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A numerical method for correcting the influence of the additional quantities for nonselective sensors

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Abstract - At present the modern sensors, based on the microelectronic, optoelectronic and bio-electronic technologies, are widely applied in various measuring systems. However, these sensors have often one essential disadvantage - wrong properties in metrological sense, mainly due to the poor selectivity and high sensitivity to the impact of the additional physical quantities. To apply such sensors in measuring transducers, for example in gas concentration transducers, effective methods of correction of these quantities influence are required.
An effective numerical method based on model with variable coefficients is described in this paper. An example of using this method for the simultaneous correction of influences both temperature and humidity for a gas concentration measuring transducer with Figaro TGS2442 carbon monoxide sensor is given.
Dispersion of measurement results due to the influence of these quantities, changing in a fairly wide range, is reduced about 11 times, from 64% to 6 % of range.

I. Nonselective sensors in measuring transducer

Contemporarily developed sensors have very wide possibilities of application in various fields, both to the measurement of physical quantities, and also to the measurement of chemical or biological parameters. Such sensors have essential advantages, e.g. the miniaturization, sensitivity on miscellaneous quantities, the possibility of application in multiparameter measurements (matrix sensors), simple integration with other parts of the measuring chain, low costs. On the other hand, the current condition of technology development does not allow obtaining sufficiently good properties of sensors in the metrological sense. Result of measurement obtained using such sensors without additional processing has often only qualitative character - it is not a precise value with known uncertainty. In the measuring applications as the main disadvantages the following are named [1..5]: strong nonlinearity of the response curve, sensibility not only to the main measured quantity, but to some additional physical quantities, which are not measured with intention (e.g. temperature, humidity, pressure), poor selectivity (particularly inconvenient in the case of chemical sensors) and changes of parameters resulting from ageing effects. In spite of efforts, in current level of the technology development these imperfections are often hard to correct only by optimization of the sensors construction. The correction in the next parts of the measuring chain (Fig. 1) is usually indispensable. In limited range it may be done by using a suitable primary electronic circuit (conditioning circuit) [eg. 6]. Much better results may be achieved by applying various advanced numeric or algorithmic methods, e.g. [7].

II. Structure of the measuring transducer with nonselective sensors

A measuring transducer is composed of sensor and additional elements. The typical structure of the measuring chain is shown schematically in Figure 1. The tasks carried out by elements of the transducer are as follows: converting by the sensor the measured value M in to its output signal or output parameter P, conditioning of it into output signal U, which is suitable for further processing and, at the end, calculation of the corrected result of measurement M^*. The sensitivity of sensor to influencing quantities $\boldsymbol{Q}$ is shown, too. Additional sensors are necessary for correcting the influence of the $\boldsymbol{Q}$ and, therefore, to calculate the correct measurement result.

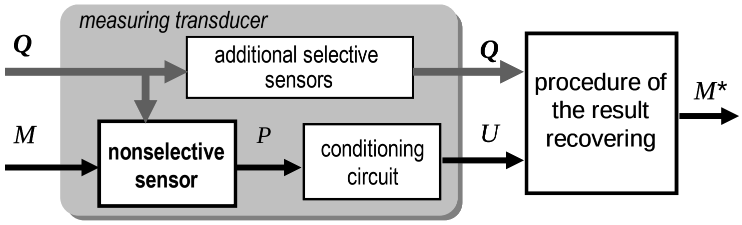

Figure 1. Structure of the measuring chain with the nonselective sensor

For a selective sensor the conversion of measurand M into signal U is described by response function $U=f_r(M)$. By inverting this function it would be possible to calculate the result of measuring $M^*=f_{ir}(U)$. In case of nonselective sensor a more complicated model is needed: $U=f_r(M, \boldsymbol{Q})$ and in consequence the inverted model $M^*=f_{ir}(U, \boldsymbol{Q})$ is more complicated, too. Correction of the influencing quantities is included in the inverted model. No one of these two named functions is usually known a priori. In practice they may be determined only approximately on the base of calibration procedure. The type of function is usually assumed and values of coefficients are calculated using calibration data.

III. Correction method based on model of inverted response function

The "procedure of the result recovering" in conditions of other quantities influence has to be based on the inverted model f_{ir}. Form of the inverse response function for nonlinear sensors is usually assumed as a linear combination of a number of nonlinear base functions $f_i(U)$. For the power type base function the polynomial is obtained:

$$M^* = f_{\mathrm{ir}}(U) = \sum_{i=0}^{I} a_i f_i(U) = \sum_{i=0}^{I} a_i U^i \,, \tag{1}$$

where a_i are a constant coefficients, I is the order of polynomial and I+1 is the number of constant coefficients a_i, which should be determined. Such model is usually not precise enough, because it does not take into account the additional influencing quantities $\boldsymbol{Q}$. It may be useful only if measurements are done in so called "nominal conditions", which means fixed values of $\boldsymbol{Q}$. This is rarely acceptable in practice.

As the research of various types of sensors shows [1,2,8], their response curves obtained at different conditions (values of influencing quantities) are deformed in relation to the response curve assumed as a nominal one. In simple cases they can only be moved (the additive effect) - a correction is made by addition an amendment depending on actual values of $\boldsymbol{Q}$. In other cases, the slope of response curve may change (the so-called multiplicative effect) - the correction is based on multiplying (1) by an adequate factor. In most cases, however, the bending of response curve occurs (as it is visible in example on Fig. 2a). In this case, each of the coefficients a_i of model (1) must be corrected in various degrees, depending on the current values of influenced quantities. An extended model may be described by the following formula:

$$M_c^*(U,\boldsymbol{Q}) = \sum_{i=0}^{I} \left[a_i(\boldsymbol{Q}) \cdot U^i \right]. \tag{2}$$

It is relevant that all coefficients a_i in this model are functions of the N influenced quantities $\boldsymbol{Q}=[Q_1, \ldots Q_N]$ as it is for example ilustrated in Fig. 2b.

Determination of a function $a_i(\boldsymbol{Q})$ is possible on the basis of data obtained in the calibration process, run by changing the values of influence quantities $\boldsymbol{Q}$. However, the method of determining these functions can be onerous and time consuming. With such a notation of the model (2) the calculation is difficult to formalize, it should be instead develope a suitable algorithm for processing calibration data.

The use of this model to calculate the measurement result in the "procedure of the result recovering" is performed in two steps. In the first step, based on the results of quantities $\boldsymbol{Q}$ measurement, the actual values of the model coefficients $a_i(\boldsymbol{Q})$ are calculated. In the second step, using this coefficients the measured value M^* is calculated according the formula (2).

Assuming the form of a polynomial for $a_i(\boldsymbol{Q})=b_0+b_1Q_1^1+b_2Q_2^1+ b_3Q_1^1Q_2^1\ldots$ and doing all the multiplications, the model (2) can be converted into a more convenient form, both in the tranducer calibration process and the calculation of measurement results. It is the following vectorial equation:

$$M^*(U,\boldsymbol{Q}) = \sum_{k=0}^{K} b_k Y_k = \boldsymbol{bY}^{\mathrm{T}}, \tag{3}$$

where $\boldsymbol{b} = [b_0 \ldots b_K]$ is the vector of constant coefficients of the model and $\boldsymbol{Y} = [Y_1 \ldots Y_K]$ is a vector of auxiliary variables Y_k calculated by multiplying the values of U^i and Q_n^j, current at the moment of measurement. It is done in the following way:

$$Y_k = \prod_{(i,j,n)} U^i Q_n^j, \qquad \text{e.g. } Y_0 = U^0 \prod_{(n)} Q_n^0 = 1,\quad Y_1 = U^1 \prod_{(n)} W_n^0,\quad Y_2 = U^1 \prod_{(n)} W_n^1 \quad \text{etc.} \tag{4}$$

The coefficients $\boldsymbol{b}$ can be easily determined from the data obtained during the calibration of the transducer, using linear regression to the relation (3), as this expression is a linear function of the auxiliary variables Y_k (resulting from the U and $\boldsymbol{Q}$). This method allows performing the calculation of the measurement result in one-step calculation. The proposed above method is illustrated in the example given in the next section.

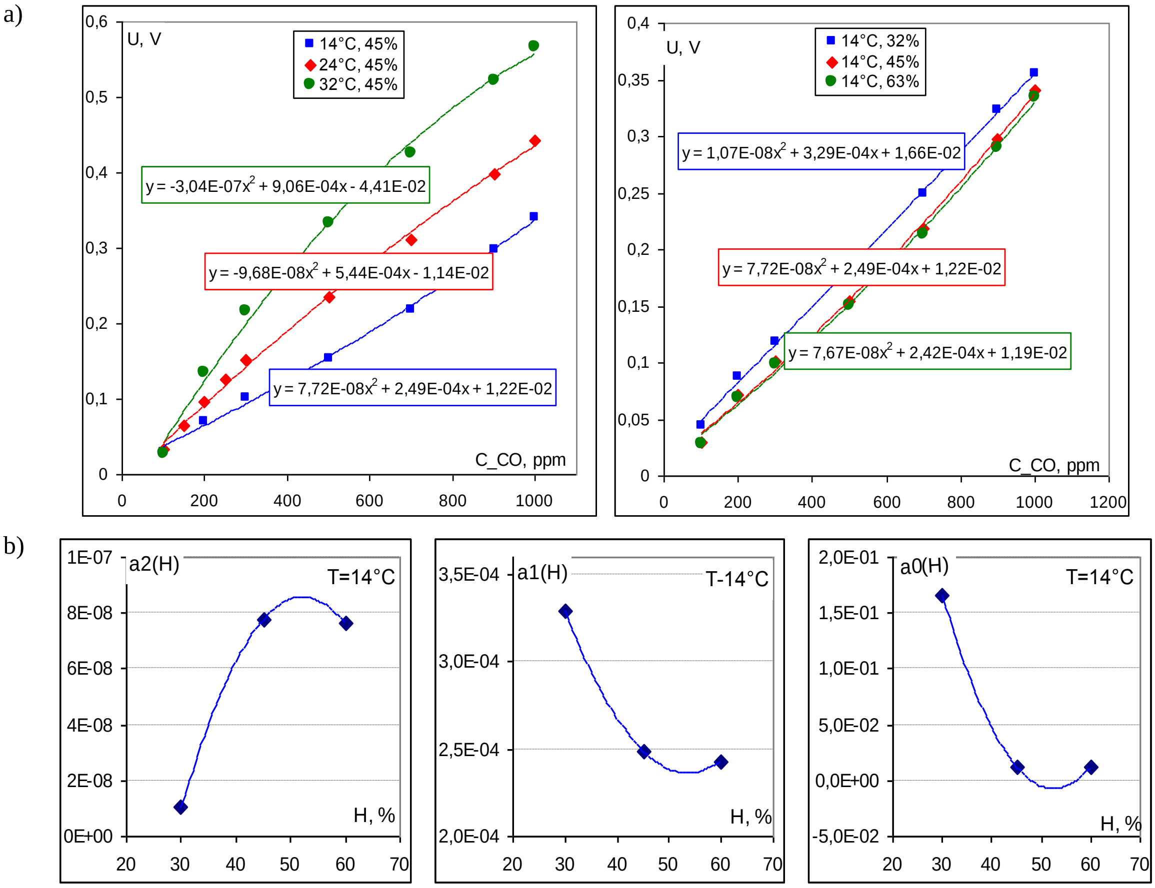

Figure 2. Example of the response curve shape changes (a) caused by temperature and humidity influence for the carbon monoxide concentration measuring transducer [8]
and example of the model coefficients changes (b).

IV. Example of application of the presented method

Effectiveness of the correction method described above was checked in application to the transducer designed to measure the concentrations of various gases in the gas mixture, which is described in detail in [8]. For the measurement of carbon monoxide the TGS2442 Figaro sensor, equipped with a suitable conditioning system, was used. The voltage U forms an output signal. This sensor is also (to varying degrees) sensitive to influence of temperature T and relative humidity H of gas mixture, as is illustrated by the response curves shown in Fig. 2. In order to allow the correction of these influences the transducer is equipped with an additional calibrated sensor

SHT75 for temperature and humidity measurement.

Calibration of the transducer for carbon monoxide was performed in 27 points (for three different concentrations, at three different temperatures and humidities). Values were chosen to cover a broad range of changes expected in the operation of the transducer. For the approximation of the inverted response curve a polynomial model of the form (2) and the second degree was adopted. Also the dependence of coefficients a_i on temperature and humidity was expressed as a polynomial of second degree in the following form:

$$a_i(\boldsymbol{Q}) = a_i(T,H) = \sum_{j=0}^{5} b_{i,j} T^k H^l; \quad k = 0,1,2; \quad l = 0,1,2; \quad \text{and} \quad (k+l) \le 2 \quad . \qquad (5)$$

$$a_i(T,H) = b_{i,0} + b_{i,1}T + b_{i,2}H + b_{i,3}TH + b_{i,4}T^2 + b_{i,5}H^2$$

As a consequence from equation (2) we obtain the expression:

$$C(U,\boldsymbol{Q}) = \sum_{i=0}^{2} \left(b_{i,0} + b_{i,1}T + b_{i,2}H + b_{i,3}TH + b_{i,4}T^2 + b_{i,5}H^2\right)U^i = \boldsymbol{bY}^{\mathrm{T}} \quad , \qquad (6)$$

which is a linear vactorial equation,

where $\boldsymbol{b}$ = $[b_{1,0}\ b_{1,1}\ b_{1,2}\ b_{1,3}\ b_{1,4}\ b_{1,5}\ b_{2,0}\ b_{2,1}\ b_{2,2}\ b_{2,3}\ b_{2,4}\ b_{2,5}\ b_{3,0}\ b_{3,1}\ b_{3,2}\ b_{3,3}\ b_{3,4}\ b_{3,5}]$ is the vector of constant coefficients of the model , and

$$\boldsymbol{Y} = [1\ T\ H\ TH\ T^2\ H^2\ U\ TU\ HU\ THU\ T^2U\ H^2U\ U^2\ TU^2\ HU^2\ THU^2\ T^2U^2\ H^2U^2] \qquad (7)$$

is the vector calculated for the actual (in the moment of measurement) values of the output voltage U, the temperature T and the humidity H.

Values of the model coefficients can be calculated using a linear regression method on the data obtained in the calibration process for the selected valuse of gas concentration C_c, temperature T_c and humidity H_c as:

$$\boldsymbol{b} = (\boldsymbol{Y}_c \boldsymbol{Y}_c^{\mathrm{T}})^{-1} \boldsymbol{Y}_c \boldsymbol{C}_c \, , \qquad (8)$$

Vector Y_c is calculated according to equation (7).

The effectiveness of the temperature and humidity influence correction for the tested transducer by applying the described method is illustrated in Fig. 3.

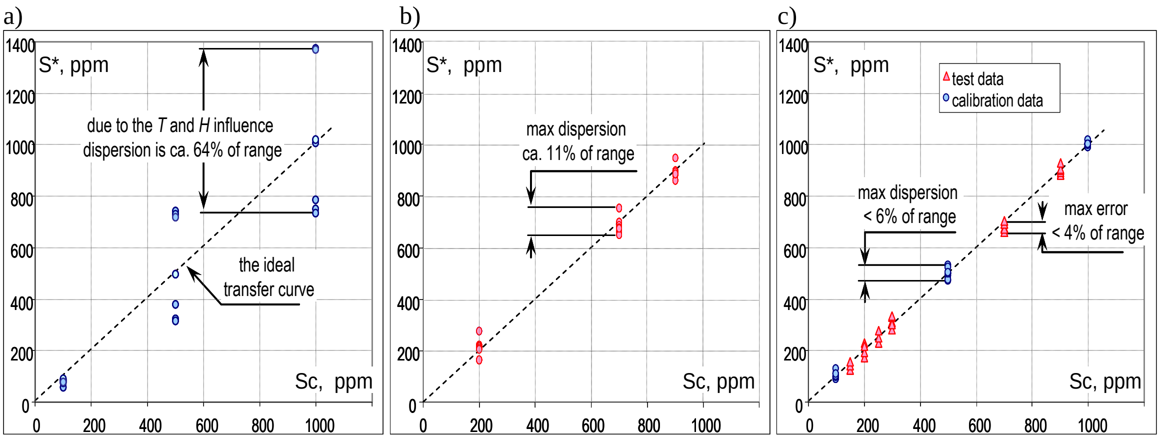

Figure 3. Example of the effectiveness of influence correction; results without correction (a), with only temperature correction (b) and with both temperature and humidity correction (c)
C is the gas concentration (measurand), *C** are the non-corrected (plot a)) or corrected results (plots b and c)

Figure a) shows the measurement results obtained on the basis of the simple inverse model with constant coefficients in the general form (1). The coefficients a_i, were calculated for assumed nominal values of temperature and humidity (24°C, 45%, the middle curve in Fig. 2a). As it is visible there is a strong sensitivity to the influence of temperature and humidity - dispersion of reaches 64% of the measuring range. Such results of measurement should be rather regarded as worthless.

Correction was made based on the model in the general form (3) equivalent in this case to (6), taking into account both temperature and humidity. The dispersions of results is in this case about 11 times reduced and do not exceed 6% and the maximum error is less than 4% of range. For comparison, shows the results early obtained with the use of analogous method, but only for a temperature correction [9]. In this case, only approximately 6-fold reduction of dispersion is achieved, although it is clear from Figure 2a, that the influence of humidity on the transducer's response curve is much weaker than this one for the temperature.

V. Conclusions

Due to the properties of sensors, simple correction methods of the additional influences on the result of measurement based on a model with constant coefficients are not always effective enough. The correction method described in this paper based on the model with variable coefficients is relatively easy to implement in terms of complexity of the computation algorithm. The calibration procedure is not very laborious and determination of the model coefficients is simple. Although the traditional approach, the efficiency correction can be very high.

The efficiency of the proposed method was confirmed with regard to a carbon monoxide sensor, which was described in the above given example. A significant (11-fold) reduction in the influence of temperature and humidity was achieved. Theoretically, further increasing the effectiveness of correction could be possible by better matching both, the base model (formula (3)) and models describing the influence of additional quantities (formula (4)), using higher-order polynomials. However, this leads to increasing the laborious of the calibration procedure, due to the need for a larger number of calibration points in the range of changes of all determinants C_c, T_c, H_c.

In practice however, further reducing the dispersion of results is difficult due to another reason - uncertainty of the calibration data. The standard gases concentrations in the mixture were fixed by using mass flow controllers. It was possible to achieve the concentration's uncertainty not less than about 2% of their values. Uncertainty in humidity and temperature measurement using additional sensors were estimated at the level of 1% each, while the uncertainty of the sensor's parameter conversion into output voltage and measuring the voltage was at about 0,5%. As a result, the final uncertainties of vector $\boldsymbol{Y}$ components increases strongly with increasing degree of the polynomial and therefore the efficiency of correction can not be improved.

The a priori assumed models in the form of polynomials might be not exactly matched to the actual processing functions of the transducer. Application in the model (2) of some (byt not any) others functions instead the power type ones as base functions is also possible in this method. In that case, a vectorial notation can also be created, corresponding to (3). The method of calculation of the vector $\boldsymbol{b}$ elements, based on equation (8), remains the same. Only the method of calculating elements of the vector $\boldsymbol{Y}$ must be appropriately modified. The use of other types of base functions will be the subject of further work.

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