Metallophysics and Advanced Technologies
Металофіз. новітні технол.
Metallofiz. Noveishie Tekhnol.
2026, vol. 48, No. 4, pp. 435–447
https://doi.org/10.15407/mfint.48.04.0435
Reprints available directly from the publisher

PACS numbers: 06.30.Dr, 06.30.Gv, 62.25.Jk, 81.05.Bx, 81.70.Ha, 81.70.Jb, 81.70.Pg

Experimental Method for Determining the Composition of Materials in a Sample Using an Intelligent Ballistic Dual-Channel Gravimeter

O. M. Bezvesilna, Yu. M. Koval*, M. S. Grynevych, and T. A. Tolochko

National Technical University of Ukraine
'Igor Sikorsky Kyiv Polytechnic Institute',
37 Beresteiskyi Ave.,
UA-03056 Kyiv, Ukraine
**G. V. Kurdyumov Institute for Metal Physics, N.A.S. of Ukraine,*
36 Academician Vernadsky Blvd.,
UA-03142 Kyiv

This article proposes and examines an experimental method for determining the composition of materials in a sample using a new intelligent ballistic dual-channel transformer gravimeter (IBDTG) in a diagnostic setup (the GS gravimetric system). It is demonstrated that the IBDTG accuracy, speed, and reliability are superior to those of currently available gravimeters. Its design and operating principle are described. Currently, there are no theoretical or practical studies devoted to the feasibility and practicality of using an intelligent ballistic dual-channel transformer gravimeter to analyse metal composition in a sample or on a surveyed area of the Earth's surface. A new intelligent ballistic two-channel transformer gravimeter contains a fixed tube, a magnetized test body in the form of a ball, a device for holding the test body in the initial position, a computer and an inductance winding, which is distinguished by the fact that the fixed tube is made of a dielectric material, the inductance winding acts as a primary excitation winding connected to a pow-

Corresponding author: Olena Mykolayivna Bezvesilna
E-mail: o.bezvesilna@gmail.com

Citation: O. M. Bezvesilna, Yu. M. Koval, M. S. Grynevych, and T. A. Tolochko, Experimental Method for Determining the Composition of Materials in a Sample Using an Intelligent Ballistic Dual-Channel Gravimeter, *Metallofiz. Noveishie Tekhnol.*, **48**, No. 4: 435–447 (2026). DOI: 10.15407/mfint.48.04.0435

er source, which additionally contains two identical sections of a secondary output winding, connected in series-opposite to create two measurement channels, and the device for holding the test body in the initial position contains an electromagnet, which consists of an anchor made of a soft magnetic material and an additional winding, which is connected through a switch to an additional power source. This improves accuracy and reliability, reduces temperature dependence and sensitivity to cross-accelerations, and enhances linearity. The influence of vertical acceleration, instrumental errors, and errors due to non-identical parameters of the two channels are eliminated. The output signal power of the new IBDTG is increased by feeding the output signals of the two IBDTG channels to a computer, which generates an output signal from the gravimeter equal to twice the acceleration of gravity. The computer output signal is fed to a pre-trained Fuzzy module, which determines the metal composition of the sample or the area of the Earth's surface being studied.

Key words: Fuzzy module, intelligent ballistic two-channel transformer gravimeter, automated diagnostic gravimetric system, disturbance effect, vibration acceleration, acceleration of gravity.

У цій статті запропоновано та розглянуто експериментальний метод визначення складу матеріялів у зразку шляхом використання нового інтелектуального балістичного двоканального трансформаторного ґравіметра (ІБДТҐ) діягностичної установки (ґравіметричної системи ҐС). Обґрунтовано, що точність, швидкодія та надійність ІБДТҐ вище відомих нині ґравіметрів. Описано його конструкцію та принцип дії. Нині відсутні науково-теоретичні та практичні роботи, присвячені дослідженням можливости та доцільности використання інтелектуального балістичного двоканального трансформаторного ґравіметра для аналізи складу металів у зразку або на досліджуваній ділянці Земної поверхні. Новий інтелектуальний балістичний двоканальний трансформаторний ґравіметер містить нерухому трубку, намагнетоване пробне тіло у вигляді шару, пристрій утримання пробного тіла у початковому положенні, комп'ютер і обмотку індуктивности, який вирізняється тим, що нерухому трубку виконано з діелектричного матеріялу, обмотка індуктивности виконує роль первинної обмотки збудження, підключеної до джерела живлення, яке додатково містить дві однакові секції вторинної вихідної обмотки, включені послідовно-зустрічно для створення двох каналів міряння, а пристрій утримання пробного тіла у початковому положенні містить електромагнет, який складається з якоря із магнетом'якого матеріялу та додаткової обмотки, яку через перемикач підключено до додаткового джерела живлення. Воднораз підвищуються точність і надійність, зменшуються залежність від температури, чутливість до перехресних пришвидшень та збільшується лінійність. Усуваються вплив вертикального пришвидшення, інструментальні похибки та похибки від неідентичности параметрів двох каналів. Збільшення потужности вихідного сиґналу нового ІБДТҐ забезпечується шляхом подачі вихідних сиґналів двох каналів ІБДТҐ у комп'ютер, в якому формується вихідний сиґнал ґравіметра, рівний подвоєному значенню пришвидшення сили тяжіння. Вихідний сиґнал комп'ютера подається на попередньо навчений Fuzzy-модуль, який ви-

значає склад металів у зразку або на досліджуваній ділянці Земної поверхні.
Ключові слова: Fuzzy-модуль, інтелектуальний балістичний двоканальний трансформаторний ґравіметер, автоматизована діягностична ґравіметрична система, збурювальний вплив, вібраційні пришвидшення, пришвидшення сили тяжіння.

(Received 23 March, 2026; in final version, 25 March, 2026)

1. INTRODUCTION

In many countries, diagnosing metal content in samples and detecting and diagnosing mineral deposits are extremely important. This information is used in various fields, including metal physics, geology, geophysics, surveying, and other fields. An experimental setup, called a gravimetric system (GS), whose sensing element is a gravimeter, can be used for this purpose. Gravimetric measurements are conducted on a fixed base (on the Earth's surface) and on a moving base (on submarines, surface vessels, and aircraft). Each type of measurement has its own advantages and disadvantages.

The most accurate measurements are made on Earth using the well-known ballistic gravimeter. It is possible to significantly increase the accuracy by using a diagnostic gravimetric system [3], the sensitive element of which is a new intelligent ballistic two-channel transformer gravimeter, the advantages of which over the known ballistic gravimeter are higher accuracy, speed, reliability, powerful output signal, linearity of characteristics over a wide range, *etc*.

The conducted analysis of the literature showed that a great contribution to the theory and practice of experimental gravimetric measurements is associated with the names of E. I. Popov, A. M. Lozinskaya, A. A. Andreev, V. V. Malov, N. A. Shulga, V. V. Lavrinenko, S. I. Pugachev, O. P. Kramarov, A. E. Kolesnikov, P. A. Gribovsky and others [1–34].

Several types of gravimeters and gravimetric systems are known, each with its own advantages and disadvantages. In [7], the elastic element and moving mass are made of a sapphire single crystal. The invention [8] improves accuracy by reducing zero drift, increasing the linearity range, and improving inertial noise filtration. In the gravimeter [9], the sensing element for determining the acceleration of gravity (AG) is made of silicon or glass. This provides the sensing element with relatively high reliability, accuracy, and stability of readings.

Leading technical universities in the USA, Japan, Germany and other countries are working on developing new models of GS gravimeters and improving their accuracy [14–17].

However, virtually all known gravimeters simultaneously measure the useful gravity acceleration (GAC) signal g and the vertical acceleration interference signal [4, 12, 18], which is 10^3 times greater than the useful g signal [4, 12]. They require lengthy periodic calibration, adjustment, and output signal filtration [19], which significantly complicates their operation. Furthermore, known gravimeters do not allow for the detailed determination of the material composition of the sample or section of the Earth's surface being studied. Existing latest developments relate to marine [20, 21] and aviation [19] measurement methods, which are not used in terrestrial gravimetry.

In recent years, a ballistic gravimeter (BG) [2] has been used, consisting of systems for measuring the path and time of free motion of a test body. The BG includes a measurement system consisting of a test body in the form of a magnetic sphere, a transparent tube on a fixed base, an induction coil, a device for holding the test body in its initial position, and a computer.

The well-known gravimeter [2] has a number of significant disadvantages. The known gravimeter is a single-channel inductive device. When exposed to an external electromagnetic flux (interference), the known ballistic gravimeter experiences significant errors, acting along the OZ sensitivity axis simultaneously with the useful gravitational acceleration signal g and significantly greater it in 10^3. The vertical inertial acceleration, instrumental errors caused by changes in temperature, humidity, vibration, pressure, dry friction torque and other factors act directly along the sensitivity axis OZ, distorting the operation of the known gravimeter. The measuring system of a known gravimeter consists of two subsystems, each containing a large number of devices operating on different principles, each with its own inherent errors. Therefore, combining the two subsystems does not improve accuracy, as the errors of the devices in both subsystems will be additive. The multitude of parts and components of the measuring system of the known gravimeter and the complex connections between them significantly reduce the reliability and speed of operation of the known gravimeter. The known BG does not allow the analysis of the metal content in the sample being studied or in the area of the Earth's surface being studied.

It should also be taken into account that the accuracy of measuring the acceleration of gravity by a known ballistic gravimeter is significantly affected by external electromagnetic flows: interference.

Without eliminating the above-mentioned significant shortcomings, the accuracy, speed, and reliability of measurements of metal content in a sample or on a section of the Earth's surface being studied by a known ballistic gravimeter will be low.

This article proposes and reviews a new intelligent dual-channel ballistic gravimeter (IBDTG) [1], which has clear advantages over known gravimeters: IBDTG can measure the metal content in a sample or on a section of the Earth's surface with greater accuracy, speed, and reliability, and also has a twice as powerful output signal.

2. SUMMARY OF THE ARTICLE CONTENTS

In order to improve the accuracy, speed and reliability of measurements of the metal content in a test sample or on a test section of the Earth's surface, as well as the measurement of the gravity field, an intelligent ballistic two-channel transformer gravimeter is proposed for measuring the doubled value of the acceleration of gravity, containing a fixed tube, a magnetized test body in the form of a ball, a device for holding the test body in the initial position, a computer and an inductance winding, in which the new feature is that the fixed tube is made of a dielectric material, the inductance winding acts as a primary excitation winding connected to a power source, which additionally contains two identical sections of the secondary output winding, connected in series-opposite to create two measurement channels, and the device for holding the test body in the initial position contains an electromagnet, which consists of an anchor made of a soft magnetic material and an additional winding, which is connected through a switch to an additional power source.

This improves accuracy and reliability, reduces temperature dependence and sensitivity to cross-acceleration, and enhances linearity. The influence of vertical acceleration is eliminated, as are instrumental errors and errors due to non-identical parameters of the two channels. The output power of the new IBDTG is increased by feeding the output signals of the two IBDTG channels to the computer input, from which a signal proportional to twice the value of AG is read. The computer output is connected to an intelligent Fuzzy module, the output of which is the output of the experimental setup (gravimetric system). The intelligent Fuzzy module is pre-trained using the gravitational anomaly signal Δg to determine the metal content in a given sample or to determine the composition of minerals in a given area of the Earth's surface. The results of measurements of the gravity anomaly Δg are automatically analysed in the intelligent Fuzzy module, which contains a database of fuzzy rules and linguistic variables and generates a logical conclusion regarding the presence and type of metals in a sample or the composition of minerals in a given area. The intelligent Fuzzy module enables the processing of multiple measured data sets when analysing the composition of metals in a sample or determining the composition of minerals in a given area in real time.

Today, there are no scientific, theoretical, or practical works devoted to the study of the possibility and feasibility of using a new intelligent ballistic gravimeter of a ground-based experimental setup (GS) [1] to determine the composition of metals in a sample or on a section of the Earth's surface. Its advantages over the known ballistic gravimeter [2] are greater accuracy (due to the use of a pre-trained Fuzzy module, eliminating the impact of vertical acceleration, instrumental and other errors), speed of operation, and reliability [1].

The object of study of this article is the process of measuring the content of metals in a sample or on a section of the Earth's surface.

The purpose of this article is to improve the accuracy, speed and reliability of a new intelligent ballistic two-channel transformer gravimeter of a diagnostic experimental setup (gravimetric system) for determining the composition of materials in a sample.

The objectives of the article are to examine the design and analyse the operating principle of a new intelligent ballistic two-channel transformer gravimeter to ensure greater accuracy, power, speed, and reliability of the output signal through the use of a pre-trained Fuzzy module by eliminating the effects of vertical acceleration, instrumental and other errors.

3. RESEARCH METHODS AND MATERIALS

Below we will outline the main methods and materials of the study in accordance with the stated goals and objectives.

3.1. Design of an Intelligent Ballistic Two-Channel Transformer Gravimeter

We solve this problem by creating an intelligent ballistic dual-channel transformer gravimeter for measuring double the acceleration of gravity. This device comprises a stationary tube, a magnetized spherical test body, a device for holding the test body in its initial position, a computer, and an inductor winding. The new intelligent ballistic dual-channel transformer gravimeter is distinguished by its stationary tube being made of a dielectric material, the inductor winding serving as the primary excitation winding connected to a power source, the gravimeter additionally containing two identical sections of a secondary output winding connected in series-opposite fashion to create two measurement channels, and the device for holding the test body in its initial position containing an electromagnet consisting of a soft magnetic armature and an additional winding connected via a switch to an additional power source.

Figure 1 shows the structural diagram of an intelligent ballistic two-channel gravimeter with a pre-trained Fuzzy module for analysing the metal content in a sample.

Figure 2 shows a generalized diagram of the design of a new intelligent ballistic two-channel transformer gravimeter [1], showing how error compensation is carried out.

The structural diagram of the intelligent BDTG (Fig. 1) shows a fixed tube *2* made of a dielectric material, attached to a base (not indicated in Fig. 1), containing a magnetized test body *1* in the form of a ball, which can move along the tube up and down parallel to the O*Z* axis. At the top of the tube *2* is a device *12* for holding the test body in its initial position, which consists of an electromagnet *6* consisting of an anchor *7* made of a soft magnetic material and an additional winding *8*. This additional winding *8* is connected via a switch *9* to an additional power source *10*.

On the outer part of the tube *2* there is an inductance winding *3*, which acts as a primary excitation winding and is connected to a power source *5*, and two identical sections *13*, *14* of the secondary output winding *4*, connected in series-opposite to create two measurement channels.

The outputs of the secondary output winding *4* are connected to computer *11*. The output power of the new intelligent IBDTG is increased by feeding the output signals of two IBDTG channels to the input of computer *11*, from which a signal proportional to twice the val-

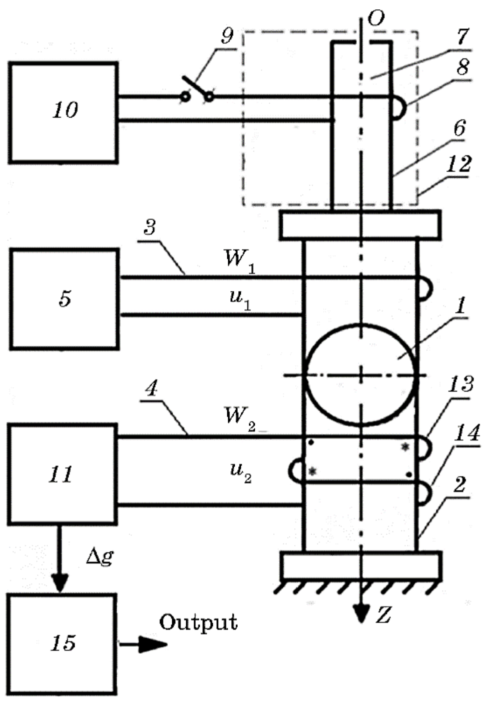

Fig. 1. Structural diagram of the intelligent ballistic dual-channel transformer gravimeter.

ue of g is read.

The output of computer *11* is connected to intelligent Fuzzy module *15*, the output of which is the output of the intelligent experimental setup (gravimetric system). Intelligent Fuzzy module *15* is pre-trained using the gravitational anomaly signal Δg to determine the types of metals in a given sample or the composition of minerals in a given area of the Earth's surface.

The results of measuring the gravitational anomaly Δg are automatically analysed in the intelligent Fuzzy module, which contains a database of fuzzy rules and linguistic variables and forms a logical conclusion regarding the composition of materials in the sample or the presence and type of minerals in a section of the Earth's surface. The intelligent Fuzzy Module *15* enables the processing of multiple measured data during sample composition analysis or in real time during the process of identifying minerals in a given area.

Figure 2 shows a generalized diagram of the design of an intelligent ballistic two-channel transformer gravimeter, where *1* is a test body of mass m, and *13* and *14* are the first and second sections of the secondary winding *4* of the intelligent ballistic two-channel transformer gra-

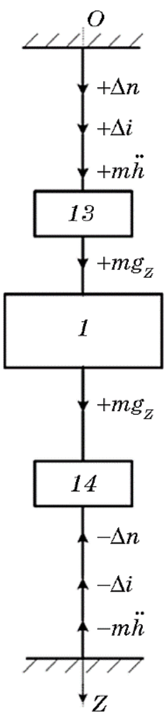

Fig. 2. Generalized diagram of the design of an intelligent ballistic two-channel transformer gravimeter (see Eq. (1)).

vimeter.

3.2. The Operating Principle of the Intelligent Two-Channel Ballistic Transformer Gravimeter

The proposed new intelligent BDTG works as follows. According to the law of electromagnetic induction, the excitation flux created by the primary excitation winding induces two oppositely directed electromotive forces in two sections of the secondary output winding, due to which, in the presence of effects from harmful external electromagnetic fluxes, inertial vertical acceleration, instrumental errors caused by changes in temperature, humidity, vibration, pressure, dry friction torque, residual non-identity of the parameters of two identical sections of the secondary output winding and other factors, their influence on the resulting accuracy of g measurement is eliminated. To create vertical movement in two opposite directions along the OZ axis of a test body in the form of a magnetized ball, the electromagnet winding is connected to a power source with a switch to create an electromagnetic flow of attraction of the test body, which, due to this, will rise to the extreme upper position, at the next moment the electromagnet switch is turned off, and the test body falls down under the action of gravity, the doubled output signal g, which is removed from the secondary winding, free from the influence of interference: external electromagnetic flows, inertial vertical acceleration, instrumental errors caused by changes in temperature, humidity, vibrations, pressure, the moment of dry friction forces, non-identity of the designs of two identical sections of the secondary output winding and other factors, is fed to the computer, from which the output signal of the gravimeter is removed, proportional to the doubled value of the SET.

The doubled value of the acceleration due to gravity is measured due to the fact that the output electrical signal of the ballistic two-channel transformer sensing element u_2, proportional to the total electromotive force of the two sections of the output secondary winding, will have the form (Fig. 2):

$$u_2 \equiv E_z = E_1 + E_2 \equiv mg + m\Delta\ddot{h} + \Delta i + \Delta n + mg - m\Delta\ddot{h} - \Delta i - \Delta n = 2mg\,, \qquad (1)$$

where E_1 is output signal from the first section of the secondary winding, E_2 is output signal from the second section of the secondary winding, $u_2 \equiv E_z$ is output signal of the ballistic two-channel transformer sensitive gravimeter, m is mass of the test body, Δh is vertical acceleration error, Δi is instrumental errors, Δn is errors of non-identity of parameters of two identical sections of the secondary winding.

The generalized diagram of a ballistic two-channel transformer gravimeter is shown in Fig. 2.

$$\Delta g = u_2 - \gamma_0 , \qquad (2)$$

where γ_0 is reference value of acceleration due to gravity [4].

From equation (1), it is evident that the output signal of the ballistic two-channel transformer gravimeter u_2 contains the doubled value of the useful signal AG and does not contain the inertial vertical acceleration $\ddot{h}$, total instrumental Δi errors, errors from non-identity of parameters of two sections of the secondary output winding, which increases the accuracy of measurements, Signal u_2 is fed to the computer input, from the output of which a signal proportional to the doubled value of the SET is taken.

Output is connected to an intelligent Fuzzy module, whose output is the output of the experimental setup (gravimetric system). The intelligent Fuzzy module is pre-trained using the gravitational anomaly signal Δg to determine the types of metals in a given sample or the composition of minerals in a given area of the Earth's surface.

The results of gravitational anomaly Δg measurements are automatically analysed in the intelligent Fuzzy module, which contains a database of fuzzy rules and linguistic variables and generates a logical conclusion regarding the presence and type of metals in the sample or the presence and composition of minerals in a given area of the Earth's surface. The intelligent Fuzzy module enables the processing of multiple measured data during the analysis of metal composition in a sample or in real time during the determination of mineral composition in a given area.

The design features of the intelligent ballistic dual-channel transformer gravimeter significantly improve the accuracy, speed, and reliability of measurements. This enables highly accurate, reliable, and fast determination of the metal composition of a sample or the presence and composition of mineral deposits in a given area of the Earth's surface.

4. CONCLUSION

An analysis of the operation of a well-known ballistic gravimeter is conducted.

Its main shortcomings limiting its application are noted, namely: does not allow one to determine the content of metals in a sample or the presence and composition of minerals in the area of the Earth's surface being studied, the known gravimeter is a single-channel inductive device.

When exposed to an external electromagnetic flux, the known gravimeter experiences significant errors, acting along the OZ sensitivity axis simultaneously with the useful gravitational acceleration signal g and significantly exceeding it, the vertical inertial acceleration, instrumental errors caused by changes in temperature, humidity, vibration, pressure, dry friction torque and other factors act directly along the sensitivity axis OZ, distorting the correct operation of the known gravimeter.

The first and second subsystems of the known gravimeter consist of a large number of devices operating on different principles, each with its own inherent errors. Therefore, combining the two subsystems does not improve accuracy, as the errors of the devices in both subsystems will be additive, the multitude of parts and components of the measuring system of the known gravimeter and the complex connections between them significantly reduce the reliability of such a system.

The relevance of applying an experimental method for determining the metal composition of a sample using a new intelligent dual-channel ballistic transformer gravimeter, which eliminates the aforementioned shortcomings of existing ballistic gravimeters, is substantiated. It is demonstrated that the new IBDTG has a twice-powerful output signal and greater accuracy due to the presence of a pre-trained Fuzzy module, which provides analysis of the metal content in the sample, as well as compensation for vertical acceleration, instrumental errors, errors due to the non-identical design of the two channels, errors due to changes in temperature, humidity, pressure, and other factors. The new IBDTG is also more reliable, as it has fewer parts and components of the measuring system with different operating principles and fewer complex connections between them.

This article presents the following new results: for the first time, the scientific aspects of applying a new experimental method for determining the composition of metals in a sample using an intelligent dual-channel ballistic transformer gravimeter with a pre-trained Fuzzy module are presented. It is demonstrated that the new intelligent BDTG possesses greater accuracy, speed, and reliability.

The practical value of the results obtained in this article is that the feasibility of the practical use of a new experimental method for determining the composition of metals in a sample by using an intelligent ballistic two-channel transformer gravimeter is substantiated, since it has greater accuracy, speed and reliability compared to the known single-channel ballistic gravimeter, has a simpler design and a doubled output signal.

AUTHORS' CONTRIBUTIONS

O. M. Bezvesilna provided a description of the IBDTG design, explained the physics of the IBDTG operation, formulated the research task. Yu. M. Koval explained the physics of the IBDTG operation, provided the principle of operation of the IBDTG. M. S. Grynevych performed a literature review on the topic of the study. T. O. Tolochko participated in presenting the literature review and its analysis, formatted the article.

REFERENCES

1. O. M. Bezvesilnaya, S. A. Nechay, and T. A. Tolochko, *Ballistic Two-Channel Transformer Gravimeter*, Patent for Utility Model No. 159371 (Published May 21, 2025) (in Ukrainian).
2. O. M. Bezvesilnaya, *Ballistic Gravimeter*, Patent of Ukraine No. 98058 (Published April 10, 2012) (in Ukrainian).
3. O. M. Bezvesilnaya and A. G. Tkachuk, *Aviation Gravimetric System for Measuring Gravity Acceleration Anomalies*, Patent of Ukraine No. 107637 (Published January 26, 2015) (in Ukrainian).
4. O. M. Bezvesilnaya, *Acceleration Measurements* (Kyiv: Lybid: 2021) (in Ukrainian).
5. O. M. Bezvesilnaya and T. A. Tolochko, *Tekhnichna Diahnostyka ta Neruinivnyi Kontrol*, No. 1: 16 (2025).
6. O. Bezvesilnaya, S. Nechai, M. Hrynevych, and T. Tolochko, *Herald of the Khmelnytsky National University. Techn. Sci.*: **355**, No. 4: 753 (2025).
7. O. M. Bezvesilnaya and G. S. Tymchik, *Technological Measurements and Devices. Transforming Devices of Devices* (Zhitomir: ZhTU: 2012) (in Ukrainian).
8. O. M. Bezvesilnaya and A. G. Tkachuk, *Three-Coordinate Piezoelectric Gravimeter of Aviation Gravimetric System*, Patent of Ukraine No. 113033 (Published November 25, 2016) (in Ukrainian).
9. Y. Huang, A. V. Olesen, M. Wu, and K. Zhang, *Sensors*, **12**, Iss. 12: 9336 (2012).
10. A. G. Tkachuk and O. M. Bezvesilnaya, *Transformer Gravimeter*, Patent for Utility Model No. 142824 (Published June 25, 2020) (in Ukrainian).
11. B. B. Samotokin, *Lektsiyi z Teoriyi Avtomatychnoho Keruvannya* [Lectures on the Theory of Automatic Control] (Zhitomir: ZHITI: 2001) (in Ukrainian).
12. O. M. Bezvesilnaya and N. V. Ilchenko, *Methods and Means of Improving the Accuracy Characteristics of an Instrumented System for Measuring Mechanical Parameters and Stabilization* (Kyiv: Igor Sikorsky Kyiv Polytechnic Institute: 2020) (in Ukrainian).
13. C. Roussel, J. Verdun, J. Cali, and M. Maia, *Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sci.*, **XL-5/W5**: 199 (2015).
14. E. N. Bezvesilnaya, Y. V. Kyrychuk, M. S. Hrynevych, and T. A. Tolochko, *Bulletin of the Karaganda University Physics Series*, **112**, No. 4: 23 (2023).
15. I. Korobiichuk, O. Bezvesilna, A. Tkachuk, A. Praczukowska, and T. Khylchenko, *Systems, Control and Information Technology (May 20–21, 2016)* (Warsaw: 2016), p. 481.
16. K. Hehl, *Int. Association of Geodesy Symposium*, No. 113: 161 (1994).
17. C. Jekeli, *Bulletin Géodésique*, **69**, No. 1: 1 (1995).
18. C. Jekeli and J. H. Kwon, *Geophysical Research Lett.*, **26**, No. 3: 3533 (1999).
19. Y. Huang, A. V. Olesen, M. Wu, and K. Zhang, *Sensors*, **12**, Iss. 7: 9336 (2012).
20. M. Calvoa, J. Hinderera, S. Rosata, H. Legrosa, J.-P. Boya, B. Ducarmec, and W. Zürnd, *J. Geodynamics*, No. 80: 20 (2014).
21. G. Agostino, S. Desogus, A. Germak, C. Origlia, D. Quagliotti, G. Berrino,

G. Corrado, V. Derrico, and G. Ricciardi, *Annals of Geophysics*, No. 51: 39 (2008).
22. C. Roussela, J. Verduna, J. Calia, and M. Maiab, *The Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, No. XL-5/W5: 199 (2015).
23. O. Bezvesilnaya, L. Chepyuk, A. Tkachuk, S. Nechai, and T. Khylchenko, *Technology Audit and Production Reserves*, **3**, No. 1: 53 (2017).
24. O. M. Bezvesilnaya, *Aviation Gravimetric System for Measuring Gravity Acceleration Anomalies*, Patent of Ukraine No. 105122 (Published April 10, 2014) (in Ukrainian).
25. O. M. Bezvesilnaya and A. G. Tkachuk, *Aviation Gravimetric System for Measuring Gravity Acceleration Anomalies*, Patent of Ukraine No. 113038 (Published November 25, 2016) (in Ukrainian).
26. T. V. Khylchenko, *Electronic Modeling*, **40**, No. 3: 87 (2018).
27. Y. Bezvesilnaya, S. Nechai, and T. Tolochko, *String Accelerometer of the Automated System* (DeProMonograph: 2025).
28. A. Tkachuk, O. Bezvesilna, I. Kryzhanivska, and M. Bogdanovsky, *Sci. Heritage*, No. 142: 58 (2024).
29. O. Bezvesilnaya, *Aviation Gravimetric System for Measuring Gravity Anomalies*, Patent of Ukraine No. 109746 (Published September 25, 2015) (in Ukrainian).
30. O. Bezvesilna, S. Nechai, and T. Tolochko, *Proc. of the 8th Int. Sci. Practical Conf.* (Berlin: 2024), p. 77.
31. O. M. Bezvesilnaya, L. V. Kolomiets, M. S. Grynevych and T. O. Tolochko, *Collection of Scientific Works of the Odessa State Academy of Technical Regulation and Quality*, **1**: 17 (2022).
32. O. M. Bezvesilnaya and M. S. Hrynevych, *Tavria Scientific Bulletin. Series: Technical Sci.*, **6**: 3 (2022).
33. O. M. Bezvesilnaya and A. G. Tkachuk, *Strain Gauge Gravimeter*, Patent of Ukraine No. 132179 (Published February 11, 2019) (in Ukrainian).
34. O. M. Bezvesilnaya, *Aviation Gravimetric System for Measuring Gravity Acceleration Anomalies*, Patent of Ukraine No. 105949 (Published July 10, 2014) (in Ukrainian).