Викладено загальні принципи побудови авіаційної гравіметричної системи (АГС) з будь-яким типом гравіметра. Наведено перелік основних компонентів АГС. Проаналізовано методичні та інструментальні похибки системи. Сформульовано точносні вимоги до компонентів АГС. Обґрунтовано вибір власної частоти коливань гравіметра АГС. Показано важливість врахування впливу кутової швидкості обертання Землі. Обґрунтовано використання методу двоканальності для побудови гравіметра АГС

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

Изложены общие принципы построения авиационной гравиметрической системы (АГС) с любым типом гравиметра. Приведен перечень основных компонентов АГС. Проанализированы методические и инструментальные погрешности системы. Сформулированы точностные требования к компонентам АГС. Обоснован выбор собственной частоты колебаний гравиметра АГС. Показана важность учета влияния угловой скорости вращения Земли. Обосновано использование метода двухканальности для построения гравиметра АГС

Ключевые слова: гравиметр, ускорение силы тяжести, гравитационное поле Земли, авиационная гравиметрическая система

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INTRODUCING THE PRINCIPLE OF CONSTRUCTING AN AVIATION GRAVIMETRIC SYSTEM WITH ANY TYPE OF GRAVIMETER

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1. Introduction

Studying parameters of gravitational field of the Earth (acceleration of gravity (AG) g and its anomalies Δg)) is an important scientific task. These parameters are necessary for:

– geodesy, geophysics for the exploration of mineral resources;

– seismology to predict earthquakes and tsunamis;

– aviation and space engineering to correct the systems for inertial navigation of aerospace objects [1].

At present, the most relevant is the measurements of parameters of gravitational field of the Earth from the aircraft (AC). They allow measuring of Δg in the remote areas of the Earth (zones of the Earth's poles, the equator, mountain ranges) at lower cost and at the rate that is considerably larger than terrestrial measurements. For these purposes, the aviation gravimetric systems (AGS) are employed whose sensing element is a gravimeter. Data on the Earth's gravitational field, entered into memory of the onboard digital computing machine (ODCM) of AGS, will essentially enhance both the accuracy of determining the navigation parameters and effectiveness of gravimetric exploration. That is why it is important to conduct high-precision aerial measurements.

2. Literature review and problem statement

At present there are many types of AGS gravimeters: quartz [2], string with a fluid damping [3], magnetic [4, 5], quartz [6], spring [7], whose principle of work is based on different physical phenomena [1]. They have both their advantages and disadvantages. Almost all of the known gravimeters measure the error of vertical acceleration [8–10], which is tens of times larger than the useful signal. They are complicated by supporting systems (the global positioning system (GPS)) [11]. They need long periodic calibration and tuning [12], which significantly complicates operation. Existing innovative designs belong to the sub-, surface-water

[13, 14] and ground-based [15] measurement methods, which are not used in the aviation gravimetry.

The following articles examined separate types of gravimeters: gyroscopic single-channel and dual-channel gravimeters [16], piezoelectric single-channel and dual-channel gravimeters [17, 18], string gravimeters [19, 20], capacitive single-channel and dual-channel gravimeters [21, 22].

However, the literature on aviation gravimetry [1, 23] did not highlight general principles of constructing AGS with any type of gravimeters.

3. The aim and tasks of the study

The aim of present study is to highlight general aspects of constructing AGS with any type of gravimeters.

To achieve the set aim, the following tasks were to be solved:

– to enumerate basic components of AGS;

– to substantiate the choice of natural oscillation frequency of AGS gravimeter;

– to demonstrate feasibility of applying a dual-channel method to construct AGS gravimeter;

– to demonstrate expediency of employing artificial neural networks to eliminate instrumental errors of AGS gravimeters;

– to conduct analysis of methodological errors;

– to demonstrate importance of taking into account a correction on the impact of angular velocity of the Earth.

4. Basic provisions and recommendations for the design of AGS

4. 1. General scheme and main components of AGS

We shall provide a description of the aviation gravimetric system that includes a gravimeter [1].

Aviation gravimetric system for measuring anomalies in the acceleration of gravity contains (Fig. 1):

– a system for determining navigation parameters 1;

– altitude gauge 2;

– gravimeter 3 mounted on biaxial platform;

– ODCM 4.

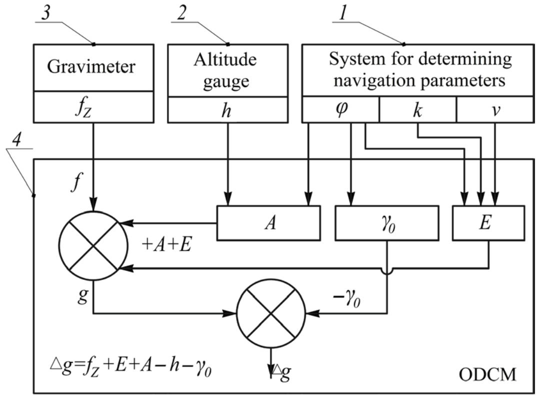

Fig. 1. Aviation gravimetric system for measuring anomalies in the acceleration of gravity

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

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

where f_z is the output signal of gravimeter; g_z is the acceleration of gravity along the sensitivity axis of gravimeter; v is the velocity of aircraft; r is the radius of location of aircraft; e is the compression of ellipsoid of the Earth; ϕ is the geographical latitude; k is the course of aircraft; ω_e is the angular velocity of rotation of the Earth; h is the altitude of aircraft above the ellipsoid; $\dot{h}$ is the vertical velocity of aircraft; $\ddot{h}$ is the vertical acceleration of aircraft; γ_0 is the reference acceleration of gravity.

In equation (1), g_z is the useful signal; all other signals are the interference signals that require consideration or elimination.

Let us represent equation (1) in the form:

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

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

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

Let us rewrite (1) in the form [1]:

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

where f_z is the output signal of new AGS gravimeter;

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

Eotvos correction [1];

$$A = 2\frac{\gamma_0 h}{r} + \omega_e^2 h \cos^2\phi,$$

– height correction [1];

$$\gamma_0 = \gamma_{0e}(1 + 0{,}0052884\sin^2\phi - 0{,}0000059\sin^2 2\phi),$$

– AG reference value (Cassini's formula) [24]; $\ddot{h}$ – AC vertical acceleration [1]; $\gamma_{0e} = 9{,}78049$ m/s^2 – AG reference value (equatorial) [25].

Equation of motion (3) shows that AGS should consist of the following components:

– AG gauge (gravimeter);

– stabilizer of the sensitivity axis of gravimeter in vertical state;

– navigation system to determine the coordinates of AC location and its velocity;

– altitude gauge;

– ODCM for performing computing operations according to algorithm (3) [1].

4. 2. Filtering the original signal of gravimeter

Main errors of the known gravimeters are caused by the fact that gravimeter measures the projection of signals totality on the sensitivity axis: useful signal (the acceleration of gravity), and interference signal. The latter is caused mainly by vertical acceleration (that exceeds the useful signal of AG by 10^3) [1, 26].

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

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

$$T = f_z = g_z + \ddot{h}, \qquad (5)$$

where $\ddot{h}$ is the error from the effect of AC vertical acceleration.

As a rule, known gravimeters employ low-frequency filters for filtering $\ddot{h}$. However, in the course of time, work of electronic components of the filter becomes unstable. The filter starts to accept interference at the output of gravimeter or not to let in a part of the useful signal. The existence of low-frequency filter in the set-up of gravimeter significantly reduces reliability of the instrument and its accuracy [1, 27].

We shall propose a different approach.

Analytical expressions of spectral densities of useful signal $G_{\Delta g}(\omega)$ and AC vertical acceleration $G_{\ddot{h}}(\omega)$ and their charts (Fig. 2) we received in paper [1].

Fig. 2 shows that the charts of spectral densities of AG useful signal and the main disturbance intersect in one point ω=0.1 rad/s. That is why we propose a method of filtering the output signal of gravimeter by selecting the frequency of natural oscillations of gravimeter at 0.1 rad/s, equal to the frequency of intersection of two charts in Fig. 2.

By using low-frequency filtering with a cutoff frequency at 0.1 rad/s, it is possible to separate the acceleration of gravity g from the vertical acceleration $\ddot{h}$ with accuracy 1 mGal. In the output signal of gravimeter, other components of the disturbances are eliminated whose frequency exceeds 0.1 rad/s:

– translational vibration accelerations (whose prevailing frequency is 3140 rad/s);

– angular vibration accelerations (whose prevailing frequency is above 0.1 rad/s) [1].

Thus, we choose the frequency of natural oscillations of gravimeter at 0.1 s^{-1}.

As a result, we obtain output signal T' of gravimeter, which contains only a useful signal of AG. It lacks all the errors whose prevailing frequency is above 0.1 rad/s [1].

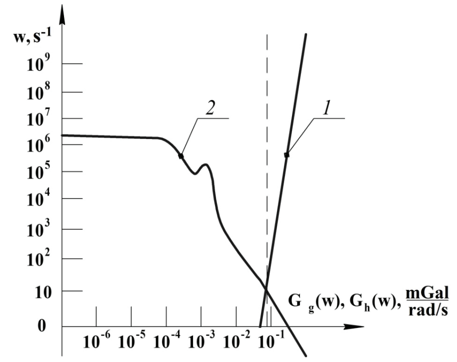

Fig. 2. Dependences on the frequency: 1 — AC vertical acceleration, 2 — spectral density of AG useful signal

The equation of AGS motion with gravimeter for determining Δg will take the form [1]:

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

Equation (6), in contrast to known studies, lacks vertical acceleration $\ddot{h}$.

Choosing a natural frequency of gravimeter equal to 0.1 s^{-1} provides for the absence of effect from vertical acceleration on the work of AGS gravimeter and eliminates the necessity in applying additional electronic filters.

Another way to solve the problem of filtering the effect of vertical acceleration on the output parameters is the use of dual-channel method of measurement. It is implemented in the new dual-channel gravimeters: string [19], capacitive, dual-channel capacitive [21].

4. 3. Applying a dual-channel method

When constructing any type of gravimeter, it is advisable to use a dual-channel method or invariance method, which allows us to eliminate a number of significant errors:

– from the effect of vertical acceleration;

– instrumental errors from the influence of residual nonidentity in the designs of sensitive elements;

– instrumental errors from the effect of changes in ambient temperatures, humidity, pressure, and other factors.

Let us consider a generalized scheme for constructing a dual gravimeter (Fig. 3).

Inertial mass M is exposed to the acceleration of gravity g, vertical acceleration $\ddot{h}$ of the aircraft and total instrumental errors Δi, specified above. Sensing elements are arranged so that the vertical accelerations in them act oppositely. A more detailed description of the way the two similar sensing elements are located, is available (depending on the type of gravimeter): in string [20], capacitive, dual channel MEMS capacitive [21].

The equation of forces along the axis Oz of dual-channel gravimeter sensitivity, directed along geographical vertical, will take the form:

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

where f_1 is the output signal from sensing element 1; f_2 is the output signal from sensing element 2; f_z is the output signal of dual-channel gravimeter; m is the weight of inertial mass M.

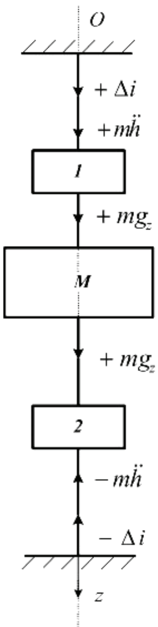

Fig. 3. Generalized scheme for constructing a dual-channel gravimeter: 1, 2 — sensing elements of the dual-channel gravimeter, M — inertial mass

Equation (7) shows that the output signal of dual-channel gravimeter contains doubled value of AG useful signal and has no vertical acceleration $\ddot{h}$ of aircraft and total instrumental errors Δi.

The output signal f_z of dual-channel gravimeter is sent to ODCM, which also receives output signals from the system of determining navigation parameters and altitude gauge. ODCM calculates values of anomaly Δg in the acceleration of gravity according to formula [1]:

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

where f_z is the output signal of dual-channel gravimeter; E is the Eotvos correction; A is the altitude correction; γ_0 is the reference value of the acceleration of gravity.

Equation (8) shows that it lacks the component of the largest error $\ddot{h}$. All known single-channel gravimeters measure $\ddot{h}$ simultaneously with g. This leads to large errors. The magnitude of $\ddot{h}$ is 10^3 times larger than g.

Thus, the dual-channel gravimeter enables substantial enhancement in the accuracy of measurements by compensating for the action of vertical acceleration $\ddot{h}$ of aircraft and total instrumental errors Δi.

4. 4. The motion equation and structural scheme for the system of AGS stabilization

In order to ensure alignment of the measuring axis of gravimeter with the reference vertical, it is necessary to have a stabilization system of AGS. Gravimeter should be placed on the horizontal stabilized platform (HSP). HSP consists of two linear accelerometers and controlling mechanisms in the form of special motors (Fig. 4) [28].

Let us consider operation of the stabilization system. Linear accelerometers f_y, f_x, installed on the HSP, are oriented in the geographical coordinate system. Their axes of sensitivity are directed to the North and East, respectively. The uutput signals are denoted by expressions [1]:

$$f_x = -(2\dot{r}\dot{\phi}_c + r\ddot{\phi}_c)\cos\chi + (\ddot{r} - r\dot{\phi}_c^2)\sin\chi - \\ -2r\omega_e\dot{\lambda}\cos\phi_c\sin\phi - r\dot{\lambda}\cos\phi_c\sin\phi + \aleph g; \tag{9}$$

$$f_y = 2r\dot{\phi}_e\omega_e\sin\phi_c + 2r\phi_c\dot{\lambda}\sin\phi_c - \\ -2\dot{r}\dot{\lambda}\cos\phi_c - r\ddot{\lambda}\cos\phi_c - 2\dot{r}\omega_e\cos\phi_c - \nu g, \tag{10}$$

where $\aleph$, ν are the angles between normals to the ellipsoid and to the geoid, respectively, in meridian cross-section and in the plane of cross-section that is perpendicular to the plane of the meridian; ϕ, ϕ_c are the geographical and geocentric latitude, respectively; χ is the deviation from the vertical; λ is the longitude of the place.

The output signals of accelerometers are sent to ODCM that forms a controlling signal, which arrives to the motors. Motors return HSP to zero position.

Horizontal components of the acceleration of gravity are equal to zero if HSP is set exactly in the position of the vertical. Let us accept that:

$$\aleph g = -\nu g = 0.$$

Expression for the components that will be compensated for by ODCM takes the form [1]:

$$f_x \Rightarrow 0 = 2r\omega_e\dot{\lambda}\cos\phi_c\sin\phi - r\dot{\lambda}\cos\phi_c\sin\phi; \tag{11}$$

$$f_y \Rightarrow 0 = 2r\dot{\phi}_e\omega_e\sin\phi_c + \\ +2r\phi_c\dot{\lambda}\sin\phi_c - 2\dot{r}\dot{\lambda}\cos\phi_c - 2\dot{r}\omega_e\cos\phi_c. \tag{12}$$

We shall disregard components of second order and assume that deviation from the vertical is equal to zero. As a result, we obtain:

$$f_x = -r\ddot{\phi}_c, \tag{13}$$

$$f_y = -2r\ddot{\lambda}\cos\phi_c. \tag{14}$$

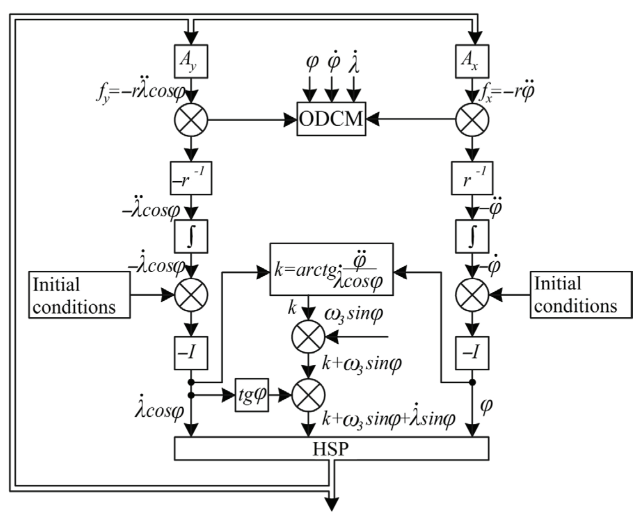

Fig. 4. Structural scheme of the AGS stabilization system

Each of the signals f_y and f_x will be multiplied by r^{-1}, integrated and multiplied by (–1). At the output of the corresponding channels, we shall receive $\dot{\phi}$ and $\dot{\lambda}\cos\phi$ (Fig. 4). To control HSP relative to the x axis, directed to the North, we shall use signal $\dot{\phi}$. To control relative to the y axis, directed to the East, we shall use signal $\dot{\lambda}\cos\phi$. To receive a signal from the system of inertial navigation, it is necessary to once again integrate the signals of velocity of change in latitude and longitude. Then the total values of latitude and longitude are to be entered to ODCM to calculate accelerations, which are compensated for by the signals of accelerometers.

4. 5. The motion equation and structural scheme for the AGS navigation system

There are three basic types of navigation systems for AC [1]:

1) systems that measure the acceleration or velocity of object and thus determine current position (systems of inertial navigation);

2) systems in which position of object is determined directly by using external information sources (terrestrial or satellite navigation systems);

3) systems, which are a combination of the two previous types of systems.

Precision requirements of aviation gravimetry entirely satisfy the requirements of modern systems of inertial navigation (SIN), which allows us to subsequently consider SIN the source of navigation information of AGS [1].

Structural scheme of such SIN is presented in Fig. 5 [1].

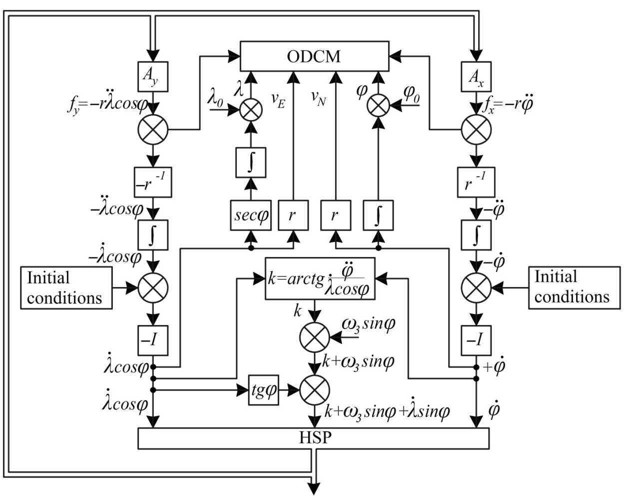

Fig. 5. Structural scheme of the system of AGS inertial navigation

Equations for angular velocities relative to the northern and eastern axes can be obtained from the output signals of accelerometers (Fig. 5). Let us divide the output signals of accelerometers by r^{-1}, integrate with regard to initial conditions and change the sign [1]:

$$\omega_x = -r\ddot{\phi}_c, \tag{15}$$

$$\omega_y = -r\ddot{\lambda}\cos\phi_c. \tag{16}$$

To obtain longitude λ with regard to the assigned initial value, it is necessary to multiply ω_y by sec φ and perform integration. To obtain latitude φ, it is necessary to perform integration of ω_x with regard to the assigned initial value of latitude.

To receive northern and eastern components of the aircraft velocity, it is necessary to obtain products of ω_y, ω_x by r [1].

4. 6. Structural scheme of AGS for measuring anomalies in the acceleration of gravity

The motion equation of AGS (15) differs from the known ones by additional members:

$$\omega_e^2 h\cos^2\phi \ \text{ and } \ 2\dot{h}er^{-1}v\cos k\sin 2\phi,$$

with the error of underestimation of their impact at about 2.67 mGal and 1 mGal, respectively. When measuring Δg with accuracy of 1 mGal, it is necessary to take into account the impact of these additional members [1].

Structural scheme of a mathematical model of AGS with regard to the northern and eastern components of AC ground speed is shown in Fig. 6:

$$v = r\dot{\lambda}\cos\phi(\sin k)^{-1},$$

$$v_N = v\cos k = r\dot{\phi};$$

$$v_E = v\sin k = r\dot{\lambda}\cos\phi, \tag{17}$$

where v_N, v_E are the northern and eastern components of aircraft ground speed, respectively.

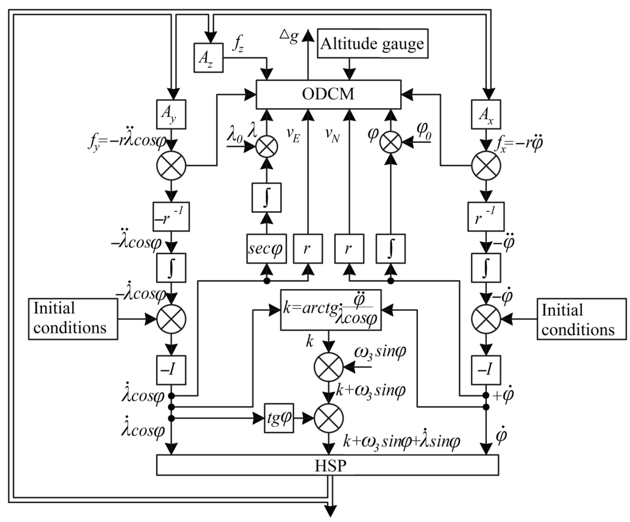

Fig. 6. Structural scheme of the system for determining the AG anomalies

The AGS navigation system to determine position of AC and AGS stabilization system are also part of the system in Fig. 6 [1].

4. 7. Compensation for the errors of measuring anomalies in the acceleration of gravity of gravimeter and horizontal accelerometers using a neural network

Existing AGS lack the means to compensate for instrumental errors that are observes at the outputs of gravimeter and horizontal accelerometers. Therefore, the results of measuring anomalies in the acceleration of gravity, which are formed in ODCM based on data from the outputs of gravimeter and two horizontal accelerometers, contain errors. These are instrumental errors during determining the coordinates, which are caused by systematic drift errors, errors of scale coefficients and errors in setting the axes of sensitivity.

All of these errors significantly reduce the accuracy of results when measuring anomalies in the acceleration of gravity. We propose a method for eliminating instrumental errors of AGS gravimeter and accelerometers by using a neural network [29].

The task is set to improve the aviation gravimetric system for measuring anomalies in the acceleration of gravity by introducing an additional block of neural network.

The set problem is solved in the following way [1, 30]. To compensate for the errors of measuring anomalies in the acceleration of gravity of gravimeter and horizontal accelerometers, a block of neural network is additionally introduced. Its inputs are connected to the outputs of horizontal accelerometers and the output of gravimeter. The outputs of the neural network block are connected to the inputs of ODCM.

Because a block of neural network performs compensation of instrumental errors of gravimeter and two horizontal accelerometers, a substantial increase in the accuracy of measurements is provided.

Thus, the proposed system provides for a considerable improvement in the accuracy of measuring anomalies in the acceleration of gravity.

To compensate for the errors of measuring anomalies in the acceleration of gravity of gravimeter and horizontal accelerometers, a block of neural network is additionally introduced (Fig. 7) [1, 31]. Its inputs are connected to the outputs of horizontal accelerometers and the output of gravimeter. The outputs of the neural network block are connected to the inputs of ODCM.

Aviation gravimetric system for measuring anomalies in the acceleration of gravity includes gravimeter 1, two horizontal accelerometers 2, 3, altitude gauge 4 and ODCM 5, and block 6 of neural network. Gravimeter 1 and vertical accelerometers 2, 3 are placed on a gyrostabilized platform. The output of altitude gauge 4 is connected to the input of ODCM 5.

The outputs of block 6 of neural network are connected to the outputs of gravimeter 1 and horizontal accelerometers 2, 3. The outputs of block of 6 neural network are connected to the inputs of ODCM 5.

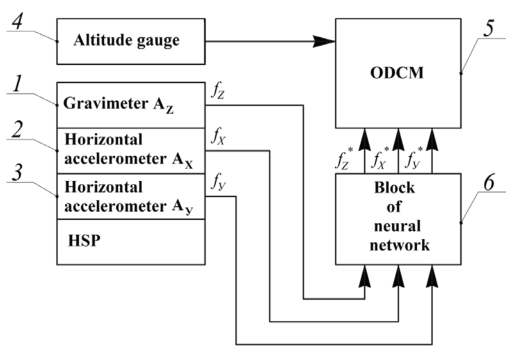

Fig. 7. Automated AGS with the compensation for errors of measuring the anomalies in the acceleration of gravity by a block of neural network

Aviation gravimetric system for measuring anomalies in the acceleration of gravity operates in the following way.

Signals f_z, f_x, f_y from the outputs of gravimeter 1 and two horizontal accelerometers 2, 3 enter the inputs of block 6 of neural network. The output of ODCM 5 is fed with the output signal of altitude gauge 4. The output signals, calculated by gravimeter 1 and two horizontal accelerometers 2, 3, contain instrumental errors. As we know from [1], these instrumental errors are caused by the action on gravimeter 1 and horizontal accelerometers 2, 3 from the following factors:

– systematic errors ΔA_i of drift;

– errors ΔB_i of scale factors;

– errors ΔC_i of setting the axes of sensitivity, where i are the Ox, Oy, Oz coordinate axes.

Block 6 of neural network performs projection calculation of instrumental errors ΔA_i, ΔB_i, ΔC_i along the Ox, Oy, Oz coordinate axis based on the approaches set forth in [29]. This block also performs compensation for the total instrumental errors $\sum_i^N \Delta A_i$, $\sum_i^N \Delta B_i$, $\sum_i^N \Delta C_i$ (where $i=\overline{1,N}$, N is the number of projections of instrumental errors along the Ox, Oy, Oz coordinate axis) by their exclusion according to formulas:

$$f_z^* = f_z - \sum_i^N (\Delta A_i + \Delta B_i + \Delta C_i),$$

$$f_x^* = f_x - \sum_i^N (\Delta A_i + \Delta B_i + \Delta C_i),$$

$$f_y^* = f_y - \sum_i^N (\Delta A_i + \Delta B_i + \Delta C_i), \quad (18)$$

where f_z^*, f_x^*, f_y^* are the corrected values of gravimeter 1 output signals and horizontal accelerometers 2, 3, respectively.

Next, ODCM 5, based on signals f_z^*, f_x^*, f_y^* and the output signal of altitude gauge 4, computes the values for anomaly in the acceleration of gravity [1, 32].

Thus, it is demonstrated that the use of neural network in the aviation gravimetric system with a gravimeter of any type enabled the elimination of effect of instrumental errors, that is, allowed us to improve the accuracy of measurements.

5. Results of calculation of errors in the system

5. 1. Analysis of methodological errors in the aviation gravimetric system

To determine permissible errors in the measurement of parameters of aircraft motion by the components of AGS, we shall employ the methodology laid down in [1].

$$\Delta g = f_z + D, \quad (19)$$

where D is the total error of AGS:

$$D = \frac{v^2}{r}\left\{1 - 2e\cdot\left[1 - 2\cos^2\phi\cdot\left(1 - \frac{\sin^2 k}{2}\right)\right]\right\} +$$
$$+2\omega_e v \sin k \cos\phi - 2\dot{h}\frac{e}{r} v \cos k \sin 2\phi +$$
$$+2\frac{\gamma_0 h}{r} + \omega_e^2 h \cos^2\phi - \gamma_0. \quad (20)$$

Separate subsystems of AGS define parameters that are included in equation (19).

Complete differential of function D defines the relationship between absolute values of errors in the subsystems for measuring velocity Δv, course Δk, latitude $\Delta\phi$, altitude Δh, vertical velocity $\Delta\dot{h}$ [1]:

$$\Delta D=\left(\frac{dD}{dv}\right)\Delta v+\left(\frac{dD}{dk}\right)\Delta k+$$
$$+\left(\frac{dD}{d\phi}\right)\Delta\phi+\left(\frac{dD}{dh}\right)\Delta h+\left(\frac{dD}{d\dot{h}}\right)\Delta\dot{h}, \qquad (21)$$

where

$$\frac{dD}{dv}=\frac{2v}{r}\left\{1-2e\cdot\left[1-2\cos^2\phi\cdot(1-\frac{\sin^2 k}{2})\right]\right\}+$$
$$+2\omega_e\sin k\cos\phi-2\dot{h}\frac{e}{r}\cos k\sin 2\phi;$$

– AGS sensitivity factor to the errors of measuring velocity;

$$\frac{dD}{dk}=2\omega_e v\cos k\cos\phi-$$
$$-2e\frac{v^2}{r}\cos^2\phi\sin 2k+2\dot{h}\frac{e}{r}v\sin k\sin 2\phi,$$

– AGS sensitivity factor to the errors of measuring course;

$$\frac{dD}{d\phi}=2\omega_e v\sin k\sin\phi-$$
$$-\omega_e^2 h\sin 2\phi-4e\frac{v^2}{r}(1-\frac{\sin^2 k}{2})\sin 2\phi-$$
$$-4\dot{h}\frac{e}{r}v\cos k\cos 2\phi-\gamma_{0e}\cdot 5.3\cdot 10^{-3}(1-2\frac{h}{r})\sin 2\phi,$$

– AGS sensitivity factor to the errors of measuring latitude;

$$\frac{dD}{dh}=\omega_e{}^2\cos^2\phi+2\frac{\gamma_{0e}}{r},$$

– AGS sensitivity factor to the errors of measuring altitude;

$$\frac{dD}{d\dot{h}}=-2\frac{e}{r}v\cos k\sin 2\phi,$$

– AGS sensitivity factor to the errors of measuring vertical velocity.

Maximally permissible errors of measuring basic parameters by the components of AGS can be determined according to data in Table 1.

Parameters: $h=5\cdot10^3$ m, $e=3.4\cdot10^{-3}$, $r=6.4\cdot10^6$ m, $\omega_e=7.3\times$ $\times10^{-5}\,s^{-1}$, $\gamma_{0e}=9.78049$ m/s^2 correspond to the numerical values of sensitivity coefficients that are given in Table 1.

Maximum values of errors in the measurement of AGS parameters are given in Table 2.

As follows from Table 2, the maximum values of measurement errors of the examined parameters of AGS are relatively low. However, not to a degree when it is possible to neglect them when designing the aviation system.

Table 1

Values of maximum sensitivity coefficients of error in the output signal of aviation gravimetric system to the errors in the measurement of parameters

No. of entry	Maximum sensitivity coefficients of error in the output signal of AGS to the errors in the measurement of parameters			
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/arcmin	1,08	0,65	0,39
5	$\frac{dD}{d\phi}$, mGal/arcmin	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}	2,8·10^{-2}	1,9·10^{-2}	1,03·10^{-2}

Table 2

Maximum values of measurement errors of the examined parameters of aviation gravimetric system

No. of entry	Measurement errors	Maximum value of error in the measurement of gravitational anomaly (Δg)	
		1 mGal	3 mGal
1	Ground speed v, m/s	0,05	0,15
2	Course k, arcmin	1,43	3,0
3	Geographic latitude ϕ, arcmin	0,5	1,
4	Height h, m	3,3	10,0
5	Vertical velocity $\Delta\dot{h}$, m/s	0,5·10^{-2}	1·10^{-2}
6	Path s, m	1,5	4,5
7	Error of stabilization of sensitivity axis of gravimeter, angle	5	15

5. 2. Error of AGS gravimeter from transferable (relative to device) angular velocity of the Earth's rotation

[1] presents formulas for calculating error from transferable (relative to gravimeter) angular velocity ω_z of the Earth's rotation:

$$\Delta_e=K_g\omega_e, \qquad (22)$$

$$\delta_e=\frac{\Delta_e}{\alpha_{cor}}\cdot 100\,\%, \qquad (23)$$

where K_g is the transmission coefficient of gravimeter; ω_e is the velocity of the Earth's rotation; α_{cor} is the useful signal of gravimeter.

Vertical component of the transferable angular velocity of the main xOyz axis is caused by the Earth's rotation and natural motion of AC:

$$\omega_z = \omega_e \sin\phi + \frac{v_y}{r}\mathrm{tg}\phi; \tag{24}$$

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

$$\frac{v_y}{r}\mathrm{tg}\phi = \dot{\lambda}\sin\phi, \tag{26}$$

where v_y is the eastern component of ground speed of aircraft; r is the geocentric the radius of the Earth; $\dot{\lambda}$ is the rate of change in longitude.

Let us write down formula (24) with regard to (26):

$$\omega_z = (\omega_e + \dot{\lambda})\sin\phi. \tag{27}$$

With regard to AC rotating around the Oz axis with angular velocity $\dot{k}$ in the case of motion:

$$\omega_z = (\omega_e + \dot{\lambda})\sin\phi + \dot{k}, \tag{28}$$

where k is the course angle in the plane of horizon, which is counted by a movement clockwise from the direction to North to the longitudinal axis of the object.

Let us write down formula (22) with regard to (28):

$$\Delta_e = K_g[(\omega_e + \dot{\lambda})\sin\phi + \dot{k}]. \tag{29}$$

Over averaging interval $(t_2 - t_1)$, we shall obtain mean value of absolute error $\overline{\Delta}_3$ [1]:

$$(t_2 - t_1)\overline{\Delta} = K_g[k(t_2) - k(t_1)] + \\ +K_g\int_{t_1}^{t_2}\omega_e \sin\phi(t)dt + K_g\int_{t_1}^{t_2}\dot{\lambda}\sin\phi(t)dt. \tag{30}$$

Maximum value $K_g\omega_e \sin\phi = 2.92{\cdot}10^{-5}$ rad and corresponds to ϕ=90° and velocity of the Earth's rotation ω_e= =7.29·10^{-5} s^{-1} [1].

Calculation error $K_g\omega_e \sin\phi$ at assigned K_g and stable value of ω_e depends on the error of determining ϕ. The error of determining latitude should be lower than 0.5° if the calculation error $K_g\omega_e \sin\phi$ is not larger than 2.92·10^{-7} rad (this amounts to 0.01 %) [1].

If we replace:

$$\int_{t_1}^{t_2}\sin\phi(t)dt,$$

with the mean value $\overline{\sin\phi}$ for the averaging interval $(t_2 - t_1)$, then the error of determining latitude does not exceed 0.5°. The mean value $\overline{\phi}$ corresponds to the middle of interval $(t_2 - t_1)$ and $\overline{\sin\phi}$ differs insignificantly from $\sin\overline{\phi}$ under condition that flights take place at constant velocity [1]:

$$K_g\int_{t_1}^{t_2}\omega_e \sin\phi(t)dt = K_g\omega_e \sin\overline{\phi}(t_2 - t_1). \tag{31}$$

During aircraft motion in mid-latitudes (at ϕ=65° and v_y=234 m/s, =6.4·10^6 m), sensitivity of the aviation gravimetric system to errors in the measurement of latitude is maximal. Let us obtain value $\dot{\lambda}(t)\sin\phi$ [1]:

$$\dot{\lambda}(t)\sin\phi = 7.3\cdot 10^{-5}\,\mathrm{s}^{-1}. \tag{32}$$

At the assigned parameters of motion, value $\dot{\lambda}(t)\sin\phi$ will be equal velocity of the Earth's rotation.

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

$$K_g\int_{t_1}^{t_2}\dot{\lambda}(t)\sin\phi(t)dt = K_g[\lambda(t_2) - \lambda(t_1)]\sin\overline{\phi}. \tag{33}$$

The route of the flight during testing program should be laid along the parallel (latitude value is practically constant and for calculation it is possible to use the assigned ϕ) or along the meridian (it is possible to apply decomposition into a series for relatively rough approximation of $\sin\overline{\phi}$). For computing $\overline{\phi}$ when compiling flight data, it is necessary to choose the middle of interval $(t_2 - t_1)$ [1].

Formula (29) takes the final form:

$$\Delta_e = K_{sg}\left(\frac{k(t_2) - k(t_1)}{t_2 - t_1} + \omega_e \sin\overline{\phi} + \frac{\lambda(t_2) - \lambda(t_1)}{t_2 - t_1}\sin\overline{\phi}\right). \tag{34}$$

Let us calculate values $\overline{\Delta}_e$ and $\overline{\delta}_e$ when $\dot{k}$=0 for ϕ=65° and $v_y = 234$ m/s, r=6.4·10^6 m. $\overline{\Delta}_e$=5.8·10^{-5} rad=584 mGal,

$$\overline{\delta}_e = 2.92{\cdot}10^{-2}\,\%.$$

We can conclude that the error of gravimeter $\overline{\Delta}_e$ = =584 mGal, caused by the transferable (relative to device) angular velocity of the Earth's rotation ω_z, is very large compared to other errors. For its consideration, it is necessary to introduce corrections into the AGS motion equation (17).

It is necessary to write down the AGS motion equation with a gravimeter of any type with regard to error from the impact of ω_z [1]:

$$\overline{\Delta g} = \\ = \frac{1}{S}\left\{\frac{\alpha(t_2) - \alpha(t_1)}{t_2 - t_1} + \right. \\ + \frac{K_g}{k_2}\left[\frac{k(t_2) - k(t_1)}{t_2 - t_1} + \frac{\lambda(t_2) - \lambda(t_1)}{t_2 - t_1}\sin\overline{\phi} + \omega_e \sin\overline{\phi}\right]\Bigg\} + \\ + \frac{\overline{V}^2}{r}\left\{1 - 2e\left[1 - 2\cos^2\phi\left(1 - \frac{\sin^2\overline{k}}{2}\right)\right]\right\} + \\ + 2\overline{V}\omega_e \sin\overline{k}\cos\overline{\phi} - 2\dot{h}\frac{e}{r}\overline{V}\cos\overline{k}\sin\overline{2\phi} + \\ + 2\frac{\overline{\gamma_0}\overline{h}}{r} + \omega_e^2\cos^2\overline{\phi}\overline{h} - \overline{\ddot{h}} - \overline{\gamma}_0. \tag{35}$$

The impact of error from ω_z is extremely large (584 mGal), which is why it is necessary to consider this error when analyzing the work of any type of gravimeter.

5. 3. Algorithm for solving differential equation of gravimeter motion on computer

In [1], the equation of AGS gravimeter motion was obtained in the form convenient for computer simulation:

$$\ddot{x}' + 2\xi\omega_0\dot{x}' + (\omega_0^2 + v_1 w_b \sin\omega t)x' = 0{,}005 w_a \sin\omega t, \quad (36)$$

where

$$v_1 = \frac{v_0}{w_b}.$$

Article [1] gives the description of computer simulation program for the specified equation of gravimeter motion. Its interface (Fig. 8) includes:

– 11 fields where parameters for modeling are assigned;

– graphic field where results are displayed in the form of charts;

– resulting table with step by step output values.

Table 3 gives all the parameters that are included in the calculations and in the program interface.

Table 3

Parameters used for programming

No. of entry	Conditional designation	Name
1	ξ (eps)	Gravimeter damping coefficient
2	w	Oscillations frequency
3	w0	Gravimeter natural frequency
4	w_a	Amplitude of disturbing influence along the Oz axis
5	w_b	Amplitude of disturbing influence along the Oy axis
6	T0	Initial time
7	Tmax	Integration bound (end time)
8	step	Integration step
9	m	Mass of gravimeter sensing element

Let us write down equation (36) in the form, convenient for computing:

$$\dot{x}' = \dot{Y},$$

$$\dot{Y} = 0{,}005 w_a \sin\omega t - 2\xi\omega_0\dot{x} - (\omega_0^2 + v_1 w_b \sin\omega t)x'. \quad (37)$$

Assign initial conditions:

$$x\varnothing = 10^{-5},\ Y\varnothing = 10^{-4}. \quad (38)$$

Determine constants:

P=2, w∅=0.1, w=0.01, R=0.01.

Let us introduce machine variables:

$$z = \xi,\ \ Q = v_1,\ \ w = \omega,\ \ wA = w_a,\ \ wB = w_b,$$

observation time

$$T = x'(t),$$

integration bound:

$$TMAX = T_{max},$$

integration step:

$$H = \Delta t,$$

variable argument:

$$T = t.$$

Variables:

$$AA = wa * R,\ \ BB = wB * Q,\ \ CC = P * w\,\varnothing * z,$$

where $*$ is the multiplication sign. Then expressions (37) can be written down as:

$$\dot{X}' = Y;$$

$$\dot{Y} = \sin(w * T) * (AA - BB * X') - \\ - CC * Y - ww * X'. \quad (39)$$

In order to integrate a system of differential equations (39), we shall employ the Runge-Kutta method of fourth order [33]. We obtain solutions to system (39):

$$X'(T+H) = \\ = X'(T) + \frac{1}{6} * [X1 + X4 + 2. * (X2 + X3)];$$

$$Y(T+H) = \\ = Y(T) + \frac{1}{6} * [Y1 + Y2 + 2. * (Y2 + Y3)],$$

where coefficients X1, X2, X3, X4, Y1, Y2, Y3, Y4 can be determined as follows:

$$X1 = H * Y;\ Y1 = H * [\sin(w * T) * (AA - BB * x) - \\ - CC * Y - ww * x]; X2 = H * (Y - 0{,}5 * Y1),$$

$$Y2 = H * \begin{cases} \sin[w * (T + 0{,}5 * H)] * [AA - BB * (X + 0{,}5 * X1)] - \\ - CC * [Y + 0{,}5 * Y1] - ww * (X + 0{,}5 * X1) \end{cases};$$

$$X3 = H * (Y + 0{,}5 * Y2),$$

$$Y3 = H * \begin{cases} \sin[w * (T + 0{,}5 * H] * [AA - BB * (X + 0{,}5 * X2)] - \\ - CC * (Y + 0{,}5 * Y2) - ww * (X + 0{,}5 * X2) \end{cases},$$

$$X4 = H * (Y + Y3),$$

$$Y4 = H * \begin{cases} \sin[w * (T + H)] * [AA - BB * (X + X3)] - \\ - CC * (Y + Y3) - ww * (X + X3) \end{cases}.$$

Using the algorithm specified, it is possible to write in any programming language a program that will simulate the work of gravimeter under the action of external disturbances.

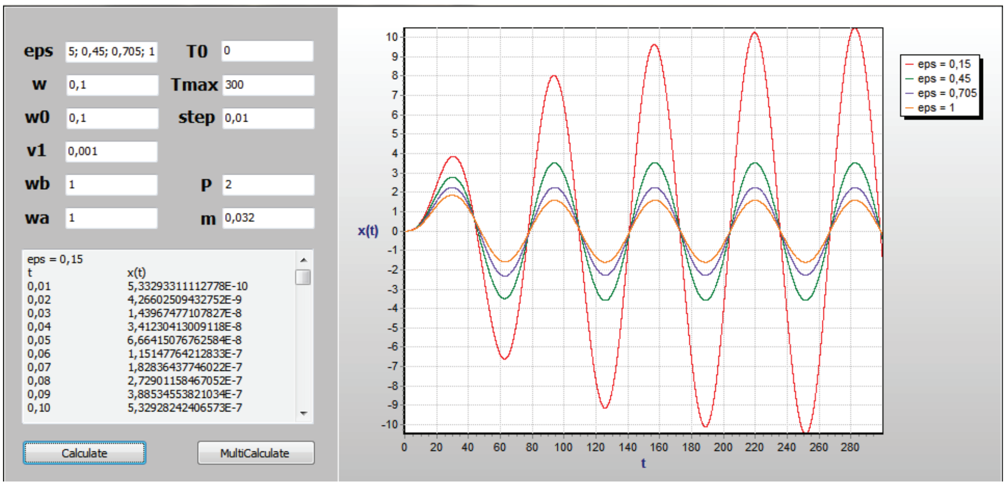

Fig. 8. Program interface for computer modeling of the work of gravimeter under the action of external disturbances

6. Discussion of the obtained values of errors in AGS

In [1] and in publications [18–22]: digital simulation and analysis of the AGS gravimeter motion under the action of external disturbances is described in detail. That is why we shall include only the main findings based on analysis of the obtained charts and tables.

As a result of performed simulation, we obtained charts [18–22] of change in the output signal x(t) for different values of perturbation frequency ω, damping coefficient ξ and different values of amplitudes of perturbing vibration accelerations w_a, w_b.

Charts obtained by computer simulation demonstrate that:

– only at perturbation frequency

$$\omega=\omega_0=0.1 \text{ rad/s},$$

there occurs the main resonance, the most dangerous for a gravimeter;

– at frequencies:

$$\omega=\omega_0/2=0.05 \text{ rad/s}, \ \omega=\omega_0/3=0.033 \text{ rad/s},$$

the output signal is not distorted (sub-harmonic oscillations are established);

– at frequencies:

$$\omega=2\omega_0=0.2 \text{ rad/s}, \ \omega=3\omega_0=0.3 \text{ rad/s},$$

the output signal is distorted (the beating sets in);

– increase in the amplitudes of horizontal accelerations does not affect the amplitude of the forced oscillations of gravimeter;

– it was established that damping coefficient ξ is advisable to increase only in the case of main resonance:

$$\omega=\omega_0 \ (\xi=0.705)$$

and in the case:

$$\omega=2\omega_0, \ \omega=3\omega_0,$$

when the beating sets in (ξ=0,45). That is, it was substantiated that it is expedient to choose damping coefficient of gravimeter of 0.705.

7. Conclusions

1. We put forth general principles for constructing aviation gravimetric system with any type of gravimeter. A list of basic components of AGS is compiled: gravimeter of any type, system for determining navigation parameters, altitude gauge, and onboard computing machine.

2. It was substantiated that the choice of natural frequency of gravimeter of any type equal to 0.1 s^{-1} ensures the absence of effect of vertical acceleration on the work of AGS gravimeter and eliminates the need for applying additional electronic filters.

3. We demonstrated feasibility of employing a dual-channel method for constructing an AGS gravimeter because this method makes it possible to compensate for the residual instrumental errors.

4. An analysis of methodological errors in the system was conducted, based on which we formulated precision requirements to the components of AGS provided the accuracy of AG measurements is 1–2 mGal.

5. It was substantiated that error of the AGS gravimeter of any type from the influence of angular velocity of the Earth's rotation is unacceptably large ($\overline{\Delta}_e$=584 mGal) compared to other errors. In order to take it into consideration, it is necessary to introduce appropriate correction

$$\Delta_e = K_{sg}\left(\frac{k(t_2)-k(t_1)}{t_2-t_1}+\omega_e\sin\bar{\phi}+\frac{\lambda(t_2)-\lambda(t_1)}{t_2-t_1}\sin\bar{\phi}\right)$$

into the AGS motion equation. We received final equation of AGS with this correction

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

6. It is demonstrated that the use of neural network in the aviation gravimetric system with a gravimeter of any type provided for the elimination of impact of instrumental errors, that is, allowed us to improve the accuracy of measurements.

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