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CONSIDERATION OF THE ISSUE OF REGULATING LOW-FREQUENCY VIBRATIONS OF THE DRILL STRING WHEN DRILLING WITH A DOWNHOLE MOTOR

The object of research is the dynamic processes that occur in the drill string during the deepening of the hole in deep wells. The work is aimed at solving the problem for an idealized system in the form of rod systems while preserving its main oscillatory properties.

The nature of oscillatory processes that occur in the drill string during drilling with downhole motors is considered, in some cases it turns out to be very complicated. In the general case, the dynamic process changes according to an aperiodic law, which is superimposed by processes of an oscillating nature with an increasing (damping) nature of the amplitudes of different frequencies.

The influence of the torque characteristics of the downhole motor and bit on the development of oscillatory processes in the drill string during well drilling has been theoretically determined.

The results of theoretical and experimental studies of oscillatory processes and their interaction with the use of proposed models of hole deepening in the future make it possible to create a simulation model. This model would include taking into account the mode parameters of drilling, the mechanical properties of the rocks to be drilled and the layout of the drill string bottom (DSB).

The obtained research results can be applied in practice in the process of designing the structure of the drill string bottom (DSB) with the use of downhole motors, in particular, screw motors, the use of which leads to energy stress, the complication of work processes and structural schemes. As a result, the nature of vibrations changes and the vibration loads on parts of the downhole motor, bits and elements of the drill string are reduced.

In the future, it is necessary to take into account the hydrodynamics and the type, as well as the design and parameters of the applied downhole elements for the development of their dynamic models.

Keywords: *drill string, downhole motor, bit, low-frequency oscillations, oscillatory processes, hole deepening.*

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1. Introduction

Efforts to improve the performance of drilling with downhole motors, in particular screw motors, lead to energy tension, complication of work processes and design schemes [1–3]. As a result, the nature of the vibrations becomes more complicated and the vibration loads on the parts of the downhole motor, bits and elements of the drill string increase.

Adjusting the vibration loads on the elements of the drill string when drilling with downhole motors on the one hand makes it possible to increase drilling performance, and on the other hand, under certain conditions, to increase the reliability of its elements and the string as a whole [4–6].

The complexity of oscillatory (vibration) processes that occur in the drill string during the deepening of the hole lead to the dominance of the experiment. It follows from this that adjusting the vibration state of the drill string, taking into account the improvement of drilling performance or the improvement of operational reliability, requires a skillful combination of calculation and experimental methods [7–9].

The vibration of the drill string is its reaction to the action of disturbing forces. The characteristic and magnitude of the reaction depends on many factors, in particular, on the design of the downhole motor, the design of the spindle, the geological and technical conditions of deepening the downhole, the composition of the heavy bottom as an oscillating system, etc. [10–12].

An exhaustive study of the oscillatory processes of the drill string is impossible neither experimentally nor theoretically, due to the specifics of the well depth, geological conditions of drilling, the shape of the drill string, etc. [11, 13, 14].

Therefore, it is relevant to study the processes occurring in the drill string during well drilling.

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Thus, the dynamic processes occurring in the drill string during the deepening of the hole in deep wells were chosen as *the object of research*. *The aim of research* is to obtain a solution to the problem for an idealized system in the form of rod systems while preserving its main oscillatory properties.

2. Materials and Methods

In order to rationally work out the reaches when drilling with downhole motors (screw motors), it is important to take into account the dynamic loads that are transmitted from the disturbed column through the motor body, its spindle and the bit guide. The intensity of wear of the supports of the chip bit depends not only on the influence of low-frequency component vibrations, but also on high-frequency oscillations caused by cavitation phenomena, which occur when the flushing liquid flows through the nozzle of the bit and the interaction of the jet with the hole.

Under the action of the rotating vector of the unbalanced force of the rotor of the reciprocating motor, each point of its body describes a circle, an ellipse, or another closed figure in a plane perpendicular to the axis of rotation. The linear displacement of each point of the body in the radial direction follows a harmonic law with the frequency of rotation of the rotor. The radial casings of the downhole motor are transformed into longitudinal oscillations of its ends, which disturb the longitudinal oscillations of the drill string. In turn, the oscillating process generates a pulsation of the axial load, which is transmitted to the bit. In addition, significant fluctuations can be caused by the mutual influence of torsional and transverse vibrations of the rotor of the reciprocating motor. As a rule, their frequency is proportional to the rotation frequency of the bit. On the other hand, the falling moment characteristic of the bit can cause the occurrence of intense low-frequency vibrations of the drill string and lead to the occurrence of a pothole-like bump, and as a result, to resonance phenomena. Thus, the bit supports are loaded with variable loads in a wide frequency spectrum (from tens of Hz to hundreds of Hz). In the case of reciprocating motors, especially a turbo-drill, the power connections between the rotor and the stator (fluid link) do not allow the equation of the connection to be obtained with the help of the equations of statics, and therefore the equations of dynamics have to be applied.

Fig. 1 shows the mechanical characteristics of reciprocating motors.

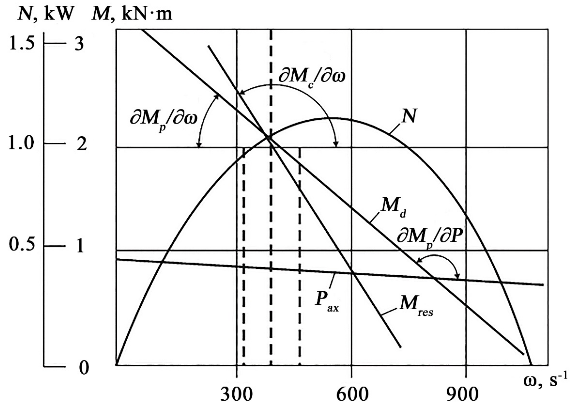

Fig. 1. Dependence of power N, driving torque M_d, axial load P_{ax} and shaft resistance moment M_{res} on angular velocity [12]

In the process of regulation, the M_d and M_{res} characteristics are not used on all intervals of ω and P, but only within certain limits. The limits of the change of ω are highlighted by dashed lines. Then it can be emphasized that the dependence of the angular speed of the turbodrill shaft on the set value ω_0 changes by a small value $\Delta\omega$ (Fig. 1).

Therefore, the real nonlinear characteristics within the defined limits of the change of variables are replaced by linear ones.

3. Results and Discussion

Let's consider the issue of the interaction of all three elements of the drill string: bit – downhole motor – drill string. The task of building such a dynamic model of a real system is multifaceted and its solution depends on the class of processes being studied. In connection with the fact that there is a problem of the possibility of self-oscillations in the drill string, which occur in real drilling conditions, especially in hard rocks with very low frequencies, let's adopt the dynamic model of the downhole motor as a system with concentrated parameters. Based on this position, the differential equation of motion will be written:

$$J\frac{d\omega}{dt} = M_{mot}(\omega, P) - M_{res}(\omega, P), \quad (1)$$

where J – the moment of inertia of the motor rotor; ω – angular speed of the rotor (spindle shaft and bit); $M_{mot} = M_{mot}(\omega, P)$ – the torque developed by the reciprocating motor; $M_{res} = M_{res}(\omega, P)$ – moment of resistance on the bit; P – axial load on the bit.

In the process of deepening the well, a dynamic component is superimposed on the static component of the axial load:

$$P = P_{st} - \Delta P_d. \quad (2)$$

Taking into account the deformation properties of the drill string, the rod system ΔP_d can be represented as:

$$\Delta P_d = EF\frac{\partial U_d}{\partial x}. \quad (3)$$

Then expression (2) will be written:

$$P = P_{st} - EF\frac{\partial U_d}{\partial x}. \quad (4)$$

Rewriting equation (1) taking into account (4), let's obtain:

$$J\frac{d\omega}{dt} = M_{mot}\left(\omega, P_{st} - EF\frac{\partial U_d}{\partial x}\right) - M_{res}\left(\omega, P_{st} - EF\frac{\partial U_d}{\partial x}\right), \quad (5)$$

where U_d – the dynamic longitudinal displacement of the column sections; E – Young's modulus of the first kind; F – the cross-sectional area of the column.

A combined consideration of graphical dependencies: axial load, rotation frequency of the shaft of the drilling motor, its momentary characteristics, momentary characteristics of the bit [6, 14] in the first approximation makes it possible to write analytical dependences between power and kinematic parameters of motion:

$$P = P_T\left(1+\frac{\omega}{\omega_{\max}}\right), \quad (6)$$

or

$$\omega = \omega_{\max}\left(1+\frac{P}{P_T}\right). \quad (7)$$

Considering (4) and (7), it is possible to write:

$$\omega = \omega_{\max}\left(1+\frac{P_{st}}{P_T}\right)-\omega_{\max}\frac{EF}{P_T}\frac{\partial U_d}{\partial x}, \quad (8)$$

where $\omega_{\max}$ – the angular speed of idle rotation of the motor spindle; P_T – axial load, which corresponds to the braking torque of the motor.

Similarly, it is possible to write:

$$M_{mot} = M_T\frac{P_{st}}{P_T}\left(1-\frac{EF}{P_{st}}\frac{\partial U_d}{\partial x}\right). \quad (9)$$

Let's present the moment of resistance on the bit as:

$$M_{res} = M_{res}(\omega,P) = M_{res}(\omega,P_{st}+\omega,\Delta P_d). \quad (10)$$

Under the condition of continuous operation of the bit and the absence of a pothole-like pothole, it is possible to record at $P \geq \Delta P_d$:

$$M_{res} = M_{res}(P,\omega_{st}+P,\omega_d) \approx$$
$$\approx M_{res}(P,\omega_{st})\omega_d + M_{res}(P,\omega_{st}), \quad (11)$$

where ω_d – the dynamic component of the angular velocity.

Let's take the time derivative of expression (8):

$$\frac{d\omega}{dt} = -\omega_{\max}\frac{EF}{P_T}\frac{\partial}{\partial x}\frac{d}{dt}U_d, \quad (12)$$

or taking into account that $dU_d/dt = V_d$ – the dynamic component of the mechanical speed, let's obtain:

$$\frac{d\omega}{dt} = -\omega_{\max}\frac{EF}{P_T}\frac{\partial V_d}{\partial x} = \varepsilon_0. \quad (13)$$

Substituting (9), (11) and (13) into (5), let's finally obtain:

$$\frac{\partial V_d}{\partial x} = -\left(\frac{M_T}{J\omega_{\max}}-\frac{M'_{A\omega}}{J}\right)\frac{\partial U_d}{\partial x}. \quad (14)$$

Expression (14) is an equation of the relationship between the dynamic and kinematic parameters of the system. It should be noted that the value $M_{res,\omega} = \partial M_{nres}/\partial\omega$, is the main loading indicator of the bit mode according to the main kinematic indicator of the latter and depends on the design of the bit, the properties of the rock being drilled, etc.

The equation of longitudinal oscillations of a one-piece drill string, as a homogeneous rod, is written:

$$\frac{\partial^2 U_d}{\partial t^2} = \gamma^2\frac{\partial^2 U_d}{\partial x^2}, \quad (15)$$

where γ – the propagation speed of an elastic longitudinal wave; x – longitudinal coordinate.

Differentiating the right and left parts of (14) in time, let's obtain:

$$\frac{\partial^2 V_d}{\partial t^2} = \gamma^2\frac{\partial^2 V_d}{\partial x^2}. \quad (16)$$

Assuming that the drill string is modeled as a rod with distributed parameters, which is suspended on an elastic beam system with stiffness h, the boundary conditions at the upper end will be:

$$x=0;\ \frac{\partial V_d}{\partial x} = hU_d \rightarrow \frac{\partial V_d}{\partial x} = hV_d. \quad (17)$$

Boundary conditions for the lower end (bow):

$$x=H;\ \frac{\partial V_d}{\partial x\partial t} = -\left(\frac{M_T}{J\omega_{\max}}+\frac{M'_{res}(\omega)}{J}\right)\frac{\partial V_d}{\partial x}, \quad (18)$$

denote:

$$A = \frac{M_T}{J\omega_{\max}}+\frac{M'_{res}(\omega)}{J}. \quad (19)$$

Initial conditions:

$$t=0; V_d = \frac{dU_d}{dt} = 0;\ x=H;\ \frac{\partial V_d}{\partial x} = \frac{P_T\varepsilon_0}{\omega_{\max}EF} = \delta_0. \quad (20)$$

Applying the Laplace transform, let's obtain:

$$V'' - \left(\frac{P}{x}\right)^2 V = 0, \quad (21)$$

where

$$V(x,P) = C_1\sinh\frac{P_x}{x}+C_2\cosh\frac{P_x}{\gamma}. \quad (22)$$

From the boundary conditions (17) and (18), let's determine the constant integrations C_1 and C_2:

$$\frac{\partial V_d}{\partial x} = \frac{P_x}{x}\left(C_1\cosh\frac{P_x}{x}+C_2\sinh\frac{P_x}{\gamma}\right). \quad (23)$$

Considering (18), let's obtain:

$$C_2 = \frac{P}{\gamma h}C_1. \quad (24)$$

After simple transformations, let's obtain:

$$C_1 = \frac{\delta_0\gamma}{P(P+A)\left(\cosh\frac{PH}{x}+\frac{P}{\gamma h}\sinh\frac{PH}{\gamma}\right)}, \quad (25)$$

where C_2 are obtained by direct substitution (25) in (24). And finally let's obtain:

$$V(x,t) = \frac{\delta_0\gamma\left(\sinh\frac{P_x}{x}+\frac{P}{\gamma h}\cosh\frac{P_x}{\gamma}\right)}{P(P+A)\left(\cosh\frac{PH}{x}+\frac{P}{\gamma h}\sinh\frac{PH}{\gamma}\right)} = \delta_0\gamma\frac{F_1(P)}{F_2(P)}, \quad (26)$$

where

$$F_1(P)=\frac{\sinh\frac{P_x}{x}+\frac{P}{\gamma h}\cosh\frac{P_x}{\gamma}}{P}, \quad (27)$$

$$F_2(P)=(P+A)\left(\cosh\frac{PH}{x}+\frac{P}{\gamma h}\sinh\frac{PH}{\gamma}\right). \quad (28)$$

According to the second decomposition theorem, there is:

$$\frac{F_1}{F_2}\to\frac{F_1(0)}{F_2(0)}+\sum\frac{P_1(P_n)}{P_m F_2'(P_n)}e^{P_n t}. \quad (29)$$

Let's mark $P=\lambda i$.

After a number of transformations, let's obtain:

$$V(x,t)=\delta_0 x\frac{\frac{1}{x}+\frac{1}{x}h}{A}-\frac{\sinh\frac{Ax}{\gamma}+\frac{A}{\gamma h}\cosh\frac{Ax}{\gamma}}{A^2\left(\cosh\frac{AH}{\gamma}+\frac{A}{\gamma h}\sinh\frac{AH}{\gamma}\right)}e^{-At}-$$

$$-2\frac{x}{h}\sum\frac{\left(\sinh\frac{\lambda_n x}{\gamma}+\frac{\lambda_n}{\gamma h}\cosh\frac{\lambda_n x}{\gamma}\right)\sin(\lambda_n t+\varphi)\gamma}{\sqrt{A^2+\lambda_n^2}\lambda_n^2\left(\sinh\frac{\lambda_n x}{\gamma}+\frac{\lambda_n}{\gamma h}\cosh\frac{\lambda_n H}{\gamma}\right)}, \quad (30)$$

where $\tan\varphi=A/\lambda$.

The nature of processes corresponding to equation (30) can be very complex. In the general case, the change $V(x,t)$ takes place according to an aperiodic law, which is superimposed by oscillatory processes with increasing or constant amplitudes.

The process caused by the aperiodic term $A<0$ increases monotonically, and decreases monotonically with $A>0$.

Thus, the moment characteristics of the bit and the downhole motor affect the nature of the longitudinal and torsional vibrations of the drill string.

The obtained dependence makes it possible to investigate the stability of the movement of the drill string and to assume the possibility of the occurrence of low-frequency oscillations under the influence of the mathematical model of the elementary disturbance.

Based on the analysis of the first term (30), it can be concluded that when $A<0$, the vibrations of the drill string increase monotonically, which is related to the axial load, the moment characteristics of the bit and the turbo drill bit. Low-frequency oscillations can be expected during the drilling process. When $A>0$, low-frequency oscillations decrease monotonically. It is possible to expect a «calm» drilling process.

The second term reflects the occurrence of vibrational processes that are associated with the vibrations of the drill string, mostly at high frequencies, which mainly affect the process of «tooth-rock» interaction.

Therefore, the decreasing nature of the momentary characteristics of the bit and turbo drill is one of the main reasons for the occurrence of undesirable low-frequency vibrations of the drill string.

The obtained main provisions of the above analysis can be used to develop a technique for eliminating low-frequency oscillations.

Using the obtained dependencies and the similarity of longitudinal and torsional oscillations, after a number of transformations, for the torsional oscillations of a two-syllabic drill string, it is possible to write:

$$\omega_d=\omega_1(t,H_0)=\frac{\lambda b_n}{\lambda b_n+GJ_p}\delta\Phi_0\left[1-e^{-\frac{1}{J}\left(b_n-\frac{GJ}{\lambda}\right)}t\right](-1)^n,$$

$$2n\le t\le(n+1)\frac{H_0}{\lambda}. \quad (31)$$

Examining the stability of the drill string according to expression (31), it is possible to see that at $b_n-(GJ_p/\lambda)<0$ oscillations are constantly increasing and resonance is possible. The forecast shows that the selected mathematical drillability model for the given geological and technical conditions is not suitable for obtaining real drilling performance. For normal operation of the model, it is necessary to change the drilling modes or the drill string bottom structure (DSBS).

The obtained results of research can be applied in practice in the process of designing DSBS using reciprocating motors, in particular screw motors, the use of which leads to energy stress, complication of work processes and design schemes. As a result, the nature of vibrations changes and the vibration loads on parts of the downhole motor, bits and elements of the drill string are reduced.

In the future, it is necessary to take into account the hydrodynamics and type, as well as the design and parameters of the applied drilling elements for the development of their dynamic models.

4. Conclusions

It is shown that the nature of the oscillatory processes that occur in the drill string during drilling with downhole motors is in some cases very complex. In the general case, the dynamic process changes according to an aperiodic law, which is superimposed by processes of an oscillating nature with an increasing (damping) nature of the amplitudes of different frequencies.

The influence of the torque characteristics of the downhole motor and bit on the development of oscillatory processes in the drill string during well drilling has been theoretically determined.

The results of theoretical and experimental studies of oscillatory processes and their interaction with the use of the proposed models of hole deepening, in the future, make it possible to create a simulation model that would include taking into account the regime parameters of drilling, the mechanical properties of the rocks to be drilled and DSBS.

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Conflict of interest

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating this work.

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