A software-hardware unit for studying the output characteristic of MEMS pressure sensors and its linearization

A A Kabanov, A M Esimkhanova, G V Nikonova, N Yu Sirotenko and V V Soloviev

1International Business Academy, 12, Nursultan Nazarbayev ave., Karaganda, 100027, Kazakhstan
2Omsk State Technical University, 11, Mira ave. Omsk, 644050, Russia

Corresponding author’s e-mail address: alina.esimhanova@yandex.ru, ngvlad@mail.ru

Abstract. The paper presents the development of a linearization algorithm of the output parameters of the sensors based on the circuits that determine the static characteristics of the correction transducers, ensuring the linearity of the general conversion function with a given accuracy. Simulation modeling of correcting the output parameters of MEMS pressure sensors has been carried out. The qualitative characteristics of the measuring system are determined via providing the sensors with a means for determining the degree of reliability of their output data using a virtual exemplary tool. A technique for calibrating and linearizing the output characteristic of an analog MEMS pressure sensor has been developed. An algorithm for polynomial approximation of the nonlinear output characteristic of the sensor and a method for its implementation in LabView software environment (by National Instruments) are presented. Virtual instruments developed in LabView software environment have been the basis of software-hardware means for monitoring and processing of measuring data. The developed methodology and means of automation of measuring processes with the use of virtual devices made it possible to make the process of correcting the output parameters of sensors autonomous, independent of stationary measuring devices and debugging tools.

1. Introduction

The growth of production needs associated with the expansion of automation areas and the complication of the technological process as well as the technological progress stimulate the usage of sensors for autonomous control systems. The priority here is to create a flexible control system for operating the rig equipment and measuring the parameters of the tested product. Automation of such processes is possible on the basis of both standard hardware and software solutions, and intelligent measurement technologies.

Thus, it is possible to increase the quality indicators of the testing process for sensors and converting equipment.

Development of measuring instruments and virtual devices using visual programming languages makes the development of a system (that not only has a complex behavior algorithm, but also is flexible in reconfiguration) natural and repeatedly reproducible in real time [1].

A possible solution to the problem of increasing the reliability of the operation results of control devices that use sensors with nonlinearity can be the use of a nonlinear signal conversion unit, which makes it possible to provide linearization and correction, and a decrease in sensitivity to nonstationary interference.

The peculiarity of MEMS devices is that they can not only improve the characteristics of electronic products, but also make them susceptible to what is happening around.
Nowadays, the problem of approximation is a hot topic for almost every technical study. The quantitative characteristics and qualitative properties of the description of the testing objects largely depend on the choice of the approximation type.

2. Theory
Methods and theories of linearization of sensor characteristics are widely used in practice, both in the most developed control systems for transmitting and processing information, and in measuring systems in technology. Nowadays, we know the main principles of the theory in the field of reducing the conversion function of the output parameters of a large number of sensors (primary measuring transducers) to a linear form.

However, at the same time, there is a need for correction and linearization of primary transducers in real time outside laboratories equipped with all measuring instruments for sensors calibration [2].

In our work, the object of research was the sensors of physical quantities. For testing the pressure sensors hardware and software tools for linearizing the static and dynamic characteristics of transducers and tools for simulating the process of correcting the output parameters of sensors are used [1].

The subject of research is the laws, describing the processes of correction and linearization of data, and their relationship between the parameters that determine the course of these processes. It is necessary to obtain a formalized description using approximating equations, which quite accurately correspond (are adequate) to the original experimental sample.

Classical methods of approximation, interpolation polynomial, methods of analytical approximation of functions, theories of electrical circuits and signals, methods and means of mathematical and computer modeling are used as basic research methods.

3. Priority solution
Using digital signal processing to reduce the pressure measurement errors associated with nonlinearity and temperature dependence of the output characteristics of the sensor, it is advisable to calibrate each primary transducer. In a production environment, for the task implementation it is important to have an economical, and at the same time effective and reasonable method of forming an individual sensor characteristic.

Increasing the accuracy of calculating the pressure in the sensor requires solving the problems of increasing the accuracy of approximating its calibration characteristic and reducing the errors associated with calculations directly carried out by the sensor's microprocessor system.

The problem of constructing an inverse calibration characteristic, with a high accuracy of reflecting the imperfection of the output characteristic of the pressure sensor's sensitive element largely depends on the choice of the approximating function type [2]. Splines and polynomials of various degrees are most often used as approximating functions [3, 4].

The main idea of the work is to use software-hardware means of automating the measuring processes using virtual devices to increase the autonomy of correcting the sensors output parameters, including the situations when stationary measuring devices and debugging tools are absent.

4. Experiment

4.1. Hardware complex for MEMS pressure sensor research
To study the non-linear characteristics of the MEMS pressure sensor [5, 6], it is necessary to record the change in the output signal when the external pressure changes. To display the signal form and change of the signal in real time, a rig has been designed for studying the sensor. The block diagram of the rig is shown in Figure 1.

As a result of the external pressure influence on the sensor, its output signal changes. Further, the analog-to-digital converter fixes the signal change and transmits it to a microcontroller, which transmits the acquired value to a personal computer. The computer receives the transmitted values from the microcontroller and converts them and displays the data on a graph in a software environment.
The MPX5700 series piezoresistive transducer from Motorola has been selected as the testing sensor. It is a state-of-the-art monolithic silicon pressure transducer designed to measure pressure in the range from 0 to 700 kPa [7]. It is a patented single-element transducer that combines advanced micromachining technologies, thin-film metallization, and bipolar processing techniques to provide an accurate high level analog output signal that is proportional to the applied pressure. The MPX5700dp sensor is shown in Figure 2a.

Features of this sensor:
- Maximum error is 2.5% (0° to 85°C).
- Ideal for microprocessor and microcontroller systems.
- Available in two configurations – differential and gauge.
- Patented silicon shear stress strain sensor.
- Temperature compensation.

Figure 2b shows a graph of the temperature non-linearity of the sensor in the dynamic temperature range [7].

\[ V_{out} = V_{off} + \text{sensitivity} \cdot P \]  

where \( V_{out} \) is the output value (mV); \( V_{off} \) is the sensor initial offset; \( P \) is the pressure. As an analog-to-digital converter (ADC), a Texas Instruments ADS1110 microcircuit has been chosen; it is designed for precision measurements that require compact size and low power consumption [8].

The ADS1110 is a precision, continuously self-calibrating Analog-to-Digital (A/D) converter with differential inputs and up to 16 bits of resolution in a small SOT23-6 package. The onboard 2.048 V reference provides a differential input range of ±2.048 V.
The ADS1110 uses a serial I²C-compatible interface and operates from a single +2.7...5.5 V power supply. The ADS1110 can perform conversions at 15, 30, 60 or 240 samples per second. Onboard programmable gain amplifier offers gains of up to 8 and enables measurement of weak signals with high resolution.

The interaction of the test rig with a personal computer is provided by a microcontroller [9]. Here the method of receiving data from the ADC and transferring it to a PC is implemented. The ADRUINO UNO board based on the Atmel AVR ATmega328P microcontroller has been chosen as the microcontroller.

The ATmega328 has a UART transceiver that allows serial communication via digital pins 0 (RX) and 1 (TX). When the board is connected to a PC, Arduino is defined as a virtual COM port.

The Arduino IDE is a cross-platform Java application that includes a code editor, a compiler, and a firmware flashing module.

The development environment is based on the Processing programming language. The programming language is similar to C/C++, supplemented with certain libraries. Code is processed using a preprocessor and then compiled using AVR-GCC. The library for working with the I²C interface and the of USB input/output facilitates the process of programming and pairing the controller with a personal computer.

4.2. Linearization function and the static characteristics analysis in LabView

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a development environment and a platform for executing programs created in the visual G programming language from National Instruments (USA). Currently, there are versions for UNIX, Linux, Mac OS, etc., and the most developed and popular are versions for Microsoft Windows. LabVIEW is used in data acquisition and processing systems, and is suitable for controlling technical objects and technological processes [10].

The visual G programming language used in LabVIEW is based on a data stream architecture. The execution queue of operators in such languages is determined not by their order (as in imperative programming languages) but by the presence of data at the inputs of these operators. Operators that are not data bound are executed simultaneously and in no particular order.

Built-in libraries and clear interface makes the task of developing applications easier [11].

Essentially, linearization is a set of methods that allows you to reduce the solution of nonlinear problems to the sequential solution of related linear problems [12].

The linearization of the sensor output parameter is carried out by introducing correction factors and approximating the real nonlinear output characteristic to the ideal linear one. Since the real transformation function is unknown, it is necessary to reveal this dependence empirically [13]. To do this we implement a program for calibrating the used sensor.

4.3. Development of virtual instruments in LabVIEW

For the proper program operation, it is necessary to set the range and step of pressure change, and select the COM port.

Description of the performed tasks:

- A system, consisting of a compressor, a manometer and a differential pressure sensor, has been created for calibration [14, 15].
- When the compressor has supplied the pressure indicated on the front panel of the device, the record button is pressed. The program writes an array consisting of the output voltage value and the corresponding pressure into a file.
- Repeat the process over the entire selected range.
- The program builds a calibration graph, based on the received data.

Figure 3 shows the calibration algorithm. Calibration is performed in the sensor operating range from 0 to 10 kPa with a step of 1 kPa. The experimental points obtained during the calibration are approximated by an n-order polynomial; the greater the order of the polynomial, the higher the approximation accuracy.
Figure 3. Calibration program algorithm

The virtual device developed in LabVIEW performs calibration of the pressure sensor and writes the calibration table in a file (Figure 4).

The graph after the calibration is shown in Figure 5.
Figure 5. The front panel of the calibration device

The LabView environment allows to build an approximating polynomial of the required order and calculate its coefficients using the General Polynomial Fit function [11].

The front panel of the second device performing the approximation function displays a calibration graph and an approximating curve (Figure 6). The implemented program automatically selects the order of the polynomial based on the specified error, after which it corrects the pressure value and builds a graph.

Figure 6. Calibration graph and instrument fit curve

4.4. Program operation
In order to choose the order of the polynomial, it is necessary that it provides the greatest approximation to the experimental data.

The developed program contains the equation of an ideal function, and from the coefficients obtained in the construction of the polynomial, the equations of the polynomial function are compiled. The output voltage value is fed to an ADC, then – to a microcontroller, and transmitted to the program via a USB port; this value is compensated based on the previously built calibration characteristic and the polynomial dependence built on it.
The difference in values between the real characteristic and the constructed polynomial is the correction factor that brings the measured value closer to the ideal linear conversion function of the sensor. The linearization function implemented in such a way allows reducing the multiplicative error of the sensor nonlinearity.

The program also eliminates the initial zero offset of the sensor and the analog-to-digital converter, thereby eliminating their additive error.

To start the program, it is necessary to connect the test rig with the investigated sensor to a personal computer via USB. Next, determine the COM-port number, to which the device is attached, and then – run the program.

To display on the graph an ideal output function of the sensor and the real polynomial function along with the measurement results, it is necessary to set the relative error (Figure 6).

After preliminary settings, the program will display on the graph the real measurement values of the sensor output signal and the compensated pressure value in real time (Figure 7).

![Figure 7. The graph that shows proper values of the measured pressure](image)

The LabVIEW program diagram is shown in Figure 8.

![Figure 8. The diagram of the approximation program](image)
5. Conclusion
The paper presents the results of a study of the nonlinear output characteristic of MEMS pressure sensors and the methods of its linearization. An algorithm for polynomial approximation of the nonlinear output characteristic of the sensor and a method for its implementation in the LabVIEW software environment are presented.

The virtual device developed in LabVIEW performs calibration of the pressure sensor and writes the calibration table in a file. This file is used by the second virtual device, which performs a polynomial approximation of the sensor output characteristic. This virtual device also automatically selects the order of the polynomial, based on the user-specified error. Using the correction factors, the program builds a compensated pressure graph in real time.

The presented process is the basis of the developed method of calibration and linearization of the output characteristic of an analog MEMS pressure sensor.

The developed technique and correction device are designed to ensure high accuracy of the transducers that transform physical pressure quantities (that are determined mainly by the stability of the characteristics of measuring transducers in the entire range of operating temperatures). Accounting the sensor characteristics by a software and the automating of calibration process allows the use of primary transducers with a large scatter of parameters.

The studies of the output characteristics of analog sensors have shown that the method of using software-hardware means and virtual devices is universal and allows the analysis of nonlinearity and its compensation for various types of sensors. The method of compensating the nonlinearity of the pressure sensor output parameters, based on the experimental points obtained during calibration of the signal from the MEMS sensor (using a virtual device), makes it possible to automate the measuring process and control its accuracy, and display the pressure values in real time [16].

6. References
[1] Esimkhanova A and Nikonova G 2018 Virtual Device for Processing the Signals from MEMS Pressure Sensors (in IEEE International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices EDM-2018) pp 676–680
[2] Klevtsov S and Klevtsova A 2005 Multisegment spatial model of the calibration characteristic of an intelligent sensor (Digital Methods and Technologies) Proc. of the International Scientific Conference Part. 4 pp 21–23
[3] Shaponich D and Zhigich A 2001 Correction of a piezoresistive pressure sensor using a microcontroller (Instruments and experimental techniques) Part. 1
[4] Bobrovnikov N, Yarkin S, Gridin Yu, Strygin V and Chertov E 2002 Mathematical support of microprocessor-based converters of analog pneumatic signals (Pribory i sistemy. Management, control, diagnostics) Part. 2 pp 36–39
[5] Peter G Hartwell 2010 Rethinking MEMS sensor design for the masses (Electronic Engineering Times Europe) March 2010
[6] Vasiliev V et al. 2012 Measuring instrument-calibrator for pressure sensors based on resistive nano- and microelectromechanical systems (Sensors and Systems: Methods, Means and Technologies for Obtaining and Processing Measurement Information Proceedings of the IRTC) pp 111–114
[7] Data Sheet: Technical Data 2012 Integrated Silicon Pressure Sensor On-Chip Signal Conditioned, Temperature Compensated and Calibrated (Freescale Semiconductor Inc.) URL: https://www.nxp.com/docs/en/data-sheet/MPX5700.pdf
[8] Data Sheet 2020 16-Bit Analog-to-Digital Converter with Onboard Reference (Texas Instruments Inc.) URL: https://www.ti.com/lit/ds/symlink/ads1110.pdf
[9] Nikonova G V, Esimkhanova A M and Markelov A S 2015 Fuel level sensor MEMS technology in satellite monitoring of transport (Advances in current natural sciences) part 11–2 pp 198-202
[10] Yang Yik 2014 LabVIEW Graphical Programming Cookbook (Birmingham: Packt Publishing) p 252
[11] Kehtarnavaz N and Kim N 2005 Digital Signal Processing System-Level Design Using LabView (Newnes: Elsevier) p 304
[12] Vovk S and Ginis L 2012 *Modelling and forecasting of transitions between levels of hierarchies in Difficult formalized systems* (European Researcher) vol 20, part 5–1 pp 541–545

[13] Brown R G 2004 *Smoothing, forecasting and prediction of discrete time series* (Dover Publications; Dover Phoenix Ed edition) p 480

[14] Lihua Sun, Yingjun Guo, Haichao Ran 2010 *A New Method of Early Real-Time Fault Diagnosis for Technical Process* International Conference Electrical and Control Engineering (ICECE), Wuhan, China, pp 4912–4915

[15] Klevtsov S 2016 *Identification of the State of Technical Objects Based on Analyzing a Limited Set of Parameters* (International Siberian Conference on Control and Communications SIBCON) pp 749–752

[16] Zhilin N S, Nikonov A V and Nikonova G V 2002 *Measuring devices with a self-adapting adaptive system of automatic control* (Electronic Instrument Engineering Proceedings) pp 91–96

**Acknowledgments**

The reported study was funded by RFBR, project number 19-38-90162