A BALLISTIC LASER GRAVIMETER FOR A SYMMETRICAL MEASUREMENT METHOD WITH THE INDUCTIVE-DYNAMIC CATAPULT AND AUTO-SEISMIC VIBRATION PREVENTING

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Abstract

A ballistic laser gravimeter (BLG) with a symmetrical measurement method of the gravity acceleration (GA) is considered. Special treatment is given to the problem of eliminating the measurement error due throw of the catapult when it speeds up the test body (TB). It is possible to decrease the indicated errors thanks to the use of the induction and dynamic catapult. However, a short-term boost catapult generates vibrations of the basement (i.e. a pillar) and the mechanical elements of the gravimeter, what causes auto-seismic (i.e. recoil-related) component of the measurement error. To reduce them it is proposed to launch the TB with the help of a massive platform, installed on a light spring. It is shown, that the considered BLG can provide auto-seismic component of the measurement error of less than 1 μGal. With the reduction of the light spring constant the auto-seismic component of GA measurement uncertainty is reduced. The value of this measurement error can be reduced by the use of damping in the system of BG protection from auto-seismic fluctuations. A concept of BLG with induction-dynamic catapult for symmetric method of gravitational acceleration measuring is presented. The concept is based on using electromagnetic compensator of stiffness.

Introduction

For high-precise measurements of the gravity acceleration (GA) ballistic laser gravimeters (BLG) are used. These gravimeters employ either symmetrical or nonsymmetrical schemes of measurements. Gravimeters with symmetrical scheme of measurements don not require high vacuum, because the force of resistance of the gas atmosphere influence the result of measurement with the opposite signs at the rise and fall of the test body (TB) with a retroreflector, resulting in their mutual compensation. Furthermore, these gravimeters have small sizes and may be used as transportable measuring devices. The main drawback of gravity meters with a symmetrical pattern - mechanical effect, which occurs when throwing by TB catapult. Push of catapult causes fluctuations of the fundament called auto-seismic, and other mechanical elements of gravimeter, what causes the appropriate component of measurement uncertainty of GA, reaching the values of several tens or even hundreds μGal [1, 2].

To reduce the level of auto-seismic fluctuations it is proposed to launch the TB from a massive platform, installed on soft springs. To implement this spring it is proposed to use electromagnetic compensator of stiffness.

The aim of this paper is to study ways of non-rigid mounting of the platform with a catapult in the BLG with the symmetrical scheme of GA measurement, which provides a reduced auto-seismic component of the error (ACE) of the GA measurement.

Mathematical model of ballistic laser gravimeter

In the interferometer of BLG a flexible suspension (vibroprotective device) of the reference reflector is usually used [3]. Acting in this manner allows us to depress the impact of both external seismic and auto-seismic disturbances when the self-exited vibrations in the suspension system have a relatively long period. This paper is devoted to one other method for depressing the auto-seismic effect at the expense of suspending the launching platform. To examine the efficiency of the proposed method we consider such a model of the BLG mechanical system where the reference reflector is rigidly attached to the basement. Further it is supposed to use this method together with flexible suspending of the interferometer reference reflector. This suspension has to eliminate almost completely the influence of the auto-seismic effect on the error of gravity acceleration measurement.

In principle, for elimination of the recoil in BLG a constant-force spring can be used. However, in practice, to implement a spring with a constant force for the platform with catapult is possible only with some approximation due to technological difficulties. Furthermore, at the zero stiffness of a spring and platform with catapult, it will be unstable. Therefore, let us consider the case where the spring constant holding the catapult with the TB, is positive.

Fig. 1 depicts a model of the mechanical system of BLG corresponding to the scheme when the reference reflector is rigidly attached to the basement (there is no reference reflector shown in the Fig. 1). This model can be used to analyze the impacts of the transmission impulse catapult to a reference reflector. The following notation is used: *m* is for the mass of the TB; *m₀* is for the total weight of the basement, the ballistic unit and the interferometer, c_0 is for the stiffness coefficient of the ground base, b_0 is for the viscous damping coefficient of the basics; m_1 is for the mass of the launching platform; *c* and b_1 are respectively the stiffness and damping coefficients of the catapult platform.

Let *F(t)* be the force to act on the platform vertically downward as the TB speeds up. The impact of the rectangular type can be considered as the simplest model of force

$$F(t)=\begin{cases} mg,\ if\ \ t\le 0; \\ mg+F_0,\ if\ \ 0<t\le\tau; \\ 0,\ t>\tau, \end{cases} \tag{1}$$

where τ stands for the time to speed up of the TB.

From the condition of the law of conservation of momentum $F_0\tau = vm$, where v is the velocity of the TB at $t=\tau$, it follows

$$F_0=\frac{v}{\tau}m. \tag{2}$$

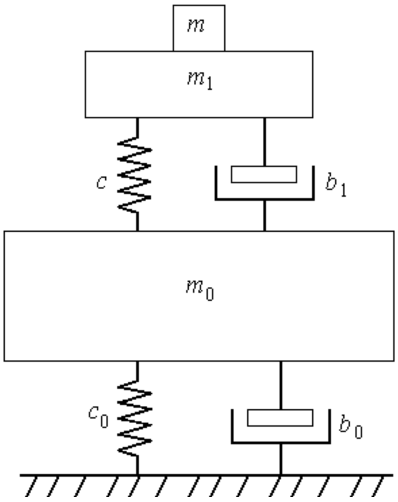


Figure 1 – Model of the BLG mechanical system

Movement of the platform and the basement in a vertical direction, and hence the reference reflector, is described by a system of differential equations

$$\begin{cases} m_1\dfrac{d^2x_1}{dt^2}=b_1\cdot\dfrac{d}{dt}(x_0-x_1)+c\cdot(x_0-x_1)+F; \\ m_0\dfrac{d^2x_0}{dt^2}=-b_0\dfrac{dx_0}{dt}-b_1\cdot\dfrac{d}{dt}(x_0-x_1)-c_0x_0-c(x_0-x_1), \end{cases} \tag{3}$$

where x_0 and x_1 are respectively deviations of the basement and launching platform from the positions they would have if the TB was absent.

In the initial position of the system of equations (3) takes the form

$$\begin{cases} c\cdot(x_0-x_1)+mg=0; \\ c_0x_0=cx_1, \end{cases}$$

when

$$x_0(0)=\frac{mg}{c_0},\qquad x_1(0)=\frac{(c+c_0)mg}{c_0c}=(\frac{1}{c_0}+\frac{1}{c})mg. \tag{4}$$

From the solutions of the equations (3) with the initial conditions (4) and

$$\frac{dx_0(0)}{dt}=\frac{dx_1(0)}{dt}=0 \tag{5}$$

we define functions $x_0(t)$ and $x_1(t)$.

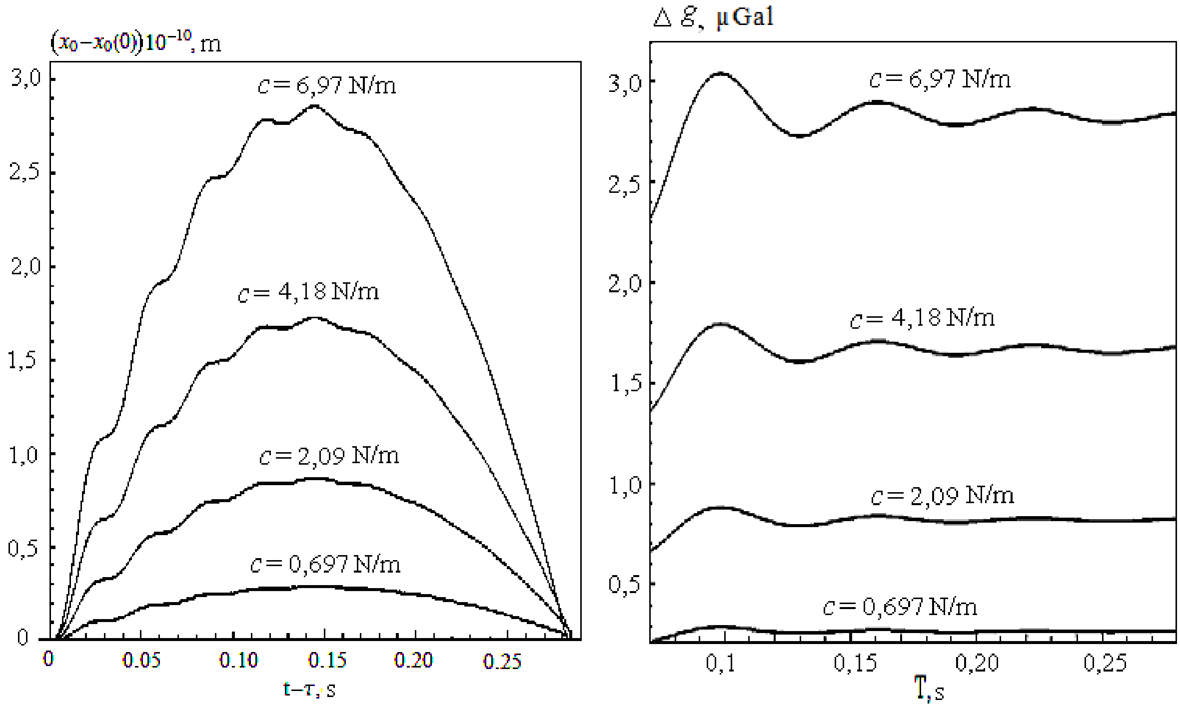
When the interferometer with the reference reflector is rigidly attached to the basement, the ACE of measurement of GA, Δg, is defined in accordance with the expression [1, 2]

$$\Delta g=\sum_{k=0}^{K-1}x_0(kh+t_0-\frac{T}{2})\cdot w(k), \tag{6}$$

where $x_0(t)$ is for the process of moving the basement; h is for discretization interval sampling path traversed by the TB; t_0 is for the moment of reaching the top by the TB, *w(k)* are for weighting coefficients of processing. The coefficients *w(k)* can be determined by the method of least squares.

Let us consider the kind of functions for typical conditions and different values of the spring constant *c*. Following the work [1], let us take the mass of the basement $m_0=3000\,kg$, base stiffness $c_0=125.88$ *MN/m*, coefficient of viscous base damping $b_0=73743.2\,N\cdot$s/m; mass of TB $m=0.08$ *kg*; TB initial velocity $v=1.4$ m/s (corresponding to a roll at a height of about 0.10 *m*). TB acceleration time is set equal to 2 *ms*.

Let's assume first damping factor $b_1=0$ and using Wolfram Mathematica programming system system of equations (3) with the initial conditions (4, 5) for different values of the spring constant c. Let's consider that in the absence of the electromagnetic compensator according to the earlier performed calculations $c\approx 209\ N/m$. The calculation results are presented in Fig. 2a.



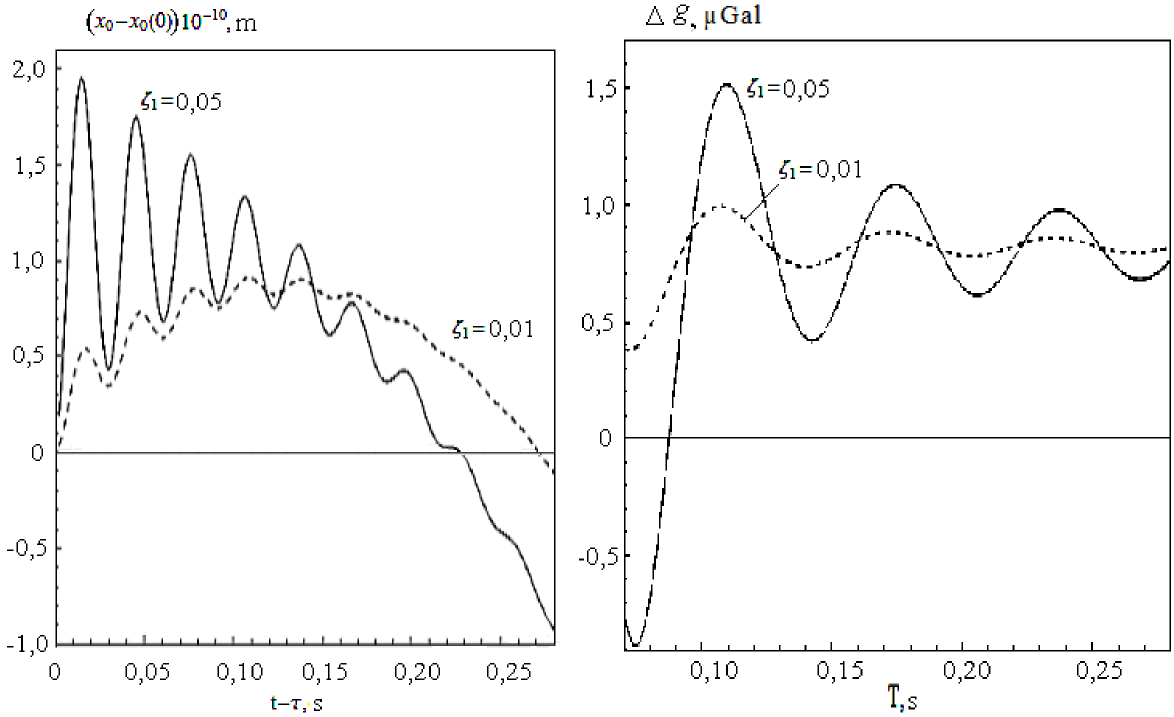
a) b)

Figure 2 – The movement of the basement (a) and dependence of ACE of GA measurement from processing time (b) for various stiffness platform installations without damping

The value Δg is determined using the expression (6) by setting the sampling interval h of 0.5 ms. Fig. 2b shows the depending of ACE of AG measurement by the symmetrical BLG using the least squares method of T processing. From the analysis of dependencies, presented in Fig. 2b, it follows that when setting the starting platform (mass $m_1 = 1.6$ kg) with a coefficient of stiffness $c \approx 2.1\, N/m$ of ACE measurement GA doesn't exceed 1 μGal.

Let's consider the effect of a damper on the characteristics of BG. The results of calculations for the case of damped system of protection against auto-seismic fluctuations ($b_1 = 0$) executed by the method described above for different relative damping coefficients $\xi_1 = \dfrac{b_1}{2\sqrt{c_1 m_1}}$ are shown in Fig. 3a and Fig. 3b. At the same time all described above modeling conditions are stored.

On the basis of a comparison of curves in Fig. 2a and Fig. 3a it follows that increasing the damping increases the amplitude of oscillations of auto-seismic fluctuations of BG basement, which entails an increase in the error of measurement of GA (see Fig. 3b). At the same time, it was established during the investigations, the damping coefficient has very small effect on the frequency response of the mechanical system of ballistic gravimeter relative to foreign interference. Therefore, it is rationally to eliminate the damper in the system of protection against mechanical vibrations.



a) b)

Figure 3 – The movement of the basement (a) and dependence of ACE of GA measurement from processing time (b) during the installation of start platform with stiffness $c \approx 2.1\,N/m$ and damping

Thus, a ballistic gravimeter with symmetrical measurement circuit can provide ACE less than 1 μGal. To do this, throw the TB from a massive base, installed in the spring low stiffness. With a decrease in stiffness of the spring due to the use of the electromagnetic compensator of ACE of GA measurement decreases.

When hanging the launching platform on a soft spring, the period of the self-exited vibrations in the suspension system exceeds the TB flight time. Thus, as soon as the TB felt down, the launching platform had to be stopped and returned to the initial position. These actions are done by the electromagnetic compensator.

Concept of ballistic laser gravimeter

Let's consider the concept of ballistic gravimeter with induction-dynamic catapult symmetric method for measuring gravitational acceleration, which uses electro-magnetic compensator stiffness. Gravimeter comprises a vacuum chamber 1, in which there are located PT 2 with optical angle reflector 3, the power drive 4, holding the PT 2 and the induction-dynamic catapult (Figure 4) [4]. Catapult consists of winding 5 to be connected to the capacitive energy storage device, and disposed coaxially of the armature 6 made in the form of a disc made from electro-conductive material such as copper. Power disc 4 is made with a guide cone 7 made from insulating material. The shape of the side walls of the cone 7 coincides with the shape of the side walls of the guide cone axial groove 8 of the inner frame 9 of the winding 5.

,The anchor 6 provided with a central-site up responses to the guide cone 7. The winding 6 induction-dynamic catapult located inside the ferromagnetic core 10 covering its outer side and bottom end side, the outer diameter of the ferromagnetic core coincides with the outer diameter of the armature 6. The ferromagnetic core is made of magnetodielectric [5]. Gravimeter comprises a platform 11 and a base plate 12. On the platform 11 is fixed the vacuum chamber 1. On the outer portions of the platform 11 with holes, which cover vacuum chamber 1. Inside the vacuum chamber openings are arranged vertical uprights 13 which are interconnected with the support plate 12. Plate 12 is mounted on a massive basement 15 with the help of supports 14.

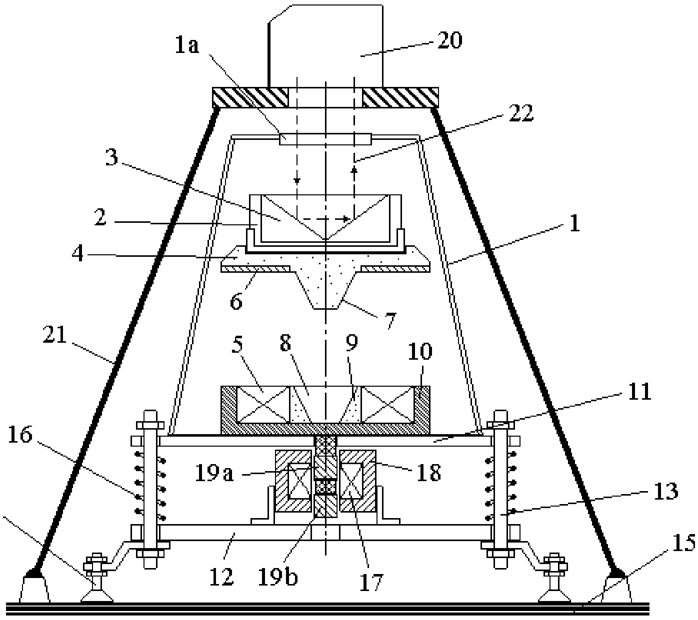
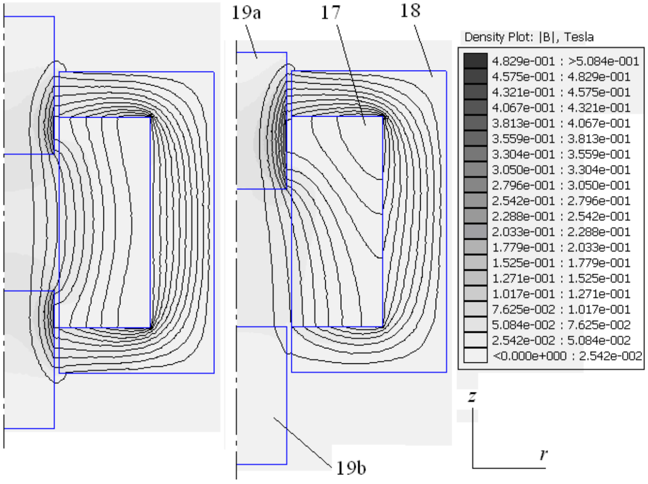


Figure 4 – Ballistic laser gravimeter in operable condition

Vertical racks 13 covered by coil springs 16 which hold the platform 11 relative to the base plate 12. To the plate 12 is connected coaxial magnet 17 covered by ferromagnetic core 18. The central bore of the magnet 17 is a cylindrical moving element 19, comprising an upper element 19a and lower ferromagnetic portions 19b which are located symmetrically relative to the central plane of the magnet between the nonmagnetic portions. Cylindrically movable element 19 is connected to platform 11. The optical receiving and emitting device 20 positioned on a tripod 21 installed on the massive base 15. In this case, the central hole of the tripod for the laser beam 22 is located opposite the optical window 1a of the vacuum chamber.

In the initial state between the movable element 19 and coaxial magnet 17 there is no electromagnetic force, since the upper 19a and lower 19b sections of the ferromagnetic elements 19 are arranged symmetrically about the central plane of the magnet 17 (Figure 5a). By guiding cone 7 and 8 of the axial recess of the inner frame 9 Power drive winding 4 and 5 are set strictly axially.



a b

Figure 5 - Distribution of magnetic fields in the electromagnetic compensator stiffness at the position of the movable element 19 in the initial state (a) and downward displacement (b)

To start the measurement process of GA winding 5 of induction and dynamic catapult is to be connected to a charged storage capacitor. Flowing inside pulsed current induces a magnetic field in the electroconductive armature 6 eddy current. The resulting electrodynamic repulsive force between the winding 5 and the armature 6 pushes up the TB 2 followed by a fall down. In the process of moving the TB 2 laser beam 22 emitted from the optical receiving and emitting unit 20 passes through the opening 21 of the tripod and the optical window 1a of vacuum chamber 1 is reacts with 3 optical corner reflector of TB 2. At the same time the reflected beam is received by the device 20 and measurement of the gravitational acceleration g by the symmetrical method.

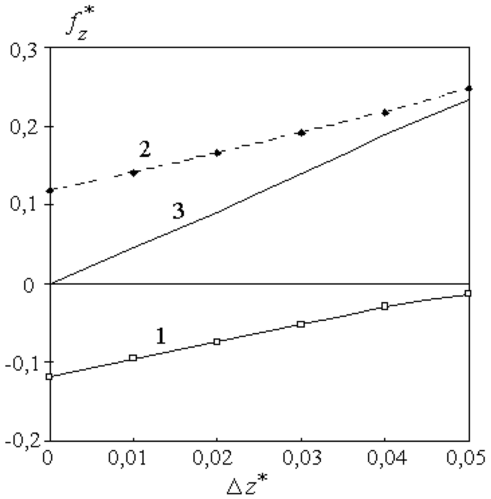


Figure 6 - The relative strength of the element 19a (2) of the element 19b (1) and the resultant force (3) depending on the relative displacement of the movable member 19 downward

Under the influence of the electrodynamic repulsion forces winding 5 with a ferromagnetic core 10 moves downward. The platform 11 to the uprights 13 also moves downward. In this case coil springs 16 are compressed. Under the influence of coil springs on the base plate 12 acts increased downward force. Together with the platform 11 and down going movement of the cylindrical movable element 19 (fig.5b). At the same time the upper portion 19a of the ferromagnetic element closer to the central plane of the magnet coaxial, and the lower portion 19b moves away from this plane. As a result, the attractive force by the magnet 17 coaxial to the upper ferromagnetic portion 19a increases and the lower ferromagnetic portion 19b decreases. Calculations of electromagnetic fields and forces formed by the method are presented in the paper [6].

The force of attraction exerted on the coaxial magnet 17, is pointed up. Since the magnet is connected to the base plate 12, then this attractive force compensates for the increased power down, which acts on the plate 12 by the coil springs. It diminishes the force by the coil springs on the base plate 12 but a corresponding force is applied on the supports of 17 in the center of 12. So the total force on 12 is not changed. The force which acts from the bottom force through the supports 14 on the massive base 15 substantially retained. Since this base 15 of the tripod 21 is installed with the optical emitting-receiving device 20, the force exerted on them almost remains unchanged, and there are no substantial vibrations. This increases the accuracy of measurement of GA.

Calculations show that in the range of relative displacement to Δz^*=0.04 resultant force f_z* is linear (Fig. 6). This shows the prospectively of the proposed concept of ballistic laser gravimeter with induction-dynamic catapult for symmetric measuring method having a reduced level of auto-seismic fluctuations.

Conclusions

The conception of the BLG with the symmetrical scheme of GA measurements has been proposed. In this BLG the TB is thrown by the induction and dynamic catapult. To reduce the level of auto-seismic vibrations it is proposed to launch the TB from a massive platform, installed on a spring of small rigidity.

A non-rigid attachment of the launch platform with the catapult has been justified. This attachment provides a reduced ACE of AG measurement.

It is shown that the considered BLG is capable of providing auto-seismic component of the measurement error which is less than 1 μGal. As the spring rigidity decreases, auto-seismic component of the measurement error of GA decreases too.

The conception of the BLG with induction and dynamic catapult for symmetric method of GA measurement has been proposed. This BLG utilizes the electromagnetic compensator of rigidity.

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