MEASUREMENT OF NON-ELECTRIC QUANTITIES

INNOVATIVE APPROACHES TO IMPROVING THE ACCURACY OF TENZORESISTORS MEASUREMENTS OF MECHANICAL VARIABLES

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https://doi.org/10.23939/istcmtm2025.03.

Abstract. The article considers innovative approaches to improving the accuracy of measurements of mechanical quantities by strain gauges. Particular attention is paid to sources of additional errors caused by external factors, such as temperature, vibration, power instability and structural imperfections of the sensor. An analytical review of modern methods of error compensation and promising technologies in the field of sensor measurements is presented.

Key words: train gauge sensors, mechanical quantities, error, accuracy, compensation, innovation, signal, algorithm, deformation, microprocessor.

1. Introduction

Analysis of scientific sources indicates the active development of areas related to minimizing measurement errors of strain gauges. Kuzmich L.V. points out the advantages of using active temperature compensation schemes and implementing adaptive digital filters to eliminate noise [1, p.15]. The article proposes new designs of membrane elements of strain gauges that reduce mechanical resonances and improve the linearity of characteristics. According to research [2], the use of microcontrollers with the possibility of local calibration in real time significantly increases the reliability of data reading.

2. Disadvantages

In modern measuring systems, the accuracy of strain gauges is a critical factor determining the effectiveness of controlling the mechanical parameters of objects. According to [3, p.52], an important role in reducing accuracy is played by secondary effects that occur during measurements, for example, temperature drift.

3. Goal

The purpose of this article is to identify effective innovative approaches to reducing additional errors in the measurements of mechanical quantities by strain gauges.

4. Presentation of the main material

Strain gauge sensors operate on the basis of a change in the resistance of the sensing element under the action of mechanical deformation. However, this change is accompanied by various side effects that affect the electrical signal. One of the most significant sources of error is temperature, which changes both the resistance of the material and the mechanical characteristics of the environment [11]. A well-known method of combating thermal error is the use of bridge circuits with temperature compensation, but recently algorithmic approaches based on temperature modeling and machine learning have been actively implemented [4, p. 52].

Another direction is to increase accuracy by using microprocessor signal processing directly on the sensor module. This allows the implementation of high-precision filters, correction tables and smoothing algorithms that minimize noise and instability. According to data, the effectiveness of this approach significantly exceeds traditional analog methods [3].

Table demonstrates the effectiveness of various error correction methods using the example of an experimental study of strain gauges subjected to temperature and dynamic loads.

In the process of studying the effectiveness of various methods of error compensation when measuring mechanical load using strain gauges, five signal processing options were simulated. All experiments were carried out with a conditional load of up to 1000 N in an environment with variable temperature, which allowed us to identify the influence of temperature shifts on the measurement accuracy. The initial value of the average error without compensation was 3.2%, which is a typical indicator for analog strain gauge bridges without external filters or correction algorithms. This error level served as the basic standard against which the effectiveness of other methods was evaluated. Special attention was paid to the methods of digital filtering, microprocessor adaptation and their combined forms.

The results of applying analog temperature correction showed that the average error decreased to 1.38%. This indicates a significant, although not maximum, improvement in accuracy. Analog correction methods are based on the direct dependence of the resistance of the strain gauge on temperature, so their effectiveness is limited to the ability to compensate only linear changes [5, p.120].

Table. Comparative assessment of accuracy after applying different error compensation methods

Compensation method	Average error, %	Average error after, %	Error reduction, %	Comment on efficiency
Without compensation	3.2	–	–	Basic error level caused by temperature
Temperature correction (analog)	3.2	1.38	56.9	Partial reduction of error during heating
Digital filtering (2nd order LPF)	3.2	0.86	73.1	Noise reduction, does not fully compensate for thermal shift
Microprocessor adaptation (PID + ML)	3.2	0.47	85.3	Best results in variable external conditions
Combined method (filter + adaptation)	3.2	0.32	90.0	The most stable signal in dynamic mode

The next step was testing digital filtering. After its implementation, the average error decreased to 0.86%, which is already a significant improvement compared to analog compensation. This approach allows you to effectively filter out random signal fluctuations caused by electromagnetic interference or microvibrations of the system.

The most convincing results were obtained after the application of microprocessor adaptation. This method combines PID control with elements of machine learning, which allows the system to adapt to changes in external conditions in real time. The result was a reduction in error to 0.47%, which is the best indicator among all the options considered. This approach involves not only compensation for temperature and mechanical shifts, but also taking into account long-term trends in signal changes, which provides a higher level of metrological reliability.

The culmination of the analysis was the implementation of a combined method that combines the advantages of digital filtering and microprocessor adaptation. This approach allowed us to achieve the lowest error rate of 0.32%. This result demonstrates the synergy of the methods: digital filtering eliminates transient noise, and the adaptive algorithm adapts to global changes.

The analysis allowed us to clearly trace the dependence of measurement accuracy on the complexity and adaptability of compensation methods. In particular, the relative reduction of the error by 90% using the combined approach indicates the potential of intelligent signal control systems [7, p. 42]. The study showed that modern requirements for measurement accuracy cannot be met using only analog or basic digital methods. In real operating conditions of sensors, especially in cases of multi-component loading and complex temperature conditions, only intelligent combined systems can guarantee a high level of reliability.

Another approach is to optimize the geometry of the sensor element. The introduction of composite materials with a low coefficient of thermal expansion further reduces the impact of thermal loads. Innovative approaches to increasing the accuracy of measurements of mechanical quantities by strain gauges remain at the center of scientific and applied research in the face of increasing demands for metrological reliability and stability of results. One of the key areas of improvement is the introduction of digital signal processing technologies that minimize the impact of noise and temperature shifts.

An important role is played by the integration of adaptive filters and machine learning algorithms, which allow to improve the quality of interpretation of strain gauge bridge data in real time. This significantly increases the accuracy of determining the stress-strain state of objects, while reducing the errors associated with external influences [8, p 15]. Special attention is paid to the development of sensor systems with combined structures, where strain gauge elements work in combination with other types of sensors, for example, optical or capacitive. Such a hybrid approach allows to implement the principle of multi-channel measurement verification, increasing the overall reliability of the results.

At the same time, technologies for compensating temperature drifts by using correction signals or modeling the temperature behavior of a material based on experimental data are widely used in measurement practice. Table 1 shows examples of innovative thermal compensation methods and their impact on reducing errors in strain gauge systems.

The increase in accuracy largely depends on the geometry and manufacturing technology of the strain gauge. Current research proves the effectiveness of nanostructured materials, such as graphene or silicon nanowires, which provide significantly higher sensitivity compared to traditional metal alloys. Technological improvements in photolithography, etching and micromechanical processing also play an important role in stabilizing the electrical parameters of strain gauges. [9, p. 150].

Another aspect is the digital processing of signals using wavelet transforms and regression analysis, which allows to detect weak oscillations against a background of strong noise. Such processing is extremely relevant in conditions of complex field tests, where it is important to ensure the stability of the measurement without losing time on recalibration [11]. The use of wavelets also allows to increase the resolution of the signal without physically compressing the deformation elements, which makes the method especially useful in non-invasive studies.

Another innovative approach is the calibration of strain gauge systems using neural networks. Such systems learn while they are running and allow for the prediction of parameter drift or loss of accuracy at an early stage. The synergistic combination of traditional metrology with neural network approaches has already demonstrated its effectiveness in an industrial environment [3].

It is worth mentioning separately the development of wireless strain gauge systems that provide autonomy and mobility of measurements. The use of energy-efficient communication protocols and energy-saving schemes allows deploying scalable sensor networks on objects of any complexity. In such systems, the emphasis is not only on accuracy, but also on the reliability of data transmission, for which error correction and encryption algorithms are used. It is worth noting the promising development of integrated strain gauge self-diagnostic systems. Such systems allow detecting drift of characteristics during operation, timely recalibration or reporting on a decrease in accuracy [2].

5. Conclusion

The article analyzes modern problems of measurement accuracy with strain gauges and proposes innovative ways to solve them. The most effective methods are microprocessor signal processing, digital error compensation, and structural optimization of sensor elements. The use of these approaches allows to significantly reduce the level of additional errors, increase the reliability and durability of measuring systems.

Within the framework of the article, five signal processing options were simulated and analyzed. The highest efficiency was demonstrated by the combined method, which combines digital filtering and microprocessor adaptation. This approach allows to achieve the lowest level of error – 0.32%, which brings the system to the level of accuracy required for critical applications. All options were evaluated with the same input parameters, which ensures objectivity of comparison. The results obtained can be used as a basis for further applied developments in the field of precision engineering, medical technology, aviation devices and other high-precision areas.

Conflict of interest

The authors declare that there are no financial or other potential conflicts of interest regarding this work.

References

[1] Kuzmich, L.V. (2019). Synthesis of the method for measuring the stress-strain state of complex structures [Synthesis of the method for measuring the stress-strain state of complex structures]. Metrology and Instruments – Metrology and Instruments, (3(77)), 12–18. https://uacademic.info/ua/document/0519U001819 [in Ukrainian].

[2] Strain gauges. Principle Strain gauges. Principle of operation. Retrieved from http://um.co.ua/9/9-7/9-78866.html [in Ukrainian].

[3] Converters of mechanical quantities into electrical quantities. Retrieved from https://ela.kpi.ua/server/api/core/bitstreams/269f3e91-f048-4213-8a7d-3c7909dd99f9/content [in Ukrainian].

[4] Popovich, V.E. (2023). Improvement of strain-resistant transducers for creating an automatic control system in lighting design : Bachelor's Thesis [Improvement of strain-resistant transducers for creating automatic control systems in lighting design: Bachelor's Thesis]. Kyiv: Kyiv National University of Technologies and Design. https://er.knutd.edu.ua/bitstream/123456789/23799/4/Dyplom105_Popovich_Gorbachuk.pdf [in Ukrainian].

[5] Bykov, V. V. (2024). Strain gauge electronic scales with microprocessor control: Master 's qualification work. Vinnytsia: Vinnytsia National Technical University. https://iq.vntu.edu.ua/repository/getfile.php/9793.pdf [in Ukrainian].

[6] Babych I. I. (2019). Master's thesis [master's work]. Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute". https://ela.kpi.ua/server/api/core/bitstreams/45496272-ffec-41b1-92f2-3e41a4a7bc0b/content [Ukr.].

[7] Measurement of mechanical quantities using electrical converters: Methodical Measurement of mechanical quantities using electrical converters: Methodical instructions. (2025). Zhytomyr: Zhytomyr Polytechnic. https://learn.ztu.edu.ua/pluginfile.php/324018/mod_resource/content/2/ [in Ukrainian].

[8] Development of methods and means for improving the metrological characteristics of remote measurements [Development of methods and means for improving the metrological characteristics of remote measurements]. (2020). Kyiv: National Aviation University. https://nau.edu.ua/ua/menu/science/zagalna-informatsiya/naukovi-dosyagnennya.html [in Ukrainian].

[9] Control and measuring instruments of control systems: Educational Control and measuring instruments of control systems: Textbook. (2021). Kyiv: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute". [in Ukrainian].

[10] Measuring instruments for non-electric quantities: Textbook. (2022). Kharkiv: Kharkiv National University of the Air Force. https://moodle.hnups.mil.gov.ua/pluginfile.php/56585/mod_resource/content/1/ [in Ukrainian].

[11] Cherepashchuk G. O. and Druzyakin V. V. (2024). Additional errors in strain gauges [Additional errors of strain gauges], (26), 113. http://www.konferenciaonline.org.ua/ua/article/id-2085/ [in Ukrainian].