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SECONDARY INFORMATION PROCESSING METHODS WHILE ESTIMATING THE SPATIAL ORIENTATION OF OBJECTS

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ABSTRACT

The study is devoted to solving the scientific problem of ensuring unbiasedness and increasing the efficiency of assessing the spatial orientation of objects by applying new methods of secondary information processing in software and hardware components of computer systems. The paper describes a developed method for compensating for magnetic anomalies that affect magnetically sensitive sensors of the inclinometer rotation angles. It is based on recording the inclinometer readings and the angle of rotation of the drill pipe as it rotates in the mouth of well in a range of 360 degrees. This makes it possible to determine and further take into account the value of the magnetic deviation from the drill string in the readings of the inclinometer. A method is described for determining the parameters of a magnetic anomaly from an external stationary source of a constant magnetic field by using redundant information from the readings of inclinometery transducers in the mouth of well and at the point of assessment. This allows to expand the boundaries and scope of magnetometric transducers in difficult conditions. Methods for calculating the desired azimuth, as well as the parameters of the intensity vector of the magnetic anomaly are proposed. The errors of inclinometers based on sensor devices of various physical nature (fluxgates, gyroscopes, accelerometers), both rigidly fixed and with the use of gimbals pendulum suspensions, are considered. The factors influencing the bias of the estimation of the angles of the spatial orientation of the drilling tool, expressed through the Euler angles, are analyzed. The analysis took into account the effect of various reasons: deviations of the transducers' sensitivity axes from mutual orthogonality and the reference trihedron of the axes associated with the body; changes in the zero signal and transfer ratios under the influence of temperature; non-identical electrical parameters; inaccurate installation of the pendulum gimbal sensor frames in the tilt plane and along the vertical of the place. The permissible boundary values of each of the given errors have been determined. Consideration of these errors can significantly increase the unbiasedness of the assessment of the position of the object in difficult conditions. The practical significance of the results presented in the paper is the development of software and hardware components for assessing the spatial orientation of objects on the basis of the designed inclinometers capable of operating in difficult operating conditions and having a small diameter of the protective casing. Similar software and hardware components for assessing the spatial orientation of objects can be used: for the construction of underground communications; for the assembly of large-sized and remote objects; for static sounding of soils; for monitoring the state of building structure elements during operation.

Keywords: spatial orientation; magnetic anomalies; orientation sensor; inclinometer; azimuth; zenith angle; deflector installation angle; bias in the assessment of orientation; mathematical model

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INTRODUCTION

Nowadays computerized systems are widely used in practice, in which it is necessary to assess the parameters of the spatial orientation of objects. Examples of such systems are computer systems (CS) for controlling a drill string during geoprospecting, seismic hazard forecasting systems, monitoring the state of buildings and structures during operation, diagnostic systems in nuclear power, etc. [1-8].

When carrying out geological prospecting, construction of deep and super-deep wells (several kilometers deep) and cluster drilling methods are used, when a whole cluster of wells (tens and hundreds) is built from one mouth. This is necessary for conditions of limited territorial opportunities (due to the landscape, buildings, sea shelves, etc.). In this case, increasing the accuracy of monitoring the well's path allows not only to conduct better exploration but also to increase the oil and gas production of the field by several times [9-12].

When monitoring the state of building structures of critical systems (nuclear power plants, state district power plants, hydroelectric power plants, oil pipelines, high-rise buildings, etc.), it is necessary to control the orientation of the structure elements during operation with the maximum possible accuracy [8].

All these processes are associated with special operating conditions (vibrations, magnetic anomalies, remoteness, temperature, etc.)

Therefore, the development of computer systems and methods for processing measurement information is an urgent scientific and industrial task.

LITERATURE REVIEW

The analysis of known sources shows that the assessment of the spatial orientation in the above cases is carried out, as a rule, by the hardware and software components for the assessment of spatial orientation (HSCASO), which are included in specialized computer systems and intended for primary (obtaining the measurement information) and secondary (measurement information processing) data handling [13-17].

At the same time, the accuracy of the orientation assessment largely determines the efficiency of the en-tire system. So, for example, increasing the azimuth measurement accuracy by only two times makes it possible to triple the number of wells in one "cluster" and increase oil recovery by 1.2 ... 1.5 times [9-12; 14].

The most universal, from a scientific point of view, is the technological process of construction of deep wells, since HSCASO, in this case, operate in difficult conditions, characterized by the presence of vibration and magnetic anomalies, temperature instability, etc., with severe restrictions on the size of sensor devices (SDs), which leads to a bias in the assessment of orientation [12; 15-20]. That is, considering this technological process, we can simulate the whole complex of harmful factors that affect the assessment bias in spatial orientation. In the absence of this or that factor in a particular case, it is enough not to take this parameter into account at the stage of secondary information processing.

It is known from the literature that modern inclinometric complexes, including such SDs as accelerometers, gyroscopes (Solid-state Wave Gyroscope, hereinafter referred to as SWG) and magnetometric transducers (fluxgates), are used as SDs in spatial orientation assessing [1-7; 9; 12; 15-17; 19; 21-26]. At the same time, it is technically difficult to ensure the stability of the primary transformation of HSCASOs to all types of disturbing influences. Analysis of existing HSCASOs showed that the technological solution to this problem leads to a significant increase in the resource intensity of computer systems in general and significantly narrows the field of their application [8; 12; 19-21].

Modern inclinometric complexes are a complex CS's, which includes not only SDs but also a significant ground part, consisting of an interface unit, a unit of communication channel support, as well as the computing part of the system. At the same time, maintenance of such a system requires highly qualified personnel, and the cost can reach several million and even tens of millions of USD [2-3; 6].

To resolve this contradiction in this work, the task is to develop models and methods for the secondary transformation of measurement information, which make it possible to provide given unbiaseness of the assessment and increase its efficiency when HSCASO operates in difficult conditions. In this case, the measurement errors that arise in the process of assessing the spatial orientation are not supposed to be eliminated technologically (which dramatically increases the cost of the system), but only to be determined and mathematically compensated for at the stage of secondary information processing.

This approach, on the one hand, complicates the mathematical support of the assessment process. However, when used as part of HSCASO, this complication is not significant and does not affect the labour intensity of operating the inclinometric system.

On the other hand, this approach can significantly reduce the technological requirements for the manufacture of sensors, which not only makes the system cheaper but also expands the scope of its application by reducing its cost.

To solve this problem, it is necessary to develop refined mathematical models that take into account the entire spectrum of the above errors and harmful factors affecting the bias of the assessment.

MATHEMATICAL MODEL OF THE INCLINOMETER TAKING INTO ACCOUNT THE INSTRUMENTAL ERRORS OF THE SENSOR

To construct a mathematical model of the inclinometer, it is proposed to use 3x3 matrices of direction cosines, which describe the sequential rotation of the object relative to the moving coordinate axes. As the angles of rotation we will use the spatial Euler-Krylov angles, that is, sequential rotation by the azimuth angle (around the third axis), along the zenith angle (around the second axis) and the sighting angle (around the third axis) [12; 18; 27].

Let us introduce moving $OXYZ$, $OX_1Y_1Z_1$, $OX_2Y_2Z_2$ and fixed $O\xi\eta\zeta$, $O\xi^*\eta^*\zeta^*$ coordinate axes (Fig. 1), where $O\xi\eta\zeta$ is bound to the magnetic North, and $O\xi^*\eta^*\zeta^*$ – to the geographical one. In this case, the third axes of the fixed coordinate systems are directed downward (towards the center of the Earth), along with the gravity acceleration vector g, first axes are directed to the “North” corresponding to the sensor type (geographic or magnetic), and the second axes are directed perpendicular to the two above so that the benchmark obtained is right-oriented. We will designate the benchmarks R_0 (fixed relative to the Earth) and R (movable, connected with the inclinometer).

The transition from stationary coordinate systems to moving ones is carried out by successive

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rotation through the Euler-Krylov angles (azimuth, zenith and sighting ones).

Fig. 1 shows the axes of the coordinate systems and the angles connecting them to each other, as well as the reference vectors (g is the acceleration of gravity, T is the strength of the Earth's magnetic field and Ω is the angular rotation of the Earth).

Using the matrices of direction cosines, we can form a mathematical relationship between the moving and stationary coordinate systems by multiplying successively the corresponding rotation matrices around the third and second coordinate axes and around the third one again [12; 18; 27].

Then the following relationship can be written in matrix form:

$$T_R = A_{\varphi(3)} A_{\theta(2)} A_{\alpha(3)} T_{R_0},$$
$$\Omega_R = A_{\varphi(3)} A_{\theta(2)} A_{\alpha_г(3)} \Omega_{R_0^*},$$
$$g_R = A_{\varphi(3)} A_{\theta(2)} A_{\alpha(3)} g_{R_0}.$$

While manufacturing three-component sensors, it is practically impossible to ensure their identity technologically. Even within the same batch during serial production, the electrical characteristics of the sensitive elements and their primary transducing channels have deviations. This determines the presence of a zero signal for SDs, the difference in their gain ratios and temperature coefficients.

In addition, it is practically impossible to ensure the mutual orthogonality of each sensing element of a three-component sensor.

In connection with the above, we will introduce designations to take into account the axes misalignment of the sensitivity of SDs for each of the sensors: $\mu_{ij}^M, \mu_{ij}^\Gamma, \varepsilon_{ij}\ (i, j = 1,2,3)$ are small misalignments of magnetometric SDs, SWGs and accelerometers respectively (the i-th sensor relative to the *j*-th axis), and $d_i^M, d_i^\Gamma, d_i^a\ (i = 1,2,3)$ are information signals of three-component sensors (magnetically sensitive, gyroscopes and accelerometers).

Then the mathematical model for determining the spatial orientation, taking into account misalignment in SDs, can be written in the following form:

For magnitometric SDs:

$$tg\,\alpha = -\frac{(d_1^M - \mu_{13}^M d_2^M + \mu_{12}^M d_3^M)\sin\varphi + (d_2^M + \mu_{23}^M d_1^M - \mu_{21}^M d_3^M)\cos\varphi}{(d_1^M - \mu_{13}^M d_2^M + \mu_{12}^M d_3^M)\cos\varphi\sin\theta - (d_2^M + \mu_{23}^M d_1^M - \mu_{21}^M d_3^M)\sin\varphi\cos\theta + (d_3^M - \mu_{32}^M d_1^M + \mu_{31}^M d_2^M)\sin\theta},$$

For SWGs:

$$tg\,\alpha_г = -\frac{(d_1^\Gamma - \mu_{13}^\Gamma d_2^\Gamma + \mu_{12}^\Gamma d_3^\Gamma)\sin\varphi + (d_2^\Gamma + \mu_{23}^\Gamma d_1^\Gamma - \mu_{21}^\Gamma d_3^\Gamma)\cos\varphi}{(d_1^\Gamma - \mu_{13}^\Gamma d_2^\Gamma + \mu_{12}^\Gamma d_3^\Gamma)\cos\varphi\sin\theta - (d_2^\Gamma + \mu_{23}^\Gamma d_1^\Gamma - \mu_{21}^\Gamma d_3^\Gamma)\sin\varphi\cos\theta + (d_3^\Gamma - \mu_{32}^\Gamma d_1^\Gamma + \mu_{31}^\Gamma d_2^\Gamma)\sin\theta},$$

For accelerometers:

$$tg\,\theta = \frac{\sqrt{(d_1^a - \varepsilon_{13} d_2^a + \varepsilon_{12} d_3^a)^2 + (d_2^a + \varepsilon_{23} d_1^a - \varepsilon_{21} d_3^a)^2}}{d_3^a - \varepsilon_{32} d_1^a + \varepsilon_{31} d_2^a}, \qquad tg\,\varphi = -\frac{d_2^a + \varepsilon_{23}^a d_1^a - \varepsilon_{21}^a d_3^a}{d_1^a - \varepsilon_{13}^a d_2^a + \varepsilon_{12}^a d_3^a}.$$

Thus, if the misalignment of sensitive axes is determined in advance for a given specific sensor, these coefficients can be taken into account at the stage of secondary information transformation, thereby reducing the bias of the orientation estimate made by HSCASO. It should also be noted that the values of these misalignments for a particular sensor are constant throughout its life.

Analysis of the obtained mathematical models showed the degree of influence of misalignments on the final result of orientation assessment.

So, for example, for accelerometers we get the following expressions:

$$|\Delta\theta| \le |\varepsilon_{32}| + |\varepsilon_{31}|,$$
$$|\Delta\varphi| \le |\varepsilon_{13}| + |\varepsilon_{23}| + (|\varepsilon_{21}| + |\varepsilon_{12}|) + |ctg\,\theta^*|.$$

Misalignment of accelerometer's sensitive axes leads to a twofold error in the assessment of the zenith and more than fourfold one in the assessment of the sighting angles in relation to the misalignments themselves. At the same time, with an increase in the latitude of the measurement point, the bias of the assessment of the sighting angle will further increase.

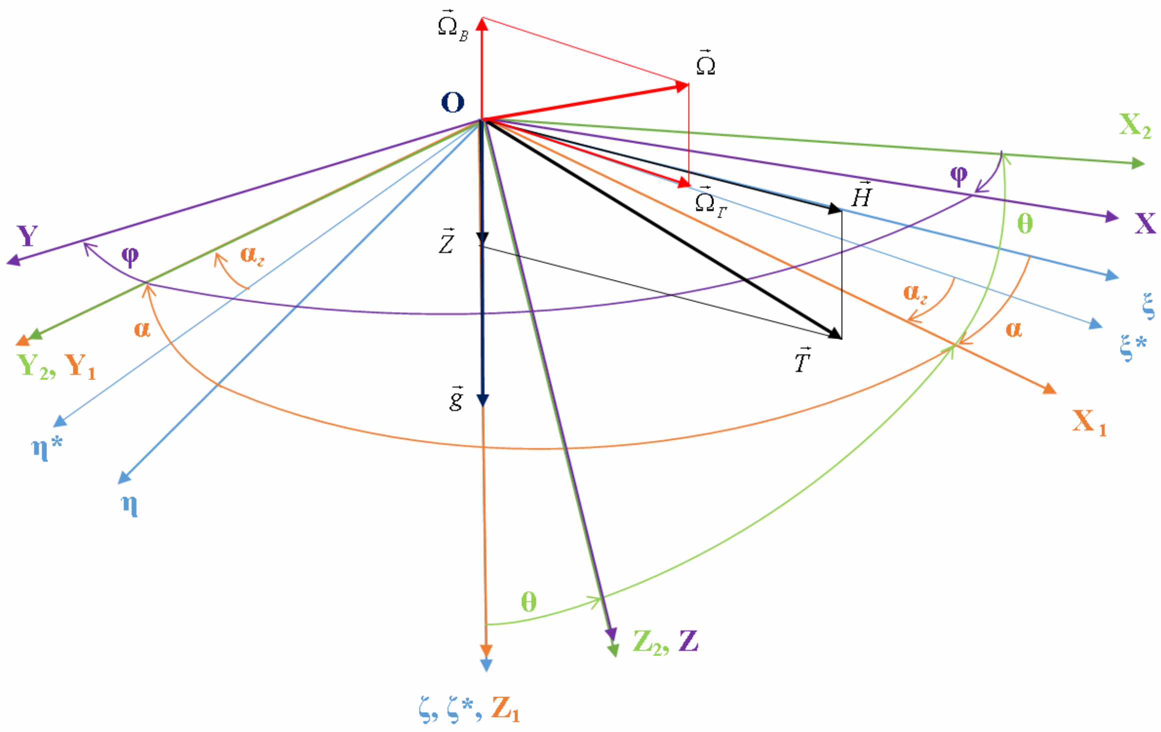

Fig. 1. **Coordinate axes**
Source: **compiled by the author**

For azimuth sensors we have:

$$|\Delta\alpha| \le 2\sqrt{3}\left\{\left[(3+2b)+\frac{(2+b)b_3^*}{\sqrt{b_1^{*2}+b_2^{*2}}}\right]\varepsilon+(2+b)\mu\right\}.$$

In practice, this means that at the latitude of the city of Dnipro, in order to ensure the unbiasedness of the azimuth estimate, within one degree, it is necessary to ensure the accuracy of the orientation of the sensitivity axes of each of the three-component SDs, no more than three arc minutes. This requirement is difficult to ensure technologically, which leads to a complication of the design, the need for adjustment of SD and a significant increase in the resource intensity of the inclinometer [12; 18; 20-21].

For an inclinometer with gimbal frames we have:

$$|\Delta\alpha| = |\Delta\delta| b^* + |\Delta\beta|(1+b^*),$$

where b* is the magnetic inclination of the measurement point.

This means that for the latitude of the city of Dnipro, the error in setting the internal and external gimbal frames (δ and β) within one degree leads to a bias in the azimuth assessment within 8.86 degrees, which is completely unacceptable for this technological process.

In addition to mechanical instrumental errors, the inclinometer also contains electrical ones obtained during the manufacturing. This is due to the technical impossibility of making absolutely identical SDs of a three-component sensor. Each of the three sensing elements has a non-zero value of the zero signal U_{i0} $(i=1,2,3)$, as well as a gain ratio different from the other two SDs, which provides unequal values U_{i0} $(i=1,2,3)$ of the output signal amplitude U_{im} $(i=1,2,3)$.

The difference in these characteristics leads to an additional bias in the assessment of the spatial orientation.

$$\Delta^2\alpha \le \frac{\left[\left|\frac{U_{10}}{U_{1m}}\right|+\left|\frac{U_{20}}{U_{2m}}\right|+\left|\frac{U_{30}}{U_{3m}}\right|+\sqrt{1+b^2}\,(3|\Delta\theta|+2|\Delta\varphi|)\right]^2+\left[\left|\frac{U_{10}}{U_{1m}}\right|+\left|\frac{U_{20}}{U_{2m}}\right|+2\sqrt{1+b^2}\,|\Delta\varphi|\right]^2}{1-\frac{\delta^2\alpha}{12}}$$

$$\Delta\theta = \arccos\left(\frac{U_3-U_{30}}{U_{3m}}\right)-\arccos\frac{U_3}{U_{3m}},$$

$$\Delta\varphi = -arcctg\left(\frac{U_1-U_{10}}{U_2-U_{20}}\,\frac{U_{2m}}{U_{1m}}\right)+arcctg\,\frac{U_1}{U_2}\,\frac{U_{2m}}{U_{1m}}.$$

In practice, this means that to ensure the unbiasedness of the object orientation estimate within one degree, the ratio of the zero signals to the maximum value for each SD should not exceed 0.012 %, and the transfer ratios of different SDs of one sensor should not differ by more than 0.6 %.

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METHODS FOR DETERMINING THE PARAMETERS OF THE INCLINOMETER'S INSTRUMENTAL ERRORS

The methods for determining the misalignments of the SD sensitivity axes are based on the following sequence of actions.

The sensor is mounted on a rotary-axis table under laboratory conditions. Further, using the rotary-axis table, the sensor rotates sequentially with a given step around two or three mutually orthogonal axes. The angles of rotation are fixed either according to the data from the rotary-axis table itself, or by an additional precision device that has sufficient accuracy in measuring the corresponding angles of rotation. The readings taken from the SD are recorded in the database. After the end of all rotations, a harmonic Fourier series is compiled and its coefficients are found by the method of least squares [12; 18; 27]. Next, the desired misalignments are determined.

In practice, the found coefficients of the Fourier series are elements of the correction matrix.

So, for example, for a three-component block of accelerometers, the sequence of actions that implements the proposed method is as follows.

1. Enter n values of the specified sighting angle φ and r values of the specified zenith angle θ:

$$\varphi_1, \varphi_2, \ldots \varphi_n, \theta_1, \theta_2, \ldots \theta_r;$$

2. Enter the appropriate accelerometer signals:

$$U^a_{ijk},\ i = 1,2,3,\ j = 1,2,\ldots n,\ \ k = 1,2,\ldots r$$

3. Calculate the elements of the adjustment matrix:

$$A = \begin{Vmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{12} & a_{22} & a_{23} & a_{24} \\ -a_{13} & -a_{23} & a_{33} & a_{34} \\ a_{14} & a_{24} & -a_{34} & a_{44} \end{Vmatrix}$$

$$B_1 = (a_1, a_2, a_3, a_4)^T,\ B_2 = (d_1, d_2, d_3, d_4)^T,$$

$$B_3 = (c_1, c_2, c_3, c_4)^T,$$

where:

$$b_{1jk} = -\cos\varphi_j \sin\theta_k, \quad b_{2jk} = \sin\varphi_j \sin\theta_k, \quad b_{3k} = \cos\theta_k, \quad a_{11} = -nr,$$

$$a_{12} = -\sum_{j=1}^{n}\sum_{k=1}^{r} b_{1jk}, \quad a_{13} = n\sum_{k=1}^{r} b_{3k}, \quad a_{14} = -\sum_{j=1}^{n}\sum_{k=1}^{r} b_{2jk},$$

$$a_{22} = -\sum_{j=1}^{n}\sum_{k=1}^{r} b^2_{1jk}, \quad a_{23} = \sum_{j=1}^{n}\sum_{k=1}^{r} b_{3k} b_{jk}, \quad a_{24} = -\sum_{j=1}^{n}\sum_{k=1}^{r} b_{2jk} b_{1jk},$$

$$a_{33} = n\sum_{k=1}^{r} b^2_{3k}, \quad a_{34} = -\sum_{j=1}^{n}\sum_{k=1}^{r} b_{2jk} b_{3k}, \quad a_{44} = -\sum_{j=1}^{n}\sum_{k=1}^{r} b^2_{2jk},$$

$$a_1 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{1jk}, \quad a_2 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{1jk} b_{1jk}, \quad a_3 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{1jk} b_{3k},$$

$$a_4 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{1jk} b_{2jk}, \quad d_1 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{2jk}, \quad d_2 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{2jk} b_{2jk},$$

$$d_3 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{2jk} b_{1jk}, \quad d_4 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{2jk} b_{3k}, \quad c_1 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{3jk},$$

$$c_2 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{3jk} b_{3k}, \quad c_3 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{3jk} b_{1jk}, \quad c_4 = -\sum_{j=1}^{n}\sum_{k=1}^{r} U^a_{3jk} b_{2jk}.$$

4. Calculate:

A^{-1}, $X_i = A^{-1} B_i$, $i = 1,2,3$. ($X_1 = (U^a_{01}, U^a_{m1}, \lambda^{(1)}_2, \lambda^{(1)}_3)^T$, $X_2 = (U^a_{02}, -\lambda^{(2)}_3, -\lambda^{(2)}_1, U^a_{m2})^T$, $X_3 = (U^a_{03}, \lambda^{(3)}_2, -U^a_{m3}, -\lambda^{(3)}_1,)^T$), $U^a_{01}, U^a_{02}, U^a_{03}, U^a_{m1}, U^a_{m2}, U^a_{m3}$.

5. Calculate misalignments:

$$\varepsilon_{12} = \frac{\lambda^{(1)}_2}{U_{m1}},\ \varepsilon_{13} = \frac{\lambda^{(1)}_3}{U_{m1}},\ \varepsilon_{23} = \frac{\lambda^{(2)}_3}{U_{m2}},$$

$$\varepsilon_{21} = \frac{\lambda^{(2)}_1}{U_{m2}},\ \varepsilon_{32} = \frac{\lambda^{(3)}_2}{U_{m3}},\ \varepsilon_{31} = \frac{\lambda^{(3)}_1}{U_{m3}}.$$

6. Calculate the transfer ratios of the accelerometers using the formula:

$$K^a_1 = \frac{U^a_{m1}}{|\vec{g}|},\ K^a_2 = \frac{U^a_{m2}}{|\vec{g}|},\ K^a_3 = \frac{U^a_{m3}}{|\vec{g}|},$$

Thus, all values of the instrumental errors of SDs of the three-component block of accelerometers are found.

This method is also applicable to find the parameters of the instrumental errors of the magnetometric SDs of a three-component azimuth sensor, as well as the instrumental errors of the SWG.

To compensate the temperature errors of two- and three-component sensors, it is necessary to approximate the temperature dependence of each SD [12; 24-25]. It should be understood that although in the case of orientation sensors the SD temperature error is partially compensated by using the arc-tan and arccotan functions, the presence of a primary transducing channel in the sensor also leads to the case when individual components of a multicomponent sensor have different signs of temperature coefficients.

Therefore, it is advisable to compensate for the temperature error with a second-order polynomial for each SD separately.

Examples of compensation for the temperature error of a two-component azimuth sensor are given for the case when both temperature coefficients are positive (Fig. 2) and for the case when the signs of the temperature coefficients of SD are different (Fig. 3).

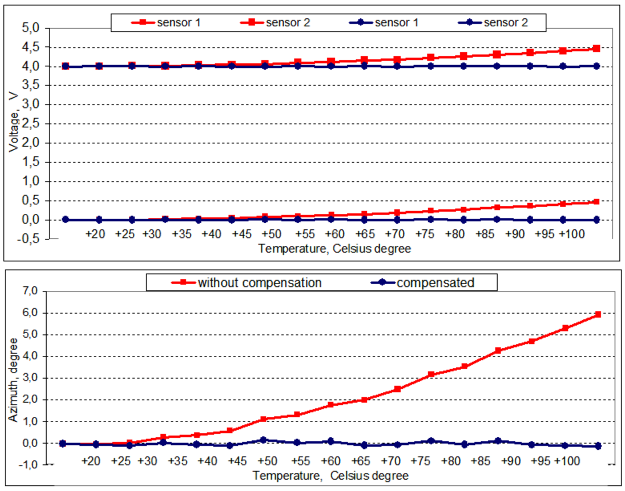

Fig. 2. **Compensation of temperature error (both coefficients are positive)**

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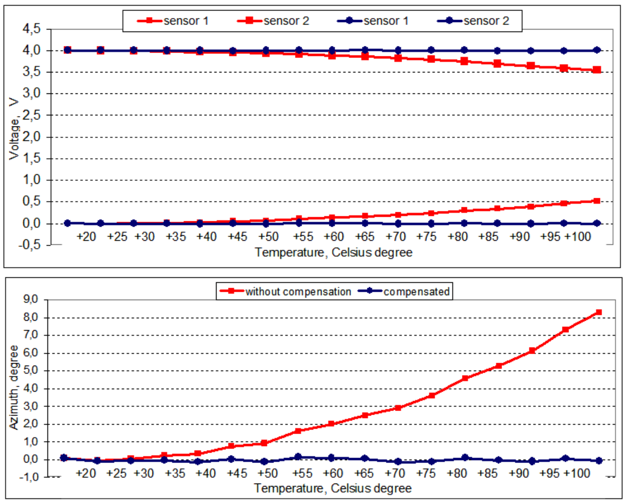

Fig. 3. **Compensation of temperature error (coefficients have different signs)**

Source: **compiled by the author**

COMPENSATION OF MAGNETIC ANOMALIES

Magnetic anomalies accompany the well construction process constantly, since the drilling rig and the drilling tool are the source of magnetic anomalies themselves. It should be noticed that borehole drilling using only one inclinometer is carried out in a wide range of magnetic latitudes and under different operating conditions. Therefore, deviation compensation, as is customary in avia and naval magnetic navigation while drilling, is practically impossible [26; 28-29].

From here, it is proposed to eliminate the magnetic deviation not with special deviation devices, but with the help of a technique that allows calculating the parameters of the magnetic deviation of the inclinometer at a given drilling point and eliminating it by registering into the inclinometer readings at the stage of secondary information processing.

Two main sources of magnetic anomalies are considered: the constant magnetic field of the anomaly from the drill string itself, in which the SD is fixed, and the external, stationary relative to the Earth, constant magnetic field of the anomaly of any origin, including from casing pipes of running or other wells and foreign underground objects, which are the source of the magnetic field.

In the first case, it is proposed to rotate the entire drill string by 360 degrees around the longitudinal axis of the well with subsequent calculation of the constant and variable components of the magnetic field. In this respect, the constant component of the measured magnetic field will correspond to the magnetic anomaly of the drill string itself, since it rotates with the sensor, and the variable component will correspond to the Earth's magnetic field.

In the second case, it is proposed to conduct preliminary measurements of the values and orientation of the support vectors g, T and Ω at the mouth of well for subsequent control of their relative position. Since the vectors g and Ω are considered stable at a given point, then any change in the magnitudes or mutual orientation of the vectors can occur only as a result of an external magnetic anomaly. Thus, by recording and calculating these changes, it is possible to determine the parameters of the magnetic anomaly at the point of assessment.

The general formula describing the deviation is:

$$\delta = A + B\sin\alpha' + C\cos\alpha' + D\sin 2\alpha' + E\cos 2\alpha' .$$

It should be noted that the semicircular components (B and C) correspond to the influence of “hard iron”, that is, permanent magnets, and the circular and quarter components (A, D, E) correspond to the influence of “soft iron”, i.e. materials that are not a source of a magnetic field, but are capable of distorting it when they enter the zone of its action.

When calculating the coefficients of the desired magnetic deviation, harmonic Fourier series with unequal steps and the least squares method were used.

GENERAL SEQUENCE OF IMPLEMENTATION OF THE PROPOSED METHODS

Consistent application of the proposed methods for determining the parameters of disturbing factors and their further consideration at the stage of secondary information processing allows eliminating their influence on the bias of the assessment of spatial orientation using HSCASO.

In Fig. 4 the sequence diagram of the HSCASO attitude assessment is given. The diagram shows that part of the work is carried out in laboratory conditions on a calibration bench (rotary-axis table) at the stage of manufacturing the inclinometer.

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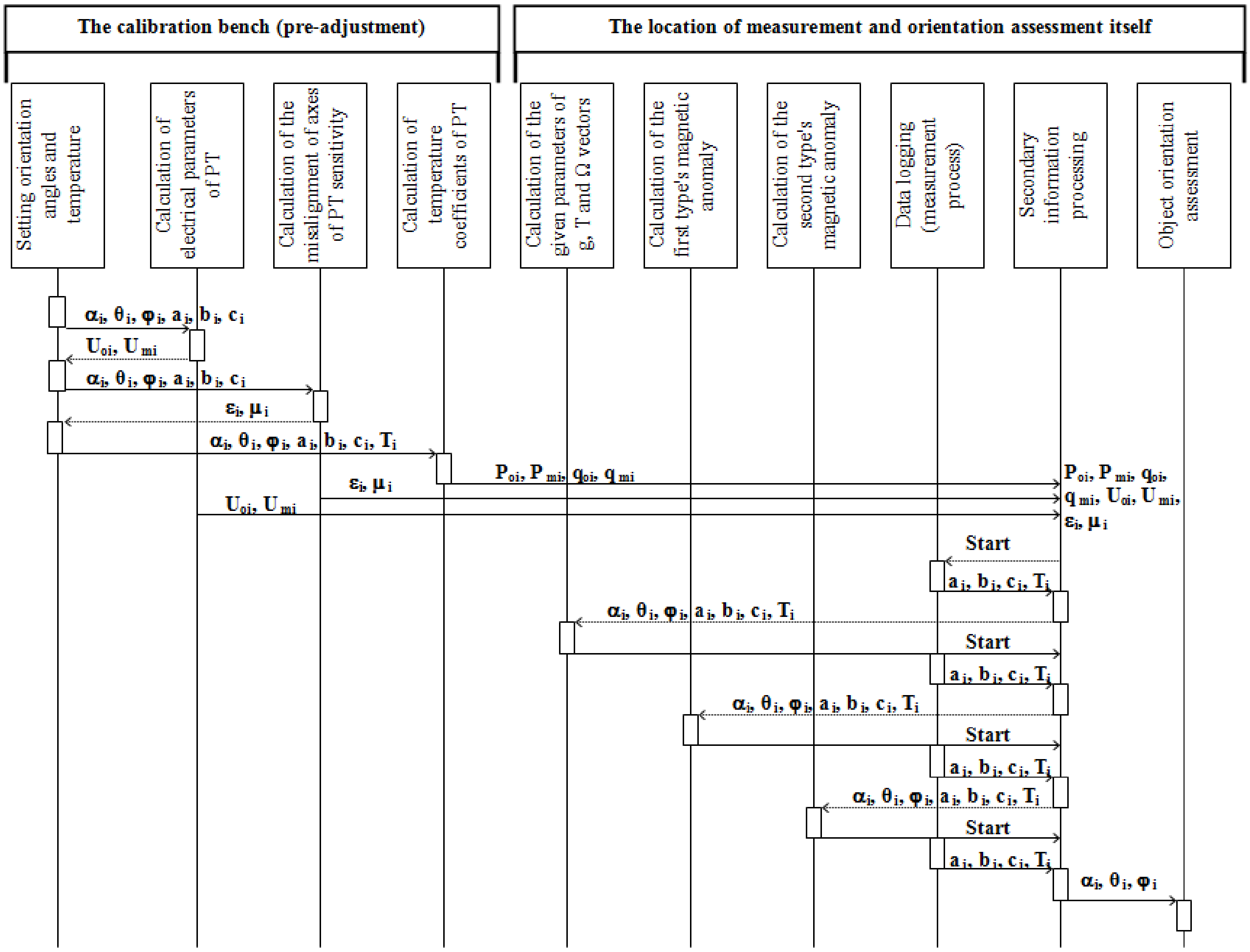

Fig. 4. **Diagram of the sequence of assessing the object orientation in difficult conditions using HSCASO**

Source: **compiled by the author**

According to the methods described above, the main individual parameters of the inclinometer are determined (misalignments of the axes of sensitivity, the magnitude of zero signals and transfer coefficients of SD, temperature coefficients of SD). All received data are unique for this particular sensor and do not change for the entire duration of its operation life.

Further, directly on the drilling site, the parameters and the relative position of the reference vectors are measured and these data are recorded.

Then a magnetic anomaly of the first type (from the drilling rig itself) is determined and recorded in the database.

Next, the spatial orientation of the object is assessed with parallel monitoring of the appearance of a magnetic anomaly of the second type (from an external source). If it appears, according to the above methodology, its parameters are determined, and the data are corrected at the stage of secondary information processing.

CONCLUSIONS

The accuracy of the assessment of the object orientation largely determines the efficiency and/or safety of work in many practically important applications, such as geological exploration, monitoring systems during construction, etc. Therefore, when developing software and hardware components for assessing spatial orientation, it is necessary to increase the efficiency of primary and secondary processing information.

1. It is shown in the work that taking into account the instrumental errors caused by the peculiarities of SD manufacturing can significantly increase the unbiasedness of the assessment of the spatial orientation of objects. Specific values of the degree of the main factors influence on the assessment bias of the objects spatial orientation (misalignment of the axes of sensitivity, the presence of a zero signal, non-identity of transfer coefficients and temperature parameters) are obtained.

2. Mathematical models and methods have been developed that make it possible to determine the

values of all the main parameters of instrumental errors of each SD in the inclinometer, and the possibility of compensating for their influence on the results of assessing the spatial orientation of objects has been shown.

3. Mathematical models of the inclinometric instrument are proposed, taking into account the instrumental errors of SD and eliminating them at the stage of secondary information processing.

4. Methods for determination and subsequent accounting at the stage of secondary information processing of magnetic anomalies of two types: anomalies from the drilling rig itself and anomalies from an external source (casing pipes, adjacent wells and other external objects of the magnetic field) are proposed.

5. Methods for eliminating the temperature error of inclinometers of various designs by a second-order polynomial are shown, as well as the results of experimental studies.

6. The proposed models and methods could be used in the development of software and hardware components of the spatial orientation of objects, which can be widely used in various fields, for example, in the construction of underground communications; when assembling large and remote objects; with static sounding of soils; when monitoring the state of foundation elements and building structures of especially critical structures (nuclear, thermal power plants, etc.) during operation, and others.

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МЕТОДИ ВТОРИННО ПЕРЕТВОРЕННЯ ІНФОРМАЦІЇ ПРИ ОЦІНЦІ ПРОСТОРОВОЇ ОРІЄНТАЦІЇ ОБ'ЄКТІВ

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АНОТАЦІЯ

Робота присвячена вирішенню наукової проблеми забезпечення незміщеності та підвищення ефективності оцінки просторової орієнтації об'єктів шляхом застосування нових методів вторинного перетворення інформації в програмно-апаратних компонентах комп'ютерних систем. У роботі представлено метод компенсації магнітних аномалій, що впливають на чутливі до магнітного поля датчики кутів повороту інклінометра. Він ґрунтується на реєстрації показань інклінометра і кута повороту бурового інструменту при його обертанні в гирлі свердловини в діапазоні триста шістдесят градусів. Це дозволяє визначити і надалі враховувати значення магнітної девіації від бурової колони в показаннях інклінометра. Описано метод визначення параметрів магнітної аномалії від зовнішнього нерухомого джерела постійного магнітного поля за рахунок використання надлишкової інформації від показань інклінометричних перетворювачів в гирлі свердловини і в точці проведення оцінки. Це дозволяє розширити межі та область застосування магнітометричних перетворювачів в складних умовах. Запропоновано методи обчислення шуканого азимуту, а також – параметрів вектора напруженості магнітної аномалії. Розглянуто похибки інклінометрів на основі первинних перетворювачів різної фізичної природи (ферозондові, гіроскопи, акселерометрами), як з жорстко закріпленими, так і з використанням карданних маятникових підвісів. Проаналізовано чинники, що впливають на зміщеність оцінки кутів просторової орієнтації бурового інструменту, що виражені через кути Ейлера внаслідок різних причин: відхилення осей чутливості перетворювачів від взаємної ортогональності й опорного тригранника осей, пов'язаного з корпусом; зміни нульового сигналу і передавального коефіцієнта під впливом температури; неідентичності електричних параметрів; неточної установки маятникових карданних рамок датчика в площину нахилу і по вертикалі місця. Визначено допустимі граничні значення кожної з наведених похибок. Облік комплексу цих похибок дозволяє значно підвищити незміщеність оцінки параметрів просторового положення об'єкта в складних умовах. Практичне застосування представлених в роботі результатів дозволяє розробити і впровадити інклінометри, здатні працювати в складних експлуатаційних умовах, що мають малий діаметр охоронного кожуха. Подібні системи можуть використовуватися: для будівництва підземних комунікацій; для збирання великогабаритних і віддалених об'єктів; для статичного зондування ґрунтів; для моніторингу стану елементів фундаменту і будівельних конструкцій особливо відповідальних споруд (атомних, теплових станцій тощо.) в процесі експлуатації.

Ключові слова: контроль просторової орієнтації; магнітні аномалії; датчик орієнтації; інклінометр; азимут; зенітний кут; кут установки відхилювача; зміщеність оцінки орієнтації; математична модель

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МЕТОДЫ ВТОРИЧНОГО ПРЕОБРАЗОВАНИЯ ИНФОРМАЦИИ ПРИ ОЦЕНКЕ ПРОСТРАНСТВЕННОЙ ОРИЕНТАЦИИ ОБЪЕКТОВ

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АННОТАЦИЯ

Работа посвящена решению научной проблемы обеспечения несмещенности и повышения эффективности оценки пространственной ориентации объектов путем применения новых методов вторичного преобразования информации в программно-аппаратных компонентах компьютерных систем. В работе описан разработанный метод компенсации магнитных аномалий, влияющих на магниточувствительные датчики углов поворота инклинометра. Он основывается на регистрации показаний инклинометра и угла поворота буровой трубы при ее вращении в устье скважины в диапазоне триста шестьдесят градусов. Это позволяет определить и в дальнейшем учитывать значение магнитной девиации от буровой колоны в показаниях инклинометра. Описан метод определения параметров магнитной аномалии от внешнего неподвижного источника постоянного магнитного поля за счет использования избыточной информации от показаний инклинометрических преобразователей в устье скважины и в точке проведения оценки. Это позволяет расширить границы и область применения магнитометрических преобразователей в сложных условиях. Предложены методы вычисления искомого азимута, а также – параметров вектора напряженности магнитной аномалии. Рассмотрены погрешности

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инклинометров на основе первичных преобразователей различной физической природы (феррозондовые, гироскопы, акселерометры), как жесткозакрепленные, так и с использованием карданных маятниковых подвесов. Проанализированы факторы, влияющие на смещенность оценки углов пространственной ориентации бурового инструмента, выраженных через углы Эйлера вследствие различных причин: отклонения осей чувствительности преобразователей от взаимной ортогональности и опорного трехгранника осей, связанного с корпусом; изменения нулевого сигнала и передаточных коэффициентов под воздействием температуры; неидентичности электрических параметров; неточной установки маятниковых карданных рамок датчика в плоскость наклона и по вертикали места. Определены допустимые граничные значения каждой из приведенных погрешностей. Учет комплекса этих погрешностей позволяет значительно повысить несмещенность оценки положения объекта в сложных условиях. Практическое применение представленных в работе результатов позволяет создать и внедрить инклинометры, способные работать в сложных эксплуатационных условиях, имеющие малый диаметр охранного кожуха. Подобные системы могут использоваться: для строительства подземных коммуникаций; для сборки крупногабаритных и удаленных объектов; для статического зондирования грунтов; для мониторинга состояния элементов фундамента и строительных конструкций особо ответственных сооружений (атомных, тепловых станций и т.д.) в процессе эксплуатации.

Ключевые слова: контроль пространственной ориентации; магнитные аномалии; датчик ориентации; инклинометр; азимут; зенитный угол; угол установки отклонителя; смещенность оценки ориентации; математическая модель

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