of an axially symmetrical temperature shock and presents surface sections of temperature distribution on the converter membrane for various values of form coefficients. Temperature distribution surfaces have a characteristic bending ring with radius \( R/k \) that divides the convex central part from the concave peripheral one. By changing parameter \( k \) the relative size of the bending ring can be changed and thus the temperature field nature on the membrane surface can be simulated and when \( T_0 \) is changed, the amplitude also changes.
Figure 1. Temperature distribution on the membrane surface of the pressure converter: a) - effect of k form coefficient and linear shift coefficient η on the temperature distribution on the membrane's surface; b) - topology of a sensor with four piezoresistors; c) - topology of a sensor with component piezoresistors

The simulation of an axially asymmetric temperature field is possible by linearly shifting the surface of temperature distribution against the center of the converter membrane in the radial direction at the distance d. Figure 1 shows the shift in temperature surface with the form coefficient k=1 by taking the coordination system center from 0 to 0’. And relative linear shift will be determined as η = d/R. If the temperature field is axially asymmetric, output voltage of the pressure converter will be the function of the angle φ between the temperature field shift direction and piezoresistor orientation on the membrane because of the discreteness of their placement (Figure 1, b, c). There are angle orientations that produce output voltage determined by the temperature impact equals zero, and orientations with output voltage that has the maximum value for this temperature field and topology of piezoresistors. In the second case the additional temperature error is maximum. The proposed model of a temperature field allows studying the function of the output converter signal that is determined by an uneven temperature field on the membrane surface and φ angle of its turn against maximum temperature direction shift. This function can be obtained by turning the converter around its axis against the temperature field, shifted to distance d from the center of the membrane (Figure 1, b, c). The current distance from the center of the temperature distribution to the location of a specific piezoresistors on an equivalent membrane radius with the traditional location of a bridge model with four piezoresistors (Figure 1, b) taking into account the turning angle is calculated using the following formulas:

\[
\begin{align*}
    r_1 & = \sqrt{R^2 \cdot \sin^2 \varphi + (d + R \cdot \cos \varphi)^2}, \\
    r_2 & = \sqrt{R^2 \cdot \cos^2 \varphi + (d - R \cdot \sin \varphi)^2}, \\
    r_3 & = \sqrt{R^2 \cdot \sin^2 \varphi + (d - R \cdot \cos \varphi)^2}, \\
    r_4 & = \sqrt{R^2 \cdot \cos^2 \varphi + (d + R \cdot \sin \varphi)^2},
\end{align*}
\]

(2)

where d - axis shift of the temperature field against the membrane axis; φ – turning angle of a converter against the direction of temperature maximum point shift.

These expressions with relative values must look like that:

\[
\begin{align*}
    \varepsilon_1 & = \sqrt{\sin^2 \varphi + (\eta + \cos \varphi)^2}, \\
    \varepsilon_2 & = \sqrt{\cos^2 \varphi + (\eta - \sin \varphi)^2}, \\
    \varepsilon_3 & = \sqrt{\sin^2 \varphi + (\eta - \cos \varphi)^2}, \\
    \varepsilon_4 & = \sqrt{\cos^2 \varphi + (\eta + \sin \varphi)^2},
\end{align*}
\]

(3)

where η = d/R – relative shift of the temperature impact axis against the membrane's axis.
Simultaneous change of the indexes $k$, $d$ ($\eta$) and $\varphi$ allows forming a virtual temperature field distribution with different configuration on the membrane's surface.

In order to simplify the analysis of specific constructive solutions with various piezoresistors placement on the membrane, the authors developed specifically tailored software. It allows simulating the temperature field distribution on the converter membrane under various temperature impacts, calculating values of a load-indicating resistor at their specific placement and for specific electrical parameters of piezochart, calculating additional temperature error with different variations of parameters of the temperature field.

To illustrate the feasibility of the proposed model of the temperature field and the developed software we should analyse the additional temperature error in pressure converters presented in Figure 1, b and c.

Figure 1, b presents a classic scheme of a four-arm piezoconverter with its circular and radial piezoresistors on the measuring membrane in the apices of the imaginary square. The calculations led to expect that piezoresistors have identical geometrical and electrical characteristics and their temperature corresponds to the membrane temperature in the geometrical centre of a piezoresistor. The distance from the temperature field surface axis to every piezoresistor and their individual temperatures were identified using the formulas (1) and (3). The values of the output voltage of the bridge model for various temperature impacts on the pressure converter that are simulated with the different relations between the model parameters $k$, $d$ ($\eta$) and $\varphi$ are identified for a specific bridge model connection layout of piezoresistors.

The results of the simulation are presented in Figure 2. Here there are functions of additional stated temperature error in pressure converters and temperature field parameters. The stated error is calculated as a function expressed in percent of the additional output piezobridge voltage caused by temperature impact and its nominal output voltage that corresponds to the input nominal pressure.

The diagrams show that classic piezoresistor layout has minimum additional temperature errors only when temperatures are constant when the measuring membrane has constant temperature on the whole surface. The temperature gradients in the membrane surface inevitably cause additional temperature errors that limit the applicability of the said topology.

Figure 1, c presents the authored topology of the sensitive element when every arm of the bridge scheme has two piezoresistors that are placed in two opposite zones of the membrane. The authors analyzed the situations with parallel and crossing placing of the elements of the bridge arm piezoresistors. The results of the simulation of the additional temperature error for the topologies with parallel and crossing piezoresistor compounds are shown in Figures 3 and 4.
Figure 3. Function of the additional stated temperature error $\gamma$ for the topology with parallel compound piezoresistors: a) and k form coefficient with constant lineal $\eta$ and the angle $\Delta \phi$ shift; b) - and lineal shift $\eta$ with constant lineal $\eta$ and the angle $\Delta \phi$ shifts; c) maximum error $\gamma_{\text{max}}$ and form k coefficient and lineal shift $\eta$

Figure 4. Function of the additional stated temperature error $\gamma$ for the topology with crossing compound piezoresistors: a) and k form coefficient with constant lineal $\eta$ and the angle $\Delta \phi$ shift; b) - and lineal shift $\eta$ with constant lineal $\eta$ and the angle $\Delta \phi$ shifts; c) maximum error $\gamma_{\text{max}}$ and form k coefficient and lineal shift $\eta$

The analysis of charts in Figures 3 and 4 allows making a conclusion that compound bridge arms and placing piezoresistors of every arm in the opposite zones of the membrane allows significantly reducing the additional temperature error in pressure converters of the analysed class. Moreover, this conclusion was made without difficult heat and technical mathematical models and physical experiments.

3. Conclusion
The approach was proposed to assess the effectiveness of topological solutions when developing new constructions of the sensitive element in piezoresistor pressure converters that identifies the additional temperature error under the conditions of a virtual experiment that corresponds to the static, dynamic and targeted temperature impacts on the converter exerted by the external and measured environments. The results of mathematic simulation show that the proposed pressure converter with parallel adjacent bridge arms allows reducing maximum state error caused by the axially asymmetric temperature impact by 2-4 times against the traditional bridge layout. These values were obtained for various ratios of the temperature field form coefficient and shift coefficient with the worst possible orientation angles of the bridge model against temperature field axis shift.
The placement of adjacent bridge arms piezoresistors in cross pattern allows reducing the stated error by more than 10-15 times. The stated error is reduced by more than 100 times in the zones of the most probable values of temperature field form coefficient from 0 to 1.5 and temperature field shift coefficient against the center of the membrane from 0 to 0.7.

Thus, the proposed technical solutions for piezoresistor topology on the pressure converter membrane allows significantly reducing the maximum state temperature error in the pressure converter that is created in case of an axis symmetrical and axis asymmetrical static and dynamic temperature impacts with different angle orientation. The proposed topology can be used in measuring pressure under the conditions of static, dynamic (thermal shock) and targeted temperature impacts on the pressure converter from the measured and immediate environment.

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