DOI 10.31891/2307-5732-2023-329-6-11-19
УДК 621.317

БЕЗВЕСІЛЬНА ОЛЕНА
НТУУ «Київський політехнічний інститут імені Ігоря Сікорського»
https://orcid.org/0000-0002-6951-1242
e-mail: o.bezvesilna@gmail.com
НЕЧАЙ СЕРГІЙ
НТУУ «Київський політехнічний інститут імені Ігоря Сікорського»
https://orcid.org/0000-0002-7821-6472
e-mail: prilad@gmail.com
ТОЛОЧКО ТЕТЯНА
НТУУ «Київський політехнічний інститут імені Ігоря Сікорського»
https://orcid.org/0000-0002-2346-0419
e-mail: prilad168@gmail.com

АНАЛІЗ МЕТОДИЧНИХ ПОХИБОК АВІАЦІЙНОЇ ГРАВІМЕТРИЧНОЇ СИСТЕМИ З ТРАНСФОРМАТОНИМ ГРАВІМЕТРОМ

Проведено аналіз методичних похибок авіаційної гравіметричної системи (АГС) з трансформаторним гравіметром, з якого сформульовано точнісні вимоги до компонентів АГС за умови, що точність вимірювань прискорення сили тяжіння 1–2 мГал. Знайдено аналітичні вирази та обчислено коефіцієнти чутливості сумарної похибки вихідного сигналу АГС до похибок вимірювання таких параметрів руху літака: швидкості, курсу, широти, висоти, вертикальної швидкості, вертикального прискорення, шляху для різних режимів польоту. Отже, дослідження чутливості АГС до похибок вимірювання швидкості, широти і курсу залежно від ряду параметрів руху літака показало, що в разі авіаційних гравіметричних вимірювань уздовж земного меридіана необхідно точно визначати курс, уздовж земної паралелі — точно вимірювати швидкість, у середніх широтах — широту. Обчислено допустимі значення похибок визначення параметрів польоту літака: швидкість 0,05...0,15 м/с, курс 1,43...3 кут. хв., широта 0,5...1,5 кут. хв., висота 3,3...10 м, вертикальна швидкість (0,5...1).10^2 м/с, вертикальне прискорення (1...3).10^{-5} м/с^2, шлях (1,5...4,5) м.

Ключові слова: гравіметр, прискорення сили тяжіння, авіаційна гравіметрична система, трансформаторний гравіметр

BEZVESILNA OLENA
NTUU «Igor Sikorsky Kyiv Polytechnic Institute»
NECHAI SERGEY
NTUU «Igor Sikorsky Kyiv Polytechnic Institute»
TOLOCHKO TETIANA
NTUU «Igor Sikorsky Kyiv Polytechnic Institute»

ANALYSIS OF METHODOLOGICAL ERRORS OF THE AVIATION GRAVIMETRIC SYSTEM WITH A TRANSFORMATON GRAVIMETER

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. An analysis of methodological errors of the aviation gravimetric system with a transformer gravimeter was carried out, from which the accuracy requirements for the AGS components were formulated, provided that the accuracy of PST measurements is 1–2 mGal Analytical expressions were found and the coefficients of sensitivity of the total error of the AGS output signal to the measurement errors of the following aircraft movement parameters were calculated: speed, course, latitude, altitude, vertical speed, vertical acceleration, path for different flight modes. Therefore, the study of the sensitivity of the AGS to errors in the measurement of speed, latitude and course, depending on a number of parameters of the aircraft movement, showed that in the case of aviation gravimetric measurements along the Earth's meridian, it is necessary to accurately determine the course, along the Earth's parallel - to accurately measure the speed, in mid-latitudes - latitude . It is substantiated that the use of a new two-channel transformer gravimeter provides the necessary increase in the accuracy of AGS. Changes in the sensitivity of the error of the AGS output signal to speed measurement errors were studied depending on the latitude of the site at constant values of the course, as well as on the course of the aircraft at constant values of the latitude. It is shown that the sensitivity of the AGS to speed measurement errors is maximum for the east and west courses (22.6 mGl/m/s and - 6.5 mGl/m/s, respectively) at the location latitude $\varphi= 0^0$; minimum for north and south courses and at $\varphi=90^0$ regardless of the course (8.05 mGl/m/s). Permissible values of errors in determining the flight parameters of the aircraft were calculated: speed 0.05...0.15 m/s, heading 1.43...3 arcmin, latitude 0.5...1.5 arcmin. min., height 3.3...10 m, vertical speed (0.5...1).10^2 m/s, vertical acceleration (1...3).10^{-5} m/s^2, path (1.5...4.5) m.

Key words: gravimeter, gravitational acceleration, aviation gravimetric system, transformer gravimeter

Formulation of the problem

Today, aviation gravimetric measurements are extremely relevant for many fields of science and technology: in geodesy and geophysics for finding mineral deposits; in cartography for studies of the shape of the Earth; in the aerospace industry for correction of inertial navigation systems, etc. For aviation gravimetric measurements, an aviation gravimetric system (AGS) is used, the sensitive element of which is a gravimeter. Different types of gravimeters were used [1-7], which have their own advantages and disadvantages. Works [1-7] provide a description of AGS and the principle of its operation.

In works [8, 9], a new sensitive element of AGS is proposed - a transformer gravimeter (TG), which allows obtaining greater accuracy of AGS measurements.

But in the known literature [1-9] there is no analysis of methodological errors of AGS with TG, which can be unacceptably significant.

Analysis of recent research and publications

In [10], an analytical review of known AGS gravimeters was conducted and a new transformer gravimeter was recommended for use. But this publication does not contain an analysis of methodological errors of AGS with TG.

In [11], a description of the measuring scheme of the experimental setup based on the transformer gravimeter for measuring the acceleration of gravity (AG), as well as conducting a cycle of experimental studies with the aim of constructing the frequency characteristics of the output signal of the TG and the induction converter, is provided. However, there is no study of methodical errors of AGS with TG.

The article [12] is devoted to the research of filtering the output signal of AGS with a two-channel transformer gravimeter. A filtering technique has been developed that allows to separate the gravity acceleration anomaly signal of the two-channel TG from the largest obstacle of the vertical acceleration signal of the aircraft in order to increase the accuracy of the gravimeter as part of the AGS by selecting the natural frequency of oscillations of the two-channel transformer gravimeter of 0.1 s-1 at the point of intersection of the spectral density graphs useful signal of the gravity anomaly and the main disturbance of the vertical acceleration. But this publication does not contain an analysis of methodological errors of AGS with TG.

Thus, in the known literature [1-12] there is no analysis and proposals for reducing the main methodical errors of the AGS transformer gravimeter.

Therefore, the purpose of this article is to provide an analysis of methodological errors of AGS with a transformer gravimeter and to provide relevant suggestions.

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;
- provide a description of a new transformer gravimeter with greater accuracy than the known ones;
- conduct an analysis of methodical errors.

Presentation of the main material of the article

Equation of motion and list of main components of AGS

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

The aviation gravimetric system for measuring gravity acceleration anomalies □g contains (Fig. 1): a system for determining navigation parameters 1; height meter 2; gravimeter 3 installed on a two-axis stabilized platform; on-board computer (BC) 4.

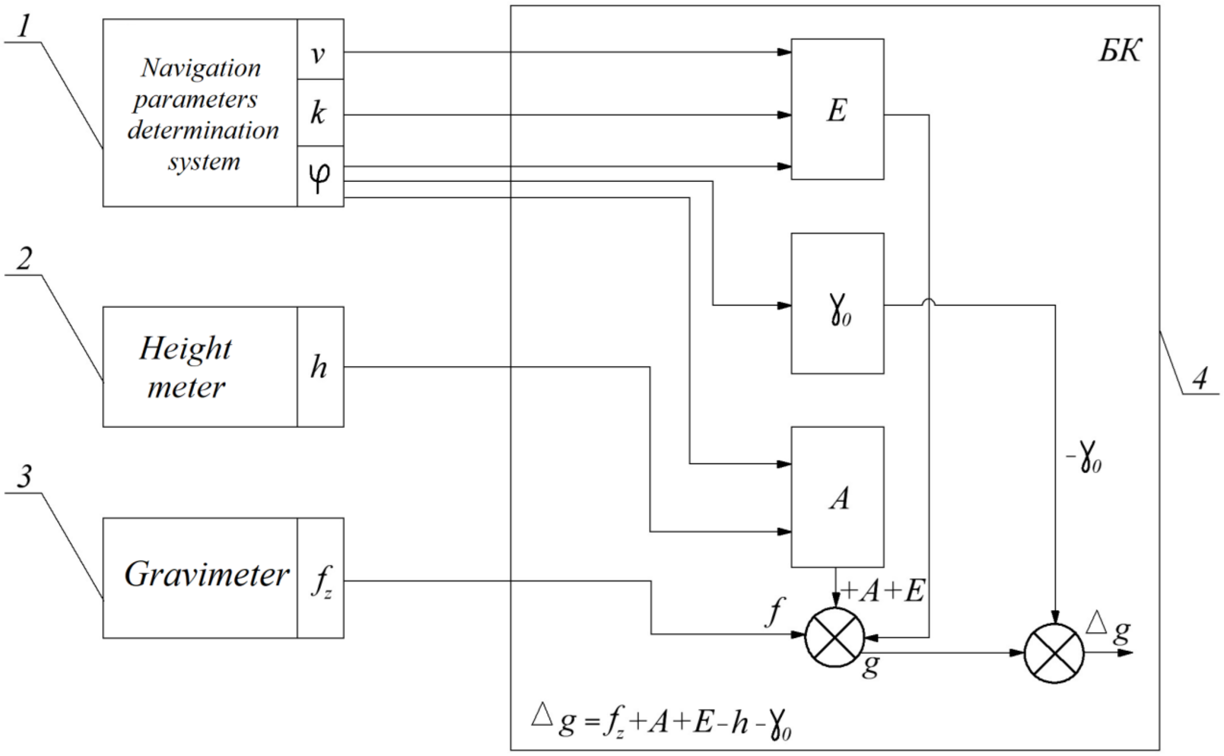

Fig. 1. Aviation gravimetric system for measuring gravity acceleration anomalies: 1 – navigation parameters determination system; 2 – height meter; 3 – gravimeter; 4 – BC [1]

In [1], the equation of motion of the AGS was obtained:

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

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

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:

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

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

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

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

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

where f_z − the output signal of the AGS gravimeter;

$E = \frac{v^2}{r}\left\{1 - 2e\cdot\left[1 - \cos^2\phi\cdot\left(1 - \frac{\sin^2 k}{2}\right)\right]\right\} + 2\omega_3 v\cos\phi\sin k - 2\dot{h}\frac{e}{r}v\cos k\sin 2\phi$ − the Etvesh correction [1] has an additional term $\omega_3^2 h\cos^2\phi$ whose influence is more than 1 mGal and which must be taken into account when measuring AG with an accuracy of 1 mGal; $A = 2\frac{\gamma_0 h}{r} + \omega_3^2 h\cos^2\phi -$ height correction [1] has an additional term $2\dot{h}er^{-1}v\cos k\sin 2\phi$, the influence of which is more than 1 mGal and which must be taken into account during PST measurements with an accuracy of 1 mGal;

$\gamma_0 = \gamma_{0e}\left(1 + 0,0052884\sin^2\phi - 0,0000059\sin^2 2\phi\right)$ − reference value of AG (Cassinis formula) [1]; $\ddot{h}$ – vertical acceleration of the aircraft [1]; $\gamma_{0e} = 9,78049$ m/s^2 is the reference value of AG (equatorial) [1].

In well-known gravimeters [1–7, etc.], additional components in the Etvesh and height corrections 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 AG;
- 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].

Transformer gravimeter

The literature [1-7] provides descriptions, the principle of operation and features of various types of gravimeters: piezoelectric, string, capacitive, gyroscopic.

In [8], the expediency of using a transformer gravimeter as a sensitive element of AGS is substantiated.

An increase in the accuracy of the measurement of the acceleration of gravity in the new transformer gravimeter (TG) 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 electric motive force 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]

In fig. 2 the design of the transformer gravimeter and the essence of its operation are presented.

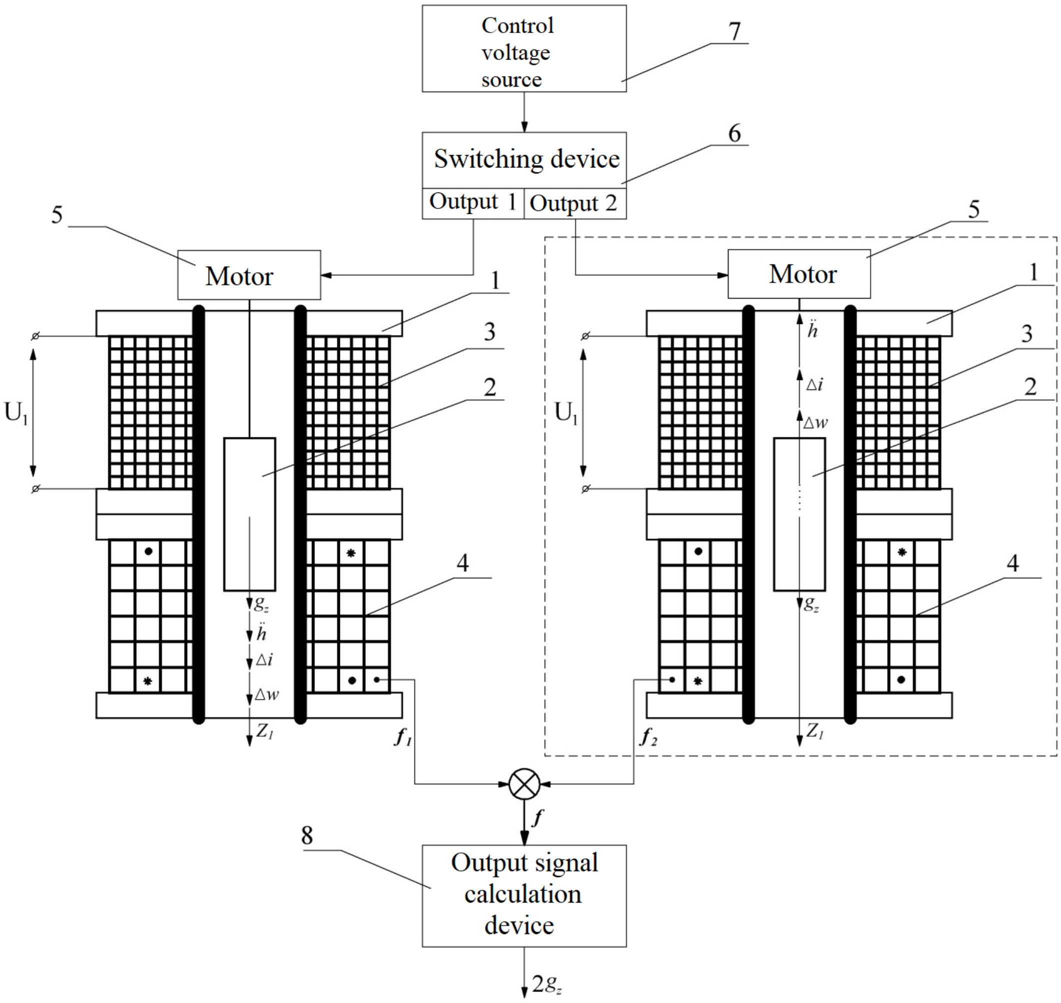

Fig. 2. Transformer gravimeter: 1 – magnet wire, 2 – movable armature, 3 – excitation winding W_1, 4 – secondary winding W_2, 5 – motor, 6 – switching device, 7 – control voltage source, 8 – output signal calculation device

The sensitive element TG 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 the TG consists in the change of the electromagnetic excitation flux Φ_1 in the excitation winding W_1 and, accordingly, in two electric motive forces E_2 and $-E'_2$ in two sections of the winding W2 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 Φ_1 and, respectively, E_2 and $-E'_2$.

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

When the anchor 2 is moved relative to the point of symmetry down (Fig. 2) or up (Fig. 2, dotted) $E_2 \neq \left|-E'_2\right|$, the output signal of the gravimeter will be proportional:

$$U_2 \equiv \left|E_2 - E'_2\right| \equiv mg_z \tag{5}$$

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

When a downward motion pulse is supplied from SD 6 to armature 2, f_1 the output signal of the sensitive element is fed to the output signal calculation device 8. After 1s, 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:

$$f = f_1 + f_2 = g_Z + \ddot{h} + \Delta i + \Delta w + g_Z - \ddot{h} - \Delta i - \Delta w = 2g_Z, \tag{6}$$

where $f_1 = g_Z + \ddot{h} + \Delta i + \Delta w -$ is the output signal when anchor 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 TG, an output signal equal to the doubled value is formed $2g_Z$. In contrast to the transformer converter, the output signal of TG 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 TG has greater accuracy compared to known gravimeters. The influence of external electromagnetic interference flows, which are significant on the aircraft, in the TG is also canceled due to the counter-connection of the secondary windings (in contrast to the transformer converter, where this influence is significant and is not neutralized).

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

Analysis of methodical errors

To determine the permissible measurement errors of the parameters of the aircraft motion by the components of the AGS with a transformer gravimeter, we use the equation:

$$\Delta g = f_z + D, \tag{7}$$

where D – is the total error of AGS:

$$\begin{aligned} D = {} & \frac{v^2}{r}\left\{1 - 2e\cdot\left[1 - 2\cos^2\varphi\cdot\left(1 - \frac{\sin^2 k}{2}\right)\right]\right\} + \\ & + 2\omega_3 v\cos\varphi\sin k - 2\dot{h}\frac{e}{r}v\cos k\sin 2\varphi + \\ & + 2\frac{\gamma_0 h}{r} + \omega_3^2 h\cos^2\varphi - \gamma_0. \end{aligned} \tag{8}$$

The parameters included in equation (8) are determined by separate 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, $\Delta\phi$ latitude, Δh altitude, $\Delta\dot{h}$ vertical speed [1]:

$$\Delta D = \left(\frac{dD}{dv}\right)\Delta v + \left(\frac{dD}{dk}\right)\Delta k + \left(\frac{dD}{d\phi}\right)\Delta\phi + \left(\frac{dD}{dh}\right)\Delta h + \left(\frac{dD}{d\dot{h}}\right)\Delta\dot{h}, \tag{9}$$

де $\dfrac{dD}{dv} = \dfrac{2v}{r}\left\{1 - 2e\cdot\left[1 - 2\cos^2\phi\cdot\left(1 - \dfrac{\sin^2 k}{2}\right)\right]\right\} + 2\omega_3\cos\phi\sin k - 2\dot{h}\dfrac{e}{r}\cos k\sin 2\phi$ – AGS sensitivity coefficient 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;

$\frac{dD}{d\dot{h}} = -2\frac{e}{r}v\cos k \sin 2\varphi$ – sensitivity coefficient of AGS to vertical speed measurement errors.

The maximum permissible measurement errors of the main parameters by the AGS components can be determined according to the data in Table 1. The parameters are: h=5·10^3 м, e=3,4·10^{-3}, r=6,4·10^6 м, ω_3 =7,3·10^{-5} с$^{-1}$, γ_{0e} =9,78049 м/с^2 correspond to the numerical values of the sensitivity coefficients given in Table 2.

Table 1

The value of the maximum coefficients of sensitivity of the error of the output signal aviation gravimetric system to parameter measurement errors

The maximum sensitivity coefficients of the error of the AGS output signal to parameter measurement errors			
v	260	140	85
$\dot{h}$	45	28	19
$\frac{dD}{dv}$	22,67	17,68	16,47
$\frac{dD}{dk}$	1,08	0,65	0,39
$\frac{dD}{d\varphi}$	2,29	1,93	1,77
$\frac{dD}{dh}$	0.29	0,29	0,29
$\frac{dD}{d\dot{h}}$	2,8·10^{-2}	1,9·10^{-2}	1,03·10^{-2}

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

Table 2

The maximum values of the measurement errors of the studied parameters of AGS

Measurement errors	The maximum value of the measurement error of the gravitational anomaly (Δg)	
	1 mGal	3 mGal
Road speed v, m/s	0,05	0,15
Course k, angle. min.	1,43	3,0
Geographical latitude φ, angle. min.	0,5	1,
Height h, m	3,3	10,0
Vertical speed $\Delta\dot{h}$, m/s	0,5·10^{-2}	1·10^{-2}
Way s, m	1,5	4,5
Stabilization error of the sensitivity axis of the gravimeter, angle.	5	15

Table 2 shows the accuracy with which it is necessary to measure the navigational parameters of the aircraft movement with an aviation gravimetric system with a transformer gravimeter to ensure the specified measurement accuracy.

Taking into account the errors of TG AGS 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 ωz of the Earth's rotation are given in [1]:

$$\Delta_3 = K_r \omega_3, \tag{10}$$

$$\delta_3 = \frac{\Delta_3}{\alpha_{кор}} \cdot 100\%, \tag{11}$$

where K_r – is the transmission coefficient of the gravimeter; ω_3 – speed of rotation of the Earth; $\alpha_{кор}$ – is a 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:

$$\omega_z = \omega_3 \sin\varphi + \frac{v_y}{r} tg\varphi; \tag{12}$$

$$v_y = r\dot{\lambda}\cos\varphi; \tag{13}$$

$$\frac{v_y}{r} tg\varphi = \dot{\lambda}\sin\varphi; \tag{14}$$

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

Let's write formula (12) taking into account (14):

$$\omega_z = \left(\omega_3 + \dot{\lambda}\right)\sin\varphi. \tag{15}$$

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

$$\omega_z = \left(\omega_3 + \dot{\lambda}\right)\sin\varphi + \dot{k}. \tag{16}$$

where k is the heading angle in the horizon plane, measured clockwise from the direction north to the longitudinal axis of the object.

Let's write formula (10) taking into account (16):

$$\Delta_3 = K_r\left[\left(\omega_3 + \dot{\lambda}\right)\sin\varphi + \dot{k}\right] \tag{17}$$

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

$$\begin{aligned}(t_2 - t_1)\overline{\Delta} &= K_r\left[k(t_2) - k(t_1)\right] + \\ &+ K_r\int_{t_1}^{t_2}\omega_3\sin\varphi(t)dt + K_r\int_{t_1}^{t_2}\dot{\lambda}\sin\varphi(t)dt.\end{aligned} \tag{18}$$

The maximum value of $K_r\omega_3\sin\varphi = 2{,}92\cdot10^{-5}$ rad. It corresponds to φ= 90° and the speed of rotation of the Earth ω_3 = 7,29·10^{-5} c^{-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 0.5°, if the calculation error $K_r\omega_3\sin\varphi$ is no more than 2,92·10^{-7} rad (this is 0.01%) [1].

If replaced $\int_{t_1}^{t_2}\sin\phi(t)\,dt$ by the average value $\overline{\sin\varphi}$ for the averaging interval $\left(t_2 - t_1\right)$, then the latitude determination error will not exceed 0.5°. 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 condition that flights take place at a constant speed [1]:

$$K_r\int_{t_1}^{t_2}\omega_3\sin\varphi(t)dt = K_r\omega_3\sin\overline{\varphi}\left(t_2 - t_1\right). \tag{19}$$

During the movement of the aircraft in mid-latitudes (at φ=65° and v_y =234 m/s, *r*=6,4·10^6 m), the sensitivity of the AGS to latitude measurement errors is maximum. We will get the value $\dot{\lambda}(t)\sin\varphi$ [1]:

$$\dot{\lambda}(t)\sin\varphi = 7{,}3\cdot10^{-5}\ c^{-1}. \tag{20}$$

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]:

$$K_r \int_{t_1}^{t_2} \dot{\lambda}(t) \sin \varphi(t) dt = K_r [\lambda(t_2) - \lambda(t_1)] \sin \overline{\varphi}. \tag{21}$$

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 can be used in the calculations φ) 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 $(t_2 - t_1)$ [1].

Formula (10) has the final form:

$$\Delta_3 = K_{cr} \left(\frac{k(t_2) - k(t_1)}{t_2 - t_1} + \omega_3 \sin\overline{\phi} + \frac{\lambda(t_2) - \lambda(t_1)}{t_2 - t_1} \sin\overline{\phi} \right). \tag{22}$$

Let's calculate the values of $\overline{\Delta_3}$ and $\overline{\delta_3}$ when 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 (1) of the AGS.

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

$$\begin{gathered} \overline{\Delta g} = \frac{1}{S} \left\{ \frac{\alpha(t_2) - \alpha(t_1)}{t_2 - t_1} + \frac{K_r}{k_2} \left[\frac{k(t_2) - k(t_1)}{t_2 - t_1} + \frac{\lambda(t_2) - \lambda(t_1)}{t_2 - t_1} \sin\overline{\varphi} + \omega_3 \sin\overline{\varphi} \right] \right\} + \\ + \frac{\overline{V}^2}{r} \left\{ 1 - 2e \left[1 - 2\cos^2 \varphi \left(1 - \frac{\sin^2 \overline{k}}{2} \right) \right] \right\} + 2\overline{V} \omega_3 \sin\overline{k} \cos\overline{\varphi} - \\ - 2\dot{h} \frac{e}{r} \overline{V} \cos\overline{k} \sin\overline{2\varphi} + 2 \frac{\overline{\gamma}_0 \overline{h}}{r} + \omega_3^2 \cos^2 \overline{\varphi} \overline{h} - \overline{\ddot{h}} - \overline{\gamma}_0. \end{gathered} \tag{23}$$

The influence of the error ω_z from 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 transformer gravimeter. In known gravimeters, the effect of this error is not taken into account. Therefore, their accuracy can be considered insufficient.

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. An analysis of methodological errors of AGS was carried out, from which accuracy requirements for AGS components were formulated, provided that the accuracy of AG measurements is 1–2 mGal.
3. Analytical expressions were found and coefficients of sensitivity of the total error of the output signal of the AGS with a transformer gravimeter to the measurement errors of the following parameters of the aircraft movement were found and calculated: speed, course, latitude, altitude, vertical speed, vertical acceleration, path for different flight modes.
4. It is substantiated that the use of a new two-channel transformer gravimeter provides the necessary increase in the accuracy of AGS.
5. Changes in the sensitivity of the error of the AGS output signal to speed measurement errors were studied depending on the latitude of the place at constant values of the course, as well as on the course of the aircraft at constant values of the latitude. It is shown that the sensitivity of the AGS to speed measurement errors is maximum for the east and west courses (22.6 mGl/m/s and - 6.5 mGl/m/s, respectively) at the location latitude φ= 0^0; minimum for north and south courses and at φ=90^0 regardless of the course (8.05 mGl/m/s).
6. Changes in the sensitivity of the system output signal error to latitude measurement errors were analyzed depending on the latitude when the aircraft course changed. It is shown that the sensitivity of the error of the AGS output signal to latitude measurement errors is maximal when the aircraft is moving to the east (2.35 mGl/min at φ= 60^0) and minimal when the aircraft is moving to the west (0.81 mGl/ angle min at φ= 30^0). The sensitivity of the error of the output signal of the system to latitude measurement errors will be maximum for the aircraft in mid-latitudes φ= 45^0 - 60^0 and close to zero for all courses when the AGS is operating at the equator, and for the aircraft moving on a course of k= 180^0 or k= 360^0, at φ= 90^0.
7. An analysis of the change in the sensitivity of the output signal error to course determination errors was

performed depending on the aircraft course in the most unfavorable case, when the aircraft was on the equator. It is shown that in the case of the aircraft moving on north or south courses, the sensitivity of the error of the AGS output signal to the course measurement errors is the greatest (± 1.09 mGl/angle min, respectively); in the case of east or west course, the sensitivity of the error of the AGS output signal to course measurement errors is the lowest. Therefore, the study of the sensitivity of the AGS to errors in measuring speed, latitude and course depending on a number of parameters of the aircraft movement showed that in the case of aviation gravimetric measurements along the Earth's meridian, it is necessary to accurately determine the course, along the Earth's parallel - to accurately measure the speed, in mid-latitudes — latitude.

8. Calculated permissible values of errors in determining the flight parameters of the aircraft: speed 0.05...0.15 m/s, heading 1.43...3 angle. min., width 0.5...1.5 kut. min., height 3.3...10 m, vertical speed (0.5...1).10^2 m/s, vertical acceleration (1...3).10^{-5} m/s^2, distance (1.5...4 ,5) m.

9. 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 make a corresponding amendment $\Delta_3 = K_{cr}\left(\frac{k(t_2)-k(t_1)}{t_2-t_1}+\omega_3\sin\bar{\phi}+\frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\bar{\phi}\right)$ to the equation of motion of the AGS. The final AGS equation with this correction is obtained:

$$\overline{\Delta g} = \frac{1}{S}\left\{\frac{\alpha(t_2)-\alpha(t_1)}{t_2-t_1}+\frac{K_r}{k_2}\left[\frac{k(t_2)-k(t_1)}{t_2-t_1}+\frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\bar{\phi}+\omega_3\sin\bar{\phi}\right]\right\}+$$

$$+\frac{\bar{V}^2}{r}\left\{1-2e\left[1-2\cos^2\phi\left(1-\frac{\sin^2\bar{k}}{2}\right)\right]\right\}+2\bar{V}\omega_3\sin\bar{k}\cos\bar{\phi}-$$

$$-2\dot{h}\frac{e}{r}\bar{V}\cos\bar{k}\sin\overline{2\phi}+2\frac{\bar{\gamma}_0\bar{h}}{r}+\omega_3^2\cos^2\bar{\phi}\bar{h}-\bar{\ddot{h}}-\bar{\gamma}_0$$

References

1. Bezvesilna O. M. Aviation gravimetric systems and gravimeters. Monograph. Zhytomyr: ZHDTU, 2007. 604 p.

2. Bezvesilna O.M., Tkachuk A.G., Kozko K.S. Modern gravimeters of the aviation gravimetric system Monograph. Geophysical Journal. 2015. No. 2 (T37). P. 86–94.

3. Bezvesilna O. M., Korobiichuk I., Tkachuk A., Nowicki M., Szewczyk R. Design of Piezoelectric Gravimeter for Automated Aviation Gravimetric System. International Journal of Automation, Mobile Robotics & Intelligent Systems (10), 2016. 43-47.

4. Bezvesilna O. M., Korobiichuk I., Tkachuk A., Nowicki M., Szewczyk R. Piezoelectric gravimeter of aviation gravimetric system. Advances in Intelligent Systems and Computing. 2016.

5. Bezvesilna O.M., Chepyuk L.O. String gravimeter of the aviation gravimetric system. Zhytomyr: ZHDTU, 2015. 208 p.

6. Bezvesilna O.M., Tkachuk A.H., Khylchenko T.V., Chepyuk L.O. Aviation Gravimetric system with low-frequency vibration gravimeter. International Journal "Technological complexes" (1/2), 2015. P. 46-51.

7. Bezvesilna O.M., Korobiichuk I., Bezvesilna O., Kachniarz M., Tkachuk A., Chilchenko T. Two-channel MEMS gravimeter of the automated aircraft gravimetric system. Advances in Intelligent Systems and Computing. 2017.

8. Bezvesilna O.M., Tkachuk A.G., Tolochko T.O., Hrynevych M.S. Aviation intelligent gravimetric system Utility model patent u202301660 Entry No. 43738 Date of receipt 04/13/20

9. Bezvesilna O.M., Tolochko T.O., Hrynevych M.S. Aviation gravimetric system with a two-channel transformer gravimeter Decision on state registration of a utility model 08/22/2023 No. 8441/ЗУ/23 on the application for a patent for a utility model u202301114 Enter. No. 30481 Date of receipt 03/17/2023

10. Bezvesilna O.M., Hrynevych M.S. Peculiarities of gravimeters in modern gravimetric systems Bulletin of Khmelnytskyi National University. Series: Technical Sciences, No. 6 (315), 2022, pp. 28-32. DOI: https://www.doi.org/10.31891/2307-5732-2022-315-6-28-32

11. Bezvesilna O.M., Hrynevych M.S. Experimental studies of the transformer gravimeter Tavriyskyi scientific bulletin. Series: Computer science and information technology. No. 6, p. 3-9. DOI https://doi.org/10.32851/tnv-tech.2022.6.1

12. Bezvesilna O., Kyrychuk Y., Grynevych M., Tolochko T. Filtering of the output signal of the two-channel transformer gravimeter. Modern engineering and innovative technologies International periodic scientific journal Published by: Sergeieva&Co Karlsruhe, Germany Issue No25 Part 1, January 2023, pp. 30-35. (Index Copernicus, Google Scholar) https://www.moderntechno.de/index.php/meit/issue/view/meit25-01/meit25-01.