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INCREASING THE ACCURACY OF THE AVIATION GRAVIMETRIC SYSTEM WITH A TRANSFORMER GRAVIMETER AS A SENSITIVE ELEMENT

ПІДВИЩЕННЯ ТОЧНОСТІ АВІАЦІЙНОЇ ГРАВІМЕТРИЧНОЇ СИСТЕМИ З ТРАНСФОРМАТОРНИМ ГРАВІМЕТРОМ В ЯКОСТІ ЧУТЛИВОГО ЕЛЕМЕНТА

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Abstract. *The relevance of aviation gravimetric measurements is indisputable. Known aviation gravimeters have both advantages and disadvantages, which are defined in this article. The basis of this work is the highlighting of methods and means of improving the accuracy of the aviation gravimetric system. The objectives of this article are to provide the equation of motion and the list of the main elements of the aviation gravimetric system, the characteristics of the two-channel method for building a gravimeter and its advantages over others. The selection of the natural frequency of the gravimeter oscillations is also substantiated and the importance of taking into account the correction due to the influence of the angular velocity of the Earth's rotation is shown. A new transformer gravimeter with higher accuracy is proposed and investigated. It is substantiated that the use of a new two-channel transformer gravimeter provides the necessary increase in accuracy. The methodical and instrumental errors of the system were analyzed. The accuracy requirements for the components of the measuring system are formulated.*

Key words: *gravimeter, gravitational acceleration, Earth's gravitational field, aviation gravimetric system.*

1. Introduction.

The study of the Earth's gravitational field is an important scientific problem. Information about the Earth's gravitational field is necessary in geodesy, geophysics for mineral exploration; seismology for forecasting earthquakes and tsunamis; aviation and space technology for correction of inertial navigation systems of aerospace objects; in the defense industry for correction of control and stabilization systems of light armored vehicles [1].

Today, measurements of the parameters of the Earth's gravitational field on an aircraft are the most relevant (UAV). They make it possible to measure gravity anomalies Δg in such hard-to-reach areas of the Earth as mountain ranges, the Earth's poles, and the equator – cheaper and at a much higher speed than land or sea measurements. For these purposes, aviation gravimetric systems (AGS) are usually used, the sensitive element of which is a gravimeter. Data on gravitational anomalies Δg or gravitational acceleration g, entered into the memory of the on-board computer (BC) of the AGS, will significantly contribute to increasing both the accuracy of determining the navigational parameters of moving objects and the efficiency of gravimetric reconnaissance. Therefore, conducting high-precision aviation gravimetric measurements at high speed is relevant.

2. Analysis of literary data and statement of the problem

Today there are many types of AGS gravimeters: quartz [2], string gravimeter [3], magnetic [4, 5], mobile gravimeter [6], spring [7], the work of which is based on various physical phenomena [1]. They have their advantages and disadvantages. Almost all known gravimeters have significant errors due to the influence of the vertical acceleration of the aircraft [8–10], which are 10^3 times greater than the useful signal Δg. Known aviation gravimeters are somewhat complicated by the need to use auxiliary systems (in particular, the global positioning system (GPS)) [11]. They require periodic calibration and adjustment [12], which greatly complicates the work and takes a lot of time. Known modern gravimeters (gravimetric systems) belong to ground, surface and underwater [13-15] measurement methods that are not used in aviation gravimetry.

The following works are devoted to the analysis and research of some modern types of gravimeters: on gyroscopic single-channel and two-channel gravimeters [16], on piezoelectric single-channel and two-channel gravimeters [17, 18], on string gravimeters [19, 20], on capacitive single-channel and two-channel gravimeters [21, 22].

However, the literature on aviation gravimetry [2, 23, 24] provides information on individual types of gravimeters and does not cover methods and means of improving the accuracy and speed of AGS.

3. The purpose and objectives of the research

The purpose of the work is to highlight the methods and means of improving the accuracy and speed of the AGS.

To achieve the formulated goal, the following tasks were set:

- give the equations of motion and the list of the main components of the AGS;
- justify the choice of the natural frequency of oscillations of the AGS gravimeter;
- to show the expediency of using the two-channel method for the construction of the AGS gravimeter;
- conduct an analysis of methodical errors;
- to show the importance of taking into account the correction due to the influence of the angular velocity of the Earth's rotation;
- propose and research a new transformer gravimeter with greater accuracy than the known ones.

4. Research materials and methods

4.1. Equation of motion and list of main components of AGS

The scheme and main components of the aviation gravimetric system, which includes a gravimeter [1], are given.

The aviation gravimetric system for measuring gravity acceleration anomalies Δg includes (Figure 1):

- navigation parameters determination system 1;
- height meter 2;
- gravimeter 3 installed on a two-axis stabilized platform;
- BC 4.

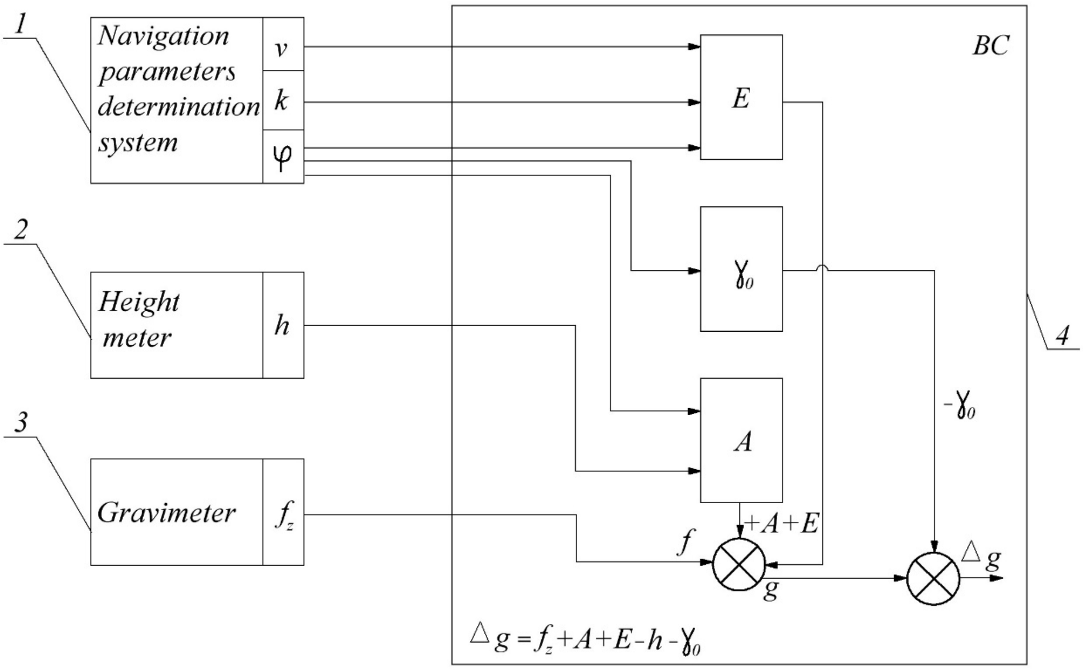

Figure 1 – Aviation gravimetric system for measuring gravity acceleration anomalies: *1 – navigation parameters determination system; 2 – height meter; 3 – gravimeter; 4 – BC [1]*

In [1], the equation of motion of the AGS with any type of gravimeter was obtained:

$$\begin{aligned} f_z = g_z - \frac{v^2}{r} + 2e\frac{v^2}{r}\left[1 - 2\cos^2\varphi \cdot \left(1 - \frac{\sin^2 k}{2}\right)\right] - \\ - 2\omega_3 v\cos\varphi\sin k + 2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi - \\ - 2\frac{\gamma_0 h}{r} - \omega_3^2 h\cos^2\varphi + \ddot{h}, \end{aligned} \tag{1}$$

where f_z – is the output signal of the gravimeter; g_z – acceleration of gravity (GA) along the sensitivity axis of the gravimeter; v – aircraft speed; r – radius of aircraft location; e – compression of the Earth ellipsoid; φ – geographical latitude; k – aircraft course; ω_3 – angular velocity of the Earth's rotation; h – height of aircraft above the ellipsoid; $\dot{h}$ − vertical velocity of aircraft; $\ddot{h}$ − vertical acceleration of aircraft; γ_0 − the reference value of the GA.

In equation (1) g_z is a useful signal, all other signals are interferences that must be taken into account or eliminated.

We present equation (1) in the form:

$$\begin{aligned} g_z = f_z + \frac{v^2}{r}\left\{1-2e\cdot\left[1-\cos^2\varphi\cdot\left(1-\frac{\sin^2 k}{2}\right)\right]\right\}+ \\ +2\omega_3 v\cos\varphi\sin k-2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi+ \\ +2\frac{\gamma_0 h}{r}+\omega_3^2 h\cos^2\varphi-\ddot{h}. \end{aligned} \tag{2}$$

Since the gravity acceleration anomaly is equal to the difference of the GA along the sensitivity axis of the gravimeter and the reference value of the gravity acceleration, we obtain [1]:

$$\begin{aligned} \Delta g = f_z + \frac{v^2}{r}\left\{1-2e\cdot\left[1-2\cos^2\varphi\cdot\left(1-\frac{\sin^2 k}{2}\right)\right]\right\}+ \\ +2\omega_3 v\cos\varphi\sin k- \\ -\frac{m}{k_2}\left(\frac{k(t_2)-k(t_1)}{t_2-t_1}+\omega_3\sin\overline{\varphi}+\frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\overline{\varphi}\right)- \\ -2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi+2\frac{\gamma_0 h}{r}+\omega_3^2 h\cos^2\varphi-\gamma_0. \end{aligned} \tag{3}$$

Let's rewrite (3) in the form [1]:

$$\Delta g = f_z + E + A - \ddot{h} - \gamma_0 \, , \tag{4}$$

where f_z − is the output signal of the AGS gravimeter;

$$E = \frac{v^2}{r}\left\{1-2e\cdot\left[1-\cos^2\varphi\cdot\left(1-\frac{\sin^2 k}{2}\right)\right]\right\}+2\omega_3 v\cos\varphi\sin k-2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi \quad -$$

Etvesh's correction [1] has an additional term $\omega_3^2 h\cos^2\varphi$, whose influence is more than 1 mGal and which must be taken into account when measuring GA with an accuracy of 1 mGal; $A = 2\frac{\gamma_0 h}{r}+\omega_3^2 h\cos^2\varphi$ − the height correction [1] has an additional term $2\dot{h}er^{-1}v\cos k\sin 2\varphi$, the influence of which is more than 1 mGal and which must be taken into account when measuring GA with an accuracy of 1 mGal; $\gamma_0 = \gamma_{0e}\left(1+0{,}0052884\sin^2\varphi-0{,}0000059\sin^2 2\varphi\right)$ − GA reference value (Cassinis formula) [24]; $\ddot{h}$− vertical acceleration of aircraft [1]; $\gamma_{0e} = 9{,}78049$ m/s^2 – GA reference value (equatorial) [25].

In known gravimeters [2 - 7, etc.], additional components in Etvesh corrections and for height are not taken into account, which reduces the accuracy of gravity measurements.

It can be seen from the equation of motion (3) that the AGS should consist of the following components:

- gravimeter for measuring GA;
- systems for stabilizing the gravimeter's sensitivity axis in the vertical position;
- navigation systems for determining the navigation parameters of the location of the aircraft;
- height meter;
- on-board computer BC for computing operations according to algorithm (3) or (4) [1].

4.2. Selection of the natural frequency of gravimeter oscillations.

The main errors of known gravimeters are caused by the fact that the gravimeter measures the projection of a set of signals onto the sensitivity axis: the useful GA signal and the interference signal, which is caused, mainly, by the vertical acceleration exceeding the useful GA signal by 10^3 [1, 26].

It is necessary to solve the problem of filtering the output signal of the gravimeter of the automated AGS.

The output signal of the AGS gravimeter after calculation and introduction of corrections E, A, γ_0, in (4) can be written in the form:

$$T = f_z = g_z + \ddot{h}, \tag{5}$$

where $\ddot{h}$ – error due to the effect of vertical acceleration of the aircraft.

Well-known gravimeters usually use low-pass filters for $\ddot{h}$ filtering. The presence of a low-pass filter in the gravimeter significantly reduces the reliability of the gravimeter and its accuracy [1, 27]. Over time, the operation of the electronic components of the filter becomes unstable: the filter will pass interference to the output of the gravimeter or will not pass a part of the useful signal.

A different approach is proposed.

Analytical expressions of the spectral densities of the GA useful signal $G_{\Delta g}(\omega)$ and the main obstacle of the vertical acceleration of the aircraft $G_{\ddot{h}}(\omega)$ and their graphs (Figure 2) were obtained in [1].

The graphs of the spectral densities of the GA useful signal and the main interference intersect at $\omega = 0{,}1$ rad/s point (Figure 2). A method of filtering the output signal of the gravimeter is proposed by choosing a frequency of natural oscillations of the gravimeter of 0.1 rad/s, which is equal to the frequency of the intersection of the two graphs (Figure 2).

Using low-pass filtering with a cut-off frequency of 0.1 rad/s, it is possible to separate the GA g from the vertical acceleration $\ddot{h}$ with an accuracy of 1 mGal. In the output signal of the gravimeter, the following disturbances are also eliminated, the dominant frequency of which is greater than 0.1 rad/s:

– translational vibration accelerations (predominant frequency of which is 3140 rad/s);

– angular vibration accelerations (the predominant frequency of which is over 0.1 rad/s) [1].

Therefore, we choose the frequency of natural oscillations of the gravimeter to be 0.1 s^{-1}.

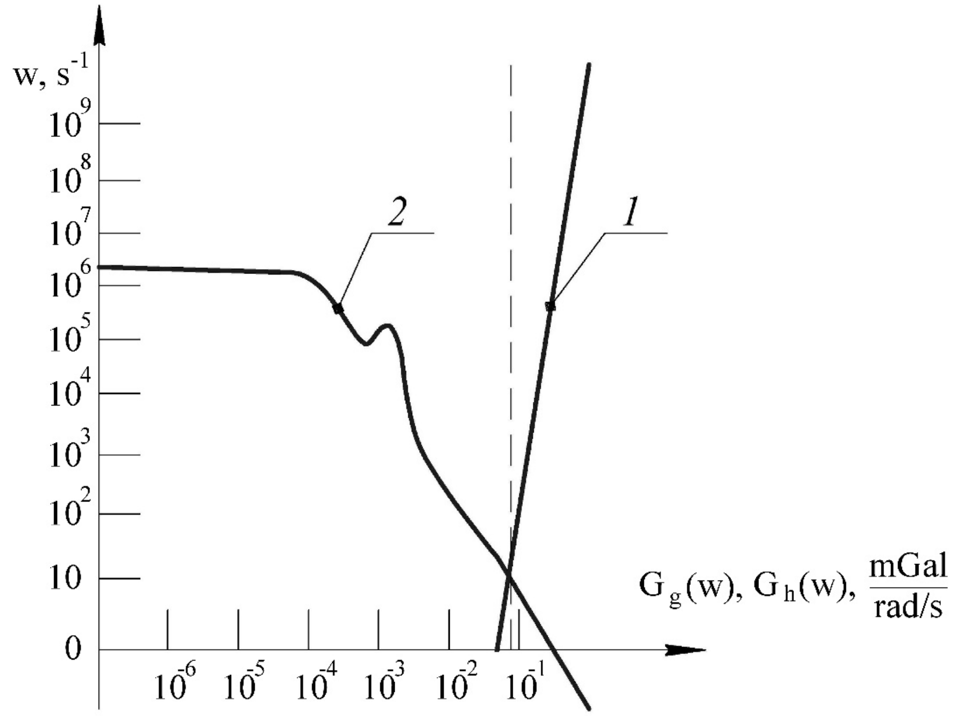

Figure 2 – Dependencies on frequency: *1 – spectral density of vertical acceleration of the aircraft, 2 – spectral density of the PST useful signal [1]*

As a result, we get the output signal *T′* of the gravimeter, which contains only the useful GA signal. It does not contain the above-mentioned errors, the predominant frequency of which is greater than 0.1 rad/s [1].

The equation of motion of the AGS with a gravimeter for determination Δg will be [1]:

$$\Delta g = f_z + \frac{v^2}{r}\left\{1 - 2e\cdot\left[1 - 2\cos^2\varphi\cdot\left(1 - \frac{\sin^2 k}{2}\right)\right]\right\} + \\ + 2\omega_3 v\cos\varphi\sin k - 2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi + \\ + 2\frac{\gamma_0 h}{r} + \omega_3^2 h\cos^2\varphi - \gamma_0. \tag{6}$$

In equation (6), in contrast to known works, there is no effect of vertical acceleration $\ddot{h}$.

The selection of the natural frequency of the gravimeter equal to 0.1 s^{-1} ensures that there is no influence of vertical acceleration on the operation of the AGS gravimeter and that there is no need to use additional electronic filters.

A solution to the problem of filtering the effect of vertical acceleration on output readings by using a two-channel measurement method is also proposed.

4.3. The use of the two-channel method for the construction of the AGS gravimeter

When building a gravimeter of any type, it is advisable to use the two-channel method (the invariance method), which allows you to eliminate a number of significant errors:

- from the influence of vertical acceleration;
- instrumental errors due to the influence of residual non-identity of structures of sensitive elements;
- instrumental errors due to the influence of changes in temperature, humidity, environmental pressure and other factors.

Let's consider the generalized scheme of the construction of a two-channel gravimeter (Figure 3).

The inertial mass M is acted upon by the acceleration of gravity g, the vertical acceleration $\ddot{h}$ of the aircraft, and the total instrumental errors Δi indicated above. Sensitive elements are located in such a way that vertical accelerations in them act oppositely. In more detail, the arrangement of two identical sensitive elements is described (depending on the type of gravimeter) in: string [20], capacitive, two-channel MEMS capacitive [21].

The equation of forces along the O_z axis of the sensitivity of the two-channel gravimeter, directed along the geographic vertical, will have the form:

$$f_z = f_1 + f_2 = mg + m\Delta\ddot{h} + \Delta i + mg - m\Delta\ddot{h} - \Delta i = 2mg, \quad (7)$$

where f_1 – the output signal from the sensitive element 1; f_2 – the output signal from the sensitive element 2; f_z – output signal of a two-channel gravimeter; m – weight of inertial mass M.

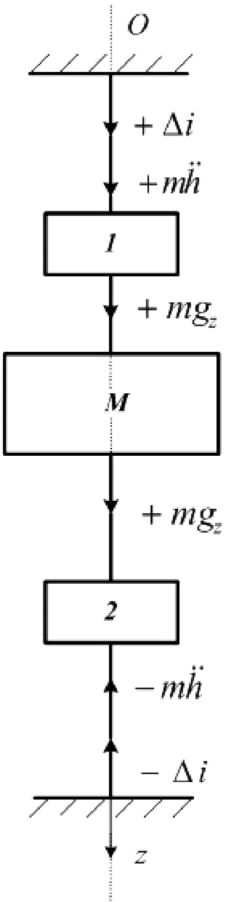

Figure 3 – Generalized construction scheme of a two-channel gravimeter:
1, 2 – sensitive elements of a two-channel gravimeter, M – inertial mass [19, 21]

It can be seen from equation (7) that the output signal of the two-channel gravimeter contains twice the value of the useful GA signal and does not contain the vertical acceleration $\ddot{h}$ of the aircraft and total instrumental errors Δi.

The output signal f_z of the two-channel gravimeter is fed to the BC, where the output signals from the system for determining navigation parameters and the altimeter are also fed. In BC, the value of the gravity acceleration anomaly Δg is calculated according to the formula [1]:

$$\Delta g = f_z + E + A - \gamma_0, \tag{8}$$

where f_z – output signal of a two-channel gravimeter; E − Etwesh's amendment; A − height correction; γ_0 − the reference value of the acceleration of gravity.

It can be seen from equation (8) that it lacks the largest error component $\ddot{h}$. All known single-channel gravimeters are measured $\ddot{h}$ simultaneously with *g*. This leads to large errors (a value of $\ddot{h}$ is 10^3 greater than *g*).

Thus, in the two-channel gravimeter, a significant increase in the accuracy of measurements is ensured by compensating the effect of the vertical acceleration $\ddot{h}$ of the aircraft and total instrumental errors Δi.

5. Results of studies on calculation of AGS errors

5.1. Analysis of methodological errors of the AGS

To determine the permissible measurement errors of the parameters of the aircraft movement by the AGS components, we will use the methodology outlined in [1].

$$\Delta g = f_z + D, \tag{19}$$

where *D* – total error of AGS:

$$\begin{aligned} D = {} & \frac{v^2}{r}\left\{1 - 2e\cdot\left[1 - 2\cos^2\varphi\cdot\left(1 - \frac{\sin^2 k}{2}\right)\right]\right\} + \\ & + 2\omega_3 v\cos\varphi\sin k - 2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi + \\ & + 2\frac{\gamma_0 h}{r} + \omega_3^2 h\cos^2\varphi - \gamma_0. \end{aligned} \tag{20}$$

The parameters included in equation (19) are determined by individual subsystems of the AGS.

The complete differential of the function *D* determines the relationship between the absolute values of the errors of the subsystems of the AGS measuring parameters: Δv speed, Δk course, $\Delta\varphi$ latitude, Δh altitude, $\Delta\dot{h}$ vertical speed [1]:

$$\begin{aligned} \Delta D = {} & \left(\frac{dD}{dv}\right)\Delta v + \left(\frac{dD}{dk}\right)\Delta k + \\ & + \left(\frac{dD}{d\varphi}\right)\Delta\varphi + \left(\frac{dD}{dh}\right)\Delta h + \left(\frac{dD}{d\dot{h}}\right)\Delta\dot{h}, \end{aligned} \tag{21}$$

where

$\frac{dD}{dv} = \frac{2v}{r}\left\{1 - 2e\cdot\left[1 - 2\cos^2\varphi\cdot\left(1 - \frac{\sin^2 k}{2}\right)\right]\right\} + 2\omega_3\cos\varphi\sin k - 2\dot{h}\frac{e}{r}\cos k\sin 2\varphi$ – coefficient of sensitivity of AGS to speed measurement errors; $\frac{dD}{dk} = 2\omega_3 v\cos\varphi\cos k - 2e\frac{v^2}{r}\cos^2\varphi\sin 2k + 2\dot{h}\frac{e}{r}v\sin k\sin 2\varphi$ – coefficient of sensitivity of AGS to course measurement errors; $\frac{dD}{d\varphi} = 2\omega_3 v\sin k\sin\varphi - \omega_3{}^2 h\sin 2\varphi - 4e\frac{v^2}{r}\left(1 - \frac{\sin^2 k}{2}\right)\sin 2\varphi - 4\dot{h}\frac{e}{r}v\cos k\cos 2\varphi - \gamma_{0e}\cdot 5{,}3\cdot 10^{-3}\left(1 - 2\frac{h}{r}\right)\sin 2\varphi$ – AGS sensitivity coefficient to latitude measurement errors; $\frac{dD}{dh} = \omega_3^2\cos^2\varphi + 2\frac{\gamma_{0e}}{r}$ – coefficient of sensitivity of AGS to height measurement errors; $\frac{dD}{d\dot{h}} = -2\frac{e}{r}v\cos k\sin 2\varphi$ – coefficient of sensitivity of AGS to vertical speed measurement errors.

The maximum permissible measurement errors of the main parameters of the AGS components can be determined according to the data in the table. 1.

Parameters: h=$5\cdot 10^3$ m, e=$3{,}4\cdot 10^{-3}$, r=$6{,}4\cdot 10^6$ m, ω_2=$7{,}3\cdot 10^{-5}$ s^{-1}, γ_{0e} =9,78049 m/s^2 correspond to numerical values sensitivity coefficients given in Table 1.

Table 1 – The value of the maximum coefficients of sensitivity of the error of the output signal of the aviation gravimetric system to the measurement errors of the parameters

№ n/p	The maximum sensitivity coefficients of the error of the AGS output signal to parameter measurement errors			
1	v, m/s	260	140	85
2	$\dot{h}$, m/s	45	28	19
3	$\frac{dD}{dv}$, mGal/m·s^{-1}	22,67	17,68	16,47
4	$\frac{dD}{dk}$, mGal / angle.min	1,08	0,65	0,39
5	$\frac{dD}{d\varphi}$, mGal / angle.min	2,29	1,93	1,77
6	$\frac{dD}{dh}$, mGal /m	0.29	0,29	0,29
7	$\frac{dD}{d\dot{h}}$, mGal /m·s^{-1}	$2{,}8\cdot 10^{-2}$	$1{,}9\cdot 10^{-2}$	$1{,}03\cdot 10^{-2}$

The maximum values of measurement errors of AGS parameters are given in Table 2.

Table 2 – Maximum values of measurement errors of the studied parameters of AGS

№ n/p	Measurement errors	The maximum value of the measurement error of the gravitational anomaly (Δg)	
		1 мГал	3 мГал
1	Road speed v, m/s	0,05	0,15
2	Route k, angle. min	1,43	3,0
3	Geographical latitude φ, angle. min	0,5	1,
4	Height h, m	3,3	10,0
5	Vertical speed $\Delta\dot{h}$, m/s	$0{,}5\cdot10^{-2}$	$1\cdot10^{-2}$
6	Course s, m	1,5	4,5
7	Stabilization error of the sensitivity axis of the gravimeter, angle.	5	15

From the table 2 shows the accuracy with which it is necessary to measure the navigational parameters of the aircraft movement with the AGS to ensure the specified measurement accuracy.

5.2. Taking into account the errors of the AGS gravimeter from the portable (relative to the device) angular velocity of the Earth's rotation

Formulas for calculating the error from the portable (relative to the gravimeter) angular velocity ω_z of the Earth's rotation are given in [1]

$$\Delta_3 = K_r \omega_3, \tag{22}$$

$$\delta_3 = \frac{\Delta_3}{\alpha_{ugs}} \cdot 100\%, \tag{23}$$

where K_r – the transmission coefficient of the gravimeter; ω_3 – speed of rotation of the Earth; α_{ugs} – useful gravimeter signal.

The vertical component of the transferable angular velocity of the main axis $xOyz$, caused by the Earth's rotation and the aircraft's own motion:

$$\omega_z = \omega_3 \sin\varphi + \frac{v_y}{r} tg\varphi; \tag{24}$$

$$v_y = r\dot{\lambda}\cos\varphi; \tag{25}$$

$$\frac{v_y}{r} tg\varphi = \dot{\lambda}\sin\varphi; \tag{26}$$

where v_y – eastern component of the aircraft's path speed; r – geocentric radius of the Earth; $\dot{\lambda}$ – rate of change of longitude.

Let's write formula (24) taking into account (26):

$$\omega_z = \left(\omega_3 + \dot{\lambda}\right)\sin\varphi. \tag{27}$$

Taking into account that the aircraft rotates around the Oz axis with an angular velocity $\dot{k}$ in the case of movement:

$$\omega_z = \left(\omega_3 + \dot{\lambda}\right)\sin\varphi + \dot{k}. \tag{28}$$

where k – course angle in the horizon plane, counted clockwise from the north direction to the longitudinal axis of the object.

Let's write formula (22) taking into account (28):

$$\Delta_3 = K_r\left[\left(\omega_3 + \dot{\lambda}\right)\sin\varphi + \dot{k}\right]. \tag{29}$$

For the averaging interval $\left(t_2 - t_1\right)$, we will get the average value of the absolute error $\overline{\Delta}_3$ [1]:

$$\begin{gathered}\left(t_2 - t_1\right)\overline{\Delta} = K_r\left[k\left(t_2\right) - k\left(t_1\right)\right] + \\ + K_r\int_{t_1}^{t_2} \omega_3 \sin\varphi(t)dt + K_r\int_{t_1}^{t_2} \dot{\lambda}\sin\varphi(t)dt.\end{gathered} \tag{30}$$

The maximum value $K_r\omega_3\sin\varphi = 2{,}92\cdot10^{-5}$ rad. It corresponds to φ = 90º and the speed of rotation of the Earth ω_3 = $7{,}29\cdot10^{-5}$ s^{-1} [1].

The calculation error $K_r\omega_3\sin\varphi$ at a given K_r and constant value ω_3 depends on the definition error φ. The latitude determination error should be less than 0.5º, if the calculation error $K_r\omega_3\sin\varphi$ is no more than $2.92\cdot10^{-7}$ rad (this is 0.01%) [1].

If you replace $\int_{t_1}^{t_2} \sin\varphi(t)dt$ with the average value $\overline{\sin\varphi}$ for the averaging interval $\left(t_2 - t_1\right)$, then the latitude determination error will not exceed 0.5º. The average value $\overline{\varphi}$ corresponds to the middle of the interval $\left(t_2 - t_1\right)$ and $\overline{\sin\varphi}$ is insignificantly different from the $\sin\overline{\varphi}$, condition that flights take place at a constant speed [1]:

$$K_r\int_{t_1}^{t_2} \omega_3 \sin\varphi(t)dt = K_r\omega_3\sin\overline{\varphi}\left(t_2 - t_1\right). \tag{31}$$

During the movement of the aircraft in middle latitudes (at φ=65º and v_y =234 m/s, r=$6{,}4\cdot10^6$ m), the sensitivity of the AGS to latitude measurement errors is maximum. We will get the value of $\dot{\lambda}(t)\sin\varphi$ [1]:

$$\dot{\lambda}(t)\sin\varphi = 7{,}3\cdot10^{-5}\ c^{-1}. \tag{32}$$

For short time intervals, which can be considered constant, the integral of $\dot{\lambda}(t)$ and φ is chosen as the middle of the averaging interval [1]:

$$K_r\int_{t_1}^{t_2} \dot{\lambda}(t)\sin\varphi(t)dt = K_r\left[\lambda\left(t_2\right) - \lambda\left(t_1\right)\right]\sin\overline{\varphi}. \tag{33}$$

The flight route during the test program must be laid along the parallel (the value of the latitude is practically constant and the given one φ and can be used in the calculations) or along the meridian (the series expansion can be used for a relatively rough approximation $\sin\overline{\varphi}$). For calculations $\overline{\varphi}$ when summarizing flight data, it is necessary to choose the middle of the interval $\left(t_2 - t_1\right)$ [1].

Formula (29) has the final form:

$$\Delta_3 = K_{cr}\left(\frac{k\left(t_2\right) - k\left(t_1\right)}{t_2 - t_1} + \omega_3\sin\overline{\varphi} + \frac{\lambda\left(t_2\right) - \lambda\left(t_1\right)}{t_2 - t_1}\sin\overline{\varphi}\right). \tag{34}$$

Let's calculate the value $\overline{\Delta}_3$ and $\overline{\delta}_3$, when $\dot{k} = 0$ for φ=65° and v_y=234 m/s, r=6,4·10^6 m:

$$\overline{\Delta}_3 = 5{,}8\cdot 10^{-5} \text{ rad} = 584 \text{ mGal},$$

$$\overline{\delta}_3 = 2{,}92\cdot 10^{-2}\,\%.$$

It can be concluded that the error of the gravimeter $\overline{\Delta}_3$=584 mGal, caused by the portable (relative to the device) angular velocity of the Earth's rotation ω_z, is very large compared to other errors. To take it into account, it is necessary to introduce a correction to the equation of motion (17) of the AGS.

The equation of motion of AGS with a gravimeter of any type must be written taking into account the error due to influence ω_z [1]:

$$\begin{aligned}\overline{\Delta g} = {} & \frac{1}{S}\left\{\frac{\alpha(t_2)-\alpha(t_1)}{t_2-t_1} + \frac{K_r}{k_2}\left[\frac{k(t_2)-k(t_1)}{t_2-t_1} + \frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\overline{\varphi} + \omega_3 \sin\overline{\varphi}\right]\right\} + \\ & + \frac{\overline{V}^2}{r}\left\{1-2e\left[1-2\cos^2\varphi\left(1-\frac{\sin^2\overline{k}}{2}\right)\right]\right\} + 2\overline{V}\omega_3 \sin\overline{k}\cos\overline{\varphi} - \\ & - 2\dot{h}\frac{e}{r}\overline{V}\cos\overline{k}\sin\overline{2\varphi} + 2\frac{\overline{\gamma}_0\overline{h}}{r} + \omega_3^2\cos^2\overline{\varphi}\overline{h} - \overline{\ddot{h}} - \overline{\gamma}_0.\end{aligned} \qquad (35)$$

The influence of the error from ω_z, is extremely large (584 mGal), so the correction from the influence of the angular velocity of the Earth's rotation must be taken into account when analyzing the operation of the gravimeter. In known gravimeters, the effect of this error is not taken into account. Therefore, their accuracy can be considered insufficient

6. A new transformer gravimeter as a sensitive element of AGS

From the analysis of the work of modern gravimeters used in the AGS, it can be concluded that all of them have their own shortcomings and application features. The main disadvantage of the piezoelectric gravimeter is its high inertia. String gravimeters are prone to resonances and often have a non-linear output characteristic. A low-power output signal is a disadvantage of capacitive gravimeters, and its amplification reduces the reliability of the system. The accuracy of such gravimeters is about 2-8 mGal, which is insufficient in modern AGS. That is why there is a need to develop new gravimeters for AGS, which are based on new principles of work and have a fundamentally different structure [1 - 4].

Considering the shortcomings of the existing gravimeters, it is necessary to propose and research a new design of the gravimeter, which will be devoid of the above-mentioned shortcomings of the known gravimeters and will have a higher accuracy compared to the existing gravimeters.

A new transformer gravimeter (TrG) was proposed [28], which has significant advantages over known gravimeters: it has a linear characteristic in a wide operating range and has a powerful output signal compared to a capacitive gravimeter, it does not have as much inertia as a piezoelectric gravimeter, it is not subject to resonances like a string gravimeter, allows to obtain a unified electrical signal proportional to the results of measurements in analog or digital form, etc.

The new TrG is based on a transformer converter (TrC), the scheme of which is shown in Figure 4.

6.1. Transformer converter

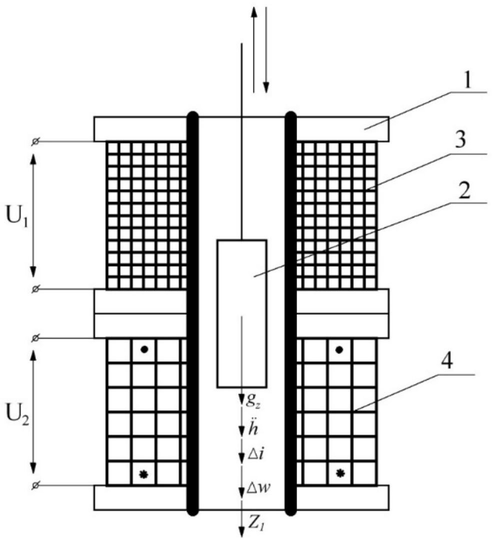

Figure 4 – Transformer converter, *where 1 – magnetic wire, 2 – anchor, 3 – excitation winding* W_1*, 4 – secondary winding* W_2

TrC contains a sensitive element, which consists of a magnetic circuit, a moving armature, a primary excitation winding and a secondary output winding, which has two identical sections.

The main disadvantage of the transformer converter is the series-matched (start-end of one section, start-end of another section) connection of two sections of the secondary winding 4 W_2. Output winding 4 W_2 is continuous. As a result of such a connection, the action of horizontal accelerations will cause significant measurement errors when installing the TrC on an aircraft.

Under the action of acceleration of the force of gravity g_z, which acts along the sensitivity axis of the transformer converter *Oz*, the force of gravity arises $G = mg_z$. Excitation winding 3 W_1 is connected to voltage U_1 and forms an electromagnetic flux of excitation Φ_1. According to the law of electromagnetic induction, this flux induces EMF E_2 in winding 4 W_2. Under the action of the acceleration of gravity, the anchor 2 moves down in the middle of the magnetic conductor 1 and causes a change in the electromagnetic flux Φ_1. Then the electromotive force E_2 in winding 4 W_2 will change in proportion to the acceleration of gravity g_z: $E_2 = mg_z$. The output electrical signal U_2 will be proportional to g_z: $U_2 = mg_z$.

Under the action of an external electromagnetic flux of an obstacle (significant extraneous electromagnetic fluxes occur on moving objects: aircraft, surface and submarines), the EMF E_{Π} of the obstacle will be induced in the output winding 4 W_2: $E_2 = mg_Z + E_n$. Accordingly, the output signal will be $U_2 = mg_Z + U_n$.

Vertical acceleration $\ddot{h}$, when installing TrC on aircraft, will act along the axis of sensitivity of the TrC, then: $E_2 = mg_Z + m\ddot{h}$. The value of the vertical acceleration $\ddot{h}$ is 10^3 times greater than the value of g_Z, that is, the value of the error significantly exceeds the useful signal.

6.2. Transformer gravimeter

Increasing the accuracy of GA measurement in the new transformer gravimeter (TrG) is ensured by connecting two sections of the secondary winding in series-opposite. The movable armature is connected to the motor for sequential lowering and raising of the armature along the magnetic line every second. The motor is controlled by a switching device that is connected to the control voltage source, and the output signal from the secondary output winding is fed to the input of the output signal calculation device. As a result, a signal is obtained that is proportional to the doubled value of the acceleration of gravity. This signal does not contain errors from the influence of vertical acceleration of the aircraft, residual instrumental errors, residual errors from projections of horizontal cross accelerations and errors caused by the influence of external electromagnetic flows. This, in turn, provides an increase in the accuracy of measurements of the acceleration of gravity.

Under the action of an external electromagnetic flow of an obstacle, this flow will induce two EMF obstacles in two sections W_2, which are included in series-opposite $E_{2\Pi}$ and $-E'_{2\Pi}$. In total, these errors are compensated [6]

The design of the transformer gravimeter and the essence of its work are presented (Figure 5).

The sensitive element of the TrG, as in the case of a transformer converter, consists of a magnetic circuit 1, a moving armature 2, a primary excitation winding 3 and a secondary output winding 4, which has two identical sections. The moving armature 2 is connected to the motor 5, which every second successively lowers the armature 2 down and up the magnetic circuit 1. The motor 5 is controlled by the switching device 6, which is connected to the source 7 of the control voltage. The output signal from the secondary output winding 4 is fed to the input of the device 8 for calculating the output signal.

The principle of operation of TrG is similar to TrP and consists in the change of the electromagnetic flux of excitation $\varPhi_1$ in the excitation winding W_1 and, accordingly, two EMFs E_2 and $-E'_2$ in two sections of the winding W_2 under the action of the acceleration of gravity g_Z. Under the influence of gravity, the anchor 2 moves down in the middle of the magnetic conductor 1 and causes a change in the electromagnetic flux $\varPhi_1$ and, respectively, E_2 and $-E'_2$.

At the point of electromagnetic symmetry TrG we will also receive $E_2 = \left|-E'_2\right|$ and the output signal $U_2 = 0$.

When the anchor 2 is moved relative to the point of symmetry down (Figure 5) or up (Figure 5, circled with dashed lines) $E_2 \neq \left|-E'_2\right|$, the output signal of the gravimeter will be proportional:

$$U_2 \equiv \left|E_2 - E'_2\right| \equiv mg_z \tag{36}$$

In TrG, the switch device 6, which is powered by the control voltage source 7, at equal time intervals of 1 s. switches the supply of vertical movement of the anchor 2 down (Figure 5) and up (Figure 5, dotted line) through the motor 5.

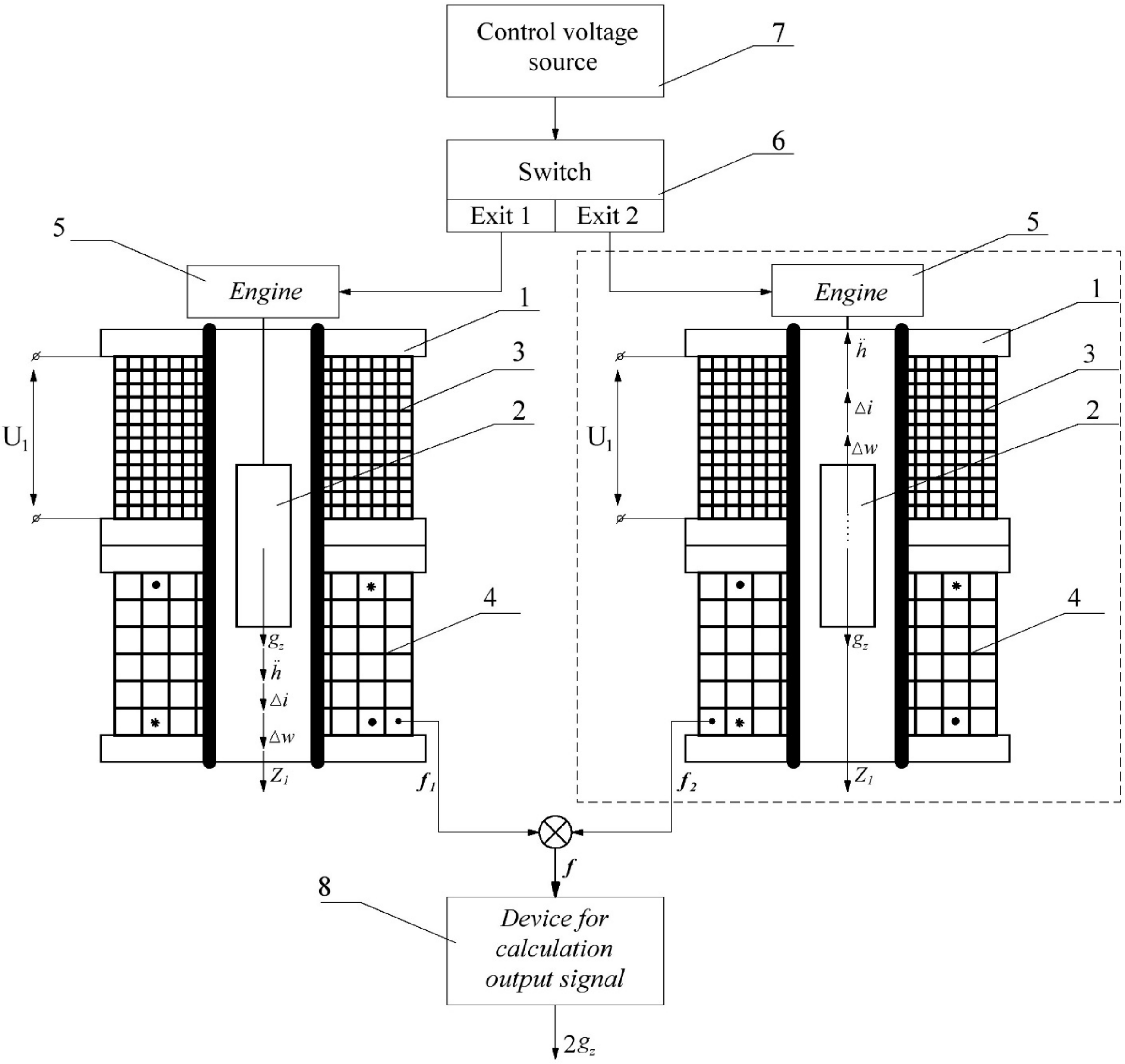

Figure 5 – Transformer gravimeter

1 – magnet wire, 2 – movable armature, 3 – excitation winding W_1*, 4 – secondary winding* W_2*, 5 – motor, 6 – switching device, 7 – control voltage source, 8 – output signal calculation device*

When a downward motion pulse is supplied from switch device 6 to armature 2, the output signal f_1 of the sensitive element is fed to the output signal calculation device 8. After 1 s., an upward movement pulse is applied to armature 2 and the output signal calculation device 8 receives a signal f_2.

In the device for calculating the output signal 7, the final output signal is formed:

$$f = f_1 + f_2 = g_Z + \ddot{h} + \Delta i + \Delta w + g_Z - \ddot{h} - \Delta i - \Delta w = 2g_Z, \tag{37}$$

where $f_1 = g_Z + \ddot{h} + \Delta i + \Delta w$ – output signal when armature 2 moves down; $f_2 = g_Z - \ddot{h} - \Delta i - \Delta w$ – output signal when armature 2 moves up; $\ddot{h}$ – vertical acceleration of the aircraft; Δi – residual instrumental errors; Δw – residual errors from the influence of projections of horizontal cross accelerations on the sensitivity axis of the invention.

That is, in the device 8 for calculating the output signal TrG, an output signal equal to the doubled value is formed $2g_Z$. Unlike the transformer converter, the output signal of TrG does not have measurement errors caused by the influence of vertical acceleration $\ddot{h}$, residual instrumental errors Δi and residual errors from the influence of horizontal cross accelerations Δw. Thus, it is shown that TrG has a higher accuracy compared to known gravimeters. The influence of external electromagnetic interference flows, which are significant on the aircraft, is also canceled in TrG due to the opposite connection of the secondary windings (in contrast to the transformer converter, where this influence is significant and is not neutralized).

The doubled TrG signal is part of the AGS output signal.

7. Conclusions

1) The equations of motion and a list of the main components of the AGS are given: gravimeter, stabilization system, system for determining navigation parameters, height meter, on-board digital computer;

2) It is substantiated that the choice of the gravimeter's own frequency equal to 0.1 s^{-1} ensures the absence of the influence of the largest disturbances (vertical acceleration and other accelerations whose frequency is greater than 0.1 rad/s) on the operation of the AGS gravimeter and the absence of the need to use additional electronic filters;

3) The expediency of using the two-channel method for the construction of the AGS gravimeter is shown, because this method makes it possible to compensate for residual instrumental errors;

4) An analysis of methodological errors of AGS was carried out, from which accuracy requirements for AGS components were formulated, provided that the accuracy of PST measurements is 1–2 mGal.

5) The importance of taking into account the correction due to the influence of the angular velocity of the Earth's rotation is substantiated (it is unacceptably large $\overline{\Delta}_3$ =584 mGal compared to other errors). In order to take it into account, it is necessary to introduce a corresponding amendment $\Delta_3 = K_{cr}\left(\frac{k(t_2)-k(t_1)}{t_2-t_1} + \omega_3 \sin\overline{\varphi} + \frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\overline{\varphi}\right)$ in the equation of motion of the AGS. The final AGS equation with this correction is obtained:

$$\overline{\Delta g} = \frac{1}{S}\left\{\frac{\alpha(t_2)-\alpha(t_1)}{t_2-t_1} + \frac{K_r}{k_2}\left[\frac{k(t_2)-k(t_1)}{t_2-t_1} + \frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\overline{\varphi} + \omega_3 \sin\overline{\varphi}\right]\right\} +$$
$$+\frac{\overline{V}^2}{r}\left\{1-2e\left[1-2\cos^2\varphi\left(1-\frac{\sin^2\overline{k}}{2}\right)\right]\right\} + 2\overline{V}\omega_3 \sin\overline{k}\cos\overline{\varphi} - \quad .$$
$$-2\dot{h}\frac{e}{r}\overline{V}\cos\overline{k}\sin\overline{2\varphi} + 2\frac{\overline{\gamma}_0\overline{h}}{r} + \omega_3^2\cos^2\overline{\varphi}\overline{h} - \overline{\ddot{h}} - \overline{\gamma}_0.$$

6. It is substantiated that the use of a new two-channel transformer gravimeter provides the necessary increase in the accuracy of AGS.

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Анотація. *Актуальність авіаційних гравіметричних вимірювань є безперечною. Відомі авіаційні гравіметри мають як переваги так і недоліки, які визначено в цій статті. В основі даної роботи – висвітлення методів та засобів покращення точності авіаційної гравіметричної системи. Задачами даної статті є наведення рівняння руху та переліку основних елементів авіаційної гравіметричної системи, характеристика методу двоканальності для побудови гравіметра та його переваг перед іншими. Також обґрунтовано вибір власної частоти коливань гравіметра та показано важливість врахування поправки від впливу кутової швидкості обертання Землі. Запропоновано та досліджено новий трансформаторний гравіметр більшої точності. Обґрунтовано, що використання нового двоканального трансформаторного гравіметра забезпечує необхідне підвищення точності. Проаналізовано методичні та інструментальні похибки системи. Сформульовано точністні вимоги до компонентів вимірювальної системи.*

Ключові слова: *гравіметр, прискорення сили тяжіння, гравітаційне поле Землі, авіаційна гравіметрична система.*

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