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JUSTIFICATION OF THE TECHNOLOGICAL PARAMETERS CHOICE FOR WELL DRILLING BY ROTARY STEERABLE SYSTEMS

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Paper presents the analysis of the investigation results of vibrational accelerations and beating amplitudes of the downhole drilling motor, which help to define the ranges of optimum energy characteristics of the gerotor mechanism, ensuring its stable operation.

Dependencies describing the operation of the «drilling bit – rotary steerable system with power screw section – drilling string» system and the values of the self-oscillation boundaries and the onset of system resonance when it is used jointly, were defined as a result of computational and full-scale experimental research.

A mathematical model is proposed, which allows determining the optimal range of technological parameters for well drilling, reducing the extreme vibration accelerations of the bottomhole assembly by controlling the torque-power and frequency characteristics of the drilling string, taking into account the energy characteristics of the power screw section of the rotary steerable system. Recommendations on the choice of drilling mode parameters were given.

Key words: well drilling; oscillation amplitude; downhole screw motor; drilling string

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Introduction. In recent years, the production of hydrocarbons at large oil and gas fields, which were developed in the 1970s-1980s, has noticeably decreased. Thereby, the amount of drilling wells, aimed at developing areas of the continental shelf, is increasing. The construction of such wells needs complexly constructed design profiles containing intervals which are limited by the radius of curvature or obliquely rectilinear sections of great length, and bore making of these is based on using highly intelligent, both surface and deep equipment [1, 8].

With the current practice of drilling with the use of modern technical and technological methods of borehole making, problems associated with complications and accidents in the well are noted. As technical and technological solution aimed at reducing accidents and improving the quality for extended reach drilling (ERD), rotary steerable systems (RSS) are used. These systems allow directed drilling along the entire length of the well [6]. Now, the using of rotary steerable system (RSS) is more than 15 %.

World leaders in the production of RSS are following enterprises: Baker Hughes, Schlumberger, Halliburton, Weatherford. Currently, in the Russian Federation, these four companies provide the full range of high-tech services RSS + MWD/LWD. Many smaller enterprises have their own development projects: Aps Technology, Gyrodata, National Oilwell Varco, Scientific Drilling, Smart Drilling, Double Barrel RSS, Terravici Drilling Solutions, Renhe Group, BHDC, TIANJIN, ZPEC, etc [4].

However, the existence of complexly constructed well profiles, containing extended obliquely rectilinear sections, which in turn are associated with curved sections of the increasing and decreasing inclination angle with an intensity from 0.5° to 2.5° leads to crippling of the drilling string (DS), uncontrollability of torsional oscillations, causing damage to the directing (controlling) part of the RSS [10-12, 15].

It must be taken into account that, depending on the type of drilling tools, the composition of the borehole assembly (BHA) and the physical and mechanical properties of the rock, as well as the modes of drilling, complex shapes of RSS oscillations arise, which are discrete.

Research on RSS dynamics have revealed that main vibration source is associated with bending and compressive stresses caused by the curvature of the well and the rigidity of the drilling tool, as well as technological drilling parameters. As a result, self-oscillations appear in the BHA, which

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leads to the impossibility of adjusting the azimuth and zenith angles. The change in the rigidity of the bottom part of the drilling tool and the drilling parameters, which involve reducing the rotation frequency of the drilling string and controlling the weight on the bit, partially solves this problem, but the increase in frequency is limited by the technical characteristics of using top drive systems [2].

It should be noted that an increase in the amplitude of torsional vibrations can lead to accidents in the lower part of the BHA. Changing the rigidity of the BHA, for instance, using the material properties of the tool, the length or diametric ratios of drilling pipes, can partially solve this problem and will allow increasing the range of rotation frequency parameters of the top drive from 120 to 140 rpm. Herewith, the controllability of the BHA will decrease, and risk of string sticking and key-seating will increase.

Considered torsional vibrations, which are associated with the rotation of the drilling string, taking into account such factors, as the well profile and the stressed-deformed state of the tool do not give a complete picture of the dynamically active system operation and the causes of the onset of resonance of the system [10, 11].

For a more detailed study of the BHA dynamics with the inclusion of the RSS it is required to study all sources, causing the arising of lateral and axial vibrations. One of such sources is the power screw section, which is installed in the RSS. By virtue of its design feature, this element is presented by a gerotor mechanism that performs its axial and lateral oscillations independent of the DS and drilling bit.

The systems of Baker Hughes Company can be attributed to the RSS, which contain the power screw section: AutoTrak™; AutoTrak Curve™; TruTrak™ and VertiTrak™ vertical drilling systems (see table).

The RSS with the power screw section by Baker Hughes

Conventional drilling systems	Automated drilling systems		Special drilling solutions
Steerable motors	3D Rotary steerable systems	Vertical and low inclination solutions	
Ultra™ Motors	AutoTrak™ Curve	VertiTrak™	CoilTrak™
Ultra X-treme™ Motors	AutoTrak™ eXpress AutoTrak™ G3	TruTrak™	Through-Tubing RotaryDrilling
X-treme™ Motors	AutoTrak™ X-treme	AutoTrak™ V	SureTrak™

The rotation of the DS combined with the RSS, which is represented by a different-rigid length elastic rod, bounded by the walls of the well and located in an variable stressed-deformed state (SDS), causes an arising of complex forms of forced, axial, transverse and torsion oscillations.

Changing frequencies and amplitudes of drilling bit are mathematically difficult to determine. In practice, a three-position accelerometer is located to measure the vibration of the bit in the telemetry system, which allows controlling the acceleration of the BHA [13, 14]. According to the passport data of the equipment used for geophysical survey of the wells, in order to avoid damage to the elements of the drilling string, vibration accelerations from 30 to 45 g are allowable. Maintaining the required vibration accelerations is possible by controlling the dynamics of the system «drilling bit – rotary steerable system with power screw section – drilling string».

Drilling string and a downhole drilling motor, combined into one system, have a different nature of energy transfer. The dynamics of the drilling string is determined by the mechanical energy, which is transmitted from the top drive, while the operation of the power steering section of RSS is based on the conversion of energy by the flow of drilling fluid pumped by the mud pump units.

The presence of combined rotational, lateral, axial and torsion oscillations of the drilling bit, RSS and DS, which exceed the critical range of vibration accelerations, leads to crippling of the drilling tool, negatively affects the formation of the borehole walls, reduces the quality of trajectory control, and also increases the risk of emergencies represented by unscrewing of the threaded connection and the destruction of the BHA elements.

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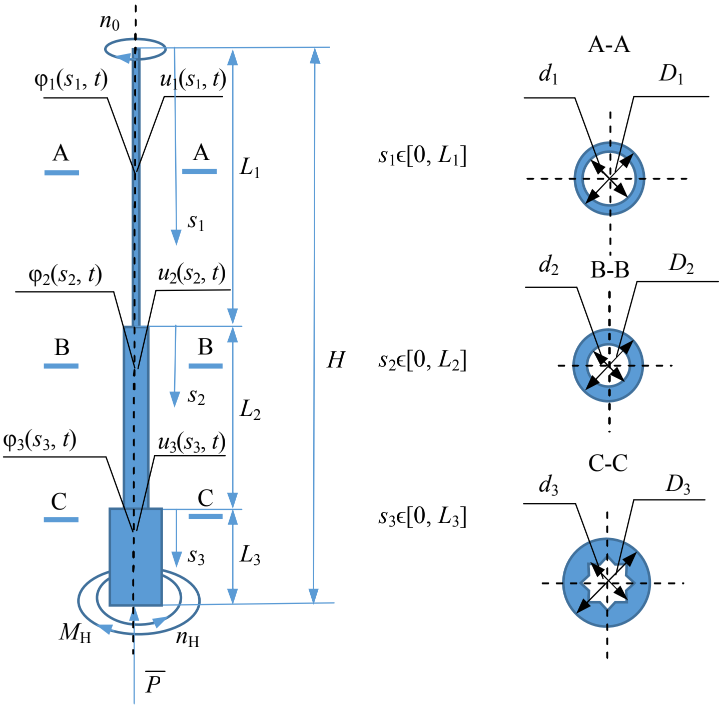

Fig.1. Calculation model of «bottom hole motor – drilling string» system dynamics

Maintaining a stable operation of the RSS by regulating the dynamics of the drilling string, the power screw section, taking into account the destruction of the rock by drill bit, will increase the efficiency of well drilling.

Methodology and research results. In order to research the limits of self-oscillations of the «drilling bit – RSS with power screw section – drill string», in the process of translation a rotational movement to it so to deepen the bottom hole, mathematical model proposed by E.K.Yunin and V.K.Khegay was enhanced [7].

The calculation model for analyzing the behavior of a drilling tool is presented in Fig.1.

As a result of theoretical studies, the conditions for the development of torsional self-oscillations and the limits of the drilling tool temporary halts so as to identify the values of the parameters of the stable operation mode of the dynamically active system were specified [5, 7]:

$$\begin{cases} P = \dfrac{G_3 J_3}{\lambda_3}\left(n_0^{\,2}\right)\dfrac{1+ke^{\frac{\mu_3 L_3}{2\lambda_3}}}{1-ke^{\frac{\mu_3 L_3}{2\lambda_3}}}; \\[2ex] P_{\text{в}} = \dfrac{1+ke^{\frac{\mu_3 L_3}{\lambda_3}}\;P\left(ch\left(\frac{\mu_1 L_1}{2\lambda_1}+\frac{\mu_2 L_2}{2\lambda_2}+\frac{\mu_3 L_3}{2\lambda_3}\right)+kch\left(\frac{\mu_1 L_1}{2\lambda_1}-\frac{\mu_2 L_2}{2\lambda_2}-\frac{\mu_3 L_3}{2\lambda_3}\right)\right)}{1-ke^{\frac{\mu_3 L_3}{\lambda_3}}\;n_0\left(sh\left(\frac{\mu_1 L_1}{2\lambda_1}+\frac{\mu_2 L_2}{2\lambda_2}+\frac{\mu_3 L_3}{2\lambda_3}\right)+ksh\left(\frac{\mu_1 L_1}{2\lambda_1}-\frac{\mu_2 L_2}{2\lambda_2}-\frac{\mu_3 L_3}{2\lambda_3}\right)\right)}; \\[2ex] P_{\text{н}} = \dfrac{1+ke^{\frac{\mu_3 L_3}{\lambda_3}}\;P\left(sh\left(\frac{\mu_1 L_1}{2\lambda_1}+\frac{\mu_2 L_2}{2\lambda_2}+\frac{\mu_3 L_3}{2\lambda_3}\right)+ksh\left(\frac{\mu_1 L_1}{2\lambda_1}-\frac{\mu_2 L_2}{2\lambda_2}-\frac{\mu_3 L_3}{2\lambda_3}\right)\right)}{1-ke^{\frac{\mu_3 L_3}{\lambda_3}}\;n_0\left(ch\left(\frac{\mu_1 L_1}{2\lambda_1}+\frac{\mu_2 L_2}{2\lambda_2}+\frac{\mu_3 L_3}{2\lambda_3}\right)+kch\left(\frac{\mu_1 L_1}{2\lambda_1}-\frac{\mu_2 L_2}{2\lambda_2}-\frac{\mu_3 L_3}{2\lambda_3}\right)\right)}; \\[2ex] n_0^{*} = \dfrac{1-k^2}{sh^2\left(\frac{\mu_1 L_1}{2\lambda_1}+\frac{\mu_2 L_2}{2\lambda_2}+\frac{\mu_3 L_3}{2\lambda_3}\right)+kch^2\left(\frac{\mu_1 L_1}{2\lambda_1}-\frac{\mu_2 L_2}{2\lambda_2}-\frac{\mu_3 L_3}{2\lambda_3}\right)}, \end{cases}$$

where L_1 – drilling string length, m; L_2 – drill-collar string length, m; L_3 – length of the RSS with power screw section, m; k – coefficient of torsional wave reflection at the interface of dissimilar sections of a composite rod,

$$k = \frac{k_1 - k_2}{k_1 + k_2},\quad k_1 = \frac{\lambda_2 G_1 J_1 - \lambda_1 G_2 J_2}{\lambda_2 G_1 J_1 + \lambda_1 G_2 J_2},$$

$$k_2 = \frac{\lambda_3 G_2 J_2 - \lambda_2 G_1 J_1}{\lambda_3 G_2 J_2 + \lambda_2 G_1 J_1};$$

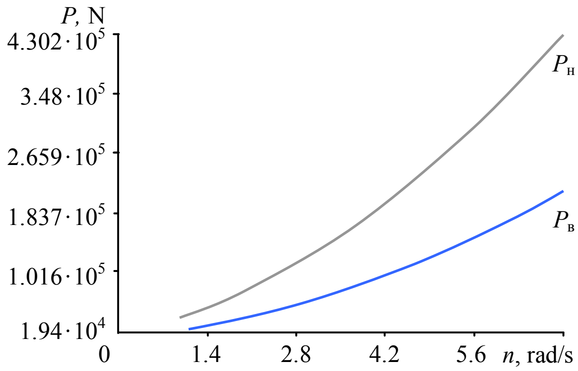

Fig.2. Limits of self-oscillations for «RSS – drilling string» system

μ_1, μ_2, μ_3 – dissipation factor at the corresponding sections; $\lambda_{L_1}, \lambda_{L_2}, \lambda_{L_3}$ – the speed of torsional vibrations propagation in the corresponding sections, m/s; n_0 – rotational speed of the upper end of the string, rad/s; G_1, G_2, G_3 – rigidity modulus of corresponding sections' materials, N·m^2; J_1, J_2, J_3 – polar inertia of the string cross-section in the corresponding sections, m^4; P – axial stress on the lower end of the RSS frame for the case of unstable uniform rotation, N; $P_в$ and $P_н$ – axial stress on the lower end of the RSS frame, corresponding to the upper and lower limits of self-oscillations, N; n_0^* – rotor speed for $P_в = P_н$.

The dependence of the drilling bit weight on the frequency of top drive rotation and the range of the lower and upper limits of self-oscillations is determined according to system mentioned above (Fig.2). Input parameters for simulation:

$$L_1 = 1800 \text{ m}; L_2 = 190 \text{ m}; L_3 = 10 \text{ m}; J_1 = 5.841 \cdot 10^{-6} \text{ m}^4; J_2 = 1{,}941 \cdot 10^{-6} \text{ m}^4; J_3 = 4.928 \cdot 10^{-6} \text{ m}^4;$$

$$k = 0.106;\ G_1 = G_2 = G_3 = 8 \cdot 10^{10} \text{ N·m}^2;\ \lambda_{L_1} = \lambda_{L_2} = \lambda_{L_3} = 3200 \text{ m/s};\ n_0 = [0; 5] \text{ s}^{-1};$$

$$\mu_1 = 0.1;\ \mu_2 = 0.2;\ \mu_3 = 0.3.$$

According to the presented calculations, self-oscillations arise at a rotational speed of the drilling string from 60 to 65 rpm and a weight on the bit 19 kN. In this case, beginning of the upper limit of self-oscillations corresponds to the parameters of drilling – rotational speed of 50 rpm and a load on the bit from 25 to 35 kN.

Analysis of the research results showed that the interval of optimal frequencies of the RSS power screw section frame beating with the lobe of rotor/stator relationship 6/5 is from 35 to 24.5 Hz. When the screw section is in idle mode, the maximum amplitude of the lateral beats of the frame is 5 mm, whereas the amplitude of axial oscillations is not more than 3 mm. During torque producing the amplitude of lateral oscillations of the frame is decreasing to 3.5-4 mm, and the amplitude of the axial vibration is increasing to 8 mm.

Producing of additional torque of up to 4.5 kN·m leads to an increase in the amplitude of the lateral beats of the screw section frame up to 6 mm and a reduction in the longitudinal amplitude to 8 mm. The frequency of the beats is reduced to 24.5 s^{-1} (210 rpm), which is 30 % of the idle mode. With an increase in torque from 4.5 to 9 kN·m, the screw section enters the braking (extreme) mode of operation. As a result, there is an intensive increase in the amplitude of lateral oscillations of the RSS frame from 6 to 10 mm, with a corresponding decrease in the amplitude of axial vibrations from 8 to 2 mm [3].

Comparison of the obtained results on RSS power screw section's oscillations in test bench conditions with the calculated values of the drilling string self-oscillations' limits (Fig.2) will allow determining the range of stable operation of the «RSS – drilling string» system.

In order to provide the stable operation of the «drilling bit – RSS with power screw section– drilling string» system, taking into account the dynamics, it is supposed to use data recorded by measuring devices (three-position accelerometer and gyro compass), which allow determining the vibration of the bit. Knowing the amplitude and vibration acceleration on the bit (depending on the type of bit and the properties of rocks), it is proposed to correct the system calculations in real time.

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a

b

Fig.3. Data from the MWD telemetry system: *a* – axial and lateral vibration accelerations;
b – axial and lateral amplitude of oscillations

Approbation of research results was carried out on the Vyngapurovsk field. The depth of the well is 2250 m. Assembly is as follows: PDC bit with a diameter of 220 mm; Auto Trak system (with Ultra Motors power screw section) with MWD and LWD measuring devices; string of thick-walled drilling pipes with a diameter of 155 mm-20 m; hydromechanical jar with a diameter of 165 mm and a length of 7.36 m; drilling string with a diameter of 140 mm-2204 m.

According to the geotechnical well testing station and downhole sensors, the weight on the bit is from 50 kN, and the rotational speed of the top drive is 130 rpm. At the same time, the received Shock and Vibration data from the accelerometer and gyroscope indicate that the allowable range of lateral vibration accelerations and BHA movements reflecting the same forced and self-oscillations of the system, are exceeded (Fig.3).

According to the accelerometer and gyroscope readings, lateral vibration accelerations range from 45 to 50 g, and lateral vibrations are more than 10 inches. The lateral movements of the BHA by 9-10 inches show that the tool at the installation site of the gyroscope is pressed against the borehole wall. Fig.3 also shows that the discrete length of the BHA half-wave represented by the elastic rod is in constant contact with the borehole wall (maximum displacement of the tool axis from the borehole axis) and without the presence of eccentricity.

Figure 2 reflects the limits of BHA self-oscillations, so it can also be seen that the operation of the «RSS with a power screw section – drilling string» system at set parameters of top drive load and rotation frequency (50 kN and 130 rpm) is in the range of the resonance lower limit (area I).

In order to ensure the stable operation of the system, a gradual increase in the rotational speed to 145-165 rpm (2.75 s^{-1}) is made. As a result, the amplitude of lateral vibrations (area II and III) is reduced to 2.5 inches and the vibration acceleration is no more than 10 g.

Conclusion. Based on the mathematical model, which characterizes the dynamics of the drilling string during rotary drilling and the real-time accelerometer and gyroscope data, a method is proposed for determining and predicting the self-oscillation limits and the onset of the BHA resonance.

Adjusting the range of lateral vibration accelerations and movements of the drilling tool elements, which show match of forced and natural oscillations by changing the weight and torque frequency characteristics of the «drilling bit – RSS with a power screw section – drilling string» system, ensures the consistency of operation of high-intelligence rotary BHA.

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