Analysis of the Downhole Measurement System’s Pressure and Temperature Measuring Channel Calibration Errors

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Abstract. Various measurements in wells are quite challenging due to the specific measurement conditions. There are some additional requirements for measurement systems, in particular, space restrictions. Therefore, measuring several parameters with a single sensor is rather important. The paper discusses a measurement system that allows measuring temperature and pressure with a single sensor – an SOS-based strain gauge pressure transducer with a bridge or half-bridge circuit. In this case, pressure and temperature measuring channels are calibrated individually, which creates another error component. The numerical simulation of calibration described herein shows that regardless of the sensor circuit, the voltage uncertainty band of both measuring channels is characterized by a reduced error of 0.03 % with a confidence probability $P = 0.9$.

1. Introduction

Oil production is a complex process, the efficiency of which depends on several interrelated components: the oil-bearing formation itself and the downhole and surface equipment. In this case, obtaining measurement data on the process progress is a separate problem since placing various sensors directly in the well is associated with many complications. They comprise the space restrictions of measuring devices, the complexity of transmitting data to the surface, rather harsh measurement conditions, etc. Therefore, continuous measurement is often replaced by hydrodynamic studies (HDS) of wells, performed at a certain frequency, e.g., once every six months. This approach does not always give satisfactory results.

Recently, there has been a transition to the so-called smart wells. This concept is relatively new for the oil industry. In the broadest sense, a smart well is understood as that having the following functionality: gathering real-time data on the well rate, temperature, and pressure, the downhole unit state, etc.; processing and analyzing the data gathered; making decisions on changing the operating parameters of the ‘formation-well-pumping unit’ system according to a given criterion [1]. This concept can be implemented only if there is a system to obtain reliable data from the downhole sensors. Since their placement space is very limited, the best option is to use the so-called multisensor systems that allow measuring several parameters using a single sensor [2].

Measuring pressure and temperature with a single sensor is an option for such systems. In this case, the issue of analyzing and evaluating metrological characteristics arises since for multisensor systems, this procedure has some specifics [3, 4].

The paper discusses the main error sources of the downhole temperature and pressure measuring...
system and the numerical simulation of its calibration.

2. Reviewing known solutions and formulating the research objective

Any pressure sensor comprises two parts: a direct pressure sensor (sensing element) and a converter of the sensor's natural output into an electrical signal. The pressure measurement accuracy depends on both components, i.e. the physical sensor nature and the method of converting its output into an electrical signal.

Strain gauge, piezoresistive, capacitive, and resonant sensors are the most widespread in the industry, in particular, the oil and gas sector [5]. As for downhole measurements, these systems mainly use strain gauges based on the SOS structure – silicon on sapphire). This sensor is a sapphire substrate located on the input titanium diaphragm, on which silicon strain gauges are 'grown' in a heteroepitaxial process, forming a bridge or half-bridge measuring circuit. The sensor output parameter is either individual circuit element voltage or that between different points of the half-bridge and bridge circuit connecting strain gauges. E.g., the half-bridge sensor output may be an individual strain gauge voltage, and the bridge sensor output – the measuring or power diagonal voltage. The sensor circuit may differ depending on the output signal reading point.

The idea of using a single sensor to measure at least two parameters is also being implemented quite successfully, including in the oil industry. In such systems, one parameter is measured directly, and another is calculated according to an algorithm built in the system, or both quantities are determined numerically using different combinations of the sensor measurements [6 – 11]. Vibrating density and viscosity meters, most multi-component or multiphase process media analyzers, etc. are built on this principle.

In general, the block diagram of such a single sensor-based two-channel system is shown in Fig. 1.

![Figure 1. General Two-Channel Measurement Structure.](image)

In general, an analytical description of this structure can be represented as follows:

\[
\begin{align*}
\gamma_1 &= f_1(x_1, x_2, \alpha_1, \alpha_2, \alpha_3) ; \\
\gamma_2 &= f_2(x_1, x_2, \alpha'_1, \alpha'_2, \alpha'_3) ,
\end{align*}
\]

where \(x_1, x_2\) are measured parameters; \(\alpha_1, \alpha_2, \alpha_3\) and \(\alpha'_1, \alpha'_2, \alpha'_3\) are the sensitivity coefficients for each measured parameter of the first and second measurement channels, respectively.

Solving this system by numerical or analytical methods gives the \(x_1\) and \(x_2\) measured value codes –
\( N_1, N_2: \)
\[
\begin{aligned}
N_1 &= \psi_1(y_1, y_2); \\
N_2 &= \psi_2(y_1, y_2).
\end{aligned}
\]  
(2)

To create such a two-channel measurement system topology, the below condition should be met:
\[
\begin{vmatrix}
\frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\
\frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2}
\end{vmatrix} \neq 0
\]
(3)

The considered structure is a common one and may serve as a starting point in the study and development of a specific multisensor system.

Geophysical equipment uses both spatial and temporal channelizing [12]. With spatial channelizing, all measurement channels are physical. Thus, for two measuring channels, at least two two-wire communication lines are used. With temporal channelizing, to build the two-channel topology, the same two-wire communication line is used sequentially, and the sensor circuit channelizing is contactless and ensured by key elements with different control methods [13].

The general idea of remote downhole temperature and pressure measurement with a single SOS sensor is illustrated by circuits shown in Fig. 2.

![Figure 2](image)

**Figure 2.** Half-Bridge (a) and Bridge (b) Sensor Circuits.

The study objective is to analyze the calibration errors of the pressure and temperature measuring channels of a multisensor downhole measurement system (DMS) based on the SOS pressure transducer.

### 3. Theoretical part

#### 3.1. The main error sources

To identify the main error sources in determining pressure and temperature using a strain gauge pressure sensor, let us represent the measurement as a sequential structure of analog, analog-to-digital, and digital converters (Fig. 3).
Figure 3. Block Diagram of Pressure and Temperature Measurement.

This block diagram is the same for bridge and half-bridge sensor circuits. In this scheme, blocks 1 and 1’ are two measuring channels converting pressure P and temperature T into the resistances $R_1(P, T)$ and $R_2(P, T)$. In blocks 2 and 2’, the resistances $R_1(P, T)$ and $R_2(P, T)$ are converted into voltages $U_1(R1)$ and $U_1'(R2)$; in blocks 3 and 3’, analog-to-digital conversion occurs, and in blocks 4 and 4’, pressure $N_p$ and temperature $N_t$ are determined and scaled. The impact of chartjunk on the strain gauge is reflected by the $F$ parameter. $I_0$ and $U_0$ are the current and voltage standards, and $N_0$ is the scaling factor.

According to the above scheme, the operator representation of the numerical pressure and temperature values will be written as follows:

$$N_p = A_4 \cdot A_3 \cdot A_2 \cdot A_1 \cdot P;$$

$$N_t = A_4' \cdot A_3' \cdot A_2' \cdot A_1' \cdot T.$$ (7) (8)

Obviously, each transformation introduces a certain error in the measurement. Thus, the main error components can be determined as follows:

- errors due to the conversion of pressure and temperature into resistance,
- errors due to the conversion of resistance into voltage or current,
- errors introduced by the analog-to-digital converter,
- computation and scaling errors,
- dynamic errors.

3.2. Analysis of error components

The error component arising at the first conversion step is completely determined by the metrological characteristics of the strain-gauge sensor. For the combined measurement method and individual sensor calibration, the greatest error is caused by the drift of the $R_1(P, T)$ and $R_2(P, T)$ dependencies and their reproducibility after repeated thermal and mechanical loads. These are systematic factors causing an instrumental error. For all strain-gauge sensor circuits, the $R_1(P, T)$ and $R_2(P, T)$ dependencies are nonlinear and obtained by power polynomial approximation of empirical calibration data. In this case, an approximation method error arises, which is systematic for the given P and T points and random for various points within the P and T measurement ranges.

The impact of current that causes heating of the sensor’s sensitive elements and, consequently, the change in the $R_1(P, T)$ and $R_2(P, T)$ dependencies, and the impact of electromagnetic interference on the sensor semiconductor element parameters should also be noted.

The resistances $R_1(P, T)$ and $R_2(P, T)$ are converted according to a linear law without method errors. The instrumental error arises when the feed current $I_0$ is set inaccurately when it changes, and
there is a difference in the channel feed currents, i.e., for jointly calibrated blocks 1, 2, 3, the error is caused by the feed current drifts and the inequality of the feed currents of various channels.

The analog-to-digital conversion errors, in turn, depend on the ADC type and its metrological characteristics and are determined using standard techniques.

Computational operations introduce an error due to the limited number of bits, caused by the architecture of the processor used to calculate and operate with rounded-off data. Obviously, the last block (Fig. 3) errors depend on the algorithms used.

All the error components considered are static. Since the downhole pressure and temperature are constantly changing, dynamic errors associated with changes in these parameters during the measurement will also contribute to the overall error. Considering that the strain gauge has significant thermal inertia, this error can become dominant when measuring temperature.

Static errors are conventionally divided into three groups according to their occurrence point. The first group comprises errors occurring in blocks 1, 2, and 1′, 2′. This part of the measuring channels should be calibrated individually during the DMS manufacture. The second group comprises analog-to-digital conversion errors, and, finally, the third one includes the computation errors.

This paper studies the calibration errors.

4. Results and discussion

4.1. Numerical simulation of calibration

The calibration purpose is to determine the dependencies \( U_1 = U_1(P, T) \) and \( U'_1 = U'_1(P, T) \). The calibration errors include the approximation error arising as a result of second-order polynomial approximation of these dependencies and the \( U_1 \) and \( U'_1 \) uncertainties due to the inaccurate pressure and temperature settings.

In the first approximation, the \( U_1 \) and \( U'_1 \) uncertainty bands can be determined by the Taylor series expansion. When leaving only the first-order derivatives in the expansion, we have

\[
\Delta U = \frac{\partial U}{\partial P} \cdot \Delta P + \frac{\partial U}{\partial T} \cdot \Delta T, \tag{9}
\]

The last expression shows that the uncertainty band depends on pressure and temperature. Therefore, three values – maximum, average, and minimum ones, should be calculated for pressure and temperature, i.e., \( P_{\text{min}}, (P_{\text{max}} \cdot P_{\text{min}})/2, P_{\text{max}}, \) and \( T_{\text{min}}, (T_{\text{max}} \cdot T_{\text{min}})/2, T_{\text{max}}. \)

Table 1 shows the reduced calibration error calculation results

\[
y^r_{U_1} = \frac{\Delta U_{\text{1max}}}{U'_{\text{1max}}} \cdot 100\%; \tag{10}
y^r_{U'_1} = \frac{\Delta U'_{\text{1max}}}{U'_{\text{1max}}} \cdot 100\%;
\]

for a given accuracy class of pressure and temperature setters \( N=0.02 \). The upper record corresponds to the reduced error in determining the voltage \( U_1 \), and the lower one corresponds to the voltage \( U'_1 \).

Analysis of the results obtained shows that within the considered pressure and temperature measurement ranges, the reduced errors in determining the voltages \( U_1, U'_1, \) and \( U_2, U'_2 \) for half-bridge and bridge sensors, respectively, do not depend on the current pressure and temperature values.

The dependencies of the calibration voltage uncertainty band on the accuracy class of the pressure and temperature setters \( \gamma^r_U = f(\gamma^3_{\text{p}}, \gamma^3_{\text{t}}) \) are shown in Fig. 4. They can be approximated by linear equations

\[
\begin{align*}
y^r_{U_1} &= 1.1 \cdot \gamma^3_{\text{p}} + 0.04 \cdot \gamma^3_{\text{t}}; \\
y^r_{U'_1} &= 1.1 \cdot \gamma^3_{\text{p}} + 0.03 \cdot \gamma^3_{\text{t}}; \\
y^r_{U_2} &= 1.1 \cdot \gamma^3_{\text{p}} + 0.03 \cdot \gamma^3_{\text{t}}; \\
y^r_{U'_2} &= 1.1 \cdot \gamma^3_{\text{p}} + 0.03 \cdot \gamma^3_{\text{t}}.
\end{align*}
\]
For both sensors, for the 0.02 accuracy class of pressure and temperature setters, the reduced errors do not exceed 0.03 %.

Table 1. The Reduced Error Calculating Results for Half-Bridge and Bridge Sensor Circuits.

| T, °C | P, MPa, for the sensor circuit |
|------|-------------------------------|
|      | half-bridge | bridge |
| 25   | 0.019 | 0.020 | 0.029 | 0.019 | 0.019 | 0.020 |
| 50   | 0.019 | 0.019 | 0.019 | 0.020 | 0.019 | 0.020 |
| 75   | 0.019 | 0.02 | 0.021 | 0.019 | 0.020 | 0.021 |

Calculating errors by (9), as a rule, gives overestimated results. This is due to the use of the maximum errors of pressure and temperature setters, based on the accuracy class. Therefore, this option is taken as the worst one. The most reliable results, suitable for designing instruments can be obtained by simulation [14], the diagram of which is shown in Fig. 5 for determining the uncertainty band of voltages $U_1$ and $U'_1$.

![Figure 4](image1)

**Figure 4.** Dependencies of the Reduced Error in Determining Voltage on the Reduced Error of the Pressure (a) and Temperature (b) Setters.

![Figure 5](image2)

**Figure 5.** Calibration Simulation Diagram.
The simulation algorithm is as follows. The random number generator (RNG) generates random numbers $x_5$ and $x_6$ with uniform distribution density within the interval $[0, 1]$. They are used to calculate the $P$ and $T$ setting errors. The $\Delta P_5$ and $\Delta T_6$ error distribution law depends on the specific pressure and temperature setter type, i.e., there is no a priori data on the $\Delta P_5$ and $\Delta T_6$ error distribution law. Therefore, a uniform $\Delta P_5$ and $\Delta T_6$ distribution law is chosen. The $\Delta P_5$ and $\Delta T_6$ measurement interval is chosen based on the actually existing setters corresponding to accuracy classes from 0.01 to 0.1. Further, the pressure and temperature values are generated with an error of $P_0 + \Delta P_i$ and $T_0 + \Delta T_j$, respectively. Based on these values, the voltages $U_i$ and $U_i'$ are calculated for various sensor circuits.

Performing these operations $N$ times, the probabilistic characteristics of the voltages $U_i$ and $U_i'$ can be determined as random variables: distribution density $w(U_i)$, variance $D(U_i)$, standard deviation $\delta(U_i)$, etc.

For clarity and the possibility of comparing the results with the worst-case data, let us go from the standard deviation to the reduced error. For most unimodal distribution laws, the standard deviation $\delta(U_i)$ is related with an error $\Delta_{0.9}$ with a confidence probability $P=0.9$ by the equation $\Delta_{0.9} = 1.65 \delta(U_i)$.

Table 2 shows the simulation results for both sensor circuits for the pressure and temperature setter accuracy class $N = 0.02$.

| T, °C | P, MPa, for the Sensor Circuit |
|------|------------------------------|
|      | half-bridge                  | bridge                        |
|      | 5    | 10   | 15   | 5    | 10   | 15   |
| 25   | 0.0197 | 0.0198 | 0.0200 | 0.0200 | 0.0196 | 0.0196 |
|      | 0.0175 | 0.0175 | 0.0175 | 0.0173 | 0.0173 | 0.0173 |
| 50   | 0.0196 | 0.0198 | 0.0200 | 0.0195 | 0.0195 | 0.0195 |
|      | 0.0178 | 0.0178 | 0.0178 | 0.0183 | 0.0183 | 0.018  |
| 75   | 0.0195 | 0.0197 | 0.0198 | 0.0193 | 0.0193 | 0.019  |
|      | 0.0180 | 0.0181 | 0.0180 | 0.0193 | 0.0193 | 0.0192 |

These data justify the conclusions drawn from the worst-case calculations.

5. Conclusions
The calibration simulation allows drawing the following conclusions.

The $U_i$ and $U_i'$ and $U_2$ and $U_2'$ voltage uncertainty band within the pressure and temperature range studied remains virtually constant. This indicates that the calibration error is additive.

The results obtained allow determining the calibration voltage uncertainty band for the given setter accuracy class or finding the required setter accuracy class for a given uncertainty band. Thus, when using the TM-60 deadweight gauge (accuracy class 0.02), the voltage uncertainty band of the measuring circuit’s first and second MCs for a half-bridge and bridge sensor will be characterized by a reduced error of 0.03 % with a confidence probability $P = 0.9$.

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