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RESEARCH ON TECHNICAL AND TECHNOLOGICAL PARAMETERS OF INCLINED DRILLING

Mikhail V. DVOYNIKOV
Saint-Petersburg Mining University, Saint-Petersburg, Russia

An analysis of operational capabilities of inclined drilling equipment and technology is presented. Two options of rotary drilling are reviewed as technical and technological solutions, facilitating construction of wells with difficult profiles. The first option implies that the driver unit of the drill bit is represented by downhole drilling motor, the second one utilizes sophisticated rotary steerable systems.

Practical results of drilling wells with difficult profiles are presented. A quality assessment of drilling is provided through the example of comparing designed and actual trajectories, using different driver units for the drill bit, as well as properties of surrounding rocks, rheology of the drill fluid and other characteristics of dynamically active systems. A range of rotation speed has been determined that allows rotary steerable systems to have minimal oscillation amplitude of the bottom-hole assembly.

Analysis of investigation results showed that the main source of oscillations is linked to bending and compressing stresses, caused by well deviations as well as rigidity of the drilling tool. In effect, in the bottom-hole assembly occur auto-oscillations, making it impossible to correct azimuth and zenith angles. Alteration of rigidity in the bottom part of the tool and drilling parameters, implying reduced rotation speed of the drill string and regulation of drill bit pressure, can partially solve this problem, though increase in rotation speed is limited by technical characteristics of existing top drive systems.

Key words: well drilling, vibrations, downhole drilling motor, rotary steerable system, trajectory

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Introduction. Increasing production of hydrocarbons by means of offshore deposit exploitation and development of previously drilled areas suggests implementation of difficult well profiles, trajectories of which can contain deviating sections with a limited (as low as practicable) radius or hold sections of great length (over 3000 m). Presence of such trajectories is dictated by inaccessibility of oil and gas objects, located, e.g., under residential areas, water reservoirs and nature reserves, or by remoteness from the shoreline [2, 10].

Analysis of practical drilling data for the wells with difficult profiles has shown that in many cases actual penetration trajectory differs significantly from the designed profile. In effect, the well shaft is formed with numerous caves and ledges, complicating advancement of bottom-hole assembly (BHA), whereas deviation intensity and radius of build-and-drop-off sections do not match permissible strength characteristics of drill pipes. Drilling of this sections using downhole drilling motor (DDM) as the only driver unit is nearly impossible. The reason for this, in the first place, is intensive friction between the drill string (DS) and the rock [1].

A technological trick to increase drilling efficiency using DDM is simultaneous periodic or continuous rotation of the drill string by the rotor or top drive [3]. Industrial workers call this method rotary-turbine or combined drilling. Its implementation permits to drill wells of various depths with a wide range of alterations regarding type and properties of drill fluids, parameters of drilling mode, application of drill bits of various sizes and construction [5].

However, existing technology of combined drilling faces certain problems related to instability of DDM, its stoppages as well as accidents (backing off, destruction of DDM elements) of DS array [4, 9]. The main drawback of simultaneous rotation of DDM and DS is impossibility of correcting trajectory of well profile in the process of drilling hold (tangential) sections.

In case of drilling subsequent intervals, located after tangential sections, e.g. build-and-drop-off sections, application of DDM without rotation of DS with simultaneous correction of the trajectory is practically impossible. This happens due to additional friction between the drill bit and

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the rock. Friction prevents the pressure on the drill bit from reaching required level, reduces operational flexibility in managing and controlling trajectory parameters of well profile [7].

Research method. In order to carry out investigations that will identify matches between designed and actual well profiles, using inclinometry data, as well as to optimize operational dynamics of rotary steerable systems, correlation and regression analysis has been used for strain-stress states of the drill bit and drilling parameters with due consideration of spatial deviation of well trajectory.

Range of rotation speed for rotary steerable systems has been optimized basing on deterministic mathematical models, allowing to make reliable predictions about direction and stress indicators of the well.

Results and discussion. Consider an example of drilling an inclined well using DDM as a driver unit for the drill bit. The Table contains inclinometric data for the well of Priobskoye deposit.

Inclinometry for the well of Priobskoye deposit

Vertical depth, m			Angle, °			Displacement, m		Extension, m		Depth along the shaft, m		
From	To	Interval	Initial	Final	Average	In the interval	Total	In the interval	Total	From	To	Total
0	80	80	0	0	0	0	0	0	0	0	80	80
80	395	315	0	40	20	115	115	25	25	80	420	340
395	800	405	40	40	40	342	457	125	150	420	945	525
800	1110	310	40	40	40	262	719	96	246	945	1356	411
1110	1449	339	40	40	40	287	1006	105	351	1356	1800	444
1449	1824	382	40	40	40	323	1328	126	476	1800	2300	500
1824	2162	338	40	24	32	213	1541	62	538	2300	2700	400
2162	2448	286	24	15	20	102	1643	18	556	2700	3004	304
2448	2548	100	15	13	14	25	1669	3	559	3004	3107	103
2548	2648	100	13	11	12	21	1690	2	561	3107	3209	102
2648	2810	162	11	9	10	29	1719	3	564	3209	3374	165

As Table shows, the length of vertical section is 80 m, zenith angle at the end of build section (395 m of vertical depth, 500 m along the shaft) is 40° with maximum deviation intensity no more than 1°/10 m. Along the entire slant-type area – hold section (till vertical depth of 2162 m) – the angle does not exceed 41°. Starting from the depth of 2162 m, the angle is evenly dropping off from 41 to 1°. Intensity in the drop-off section does not go beyond 0.8°/10 m. Total well length along the shaft, taking into account two sections of build and drop-off and a hold section, amounts to 3374 m. Horizontal displacement equals 1719 m.

BHA construction for different drilling intervals:

Interval, m	BHA intervals
0-30	Drill bit 393.7; stabilizer Ø390; drill collars – 9 m
30-80	BIT 295.3; turbo-drill T12RT-240; rigid stabilizer Ø280 mm; drill collars-178; turbo-drill TRO-240; MWD; high-strength lightweight drill pipes-147
80-1356	BIT 295.3; turbo-drill TRO-240; MWD; high-strength lightweight drill pipes-147 – 300 m; drill pipes TBPK – 9000 m
1356-3159	BIT 215.9; engine DRU-178; MWD; drill pipes TBPK-127 – 24.5 m; jar – 6.5 m; high-strength lightweight drill pipes-147 – 75 m; drill pipes TBPK – 1700 m
3159-3374	BIT 215.9; engine DRU-178; MWD; drill pipes TBPK-127 – 24.5 m; jar – 6.5 m; high-strength lightweight drill pipes-147 – 75 m; drill pipes TBPK – 100 m

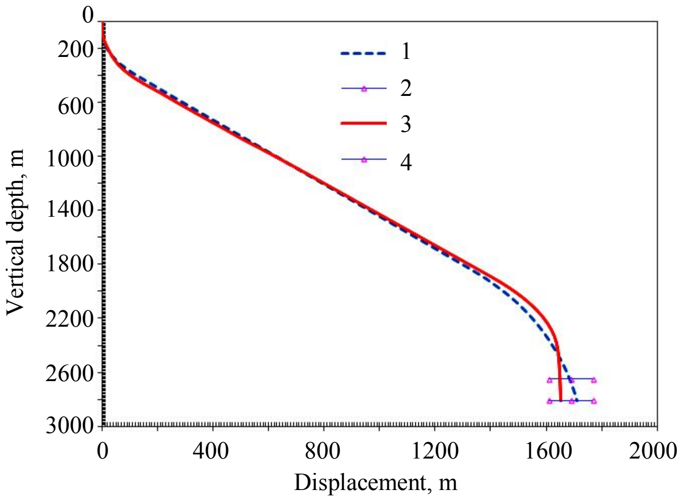

Fig.1. Vertical projection of the well profile N 44197, Priobskoye deposit

1 – trajectory of actual profile; 2 – pay top; 3 – trajectory of designed profile; 4 – pay bottom

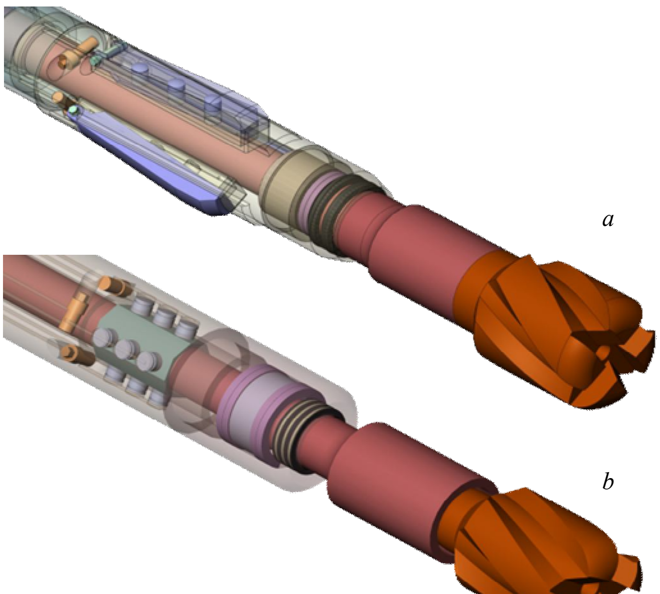

Fig.2. Types of RSS controlling systems: *a* – Push-the-bit; *b* – Point-the-bit

Well construction consists of three casing strings, conductor and surface casings, 0.324 and 0.245 m in diameter, are lowered to the depth of 30 and 800 m respectively. From the depth of 800 m to the hole bottom, diameter of the production casing is 0.146 m. The driver unit for the drill bit (BIT 215.9) is a DDM DRU-178 with a combined method of drilling.

Constant corrections and operational control over the shaft trajectory are carried out using navigation equipment MWD. Preservation of designed trajectory – linear hold section (over 1400 m) has been done by regulating drill bit pressure and rotation speed of the top drive.

Fig.1 demonstrates that the construction project of production wells for Priobskoye deposit (line 3) has a four-interval profile, consisting of a vertical section, section of building-up a zenith angle in the interval of surface casing drilling, a linear hold section and section of evenly dropping-off a zenith angle and entering the productive seam. However, actual profile of the well (line 1) after drilling and inclinometric measurements contained five intervals. Additional section was a linear (vertical) entry into the seam.

Analysis of research results for interpretation of inclinometric data on designed and actual trajectories showed that mismatches between profile trajectories in case of DDM drilling, as well as in cases of periodic or continuous rotation of drill string vary from 15 to 20 % [5]. The most efficient solution to this problem, aimed at quality improvement of designed trajectory implementation, is application of rotary steerable system (RSS) as a driver unit for the drill bit. RSS provide an opportunity to construct wells with a constant rotation of the drill string and simultaneous alteration of azimuth and zenith angles.

It is known that the controlling element of RSS, maintaining intensity of well spatial deviation, is either a mechanical or hydraulic deviating mechanism [8]. The function principle of deviating mechanism defines the type of system. Today the widest application has been found by two control systems: Push-the-bit – radial displacement of the entire array or its major part relative to the well axis – and Point-the-bit – drill bit positioning is attained by displacement of the driving drum relative to the array or by alteration of its deviation (Fig.2).

To analyze RSS performance and quality of profile trajectory implementation, an example of two wells of Priobskoye and Ust-Tegusskoye deposits will be reviewed. Both wells have a horizontal ending. Horizontal sections of the wells equal 800 and 900 m. Below BHA composition for RSS drilling is presented for Priobskoye deposit well:

Name	Diameter, m	Length, m
155.6 PDC Bit	0.155	0.21
PD 475 X5 AA 6" Stabilized CC (RSS PowerDrive X6)	0.149	4.05
IMPulse 25k Medium Flow (MWD IMPulse)	0.133	9.63
4.75" NMDC (Non-Magnetic Drill Collar)	0.119	2.10
4" 14.00 DPX, 10% Wear (70 joints)	0.133	860.80

Analysis of drilling data showed that the length of vertical section amounted to 300 m. From 300 to 1650 m, rotary method of drilling has been utilized, with DDM as a driver unit. Starting from 1650 m to the hole bottom, RSS has been applied. Maximum intensity of deviation did not exceed 1.26°/10 m.

Due to application of RSS in the interval from 1650 m to the hole bottom at the depth of 3894 m, zenith angles of estimated and actual profiles were almost identical, except for the horizontal section, where corrections had been made considering geochemical and physical characteristics of reservoir section (gas-liquid contact, oil-water contact etc.).

Fig.3 presents a vertical projection of the well profile. Discrepancy between actual and projected profile does not go over 3 %. This indicator once again proves reliability, precision of well construction along the given trajectory and marks the prospect of applying intellectual rotary steerable systems.

But with rising rotation speed of RSS in order to change mechanical speed of drilling comes an increase in the amplitude of torsional oscillations, which leads to top drive failures. There is a need for further investigations of optimal rotation speed of the top drive under given conditions of well construction, profile trajectory and DS technical characteristics [6].

Modeling of computational tests. Computational tests have been carried out in software complex Landmark belonging to Halliburton company. Data on well construction, composition of drilling tools and BHA have been used as input parameters for modeling of computational test.

Experimental research, aimed at investigating RSS dynamics depending on the profile type, parameters of casing construction and BHA composition, has been carried out on the example of Ust-Tegusskoye deposit well. Well under consideration has a four-interval profile, containing a vertical section, build section in the interval of surface casing drilling, linear hold section till the depth lower than the interval of pumping equipment operation, drop-off section (Fig.4).

Length of vertical section is 80 m, zenith angle at the end of build section (997 m) is 63° with maximal intensity of deviation no more than 1.1°/10 m. Along the entire length of linear hold section (till the depth 2199.27 m) the angle does not exceed 62-63°. From the depth 2199.27 m to the hole bottom at 2577.23 m occurs even dropping-off of the angle from 63 to 42°. Intensity in the drop-off interval does not go beyond 0.33°/10 m. Total length of the well along the shaft, taking into account build, hold and drop-off sections, amounts to 4863 m. Vertical displacement is 3762.37 m.

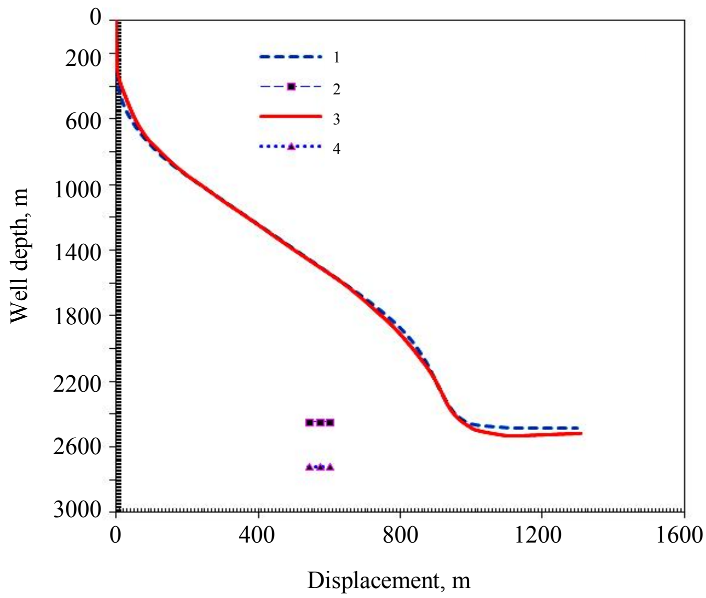

Fig.3. Vertical projection of the well profile N 55666, Priobskoye deposit

1 – actual profile trajectory; 2 – pay top; 3 – designed profile trajectory; 4 – pay bottom

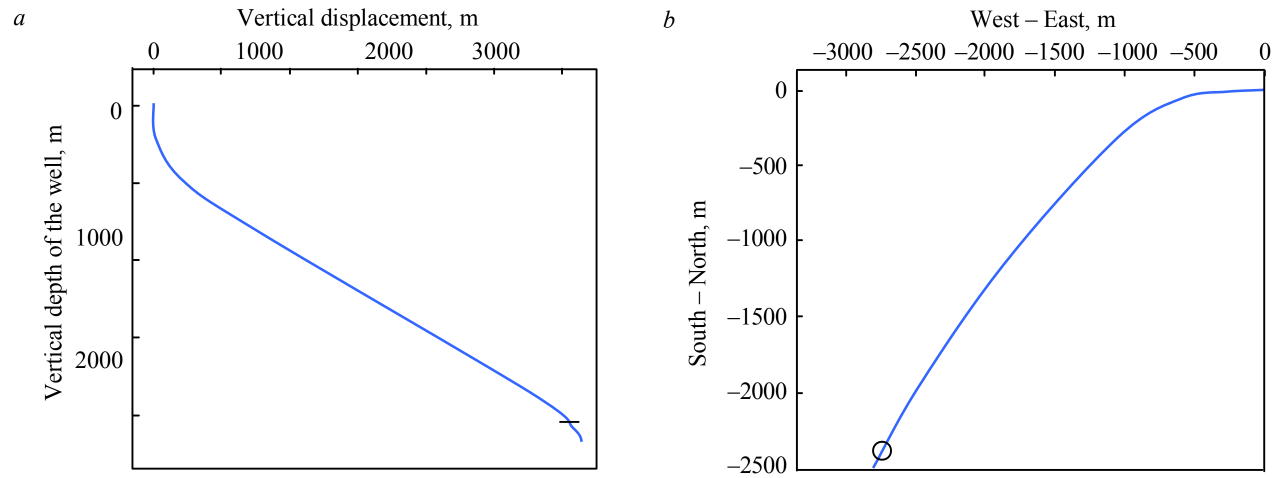

Fig.4. Vertical (*a*) and horizontal (*b*) well projections, Ust-Tegusskoye deposit

Well construction consists of two casing strings: conductor, surface and production ones. Conductor and surface casings, 0.53 and 0.245 m in diameter, are lowered to the depth of 55 and 1000 m respectively. Production casing, 178 mm in diameter, is lowered to the depth 3705 m. Both DDM and RSS have been used as driver units for the drill bit. Composition and characteristics of BHA:

Element name/diameter, model	Element length, m
Drill bit/219,1 mm, PDC FXD65R	0.29
Rotary Steerable System/PD 675 X5 AB 8 3/8" Stabilized CC	4.11
Receiver/PD SRX w Float valve	1.72
Flex Joint	2.95
Lower Saver Sub	0.37
EcoScope with 8.25" Stabilizer	7.66
Lower Saver Sub	0.36
MWD/TeleScope 675	7.66
Upper Saver Sub	0.91
Non-Magnetic Drill Collar /6 3/4" NMDC	8.71
Drill Pipes/5" 19.50 DPS, Premium (15 Joint)	142.50
Drill Pipes/TBT (1stand)	28.35
Hydro-Mechanical Jar	6.17
Drill Pipes/TBT (1stand)	28.35
Drill Pipes/5" 19.50 DPS, Premium (390 Joint)	3705.00
Crossover	1.23
Drill Pipes/5-1/2 " 21.90 DPS, Premium	916.66

Software calculation of optimal top drive rotation speed has been carried out in the range from 20 to 200 rpm with a step of two rotations.

Fig.5 demonstrates results of computational test of defining bit load, bend and drilling torque. It shows that losses of axial (sinusoidal bend) and spatial (spiral) stability (Fig.5, *a*) occur in upper interval from 100 to 1000 m, as well as in the lower interval from 4600 to 4700 m – where zenith angle is dropping off (transition from linear hold section to the curved one) [12]. Due to stability losses in the areas where profile trajectory switches from a curved section to a linear hold one, the torque of the top drive exceeds 50 kN·m, which is practically 80 % of torsion strength of the drill pipe material.

Presence of difficult well profiles, containing long linear hold sections, which in their turn link to curved build and drop-off sections with deviation intensity from 0.5 to 2.5°, leads to stability losses of DS and accidents of BHA.

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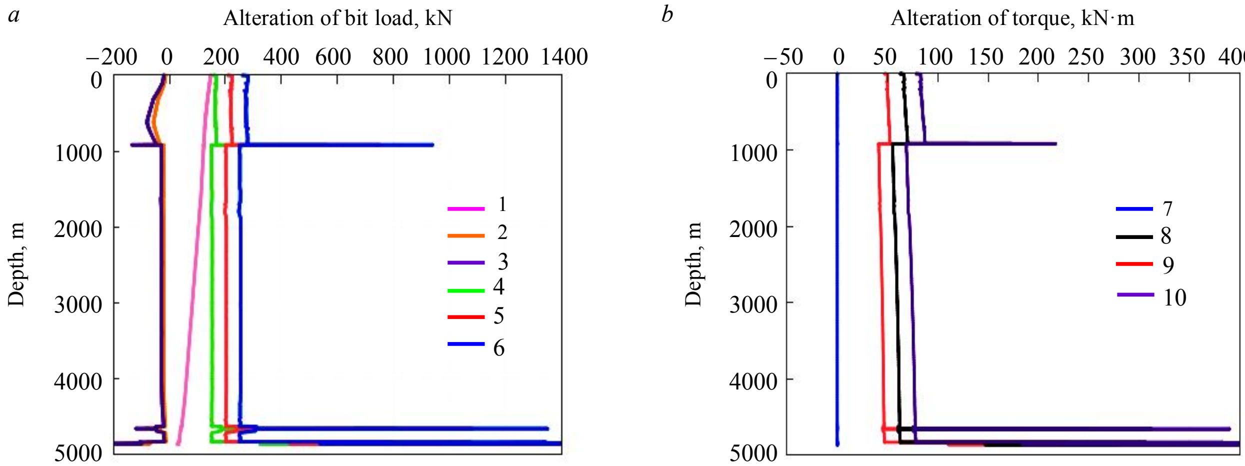

Fig.5. Bending stresses (*a*) and torque (*b*) in the process of well drilling

1 – bit load; 2 – sinusoidal bend; 3 – spiral bend; 4 – 60 % of material's bending strength; 5 – 80 % of material's bending strength; 6 – material's bending strength; 7 – torque; 8 – 80 % of material's torsion strength; 9 – 60 % of material's torsion strength; 10 – material's torsion strength

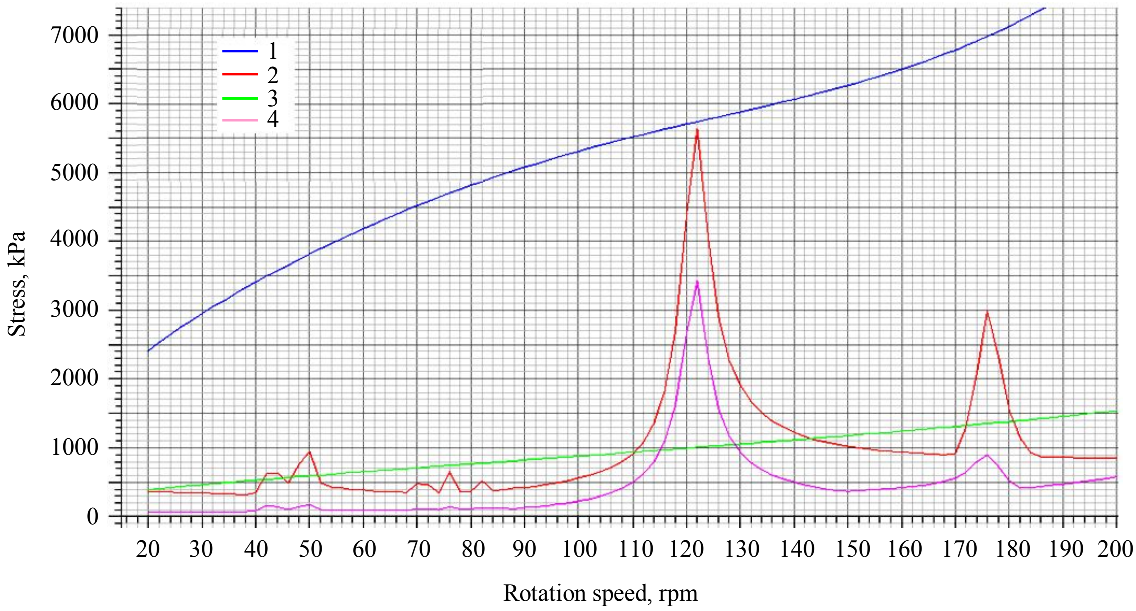

Fig.6. Dependence of stresses in BHA on DS rotation speed

1 – bit load; 2 – bending stress; 3 – torsional stress; 4 – shearing stress

Analysis of exploitation results for rotary steerable systems showed that when the top drive rotates at the speed of 120-125 rpm, resonance occurs (Fig.6). In this range lies maximum impact of bending stresses (transverse oscillations) and shearing oscillations (deformation torque). The main source of oscillations is related to the rigid bottom part of BHA [11, 13], located up to 20 m from the drill bit.

Second peak of the resonance occurs in the speed range of 170-180 rpm. In this case rotations are related to the BHA section from 30 to 150 m away from the drill bit, which corresponds to the section of heavyweight drill pipes (HWDP), 140 mm in diameter. One possible option to reduce stress values implies exclusion of this section of HWDP from the lower part of BHA and their installation by 200-300 m higher from the drill bit, on the level of hydro-mechanical jar. Besides, alteration of second peak values of resonance is possible by reducing rotation speed of the string down to 160 rpm or increasing it up till 185 rpm. Increasing the speed over 185 rpm, however, is constrained by technical characteristics of existing top drive systems.

Conclusions

1. Observed peaks of torsional oscillations are caused by greatest bending and shearing stresses. In the current system of drill string and BHA, auto-oscillations take place that make it impossible to execute prompt corrections to azimuth and zenith angles

2. Increasing amplitude of torsional oscillations can lead to accidents in the lower part of BHA. Alterations of BHA rigidity, e.g. using properties of tool materials, length or diameter ratios of drill pipes can partially solve this issue and increase the range of rotation speed of the top drive from 120 to 140 rpm. But this decreases manageability of BHA and increases the risk of string-sticking and key-seating in the well.

3. Optimization of drill string rotation speed should be done individually for each well under consideration, taking into account its profile trajectory, rock properties, rheology of the drill fluid and other key technical characteristics of dynamically active systems.

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***Author* Mikhail V. Dvoynikov**, *Doctor of Engineering Sciences*, *Professor*, *dvoinik72@gmail.com*. (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

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