

IMPEDANCE MEASUREMENT MODULE FOR GAS SENSORS WITH TEMPERATURE CONDITIONING FEATURE

*Grzegorz Lentka*¹, *Jakub Mróz*²

¹Gdansk University of Technology, Gdansk, Poland, lentka@eti.pg.gda.pl

²Gdansk University of Technology (student), Gdansk, Poland, jakmroz@pg.gda.pl

Abstract – The paper presents an impedance measurement module which is aimed for gas sensor. Sensor's heater temperature conditioning and modulation feature is available in order to allow implementation of different techniques improving selectivity and sensitivity of gas sensors. The measurement module uses three-parameter sine-fitting technique for impedance measurement. To monitor sensor temperature, the resistance of the sensor's heater is measured while continuously maintaining temperature control with the aid of PID regulator.

Keywords: gas sensors, impedance spectroscopy, impedance measurement, sine-fitting, digital signal processing

1. INTRODUCTION

Nowadays, the environmental protection has more and more greater impact. One of the most important factors influencing the environment degradation is an emission of air pollutants arising during manufacturing processes. Traditional methods for air contents are based on chemical or optical analysis which is expensive and time-consuming.

Gas sensors (electrochemical or semiconductor) are one of the alternative solution. As an example, the system for detection of air contaminants based on gas sensors made of low thickness layer of polycrystalline tin dioxide (SnO_2) [1] can be recalled. The system allows monitoring a concentration of gases assumed as dangerous for environment (NH_3 , CO, R113 and R22 freons). Another important application area of gas sensors is detection of flammable and explosive gases. Due to increasing usage of LNG and LPG, the number of incidents caused by gas leakage (and possible explosions) has increased. This situation led to research works aimed to develop low-cost system for monitoring of explosive gases concentration [2].

All the above presented systems are based on gas sensors made of thin layer of metal oxide. In order to determine specified gas contents in the mixture, it is necessary to detect the change in the sensor's resistance. Unfortunately, most of gas sensors react also with other gases than required. To differentiate gases, it is worth to measure not only the resistance of the sensor, but also the sensor's impedance. Another technique used to improve selectivity as well as sensitivity of the sensor is to modulate the sensor temperature and to analyse its response to gases mixture as a function of the temperature (or temperature change) [3].

In the paper, we propose the impedance measurement module based on a single microcontroller which simultaneously measures gas sensor impedance (using sine-fitting technique) and controls sensor's temperature by PID controller means. The sensor's heater resistance is measured to get the sensor's temperature.

2. MEASUREMENT MODULE ARCHITECTURE

The architecture of the impedance measurement module was presented in Fig. 1.

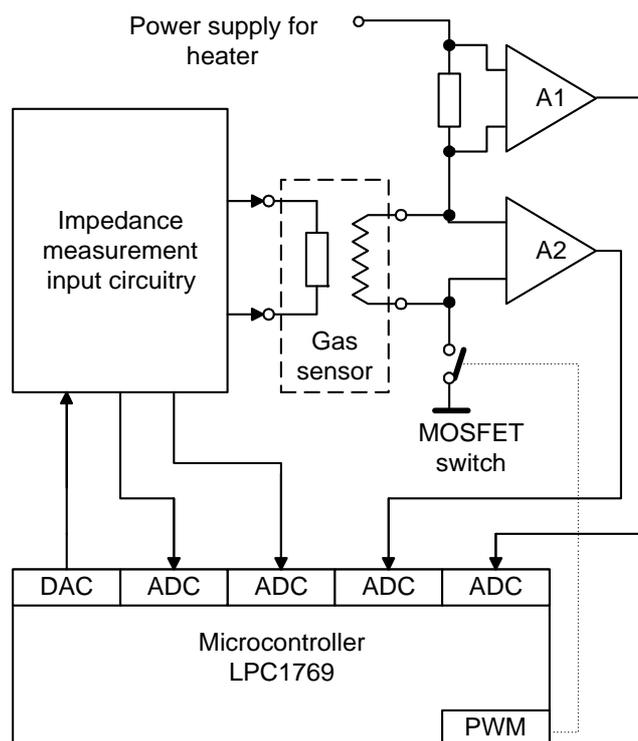


Fig. 1. Impedance measurement module architecture

The developed measurement module is characterised by the following features:

- measures gas sensor impedance in a wide frequency range (to easily adapt to different gas sensors),
- impedance measurement is based on technical method using sine-fitting algorithms to find orthogonal parts of measurement signals,

- setting temperature of the sensor (as a constant value as well as an arbitrary shape thermal profile),
- PC communication via USB interface,
- low-cost and low power consumption.

The main part of the measurement module is LPC1769 microcontroller based on Cortex-M3 core [4]. Built-in USB interface was used to communicate the device with PC using simple HID (Human Interface Device) implementation due to small amount of data to be transferred at a time (programming data to set the measurement sent to the device or measurement results sent to PC).

Only a few additional analog integrated circuits (operational amplifiers and switches) are used to make sensor signal conditioning.

The module concurrently performs two main tasks: the sensor impedance measurement for the required measurement frequency and the sensor temperature control.

2.1. Sensor impedance measurement

To connect the sensor for impedance measurement an input circuit similar to presented in [5] was used. The input circuitry makes possible supplying the sensor with sinusoidal excitation signal and extracting two signals proportional to current through and voltage across the sensor.

Excitation signal is produced by the microcontroller using internal digital-to-analog converter (DAC) with the aid of DMA (Direct Memory Access) controller. Dedicated DMA channel sends samples of excitation signal in selected time moments. In the first prototype excitation signal was assumed to be single sine signal, but finally multi-sine signal is planned to allow single-shot measurement of the impedance spectrum in the required frequency range.

Extracted sensor response signals are sampled with the aid of two channels of internal analog-to-digital converter (ADC). Signal samples are collected in the internal memory buffer and after acquisition of the required number of samples, the sine-fitting algorithm [6, 7] is performed to find amplitudes and phase shifts of both signals. The three-parameter algorithm was chosen due to smaller memory requirements and shorter execution time. In the implementation of the three-parameter sine-fitting algorithm the CMSIS 2.0 DSP library optimised for ARM Cortex-M3 core was used.

Finally, using the definition and the vector values of the sensor current and voltage, the parameters of the sensor impedance (modulus and argument) can be calculated for the actual measurement frequency.

2.2. Sensor's heater temperature control

The temperature control part of the module can be analysed as a combination of two subparts.

The first subpart consists of two amplifiers A1 and A2 and two channels of internal ADC. Amplifier A1 measures the voltage across a small resistance connected in series to sensor's heater thus allowing to measure sensor's heater current while amplifier A2 measures voltage across the sensor's heater. Combining those two parameters, the heater resistance can be calculated. Using manufacture's datasheet information or making own calibration [8], the dependence

between the sensor's heater resistance and the sensor temperature can be found. Finally, the sensor temperature can be determined.

The second subpart of the temperature control part is based on supplying the sensor's heater with PWM signal with the aid of low resistance MOSFET switch. When changing PWM duty cycle, the amount of energy supplied to the sensor's heater can be changes and as a result the temperature of the sensor also can be changed. In order to regulate the temperature, the software implementation of PID has been used.

2.3. PID controller implementation

Let make the following assumptions:

$u(t)$ – output signal of PID controller (in this case PWM duty cycle) given to the object (the sensor's heater);

$y(t)$ – the object response (the sensor temperature);

$r(t)$ – ordered value (required temperature – can be a constant value or arbitrary waveform in case of temperature modulation);

$e(t) = y(t) - r(t)$ – error (difference between actual and ordered value of temperature);

the PID controller can be described (for continuous time):

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (1)$$

where: K_p , K_i , K_d – gain of proportional, integral and differentiating part of the PID controller, respectively.

Using discrete time and using approximation for integral and differentiating operations, instead of (1) we can write:

$$u[n] = K_p e[n-1] + K_i \sum_{j=-\infty}^{n-1} e[j] T_p + K_d \frac{e[n] - e[n-1]}{T_p} \quad (2)$$

where: T_p – sampling period.

Writing the formula (2) for $u[n-1]$ and calculating the difference between them, finally, it can be written:

$$u[n] = u[n-1] + A_0 e[n] + A_1 e[n-1] + A_2 e[n-2] \quad (3)$$

where:

$$A_0 = K_p + K_i T_p + \frac{K_d}{T_p}; \quad A_1 = -(K_p + 2 \frac{K_d}{T_p}); \quad A_2 = \frac{K_d}{T_p}.$$

In this form (3), the PID controller can be treated as a digital filter (with A_0 , A_1 , A_2 coefficients) and simply implemented. The proposed PID controller algorithm was presented in Fig. 2.

After initialisation, the main loop of the PID controller samples ADC channels to get the values of sensor's heater voltage and current, then the heater resistance is calculated and, as a result, the heater temperature is determined. The dependence of the heater temperature on the heater resistance is stored as a look-up table which can be different for different sensors. In the next step, the temperature error is calculated and PID formula is evaluated to refresh the PWM duty cycle.

When the required temperature should be constant it can be given as a single value, but when the temperature should

change according to arbitrary shape, it should be stored as samples of an arbitrary waveform. In this case, an additional timer (with much smaller frequency than PWM) is used to change the momentary value of the ordered temperature for the main loop of the controller by selecting appropriate values from the waveform table.

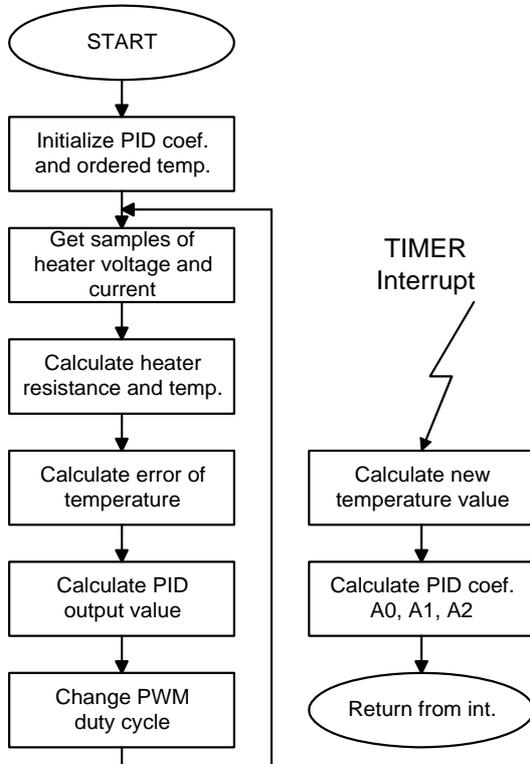


Fig. 2. Temperature control algorithm.

3. PROTOTYPE TEST RESULTS

The presented in Section 2 module architecture was realized in form of a prototype based on LPCXpresso board with LPC1769 inside. The whole device, including sensor's heater, was powered from USB which was also used to control the instrument as well as retrieve the measurement results. The device firmware was prepared and developed using dedicated LPCXpresso IDE. The PC software controlling the device was also prepared to make testing possible. Main window of the control program is presented in Fig. 3.

In the first step, the temperature controller was evaluated using TGS2600 sensor [9] as a test device. The figure presents sensor's heater temperature, which was regulated to set value of 500°C. The observed with thermographic camera actual temperature of the sensor without cover was proportional to that seen by the measurement module. The only problem that was observed can be seen in Fig. 3. In some time moments, the values of the measured temperature are incorrect. This phenomenon was further examined and the problem was addressed (some ADC samples were replaced during transmission to PC by incorrect values) and will be removed in the next prototype.

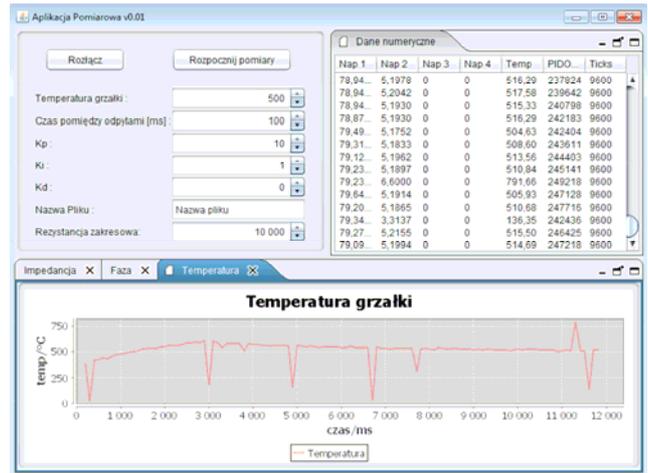


Fig. 3. Control software for the measurement module.

In the second step, the impedance measurement block was tested using reference resistors as a test device. All tests were performed using 10 kΩ range resistor and changing the measured resistor from 1 kΩ up to 100 kΩ. The actual values of the tested components were measured using Agilent 34401 multimeter.

The test measurements were performed in series (10 measurements in each series), the results were averaged and errors related to the actual values of the reference element were calculated. The exemplary errors curves for selected measurement frequencies were presented in Fig. 4.

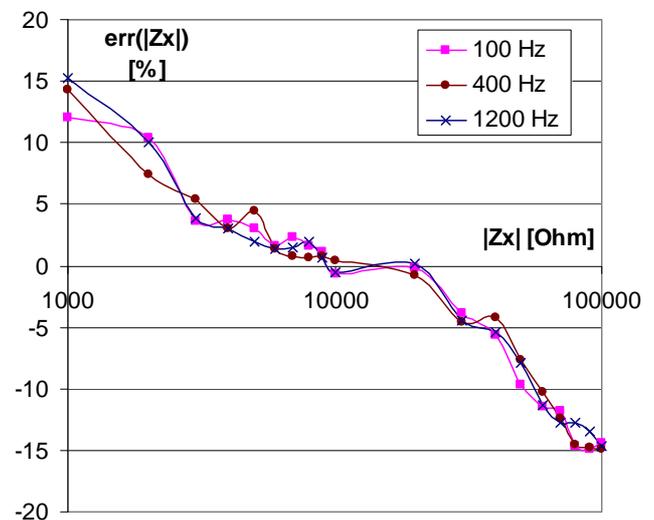


Fig. 4. Errors of the measurement of reference resistors.

The observed error was higher than expected and at the ends has exceeded +/- 10%. As an input circuitry was precisely evaluated in frame of previous works [5], the sine-fitting procedure was evaluated on a simulated data, the most probable error source is sampling of the measurement signal with the aid of ADC built-in in microcontroller.

In the next step, the modification of the prototype with external A/D converters working simultaneously is planned.

Also, the use of ellipse fitting algorithm to determine the impedance of the sensor is planned.

4. CONCLUSIONS

The impedance measurement module for gas sensors with temperature modulation feature was proposed and briefly described. One of the main design constraint was to keep the device as simple and low-cost as possible. The work-horse of the device is single microcontroller LPC1769.

The prototype tests have shown that the measurement errors have exceeded 10% so the obtained accuracy is not fully satisfactory. The main error sources were addressed and next prototype should fulfil the requirements while still keeping low complexity and low price. After improvement of the accuracy, the second prototype will be tested using gas sensors.

ACKNOWLEDGMENTS

This work was partially supported by the National Centre for Research and Development, Poland (grant # LIDER/22/103/L-2/10/NCBiR/2011).

REFERENCES

- [1] F. Caldararul, A. Vasile, M.Caldararu, "Autonomous system for real time air pollution monitoring using semiconductor toxic gas sensor", *24th International Spring Seminar on Electronics Technology*, pp. 233-237, Calimanesti-Caciulata, Romania, May 5-9, 2001.
- [2] Dae-Sik Lee, Duk-Dong Lee, Sang-Woo Ban, Minh Lee, and Youn Tae Kim, "SnO₂ Gas Sensing Array for Combustible and Explosive Gas Leakage Recognition", *IEEE Sensors Journal*, vol. 2, no. 3, pp. 140-149, June 2002.
- [3] R. Gutierrez-Osuna, S. Korah, A. Perera, "Multi-frequency Temperature Modulation for Metal-Oxide Gas Sensors", pp. 25-30, *Proc. 8th Intl. Symp. On Olfaction and Electronic Nose*, Washington, DC, USA, 25-30.03.2001.
- [4] NXP, UM10360: LPC176x/5x User manual, Rev. 3.1, 2014, http://www.nxp.com/documents/user_manual/UM10360.pdf.
- [5] J. Hoja, G. Lentka, "Interface circuit for impedance sensors using two specialized single-chip Microsystems", *Sensors and Actuators A-physical*, vol. 163, no 1, pp. 191-197, 2010.
- [6] P. Ramos, F. Janeiro, T. Radil, "Comparative Analysis of Three Algorithms for Two-Channel Common Frequency Sinewave Parameter Estimation: Ellipse Fit, Seven Parameter Sine Fit and Spectral Sinc Fit", *Metrology and Measurement Systems*. vol. XVII, No 2, pp. 255-270.
- [7] P. Ramos, T. Radil, F. Janeiro, "Implementation of sine-fitting algorithms in systems with 32-bit floating point representation", *Measurement*, vol. 45, No 2, pp. 155-163, 2012.
- [8] A. P. Lee, B. J. Reedy, "Application of radiometric temperature determination methods to semiconductor gas sensors", *Sensors and Actuators B: Chemical*, Vol. 69, No. 1-2, pp. 37-45, 10 September 2000.
- [9] Figaro, TGS2600 product information, Rev. 01/2005, <http://www.figarosensor.com/products/2600pdf.pdf>.