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RESEARCH OF THE MEASUREMENT OF GRAVITATIONAL ACCELERATION USING A TRANSFORMER GRAVIMETER

This article presents the methodology and results of experimental studies aimed at measuring the gravitational acceleration using a newly designed transformer gravimeter. The work outlines the relevance of high-precision determination of the gravitational acceleration g for solving numerous geophysical, geological, and engineering tasks, and highlights the limitations of existing ground-based gravimeters in terms of accuracy and measurement speed. The proposed approach employs a ballistic measurement method in which a test body with magnetic properties moves freely through a transparent tube equipped with inductive coils and a controlled electromagnetic release mechanism. The paper describes the structure of the experimental setup, the operating principles of the measurement channels, and the mathematical foundations used to calculate g based on time delays of induced voltage pulses and coordinate-based trajectory approximation using a video registration subsystem. A dual-channel system is implemented to enhance accuracy: the first channel determines g from signals induced in the coils, while the second uses pulsed illumination and video tracking to calculate coordinates of the falling body and apply a least-squares approximation. The results obtained from both channels are combined to form a refined estimate of gravitational acceleration with improved precision. Experimental measurements were carried out for different distances between the inductive coils, and corresponding oscillograms and calculated values of g are presented. The study confirms that the proposed transformer gravimeter and measurement methodology significantly improve the accuracy and performance of gravitational acceleration measurements, demonstrating their practical applicability for advanced gravimetric research.

Keywords: *gravitational acceleration, transformer gravimeter, experimental research, installation.*

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ДОСЛІДЖЕННЯ ВИМІРЮВАННЯ ПРИСКОРЕННЯ СИЛИ ТЯЖІННЯ ТРАНСФОРМАТОРНИМ ГРАВІМЕТРОМ

У статті представлено методику та результати експериментальних досліджень, спрямованих на вимірювання прискорення сили тяжіння за допомогою новоствореного трансформаторного гравіметра. Робота висвітлює актуальність високоточного визначення прискорення g для розв'язання широкого кола геофізичних, геологічних та інженерних задач, а також окреслює обмеження сучасних наземних гравіметрів щодо точності та швидкодії. Запропонований підхід базується на балістичному методі вимірювань, у якому пробне тіло з магнітними властивостями здійснює вільний рух у прозорій трубці, обладнаній індуктивними котушками та керованим електромагнітним механізмом утримання. У роботі детально описано структуру експериментальної установки, принципи роботи вимірювальних каналів та математичні основи розрахунку g за часовими затримками індукованих імпульсів напруги й за результатами координатної апроксимації траєкторії, отриманої за допомогою відеореєстраційної підсистеми. Для підвищення точності реалізовано дворівневу систему вимірювань: перший канал визначає g за сигналами з котушок, другий — використовує імпульсне освітлення та відеотракінг для обчислення координат падіння і подальшої апроксимації методом найменших квадратів. Об'єднання результатів обох каналів забезпечує уточнену й підвищену за точністю оцінку прискорення сили тяжіння. Проведено експериментальні вимірювання для різних відстаней між індуктивними котушками, наведено відповідні осцилограми та обчислені значення g. Дослідження підтверджує, що запропонований трансформаторний гравіметр та методика вимірювань значно підвищують точність і ефективність визначення прискорення сили тяжіння та можуть бути використані в сучасних гравіметричних дослідженнях.

Ключові слова: *прискорення сили тяжіння, трансформаторний гравіметр, експериментальні дослідження, установка.*

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Statement of the problem

Measuring the acceleration of gravity (AG) g with high accuracy is necessary for 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, finding deep density inhomogeneities, searching for mineral deposits, etc. Gravimeters are designed to determine g. Among them, transformer gravimeters (TG) are the most promising for ground-based measurements.

A significant contribution to the development of methods and means of gravimetric measurements was made by scientific schools formed at the Institute of Geophysics under the leadership of Academician of the National Academy of Sciences of Ukraine Starostenko V.I. (Kyiv), at the National Scientific Center "Institute of Metrology" under the leadership of Ph.D. Sydorenko G.S. and at the NTUU "KPI" at the Faculty of Instrumentation under the leadership of Dr. of Technical Sciences, Prof. Bezvesilna O.M.

Modern research in the field of gravimetric equipment development is focused on two main areas: the first is increasing the accuracy of g measurements by transformer gravimeters by eliminating the influence of seismic vibrations on the measurement process, the second is building effective automated systems for the gravimetric measurement process.

High-precision measurement of g is a complex scientific and technical problem and requires the use of new methods of conducting experimental research to measure the acceleration of gravity with a transformer gravimeter.

Therefore, an urgent scientific and technical task is to increase the accuracy and speed of measurements of the magnitude of the acceleration of gravity by applying a new method of conducting measurements using TG.

In this regard, **the purpose of the article is** to conduct an experimental study of the acceleration of gravity using a new method using a transformer gravimeter.

Analysis of recent research and publications

The most famous in the field of gravimetric measurements are the works of prominent CIS scientists Popov E.I. at the Institute of Earth Physics of the Russian Academy of Sciences with strongly damped gravimeters GAL, Bagromyants V.O., and earlier - Lozinskaya A.M. at the All-Russian Research Institute of Geophysics with a set of equipment based on string gravimeters GS, Polyakov L.G. at the Moscow Research Institute of Electromechanics and Automation with a set of equipment based on a strongly damped gravimeter and foreign scientists L. La Costa, D. Harrison, A. Graf, Y. Preston-Tomoda, M. Galvani, Cook, Tate, Faller with various types of gravimeters, etc. From the analysis of the literature [1-7] it is clear that the most famous modern ground-based gravimeters have insufficient accuracy (1 mGal) and speed (processing of results takes months). Their accuracy largely depends on the perfection of the determination of the measured quantities. However, the analysis of the literature showed that insufficient attention has been paid to the methodology of experimental research.

Therefore, consideration of the general composition and principle of operation of a transformer gravimeter and research into the methodology for conducting experimental studies to measure the acceleration of gravity of a TG is an urgent task.

Presentation of the main material of the article

Laboratory experimental studies of AG TG measurement
AG measurement method

To conduct experimental studies of TG, we will use the ballistic method for a ballistic gravimeter (BG), which is, in fact, a prototype of the proposed TG.

The principle of operation of the BG is based on measuring the time it takes a falling body to pass through several points, the distance between which is known.

Laboratory studies of TG were conducted to determine the AG. For this purpose, a variant of the ballistic method of measuring g was used. Let the test body A (a metal ball with magnetic properties) (Fig. 1) fall from a certain height with zero initial velocity.

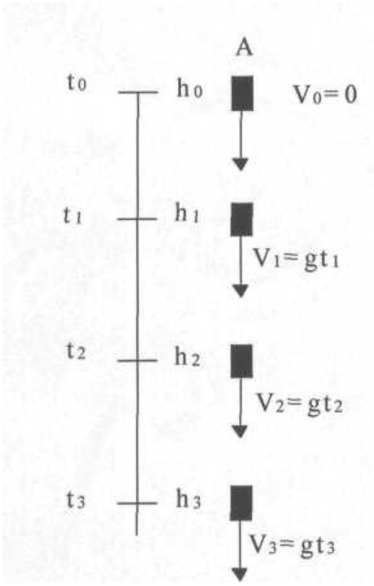

Fig. 1. Laboratory setup for experimental studies of AG TG

We will use the following equipment: a plastic tube with three movable coils vertically mounted on a tripod; a device for holding the test body in its initial position (electromagnet); a metal ball with magnetic properties; a constant voltage source; a switch; a digital computer.

Using the formulas for uniformly accelerated motion for velocity and distance traveled, we write the following relations for intervals S1 and S2 of the distance traveled:

$$S_1 = V_1 \Delta t_1 + \frac{g\Delta t_1^2}{2}; \quad (1)$$

$$S_2 = V_2 \Delta t_2 + \frac{g\Delta t_2^2}{2} = (V_1 + g\Delta t_1)\Delta t_2 + \frac{g\Delta t_2^2}{2}, \quad (2)$$

where: $S_1 = h_2 - h_1$ and $S_2 = h_3 - h_2$ are two intervals of the path successively traversed by the test body during the time $\Delta t_1 = t_2 - t_1$ and $\Delta t_2 = t_3 - t_2$, respectively.

We obtain the velocity V_1 from equation (1) and substitute its expression into formula (2). After simple transformations, we obtain the formula for determining the AG from the measured values S_1, S_2, Δt_1 and Δt_2:

$$g = \frac{2(S_2/\Delta t_2 - S_1/\Delta t_1)}{\Delta t_1 + \Delta t_2}. \quad (3)$$

If we set the distances between the measuring coils to be the same ($S = S_1 = S_2$), then the calculation formula can be represented as:

$$2S = g \cdot \frac{\Delta t_1 + \Delta t_2}{1/\Delta t_2 - 1/\Delta t_1}, \quad (4)$$

where do we get AG:

$$g = \frac{2S(1/\Delta t_2 - 1/\Delta t_1)}{\Delta t_1 + \Delta t_2}. \quad (5)$$

In this case, having performed a series of experiments for different *S*, it is possible to construct a graph on the axes of which 2 *S* and *T can be plotted.*

Let us denote

$$T = \frac{\Delta t_1 + \Delta t_2}{1/\Delta t_2 - 1/\Delta t_1}, \quad (6)$$

then the AG can be determined according to the formula

$$g = \frac{2S}{T^2}. \quad (7)$$

Description of the installation for measuring AG

The scheme of the installation for measuring AG is presented in Fig. 2.

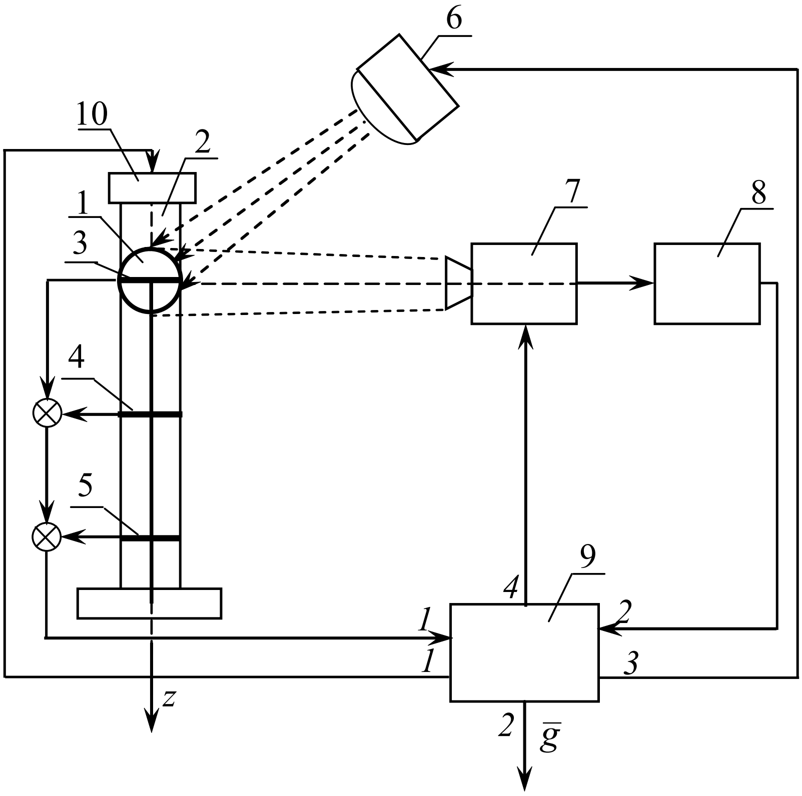

Fig. 2. Scheme of the installation for measuring AG
1 - test body - layer; 2 - plastic tube on a fixed base; 3, 4, 5 - inductance coils; 6 - pulsed light source; 7 - video camera; 8 - unit for approximating the trajectory of the test body; 9 - electronic computer (EC); 10 - electromagnet

Before the measurements, the test body 1 is fixed in the electromagnet 10. From the first output of the digital computer 9, a signal is sent to the input of the electromagnet 10, according to which the electromagnet releases the test body 1. It begins to move down the transparent tube 2 on a fixed base under the action of the AG. Since the test body 1 is made in the form of a layer with magnetic properties, when it passes past the coils 4, 5, 6, an EMF is induced in them.

From the outputs of coils 3, 4, 5, an electrical signal is supplied to the first input of the digital computer, consisting of three voltage pulses, each of which is caused by the occurrence of EMF in coils 3, 4, 5. The time delays $\hat{\tau}_1,\ \hat{\tau}_2,\ \hat{\tau}_3$ of each of the pulses relative to the moment of the beginning of the movement of the test body 1 are proportional to the absolute value of the AG g and the distances x_1, x_2, x_3 from the electromagnet 10 to coils 3, 4, 5. Since at the time $t_0 = 0$ the initial coordinate of the test body $x_0 = 0$, and its initial velocity $v_0 = 0$, then its current coordinate at the time t is determined by the formula:

$$x(t) = x_0 + v_0 t + \frac{gt^2}{2} = \frac{gt^2}{2}. \qquad (8)$$

From formula (8) we obtain an expression for determining the absolute value of the AG based on the time delays of three voltage pulses from coils 3,4,5:

$$\hat{g}_{1i} = \frac{2x_i}{\hat{\tau}_i^2}, \quad i = 1,\ 2,\ 3. \qquad (9)$$

By averaging the values calculated by formula (9), we obtain an estimate of the absolute value of the AG in the first TG measurement channel:

$$\hat{g}_1 = \frac{\hat{g}_{11}+\hat{g}_{12}+\hat{g}_{13}}{3}. \qquad (10)$$

To increase the measurement accuracy in the new TG, a second channel for measuring the absolute value of the AG is also used. In this channel, the digital computer 9 controls the operation of the pulsed light source 6 and the video camera 7. Such control is carried out by signals coming from the third and fourth outputs of the digital computer 9 to the inputs of the pulsed light source 6 and the video camera 7, respectively.

At the same time, the video camera 7 forms an image of the electromagnet 10, the transparent tube 2 on a fixed base and the test body 1 itself. Thanks to the pulsed lighting, several consecutive positions of the test body 1 are recorded in each image, corresponding to the moments of operation of the pulsed lighting source 6.

The approximation device 8, based on the image received from the digital computer 9, determines the current coordinates $\hat{x}_j$ of the center of mass of the test body 1, corresponding to the time instants $j \cdot T_{дж}$, where $T_{дж}$ is the period of generation of illumination pulses by the pulsed illumination source 6, $j = 1 \ldots N$, where N is the number of positions of the test body 1 recorded in the image by the video camera 7. The coordinates $\hat{x}_j$ are measured relative to the initial position $x_0 = 0$ of the test body 1 in the electromagnet 10.

Since the measurement results contain errors Δx_j,

$$\hat{x}_j = x_j + \Delta x_j, \qquad (11)$$

where x_j is the exact value of the coordinates of the center of mass of the test body 1 at time instants $j \cdot T_{дж}$.

Next, the approximation device 8 determines the parameter of the trajectory of motion of the test body 1 in the transparent tube 2 on a fixed base. According to formulas (8) and (11), we obtain:

$$x_j = \frac{\hat{g}_2 \cdot (j \cdot T_{дж})^2}{2}, \qquad (12)$$

where $\hat{g}_2$ is the estimate of the absolute value of the AG obtained in the second measurement channel of the new TG, and is the parameter of the trajectory of motion of the test body 1.

Based on formula (12) and the results of measurements of the current coordinates, $\hat{x}_j$ we can compile the functional

$$J = \sum_{j=1}^{N} \left[\hat{x}_j - \frac{\hat{g}_2 \cdot (j \cdot T_{дж})^2}{2}\right] \to min. \qquad (13)$$

By minimizing expression (6) by the least squares method, we determine the estimate $\hat{g}_2$ of the absolute value of the AG in the second measuring channel of the new TG.

The least squares approximation procedure allows us to eliminate the influence of random errors in coordinate measurements $\hat{x}_j$ on the estimation $\hat{g}_2$ of the absolute value of the AG.

To further increase the measurement accuracy in the new TG, it is necessary to combine the results of measurements of the absolute value of the AG obtained in the first and second measuring channels of this TG. Such a combination of results is performed by a digital computer 9, the first and second inputs of which receive signals from the coils 3, 4, 5 and from the device 8 for approximating the trajectory of the test body 1.

The results of measurements of the absolute value of the AG, calculated according to formulas (10) and (14), can be combined as follows:

$$\hat{g} = \frac{\hat{g}_1+\hat{g}_2}{2}. \qquad (14)$$

The final estimate of $\hat{g}$ the absolute value of the AG, calculated according to formula (14), has increased accuracy and is supplied to output 2 of the digital computer 9. This output 2 is the output of the new TG.

Thus, due to the properties of the procedure for approximating measurement results using the least squares method and the properties of the methods for complexing measuring instruments, the new TG has increased accuracy.

Using the existing installation of the new TG, relevant studies of the AG were conducted.

Experiment methodology

1. The computer is turned on: the appropriate software products are launched to register the signal being recorded. The circuit is assembled.

2. Oscillograms of the installation signals during the fall of the test mass were obtained for inductance coils located at a distance of 0.25 m and 0.2 m from each other, respectively (Fig. 3-22).

3. The same distances between the measuring coils were set (0.25 m). 10 measurements *of* t_1 and t_2 were made, the average values and the corresponding errors were found. From the obtained average values, the values Δt_1, Δt_2 , T and g were calculated using formulas (6, 7). The results are given in Table 1.

3. The distance between the measuring coils was changed (0.2 m) and a new series of measurements was performed. 10 series of such measurements were performed (in each case $S_1 = S_2$). The results are listed in Table 1.

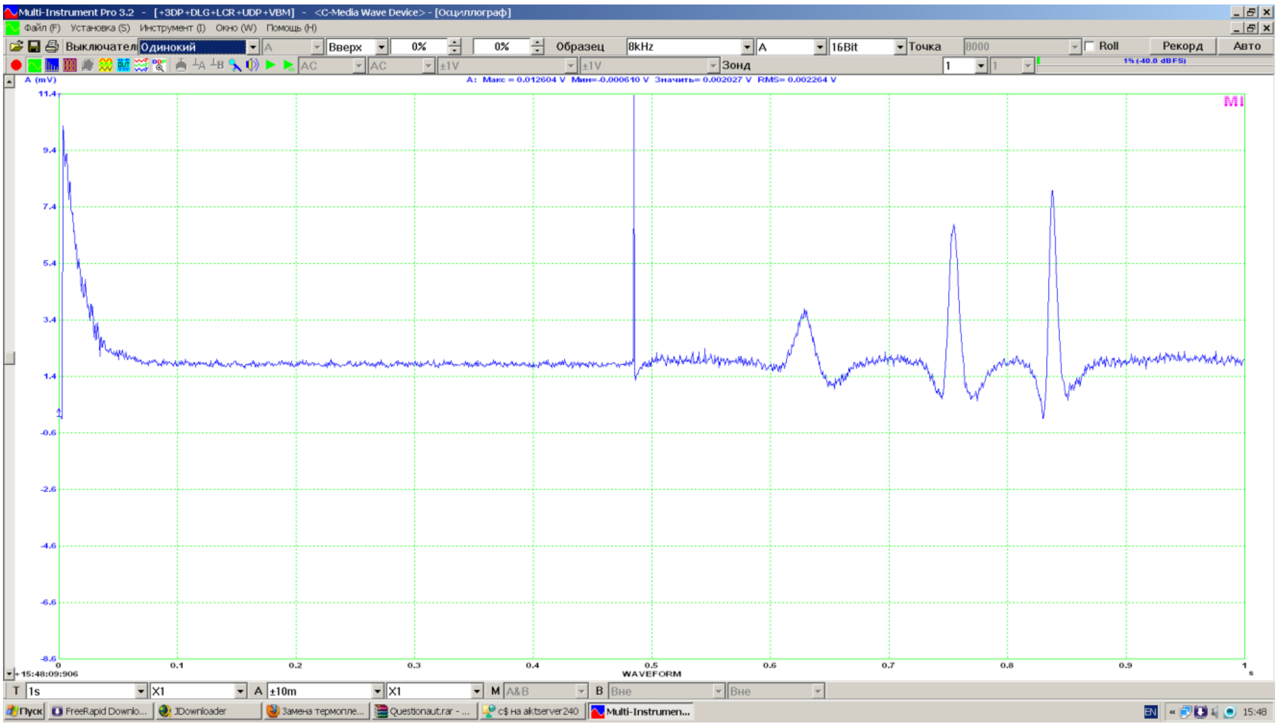

Fig. 3. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 1*)

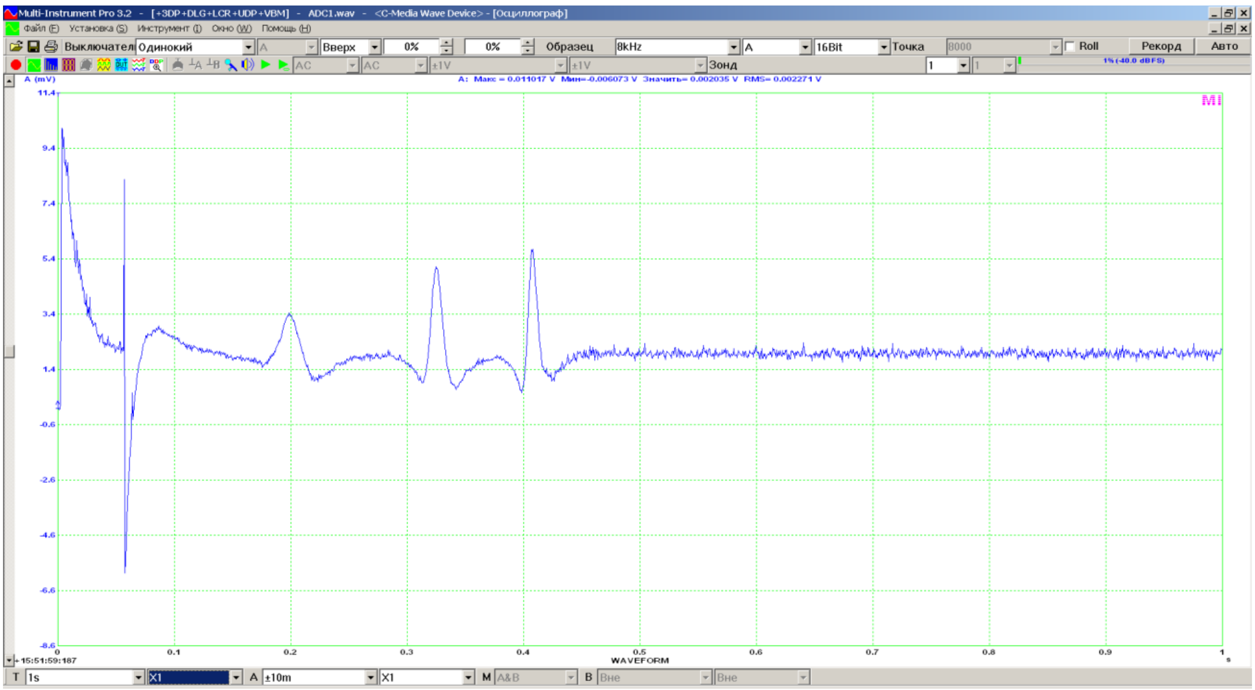

Fig. 4. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 2*)

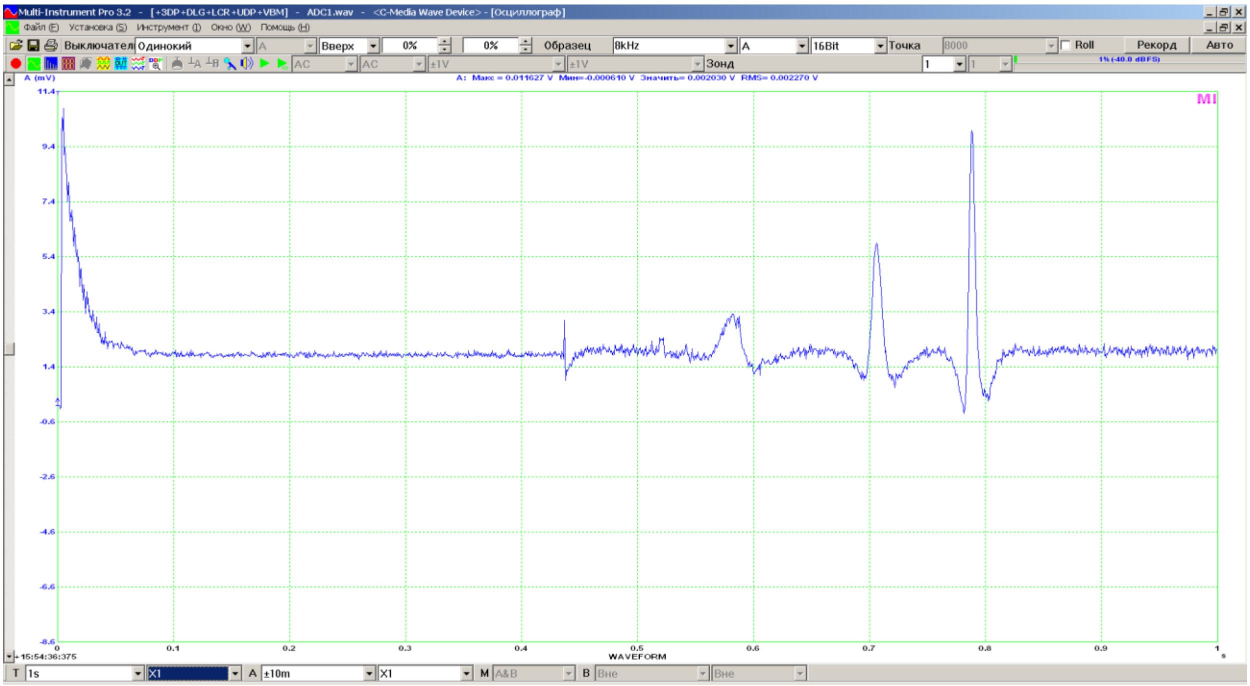

Fig. 5. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 3*)

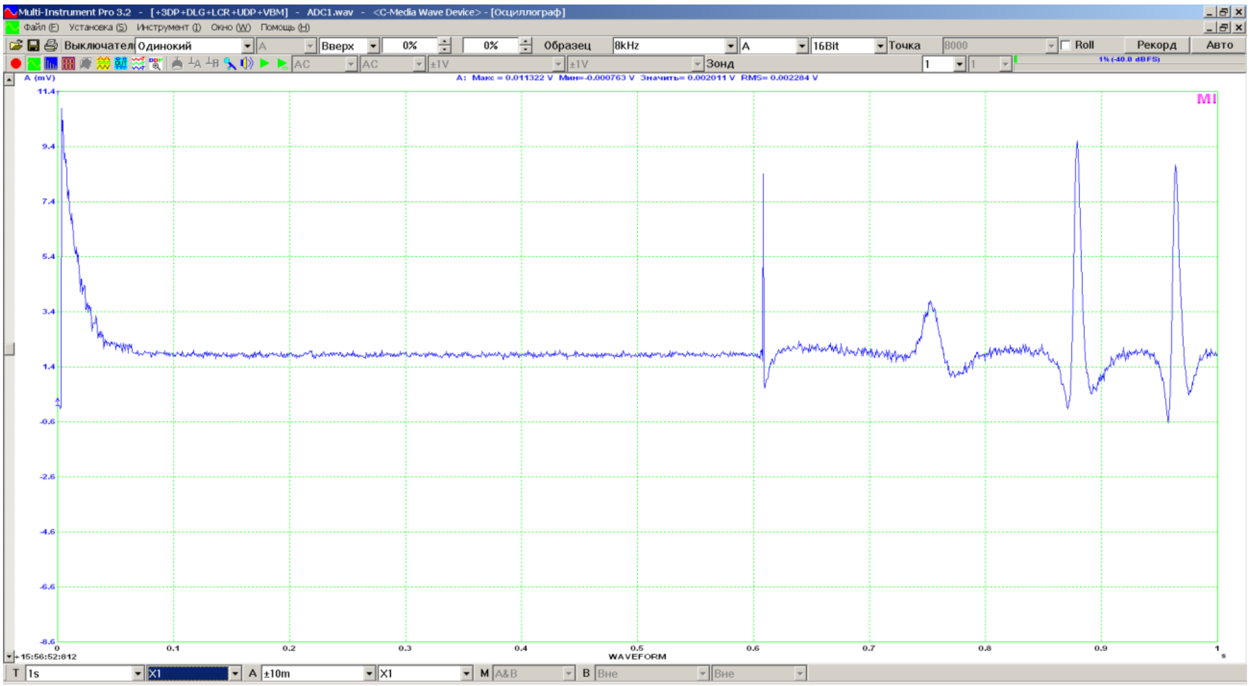

Fig. 6. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 4*)

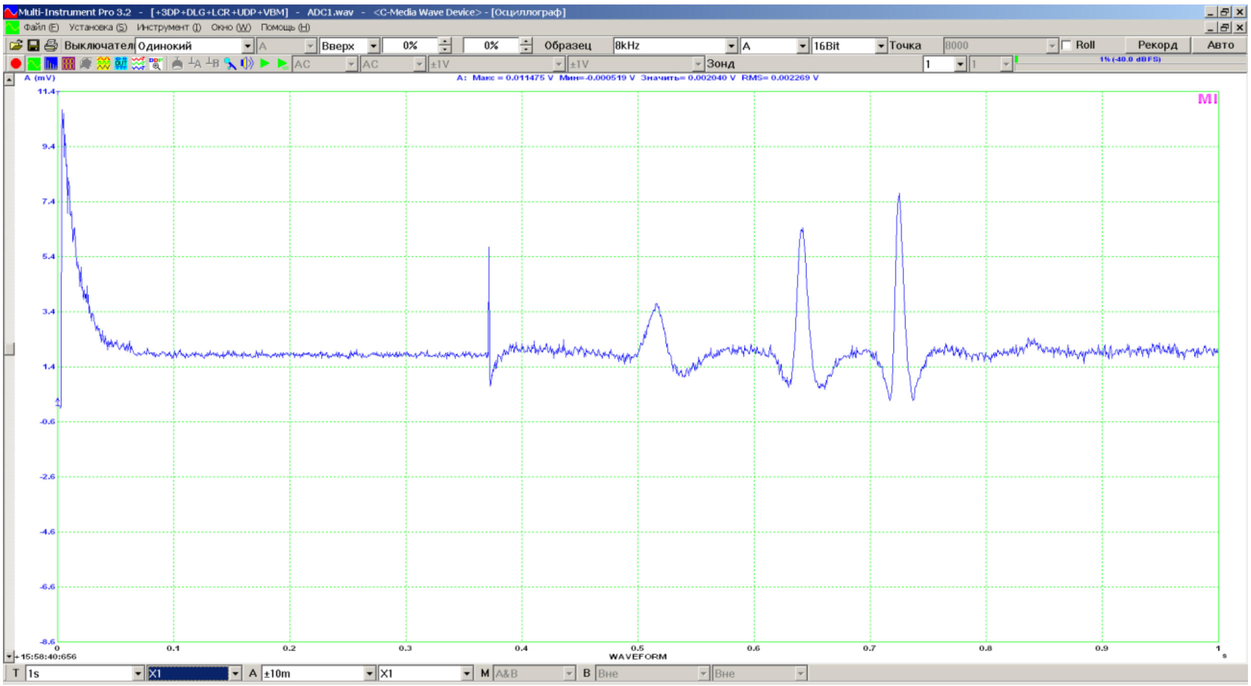

Fig. 7. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 5*)

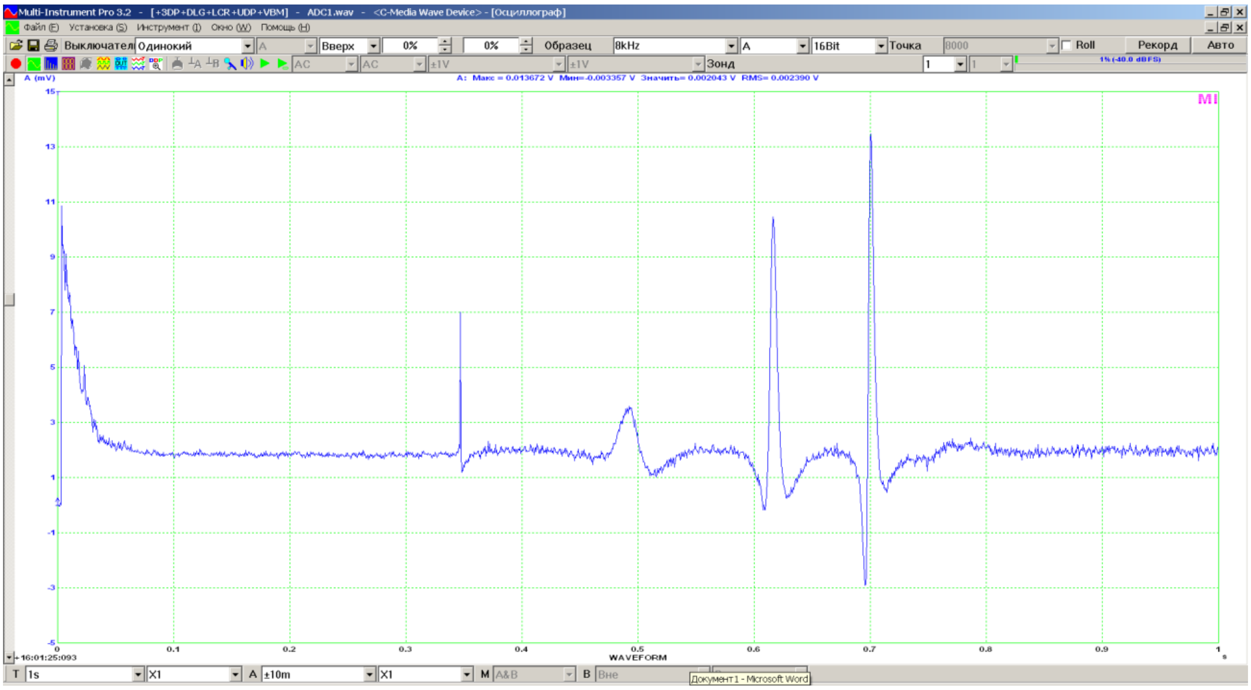

Fig. 8. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 6*)

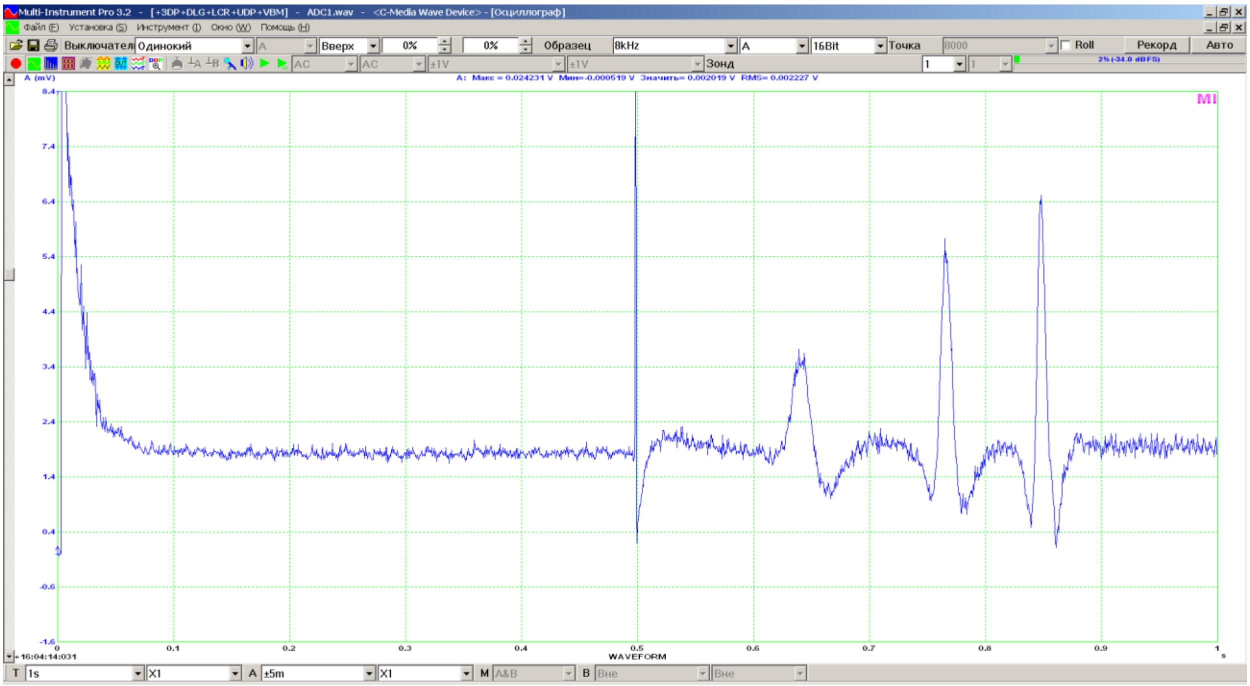

Fig. 9. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 7*)

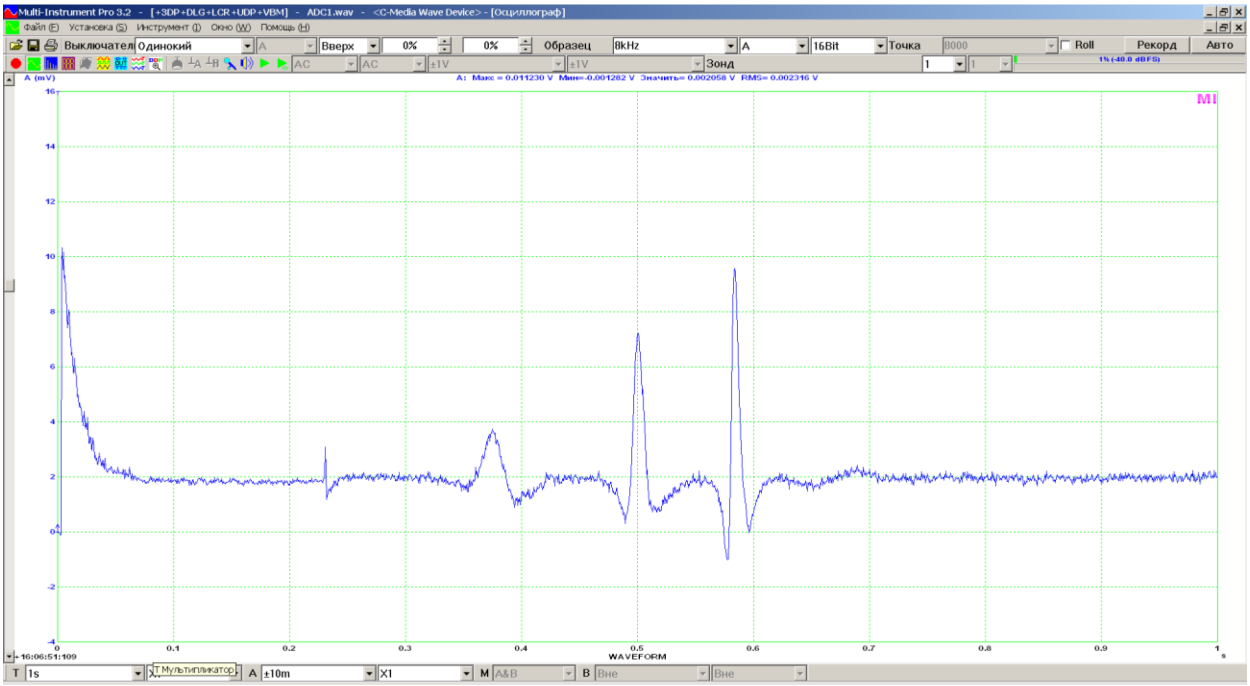

Fig. 10. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 8*)

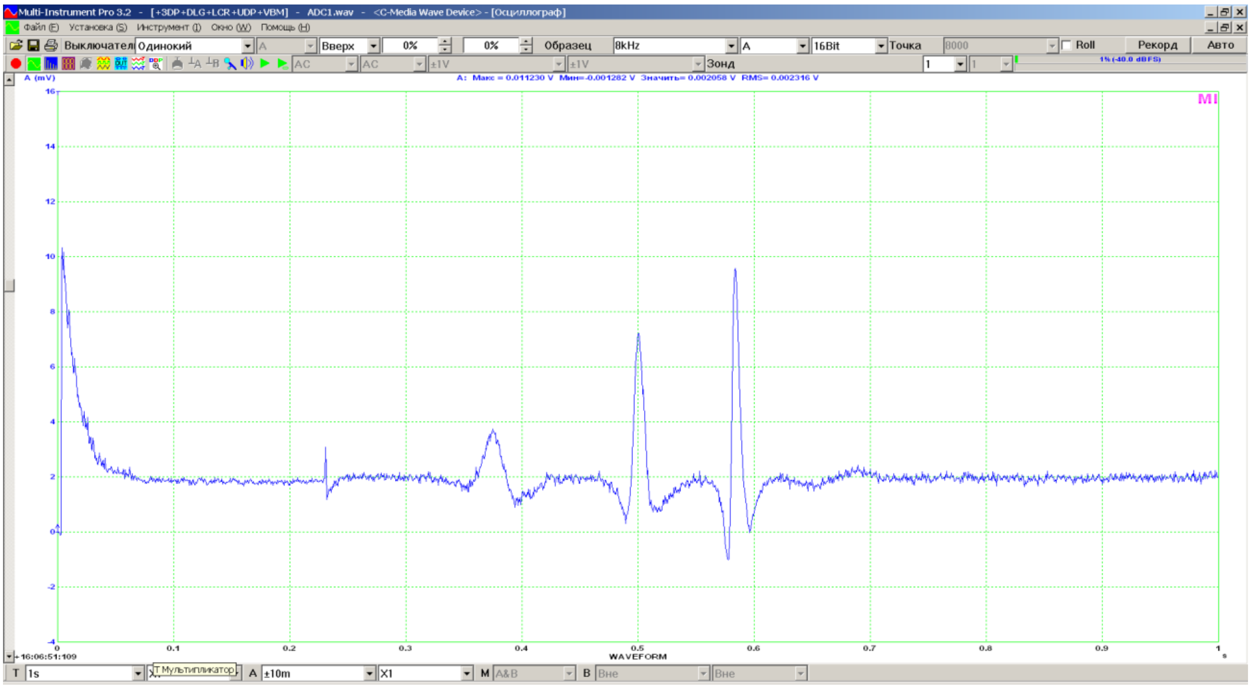

Fig. 11. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 9*)

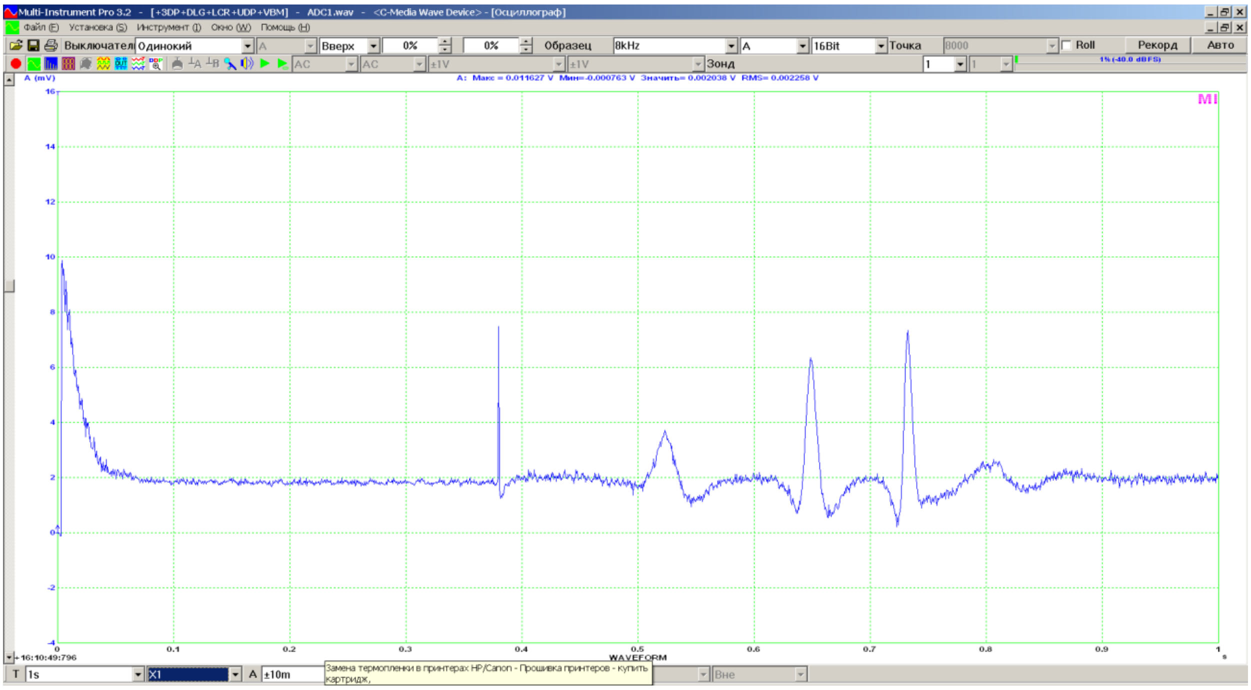

Fig. 12. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.25 m* from each other (*experiment No. 10*)

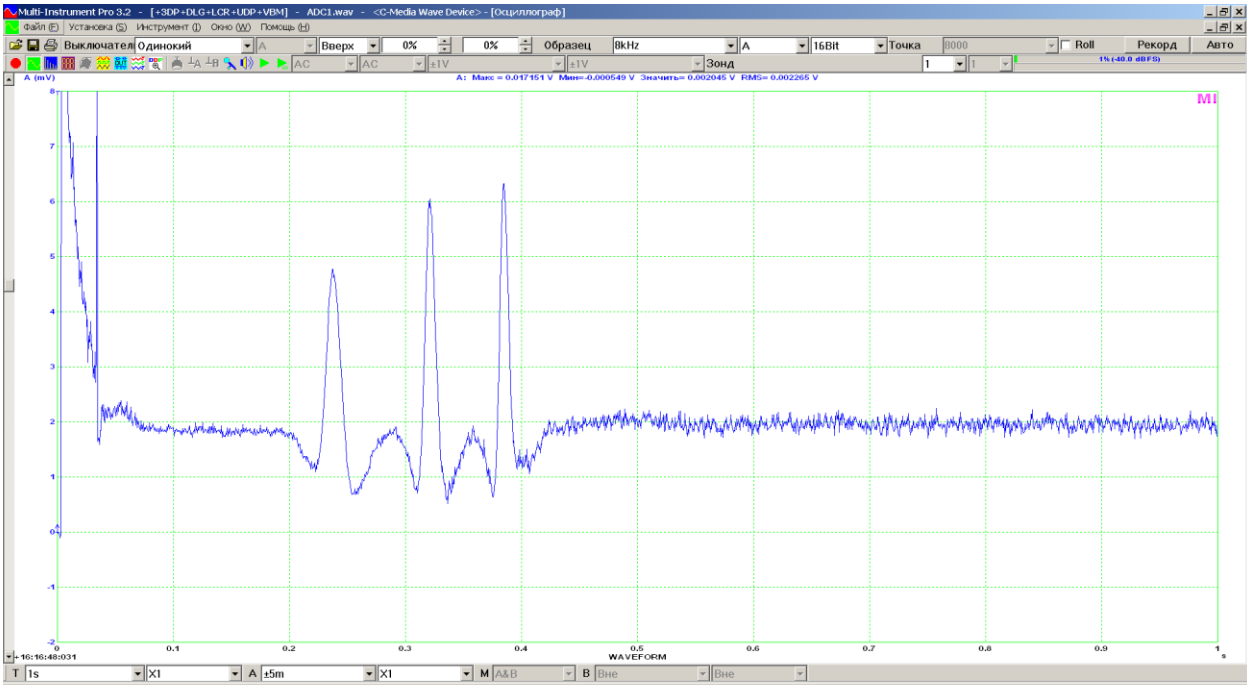

Fig. 13. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 1*)

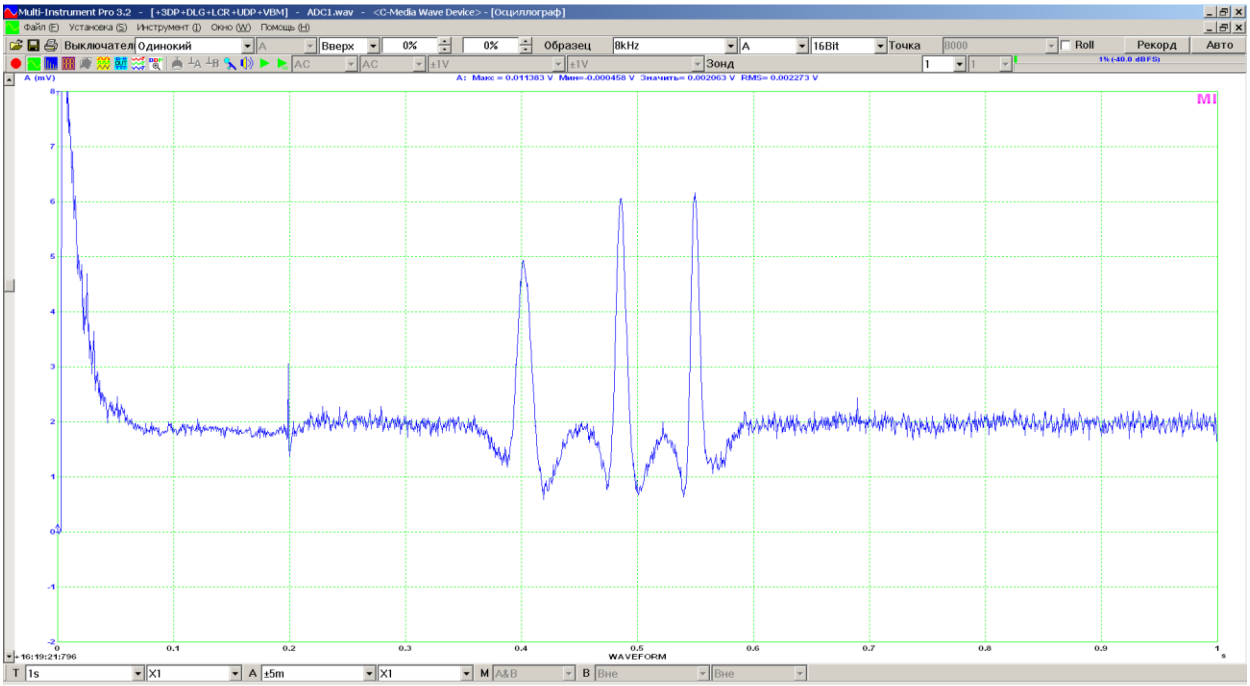

Fig. 14. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 2*)

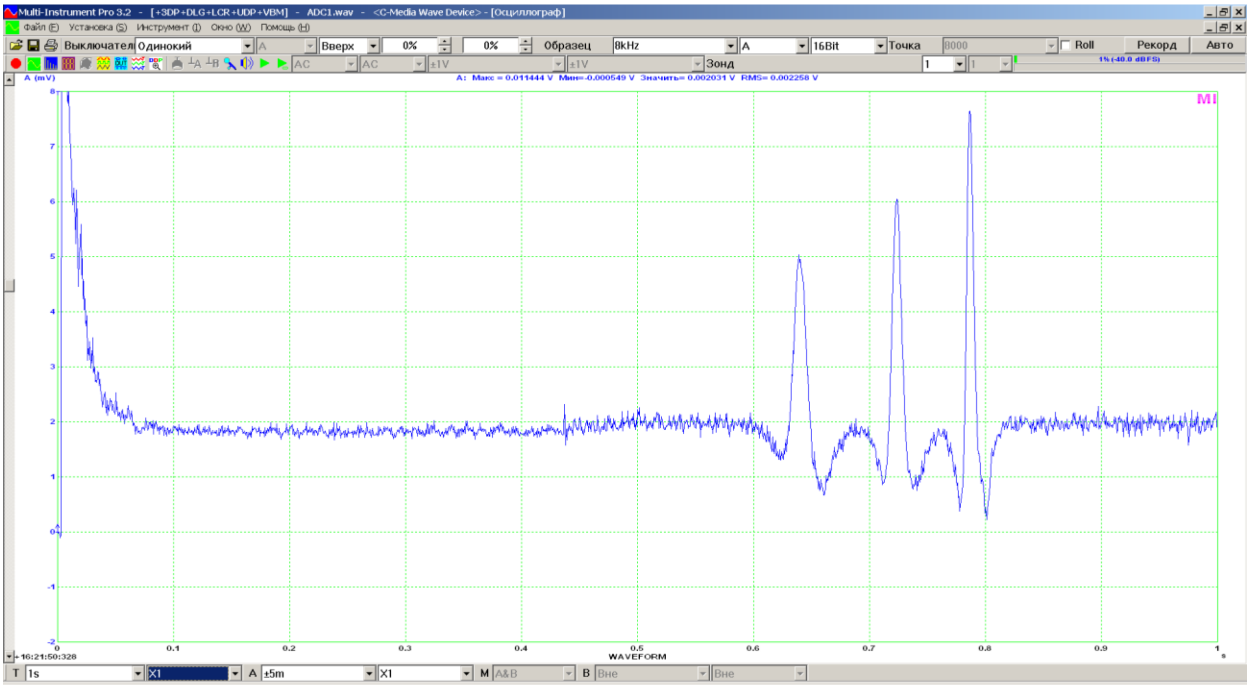

Fig. 15. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 3*)

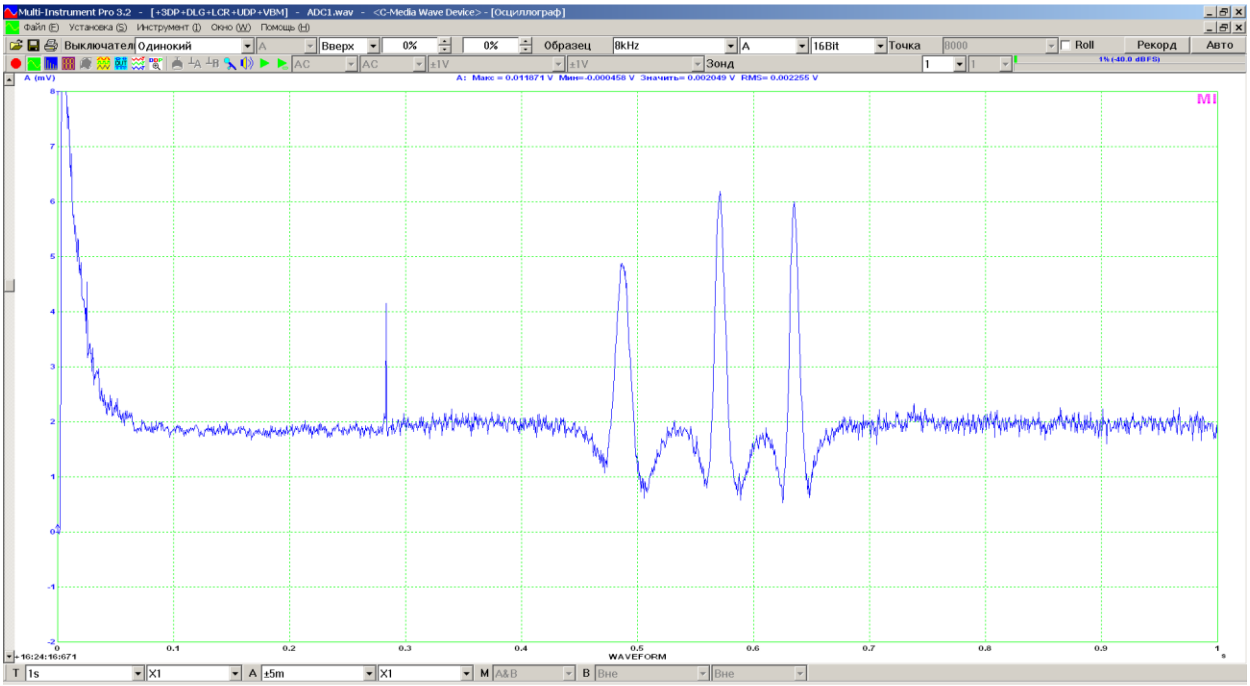

Fig. 16. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 4*)

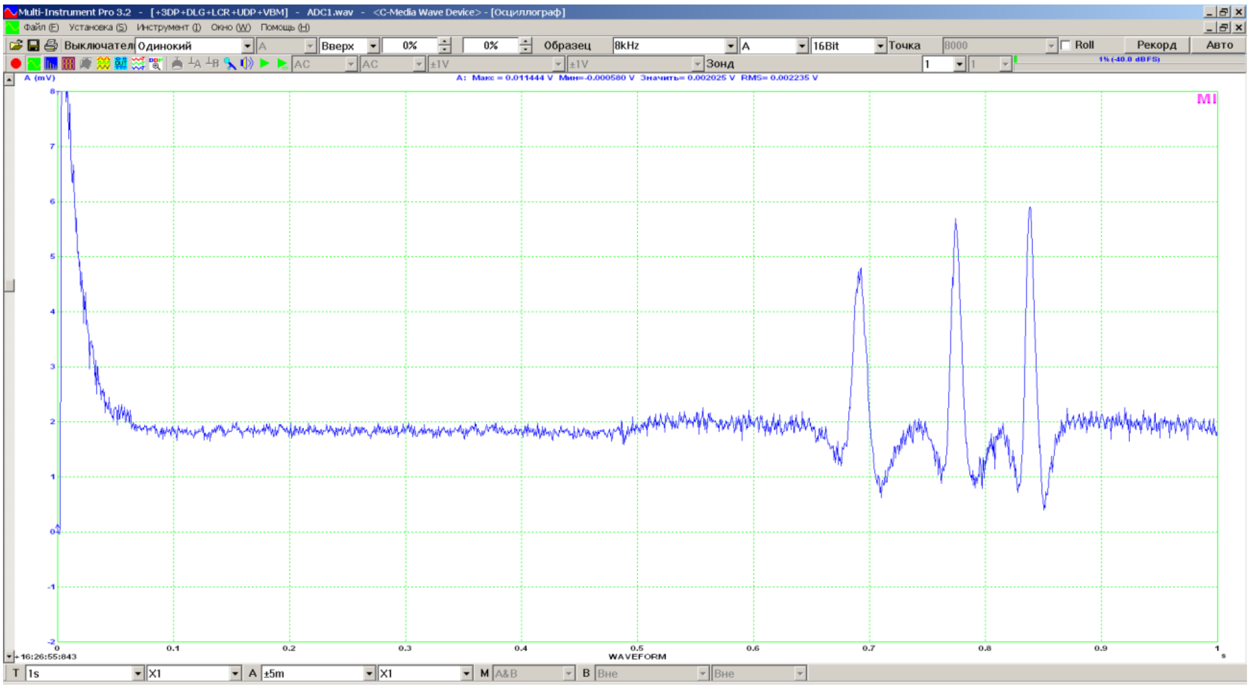

Fig. 17. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 5*)

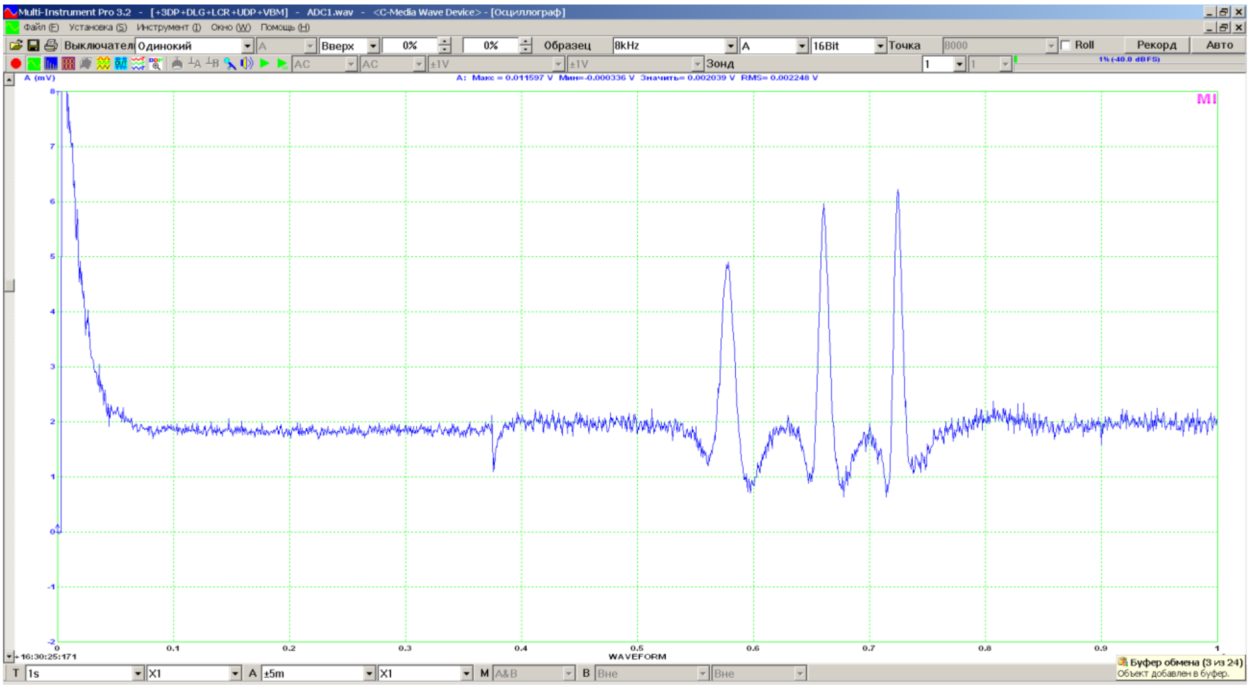

Fig. 18. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 6*)

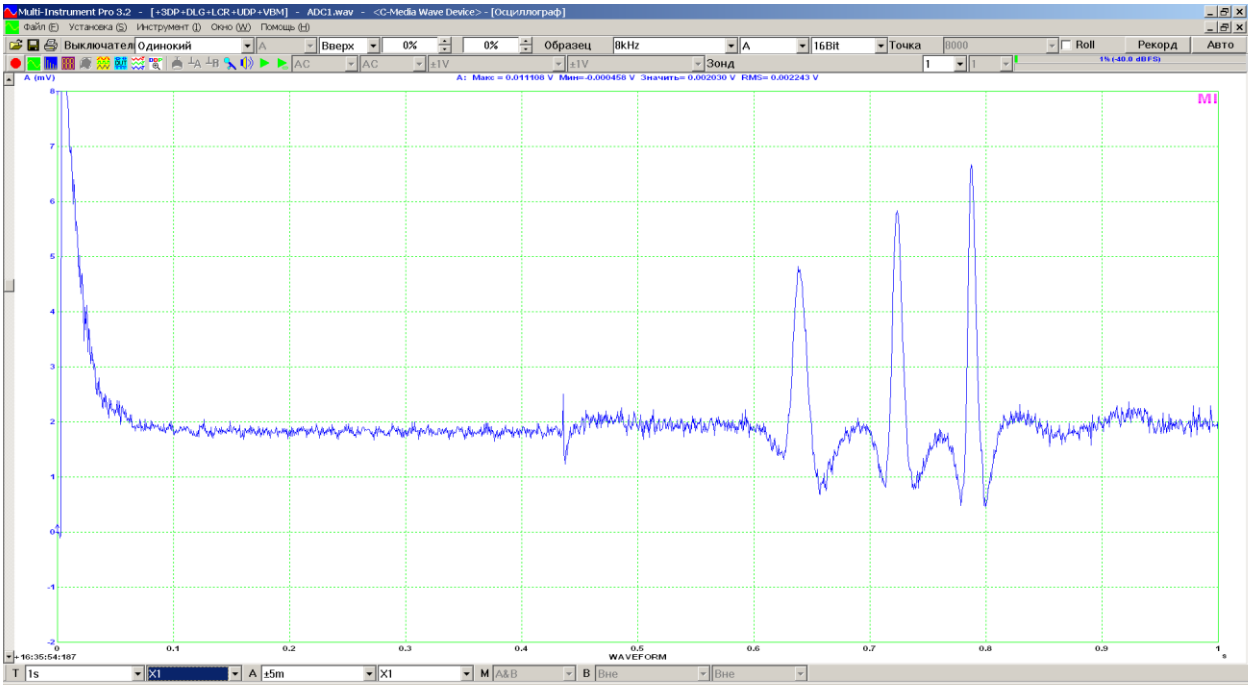

Fig. 19. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 7*)

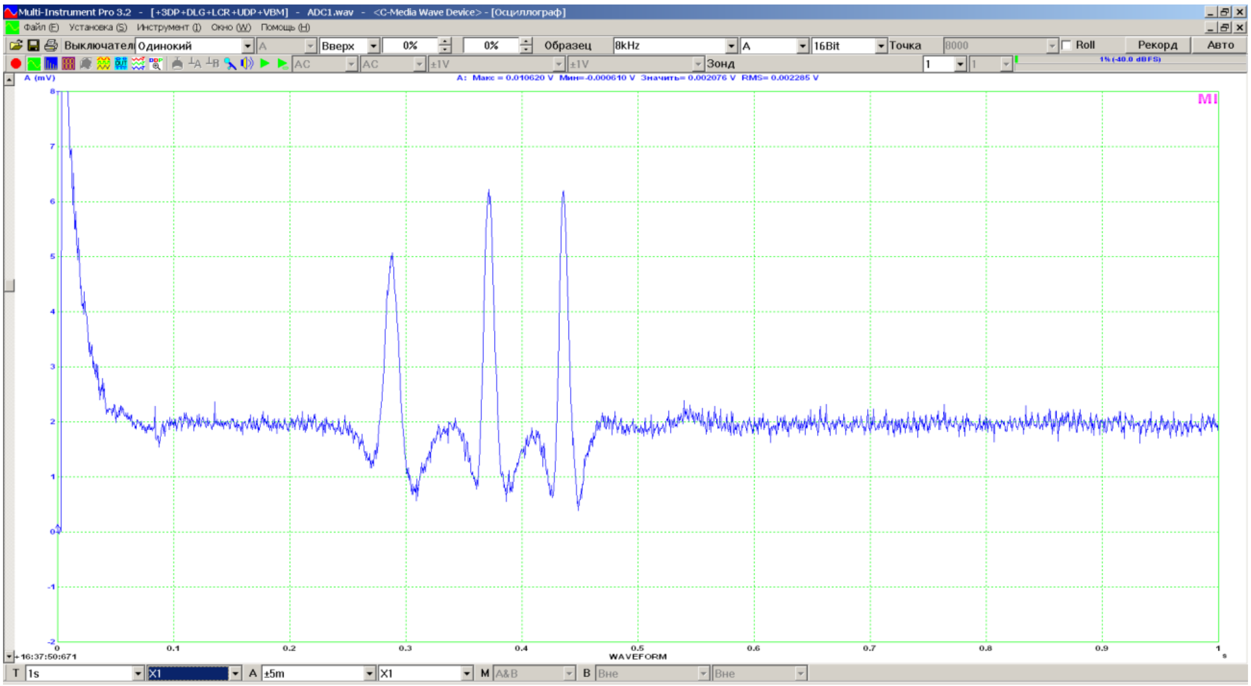

Fig. 20. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 8*)

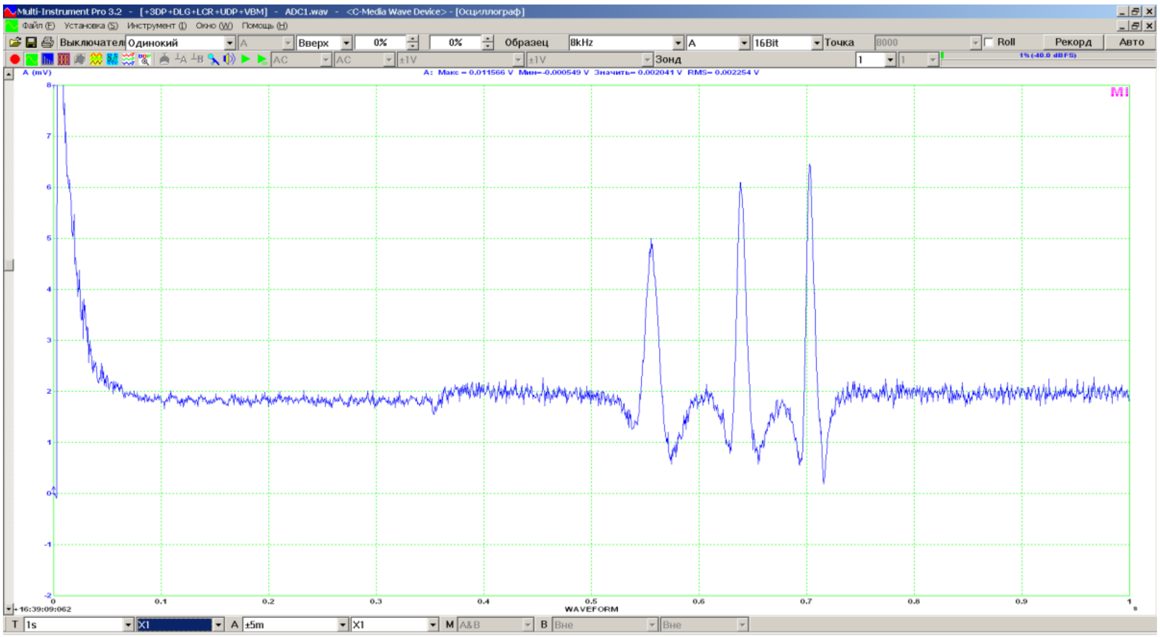

Fig. 21. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of *0.20 m* from each other (*experiment No. 9*)

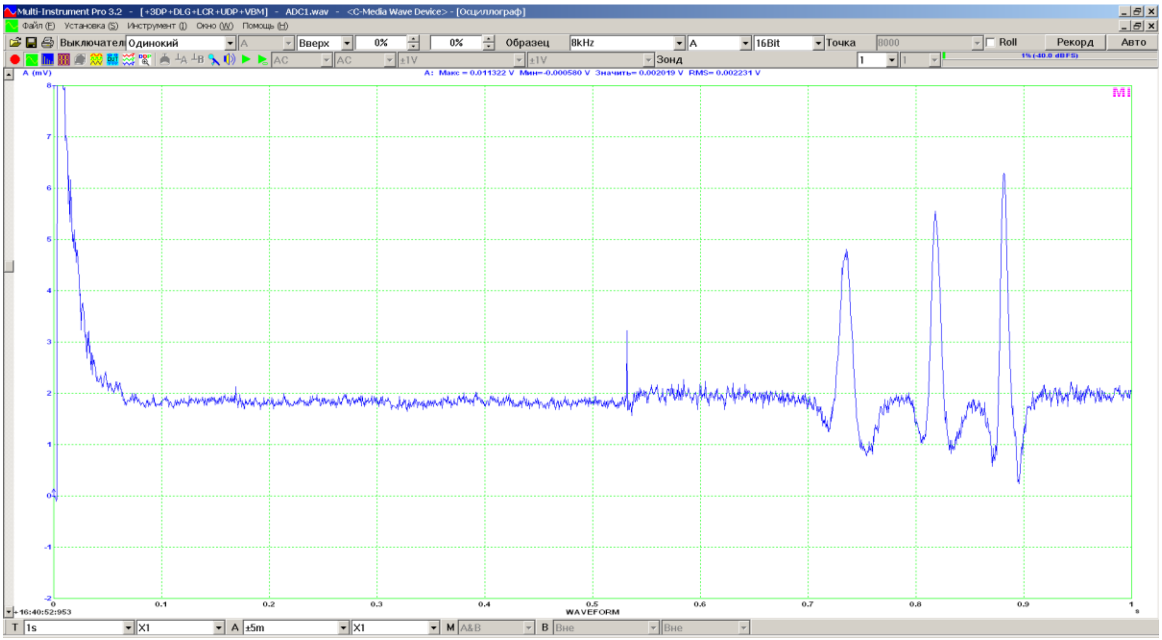

Fig. 22. Oscillogram of the signal of the laboratory setup during the fall of the test mass for inductance coils located at a distance of 0.20 m from each other (experiment No. 10)

Table 1

Values of parameters studied using a laboratory setup for measuring AG

No.exp.	t_1, s	t_2, s	t_3, s	*S, m*	Δt_1, s	Δt_2, s	*g , m/s* ^{2}
1	0.629	0.753875	0.83725	0.25	0.124875	0.083375	9.570216064
2	0.1995	0.324625	0.40725	0.25	0.125125	0.082625	9.893782047
3	0.581375	0.705625	0.78775	0.25	0.12425	0.082125	9.99186646
4	0.75275	0.8785	0.9635	0.25	0.12575	0.085	9.544886358
5	0.516	0.64075	0.724125	0.25	0.12475	0.083375	9.556686929
6	0.491625	0.615875	0.699875	0.25	0.12425	0.084	9.259236894
7	0.64125	0.76525	0.847125	0.25	0.124	0.081875	9.87704755
8	0.37475	0.499875	0.58325	0.25	0.125125	0.083375	9.897110327
9	0.593875	0.71925	0.802	0.25	0.125375	0.08275	9.870319184
10	0.523375	0.648325	0.73175	0.25	0.12495	0.083425	9.558759984
							9.84299118

Continuation of table 1

1	0.237375	0.32075	0.384125	0.2	0.083375	0.063375	9.81710992
2	0.4015	0.485125	0.549	0.2	0.083625	0.063875	9.72693102
3	0.6395	0.722875	0.786125	0.2	0.083375	0.06325	9.61097679
4	0.48675	0.570625	0.634625	0.2	0.083875	0.064	9.81520548
5	0.691375	0.774	0.837875	0.2	0.082625	0.063875	9.700212605
6	0.576875	0.660125	0.723875	0.2	0.08325	0.06375	9.997993191
7	0.639	0.723125	0.787	0.2	0.084125	0.063875	9.78514727
8	0.28725	0.371	0.435375	0.2	0.08375	0.064375	9.804457924
9	0.5555	0.6385	0.702125	0.2	0.083	0.063625	9.90893317
10	0.734625	0.817625	0.881	0.2	0.083	0.063375	9.7545669
							9.85624241

Conclusions

The article presents the methodology for conducting experimental studies to measure the acceleration of gravity with a new transformer gravimeter, considers the general composition, principle of operation, and results of experiments using a transformer gravimeter installation that provide increased accuracy and speed of AG measurements.

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