

DIGITAL SIGNAL PROCESSING ALGORITHMS FOR GAS CONCENTRATION MEASUREMENT

B. Baraboi, M. Crețu, C. Donciu, C. Foșalău

Department of Electrical Measurements, Faculty of Electrical Engineering
Bd. D. Mangeron 53, Iași, 6600, Romania
Phone (40) 32278680 Fax (40) 32237627 e-mail: bbaraboi@ee.tuiasi.ro

Abstract - The paper presents two signal processing algorithms for continuous measurement of gas concentration using low cost metal oxide semiconductor sensors. A major limitation of these sensors in quantitative analysis of gases is their non-linearity. A good solution of this problem is to combine these sensors with appropriate signal processing techniques. The first algorithm that we developed is based on artificial neural networks. As the second option, we constructed a model based on the characteristic formula of metal oxide semiconductor sensors. A detailed analysis of the developed algorithms and a comparison between them is presented in the paper.

Keywords - quantitative gas analysis, metal oxide semiconductor sensors, digital signal processing, virtual instrumentation

1. INTRODUCTION

There are many environmental applications that require inexpensive, compact systems for quantitative analysis of combustible or toxic gases such as hydrogen, methane, oxygen, carbon monoxide. Actually, the interest is focused on the development of smart measurement systems based on the combination of simple chemical sensors and complex signal processing techniques [1,2,3].

Semiconductor gas sensors have excellent performances in terms of sensitivity, reliability, and cost. However, their use is still a research area due to the problems that these sensors present: non-linearity, non-specificity, temperature and humidity dependency. We illustrate that by using appropriate data processing tools, the performance of these sensors may be significantly improved.

The goal of our work is the development of some signal processing algorithms in order to perform quantitative gas analysis with metal oxide semiconductor sensors. A Taguchi-type sensor with good sensitivity and selectivity to hydrogen was used in the practical experiments. Because of its non-linear characteristic, this sensor is dedicated only for the detection of a preset level of gas concentration. In this paper we present the results obtained by two signal processing algorithms for continuous measurement of gas concentration. At the same time we treated the problem of ambient temperature influence on sensor characteristic. The architecture of the test system and a comparison between the two algorithms are described in the paper.

2. GAS SENSOR TEST SYSTEM

A gas analysis system was integrated in our laboratory to calibrate and test the two measurement algorithms. The experimental platform combines the specific components of a virtual instrumentation system and the gas analysis equipment (Fig.1).

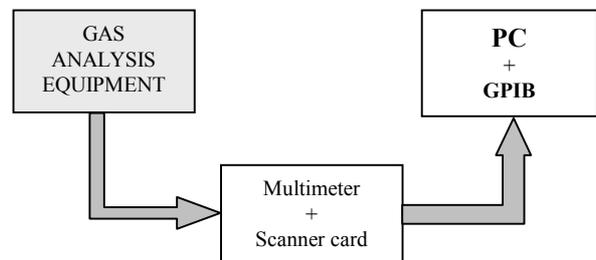


Fig.1 – Block diagram of the experimental platform

The signal processing and display functions are implemented into a PC - based system, designed as a virtual instrumentation platform, including hardware based on programmable devices and GPIB interface and a software component developed in LabVIEW graphical programming language.

The gas analysis system is mainly composed of a gas sensor and a temperature sensor placed in a special designed gas chamber (Fig.2). High purity gas cylinders ($\geq 99.995\%$) are used for calibration and test. The analyzed gas is supplied to sensors using a static gas mixture, by injecting it in the gas chamber using a syringe and a gas bag. A mixing fan located inside the chamber is switched on for 30 seconds to improve the quality of the mixture.

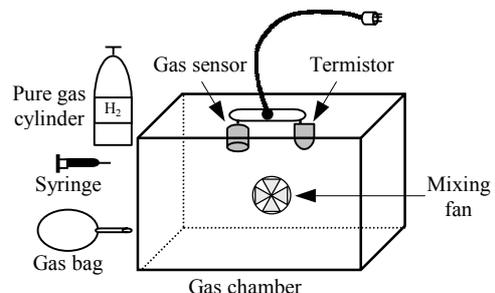


Fig.2 – Gas analysis equipment

The gas sensor that we used in experiments is TGS821, produced by Figaro Engineering Inc [4,5]. The detection principle of Taguchi-type sensors (TGS) is based on chemical adsorption and desorption of gases on the sensor surface. The sensing element is a tin dioxide (SnO_2) semiconductor that is heated at a suitable operating temperature by a built-in heater. In clean air, oxygen molecules tie up free electrons in the semiconductor material by absorbing to its surface, thereby inhibiting electrical flow. In the presence of a detectable gas, the tin dioxide surface adsorbs these gas molecules and causes oxidation, releasing free electrons and decreasing the sensor resistance. This change in resistance is measured electrically and depends on the gas concentration.

The TGS 821 has high sensitivity and selectivity to hydrogen gas. Fig.3 represents a typical sensitivity characteristic in that the Y-axis is indicated as the ratio of sensor resistance at various concentrations of gases (R_s) to the sensor resistance at 100ppm of hydrogen (R_0).

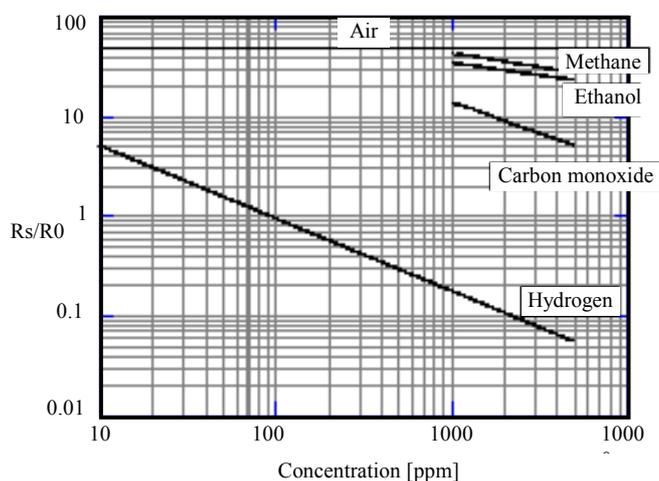


Fig.3 – Sensitivity characteristic of TGS 821

The relationship between sensor resistance and gas concentration is based on a logarithmic function, so it appears as linear on a logarithmic scale.

The sensitivity characteristics of semiconductor type gas sensors are altered by change in atmospheric temperature and humidity. To compensate for this variation in sensor performance, a negative characteristic termistor is disposed in the proximity of gas sensor (5KD-5 termistor, produced by Ishizuka Elec. Co.).

The changes in electrical resistance of the two sensors represent the outputs of the gas analysis system. The signals from the gas and temperature sensors are successively transmitted to the computer (PC) using a digital multimeter and a scanner card (Keithley 2000 type). LabVIEW virtual instruments monitors and controls the programmable devices by means of GPIB interface and also performs the digital signal processing of the acquired signals [6].

Two applications were developed in the LabVIEW environment, giving to our system flexibility, efficiency, and

a user-friendly graphical interface. The first virtual instrument (VI) is designed for the calibration and characteristics estimation of the used gas sensor (TGS 821). During this stage, various known concentrations of the target gas (hydrogen) are presented to the sensor, at different temperatures. Using a representative data set, the sensitivity characteristic and the temperature dependency of the gas sensor are experimentally established. In the second VI we have implemented the signal processing functions for continuous measurement of gas concentration. Using this VI, we can test the two quantitative analysis algorithms that we developed, performing on-line gas concentration measurement with temperature compensation, display and analysis of results.

3. SIGNAL PROCESSING ALGORITHMS

In order to ensure the better performance of the new generation of gas detectors, the special attention is put on the improvement of signal processing tools. As a result of our work carried out toward this subject, we present here two signal processing algorithms developed for continual measurement of gas concentration using metal oxide semiconductor sensors.

3.1 ANN-based algorithm

First, we analyzed a model that uses the function approximation ability of artificial neural networks (ANN) [7]. The prototyped ANN was constructed as a multilayer feed-forward network and was trained with the Levenberg-Marquardt algorithm. The structure of ANN is single input-single output, with one hidden layer. The input neuron is fed the R/R_0 resistance ratio values of TGS 821 gas sensor, obtained in the calibration stage. The output of ANN represents the corresponding values of hydrogen concentration. All neurons in the hidden layer have tangential activation function, while the output neuron is linear.

The ANN has been trained with 20 input/output pairs and it has been validated with 7 input/output pairs, all of them corresponding to hydrogen concentrations in the range 50ppm-5000ppm at the same ambient temperature (23°C). The numerical values of ANN input and output signals were normalized, being restricted to the range (0,1). The number of hidden neurons of the ANN has been adjusted experimentally to obtain the best accuracy of function approximation. Too high number of neurons in the hidden layer results in bad approximation ability of the network, while too low number makes the learning process stops on too high level of error. The experiments of learning different structures of ANN have shown that the optimal number of hidden neurons is $N=8$.

The results of gas sensor characteristic approximation are very satisfactory, as shown in Fig. 4. One can see that the validation points (*) are very close on the calibration curve.

The artificial neural network was designed and trained using Matlab 5.3 software.

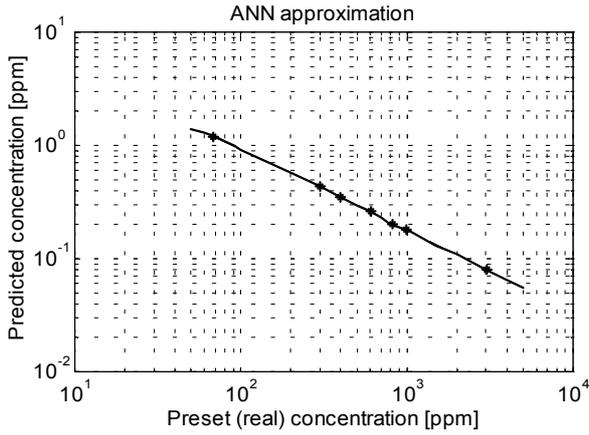


Fig.4 – ANN approximation of gas sensor characteristic

After training and validation, the obtained values of ANN parameters (weights and biases) are frozen and then used to implement the neural network algorithm in the LabVIEW virtual instrument.

To reduce the ANN complexity and to facilitate the better approximation of sensor sensitivity characteristic, the temperature compensation function was not included in the neural processing algorithm. Using the thermal dependence characteristic of TGS 821 gas sensor, obtained in the calibration stage, a temperature compensation algorithm was implemented into a LabVIEW subVI. Linear-relationships $R_s(T)$ can be approximately obtained using four temperature intervals: 0-12°C, 13-23°C, 24-33°C, 34-40°C. When measuring the temperature in a particular region of the characteristic, the specific slope for that interval is employed in the calculation of the compensation factor: $k=R_0/R_s$. Using of this scheme increases the efficiency in the compensation of ambient temperature influence.

3.2 Formula-based algorithm

The second algorithm that we developed is based on the characteristic formula of metal oxide semiconductor sensors. The relationship between the sensor resistance and the concentration of detected gas can be expressed by the following equation:

$$R_s = A \cdot [1 + \alpha(T - T_0)] \cdot C^{-B} \quad (1)$$

where R_s is the electrical resistance of the sensor, A is a sensitivity constant, α is the temperature dependence coefficient, T is the actual ambient temperature, T_0 is the reference temperature (23°C), C is the gas concentration, and B is the slope of characteristic curve.

The idea is to calculate the three parameters (A , α , and B) in order to use (1) for continual measurement of gas concentration. For this purpose, three temperature/concentration pairs were used in the calibration stage of this model: two different gas concentration at the reference temperature ($T=T_0$) and a gas concentration at another temperature ($T \neq T_0$).

The calibration process requires the following two steps:

- Sensor resistance measurement (R_s) for two different concentrations (1000ppm and 4000ppm) at the reference temperature ($T=T_0=23^\circ\text{C}$). Solving a two-equation system with two unknown parameters, we can calculate B and A factors.
- Sensor resistance measurement (R_s) for one fixed concentration (3000ppm) at a different temperature ($T=30^\circ\text{C}$). The value of the parameter α is calculated in this step.

Once the three parameters are established, the value of the gas concentration can be easily calculated measuring the sensor resistance and using the following formula:

$$C = 10^{\frac{\log \frac{R_s}{A[1+\alpha(T-T_0)]}}{B}} \quad (2)$$

A LabVIEW subVI has been designed to implement (2), performing on-line measurement of gas concentration in the testing stage of this model.

4. EXPERIMENTAL RESULTS

Using the gas analysis system, the two developed methods have been tested on a set of 20 samples of hydrogen with concentrations in the range 50ppm-5000ppm, in the same conditions of temperature and humidity. A LabVIEW VI was designed to perform on-line gas concentration measurement with both methods at the same time.

The real errors as differences between the preset and predicted concentrations were calculated to assess the accuracy of the two models. These results are presented in Fig. 5.

As it is seen, for both algorithms the real errors expressed in ppm stay on a reasonable level and are acceptable from the practical point of view. The maximum error did not exceed the value of 28 ppm in the case of ANN-based algorithm and 45 ppm with the formula-based algorithm.

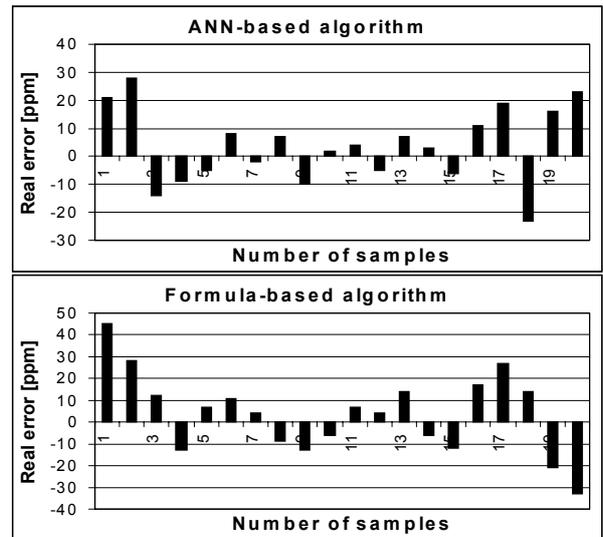


Fig.5 – Real errors obtained for the two algorithms

To make a more eloquent comparison between the two models, we have calculated the mean absolute errors expressed in percentage (MAPE) using the following formula:

$$MAPE = \frac{1}{m} \cdot \sum_{i=1}^m \frac{|Cp^{(i)} - Cr^{(i)}|}{Cr^{(i)}} \cdot 100[\%], \quad (3)$$

where m is the number of measurements ($m=20$ in the testing stage), Cp is the predicted concentration of gas, and Cr is the real (predicted) value of the concentration.

The MAPE confirmed the better performance of the ANN-based algorithm in terms of measurement accuracy. In the same testing conditions, the MAPE for the ANN-based model was 6.68%, while for the formula-based model was 9.05%.

The ability of the two models to reduce the influence of ambient temperature on the measured gas concentration has been also investigated in the testing stage. For this purpose, one fixed hydrogen concentration has been measured in 5 different atmospheric temperatures in the range 0°C-40°C. The results that we obtained are satisfactory from the practical point of view. The calculated MAE (mean absolute error) was 46 ppm using the ANN-based algorithm and 83 ppm using the formula-based algorithm.

5. CONCLUSION

The development of low-cost smart gas detectors based on metal oxide semiconductor sensors is one of the actual preoccupations with applications in the area of environmental monitoring. The research is focused on the improvement of sensor performance in gas concentration measurement by means of signal processing techniques.

In our work presented here the special attention is put on two critical points: sensor non-linearity and temperature effects. We have developed two signal processing algorithms that enable to continuously measure the gas concentration, avoiding the influence of atmospheric temperature. The first algorithm is based on the performance of ANN in function

approximation. The second model uses the characteristic formula of the semiconductor sensor response.

A virtual instrumentation-based gas analysis system, implemented in our laboratory, has been used to calibrate and test the two models.

The obtained results have shown that both developed algorithms can be used to accurately measure the gas concentration at any time. The ANN-based algorithm is a more precise model, but the number of calibration points is higher than in the formula-based algorithm and also the implementation of such a model in practice is more complex.

The experiments have been carried out for a particular gas sensor (Figaro TGS 821, for hydrogen), but the proposed methods can be applied to other types of semiconductor gas sensors.

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