Account of Temperature Change at Calibration of Air Flow Sensor

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Abstract

The article describes of temperature change consideration during the calibration of air flow sensor for a car engine. The sensor uses a blade made of elastic material with strain gauges applied to the front and the back surfaces, the deformation of which is measured and recalculated into a mass flow of air. They suggested the system of equations whose solution makes it possible to determine the mass flow rate and air temperature according to the known signal values at the measuring bridge output and the measuring circuit resistance. The coefficients of equation system are determined during calibration and then are recorded into the memory of the microcontroller sensor.

Key words: mass air flow sensor, temperature, least squares method, measuring circuit, calibration, strain gauge transducer.

1. Introduction

In modern control systems using electronic means of signal processing, the measured values at the system input are converted into equivalent electrical parameters (voltage, current, frequency) by the means of sensors. A sensor is a device that generates an equivalent signal at the output under the influence of the measured physical quantity. This signal is the function of the measured quantity: \( s = F(m) \), where \( s \) is the equivalent value at the sensor output, \( m \) is the value of the measured physical quantity at the sensor input (Kokoszyński, D. et al., 2002).

The issues of sensor and measuring path calibration were considered in a number of works. In the work (Vilop L.E., 2012; Książkiewicz, J. M., 2003) the autocalibration of electric value transformation channel was considered on a two-element simulator of an output electric value of the gauge in the measuring system with non-linear sensors. It was shown that when you use sensors with a nonlinear conversion function in a measuring system with an autocalibration according to the simulator of a sensor output electrical value with two measurement values, the calibration with the use of an external multivalued measure of the sensor output electric value at the range points is the mandatory procedure (Mazanowski, A. et al., 2001).

In work (Gritsenko A.V. et al., 2013) they provided the results of intellectual gauge model study using the method of self-diagnostics which is based on the use of transformation function nonlinear properties of a controlled device, and is realized by the analysis of an output signal noise component dispersion.

The article (Mosspan D.V. et al., 2014) deals with the development of pressure sensors with digital output and built-in self-monitoring of operability and the ability to perform calibration periodically during a device operation in real time, without the use of special reference tools.

By calibration we mean the process of signal obtaining (analog or digital one) at the output of a calibrated instrument, which, within the required accuracy, would be equal to the reference signals. They use industrial air flow meters as the source of reference signals. Based on the obtained results in the computer model of the air mass flow converter, it is proposed to use a deformation type of hydrodynamic sensor to measure the mass flow of air. The sensor operation is based on an elastic blade deformation measurement placed in the flow, which arises as a result of flow pressure on the blade surface. By the amount of deformation, the average flow velocity can be determined. The flow rate is defined as the product of the average flow velocity and the measured flow area. Therefore, the problem of new principle development for MAFS operation, as well as the methods for their calibration, remain urgent (Pingel, H., & Heimpold, M., 1983; Powell, J. C. 1992).


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digital correction methods is the auxiliary measurement of DC
temperature with the subsequent correction of air flow measurement
result according to predetermined formulas. In this paper, they
discuss a digital correction of the air flow sensor temperature error
for the abovementioned device.

In order to determine the DC temperature, one can use the
temperature dependence of DC bridge measuring circuit (MS)
resistance. In this case, the output signal and the resistance of DC
MS will be the functions of the flow rate $P$ and the temperature $T$:

$$U_{\text{out}}(P, T) = f_j(P, T), \quad R_m = f_j(P, T)$$  \hspace{1cm} (1)

However, in order to proceed to the calibration of the measuring
bridge from temperature, one must take into account the dependence
of air density on temperature and atmospheric pressure:

$$\rho(T) = \rho(0) \cdot (\frac{T}{T_0})$$

Here $B_0$ and $T_0$ - the atmospheric pressure and the calibration
temperature of the sensors. The temperature of the air drawn in from
the filter is controlled by a separate thermostat, the temperature of
the bridge may differ from the air temperature.

Having measured an output signal and the resistance of DC, and
having solved the system of equations (1), you can determine both
the required flow rate and the temperature of MS.

In order to determine the functional dependences of the output signal
and the resistance of bridge DC MS from the flow and the
temperature values, a standard flowmeter of high accuracy was used.
In the course of the experiment, the values of the output signal and
the resistance of DC MS at measured values of temperature and
fixed values of the air flow were measured and tabulated in the
reference data at a specially designed stand.

If the reference signals have a temporary instability, it is necessary
to average them in time, as well as the calibrated signal. In this case,
the approximation is carried out using the method of least squares.

Let us consider two methods for the statistical solution of equation
system (1).

Suppose that the experimental dependence of the output signal $U(T)$
on the flow rate with good accuracy can be described by a
polynomial of the second degree:

$$U_{\text{out}}(P, T) = U_0(T) + K(T) \cdot P + \delta(T) \cdot P^2$$  \hspace{1cm} (2)

where: $U_0(T)$ is the initial output signal of TP, $K(T)$ is the sensitivity
coefficient of the TP, $\delta(T)$ is the coefficient of TP load characteristic
nonlinearity, and $T$ is the temperature of the bridge sensors. These
coefficients are TP characteristics. In this case, the equation (2) can
be solved directly with respect to the consumption rate $P$.

Experimentally determined temperature dependences $U_0(T)$, $K(T)$ and
$\delta(T)$ are nonlinear ones and are approximated by the following
expressions:

$$U_0(T) = a_0 + a_1 \cdot T + a_2 \cdot T^2$$  \hspace{1cm} (3)

$$K(T) = b_0 + b_1 \cdot T + b_2 \cdot T^2$$  \hspace{1cm} (4)

$$\delta(T) = c_0 + c_1 \cdot T + c_2 \cdot T^2$$  \hspace{1cm} (5)

Thus, with an independent measurement of temperature, the
functional dependence of the output signal of the bridge DC MS on
the flow rate and the temperature has the following form:

$$U_{\text{out}}(P, T) = (a_0 + a_1 \cdot T + a_2 \cdot T^2) + (b_0 + b_1 \cdot T + b_2 \cdot T^2) \cdot P + (c_0 + c_1 \cdot T + c_2 \cdot T^2) \cdot P^2$$  \hspace{1cm} (6)

The temperature dependence of DC resistance on temperature is
non-linear one and can be represented by the following expression:

$$R_m(T) = d_0 + d_1 \cdot T + d_2 \cdot T^2$$  \hspace{1cm} (7)

The dependence of the bridge DC MS resistance on the flow rate is
negligible: when the flow rate changes from zero to maximum, the
resistance change is less than $10^{-3} \cdot R_m$ over the entire temperature
range.

Knowing the magnitude of the output signal and the resistance of
DC MS, and solving the system of equations (6) and (7) with respect
to the sought $P$ and $T$, we can determine both the flow rate and the
temperature of TP. In this case, when the equality of the TP temperature
and the measured medium is ensured, it is possible to obtain a sensor that simultaneously measures both flow and temperature.

An additional thermostat will allow for control and autocalibration.

In the case where only the flow rate is the sensor output signal, the
TP temperature value can be determined from (7) through the bridge
resistance value $T = f_2(R_m)$, so that the functional relationship of the
output signal with the flow rate will be described by the following
expression:

$$U_{\text{out}}(P) = (a_0' + a_1' \cdot R_m + a_2' \cdot R_m^2) + (b_0' + b_1' \cdot R_m + b_2' \cdot R_m^2) \cdot P + (c_0' + c_1' \cdot R_m + c_2' \cdot R_m^2) \cdot P^2$$  \hspace{1cm} (8)

Solving the equation (8) in a direct algebraic way with respect to the
quantity $P$, we obtain the following:

$$P = \frac{-(b_0' + b_1' \cdot R_m + b_2' \cdot R_m^2) \pm \sqrt{D}}{2 \cdot (c_0' + c_1' \cdot R_m + c_2' \cdot R_m^2)}$$

$$D = (b_1' + b_2' \cdot R_m + b_2' \cdot R_m^2)^2 - 4 \cdot (a_0' + a_1' \cdot R_m + a_2' \cdot R_m^2 - U_{\text{out}})^2 \cdot (c_0' + c_1' \cdot R_m + c_2' \cdot R_m^2)$$  \hspace{1cm} (9)

where: $a_0'^i, a_1'^i, b_0'^i, b_1'^i, c_0'^i, c_1'^i, c_2'^i$ — the coefficients that are found during
a sensor calibration.

The method of least squares allows to solve an inverse problem if it is
possible to select the function of airflow dependence on the output
signal of the bridge at a known sensor temperature. Instead of the
output signal, you can use a square root or a logarithm of this value
to cover a large range of the measured flow rate. In our case, square
root will be the most suitable one for the deformation sensor:

$$P(T, U_{\text{out}}) = A(T(R)) + B(T(R)) \cdot \sqrt{U_{\text{out}}} + C(T(R)) \cdot \frac{U_{\text{out}}}{2}$$  \hspace{1cm} (10)

Here $U_{\text{max}}$ — calibrated bridge indicators;
$R$ — bridge resistance.

Expanding the required flow rate depending on the polynomial of
the square root or the logarithm of an output signal, we find the
coefficients of the polynomial, which will be the functions of
temperature. This temperature dependence is either tabulated or
approximated by a polynomial whose parameters are stored in the
processor memory.

When you calibrate the microprocessor sensor, the values of the
output signal and DC MS resistance in (9) or (10) are replaced by the
corresponding N codes of the analog-to-digital converter (ADC).
In this case, when you find the coefficients, in addition to TP error, the
ADC error is taken into account additionally, which in its turn
improves the sensor accuracy additionally.

Figure 1 shows the block diagram of a sensor with a digital output,
in which the described method is implemented to determine the
value of the temperature-corrected flow value.
The flow rate \( P \) is converted to the voltage \( U_p \), taken from the diagonal of the bridge DC MS. This voltage is applied to one of ADC inputs to convert it to a code. In order to determine the resistance of DC MS a resistor is plugged in the power diagonal circuit, the resistor voltage drop \( U_R \) is fed to the second input of the ADC. \( N_p \) and \( N_R \) codes, corresponding to the \( U_p \) and \( U_R \) voltages are periodically read by a single chip microcontroller (MC). The latter, using the expression (9), calculates the required air consumption value corrected by temperature.

The received value of the flow can be read by the digital interface at any time. However, in the future, a signal is sent to the motor control system in the form of voltage or frequency. Therefore, the calibration result is the inverse dependence of the base signal on the calibrated signal. This relationship is remembered either by a matrix or by a polynomial, as in expression (6) or (10). As it was said before, the coefficients of equation (9) are determined during the individual calibration of the sensor and are stored in the energy dependent memory of MC data. The calibration procedure is the following one:

- Using the least-squares software, the coefficients of the polynomials used to correct the temperature error are calculated;
- Then these coefficients are put down to the energy independent memory of MC data via the digital interface.

The described technique allows to correct both basic and additional (temperature) errors of the additive, multiplicative and nonlinear character of all functional units of the sensor, and first of all - the strain-resistive converter.

3. Summary

The article describes the method of temperature change consideration during a mass air flow sensor calibration. The basis of the sensor is a blade made of an elastic material with applied strain gauges, the deformation of which is measured and recalculated into a mass flow of air. They proposed the system of nonlinear equations that allows one to determine the mass flow and air temperature based on known values of signal at the measuring bridge output and the measuring circuit resistance. It was shown that it is expedient to use the square root of the output voltage in the function of the air flow dependence on the output signal of the measuring bridge, which allows to cover a large range of flow variation. The coefficients of the polynomial, which act as the temperature functions, are selected during the calibration using the least squares method and then are recorded into the memory of the sensor microcontroller.

Conflict of Interest

The authors confirm that the presented data do not contain a conflict of interest.

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