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Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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A.D. Tulegulov[1], D.S. Yergaliyev[2], S.Zh. Karipbaev[2], N.A. Bazhaev[2*],
D.V. Zuev[2], Ye.G. Adilkhanov[2]

[1]Almaty University of Energy and Communications named after G. Daukeev,
Almaty, Kazakhstan;
[2]Civil Aviation Academy, Almaty, Kazakhstan.
E-mail: Bazhaev_na@mail.ru

MODERN METHODS OF GYROSCOPIC ORIENTATION OF MINE WORKINGS

Abstract. Gyroscopic orientation of mine workings is a method that allows using a gyrocompass to determine the direction of the geographic meridian at any point in a tunnel, tunneling, etc. The gyroscopic orientation of mine workings began at the beginning of the last century.

The practical application of high-tech devices, such as digital gyrocompasses, has greatly increased the accuracy of the main bases of mine surveying networks and made it possible to orient workings at great depths. Gyroscopic orientation of mine workings is indispensable for the development of inclined shafts.

Gyroscopic orientation of mine workings is carried out during connecting shooting during underground mining. The purpose of this orientation is to draw up geodetic plans, both on the surface of the earth and underground working horizons in a single coordinate system.

Key words: Gyroscopic orientation, gyrocompass, workings, “polar” disturbing moment of a synchronous hysteresis gyro motor, drift of a gyroscope from spherical support, high-tech devices.

А.Д. Тулегулов[1], Д.С. Ергалиев[2], С.Ж. Карипбаев[2], Н.А. Бажаев[2*], Д.В. Зуев[2], Е.Г. Адильханов[2]

[1]Ғ. Дәукеев атындағы Алматы энергетика және байланыс университеті,
Алматы, Қазақстан;
[2]Азаматтық авиация академиясы, Алматы, Қазақстан.
E-mail: Bazhaev_na@mail.ru

ТАУ-КЕН ЖҰМЫСТАРЫНЫҢ ГИРОСКОПИЯЛЫҚ БАҒЫТТАРЫНЫҢ ҚАЗІРГІ ӘДІСТЕРІ

Аннотация. Кен қазбаларының гироскопиялық бағдарлануы – туннель салу және т.б. гирокомпастың көмегімен туннельдің кез келген нүктесіндегі географиялық меридианның бағытын анықтауға мүмкіндік беретін әдіс. Кен қазбаларын гироскопиялық бағдарлау өткен ғасырдың басында басталды.

Цифрлық гирокомпастар сияқты жоғары технологиялық құрылғыларды іс жүзінде қолдану маркшейдерлік желілердің күшті нүктелерінің дәлдігін айтарлықтай арттырды және үлкен тереңдіктегі жұмыстарды бағдарлауға мүмкіндік берді. Көлбеу оқпандарды игеру үшін кен қазбаларының гироскопиялық бағыттылығы өте қажет.

Кен қазбаларының гироскопиялық бағдарлануы жерасты тау-кен жұмыстарын жүргізу кезінде байланыстырушы қызмет атқарады. Бұл бағдардың мақсаты жер бетінде де, жер асты горизонттарында да бір координаттар жүйесінде жұмыс істеудің геодезиялық жоспарларын жасау болып табылады.

Түйін сөздер: Гироскопиялық бағдар, гирокомпас, әзірлемелер, синхронды гистерезис гиромоторының «полярлық» алаңдату сәті, сфералық тірегі бар гироскоптың дрейфі, жоғары технологиялық құрылғылар.

А.Д. Тулегулов[1], Д.С. Ергалиев[2], С.Ж. Карипбаев[2], Н.А. Бажаев[2*], Д.В. Зуев[2], Е.Г. Адильханов[2]

[1]Алматинский университет энергетики и связи им. Г. Даукеева,
Алматы, Казахстан;
[2]Академия гражданской авиации, Алматы, Казахстан.
E-mail: Bazhaev_na@mail.ru

СОВРЕМЕННЫЕ МЕТОДЫ ГИРОСКОПИЧЕСКОГО ОРИЕНТИРОВАНИЯ ГОРНЫХ ВЫРАБОТОК

Аннотация. Гироскопическое ориентирование горных выработок – метод, позволяющий проводить при помощи гирокомпаса определение направления географического меридиана в любой точке тоннеля, проходки и т. д. Гироскопическое ориентирование горных выработок началось еще в начале прошлого столетия.

Практическое применение высокотехнологичных приборов, какими являются цифровые гирокомпасы, в значительной степени повысило точность опорных пунктов маркшейдерских сетей, позволило ориентировать выработки на больших глубинах. Гироскопическое ориентирование горных выработок незаменимо при разработке наклонных стволов.

Гироскопическое ориентирование горных выработок проводится при соединительной съемке во время подземных разработок. Цель такого ориентирования – составить геодезические планы, как поверхности земли, так и подземных горизонтов выработки в единой координатной системе.

Ключевые слова: гироскопическое ориентирование, гирокомпас, разработки, «полярный» возмущающий момент синхронного гистерезисного гиродвигателя, уход гироскопа со сферической опорой, высокотехнологичные приборы.

Introduction. The first gyrocompasses were patented in Germany and the USA in 1911. Their work is based on the principle of a spinning top: the axis of a rotating top at high speeds necessarily takes a vertical position. Today, a gyroscope is the most complicated digital device that allows the gyroscopic orientation of mine workings with the highest accuracy (Szafarczyk A. et al, 2017:77).

Also, such a connecting survey should ensure the orientation of the reference surveying network concerning the geodetic network on the ground; to ensure the alignment of the mine surveying network by accurately establishing the coordinates of a series of points in the coordinate system acting on the surface. The transfer of elevations from the ground to mine workings is another purpose of connecting surveying (Grobler H., 2015).

Before starting the gyroscopic orientation of mine workings, it is necessary to determine the “local” correction of the gyrocompass itself. With this definition, the gyroscopic azimuth of the side with a certain directional angle is specified. When the gyroscopic orientation of mine workings is performed constantly at new points, the corrections are calculated twice before it descends into the mine, and once after the work is completed (PMG Katowice, 2007).

When performing subsequent work, after each stage, a control determination is done. The correction is calculated from the last 4 measurements as arithmetic mean.

In this connection, the gyroscopic orientation of mine workings, the main task of which is the transfer of coordinates from the earth’s surface to underground horizons, is the work of the highest level of responsibility, which is performed during tunneling of:

- various tunnels;
- subway lines;
- mines (Zhen S, et al, 2013:85).

Advantages

The possibility to perform the assigned tasks regardless of the time of day, the depth of tunneling, at an arbitrary distance from the shaft - quite reasonably brings the gyroscopic orientation to the leading positions among other methods. At the same time, there is no need to stop all work at the site, which is necessary when using other survey methods.

Let us study the influence of the harmonic components of the moments on the drift of a gyroscope from a central spherical support. The disturbing moment of the electric motor contains several harmonic components (Tulegulov A.D. et al, 2021:149). In particular, imperfections in a synchronous motor cause angular vibrations of the rotor. The frequency of these perturbations is a multiple of the frequency of rotation of the stator magnetic field relative to the rotor (Vesela M. et al, 2016:98), the phases are determined by the phase of the rotating magnetic field of the motor.

Disturbing equatorial moments due to geometric defects of the supports have a spectrum of frequencies that are multiples of the rotor speed.

The main sources of forced “equatorial” oscillations of the rotor axis of gyroscopes are the dynamic unbalance of the rotor, “internal” disturbing moments, determined by technological imperfections in the manufacture of the rotor support units (Sammarco J., 2012:1127). In the case of a dynamically unbalanced gyroscope, the axis of dynamic symmetry of the rotor passes through the center of the suspension, but does not coincide with the axis of its rotation due to imperfections in the manufacturing technology of the rotor and assembling the elements of the gyroengine (Golovanov V.A., 2004).

Materials and methods. Let us compose the equations of motion of a ball gyroscope, caused by the influence of harmonic disturbing moments of the magnetic field of the engine, which allow us to analyze the motion of the rotor and identify the reasons for the drift (Hendrik C. I., 2016:108).

In the equation of motion, we will take into account only the “polar” disturbing moment of the synchronous hysteresis gyro motor. Due to technological imperfections in the manufacture of bearing supports, which contain a wide range of frequencies, disturbing moments are neglected.

Let us consider the case when the gyroscope rotor is dynamically unbalanced. Assume that all axes of the right orthogonal trihedron intersect at one point. When analyzing the kinematics of the gyroscope, we use the following coordinate systems: $O\xi$ - right orthogonal trihedron associated with inertial space; $Oy, O\eta$ - intermediate right orthogonal trihedrons; Oz, Ox - right orthogonal trihedrons associated with the rotor. The axis Oz_3 at zero readings of the sensors of the angular position of the rotor coincides with the axis of rotation of the magnetic field of the stator of the synchronous motor. Let us assume that the trihedron Ox coincides with the main central axes of inertia of the rotor and let Ox_3 be the axis of dynamic symmetry of the rotor. Except for imperfections. All coordinate systems are the same (Anderson, E. G., 2010).

Trihedrons $O\eta, Oy, Oz, Ox$ are obtained from a trihedron $O\xi$ by successive turns by angles $\Gamma_1, \Gamma_2, \Gamma_3$, ε around axes $O\xi_1, O\eta_2, Oy_3$ and Oz_1, respectively:

$$O\xi_1\xi_2\xi_3 \frac{\Gamma_1}{O\xi_1} \to O\eta_1\eta_2\eta_3 \frac{\Gamma_2}{O\eta_2} \to Oy_1y_2y_3 \frac{\Gamma_3}{Oy_3} \to Oz_1z_2z_3 \frac{\varepsilon}{Oz_1} \to Ox_1x_2x_3, \quad (1)$$

i.e. as a product of matrices $S^*_{\varepsilon 321} = S^*_{\varepsilon} S^*_3 S^*_2 S^*_1$.

Here $\Gamma_1, \Gamma_2, \varepsilon$ - small angles of rotation; $S^*_1, S^*_2, S^*_3, S^*_{\varepsilon}$ - coordinate system rotation matrices. The value of the angle ε determined between the axes of proper rotation and dynamic symmetry in modern gyroscopic instruments is small.

Denote through $\Omega_{1x}, \Omega_{2x}, \Omega_{3x}$ projections of the absolute angular velocity of the rotor on the axis of the trihedron Ox.

Using sequences (1), we can determine the projections of the absolute angular velocity of the rotor on the axes of the coordinate system $Ox_1x_2x_3$. Let us assume that the angular velocity of the rotor $\dot{\Gamma}_3$ differs from the constant value of the angular velocity of rotation of the stator magnetic field Ω_0 by a small value θ,. θ - is called the synchronization angle, i.e. this is the angle of rotation of the rotor relative to the magnetic field of the stator.

Let us write the absolute angular velocity of the rotor in projections on the axis of the trihedron x, associated with the axes of dynamic symmetry of the rotor

$$\begin{bmatrix}\Omega_{1x}\\ \Omega_{2x}\\ \Omega_{3x}\end{bmatrix} = S^*_{\varepsilon} S^*_3 S^*_2 S^*_1 \begin{bmatrix}\Omega_{1\xi}\\ \Omega_{2\xi}\\ \Omega_{3\xi}\end{bmatrix} + S^*_{\varepsilon} S^*_3 S^*_2 \begin{bmatrix}\dot{\Gamma}_1\\ 0\\ 0\end{bmatrix} + S^*_{\varepsilon} S^*_3 \begin{bmatrix}0\\ \dot{\Gamma}_2\\ 0\end{bmatrix} + S^*_{\varepsilon} \begin{bmatrix}0\\ 0\\ \dot{\Gamma}_3\end{bmatrix}. \quad (2)$$

Here $\Omega_{1\xi}, \Omega_{2\xi}, \Omega_{3\xi}$ - base angular velocity projections, $\dot{\Gamma}_3 = \Omega_c + \dot{\theta}$ - rotor angular velocity.

In the expansions of the nonlinear angular velocity of the rotor in projections onto the axis of the trihedron x, we keep the linear terms and nonlinear terms of the second order of smallness in $\Gamma_1, \dot{\Gamma}_1, \Gamma_2, \dot{\Gamma}_2$, and θ, $\dot{\theta}$. We assume that the gyroscope is mounted on a fixed base. Then the angular velocity will take the form

$$\Omega_{1x} = \dot{\Gamma}_1 \cos\Gamma_3 + \dot{\Gamma}_2 \sin\Gamma_3, \quad \Omega_{2x} = \dot{\Gamma}_3\varepsilon + \dot{\Gamma}_2 \cos\Gamma_3 - \dot{\Gamma}_1 \sin\Gamma_3,$$
$$\Omega_{3x} = \left(\dot{\Gamma}_1 \sin\Gamma_3 - \dot{\Gamma}_2 \cos\Gamma_3\right)\varepsilon + \dot{\Gamma}_1\Gamma_2 + \dot{\Gamma}_3. \quad (3)$$

When compiling the equations of motion, we use the coordinate systems and kinematic relations given above.

We introduce additional notation: $M^*_{1\xi}, M^*_{2\xi}, M^*_{3\xi}$ - projections of the moment applied to the rotor on the axis of the trihedron ξ; A, B, C - main central moments of inertia of the rotor directed along the equatorial and polar axes; H_{1x}, H_{2x}, H_{3x} и $H_{1\xi}, H_{2\xi}, H_{3\xi}$ - projections of the angular momentum vector $\mathbf{H}^*$ on the axis of trihedrons x and ξ, respectively.

Since the main cause of the gyroscope error is the “polar” disturbing moment, this moment M can be represented as a vector sum of the components directed along the axes of the right orthogonal trihedrons $O\xi,\ Oz, Ox$:

$$\mathbf{M}^* = M^*_\xi\mathbf{i} + M^*_z\mathbf{j} + M^*_x\mathbf{e}, \qquad (4)$$

and we believe that $M^*_{1\xi}, M^*_{2\xi}$ «$M^*_{3\xi}$; M^*_{1z}, M^*_{2z} «M^*_{3z}; M^*_{1x}, M^*_{2x} «M^*_{3x}.

In the future, we will consider the components of the disturbing moment $\mathbf{M}^*$ of the electric motor, represented as sums of harmonic terms with frequencies that are multiples of the frequency of rotation of the stator magnetic field Ω_c, and phases Q_l, determined by the phase of the rotating magnetic field:

$$\mathbf{M}^* = \sum_{l=1}^{\infty} \mathbf{M}^*_l \cos(l\Omega_c T + Q_l), \qquad (5)$$

Where, $\mathbf{M}^*_l = -V\mathbf{I}\times\mathbf{H}^* \sin\theta^0$; $H^*,\ Q_l$ - intensity amplitude and phase of the 1st harmonic component; I – permanent magnetization vector; V - volume of the active part of the rotor.

Projections of the angular momentum vector H^*_ξ, H^*_x are connected as follows:

$$\left\|\begin{matrix} H^*_{1\xi} \\ H^*_{2\xi} \\ H^*_{3\xi} \end{matrix}\right\| = E_{\xi x} \left\|\begin{matrix} H^*_{1x} \\ H^*_{2x} \\ H^*_{3x} \end{matrix}\right\|, \qquad (6)$$

$E_{\xi x}$ - transformation matrix, which, when taking into account terms of the second order of smallness for $\Gamma_1, \dot{\Gamma}_1, \Gamma_2, \dot{\Gamma}_2, \varepsilon$ and θ, $\dot{\theta}$ appears as follows:

$$\left\|\begin{array}{ccc} \cos\Gamma_3 & (-\sin\Gamma_3 + \Gamma_2\varepsilon) & (\varepsilon\sin\Gamma_3 + \Gamma_2) \\ (\Gamma_1\Gamma_2\cos\Gamma_3 + \sin\Gamma_3) & (-\Gamma_1\Gamma_2\sin\Gamma_3 + \cos\Gamma_3 - \Gamma_1\varepsilon) & (-\varepsilon\cos\Gamma_3 - \Gamma_1) \\ (-\Gamma_2\cos\Gamma_3 + \Gamma_1\sin\Gamma_3) & (\Gamma_2\sin\Gamma_3 + \Gamma_1\cos\Gamma_3 + \varepsilon) & (-\Gamma_2\,\varepsilon\sin\Gamma_3 - \Gamma_1\varepsilon\cos\Gamma_3 + \Gamma_4) \end{array}\right.$$

where $H_{1x}^* = A\Omega_{1x}, H_{2x}^* = B\Omega_{2x}, H_{3x}^* = C\Omega_{3x}$ - projections of the vector $\boldsymbol{H}^*$ on the axis of dynamic symmetry of the rotor, $\Gamma_4 = 1 - (\varepsilon^2 + \Gamma_1^2 + \Gamma_2^2)/2$.

Using the theorem on the change in angular momentum, we write the equations of motion of the rotor in projections on the axes of the trihedron $O\xi_1\xi_2\xi_3$:

$$\dot{H}_{n\xi}^* = M_{n\xi}^*, n = 1,2,3. \tag{7}$$

The reason for the occurrence of moments $M_{n\xi}^*$ on the right side of equation (7) is the “polar” disturbing moment of the electric motor.

If we substitute the values of the projection of the angular velocity of the rotor on the axis of dynamic symmetry into the equations of motion, then in expanded form the system of equations of motion (7) has the form:

$$d/dT\{A[\dot{\Gamma}_1 cos^2\Gamma_3 + \dot{\Gamma}_2 sin2\Gamma_3/2] + B[-\varepsilon\dot{\Gamma}_3 \sin\Gamma_3 - \dot{\Gamma}_2 sin2\Gamma_3/2 + \dot{\Gamma}_1 sin^2\Gamma_3] + C[\varepsilon\dot{\Gamma}_3 \sin\Gamma_3 + \Gamma_2\dot{\Gamma}_3]\} = M_{1\xi},$$

$$d/dT\{A[\dot{\Gamma}_1 sin2\Gamma_3/2 + \dot{\Gamma}_2 sin^2\Gamma_3] + B[\varepsilon\dot{\Gamma}_3 \cos\Gamma_3 + \dot{\Gamma}_2 cos^2\Gamma_3 - \dot{\Gamma}_1 sin2\Gamma_3/2] + C[-\varepsilon\dot{\Gamma}_3 \cos\Gamma_3 - \Gamma_1\dot{\Gamma}_3]\} = M_{2\xi},$$

$$d/dT\{A[-\dot{\Gamma}_1\Gamma_2 cos^2\Gamma_3 + \dot{\Gamma}_1\Gamma_1 sin2\Gamma_3/2 - \Gamma_2\dot{\Gamma}_2 sin2\Gamma_3] + B[\varepsilon\Gamma_2\dot{\Gamma}_3 \sin\Gamma_3 + \varepsilon\Gamma_1\dot{\Gamma}_3 \cos\Gamma_3 + \varepsilon^2\dot{\Gamma}_3 + \Gamma_2\dot{\Gamma}_2 sin2\Gamma_3/2 + \Gamma_1\dot{\Gamma}_2 cos^2\Gamma_3 + \varepsilon\dot{\Gamma}_2 \cos\Gamma_3 - \dot{\Gamma}_1\Gamma_2 sin^2\Gamma_3 - \dot{\Gamma}_1\Gamma_1 sin2\Gamma_3/2 - \varepsilon\dot{\Gamma}_1 sin\Gamma_3] + C[\varepsilon\dot{\Gamma}_1 \sin\Gamma_3 - \varepsilon\dot{\Gamma}_2 cos\,\Gamma_3 + \dot{\Gamma}_1\Gamma_2 - \varepsilon\Gamma_2\dot{\Gamma}_3 sin\,\Gamma_3 - \varepsilon\Gamma_1\dot{\Gamma}_3 cos\,\Gamma_3 + \dot{\Gamma}_3 \cos\Gamma_1 \cos\Gamma_2 \cos\varepsilon]\} = M_{3\xi}. \tag{8}$$

After substituting (3)-(6) into (8), we bring the equations of motion of the rotor (8) to a dimensionless form, having normalized the variables included in it:

$$\Gamma_1 = \Gamma_*\gamma_1^*, \Gamma_2 = \Gamma_*\gamma_2^*, \theta = \Gamma_*\theta, \Omega_{1x} = \Omega_*\omega_{1x}, \Omega_{2x} = \Omega_*\omega_{2x}, \Omega_{3x} = \Omega_{3*}\omega_{3x}, A = C_*a, B = C_*b, C = C_*c, H_{1\xi}^* = H_{\xi*}h_{1\xi}, H_{2\xi}^* = H_{\xi*}h_{2\xi}, H_{3\xi}^* = H_*h_{3\xi}, M_{n\xi} = M_*m_{n\xi}\ (n = 1,2,3), T = T_*t,\ M_{3x} = M_*m_{3x}. \tag{9}$$

The characteristic values of the variables will be chosen as follows

$$T_* = \frac{1}{\Omega_c}, \Omega_* = \Gamma_*\Omega_c, \Omega_{3*} = \Omega_c, C_* = C, H_* = H^* = C_*\Omega_{3*},$$

$$H_{\xi*} = \varepsilon H_*, M_* = H^*\,\Omega_*. \tag{10}$$

Results. The amplitudes of the angular variables $\Gamma_1, \Gamma_2, \theta$, by virtue of the very purpose of the gyroscopic system, are values of the order of a few fractions of a minute of arc. Therefore, we choose $\Gamma_* = \varepsilon$. We choose the characteristic values of the remaining variables in such a way that their dimensionless values do not exceed values of the order of unity.

Let us assume that the difference between the equatorial moments of inertia of the rotor is small: a-b= εe, where e is a dimensionless value of the order of unity.

Taking into account the normalization of variables (9) and characteristic values (10), we write equations (8) in the normalized form

$$d/dt\{a\dot{\gamma}_1 - \varepsilon e\dot{\gamma}_1 sin^2(t+\varepsilon\gamma_3) + 0.5\varepsilon e\dot{\gamma}_2 sin2(t+\varepsilon\gamma_3) + \varepsilon\dot{\gamma}_3(c - a)sin(t+\varepsilon\gamma_3) + c\gamma_2 + c\varepsilon\gamma_2\dot{\gamma}_3 - (a-\varepsilon e)sin(t+\varepsilon\gamma_3) + csin(t+\varepsilon\gamma_3)\} = m_{1\xi},$$

$$d/dt\{1/2\varepsilon e\dot{\gamma}_1 sin2(t+\varepsilon\gamma_3) + a\dot{\gamma}_2 - \varepsilon e\dot{\gamma}_2 cos^2(t+\varepsilon\gamma_3) + \varepsilon\dot{\gamma}_3(a - c)cos(t+\varepsilon\gamma_3) - c\gamma_1 - c\varepsilon\gamma_1\dot{\gamma}_3 + (a-\varepsilon e)cos(t+\varepsilon\gamma_3) - csin(t+\varepsilon\gamma_3)\} = m_{2\xi},$$

$$d/dt\{\varepsilon\dot{\gamma}_1(c-a)sin(t+\varepsilon\gamma_3) + \varepsilon\dot{\gamma}_2(a-c)cos(t+\varepsilon\gamma_3) + c\dot{\gamma}_3 + \varepsilon\gamma_1(a-c)cos(t+\varepsilon\gamma_3) + \varepsilon\gamma_2(a-c)sin(t+\varepsilon\gamma_3) - c\varepsilon\gamma_1^2 - c\varepsilon\gamma_2^2 - \dot{\gamma}_1\gamma_2(a-c)\varepsilon + a\varepsilon\gamma_1\dot{\gamma}_2\} = m_{3\xi}. \qquad (11)$$

The solution of equations (11) containing the small parameter ε will be sought in the form of an expansion in powers of the small parameter:

$$\gamma_n^* = \gamma_n^{(0)} + \varepsilon\gamma_n^{(0)} + \cdots, n = 1,2,3. \qquad (12)$$

A finite number of expansions (12) on a limited time gives an asymptotic approximation for the solution of the original system.

In the normalized form, the perturbing moment vector is represented as:

$$m_{1\xi}^0, m_{2\xi}^0 \text{ «} m_{3\xi}^0;\ m_{1z}^0, m_{2z}^0 \text{ «} m_{3z}^0;\ m_{1x}^0, m_{2x}^0 \text{ «} m_{3x}^0. \qquad (13)$$

In equation (11), we reduce the common factor ε and equating the terms at the zero degree of ε, we write the zero approximation equations

$$a\ddot{\gamma}_1^{(0)} + \dot{\gamma}_2^{(0)} = (a-1)cost,$$

$$a\ddot{\gamma}_2^{(0)} + \dot{\gamma}_1^{(0)} = (a-1)sint, \qquad (14)$$

and equating in (11) the terms at the first power of ε, we obtain the equations of the first approximation

$$a\ddot{\gamma}_1^{(1)} + \dot{\gamma}_2^{(1)} = -d/dt\left\{e\left[0.5\dot{\gamma}_2^{(0)} sin2t - \dot{\gamma}_1^{(0)} sin^2 t + sint\right] - (a - 1)\left(\dot{\theta}^{(0)} sint + \theta^{(0)} cost\right) + \gamma_2^{(0)}\dot{\theta}^{(0)}\right\} + m_{1\xi}^{(1)},$$

$$a\ddot{\gamma}_2^{(1)} - \dot{\gamma}_1^{(1)} = -d/dt\left\{e\left[0.5\dot{\gamma}_1^{(0)} sin2t - \dot{\gamma}_2^{(0)} cos^2 t - cost\right] + (a - 1)\left(\dot{\theta}^{(0)} cost - \theta^{(0)} sint\right) - \gamma_1^{(0)}\dot{\theta}^{(0)}\right\} + m_{2\xi}^{(1)},$$

$$\begin{aligned}\ddot{\theta}^{(1)} = -d/dt\Big\{(a-1)\Big[\Big(\gamma_2^{(0)} - \dot{\gamma}_1^{(0)}\Big) sint + \Big(\dot{\gamma}_2^{(0)} + \gamma_1^{(0)}\Big) cost - \\ \dot{\gamma}_1^{(0)}\gamma_2^{(0)}\Big] - \Big[\Big(\gamma_1^{(0)}\Big)^2 + \Big(\gamma_2^{(0)}\Big)^2\Big] + a\gamma_1^{(0)}\dot{\gamma}_2^{(0)}\Big\} + m_{3\xi}^{(1)} \qquad (15)\end{aligned}$$

where, $m_{1\xi}^{(1)} = m_{3z}^{(0)}\gamma_2^{(0)}, m_{2\xi}^{(1)} = -m_{3z}^{(0)}\gamma_1^{(0)}, m_{3\xi}^{(1)} = m_3^{(1)}$, since the projections of the moment $m_{3\xi}\boldsymbol{e}_{3\xi}$ on axes $O\xi_1, O\xi_2$ are equal to zero, and with the projection of the moment $m_{3x}\boldsymbol{e}_{3x}$ on axes $O\xi_1, O\xi_2$, coefficients in front of them vanish.

The solution of the equations of motion of the zero approximation (14) have the form:

$$\gamma_1^{(0)} = -cost, \qquad (16)$$

$$\gamma_2^{(0)} = -sint,$$

$$\theta^{(0)} = \textstyle\sum_{l=1}^{\infty} (m_l/l^2) cos(lt + Q_l).$$

In the first approximation equation (1.15), the linear and quadratic terms of the variables $\gamma_1^{(0)}, \gamma_2^{(0)}, \theta^{(0)}$ are already known. The constant components of these terms determine a particular solution of system (11) of the form $\dot{\gamma}_1^{(1)}, \dot{\gamma}_2^{(1)}$.

Let us calculate the explicit expressions $\dot{\gamma}_1^{(1)} and\ \dot{\gamma}_2^{(1)}$ in terms of the gyroscope and perturbation parameters. In addition, below we will take into account only the first harmonics of the perturbation $m_3^{(0)}$.

Substituting (16) into (15) and averaging the expressions over time t, we determine the departure of the ball gyroscope:

$$\langle\dot{\gamma}_1^{(1)}\rangle = -(m_{1z}cosQ_1)/2, \langle\dot{\gamma}_2^{(1)}\rangle = (m_{1z}sinQ_1)/2 \qquad (17)$$

The drift occurs when the dynamic unbalance of the rotor interacts with the first harmonic component of the “polar” magnetic moment. The drift does not depend on the small dynamic asymmetry of the rotor (Benecke, et al, 2006).

It was noted in (Caspary, et al, 2013; Mine Health and Safety Act No 29 of 1996 Government Gazette, 2011) that the drifts of a gyroscope with a hysteresis-type gyro-motor change from start to start or during short-term power failures. Assumptions are made about the connection of this phenomenon with a change in the phase angle of the rotating magnetic field of the stator relative to the rotor.

The drift can be explained by the quadratic interaction of two types of angular vibrations of the rotor, arising from the imperfection of the support nodes and the electric motor (Williams, H. S., 2015).

The constant components of the gyroscope escape velocities depend harmonically on the phase angle of the rotating magnetic field of the stator relative to the rotor, which is consistent with the results of works [5, 6, 7], in which other types of devices were considered.

Passing in (17) to the non-normalized form, we obtain

$$\langle \dot{\Gamma}_1 \rangle = -\left(\frac{M_{1z}}{(2H)}\right) \varepsilon cos Q_1 = -7.1 \times 10^{-4} \varepsilon cos Q_1 \ (\text{c}^{-1}), \langle \dot{\Gamma}_2 \rangle =$$

$$7.1 \times 10^{-4} \varepsilon sin Q_1 \ (\text{c}^{-1}) \qquad (18)$$

When estimating the numerical values of the drift of a gyroscope with a central spherical pore, the following characteristics were used (Young, E. M., 2009):

$$M_{1z} = 9.81 \times 10^{-5} \ (\text{кгм}^2\text{с}^{-2}), H = 0.069 \ (\text{кгм}^2\text{с}^{-1}). \qquad (19)$$

Discussion. In the general case, the torque depends both on the angle of rotation of the rotor relative to the magnetic field of the stator, and on the angular velocity of this rotation.

Along with the disturbing moment (5), we take into account the synchronous $K_c\theta$ and asynchronous $N_0\dot{\theta}$ components of the moment of electromagnetic forces acting along the rotor axis, where K_c is the steepness of the torque characteristic of the synchronous drive, N_0 is the damping coefficient. Having additionally normalized the values: $N_0 = N_* \, n_0, \ K_c = K_* k_c$, we choose the characteristic values of these variables as follows: $K_* = C_* \Omega_\text{c}^2, N_* = \varepsilon_1 C_* \Omega_\text{c}$, where $\varepsilon_1 = \varepsilon^{1/2}$. The third equation of system (15) can now be written in a dimensionless form as follows

$$\theta^{(0)} = m_3^0, \text{где}\, m_3^0 = \textstyle\sum_{l=1}^{\infty} m_l \, cos(lt + Q_l) - n_0 \dot{\theta}^{(0)} - k_c \theta^{(0)}, \qquad (20)$$

where k_c - natural frequency of small oscillations of the rotor relative to the magnetic field of the stator.

We give the solution of equations (15) in the form:

$$\theta^{(0)} = de_0^{-(n/2)t} sin\left(\sqrt{k_c - n_0^2 t/4} + \delta\right) + \textstyle\sum_{l=1}^{\infty} (k_c - l^2) \, m_l \, cos(lt + Q_l) /$$

$$[(k_c - l^2) + n_0^2 l^2] + \textstyle\sum_{l=1}^{\infty} n_0 l m_l \, sin(lt + Q_l) / [(k_c - l^2) + n_0^2 l^2], \qquad (21)$$

Where, d_0, d_1 – constants of integration determined from the initial conditions. At $l = 1$, substituting (21) into (15) and averaging over *t*, we determine from the first two equations (15) the constant components of the drift:

$$\langle \dot{\gamma}_1^{(1)} \rangle = l\{[-(k_c + 1) n_0 sin Q_1]/2 + (3k_c - 2k_c^2 - 2n_0^2 - 1) cos Q_1\}, \qquad (22)$$

$$\langle \dot{\gamma}_2^{(1)} \rangle = l\{(1-k_c)sinQ_1 + [(k_c+1)n_0 cosQ_1]/2\},$$

where $l = m_{1z}/\{2[(k_c-1)^2 + n_0^2]\}$.

We write (22) in dimensional quantities:

$$\begin{aligned} \langle \dot{\Gamma}_2 \rangle &= D\{(1-I_1)\varepsilon sinQ_1 + [(I_1+1)I_2 \varepsilon cosQ_1]/2\} \\ \langle \dot{\Gamma}_1 \rangle &= D\{-[(I_1+1)I_2 \varepsilon sinQ_1]/2 + [3I_1 - 2(I_1)^2 - \\ &\quad - 2(I_2)^2 - 1]\varepsilon cosQ_1\}, \end{aligned} \tag{23}$$

Where, $D = M_{1z}/\{2H[(I_1-1)^2 + (I_2)^2]\}$; $I_1 = \lambda^2/\Omega_c^2$; $I_2 = I_3/\varepsilon_1$; $I_3 = N_0/H$; $\lambda^2 = K_c/C$ - natural frequency of small oscillations of the rotor relative to the magnetic field of the stator in dimensional form.

The steepness of the torque characteristic of a synchronous drive K_c is defined as $K_c = I\ H_0^{\infty} cos\theta^{(0)}$. Here H_0^{∞} - constant term of the stator magnetic field strength, $\theta^{(0)}$ - initial timing angle.

The values N and λ vary from 10^{-8} to 10^{-3} (Nms) [6] and 0.05…0.1 [7] or 10…20 (hertz) [6], respectively. Taking into account (18) and taking $\Omega_c = 5.0{\times}10^3$ (c^{-1}), $\lambda^2 = 1.6{\times}10^4$ (c^{-2}) (20hz), $N_0/H = 1.4{\times}10^{-2}$, we determine the drift (23)

$$\langle \dot{\Gamma}_1 \rangle = -10^{-4}(0.02\varepsilon sinQ_1 + \varepsilon cosQ_1)\ (c^{-1}),$$

$$\langle \dot{\Gamma}_2 \rangle = 10^{-6}(0.3\varepsilon sinQ_1 + 2\varepsilon cosQ_1)\ (c^{-1}). \tag{24}$$

The expressions for the drift angular velocities (18) and (24) of a spherical gyroscope with a dynamically unbalanced rotor contain a dimensionless small parameter ε, which determines the angle between the axis of proper rotation and the dynamic symmetry of the rotor. These two axes do not coincide due to imperfections in the manufacturing technology of the rotor and the assembly of the gyroscope elements. The value of the constant angle ε in modern gyroscopic devices is small. It is about $10^{-4}{\div}10^{-5}$. Substituting the value $\varepsilon = 10^{-5}$ into the expression for the departure (18) of the ball gyroscope, which depends on the first harmonic component of the disturbing moment of the electric motor and the phase angle Q1 of the first harmonic of the disturbing moment, we obtain:

$$\langle \dot{\Gamma}_1 \rangle = -7.1{\times}10^{-9} cosQ_1\ (c^{-1}),$$

$$\langle \dot{\Gamma}_2 \rangle = 7.1{\times}10^{-9} sinQ_1\ (c^{-1}). \tag{25}$$

In (Golovanov, 2004), the angular velocity of the gyroscope drift in a gimbal suspension with a dynamically unbalanced rotor with a fixed base was obtained. The moments relative to the axes of the outer and inner rings and the rotor are considered to be equal to zero. At values of angular velocity, unbalance, polar and equatorial moments of inertia of the rotor, respectively, equal to 3045.8 (c-1), 10-5, $0.324 x 10^{-3}$(kgm^2), $0.196 x 10^{-3}$(kgm^2), The drift is -10^{-6} (c^{-1}).

In the same place, the angular velocity of the gyroscope drift was obtained without taking into account the influence of the perturbing moment of the electric motor.

If in the expression of the angular velocity of drift of such a gyroscope, obtained in (Tulegulov, 2021), with a dynamically unbalanced rotor with a fixed base, the influence of the disturbing moment of the electric motor is not taken into account, then the drift expression exactly coincides with the drift obtained in (Sammarco, 2012) and the drift is -8×10^{-9} (c^{-1}). In this case, the angular velocity, unbalance, polar and equatorial moments of inertia have, respectively, the following values 2500 (c^{-1}), 10^{-5}, 0.03924×10^{-3} (kgm^2), 0.02943×10^{-3} (kgm^2).

Conclusions: The drift obtained in (Tulegulov, 2021) for an integrating float gyroscope with an unbalanced rotor depends on the first harmonic component of the disturbing moment of the electric motor and the phase angle Q_1 of the first harmonic of this moment and is $5\times10^{-11}\sin(Q_1+\Psi)$ (c^{-1}). Here Ψ depends on the coefficient of viscous friction.

Dynamic reactions due to errors in the supports are detected during the assembly process and are partially eliminated by dynamic balancing.

Abroad, there are models of balancing machines specially adapted for balancing small rotors and equipped with installations for calibrated drilling.

In a Dekker type 211 semiautomatic balancing machine (USA), in which the drilling head is mounted directly based on the balancing machine, it is possible to dynamically balance the rotors of gyro motors with a mass of 160–600 (g) with an accuracy of 0.3 (μm) in terms of the displacement of the center of mass (Hendrik, 2016).

In this section, equations of motion are compiled in the form of equations of kinetic moments for the rotor in projections on the axis of a fixed trihedron connected to the gyroscope stator. The moment created by the hysteresis type electric motor along its own axis is not constant, it depends on the dynamic unbalance of the rotor and the imperfection of the motor supply. For the ball gyroscope, it is shown that the interaction of the rotor imbalance and the first harmonic component of the disturbing motor torque is the cause of the drift, which depends on the phase angle of the rotating magnetic field of the electric motor. The perturbation frequency is a multiple of the rotor rotation frequency. The influence of the synchronous and asynchronous components of the moment

of electromagnetic forces on the dynamics of the gyroscope is also considered. It can be seen from the drift expressions that the drift value averaged over the phase angle θ of the rotating magnetic field of the stator can turn to zero, which coincides with the recommendations proposed by previous authors. Quantitative estimations of ball gyroscope errors are given.

Information about the authors

Tulegulov Amandos Dabysovich – Candidate of Physical and Mathematical Sciences, Associate Professor of the Department of Electronics and Robotics, Almaty University of Energy and Communications named after G. Daukeev, Kazakhstan. Tel. +77014674565, e-mail: *tad62@ya.ru*, https://orcid.org/0000-0002-1195-6919;

Yergalieyv Dastan Syrymovich – Candidate of Technical Sciences, Professor of the Department of Aviation Engineering and Technology, Academy of Civil Aviation, Kazakhstan. Tel. +77017495854, e-mail: *DES-67@yandex.kz*, https://orcid.org/0000-0003-4197-9211;

Karipbayev Saliakyn Zhumadilovich – Candidate of Technical Sciences, Associate Professor of the Department of Aviation Engineering and Technology, Academy of Civil Aviation, Kazakhstan. Tel. +77016236350. e-mail: *Kczh.1957@mail.ru*, https://orcid.org/0000-0003-1107-2571;

Bazhaev Nurlan Amankulovich – PhD, Associate Professor of the Department of Aviation Engineering and Technology of the Academy of Civil Aviation, Kazakhstan. Tel. +77757772791. e-mail: *Bazhaev_na@mail.ru, https://orcid.org/0000-0001-8601-0688;*

Zuev Dmitriy Vyacheslavovich – Master of science, lecturer of the Department of Aviation Engineering and Technology, Academy of Civil Aviation, Kazakhstan, tel.: +77473942273, e-mail: *zuex93@gmail.com*;

Adilkhanov Yerzhan Gazizovich – PhD, Head of the Methodology Department, Academy of Civil Aviation, Kazakhstan, tel. +77712911025, email: *adilkhanov.e.g@gmail.com*, https://orcid.org/0000-0001-6454-1090.

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