Processing calibration results for measuring transducers with an integrated sensor

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Abstract. The proper production process control is possible only if there is an information-measuring system equipped with a large set of measuring transducers of physical quantities. Currently, measuring transducers with semiconductor sensors are widely used. Along with high sensitivity to the measured value and repeatability of parameters, these transducers are sensible to stray quantities, which leads to additional errors. One way to reduce the additional errors of measuring transducers with an integrated sensor is to apply algorithmic correction, which involves a multifactorial calibration experiment, the processing of the results of which allows obtaining the conversion function. Algorithmic correction solves the issue of linearizing the conversion function and minimizes the effect of influencing factors on the measurement results. The conversion function quality and, consequently, the accuracy of further measurements largely depend on the correctness of the calibration experiment results. Random outliers (spurious errors) in the calibration results inevitably cause a distortion of the conversion function and the further erroneous measurement results. This paper proposes a theoretical justification for the possibility of generating the conversion function of a measuring transducer with an integrated sensor by processing the results of a multifactorial calibration experiment including random parasitic errors. Experimental results are provided to illustrate the effectiveness of the proposed calibration results processing technique, which allows obtaining the correct conversion function in the conditions of distorted initial data.

1. Introduction
The control over complex processes is impossible without modern information-measuring systems that provide the control system with current and accurate values of the measured physical quantities and the control state. Modern information-measuring systems are characterized by using a variety of measuring transducers, among which the share of those with semiconductor sensors is steadily increasing. The increased interest in these transducers is due to their high sensitivity to the physical quantities measured, superior repeatability, and manufacturability. However, semiconductor sensors have a significant shortcoming consisting in their sensitivity to stray (unmeasured) quantities along with that to a natural (measured) input value. Thus, semiconductor sensors are integrated or, in another way, sensible to various physical quantities. This specificity leads to additional errors in the measurement of the natural input value due to the influence quantities. Controlling these errors has led to the development of techniques for correcting the characteristics of measuring transducers with an integrated sensor. Among them, the most developed ones are constructive techniques [1–5] aimed at improving the sensor design
and materials, circuitry techniques [6] based on the use of electrical circuits sensitive to influence factors, and algorithmic techniques [7] that allow generating multidimensional conversion function considering the sensor’s non-linearity with respect to the measured value and sensitivity to stray quantities.

The rapid development of computing and microprocessor technology has led to a shift in the development of correction techniques for the characteristics of measuring transducers with an integrated sensor toward algorithmic ones. It became possible to obtain and use complex multidimensional conversion functions of measuring transducers, which allow minimizing non-linearity and additional errors. To generate the conversion function, a calibration experiment is required, which involves exposing the sensor to various combinations of the natural input value and influence factors. The mathematical processing of the calibration experiment data obtained provides the mathematical model parameters for the conversion function that are further stored in the measuring transducer memory during its operation. Thus, the measuring transducer conversion function obtained in the course of calibration determines its metrological characteristics such as linearity and additional errors with respect to the influence quantities.

In turn, the conversion function correctness is determined by the arrangement of the calibration experiment and the correctness of the initial data for mathematical processing obtained in it. Random outliers and spurious errors in these data distort the calibration characteristic obtained and, as a result, cause errors during subsequent operation.

This paper provides a theoretical justification for the algorithm for processing the results of a multifactorial calibration experiment containing random parasitic errors in the initial data. The algorithm proposed allows obtaining the correct conversion function of the measuring transducer, despite the measurement errors. The experiment results are provided, which involves obtaining the conversion function of an integrated strain gage pressure transducer characterized by an additional temperature error, based on the results of two-factor calibration of data containing parasitic errors.

2. Materials and Methods
Multifactorial calibration of measuring transducers allows achieving high accuracy when processing the calibration data to obtain the conversion function provided that the data does not contain random outliers. In real conditions, the empirical data involved in the test experiment contains some measurement error, including outliers and spurious errors that negatively affect the determination of the mathematical model parameters for a measuring transducer [8].

The paper’s objective is to increase the measurement accuracy of transducers with an integrated sensor by reducing the effect of random outliers in the calibration experiment results.

The essence of the algorithm proposed for correcting the static characteristics of measuring transducers is illustrated by the example of a transducer with two measuring channels influencing each other (Figure 1, a).

![Figure 1](image_url)

**Figure 1.** Block Diagram of Measuring Transducer with an Integrated Sensor: a) - circuit with two measuring channels; b) – integrated strain gage pressure transducer circuit

Here $x_1$, $x_2$ are the input values and $y_1$, $y_2$ are the output values, which are functions of the input values, i.e. $y_1 = f_1(x_1, x_2)$ and $y_2 = f_2(x_1, x_2)$. The conversion functions $y_1$ and $y_2$ of the transducer’s measuring channels can be determined, e.g., according to [7]. For all values $x_2$ involved in the calibration experiment, the functions $y_1 = f(x_1)$ are approximated. The approximation will result in the parameter (coefficient) values of the functions $f(x_1)$, which are individual for each value $x_2$. Then, each parameter of the function $f(x_1)$ is approximated by the value $x_2$. The resulting coefficients will ultimately determine the conversion function $y_1$. The conversion function $y_2 = f_2(x_1, x_2)$ is determined...
in a similar way. The calculated input values at the calibration data matrix nodes are found by solving the inverse problem using the mathematical model obtained. The adequacy of the conversion function obtained is evaluated by analyzing the reduced errors at the nodal points defined as the ratio of the difference between the calculated and experimental values of the quantity considered to its nominal value expressed as a percentage.

Different approximation methods have corresponding criteria for the proximity of approximating functions to experimental data. Thus, the least square method taken as such a criterion uses the minimum of the sum of the squared deviations of the experimental values from those obtained using the approximating function [9].

At the next algorithm implementation stage, the measuring transducer mathematical model parameters are corrected by re-determining the model considering correction factors defined as quantities functionally related to the error values at the experimental data matrix nodes. These correction factors are considered in the criteria of the relevant approximation technique to achieve optimal approximation to the experimental data. In particular case, when using the least square method as an approximation technique, then instead of the criterion

\[ \min \sum_{i=1}^{n} [(y_i - f(x_i))^2], \]

the following form is used considering correction factors:

\[ \min \sum_{i=1}^{n} [(y_i - f(x_i))^2 \cdot k_i]. \] (2)

In formulas (1) and (2), \( y_i \) are the output values, \( x_i \) are the input values, \( f(x_i) \) is the approximating function, \( n \) is the number of points involved in the calibration experiment, \( k_i \) is the correction factor of the \( i^{th} \) data point determined, in particular, as \( k_i = 1/e_i \), where \( e_i \) is the approximation error at the \( i^{th} \) point of the experimental data matrix.

Determining the correction factors and the measuring transducer conversion function parameters are repeated in an iterative cycle, the criterion for termination of which is, e.g., the difference of the reduced errors at the experimental data matrix nodes calculated at two adjacent iterations.

3. Results and Discussion

The algorithm proposed has been tested in correcting the static characteristics of integrated strain gage pressure transducers of the D25 type. In this case, the measured input value and the influence parameter were pressure and temperature, respectively (Figure 1, b). In the calibration experiment, the main output value was the sensor measuring diagonal voltage and the additional output value was the sensor power diagonal voltage. The output voltages were converted to codes. The reference pressure and temperature values were set by the MP-600 deadweight tester with an accuracy class of 0.05 and the UT-15 thermostat (temperature was controlled by a mercury thermometer with an accuracy class of 0.1), respectively. The test experiment results are given in the table 1, where the pressure values are in kgf/cm², the temperature values are in deg. C, and the output values are in codes with the upper and lower values corresponding to the additional and main channel codes, respectively.

The conversion functions of each measuring transducer channel were determined according to [7] and approximated by second-order polynomials using the least square method. Then, using the conversion function parameters obtained for all calibration experiment points, the pairs of pressure and temperature values were determined based on the corresponding pairs of the converter output value codes. At each matrix point, the approximation errors were calculated for both the calculated and experimental values. The calculation results are summarized in the table (Figure 2, b) and indicated in the diagram (Figure 2, a). In the table, at the intersection of the input values, the upper and lower rows correspond to the temperature and pressure channel errors, respectively.

To illustrate the algorithm proposed, we artificially introduce an outlier in the calibration data matrix at a temperature of 35.3 °C and a pressure of 150 kgf/cm² for the pressure channel by changing the
We process the experimental data matrix (Table 1) considering the correction factors according to formula (2). As a criterion for terminating the iteration process, as an option, we adopt the difference of errors at the calibration data matrix nodes at two adjacent iterations, which is 0.001 %.

The resulting error values after the first, second, and last (fourth) iterations are given in the diagrams (Figure 3, a-c). The analysis of the diagrams shows that the reduced error values of the pressure channel decrease in the neighborhood of the artificially introduced outlier point, due to which we can assume that the adequacy of the conversion function mathematical model increases.

Using the parameters of the corrected conversion function of the measuring transducer in processing the initial input values (Table 1) gives the following approximation errors at the calibration data matrix nodes (Figure 4). It is seen that the reduced errors of the pressure channel do not exceed 0.01 %.

Table 1. A table of calibration results and calibration results with an outlier

| T, °C | Channel | P, kgf/cm² | A table of calibration results | A table of calibration results with an outlier: P, kgf/cm² |
|-------|---------|------------|--------------------------------|--------------------------------------------------------|
| 18.9  | N_T     | 33335      | 33384 33469 33587 33737 33925 34141 | 33335 33384 33469 33587 33737 33925 34141 |
|       | N_P     | 2090       | 8647 15199 21745 28281 34814 41343 | 2090 8647 15199 21745 28281 34814 41343 |
| 35.3  | N_T     | 38800      | 38855 38941 39057 39207 39389 39602 | 38800 38855 38941 39057 39207 39389 39602 |
|       | N_P     | 2463       | 8970 15472 21968 28458 34939 41418 | 2463 8970 15472 21968 28458 34939 41418 |
| 45.05 | N_T     | 42168      | 42223 42303 42418 42563 42740 42942 | 42168 42223 42303 42418 42563 42740 42942 |
|       | N_P     | 2687       | 9163 15639 22107 28563 35019 41469 | 2687 9163 15639 22107 28563 35019 41469 |
| 59.95 | N_T     | 47458      | 47514 47595 47710 47854 48019 48216 | 47458 47514 47595 47710 47854 48019 48216 |
|       | N_P     | 3016       | 9450 15885 22307 28722 35136 41546 | 3016 9450 15885 22307 28722 35136 41546 |

Figure 2. Diagrams of Reduced Errors: a) – reduced errors of the pressure channel at the calibration experiment points; b) - reduced errors of the pressure channel at the calibration experiment with an artificial outlier in data
Figure 3. The Results of Processing the Calibration Data Containing an Outlier: a) - the pressure channel errors after the first iteration; b) - the pressure channel errors after the second iteration; c) – the pressure channel errors after the last (fourth) iteration.

Figure 4. The Corrected Conversion Function Error without Outliers in the Initial Calibration Data

Thus, processing the calibration experiment data containing an artificial outlier according to the algorithm proposed allows obtaining the conversion function of a measuring transducer with an integrated sensor, which corresponds in its adequacy to that calculated based on the correct calibration results.

4. Conclusion

Thus, the paper proposes and justifies an algorithm for processing the calibration experiment results for measuring transducers with an integrated sensor, which allows obtaining the correct conversion function in the presence of random outliers (spurious errors) in the initial data. This algorithm has been tested in processing the calibration results of the integrated strain gage pressure transducers. It has been found that the conversion function obtained in the presence of random outliers in the calibration results corresponds in its accuracy to that obtained using the correct data.

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