**Research And Development of Vibration-Resistant Inclinometric Transducers for Control and Monitoring Systems**

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**Abstract.** One of the important tasks discussed in the article is the development of automated process control systems for drilling oil and gas wells (APCS-Drilling), which make it possible to increase labor productivity and improve the quality of operations. At present, directional and inclined drilling is becoming increasingly widespread. Drilling of directional and inclined wells is significantly more complex than single-bore vertical drilling and involves a large amount of in clinometric work for measuring well parameters. An important reserve for improving labor productivity in drilling is the development of automatic control systems (ACS) for drill tool orientation, as one of the subsystems of APCS-Drilling, which enhance the accuracy of wellbore trajectory and ensure savings in both material resources and time.

**INTRODUCTION**

The implementation of automatic control systems (ACS) for drill tool orientation is hindered by the lack of primary inclinometric transducers (IT) that meet the specific requirements imposed by the control system in terms of vibration resistance - namely, the ability to provide accurate information about the well trajectory parameters and the position of the deflecting device under conditions of strong vibration and shock loads [1-5].

To enhance the vibration resistance of inclinometric transducers, it is necessary to reduce the natural oscillation frequency of the sensitive elements (pendulums) of the IT relative to the vibration frequency. In known transducers, the natural oscillation frequency of the sensitive elements lies within the range of , which results in an additional conversion error of the zenith angle exceeding . Consequently, such transducers can only perform discrete measurements - when the drilling process is stopped - which makes their use in automatic control systems for drill tool orientation difficult. Therefore, it becomes necessary to conduct research on primary inclinometric transducers that meet the specific vibration resistance requirements of automatic drill tool orientation control systems.

The analysis of inclinometric transducers for measuring the zenith angle and the deflector setting angle shows that most existing studies focus on various designs of transducers based on a physical pendulum, their kinematic schemes, and experimental investigations. For automatic control systems (ACS) of drill tools, vibration-resistant transducers with a low natural oscillation frequency based on a liquid pendulum are considered more promising. Thus, the research and development of vibration-resistant inclinometric transducers for drill tool control systems is a relevant and significant task [6-8].

A generalized mathematical model of vibration-resistant liquid inclinometric transducers has been developed. This model encompasses a wide range of liquid-based inclinometric transducers that use a liquid pendulum consisting of communicating vessels and a connected tube arbitrarily laid in the plane of the frame. The mathematical model represents a set of second-order differential equations with variable coefficients, describing the motion of the frame and the free surface of the liquid, taking into account the inertial forces and moments acting on the pendulums of the transducer as a result of vibration-induced motion [9].

**EXPERIMENTAL RESEARCH**

It has been shown that the developed mathematical model makes it possible to quantitatively assess the influence of vibration on the accuracy characteristics of inclinometric transducers and to analyze the operational patterns of the devices - specifically, the dependence of the natural oscillation frequency on design parameters. This, in turn, enables the use of the model in the synthesis of vibration-resistant liquid inclinometric transducers intended for measuring the zenith angle of the well and the deflector setting angle within automatic control systems for drill tool orientation [10-14].

A new class of vibration-resistant inclinometric transducers with low natural oscillation frequencies of pendulums based on a liquid-filled tube has been developed. It has been established that:

a) Increasing the length of the liquid-filled tube up to 12 m by implementing the liquid pendulum in the form of communicating vessels-under strict constraints on the transducer housing’s diametral dimensions-makes it possible to reduce the natural oscillation frequency of the liquid pendulum to . At the same time, the constant component of the additional error caused by vibration decreases to degrees [15,16].

b) The vibration resistance of liquid inclinometric transducers in the vibration frequency range of and at vibration accelerations up to increases by an order of magnitude compared with inclinometric transducers based on a physical pendulum suspended on supports with dry friction. This improvement makes it possible to meet the specific vibration resistance requirements of automatic control systems for drill tool orientation [17].

A refined analytical relationship has been obtained for the constant component of the additional error caused by vibration overloads (η) and the value of - the ratio of the natural oscillation frequency of the inclinometric transducer pendulum to the vibration frequency. It has been shown that, to improve the accuracy of vibration resistance calculations for inclinometric transducers, the formula determining the additional error component due to base vibration must include a term representing the product of the fourth powers of a small parameter and a large parameter [18-21].

It has been established that the use of the refined analytical relationship in both the design process and in the vibration resistance analysis of existing inclinometric transducers increases the accuracy of engineering calculations by ten percent. This improvement makes it possible, at the design stage, to enhance the accuracy characteristics of existing transducers and render them applicable in automatic control systems for drill tool orientation from the standpoint of vibration resistance. Consequently, it increases the accuracy of wellbore trajectory tracking according to the specified profile and also improves the precision of vibration resistance calculations for the developed float-type and liquid-type inclinometric transducers [22].

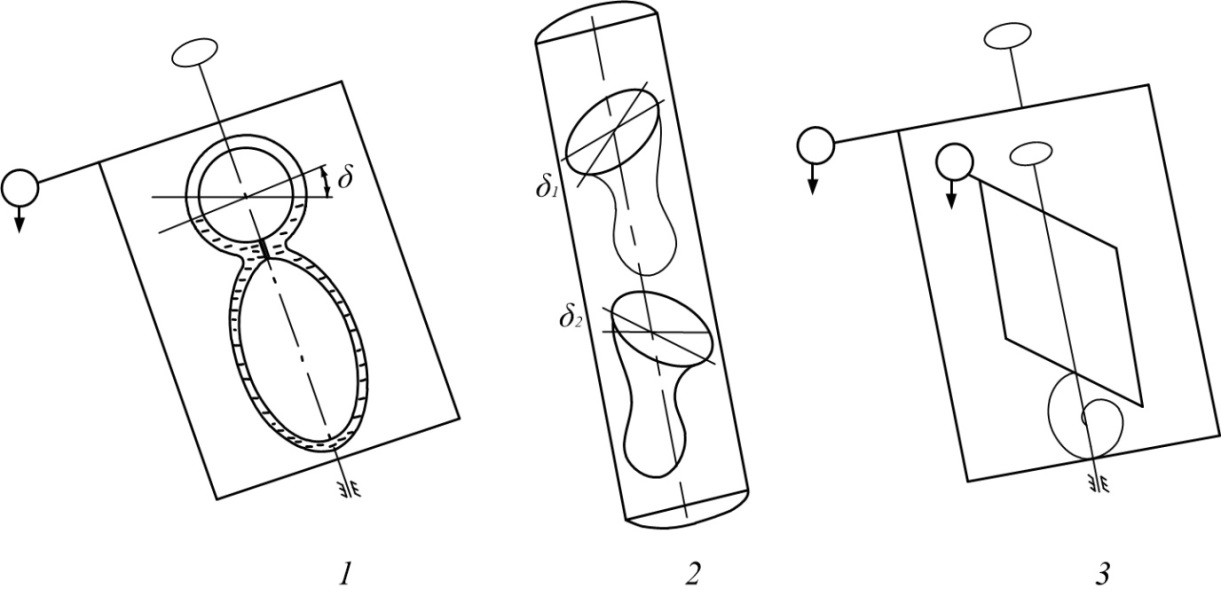
A vibration-resistant two-stage inclinometric transducer with coaxial frames has been investigated. It has been established that the coaxial arrangement of the pendulum frames of the transducer, designed as thick-walled cylindrical floats balanced in terms of buoyancy and trim within the liquid filling the transducer housing, makes it possible to significantly increase the moment of inertia of the pendulum frames and reduce the natural oscillation frequency of the zenith pendulum from to without changing the static moment or the load on the supports, even under strict constraints on the transducer housing diameter imposed by the maximum well diameter [23].

At the same time, the additional conversion error of the zenith angle caused by base vibration decreases from to at vibration accelerations of in the vibration frequency range of , which satisfies the specific vibration resistance requirements of automatic drill tool orientation control systems.

The article presents a review of transducers for measuring the zenith angle and the deflector setting angle. As a result of analyzing the drilling process and operating conditions, the main requirements imposed on inclinometric transducers (IT) by the automatic control system (ACS) for drill tool orientation have been identified [24].

At present, existing industrial transducers do not meet the vibration resistance requirements of drill tool orientation control systems, since they exhibit significant additional errors caused by base vibration (exceeding ). To systematize the designs and kinematic schemes of zenith angle transducers, a classification has been developed based on characteristics that influence the vibration resistance of inclinometric transducers [25].

According to the type of kinematic scheme, vibration-resistant inclinometric transducers can be divided into three groups (see Fig. 1).



**FIGURE 1.** Inclinometric transducers 1, 2, and 3.

The analysis of the kinematic schemes of inclinometric transducers (IT) shows that the presence of a sensitive element responding to the Earth’s gravitational field is essential. At present, only gravitational field transducers containing movable elements are known. Therefore, when developing IT intended to operate during the drilling process, primary attention should be given to ensuring vibration resistance [26].

To achieve vibration resistance in inclinometric transducers, it is necessary to reduce the natural oscillation frequency of the IT pendulums relative to the vibration frequency [27-56]. In existing inclinometric transducers for measuring the zenith angle based on a physical pendulum, it is impossible to reduce the natural oscillation frequency of the zenith pendulum below due to strict constraints on the transducer housing diameter.

More promising for use in automatic drill tool control systems are inclinometric transducers for zenith angle measurement with coaxial pendulum frames and transducers based on a liquid pendulum, whose natural oscillation frequency can be significantly reduced by increasing the length of the liquid-filled tube.

Mathematical models of vibration-resistant inclinometric transducers - to develop a generalized mathematical model of the transducer, the apparatus of matrix theory and continuum mechanics was applied. In this process, orthonormal reference frames were introduced: a fixed reference frame R₀ associated with the vector of the Earth’s magnetic field intensity (EMF), and movable reference frames associated with the following elements: the inclination plane of the well , the well axis , the transducer housing , the frame , and the liquid level .

**RESEARCH RESULTS**

The transducer type IP-1 (see Fig. 1) consists of a frame whose center of gravity is offset from the rotation axis by an eccentric weight. A liquid pendulum in the form of an annular level with a partition and a connected tube - laid arbitrarily in the plane of the frame and symmetrical with respect to the frame’s rotation axis - is fixed inside the frame.

By using Euler’s dynamic equations and the equations of motion for a viscous fluid, a generalized mathematical model of IP-1 has been obtained in the following form:

(1)

where is the angular momentum vector of the frame:

,- the inertia tensor of the frame, - the vector of the frame’s absolute angular velocity; - the moment vector of gravitational forces, - the radius vector of the coordinates of the mass center, - the mass of the weight, - the gravitational acceleration vector; - the moment vector of inertial forces, - the radius vector of the pole 0 of the reference frame.

- vector of frictional torque, - vector of the damping moment, - vector of the moment produced by the pressure forces of the liquid acting on the wall, - radius vector of the liquid level coordinates, p - pressure, - outward normal to the solid wall, *S* - solid wall surface, - velocity vector of the fluid particle, *Ω* - volume of the liquid, *dΩ* - boundary of the liquid, - unit tensor, - strain-rate (deformation-rate) tensor, ρ - density of the liquid, ν - kinematic viscosity coefficient.

It is assumed that the main motion of the fluid is one-dimensional along the tube and that the pressure in each cross-section perpendicular to the tube direction is uniform. By projecting equation (1) onto the coordinate axes of reference frame , a generalized mathematical model of IP-1 has been obtained.

(2)

where β and δ are the angles of rotation of the frame and the liquid level, respectively; α is the projection of the radius vector onto the axis; θ is the zenith angle; φ is the deflector installation angle; is a constant characterizing the tube geometry; is the damping coefficient; and is the length of the tube filled with liquid. Linearized equations of small oscillations of the inclinometric transducers relative to the position of static equilibrium have been obtained. :

(3)

where and are small deviations of the frame and the liquid level from the position of static equilibrium. The expressions for the nominal static conversion characteristics of the inclinometric transducers for zenith angles are obtained from equation (2), assuming

That is, the rotation angles of the frame and the liquid are proportional to the deflector installation angle and the zenith angle of the borehole, respectively. A generalized mathematical model of the inclinometric transducers (Fig. 1) has been obtained, whose kinematic scheme represents two single-degree-of-freedom liquid pendulums with mutually perpendicular axes of rotation, orthogonal to the borehole axis:

(4)

From this, the expressions for the nominal static characteristics of the IP-2 inclinometric transducers were obtained.

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A generalized mathematical model of the IP-3 inclinometric transducer (Fig. 1) has been obtained, whose kinematic scheme consists of two coaxial frame pendulums rotated by 90° relative to each other and connected by an elastic coupling.

(5)

where and are the moments of inertia of the outer and inner frames, respectively; is the elastic coupling coefficient; and are the rotation angles of the outer and inner frames, respectively; and and are the static moments of the outer and inner frames, respectively. Linearized equations of small oscillations of the IP-3 inclinometric transducer have been obtained.

(6)

The expressions for the nominal static characteristics have been obtained.

(7)

Additional errors of vibration-resistant single- and two-degree-of-freedom inclinometric transducers caused by base vibrations have been investigated, and possible ways to reduce them have been considered. The study of the vibration resistance of the inclinometric transducers consisted of solving equations (3,7) and subsequently analyzing the expressions for the additional error resulting from base vibrations of the inclinometric transducers.

To solve the equations, the small parameter method was used. The solution of the first equation of system (3) in the fifth approximation makes it possible to determine the constant component of the additional error caused by base vibration, as well as the periodic component of single-degree-of-freedom inclinometric transducers.

Here, only the constant component of the additional error caused by base vibration in the conversion of the deflector installation angle and the zenith angle for single-degree-of-freedom inclinometric transducers is presented.

(8)

(9)

where are vibration overloads; are the ratios of the natural oscillation frequencies of the pendulums corresponding to the deflector installation angle and the zenith angle to the vibration frequency, respectively; and are the damping ratios.

In expressions (8) and (9), the first two terms of the constant component of the additional error due to vibration are retained, as they contribute the most to the total error value.

The obtained formulas represent an approximate solution of equation (3). To assess their applicability for determining the additional error caused by base vibration, an estimation of the approximation error was performed by directly comparing the solution of system (3), obtained numerically using the Runge-Kutta method in MATLAB, with the analytical results from expressions (8) and (9). The discrepancy between the solutions, in terms of the deviation angles of the pendulums of the inclinometric transducers from the position of static equilibrium, does not exceed .

The constant component of the additional error in the conversion of the zenith angle for the IP-1 inclinometric transducer has been obtained.

(10)

From the analysis of expressions (8), (9), and (10), it follows that the reduction of the constant component of the additional error caused by base vibration can be achieved by decreasing the damping ratio and the value of , which represents the ratio of the pendulum’s natural oscillation frequency to the vibration frequency.

The constant components of the additional error in the conversion of angles caused by base vibration have been obtained for two-degree-of-freedom inclinometric transducers.

(11)

(12)

The discrepancies between the obtained solutions (11) and (12) and those obtained using the MATLAB program, in terms of the deviation angles of the pendulums of the inclinometric transducers from the position of static equilibrium, do not exceed .

From the analysis of expressions (11) and (12), it follows that the additional error caused by vibration in two-degree-of-freedom inclinometric transducers depends on the ratio of the moments of inertia and the oscillation frequencies of the inner and outer frames, and it decreases when the moment of inertia and the natural frequency of the inner frame are reduced relative to the outer one.

A comparative analysis of the oscillations of single-and two-degree-of-freedom inclinometric transducers shows that the presence of an inner gimbal frame does not affect the nature of the error; however, it increases the magnitude of the constant deviation of both the inner and outer frames. At the same time, the error of the two-degree-of-freedom inclinometric transducers, like that of the single-degree ones, can be reduced by lowering the natural oscillation frequencies of the frames.

Techniques for improving the vibration resistance of inclinometric transducers have been developed. The results of theoretical studies show that to enhance the vibration resistance of inclinometric transducers based on a physical pendulum, the following methods can be applied: optimization of the pendulum shape and increasing the pendulum’s moment of inertia by designing it as an elongated thick-walled cylindrical float. To improve the vibration resistance of liquid inclinometric transducers, it is necessary to increase the length of the liquid-filled tube and use liquids with higher viscosity.

**CONCLUSIONS**

As a result of the analytical study of additional errors caused by vibration, as well as the development of algorithms and programs based on it for the sensitive elements of vibration-resistant inclinometric transducers, a design methodology for vibration-resistant inclinometric transducers has been developed. This methodology allows, at the stage of preliminary design, using computational tools, to optimize the structure of inclinometric transducers within conventional design solutions or to apply original designs of vibration-resistant inclinometric transducers intended for continuous monitoring of the zenith angle and the deflector installation angle in automatic drilling control systems.

Thus, a generalized mathematical model of vibration-resistant liquid inclinometric transducers has been developed, taking into account the viscosity of the liquid and the effects of inertial forces and moments arising from vibration-induced motion of the transducer. This model enables the analysis of operational patterns and the dependence of the vibration resistance of inclinometric transducers on design parameters. A vibration-resistant transducer with coaxial frames has been investigated. It has been established that the coaxial arrangement of the frames allows, within limited diameter dimensions of the transducer body, by designing the pendulum frames as elongated thick-walled cylindrical floats, to significantly increase the moments of inertia of the pendulum frames and reduce the natural oscillation frequency of the zenith pendulum to .

As a result, the additional error in converting the zenith angle caused by base vibration decreases to at vibration accelerations up to within the vibration frequency range of .

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