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Reduction of the auto seismic component of error of a ballistic laser gravimeter by excitation of an induction-dynamic catapult from an AC voltage source

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Abstract

The purpose of the study is to analyse the influence of the excitation of an induction-dynamic catapult of a ballistic laser gravimeter from an AC voltage source at different frequencies on electromechanical indicators that provide a reduced value of the auto seismic component of error in measuring the gravitational acceleration *g* due to a decrease in the recoil force. A mathematical model of the gravimeter catapult when excited from an AC voltage source is proposed, taking into account the interrelated electrical, magnetic and mechanical processes. The nature of the electromechanical processes in the catapult of the gravimeter with such excitation has been established. It is shown that a phase shift occurs between the currents in active elements, as a result of which positive (repulsive) pulses of the electrodynamic force alternate with negative (attractive) pulses of force. A criterion for the efficiency of the gravimeter catapult has been introduced, taking into account the maximum value of push of the test body at the smallest values of the electrodynamic force and current of the inductor winding. It was found that the highest efficiency of the gravimeter catapult is provided at a frequency of 250 Hz, at which the catapult efficiency is 3.5 times higher than at a frequency of 50 Hz. It is shown that the transition from the method of excitation of an induction-dynamic catapult with one short pulse to excitation from an AC voltage source makes it possible to reduce the uncertainty in measuring the gravitational acceleration.

Keywords: ballistic laser gravimeter; induction-dynamic catapult; auto seismic component of measurement error; AC voltage source; efficiency criterion.

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Introduction

For high-precision measurements of the absolute value of gravitational acceleration *g*, ballistic laser gravimeters (BLGs), which implement the symmetric method, are used. According to this method, in the vacuum chamber of the gravimeter, a catapult pushes a test body (TB), which is an integral part of the measuring system of the Michelson laser interferometer. In the process of free flight of the TB, *g* is measured on the ascending and descending branches of the trajectory by registering the path and time intervals passed by the TB in free motion [1–4].

With the symmetrical method of measuring *g*, the influence of the gaseous medium is eliminated by compensating for the oppositely directed resistance forces of the medium during vertical take-off and fall of the TB. In this case, there is no problem of putting the TB to its initial position, as in gravimeters with an asymmetric method for measuring *g* [5, 6]. However, with a symmetric method of measuring *g*, a recoil force arises at the moment of the catapult pushing the TB, which leads to auto seismic vibrations of the foundation and all mechanical elements of the gravimeter, which determine the corresponding component of the measurement error of *g* [7, 8].

Analysis of literature data and problem statement

Various catapults and methods of their excitation are known for gravimeters with a symmetric method for measuring *g*. In [6], a ballistic gravimeter is described, in which the indirect transformation of electrical energy into vertical movement TB is carried out. Push of the TB is carried out using an electromagnetic catapult and a symmetrical six-bar pantograph, the central axis of which is fixed in the vacuum chamber of the ballistic unit of the gravimeter. The central axis is connected to the ferromagnetic armature of the catapult. When the catapult is excited from a capacitive energy storage (CES), the heavy ferromagnetic armature is pulled into the inner cavity of the excitation winding. Moving down, the ferromagnetic armature pulls the pantograph, which pushes the carriage with the TB vertically upward with following catching.

However, such a multistage energy conversion is accompanied by friction and subsequent wear of the contacts of the moving elements, vibration and impacts in the connecting elements, damping of a part of the energy, etc.

To eliminate these disadvantages, it was proposed to use BLG with an induction-dynamic catapult (IDC), which provides direct conversion of electrical energy of CES into mechanical energy and ease of adjusting the height of the TB pushing [9]. When the IDC is energized by the CES, the current in the inductor winding induces a current in the electrically conductive armature. Under the action of the axial electrodynamic repulsion force f_z, the armature, together with the TB, performs free vertical movement, during which the measurement of *g* is carried out. However, a short-term and significant in amplitude pulse of electrodynamic force causes auto seismic vibrations of the BLG foundation due to the recoil force [10].

It is possible to reduce these vibrations by increasing the duration of exposure and decreasing the amplitude of the electrodynamic force between the inductor winding and the armature [11]. One way to implement this idea is to sequentially excite the IDC from the CES sections [12]. With such excitation, a packet of short power pulses of low amplitudes is formed. However, this requires a rather sophisticated electronic control and charging system for the CES sections, and the recoil force remains quite high (0.5–1.1 kN). One of the ways to reduce the recoil force and the resulting auto seismic vibrations of the gravimeter is the excitation of the IDC from an AC voltage source (ACVS) [13].

The purpose of the study is to analyze the effect of the IDC excitation from the ACVS at different frequencies on electromechanical indicators that provide a reduced value of the auto seismic component of the measurement uncertainty of gravitational acceleration *g* due to a decrease in the recoil force.

Mathematical model of the gravimeter catapult

Let's consider the IDC when the inductor winding is energized by the ACVS, which allows the TB to move vertically by means of an electrically conductive armature. In the mathematical model of the IDC, we use the lumped parameters of active elements – a fixed inductor winding and a movable electrically conductive armature connected to the TB. We neglect the resistance of the connecting wires. We assume that there is no movement of the inductor winding and there is a strictly vertical movement of the armature with the TB.

Electromagnetic processes in active elements of the IDC when excited by the ACVS can be described by the system of equations:

$$R_1 i_1 + L_1 \frac{di_1}{dt} + M_{12}(z)\frac{di_2}{dt} + i_2 v_z(t)\frac{dM_{12}}{dz} = u(t), \qquad (1)$$

$$R_2 i_2 + L_2 \frac{di_2}{dt} + M_{21}(z)\frac{di_1}{dt} + i_1 v_z(t)\frac{dM_{21}}{dz} = 0, \qquad (2)$$

where $n = 1, 2$ are the indices of the winding of the inductor and the armature (active elements), respectively; $M_{12}(z) = M_{21}(z)$ is the mutual inductance between active elements; v_z is the speed of movement of the armature with the TB along the vertical axis *z*; R_n, L_n, i_n are the active resistance, inductance and current of the *n*-th active element; $u(t) = U_m \sin(\omega t)$ is the ACVS voltage; $\omega=2\pi v$; v is the ACVS frequency.

Let's introduce the following notations:

$$M = M_{12}(z) = M_{21}(z); \;\; v_z = v_z(t); \;\; u = u(t); \;\; \varsigma = v_z \frac{dM}{dz}.$$

We will find solutions for currents in active elements in the form:

$$i_1 = uR_1^{-1} - i_2 R_1^{-1}\varsigma + A_{11}\exp(\alpha_1 t) + A_{12}\exp(\alpha_2 t), \qquad (3)$$

$$i_2 = -i_1 R_1^{-1}\varsigma + A_{21}\exp(\alpha_1 t) + A_{22}\exp(\alpha_2 t), \qquad (4)$$

where $\alpha_{1,2} = -0.5\beta_1\beta_2^{-1} \pm \left\{0.25\beta_1^2\beta_2^{-2} - \left[R_1R_2 - \varsigma^2\right]\beta_2^{-1}\right\}$ are the roots of the characteristic equation for the free component of the differential equation:

$$\beta_2 \frac{d^2 i_1}{dt^2} + \beta_1 \frac{di_1}{dt} + \left(R_1R_2 - \varsigma^2\right) i_1 = 0, \qquad (5)$$

$\beta_1 = L_1R_2 + L_2R_1 - 2\varsigma M$; $\beta_2 = L_1L_2\left(1 - K_M^2\right)$; $K_M=(L_1L_2)^{-0.5}$ is the coefficient of magnetic coupling between active elements; $A_{11}, A_{12}, A_{21}, A_{22}$ are the arbitrary constants at time t_k for the free component of currents:

$$A_{1l} = \frac{\alpha_m\left[i_2(t_k)\varsigma R_1^{-1} - u(t_k)R_1^{-1} + i_1(t_k)\right] - \Xi}{\left(\alpha_m - \alpha_l\right)\exp\left(\alpha_l t_k\right)}; \qquad (6)$$

$$A_{2l} = \frac{\alpha_m\left[i_2(t_k) + i_1(t_k)\xi R_2^{-1}\right] - \iota}{\left(\alpha_m - \alpha_l\right)\exp\left(\alpha_l t_k\right)}, \qquad (7)$$

where l=1, 2; m=3-l;

$$\Xi = L_1^{-1}\left(1 - K_M^2\right)^{-1}\left\{u(t_k) + i_1(t_k)\left(ML_2^{-1}\varsigma - R_1\right) + i_2(t_k)\left(MR_2L_2^{-1} - \varsigma\right)\right\};$$

$$\iota = L_2^{-1}\left(1 - K_M^2\right)^{-1}\left\{i_2(t_k)\left(ML_1^{-1}\varsigma - R_2\right) - u(t_k)ML_1^{-1} + i_1(t_k)\left(MR_1L_1^{-1} - \varsigma\right)\right\}.$$

In the final form, the currents in the active elements of the IDC when excited from the ACVS are described by the recurrence relations:

$$i_1(t_{k+1}) = -\frac{i_2(t_k)\varsigma}{R_1} + \left[u(t_k) - R_1 i_1(t_k) - i_2(t_k)\varsigma\right]\frac{\alpha_1\exp(\alpha_2\Delta t) - \alpha_2\exp(\alpha_1\Delta t)}{R_1(\alpha_2-\alpha_1)} + \frac{u(t_k)}{R_1} + \\ + \frac{\exp(\alpha_2\Delta t) - \exp(\alpha_1\Delta t)}{L_1L_2(\alpha_2-\alpha_1)(1-K_M^2)}\left\{u(t_k)L_2 + \left[M\varsigma - R_1L_2\right]i_1(t_k) + \left[R_2M - L_2\varsigma\right]i_2(t_k)\right\}; \tag{8}$$

$$i_2(t_{k+1}) = -\frac{i_1(t_k)\varsigma}{R_2} + \left[i_2(t_k) + \frac{i_1(t_k)\varsigma}{R_2}\right]\frac{\alpha_2\exp(\alpha_1\Delta t) - \alpha_1\exp(\alpha_2\Delta t)}{\alpha_2-\alpha_1} + \frac{\exp(\alpha_2\Delta t) - \exp(\alpha_1\Delta t)}{L_1L_2(\alpha_2-\alpha_1)(1-K_M^2)}\times \\ \times\left\{i_1(t_k)\left[R_1M - L_1\varsigma\right] - u(t_k)M + i_2(t_k)\left[M\varsigma - R_2L_1\right]\right\}, \tag{9}$$

where $u(t_k) = U_m\sin(\omega t_k)$.

Axial movement of the armature with the TB is carried out under the action of an electrodynamic force:

$$f_z(z,t) = i_1(t_k)i_2(t_k)\frac{dM_{12}}{dz}(z). \tag{10}$$

The value of the vertical movement of the armature h_z can be described in the form of a recurrent relation [12]:

$$h_z(t_{k+1}) = h_z(t_k) + v_z(t_k)\Delta t + \vartheta\cdot\Delta t^2/(m_2+m_a), \tag{11}$$

where $v_z(t_{k+1}) = v_z(t_k) + \vartheta\cdot\Delta t/(m_2+m_a)$ is the speed of the armature with the TB; m_2, m_a are the masses of the armature and the TB, respectively;

$$\vartheta = i_1(t_k)i_2(t_k)\frac{dM_{12}}{dz}(z) - g(m_2+m_a).$$

Initial conditions of the mathematical model: $i_n(0)=0$; $h_z(0)=h_{z0}$; $v_z(0)=0$.

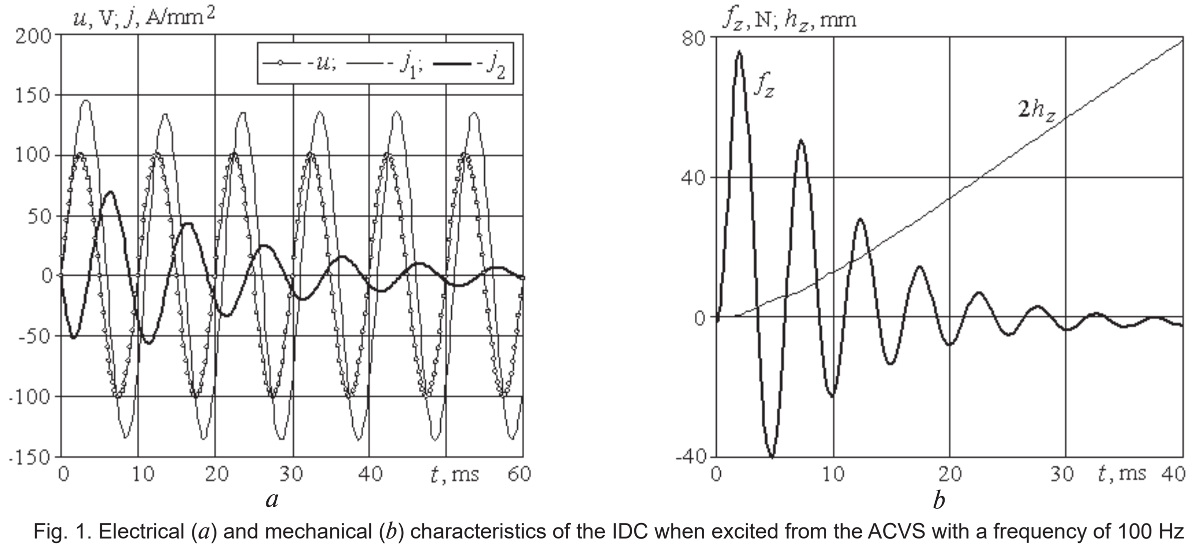
When implementing the equations describing electrical, magnetic and mechanical processes on a computer, a cyclic algorithm is used. At each numerically small calculated step Δt, the values of currents in, axial electrodynamic force $f_z(z,t)$, velocity v_z and movement h_z of the armature with the TB, mutual inductance M between the active elements of the catapult are sequentially calculated.

Electromechanical processes in the gravimeter catapult

Let's consider the IDC with the following parameters: the outer diameter of active elements D_{ex}= =80 mm, their inner diameter D_{in}=4 mm. The height of the inductor winding H_1= 6 mm, the height of the copper armature H_2=1.5 mm, the number of turns of the inductor winding N_1=228, which is wound with a copper wire with a diameter of d_0= 0.9 mm. Mass of the TB m_a= 100 g. Total pushed mass m_2 + m_a=167 g. The amplitude of the ACVS is U_m= 100 V.

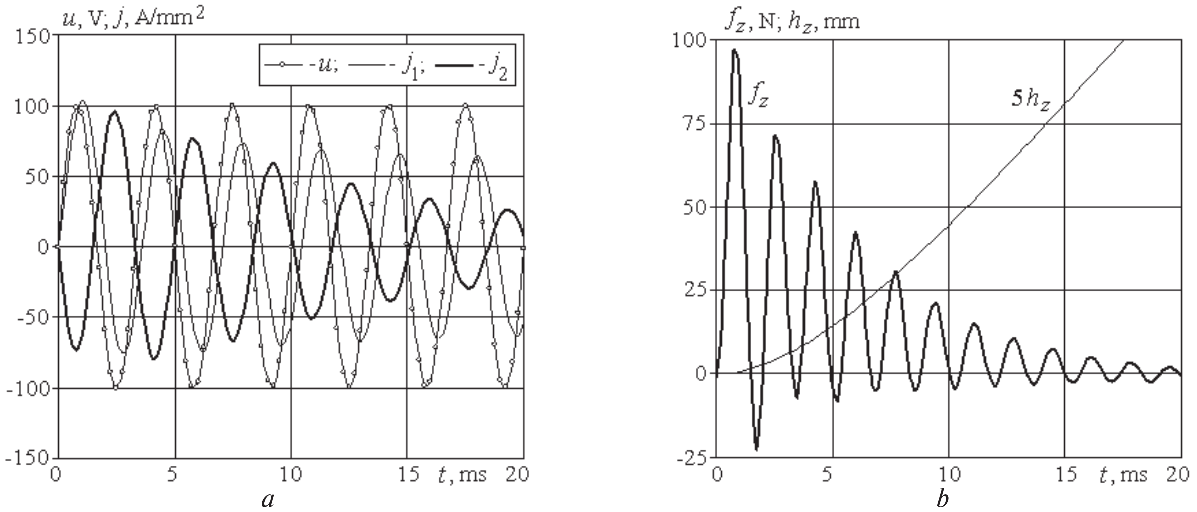
Let's consider the process of catapult excitation from the ACVS with a frequency of 100 Hz. Fig. 1*a* shows the ACVS voltage u with a frequency ν = =100 Hz, the current density in the inductor winding j_1 and in the armature j_2. The largest value of the amplitude of the current density in the inductor winding j_{1m}= 146 A/mm² occurs in the first half-cycle. In the armature in the first half-cycle, the induced current density has the opposite polarity, and the largest amplitude j_{2m} = 70 A/mm² occurs in the second half-cycle, the polarity of which coincides with that of the inductor winding current in the first half-cycle. The maximum value of the current density in the inductor winding after the first cycle practically reaches a steady-state value, while the current becomes oscillatory-damped in the armature.

Since a phase shift occurs between the currents in the active elements, the positive (repulsive) impulses of the electrodynamic force alternate with the negative (attractive) impulses of the force (Fig. 1*b*). In this case, positive impulses of force prevail over negative ones. The amplitude of the first maximum positive force impulse f_{zm}^{+} = 75.5 N, and the amplitude of the first negative force impulse f_{zm}^{-} = 40 N. The electrodynamic



a *b*

Fig. 1. Electrical (*a*) and mechanical (*b*) characteristics of the IDC when excited from the ACVS with a frequency of 100 Hz



a *b*

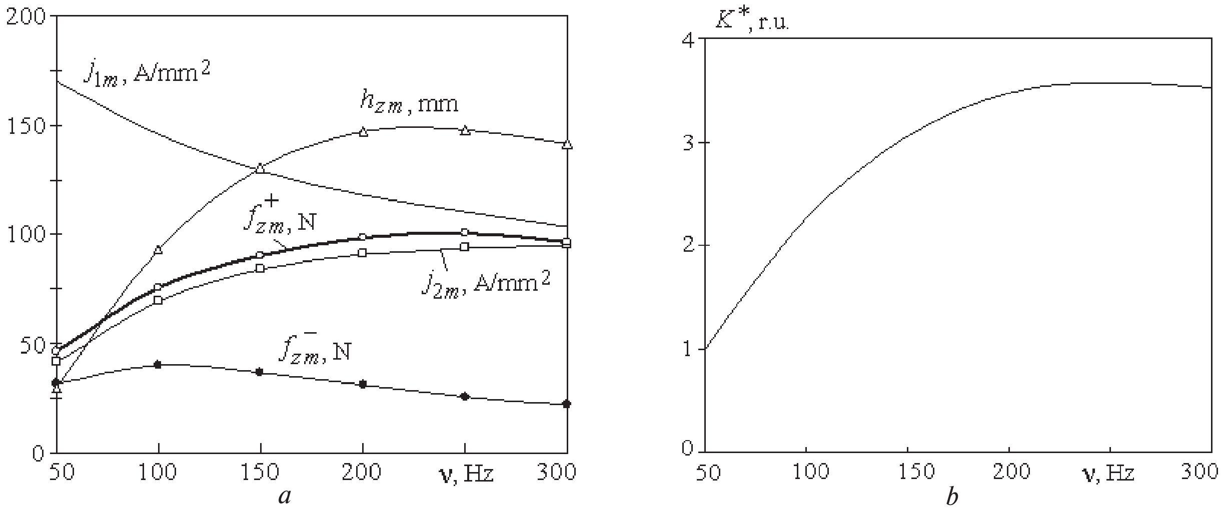
Fig. 2. Electrical (*a*) and mechanical (*b*) characteristics of the IDC when excited from the ACVS with a frequency of 300 Hz

force f_z has a strong damping character due to the vertical movement of the armature with the TB h_z during the excitation process. With this excitation, the armature together with the TB is pushed to a height of $h_{zm} = 93$ mm. Since in the process of excitation of the IDC the magnetic coupling between the movable armature and the stationary winding of the inductor is weakened, it is advisable to limit the excitation process in time.

When the catapult is excited by the ACVS with a frequency of $\nu = 300$ Hz, changes in the electromechanical characteristics occur (Fig. 2).

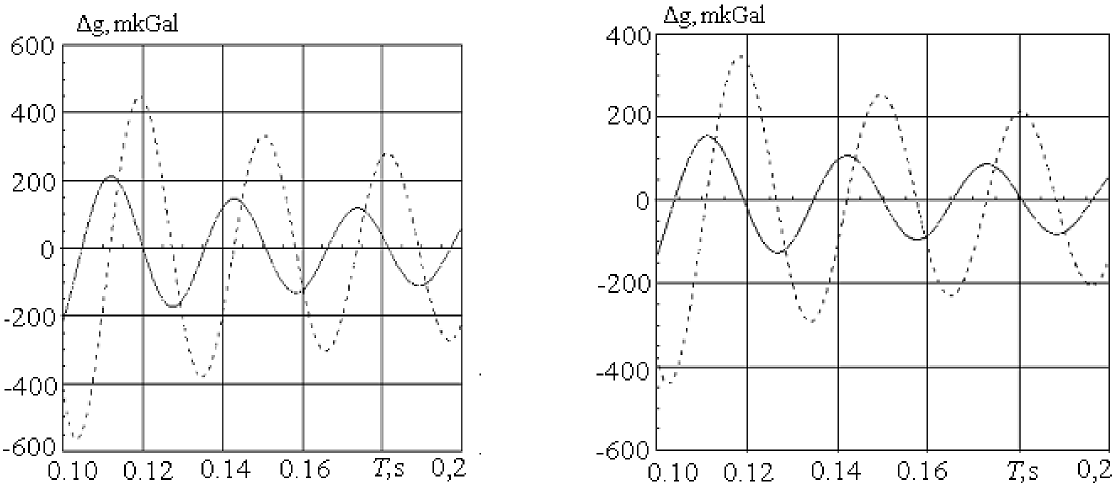
The maximum amplitude of the current density in the inductor winding in the first half-cycle decreases to $j_{1m} = 103.6$ A/mm², and in the armature, on the contrary, increases to $j_{2m} = 95$ A/mm². At this, the phase shift between the currents decreases, and the currents in the active elements change practically in antiphase. As a result, positive impulses of electrodynamic force increase, and negative impulses of force decrease. So, the maximum amplitude of the positive impulse of the force increases to $f_{zm}^{+} = 96.5$ N, and the maximum amplitude of the negative impulse of the force decreases to $f_{zm}^{-} = 22.5$ N. The electrodynamic force f_z remains damped due to the vertical movement of the armature with the TB h_z during the excitation process. The anchor together with the TB is pushed to a height $h_{zm} = 141.4$ mm. When the IDC is excited from the ACVS at 300 Hz, it is advisable to limit the process to a 30 ms interval.

With an increase in the frequency ν from 50 to 300 Hz, there is a decrease in the maximum amplitude of the current density in the winding of the inductor j_{1m} from 170.3 to 103.6 A/mm² and an increase in the maximum amplitude of the current density in the armature j_{2m} from 42 to 95 A/mm² (Fig. 3*a*). The value of the maximum amplitude of the positive impulse of force f_{zm}^{+} increases from 46.7 to 96.5 N, but the maximum value $f_{zm}^{+} = 100.7$ N occurs at $\nu = 250$ Hz. The magnitude of the maximum amplitude of the negative impulse of the force f_{zm}^{-} increases in the frequency range $\nu \in (50, 100)$ Hz from 31.8 to 40 N, and with a further increase in frequency to 300 Hz, it decreases to 22.5 N. Due to the indicated change in forces, the maximum height h_{zm} of the armature push in the range $\nu \in (50, 300)$ Hz increases from 29.6 to 141.4 mm, taking the maximum value $h_{zm} = 147.6$ mm at $\nu = 250$ Hz.



a *b*

Fig. 3. Dependence of electromechanical indicators (*a*) and efficiency factor (*b*) of the IDC on the ACVS frequency



a *b*

Fig. 4. Auto seismic component of the error of *g* measurement for the variants of excitation from the ACVS with a frequency of 300 Hz (*a*) and 500 Hz (*b*)

In order to comprehensively assess the effect of the ACVS frequency on the IDC indicators, we introduce the efficiency criterion in a dimensionless form

$$K^* = \frac{h^*_{zm}}{f^{+*}_{zm} i^*_{1m}}, \qquad (12)$$

in which all parameters are normalized by the IDC indicators at the ACVS frequency v = 50 Hz. The most effective will be the catapult, which provides the maximum value of pushing the TB at the minimum value of the electrodynamic force, manifested in the form of the recoil force, and the current of the inductor winding, which is important for the electronic system of the excitation source. Intensifying the frequency increases the efficiency of the IDC. The highest IDC efficiency is provided at a frequency of v = 250 Hz, at which the IDC efficiency is 3.5 times higher than at a frequency of v = 50 Hz.

With excitation from the ACVS, the efficiency of the BLG catapult is significantly higher than with excitation with a single pulse from the CES. So, when using a capacitance C_0= 675 μF, charged to a voltage of U_0= 210 V, at which the armature with the TB is pushed to a height h_{zm}= 150 mm, the magnitude of the electrodynamic force f_{zm} is almost 2 kN. As a result, the efficiency of the catapult is low K^*= 0.024 [12].

When the IDC is excited by a packet of 10 consecutive pulses from the CES sections with the parameters C_0 = 100 μF, U_0= 320 V, at which the armature with the TB is pushed to a height h_{zm}= 140 mm, the force f_{zm} is almost 1.0 kN, providing also quite low efficiency of the catapult K^*=0.138 [12]. Thus, the known IDC excitation methods are significantly inferior to the proposed excitation from ACVS.

Influence of the IDC excitation on the auto seismic component of the BLG error

Let's consider the influence of the excitation of the gravimeter's IDC from the ACVS on the auto seismic component of the error (ASE) of *g* measurement in comparison with the excitation of the catapult with one short pulse from the capacitive energy storage. The value of ASE is estimated by simulation in the Wolfram Mathematica programming environment using the BLG mechanical system model [10–12]. The simulation used the following parameters of the BLG mechanical system [10–12]: foundation mass m_0= 750 kg, soil base rigidity c_0= 125.88 MN/m, base viscous friction coefficient b_0= 73743.2 N·s/m; mass of the TB m = 0.167 kg. The simulation was carried out for the variant of rigid installation of the reference reflector of the BLG interferometer.

As an indicator of the efficiency of the proposed method of the IDC excitation, the following ASE of *g* measurement [10–12] was taken:

$$\Delta g = -\sum_{k=0}^{K-1} x_v(kh + t_0 - \frac{T}{2}) \cdot w(k), \qquad (13)$$

where $x_v(t)$ is the process of moving the reference reflector; h is the sampling interval of the readings of the path traveled by the TB; t_0 is the time moment of reaching the top by the TB; $w(k)$ are the weight coefficients for processing the path-time readings in the BLG; T is the duration of the processing interval.

The sampling interval in expression (13) was chosen equal to 0.5 ms. At this, processing coefficients $w(k)$ were used that correspond to the least squares method. The simulation results are presented in the form of graphs (Fig. 4), which show the dependences of the ASE of *g* measurement on the duration of the processing interval *T*. In Fig. 4*a*, the solid line shows the results for the variant of excitation of the BLG catapult from the ACVS with a frequency of 300 Hz, and in Fig. 4*b* – 500 Hz.

The dashed lines show the dependences of the ASE on the duration of the processing interval *T* for the variant of catapult excitation with a single pulse from the CES with a duration of 1 ms, at which the same push height of the TB is provided. As the analysis shows, with increasing the ACVS frequency, the ASE is significantly reduced compared to the single-pulse variant.

From the analysis of the obtained dependences of the ASE value of *g* measurement, it is concluded that the excitation of the IDC from the ACVS of higher frequency compared to the excitation by a single pulse from the CES significantly reduces the uncertainty of *g* measurement for the BLG with a symmetrical method of measurement.

Conclusions

A mathematical model of the gravimeter catapult when excited by the ACVS is proposed, taking into account the interrelated electrical, magnetic and mechanical processes. It is shown that a phase shift occurs between the currents in the active elements of the IDC, as a result of which positive (repulsive) impulses of the electrodynamic force alternate with negative (attractive) impulses of force. Positive impulses of force prevail over negative ones.

The IDC efficiency criterion has been introduced, taking into account the maximum value of pushing the TB at the smallest values of the electrodynamic force and current of the inductor winding. It is found that the highest efficiency of the IDC is provided at a frequency of ν = 250 Hz, at which the catapult efficiency is 3.5 times higher than at a frequency of ν = 50 Hz.

It is shown that the transition from the excitation method of the BLG IDC with a symmetric measurement method with one short pulse to the excitation from the ACVS of increased frequency can reduce the uncertainty of *g* measurement.

Зменшення автосейсмічної складової похибки балістичного лазерного гравіметра шляхом збудження індукційно-динамічної катапульти від джерела змінної напруги

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Анотація

Метою дослідження цієї статті є аналіз впливу збудження індукційно-динамічної катапульти балістичного лазерного гравіметра від джерела змінної напруги при різній частоті на електромеханічні показники, що забезпечують знижену величину автосейсмічної складової похибки вимірювання прискорення вільного падіння *g* за рахунок зменшення сили віддачі. Запропоновано математичну модель катапульти гравіметра при збудженні від джерела змінної напруги, що враховує взаємозалежні електричні, магнітні та механічні процеси. Встановлено характер електромеханічних процесів, які відбуваються при індукційному збудженні динамічної катапульти балістичного лазерного гравіметра. Показано, що між струмами в активних елементах виникає фазовий зсув, внаслідок чого позитивні (ті, що відштовхують) імпульси електродинамічної сили чергуються з негативними (тими, що притягують) імпульсами сили. Позитивні імпульси сили переважають над негативними імпульсами.

Введено критерій ефективності катапульти гравіметра, що враховує найбільшу величину підкидання пробного тіла при найменших величинах електродинамічної сили і струму обмотки індуктора. Встановлено, що найбільша ефективність катапульти гравіметра забезпечується при частоті 250 Гц, при якій ефективність катапульти в 3,5 разу вища, ніж при частоті 50 Гц. Показано, що перехід від способу збудження індукційно-динамічної катапульти одним коротким імпульсом до збудження від джерела змінної напруги дозволяє зменшити невизначеність вимірювання прискорення вільного падіння.

Ключові слова: балістичний лазерний гравіметр; індукційно-динамічна катапульта; автосейсмічна складова похибки вимірювання; джерело змінної напруги; критерій ефективності.

Уменьшение автосейсмической составляющей погрешности баллистического лазерного гравиметра путем возбуждения индукционно-динамической катапульты от источника переменного напряжения

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Аннотация

Статья посвящена анализу влияния возбуждения индукционно-динамической катапульты баллистического лазерного гравиметра от источника переменного напряжения при различной частоте на электромеханические показатели, обеспечивающие пониженную величину автосейсмической составляющей погрешности измерения ускорения свободного падения *g* за счет уменьшения силы отдачи.

Предложена математическая модель катапульты гравиметра при возбуждении от источника переменного напряжения, учитывающая взаимосвязанные электрические, магнитные и механические процессы. Установлен характер электромеханических процессов в катапульте гравиметра при таком возбуждении.

Введен критерий эффективности катапульты гравиметра, учитывающий наибольшую величину подбрасывания пробного тела при наименьших величинах электродинамической силы и тока обмотки индуктора. Установлено, что наибольшая эффективность катапульты гравиметра обеспечивается при частоте 250 Гц, при которой эффективность катапульты в 3,5 раза выше, чем при частоте 50 Гц. Показано, что переход от способа возбуждения индукционно-динамической катапульты одним коротким импульсом к возбуждению от источника переменного напряжения позволяет уменьшить неопределенность измерения ускорения свободного падения.

Ключевые слова: баллистический лазерный гравиметр; индукционно-динамическая катапульта; автосейсмическая составляющая погрешности измерения; источник переменного напряжения; критерий эффективности.

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