CONCEPT OF AN INDUCTION-DYNAMIC CATAPULT
FOR A BALLISTIC LASER GRAVIMETER

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A design is proposed for an inductive-dynamic catapult in a ballistic laser gravimeter with a fixed inductor and an electrically conducting armature that moves together with the test object along a vertical axis. The catapult ensures improved accuracy of the gravimeter through direct conversion of electrical into kinetic energy. The electrical circuit of the catapult provides two successive current pulses to the inductor for launching and braking of the armature during the operating cycle.

Keywords: ballistic laser gravimeter, induction-dynamic catapult, mathematical model, launching and braking of armature.

Ballistic laser gravimeters (BLG) with launching of a test object consisting of an optical corner reflector mounted in a special housing and forming part of the measurement system of a Michelson interferometer are used for high accuracy measurements of the absolute acceleration of gravity \( g \) [1–4]. The most accurate measurements of \( g \) are symmetric, with the path length and time of flight of the test object determined on rising and falling trajectories of free movement in the vacuum chamber of the BLG that are symmetric with respect to the top [5].

Highly accurate measurements of the absolute magnitude of \( g \) are obtained on the DETU 02-02–96 ballistic laser gravimeter. But its metrological parameters do not fully satisfy modern specifications, primarily because of a catapult design in which the electrical energy of the source is indirectly converted for vertical launch of the test object [6, 7]. The catapult of this gravimeter is based on a symmetric six-link lever mechanism (pantograph) with a central axis fastened to the chamber. When a current is delivered to the electromagnetic winding, a massive ferromagnetic armature is drawn into the inner cavity. As it moves vertically downward, it pulls the pantograph which, because of a decrease in its radial size and an increase in its axial dimensions launches a carriage with the test object vertically upward with subsequent capture. Thus, the following processes in the catapult are interrelated: displacement of the armature under the influence of the magnetic field of the winding of the electromagnet, transfer of the electromagnetic traction force to the central axis, turning of the segments of the pantograph around their corresponding axes, and displacement of the carriage. In order to eliminate lateral displacements, the armature and carriage are mounted in bearings attached to the walls of the vacuum vessel.

This kind of multistep conversion of electrical into mechanical energy is accompanied by friction and subsequent wear of the contacts on the moveable components, vibration and shock in coupling components, damping of part of the energy, bending-deformation processes, etc. We note also the nonlinearity of the magnetic characteristics and the inertia of the massive ferromagnetic armature, which make it more difficult to control the catapult.

These systematic errors cannot be reduced by conducting repeat measurements of \( g \) and further increases in the dynamic accuracy of the BLG will involve improvements in the catapult for the test object, in particular the use of addition-

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al apparatus such as vibration protection components in the optical and mechanical system. This, however, makes the design more complicated and increases the size and weight of the BLG.

**Design Scheme for an Induction-Dynamic Catapult.** In order to eliminate the systematic errors, we propose a BLG with an induction-dynamic catapult (IDC) which provides for direct electrical-mechanical energy conversion with free and limited motion of the armature (Fig. 1) [8].

The gravimeter contains test object 15 with an optical corner reflector 16, and a vacuum chamber 2 with an optical emitter 17 mounted at its top. A force plate 9, on which a coil 10 and winding 11 and director elements in the form of vertical supports 3 and horizontal supports 18 with vertical segments 20 are mounted, is positioned at the bottom 8 of the vacuum chamber 2 on dampers 7. An electrically conducting armature 13 in the form of a thin disk is located in the vacuum chamber 2; it is attached to a driver disk 4 with an aperture 6 and bearings 5 which surround the vertical supports 3. A director cone 14 is attached to the lower part of the test object 15; its side walls have the same shape as the conical axial director hollow 12 and the coil 10. Central apertures 21 are made in the armature 13 and disk 4.

The lower parts of the vertical supports 3 which provide for free movement of the armature 13, have an enlarged diameter for the bearings 5 of the force disk (see Fig. 1a). The vertical supports 3 which provide for limited vertical movement of the armature 13 are attached to horizontal supports 18 in the upper part and elastic dampers 1 are attached to them (see Fig. 1b). The elastic elements 19 mounted on the vertical segments 20 of the horizontal supports 18 maintain contact of the armature 13 with the force disk when there is no interaction between the test object 15 and the disk 4.

An initial current pulse is generated when the capacitive energy storage system is discharged into the winding 11 such that the magnetic field induces a current in the electrically conducting armature 13. Under the action of an axial elec-
trodynamic repulsive force $f_z$, the armature 13, together with the force disk 14 and test object 15, undergoes a free vertical displacement $\Delta z$. Then the optical emitter 17 is turned on and illuminates the optical corner reflector 16, and a measurement of $g$ is made. As the armature 13 falls and approaches the winding 11, a second discharge of the capacitive energy storage system sets in. Since the remaining voltage in the storage system is lower than the initial voltage, the resulting repulsive electrodynamic force $f_z$ is only sufficient for a smooth slowing down of the armature 13 with the test object 15.

As the test object 15 moves along the lower, thicker parts of the vertical supports 3 the bearings 5 set the horizontal position of the disk 4. Since the upper, thinner parts of the supports 3 are not in contact with the bearings 5, the test object 15 is able to move without contact, thereby ensuring maximum accuracy in measuring $g$. The interaction of the director cone 14 with the axial hollow 12 of the coil 10 ensures a strictly axial position of the armature 13 relative to the winding 11, both at the start and the end of the operating cycle of the BLG.

The gravimeter with limited movement of the armature operates in the following way (Fig. 1b). When it arrives at the horizontal supports 18, the disk 4 compresses the elastic dampers 1 and elements 19. Then the disk 4 is gradually slowed down, while the test object 15 continues its free vertical motion, during which $g$ is measured. The disk 4 with the armature 13 is held by the opened elastic elements 19. When the test object 15 falls it comes into contact with the disk, the elements 19 open up, and the force disk 4, armature 13, and test object 15 then fall together.

We now examine the electrical and mechanical processes taking place in the induction-dynamic catapult with a freely moving test object for an armature in the form of a thin copper disk.

**Mathematical Model of the Induction-Dynamic Catapult.** It contains a fixed inductor (coil with winding) and an electrically conducting armature which, together with the test object, moves along the vertical axis $Z$. The armature is located a distance $\Delta z_0$ from the inductor at which the inductor is excited in order to create a launching pulse. As the armature, which falls at a velocity $v_0$ relative to the inductor, slows down, the latter is excited at the time when the distance between them equals $z_0$ (Fig. 2a).

An electronic circuit containing a power supply PS for charging the capacitive energy storage system $C$ to a voltage $U_0$ and a control unit CU is used to create two successive pulses in a single operating cycle. The control unit successively switches on the thyristors $V_{S_0}$, $V_{S_1}$, and $V_{S_2}$, charges the capacitor, and delivers pulses for launching and braking of the armature (Fig. 2b) [8].

Since the induced current is nonuniformly distributed in the conducting armature, in the mathematical model it is represented by a set of elementary coaxial short-circuited loops $k$ that are uniformly distributed over the surface of the disk, while the inductor is represented by the primary excitation circuit. Thus, the model accounts for the changing magnetic coupling between the armature and the inductor, the nonuniform distribution of the current in the armature, and the set of axial forces acting on the armature. Then the electrical processes in the IDC can be described by the following system of differential equations [9]:

Fig. 2. Computational scheme (a) and electrical diagram (b) of the IDC: 1) base; 2) inductor; 3) electrically conducting armature; 4) test object; PS power supply; CU control unit.
where \( i_0, L_0, \) and \( R_0 \) are the current, inductance, and resistance of the inductor; \( i_k, L_k, \) and \( R_k \) are the current, inductance, and resistance of the elementary short-circuited loop \( k \) of the armature, which modes at velocity \( v(t) \) along the \( Z \) axis relative to the inductor; and \( M_{kp} \) are the mutual inductances between the current loops \( (k \neq p) \).

The axial displacement \( \Delta z \) of the armature with the operating piece consisting of the propelling disk and the test object is generated by an electrodynamic impulse

\[
F(z) = \int_0^t f_z(t, z) dt,
\]

where

\[
f_z(t, z) = i_0(t) \sum_{k=1}^{K} i_k(t) \frac{dM_{0k}}{dz}(z)
\]
is the instantaneous force.

The velocity and displacement of the armature with the operating piece obey the recurrence relations

\[
v(t_{n+1}) = v(t_n) + \hat{\vartheta} \Delta t / (m_2 + m_3);
\]

\[
\Delta z(t_{n+1}) = \Delta z(t_n) + v(t_n) \Delta t + \hat{\vartheta} \Delta t^2 / (m_2 + m_3),
\]

where

\[
\hat{\vartheta} = i_0(t_n) \sum_k \frac{dM_{0k}}{dz}(z) + (-1)^m g(m_2 + m_3);
\]

\( m_{\text{up}} \) and \( m_{\text{down}} \) are the masses of the armature and operating piece, respectively; and \( m = 1 \) for upward and \( m = 2 \) for downward motion along the free-motion trajectories.

The basic parameters of the IDC of the BLG are: inductor outer diameter 80 mm, inner diameter 4 mm, height 5 mm; armature outer diameter 80 mm and height 2 mm; 76 inductor windings of wire with a 0.4 \( \times \) 0.5 mm cross section; mass of the operating piece 0.120 kg; and capacitor bank voltage 310 V and capacitance 500 \( \mu \)F. We shall estimate the efficiency of the catapult by the maximum height \( h_m \) by which the test object is displaced during the launch phase and its minimum velocity \( v_1 \) relative to the inductor during the braking phase.

**Modelling the IDC Processes in the Operating Cycle.** Because of the changing magnetic coupling, the current density \( j_1 \) in the inductor and the averaged current density \( j_2 \) in the armature vary nonsinusoidally during the stage in which the test object is launched vertically (Fig. 3). For a larger initial gap \( \Delta z_0 \) between the armature and the inductor, the magnetic coupling coefficient in the initial position will be smaller.
which leads to a drop in the current densities in the inductor \( j_{1m} \) and the armature \( j_{2m} \). As the initial gap \( \Delta z_0 \) increases, the maxima of the current pulses shift with time and the pulse shapes approach sinusoidal. Then the force indicators of the IDC decrease (see the Table). Thus, when \( \Delta z_0 \) increases from 0.25 to 4.0 mm the maximum electrodynamic force \( f_{zm} \) decreases by almost a factor of 3, while the impulse \( F_z \) increases by only a factor of 1.88. Because of this, the launch height \( h_m \) decreases by a factor of 3.71 and the falling velocity \( v_0 \) by a factor of 1.96. Then the oppositely polarized residual voltage \( U_{CT} \) on the capacitor bank increases by a factor of 1.62.

**TABLE 1. Electrical and Mechanical Parameters of the IDC during Launching of the Test Object**

| \( \Delta z_0 \), mm | \( j_{1m} \), A/mm² | \( j_{2m} \), A/mm² | \( K_m(0) \) | \( f_{zm} \), kN | \( F_z \), N·sec | \( U_{CT} \), V | \( h_m \), m | \( v_0 \), m/sec |
|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 0.25                | 368.6                | 707.0                | 0.933                | 4.131                | 0.688                | 100.9                | 0.512                | 3.14                |
| 1.0                 | 341.7                | 602.0                | 0.888                | 3.024                | 0.599                | 117.2                | 0.385                | 2.67                |
| 2.0                 | 321.5                | 513.6                | 0.832                | 2.210                | 0.504                | 135.9                | 0.269                | 2.23                |
| 3.0                 | 308.5                | 452.2                | 0.781                | 1.712                | 0.428                | 151.1                | 0.192                | 1.90                |
| 4.0                 | 299.5                | 405.3                | 0.734                | 1.369                | 0.366                | 163.5                | 0.138                | 1.60                |

\[
K_m(0) = \sum_{k=1}^{K} M_{0k}(0) \left( KL_0 \sum_{k=1}^{K} L_k \right)^{-0.5}
\]

which leads to a drop in the current densities in the inductor \( j_{1m} \) and the armature \( j_{2m} \). As the initial gap \( \Delta z_0 \) increases, the maxima of the current pulses shift with time and the pulse shapes approach sinusoidal. Then the force indicators of the IDC decrease (see the Table). Thus, when \( \Delta z_0 \) increases from 0.25 to 4.0 mm the maximum electrodynamic force \( f_{zm} \) decreases by almost a factor of 3, while the impulse \( F_z \) increases by only a factor of 1.88. Because of this, the launch height \( h_m \) decreases by a factor of 3.71 and the falling velocity \( v_0 \) by a factor of 1.96. Then the oppositely polarized residual voltage \( U_{CT} \) on the capacitor bank increases by a factor of 1.62.
Therefore, as the initial gap $\Delta z_0$ increases, there is a drop in the launch height $h_m$ of the armature with the test object, although the performance indicators for the braking phase do improve: the falling velocity $v_0$ decreases and the residual voltage $U_{C1}$ on the capacitor bank increases.

Braking of the falling armature with the test object occurs when a signal from the control unit to thruster $V_S2$ at the time the armature is a distance $z_0$ from the inductor (see Fig. 2). The braking coefficient $K_b = W_{k0}/W_{k1}$, where $W_{k0}$ and $W_{k1}$ are the kinetic energy without and with a braking pulse, depends on the distance $z_0$ between the falling armature and the inductor at which its excitation begins and on the initial gap $\Delta z_0$ when the armature with the test object is launched (Fig. 4). The smaller $\Delta z_0$ is, the more strongly the braking coefficient falls off as a function of the distance $z_0$.

Therefore, as the initial gap $\Delta z_0$ between the armature and the inductor is increased, the launch throw height $h_m$ decreases, but the braking characteristics of the IDC improve. Here the distance $z_0$ between the falling armature and the inductor at which its excitation begins should be about 0.5 mm.

**Conclusion.** The proposed induction-dynamic catapult can be used to increase the accuracy of a ballistic gravimeter because of direct conversion of electrical into kinetic energy. This simplifies the construction, reduces its size and weight, and allows changing the throw height of the test object within a specified range by regulating the charging voltage $U_0$ on the capacitor bank. The throw height of the armature with the test object can be reduced by increasing the initial gap between the armature and the inductor with improved braking performance for the IDC.

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