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ПІДВИЩЕННЯ ТОЧНОСТІ ХАРАКТЕРИСТИК БАЛІСТИЧНОГО ГРАВІМЕТРА

В статті надано відомості про проведені експериментальні дослідження нового балістичного лазерного гравіметра (БЛГ). Надано опис створеної лабораторної установки для дослідження блоку лазера, опис процедури регулювання і перевірки лазера на величину сканування резонатора. Використано вимірювальну апаратуру, яка дозволила контролювати параметри вібрації вібраційного стенду, з точністю у 3 рази вищою за точність БЛГ. Це для сучасного БЛГ склало похибку, не більшу 5 % від величини прискорення сили тяжіння (ПСТ), що вимірюється. Проведено дослідження ПСТ на створеній лабораторній установці. Завдяки введенню у конструкцію БЛГ нових елементів та застосуванню властивостей процедури апроксимації результатів вимірювання за методом найменших квадратів, новий БЛГ має підвищену точність: 0,1 мкГал. Експериментальними дослідженнями підтверджено адекватність теоретичних досліджень, доцільність практичного використання нового БЛГ.

У статті розглянуто питання наявних можливостей вимірювання прискорення сили тяжіння за допомогою абсолютних балістичних гравіметрів, вдосконалення системи автоматизації обробки інформації та можливість подальшого створення системи відео спостереження за процесом отримання результатів, що повинно усунути похибки та забезпечити максимальну точність вимірювання.

Ключові слова: гравіметр, гравіметричні аномалії, прискорення сили тяжіння.

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IMPROVING THE ACCURACY OF BALLISTIC GRAVIMETER CHARACTERISTICS

The article provides information on the conducted experimental studies of a new ballistic laser gravimeter (BLG). A detailed description of the created laboratory setup for studying the laser unit is provided, as well as a description of the procedure for adjusting and checking the laser for the size of the resonator scan. The experiments utilize measuring equipment which allowed controlling the vibration parameters of the vibration stand with an accuracy 3 times higher than the accuracy of the BLG. For a modern BLG, this amounted to an error of no more than 5% of the measured gravitational acceleration (GGA). A GGA study was conducted on the created laboratory setup. Due to the introduction of new elements into the BLG design and the application of the properties of the procedure for approximating measurement results by the least squares method, the new BLG has an increased accuracy: 0.1 μGal. Experimental studies confirmed the adequacy of theoretical studies and the feasibility of practical use of the new BLG. Analysis of existing ballistic gravimeters revealed such disadvantage [2] as their high sensitivity to a large number of influencing factors, which, in turn, entails structural complexity, large overall dimensions and weight of gravimeters, as well as their peripheral devices, complexity of processing results, low measurement performance, etc.

The task of measuring gravitation acceleration by ballistic methods is essentially reduced to measuring distance and time. This follows, for example, from the analysis of the acceleration dimension. Therefore, the mathematical model must reveal the analytical relationship of the path traveled by the test body with time and external disturbing influences. The most constructive approach to building a model will be such that, on the one hand, the free motion of the test body in the inertial coordinate system is considered, taking into account the vertical gradient of the PST and resistance forces, and on the other hand, the law of motion of some coupled coordinate system is determined, which is displaced under the action of external inertial disturbances and the holding reference system of the gravimeter [2, 3].

The article considers the issues of existing capabilities for measuring the acceleration of gravity using absolute ballistic gravimeters, improving the information processing automation system, and the possibility of further creating a video surveillance system for the process of obtaining results, which should eliminate errors and ensure maximum measurement accuracy.

Key words: gravimeter, gravimeter anomaly, acceleration of force of weight.

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Formulation of the problem

Problem statement. Measuring the absolute value of the acceleration of gravity (g) with high accuracy is a basic element for successfully solving a wide range of scientific problems: determining the shape of the Earth, building models of the movement of deep masses, assessing elastic deformations of the planet's surface, predicting earthquakes, building models of deep density inhomogeneities, searching for mineral deposits, using the value of g as a basis for determining other physical quantities. [1-8]. The hardware for solving these scientific problems is gravimetric instruments.

Modern research in the field of gravimetric equipment development is focused mainly on two aspects: the first is increasing the accuracy of measurements by ballistic gravimeters by eliminating the influence of seismic vibrations on the measurement process, the second is building effective automated systems for the gravimetric measurement process [5].

Data on modern developments of such systems indicate that domestic devices are currently inferior in their technical characteristics (in terms of final accuracy of measurement results and other metrological parameters) to foreign developments. In addition, a program of updating the gravimetric equipment of the reference points of the national geodetic network is currently underway in Ukraine [2].

Nowadays, commercial versions of gravimeter designs are becoming widespread. Commercial gravimeters are adapted to operating conditions in harsh climatic conditions: high humidity, high ambient temperatures, local transport noise, other city noise (construction sites, industrial noise, etc.). The accuracy of such gravimeters is usually lower, which allows them to reduce their price. Large industrial groups, as a rule, purchase gravimeters for their own research work in the field of geological exploration: searching for oil, gas, and other mineral deposits. Certain requirements are imposed on such devices: compactness, versatility in use, convenience and ease of maintenance, maintainability, long operating time before failure, unification of nodes for connection with other equipment, ability to work in harsh environmental conditions, sufficient accuracy, affordable price [2].

Research analysis.

Studies in the field of measuring the acceleration of gravity have shown that the ballistic method consists in measuring the length of the path traveled by a freely falling body that began its movement from zero initial velocity over a certain period of time. Based on the dependence of the path length on time, the acceleration of gravity is determined [2, 3, 8].

The creation of perfect ballistic gravimeters (BG) became possible after the invention of lasers, which are characterized by high monochromaticity and coherence.

The widespread introduction of lasers and photoelectric converters into measuring equipment, which modulate the flow of light into electrical signals, has allowed us to create a number of designs of laser meters in our country and abroad. The main advantages of which are the following: increased measurement accuracy; reduced measurement time; automation of the measurement process; reduced training of service personnel.

The paper investigates the possibilities of increasing the accuracy characteristics of gravimetric equipment built on the basis of lasers and photoelectric converters, calculates mathematical models of a ballistic gravimeter, and considers the possibility of constructing a functional diagram of the main modules of an automated BG system.

The purpose of the work: to increase the accuracy of measuring the acceleration of gravity by studying an absolute gravimetric device and developing an automated system for measuring the acceleration of gravity based on scientific research.

The main part. The principle of operation of the gravimeter is the ballistic method of measuring the absolute value of the acceleration of gravity (GAF) g, which is determined from the results of measuring the path and time of free fall of an optical angular reflector. The path traveled by a falling body is measured by a laser interferometer, and the time intervals are measured by signals of a precision (for example, rubidium) frequency standard [2].

The determination of the absolute value of the PST is performed by known gravimeters with an error of 0.5 μGal, which includes both instrumental error and the influence of external measurement conditions.

The ballistic gravimeter used should have a practically unlimited measurement range, the instability of the wavelength of the working laser radiation during the observation should not exceed $5 \cdot 10^{-9}$, the relative error of the frequency standard should not be more than $5 \cdot 10^{-10}$, the residual gas pressure in the ballistic chamber should not exceed $5 \cdot 10^{-6}$ mm Hg. column.

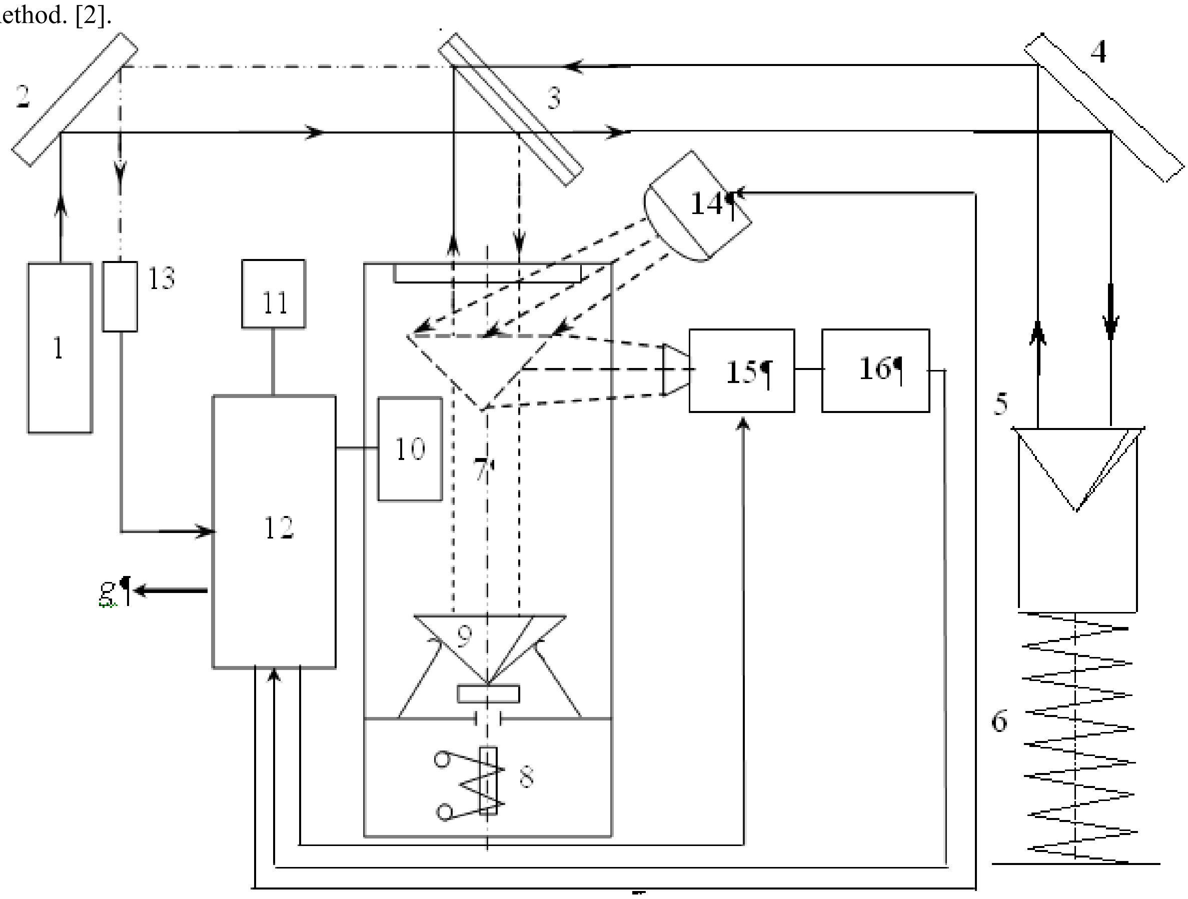
Technical characteristics of the absolute ballistic gravimeter [2]:

- root mean square measurement error – no more than $\pm 2 \cdot 10^{-8}$m/s ^{2};
- systematic error – no more than $\pm 5 \cdot 10^{-8}$m/s ^{2};
- gravimeter dimensions:
  - optical-mechanical unit – $1200 \times 700 \times 700$mm;
  - electronic unit – $620 \times 560 \times 660$mm;
- The total weight of the gravimeter is 180 kg.

Based on the study of modern patent information and scientific and technical sources, it was established that in the development of ballistic gravimetric devices, the following two directions of the ballistic method have been clearly defined: "Free-fall" and "Rise&fall" (asymmetric and symmetric). Analysis of the structural elements of the device indicates the imperfection of the structure and the complexity of solving technical problems associated with increasing the accuracy of measurements using an absolute ballistic gravimeter. To date, there is no structural diagram of a ballistic measuring device that measures the acceleration of gravity with high accuracy, which confirms the relevance of the tasks we have identified.

The set of technical methods and means of measuring path and time is diverse, but despite this, the structure of a modern ballistic absolute gravimeter can be described.

Fig. 1 shows a simplified diagram of a new ballistic laser gravimeter operating according to the symmetric method. [2].



1 – laser; 2 – laser interferometer mirror; 3 – optical dividing plate; 4 – seismograph mirror; 5 – fixed angular reflector of the seismograph; 6 – long-period seismograph; 7 – vacuum chamber; 8 – starting device; 9 – test body (angular optical reflector); 10 – manometer; 11 – time stamp generator; 12 – computer; 13 – photoelectric multiplier; 14 – pulsed light source; 15 – video camera; 16 – unit for approximating the trajectory of the test body

Fig.1. Schematic of the new ballistic laser gravimeter

The main disadvantage of ballistic gravimeters [2] is their high sensitivity to a large number of influencing factors, which, in turn, entails structural complexity, large overall dimensions and weight of gravimeters, as well as their peripheral devices, complexity of processing results, low measurement performance, etc.

The task of measuring the PST by ballistic methods is reduced to measuring length and time. This follows, for example, from the analysis of the acceleration dimension. Therefore, the mathematical model must reveal the analytical relationship between the path traveled by the test body and time and external disturbing influences. The most constructive approach to building a model will be such that, on the one hand, the free motion of the test body in the inertial coordinate system is considered, taking into account the vertical gradient of the PST and resistance forces, and on the other hand, the law of motion of some coupled coordinate system is determined, which is displaced under the action of external inertial disturbances and the holding reference system of the gravimeter [2, 3].

Consideration of the free motion of a test body thrown vertically upwards in an inertial coordinate system is reduced to solving a nonlinear 2nd order differential equation of the following form:

$$m \cdot z'' = m \cdot (g_0 + \alpha \cdot z) - \gamma_1 \cdot z' - \gamma_2 \cdot (z')^2, \tag{1}$$

where m is the mass of the test body;

z – vertical coordinate;

α – vertical gradient;

γ_1, γ_2 – coefficients that determine the contribution of resistance forces proportional to the first and second powers of the speed of motion of the test body, respectively.

Solving equation (1) by the method of successive approximations using Laplace transforms and subsequent expansion into a series in powers of z leads to the following equation:

$$z(t) = g_0 \cdot \sum_{n=0}^{\infty} A_n \cdot t^n, \tag{2}$$

where A_n is a set of coefficients that are determined from the conditions of motion of the test body in the ballistic block relative to the reference system.

This expression describes the motion of a test body in an inertial coordinate system. In the conditions of real PST measurement, the coordinate of the test body is determined in a coupled coordinate system that is subject to perturbations. As is known, the coordinates of the test body in the inertial system uniquely depend on its coordinates in the coupled system:

$$\overline{R}_i = \overline{r} + \overline{R}, \tag{3}$$

where $\bar{R}_i$is the radius vector of the test body in the inertial system;

$\overline{r}$ – radius vector of the test body in the coupled system;

$\overline{R}$ – radius vector describing the displacement of the connected system.

Therefore, as a rule, the operation of a ballistic gravimeter is carried out so that the sensitivity axis (in our case the *z axis*) is held vertical. Then equation (3) can be simplified:

$$S(t) = z(t) + R_z(t). \tag{4}$$

In this expression, the component $S(t)$ describes the behavior of the test body in the inertial system, and the component $R_z(t)$ describes the influence of external perturbing actions of an inertial nature.

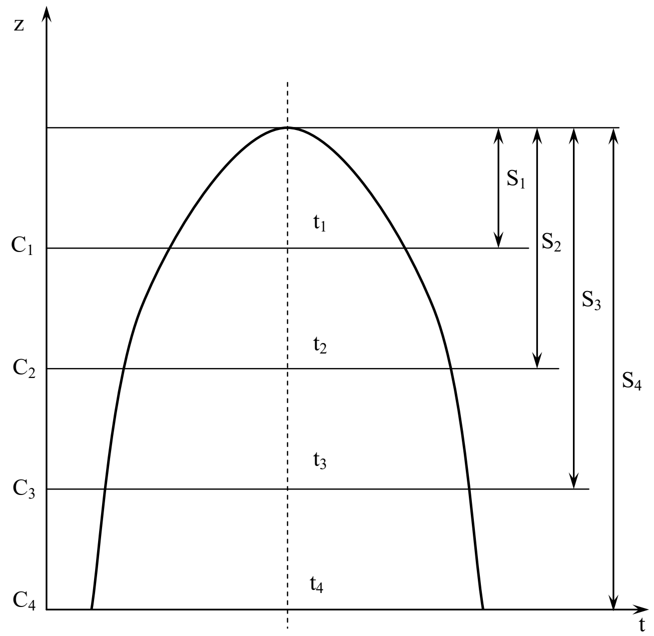
The PST measurement algorithms using the described model are very diverse, both in terms of the method of implementing the free motion of the test mass and in terms of the methods of measuring the path and time.

Depending on the method of implementing free movement, all methods can be divided into two groups [2, 3]:

- with asymmetric free movement (Fig. 2);
- with symmetrical free movement (Fig. 2).

When using symmetrical methods (both branches of the parabola in Fig. 2), the test body is thrown upwards, and the path and time measurements are taken on the ascending and descending branches of the trajectory.

When using asymmetric methods (the right branch of the parabola in Fig. 2), the test body moves freely (falls) in a vacuum.



C_1 – C_4 – observation levels (stations); t_1 – t_2 – the moments of the end of the measurement intervals; S_1 – S_2 – measurement intervals

Fig.2. Flight trajectory of a test body in a ballistic gravimeter

These methods are distinguished by the relatively simple implementation of free motion and the absence of the need to apply an impulse (impact) force when launching the test body, which depends on the height of the throw, which significantly improves the dynamic operating conditions of the gravimeter.

The advantages of symmetrical methods include the possibility of almost complete elimination of systematic errors, which are proportional to the first power of the speed of movement of the test body, with a relatively simple measurement algorithm, as well as the possibility of reducing the vertical dimensions of the device, since at the same height of the gravimeter the total path traveled by the body in this case will be large. However, at the moment of the throw, an impulse reactive force arises, which disturbs the reference system and introduces an error into the measurement results using the symmetrical method.

Given the presence of undefined coefficients A_n in expression (2), it does not allow us to directly determine PS T g_0 by the measured value of t and $z(t)$. For this, it is necessary to carry out measurements at several observation intervals: $t_1, t_2, t_3, \dots, t_n$ (Fig. 2). Then instead of equation (2) we obtain a system of equations:

$$\left.\begin{aligned}
z_0^* &= A_0 + A_1 \cdot t_0 + A_2 \cdot t_0^2 + \ldots + A_n \cdot t_0^n \\
z_1^* &= A_0 + A_1 \cdot t_1 + A_2 \cdot t_1^2 + \ldots + A_n \cdot t_1^n \\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
z_i^* &= A_0 + A_1 \cdot t_i + A_2 \cdot t_i^2 + \ldots + A_n \cdot t_i^n \\
z_N^* &= A_0 + A_1 \cdot t_N + A_2 \cdot t_N^2 + \ldots + A_n \cdot t_N^n
\end{aligned}\right\}, \quad (5)$$

where$z_i^* = z(t_i)/g_0$.

By conducting measurements on a large number of free motion intervals, it is possible to determine the number of coefficients in equation (2) that is necessary for a detailed study of the flight trajectory when investigating the influence of various factors on the law of motion of the test body, since their quantitative influence is determined by the coefficients A_{and}:

$$A_0 = S_0/g_0,$$

where S_0 is the initial position of the test body;

$$A_1 = V_0/g_0,$$

where V_0 is the initial velocity of the test body;

$$A_2 = 0{,}5$$

$$A_3 = \alpha \cdot (S_0 + V_0 \cdot t/3 + g_0 \cdot t^2/12)/2 \cdot g_0,$$

where α is the vertical gradient, etc.

Until recently, measurements at a large number of intervals were carried out with significant technical difficulties, and therefore, as a rule, they were limited to 2...4 measurement intervals, while ensuring such experimental conditions under which the coefficients A_{and} higher orders were neglected (this is the basis of the difficulties in modern accurate gravitational measurements).

Thanks to the development of microelectronics and computing, nowadays almost all foreign ballistic gravimeters are built according to the scheme of measuring a large number of path and time intervals.

Similar solutions of the system of equations (5), for different partial cases, can be found in various literature [2, 3]. Thus, the symmetric method will differ from the asymmetric one only in the value of the initial velocity, and the multi-station method from the two-station method - in the number of *i*- equations. By varying the dimensions of the matrix of coefficients of the system of equations (5), it is possible to obtain all possible combinations of the PST measurement conditions using the ballistic method. However, it should be noted that the symmetric method will be accurate only if the complete symmetry of the measurement intervals is observed (when the position of point O in Fig. 2 is clearly known in space or time, which is fundamentally impossible).

There are the following methods of approximate symmetrizing of time *t* [2, 3]:

- direct search for the trajectory vertex and time symmetrizing;
- symmetrizing the path traveled by the test body from the beginning of the measurement interval to the top of the trajectory;
- symmetrizing by the speed of movement of the test body.

The second and third methods of symmetrizing measurement moments are most often used.

Conclusions

This work considers the most important issues related to the design and functional features of a modern absolute laser ballistic gravimeter. Theoretical research was conducted on the basis of an analysis of modern domestic and foreign scientific database. A study of the PST was conducted on a created laboratory setup. Due to the introduction of new elements into the design of the BLG and the application of the properties of the procedure for approximating measurement results by the least squares method, the new BLG has increased accuracy: 0.1 μGal. Experimental studies have confirmed the adequacy of theoretical research and the feasibility of practical use of the new BLG. As noted above, the main direction of development is to increase the accuracy of BLG measurement results by improving the automation system for processing results and developing a video surveillance system for the process of obtaining information, which should also eliminate errors and ensure maximum measurement accuracy. It is this BLG that was created on the basis of the National Technical University "KPI" and Zhytomyr State Technological University, the accuracy of PST measurements of which (0.1 μGal) is 5 times higher than that of known BLGs (0.5 μGal).

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