DOI 10.31891/2307-5732-2024-333-2-47
УДК 621.317

BEZVESILNA OLENA
NTUU «Kyiv Polytechnic Institute named after Igor Sikorsky»
https://orcid.org/0000-0002-6951-1242
e-mail: o.bezvesilna@gmail.com
GRYNEVYCH MARIIA
NTUU «Kyiv Polytechnic Institute named after Igor Sikorsky»
https://orcid.org/0000-0001-9183-5211
e-mail: kakit_gms@ztu.edu.ua
TOLOCHKO TETIANA
NTUU «Kyiv Polytechnic Institute named after Igor Sikorsky»
https://orcid.org/0000-0002-2346-0419
e-mail: prilad168@gmail.com

TWO-CHANNEL GRAVIMETER OF AVIATION GRAVIMETRIC SYSTEM

A two-gyro gravimeter of the aviation gravimetric system is proposed and investigated, which provides higher measurement accuracy than known gravimeters, due to the elimination of errors from the cross angular velocities of the base and the angular velocity of the Earth's rotation and the measurement of the full vector of the acceleration of gravity. To measure the acceleration of gravity, an AGS is proposed, which has greater accuracy and speed than known and consists of a three-stage gyroscope located in the inner and outer frames, equipped with interframe correction systems, which include an angle sensor (DC) located on the axis of the inner frame of the gyroscope and a torque sensor (DM) connected to its output is located on the axis of the outer frame. DM, located on the axis of the inner frame, is connected to the DC output. An additional, identical to the first, three-stage gyroscope, the rotor of which rotates in the opposite direction from the main gyroscope, is introduced in the AGS under consideration. The additional gyroscope of the AGS is also provided with similar correction systems, which consist of a DC located on the axis of the inner frame, and a DM located on the axis of the outer frame connected to its output, a DC located on the axis of the outer frame, to the output of which a DM located on the axis is connected inner frame The centers of gravity of two identical (main and additional) gyroscopes are shifted by the same distance in one direction along the axes of rotation of the rotors of the gyroscopes relative to the axes of the outer frames. The vectors of the kinetic moments of the two gyroscopes are oppositely directed. In the two-channel gravimeter, two output signals of linear acceleration are formed as the sum of signals from DC of two gyroscopes relative to one z-axis and as the sum of signals from DC of two gyroscopes relative to the second x-axis. The output signals are fed to the computer. Both gyroscopes of the system's gyrogravimeter are mounted on a platform whose angular position is controlled by a motor (DV) installed on the x-axis and a DV on the z-axis. Both motors control the angular position of the platform by signals. The computer also receives signals from the system for determining navigation parameters and from the height meter.

Key words: two-channel gravimeter, angular velocity of the Earth's rotation, cross angular velocities of the base

БЕЗВЕСІЛЬНА ОЛЕНА, ГРИНЕВИЧ МАРІЯ, ТОЛОЧКО ТЕТЯНА
НТУУ «Київський політехнічний інститут імені Ігоря Сікорського»

ДВОКАНАЛЬНИЙ ГРАВІМЕТР АВІАЦІЙНОЇ ГРАВІМЕТРИЧНОЇ СИСТЕМИ

Запропоновано та досліджено двогіроскопний гравіметр авіаційної гравіметричної системи, який забезпечує вищу точність вимірювань, ніж відомі гравіметри, за рахунок усунення похибок від перехресних кутових швидкостей основи і кутової швидкості обертання Землі та вимірювання повного вектора прискорення сили тяжіння. Для вимірювання прискорення сили тяжіння запропоновано АГС, яка має більші точність і швидкодію, ніж відомі, та складається з тристепеневого гіроскопа, розташованого у внутрішній та зовнішній рамках, забезпеченого системами міжрамкової корекції, що містять розташований на осі внутрішньої рамки гіроскопа датчик кута (ДК) і підключений до його виходу датчик моменту (ДМ), розташований на осі зовнішньої рамки. До виходу ДК підключено ДМ, розташований на осі внутрішньої рамки. У розглядуваній АГС уведено додатковий, ідентичний першому, тристепеневий гіроскоп, ротор якого обертається в протилежний бік від основного гіроскопа. Додатковий гіроскоп АГС також забезпечують аналогічними системами корекції, які складаються з ДК, розташованого на ос внутрішньої рамки, і підключеного до його виходу ДМ, розташованого на осі зовнішньої рамки, ДК, розташовано на осі зовнішньої рамки, до виходу якого підключено ДМ, розташований на осі внутрішньої рамки. Центри ваги двох однакових (основного і додаткового) гіроскопів зміщені на однакову відстань в один бік уздовж осей обертання роторів гіроскопів відносно осей зовнішніх рамок. Вектори кінетичних моментів двох гіроскопів протилежно спрямовані. У двоканальному гравіметрі формуються два вихідні сигнали лінійного прискорення як сума сигналів з ДК двох гіроскопів відносно однієї осі z і як сума сигналів з ДК двох гіроскопів відносно другої осі x. Вихідні сигнали подаються у комп'ютер. Обидва гіроскопи гірогравіметра системи встановлюють на платформі, кутовим положенням якої керує двигун (ДВ), встановлений на осі x і ДВ – на осі z. Обидва двигуни керують кутовим положенням платформи за сигналами. У комп'ютер надходять також сигнали від системи визначення навігаційних параметрів і від вимірювача висоти.

Ключові слова: двогіроскопний гравіметр, кутова швидкість обертання Землі, перехресні кутові швидкості основи

Formulation of the problem

Today, modern instruments in the field of aviation gravimetry (string GS and quartz GAL-S) have significant errors due to the influence of the cross angular velocities of the base and the angular speed of the Earth's rotation (only the last error is 584 mGal). A gyroscopic single-rotor gravimeter also has the above-mentioned errors.

Requirements for the accuracy of measurements of the Earth's gravitational field, correction of inertial navigation systems by the Earth's gravitational field and other precision tasks of the aerospace industry are growing every year.

Therefore, the problem of increasing the accuracy of aviation gravimetric measurements by compensating errors due to the influence of the cross angular velocities of the base and the angular velocity of the Earth's rotation is urgent.

Analysis of recent research and publications

The conducted studies showed that a number of outstanding gravimetric scientists made a great contribution to the theory and practice of terrestrial gravimetric measurements: V.O. Bagromyants, Yu.D. Boulanger, K.E. Veselov, A.M. Lozynska, A.A. Mykhailov, S.A. Poddubny, E.I. Popov, V.A. Tulin, V.V. Fedinsky, M.E. Heifetz and others.

A major role in the development of gravity measurements was played by the works of foreign scientists: L. La Costa, D. Garrison, A. Graf, Y. Tomoda, M. Golvani and others.

Gravimetric studies are intensively carried out in many large scientific and technical centers: NSC "Institute of Metrology" (Kharkov) under the leadership of H.S. Sydorenko; Central research institute "Azimut" under the leadership of L.P. Nesenyuk, G.B. Wolfson, B.A. Blazhnov; HMEAS named after Professor M.E. Zhukovsky under the leadership of A.A. Krasovsky, A.I. Soroky; RV HMEAS (Riga) under the leadership of A.A. Veselov.

At the moment, there is a lot of literature in the field of methods and means of measuring the acceleration of gravity (AG) [1-4], which contains both the principle of operation and the technical characteristics of modern devices for measuring AG. Much attention is paid to single-gyro gravimeters [1, 2]. However, there is no information about dual-gyro gravimeters in the known literature.

A description of a string gravimeter is given in [3], however, this gravimeter measures only one component of the AG. Methods and means of compensating errors from the cross angular velocities of the base and the angular velocity of the Earth's rotation are not provided.

In [4] there is a description of a quartz strongly damped gravimeter, however, this gravimeter measures only one component of the AG. Methods and means of compensating errors from the cross angular velocities of the base and the angular velocity of the Earth's rotation are not provided.

It is not possible to increase the accuracy of the AG measurement if you do not take into account the errors from the cross angular velocities of the base and the angular velocity of the Earth's rotation. It is also desirable for the gravimeter to be two-channel.

The purpose of the work: to propose and investigate a two-channel gravimeter (TCG) of the aviation gravimetric system (AGS), which will provide higher measurement accuracy than known systems, due to the elimination of errors from the cross angular velocities of the base and the angular velocity of the Earth's rotation and the measurement of the full vector of the acceleration of gravity (and not one component, as in GAL-S, GS and single-gyro gravimeters).

Presentation of the main material of the article

To measure the acceleration of gravity an AGS (Fig. 1) is proposed, which has greater accuracy and speed than known, and consists of a three-stage gyroscope 1, located in the inner 2 and outer 3 frames, equipped with interframe correction systems, containing an axis 4 of the inner frame of the gyroscope 1, the angle sensor (AS) 5 and the torque sensor (TS) 6 connected to its output, located on axis 7 of the outer frame 3. TS 9, located on axis 4 of the inner frame 2, is connected to the output of the AS 8, located on axis 4 of the internal frame 2. In the AGS under consideration, an additional, identical to the first, three-stage gyroscope 1, the rotor of which rotates in the opposite direction from the main gyroscope 1. The additional gyroscope of the AGS is also provided with similar correction systems, which consist of AS 5, located on axis 4 of the inner frame 2, and connected to its output TS 6, located on axis 7 of the outer frame 3, AS 8, located on axis 7 of the outer frame 3, to the output of which TS 9 is connected, located on axis 4 of the inner frame 2. The centers of gravity of two identical (main and additional) gyroscopes 1 are shifted by the same distance l in one direction along the axes 10 of rotation of the rotors of the gyroscopes 1 relative to the axes 7 of the outer frames 3. The vectors of the kinetic moments of the two gyroscopes are oppositely directed.

In the two-channel gravimeter, two output signals f_z, f_x of linear acceleration are formed as the sum of signals from AS 8 of two gyroscopes relative to one z axis and as the sum of signals from AS 5 of two gyroscopes relative to the second x axis. The output signals f_z, f_x are fed to the on-board digital computer (DC). Both gyroscopes of the gravimeter of the system are installed on the platform 11, the angular position of which is controlled by the motor (M) 12 installed on the x axis and M 13 - on the z axis. The linear acceleration signal f_z is sent to M 12, and the signal f_x – to M 13. Both motors control the angular position of the platform 11 by signals f_z, f_x. The DC also receives signals from the system for determining navigation parameters and from the height meter.

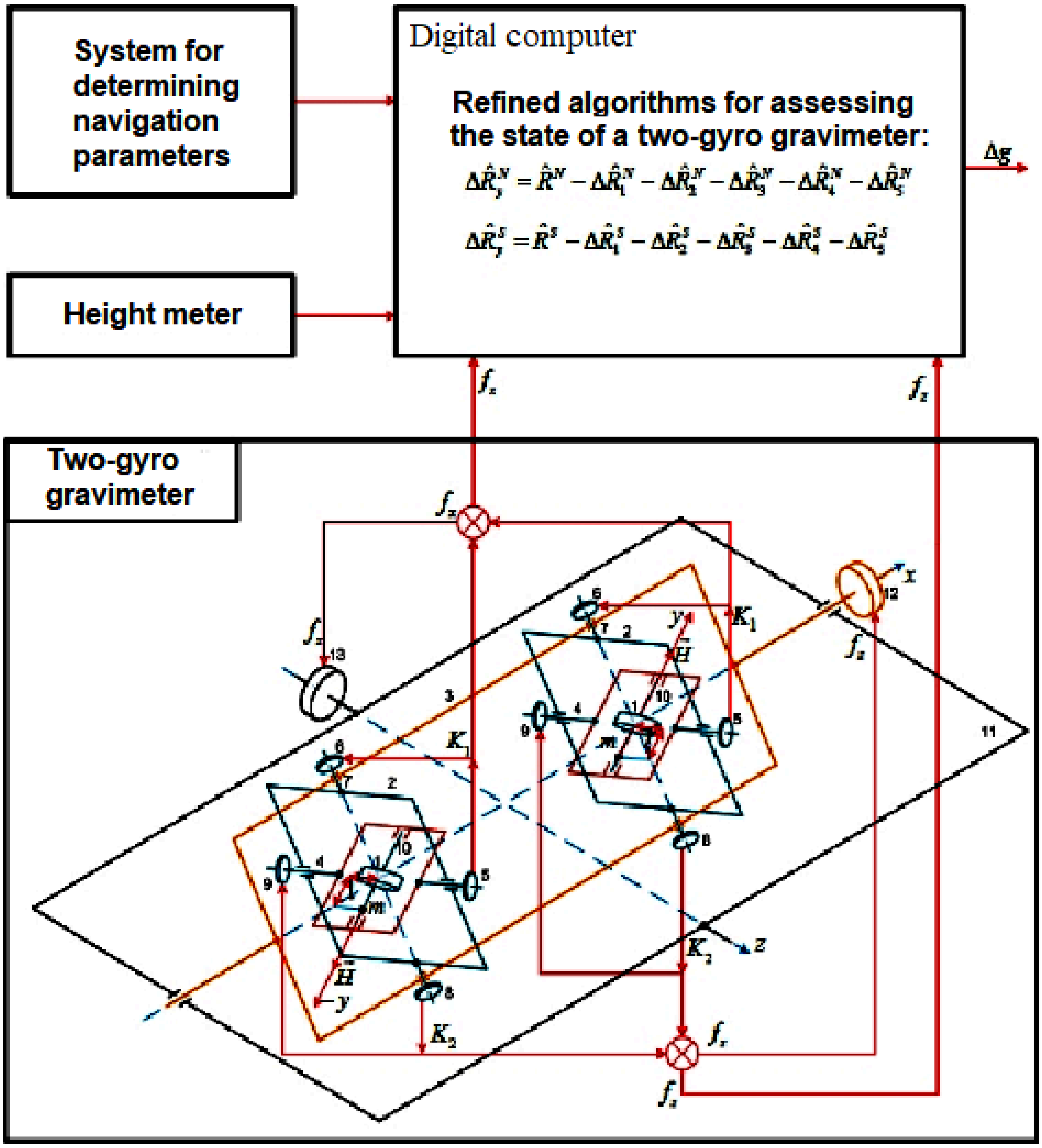

Fig. 1. Aviation gravimetric system with a two-channel gravimeter

In the presence of a component g_x of linear acceleration along the axes 4 of the inner frames 2 of the gyroscopes, the frames begin to rotate around the axes 4 of the inner frames 2 under the action of the pendulum moment mlg_x (ml – pendulum) directed along the axes 7 of the outer frames 3. The rotation of the gyroscopes under the influence of this moment causes the appearance of electrical signals from two identical AS 5, located on the axes 4 of the internal frames 2, the outputs of which are connected to the control windings of two identical TS 6, located on the axes 7 of the external frames 3. Two TS 6 create moments mlg_x that compensate for the pendulum moments, along the axes 7 of the external frames 3. Under the action of the pendulum moment mlg_z caused by the component of linear acceleration g_z along the axes of the 7 external frames and directed along the axes of the 4 internal frames of the 2 gyroscopes, two three-stage gyroscopes begin to rotate around the axes of the 7 external frames 3. The rotation of the two gyroscopes under the action of the moment causes the appearance of electrical signals from two identical DK 8, located on the axes 7 of the outer frames 3, the outputs of which are connected to the control windings of two identical TS 9, located on the axes 4 of the internal frames 2. Two identical TS 9 create moments that compensate for the pendulum moments mlg_z, that act along the axes 4 internal frames of 2 gyroscopes. In a two-channel gravimeter, output signals f_z and f_x linear acceleration are formed as the sum of signals from AS 8 of two gyroscopes on one axis z and as the sum of signals from AS 5 of two gyroscopes on the second x-axis. The output signals f_z, f_x are sent to the DC. The signals of linear acceleration f_z, f_x are received on M 12, 13, installed along the axes x, z. Both engines control the angular position of the platform 11, on which the device is installed. Output signals ν, k, ϕ from the system for determining navigation parameters and the output signal h from the height meter are also provided in the DC. DC calculates gravity acceleration anomalies.

Let's explain the principle of operation of the AGS using the system of precise equations of motion of one of the two identical gyroscopes of the system's gravimeter:

$$\begin{cases} H\dot{\beta} + k_1\beta + n_1\dot{\alpha} = mlw_x - \\ -mlg_x - H(\omega_x + \omega_y\alpha) - \\ -A\dot{\omega}_z - H\omega_3 \cos\phi , \\ H\dot{\alpha} + k_2\alpha + n_2\dot{\beta} = mlw_z - \\ -mlg_z - ml(w_x\alpha - w_y)\beta - \\ -B(\dot{\omega}_x + \dot{\omega}_y\alpha) - H\omega_y\beta - \\ -H\omega_3 \sin\phi , \end{cases} \quad (1)$$

where H – is the kinetic moment of the gyroscope; α, β – rotation angles of the outer frame relative to the object and the gyroscope casing relative to the outer frame; k_1, k_2 – coefficients equal to the product of the transmission coefficients of the corresponding AS and TS of the two correction channels; n_1, n_2 – coefficients of viscous friction forces relative to the corresponding axes; w_x, w_y, w_z – projections of the acceleration of the translational motion of the aircraft on the axis Ox, Oy, Oz of the reference coordinate system $xOyz$ associated with the aircraft (its origin coincides with the center O of mass of the moving part of the device; the axis Ox is directed parallel to the longitudinal axis of the object, the axis Oy is parallel to the transverse axis; the axis Oz is parallel to the normal axis); $\omega_x, \omega_y, \omega_z$ – projections of the angular velocity of the object on the axis associated with it; A – reduced to the axis of rotation of the outer frame, the moment of inertia of the system "gyroscope in gimbal suspension"; B – moment of inertia "rotor and inner frame of the gyroscope"; g_z, g_x – vertical and horizontal components of the acceleration of gravity acting on the gyroscope; ω_3 – angular velocity of the Earth's rotation; ϕ – latitude.

Marking the disturbing moments of obstacles relative to the axes of the suspension of the gyroscope frames

$$M_1 = mlw_x - H(\omega_x + \omega_y\alpha) - A\dot{\omega}_z - H\omega_3 \cos\phi,$$

$$M_2 = mlw_z - ml(w_x\alpha - \omega_y)\beta - B(\dot{\omega}_x + \dot{\omega}_y\alpha) - H\omega_y\beta - H\omega_3 \sin\phi,$$

rewrite system (1) in the form

$$\begin{cases} H\dot{\beta} + k_1\beta + n_1\dot{\alpha} = M_1 - mlg_x, \\ H\dot{\alpha} + k_2\alpha + n_2\dot{\beta} = M_2 - mlg_z. \end{cases} \quad (2)$$

Let's find the solution of equations (2):

$$\alpha(p) = [n_2 p(M_1 - mlg_x) - (Hp + k_1)(M_2 - mlg_z)] \times \frac{1}{n_1 n_2 p^2 - (Hp + k_1)(Hp + k_2)}; \quad (3)$$

$$\beta(p) = [n_1 p(M_2 - mlg_z) - (Hp + k_2)(M_1 - mlg_x)] \times \frac{1}{n_1 n_2 p^2 - (Hp + k_1)(Hp + k_2)}. \quad (4)$$

Let's write down the expressions for the fixed values of the rotation angles of one of the gyroscopes, using (3), (4):

$$\alpha_{ycm} = k_2^{-1}[-mlg_z + mlw_z - ml(w_x\alpha - w_y)\beta - B(\dot{\omega}_x + \dot{\omega}_y\alpha) - H\omega_y\beta - H\omega_3 \sin\phi];$$

$$\beta_{ycm} = k_1^{-1}[-mlg_x + mlw_x - H(\omega_x + \omega_y\alpha)\beta - A\dot{\omega}_z - H\omega_3 \cos\varphi].$$

We will generate signals proportional to the sum of the rotation angles of two gyroscopes. To do this, we will use two identical gyroscopes with oppositely directed vectors of kinetic moments. The signals of two gyroscopes have the form, respectively:

$$\alpha_{1ycm} = k_2^{-1}[-mlg_z + mlw_z - ml(w_x\alpha - w_y)\beta - B(\dot{\omega}_x + \dot{\omega}_y\alpha) - H\omega_y\beta - H\omega_3 \sin\phi],$$

$$\alpha_{2ycm} = k_2^{-1}[-m\,lg_z + mlw_z - ml(w_x\alpha - w_y)\beta - B(\dot{\omega}_x + \dot{\omega}_y\alpha) + H\omega_y\beta + H\omega_3 \sin\phi];$$

$$\beta_{1ycm} = k_1^{-1}[-mlg_x + mlw_x - H(w_x + w_y\alpha)\beta - A\dot{\omega}_z - H\omega_3 \cos\phi],$$

$$\beta_{2ycm} = k_1^{-1}[-mlg_x + mlw_x + H(w_x + w_y\alpha) - A\dot{\omega}_z + H\omega_3 \cos\phi].$$

Let's find two output signals of a two-channel gravimeter:

$$f_z = \alpha_{1ycm} + \alpha_{2ycm} = k_2^{-1} \times [-2mlg_z + 2mlw_z - 2ml(w_x\alpha - w_y)\beta - 2B(\dot{\omega}_x + \dot{\omega}_y\alpha)]; \quad (5)$$

$$f_x = \beta_{1ycm} + \beta_{2ycm} = k_1^{-1} \times [-2mlg_x + 2mlw_x - 2A\dot{\omega}_z] . \quad (6)$$

From the expressions (5) and (6) of the AGS output signals, it can be seen:

- the components of the useful signal $-2mlg_z, -2mlg_x$ are doubled;
- the AGS dual-gyro gravimeter can measure the final direction and modulus acceleration of gravity according to formulas

$$\vec{g} = \vec{g}_z + \vec{g}_x, |g| = \sqrt{g_z^2 + g_x^2},$$

which ensures higher accuracy of measurements and display of the AGS dual-gyro gravimeter. For this, the output signals $f_z \equiv 2g_z$ and $f_x \equiv 2g_x$ (expressions (5) and (6)) of the two-channel gravimeter are used to control two additional engines of the additionally introduced platform, on which the main and additional gyroscopes are installed;

- some hindrance moments due to cross linear and angular accelerations are doubled.

$$[2mlw_z - 2ml(w_x\alpha - w_y)\beta - 2B(\dot{\omega}_x + \dot{\omega}_y\alpha); 2mlw_x - 2A\dot{\omega}_z].$$

Only the influence of moments can be taken into account here $-2mlw_z, -2mlw_x$. Therefore, it can be assumed that

$$f_z \cong k_2^{-1}(-2mlg_z + 2mlw_z),$$

$$f_x \cong k_1^{-1}(-2mlg_x + 2mlw_x).$$

Note that the above-mentioned obstacle moments (together with the obstacle moments, the influence of which is excluded in the double-gyro gravimeter) affect the operation of the single-gyro gravimeter AGS to the same extent.

- errors caused by gyroscopic moments-obstacles from cross angular velocities $\left[H\omega_y\beta, H\left(\omega_x+\omega_y\alpha\right)\right]$ and from the angular velocity of the Earth's rotation are eliminated $(H\omega_3 \sin\phi, H\omega_3 \cos\phi)$, which can be unacceptably large (namely, the latter - 584 mGal).

Conclusions

The proposed TCG AGS has certain advantages compared to other known gravimeters:

1. The proposed and considered TCG AGS provides higher measurement accuracy than single-gyro, string, and quartz strongly-damped gravimeters [1-4] due to the compensation of errors due to cross angular velocities and the angular velocity of the Earth's rotation;
2. In TCG AGS, the components of the useful signal are doubled;
3. Unlike known gravimeters [1-4], the dual-gyro gravimeter AGS can measure the final direction and acceleration module of gravity, which provides higher accuracy of both direct measurements Δg and setting of the dual-gyro gravimeter system due to the use of two additional motors and an additional platform.

Література

1. Безвесільна О.М. Вимірювання прискорень: Підручник. – К.: Либідь, 2001. – 254с.
2. Безвесільна О.М. Авіаційні гравіметричні системи та гравіметри: Монографія. – Житомир: ЖДТУ, 2007. – 604с.
3. Безвесільна, О. М. Струнний гравіметр авіаційної гравіметричної системи / О.М. Безвесільна, Л.О. Чепюк // Житомир : ЖДТУ, 2015. – 208 с.
4. Bezvesilna, O. M. Piezoelectric gravimeter of aviation gravimetric system / O. M. Bezvesilna, I. Korobiichuk, A. Tkachuk, M. Nowicki, R. Szewczyk // Advances in Intelligent Systems and Computing. 2016

References

1. Bezvesilna O.M. Measurement of accelerations: Textbook. - K.: Lybid, 2001. – 254p.
2. Bezvesilna O.M. Aviation gravimetric systems and gravimeters: Monograph. – Zhytomyr: ZHDTU, 2007. – 604 p.
3. Bezvesilna, O.M. String gravimeter of the aviation gravimetric system / O.M. Bezvesilna, L.O. Chepyuk // Zhytomyr: ZHDTU, 2015. – 208 p.
4. Bezvesilna, O. M. Piezoelectric gravimeter of aviation gravimetric system / O. M. Bezvesilna, I. Korobiichuk, A. Tkachuk, M. Nowicki, R. Szewczyk // Advances in Intelligent Systems and Computing. 2016