Construction and Calibration of Inclinometric Systems with Fluxgate and Accelerometric Sensors

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***Abstract*—The structure of modern inclinometric systems with fluxgate and accelerometric sensors is considered, analytical expressions for the measured projections of non-collinear gravity acceleration and flux density vectors are presented. Mathematical models for determining the spatial orientation angles of the well trajectory are presented. The features of inclinometric systems calibration operations in relation to fluxgate sensors are revealed, methodological and technological solutions of calibration are proposed, which are provide an increased reliability of constants determining and the accuracy of desired angles determining.**

***Keywords*—inclinometric system, fluxgate sensor, accelerometer sensor, calibration, magnetic field deviation, measurement while drilling.**

I. Introduction

Inclinometric systems (InS) are designed to determine the spatial orientation parameters of the directional and horizontal wells trajectories. Therein the projection of the deviated well trajectory on the vertical plane is called the profile, and on the horizontal plane - is the plan.

The parameters of spatial orientation in inclinometry are listed below [1]:

• zenith angle θ is the angle between the direction of the gravitational acceleration vector $\vec{g}$ and the tangent to the profile curve at each point, measured in the vertical plane;

• azimuth α - the angle between the direction to the north of the magnetic meridian and the tangent to the plan curve at each point, measured in the horizontal plane.

Generally, directional survey is a set of tasks in the classical spatial orientation theory as applied to underground (borehole) objects. The essence of solving these problems is associated with orthogonal transformations of rectangular coordinate systems (bases) to the Euler-Krylov angles [2], subject to which analytical dependences of these angles with projections of two noncollinear vectors (gravity acceleration $\vec{g}$ and geomagnetic flux density $\vec{B}$) on the basis axis of the object body - a downhole tool moving along a curved trajectory.

Therefore, for determining the desired angles θ and α with reference to the depth, i.e., at a specific point of the borehole trajectory, it is necessary to measure the projections of the noted non-collinear vectors. This is the technical problem solving by the InS downhole tool.

Modern InS are used for geophysical surveys of uncased borehole, as well as measurement-while-drilling system (MWD system) used directly during drilling and built into the bottomhole assembly.

In the MWD systems, in addition to the traditionally measured azimuth and zenith angles, secondary technological parameter is also monitored - the sighting angle φ - the angle of sidetracking whipstock, measured in a perpendicular to the well trajectory plane.

II. The Structure of the Inclinometric System with Fluxgate and Accelerometer Sensors

Fig. 1 schematically shows the structure of InS [3]. InS includes a downhole tool and a surface part containing an interface unit, a PC and a driller's console (for MWD systems only).

The interface unit consists of power supply unit PSU, microcontroller MCU, indication unit IU, received data converter RDC. The depth sensor DS based on incremental encoder or magnetic mark is standalone device connected to interface unit.

The downhole tool and the interface unit are linked via a telecommunication line TL. The results of borehole survey are

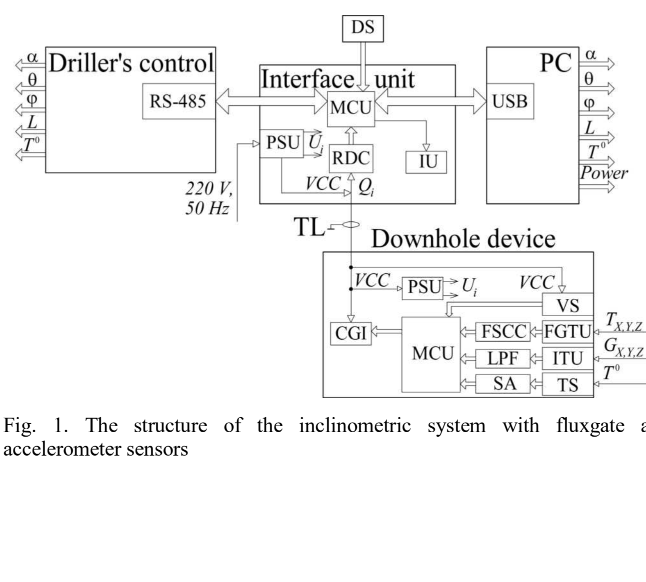

Fig. 1. The structure of the inclinometric system with fluxgate and accelerometer sensors

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presented in the form of numerical values of azimuth α, zenith angle θ, sighting angle φ, as well as the values of the modules of $\vec{B}$ and $\vec{g}$ vectors. The downhole tool contains a power supply unit PSU, voltage sensor VS, digital unit, which includes microcontroller MCU, common gateway interface CGA, fluxgate transducer unit (FGTU) with the corresponding circuits for secondary information signals conversion (fluxgate secondary conversion circuits - FSCC), inclination angle transducer unit (ITU) with low-pass filters (LPF), temperature sensor (TS) with scaling amplifier (SA) [4].

The sensor base of modern InS, which seems to be the most prospective and is recognized among the developers and creators of downhole equipment, consists of two main elements: a three-component geomagnetometer with flux-gate sensors and a three-axis accelerometric transducer (Fig. 2).

A specific construction feature of modern InS with fluxgate sensors is the complexity of ensuring strictly orthogonal sensitivity axes positioning of each fluxgates $M_{i(x,y,z)}$ of the FGTU relative to the downhole tool body basis. These misalignment angles δ_x, δ_y, χ, γ, σ_1 and σ_2 (Fig. 3), which characterize the specific spatial fluxgates arrangement in the body, leads to significant instrumental errors when determining the azimuth α and InS as a whole [5].

Accelerometric sensor A_{yz} also has additional rotations of the body base by λ_{x1}, λ_{y1} and λ_{z1} angles around three axes $0x_{a1}$, $0y_{a1}$ and $0z_{a1}$, and A_{xz} sensor - by angles λ_{x2}, λ_{y2} and λ_{z2} around three axes $0x_{a2}$, $0y_{a2}$ and $0z_{a2}$ (Fig. 3).

One of the ways to achieve InS acceptable metrological characteristics is to take into account the numerical values of these misalignment angles (Fig. 3) for both fluxgate and accelerometric sensors in the general algorithmic processing of the downhole measurements results using specialized software.

The numerical values of the misalignment angles are determined during experimental studies of newly created InS, during metrological certification and when periodic verifications are performing. These studies most commonly are carried out in the metrological services of scientific research, design and production organizations which practice is the development, creation and practical application of downhole

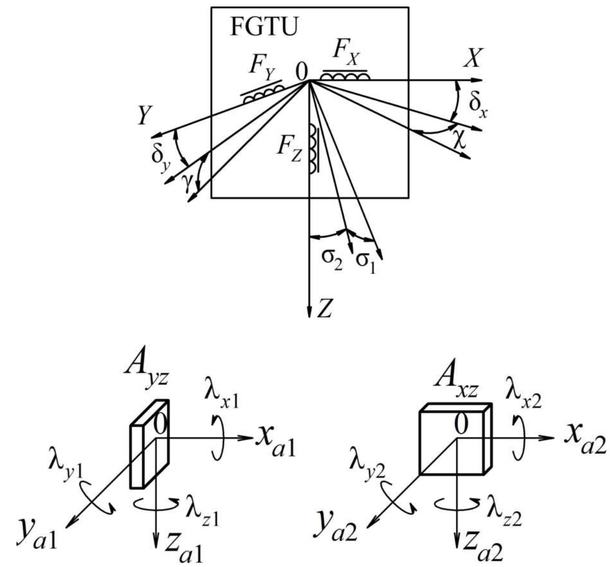

Fig. 3. The misalignment angles of fluxgates and accelerometric sensor

geophysical equipment. In this case, special verification equipment is used (calibration equipment, rotary tables, etc.) [6]. The appearance of one such calibration installations for inclinometers is shown on Fig. 4.

The normalized values of accelerometers $g_{iv(i=x,y,z)}$ information signals are related to the zenith θ and sighting φ angles as follows [4]:

$$\left.\begin{aligned} g_{yv1} &= a_{12}X + b_{12}Y + c_{12}Z \\ g_{zv1} &= a_{13}X + b_{13}Y + c_{13}Z \end{aligned}\right\},$$

$$\left.\begin{aligned} g_{xv2} &= a_{21}X + b_{21}Y + c_{21}Z \\ g_{zv2} &= a_{23}X + b_{23}Y + c_{23}Z \end{aligned}\right\},$$

where g_{yv1}, g_{zv1} – are $\vec{g}$ vector projections measured by A_{yz} accelerometer;

g_{xv2}, g_{zv2} – are $\vec{g}$ vector projections measured by A_{xz} accelerometer.

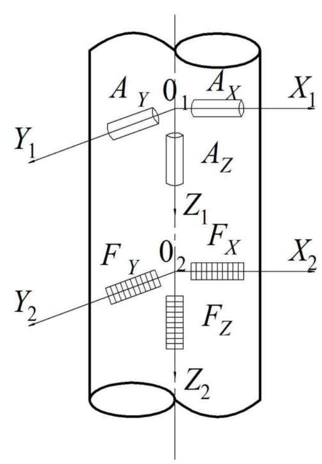

Fig. 2. The sensor base of InS

Fig. 4. Appearance of the calibration installation for inclinometers

The constants determined by the ITU design features are as follows:

$$a_{12} = \sin\lambda_{x1}\sin\lambda_{y1}\cos\lambda_{z1} - \cos\lambda_{x1}\sin\lambda_{z1};$$
$$b_{12} = \cos\lambda_{x1}\cos\lambda_{z1} + \sin\lambda_{x1}\sin\lambda_{y1}\sin\lambda_{z1};$$
$$c_{12} = \sin\lambda_{x1}\cos\lambda_{y1};$$
$$a_{13} = \sin\lambda_{x1}\sin\lambda_{z1} + \cos\lambda_{x1}\sin\lambda_{y1}\cos\lambda_{z1};$$
$$b_{13} = \cos\lambda_{x1}\sin\lambda_{y1}\sin\lambda_{z1} - \sin\lambda_{x1}\cos\lambda_{z1};$$
$$c_{13} = \cos\lambda_{x1}\cos\lambda_{y1};$$
$$a_{21} = \cos\lambda_{y2}\cos\lambda_{z2};$$
$$b_{21} = \cos\lambda_{y2}\sin\lambda_{z2};$$
$$c_{21} = -\sin\lambda_{y2};$$
$$a_{23} = \sin\lambda_{x2}\sin\lambda_{z2} + \cos\lambda_{x2}\sin\lambda_{y2}\cos\lambda_{z2};$$
$$b_{23} = \cos\lambda_{x2}\sin\lambda_{y2}\sin\lambda_{z2} - \sin\lambda_{x2}\cos\lambda_{z2};$$
$$c_{23} = \cos\lambda_{x2}\cos\lambda_{y2};$$

X, Y, Z are the unknown variables functionally related to the:

$$X = -\cos\varphi\sin\theta;\ Y = \sin\varphi\sin\theta;\ Z = \cos\theta\,.$$

Mathematical models for determining the desired θ and φ angles depending on the definition the measured projections $g_{i(x,\,y,\,z)}$ and $m_{i(x,\,y,\,z)}$ are presented by following dependencies [5]:

$$\left.\begin{aligned} \varphi &= \operatorname{arctg}\frac{B}{A} \\ \theta &= \operatorname{arctg}\frac{\sqrt{A^2+B^2}}{C} \end{aligned}\right\},$$

where A, B and C parameters are

$$\left.\begin{aligned} A &= g_{xv2}(b_{12}c_{13} - b_{13}c_{12}) + g_{yv1}(b_{13}c_{21} - b_{21}c_{13}) + \\ &\quad + g_{zv1}(b_{21}c_{12} - b_{12}c_{21}) \\ B &= g_{xv2}(a_{12}c_{13} - a_{13}c_{12}) + g_{yv1}(a_{13}c_{21} - a_{21}c_{13}) + \\ &\quad + g_{zv1}(a_{12}c_{21} - a_{21}c_{12}) \\ C &= g_{xv2}(a_{12}b_{13} - a_{13}b_{12}) + g_{yv1}(a_{13}b_{21} - a_{21}b_{13}) + \\ &\quad + g_{zv1}(a_{21}b_{12} - a_{12}b_{21}) \end{aligned}\right\}.$$

III. THE INCLINOMETRIC SYSTEM WITH FLUXGATE AND ACCELEROMETER SENSORS CALIBRATION PROBLEM

The main function of the calibration installation is to set "exact" discrete fixed values of azimuth and zenith angles by means of controlled turns in the horizontal and vertical planes and "transfer" these values to the investigated downhole tool, which is rigidly positioned in the attachment points of the calibration installation [7]. All experimental studies, calibration and verification operations of InS are carried out according to the appropriate methods given in the regulatory industry documents.

The main technological operations when performing these works include the following main stages:

- setting up the investigated InS downhole tool to the attachment points of the calibration installation;
- setting the spatial orientation position of the downhole tool body by setting specific controlled angles values of azimuth and inclination (zenith angle);
- measuring the information signals from fluxgates and accelerometers and constants calculation;
- calculation the required angles (θ, α) and comparison the obtained results with the specified values on the calibration installation.

All these operations are regulated and carried out by the relevant services of the enterprises. In addition, certain specific requirements are also imposed on such installations. The calibration installations itself is an object for calibration and metrological certification, which are carried out by authorized regional metrological centers. The essence of these works is reduced to the adjustment operations of the structural elements of the calibration installation in order to leveling the rotary (azimuthal) platform and ensure the vertical initial orientation of the inclinometer under study.

At the same time, verification precision devices are used - an optical quadrant and a magnetic compass (magnetic needle) with a limited but highly sensitive range (±5°) with an accuracy of the controlled angle of ±15 angle minutes. In addition to adjusting operations, when calibrating the rotary installation itself, zero directions are fixed on the zenith and azimuth scale dials. These procedures, performed by specialists from metrological centers, are performed periodically - once every three years with the issuance of appropriate certificates defining the license to calibrate downhole instruments of inclinometric systems in accordance with the established procedure.

Here it is necessary to note and pay special attention to the temporal stability of the corresponding zero directions of the setting scales and their actual locations. The deviation of the scale zero directions of the zenith angle limb is unlikely if external forced disturbances (relocation in the room, mechanical deformation of the structure, etc.) are excluded.

So, during periodic calibration of the calibration installation using a magnetic compass at the current values of α_i, the zero direction of the azimuthal scale $\alpha_0 = 0$ is set and fixed. Then the investigated inclinometer with fluxgate sensors is installed in the attachment points of the calibration installation, which is sequentially assigned specific spatial positions with a special emphasis on orientation in azimuth direction $\alpha_i = k\pi/2$ ($k = 0, 1, 2, 3$). At these points, the signals from the fluxgate sensors are measured and, according to known mathematical models, the numerical values of the misalignment angles characterizing the specific design of the given borehole inclinometer are found, which are saved in the "electronic passport" and participate in the subsequent general algorithm for processing borehole wells measurements aided by specialized software.

The situation is different with the temporal stability of azimuthal scale limb zero direction. The reasons for this are external magnetic field variations caused by disturbances in the natural geomagnetic field and man-made disturbances [8]-[13]. This circumstance is practically not taken into account when performing operations of inclinometers with fluxgate magnetosensitive sensors and leads to knowingly incorrect calibration results.

Undoubtedly, the accuracy of determining the misalignment angles (Fig. 3) directly determines the standardized metrological characteristics of InS and, accordingly, the quality of the obtained results of borehole measurements in general, the reliability of inclinograms.

While there is no external magnetic field perturbations, i.e., $\vec{B}$ = const (by magnitude and direction), the calibrating procedure for the borehole inclinometer and the obtained results can be considered reliable in a certain sense.

If during the calibration process or during a long period of intercalibration procedures geomagnetic disturbances of natural or man-made origin (short-term or long-term) occur [14], [15], accompanied by changes in the space of the resulting vector ($\vec{B} + \Delta\vec{B}$), this will lead to incorrect reproduction of the azimuthal angles ($\alpha_{set} + \Delta\alpha$) by a calibration installation and, as a consequence, incorrect (or rough, i.e., with a large error) determination of the misalignment angles numerical values for a particular inclinometer being calibrated. This circumstance, reflecting the calibration specifics, ultimately significantly affects the quality and competitiveness of inclinometric systems.

Studies of variations in the geomagnetic field, carried out in the regional metrological center of the State Unitary Enterprise "Ural-geo", directly confirm these provisions. In terms of solving this problem, it is proposed to use additional devices that provide real-time monitoring of azimuth scale "zero drift". As such a device can be used a digital magnetic compass [16], [17], rigidly fixed in the space near the calibration facility and having, as a measuring transducer, a steep static "output-input" characteristic in a small range of ± 5 ° with a zero initial position corresponding to "zero" azimuth scale. Fig. 5 shows this device appearance, which operation principle is based on measuring the signal from a magnetically sensitive sensor, which sensitivity axis is initially oriented horizontally and perpendicular to the geomagnetic field flux density vector.

Fig. 5. Appearance of the digital magnetic compass

It should be noted that in this technical solution it is not necessary for strict leveling the magnetosensitive sensor axis, since the functional dependence of the measuring signal itself with a possible range of magnetic field flux density vector variation in azimuth, i.e., in the horizontal plane, is established a priori. Using this additional device in the general flow chart for the calibration of inclinometric systems downhole tools allows to solve the important problem such as "tracking the zero drift" of the calibration installation azimuthal dial, namely, to increase the accuracy of determining misalignment angles (Fig.3) and, accordingly, numerical values of constants involved in the general algorithm for processing the results of downhole measurements. Such solution, of course, is quite promising in terms of ensuring the reliability of calibration operations, taking into account the features of inclinometric systems with fluxgate sensors, and is recommended for direct use in metrological services of organizations specializing in the creation and practical application of such equipment in geophysical studies of wells.

IV. CONCLUSIONS

Thus, the accuracy of the inclinometric systems calibration directly depends on the installation accuracy and the temporal stability of azimuth scale dial zero of the calibration installation. The reasons for the appearance of deviations in the azimuth scale are variations in the external geomagnetic field caused by natural disturbances in the magnetic environment on the Earth's surface and man-made disturbances. This circumstance is practically not taken into account when performing calibration operations for inclinometers with fluxgate magnetosensitive sensors and leads to incorrect calibration results, which can subsequently lead to significant financial losses when geophysical surveys of wells are provided.

Therefore, it is necessary to carefully monitor the state of the geomagnetic field both immediately before the calibration procedure and during the main process. For this, it is proposed to use additional precision equipment capable to track the direction of the resulting magnetic field flux density vector at the site of the inclinometric systems calibration procedure. Especially for these purposes, a digital magnetic compass was developed and created, which is installed directly on the rotary mechanism of the calibration installation and allows measuring the azimuth angle in a small range of ± 5 ° with a zero initial position corresponding to the "zero" of the azimuth scale of the calibration installation. When registering deviations in the azimuth readings of the magnetic compass and the scale of the calibration installation, it is necessary to stop the calibration procedure, or to correct the azimuthal angles for stationary inhomogeneities of the geomagnetic field in the working area of the calibration installation.

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