Choosing the bottom hole assemblies for drilling stabilized well bores in conditions of information uncertainty

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Abstract

A statistical model of the choice of non-steerable bottom hole assembly (BHA) for drilling stabilized well bores is proposed, based on the results of analysis of the field data and taking into account multifunctional requirements under conditions of information uncertainty. The algorithm for calculating the static and dynamic characteristics of non-steerable BHAs with non-gauged support-centering elements (SCEs) is specified. There are developed algorithms for solving the problem of the BHA choice.

Keywords: *bottom hole assembly, information uncertainty, risks, stabilized wellbore, static and dynamic characteristics, statistical decision-making model, support-centering elements.*

The efficiency of the technology of drilling stabilized wellbores depends on the use of BHA, which determines the quality of the wellbore, the technical and economic performance of drill bits. This leads to multifunctional requirements for BHA, which depend on the geological and technical conditions of drilling. The choice of BHA requires information on the effect of the process and technological parameters on the quality of the wellbore under appropriate conditions.

The problem of choosing BHA has been studied in its various aspects by many researchers [1–4]. When drilling stabilized vertical and inclined well bores, BHA is used for various functional purposes and design features, the main task of which is to form the wellbore and to control the trajectory of the well [5].

It is known that the number and location of SCEs affects the shape of the well. A.A. Derkach [6] points to a better wellbore with rigid BHAs. Ensuring the straightness of the inclined section or the verticality of the wellbore with the shape of the cross-section in the form of a circle is, as it is well known, one of the basic requirements for qualitative cementing of casing strings [7].

The choice of BHAs (drill collar (DC), number of SCEs, their location and other constituent elements) is based on the initial data on drilling conditions and the results of their static and dynamic calculations [1–5, 8, 9]. Static characteristics include the bit side force, the angle of inclination of the bit axis to the well axis, the reactions to the SCEs, the contact point of the DC with the well wall. The dynamic characteristics are natural frequencies of oscillations, amplitude and frequency characteristics, and others.

Analysis of drilling technologies of stabilized well bores indicates that the requirements for BHA and field data are inaccurate, as well as information uncertainty about the zenith angle of the borehole, the parameters of the drilling mode and the well (the presence of local unevenness of the walls and caverns).

Model of BHA selection

In general, the choice of non-steerable BHA is performed taking into account multifunctional requirements, reflecting its effectiveness depending on technical, technological and natural factors [10]. Since a number of factors affecting stabilization of the wellbore during drilling are random, the statistical model of decision making should be the basis for justifying the BHA [10].

For the corresponding intervals of directional wells, depending on the geometric parameters of the trajectories and drilling conditions, the requirements that can be implemented in a certain class of ϑ layouts have been formed. The choice of BHA should correspond to the system of constraints, which reflects the requirements for well construction conditions, taking into account information uncertainty, and is formalized in the form of a statistical decision-making model as follows

$$\begin{cases} R\left(p^{\nu}, a^{\nu}\right) \to \min, \; \nu \in \vartheta, \; \mathrm{p}^{\nu} \in D^{\nu}; \\ \varphi\left(p^{\nu}\right) \le 0, \end{cases} \tag{1}$$

where $R\left(p^{\nu}, a^{\nu}\right)$ is a risk of the ν^{th} BHA of class of ϑ layouts; $p^{\nu} = \left(p_1^{\nu}, p_2^{\nu}, \ldots, p_n^{\nu}\right)^{\mathrm{T}}$ is the vector of variable parameter of the ν^{th} BHA with the definition area D^{ν};

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$a^{\nu}=\left(a_1^{\nu},a_2^{\nu},\dots,a_m^{\nu}\right)^{\mathrm{T}}$ is the vector of known parameters; $\varphi\left(p^{\nu}\right)$ is the system of restrictions for the parameters of the BHA.

The system $\varphi\left(p^{\nu}\right)$ defines limitations on drilling mode parameters, geometric parameters and stiffness of the BHA elements, their static and dynamic characteristics in order to ensure the efficiency and quality of well drilling. The model (1) also takes into account the information uncertainty of some parameters (the zenith angle of the well, parameters of the drilling mode, coordinates of the points of contact of the SCE to the well walls, the presence of local caverns). The class ϑ of alternative variants of BHA is defined by the design features, dimensions and placement of their elements.

The risk function $R\left(p^{\nu},a^{\nu}\right)$ determines the probability of violation of the conditions for solving the problem of estimating the static and dynamic characteristics of the BHA due to inaccurate information of the decision-making model. Risk assessment is based on statistical modeling and analysis of the results obtained [11].

To evaluate the static and dynamic characteristics of the BHA in conditions of information uncertainty of the contact of the SCEs with the borehole wall, a model for a flat design scheme was used [8]. The calculation is performed in the ANSYS Mechanical APDL [12] environment and software [8].

Features of calculating BHA characteristics with non-gauged SCEs

Non-steerable BHAs, especially multi-supporting BHAs, may include non-gauged SCEs. This is due to certain functional requirements for the bottom of the drill string (for example, preventing sticking, etc.) or wear of the SCEs. Forming estimates of the static and dynamic characteristics of the BHA, including one or more non-gauged SCEs, has certain peculiarities due to the uncertainty of the boundary condition for the static displacement [8], as well as the possibility of the absence of SCE contact with the borehole wall.

In the ANSYS software environment, there can be formalized the calculation of the static and dynamic characteristics of the BHA as a task of selecting the design model, which allows various possible combinations Р of missing contacts of non-gauged SCEs with the well wall

$$\min_{r}\ \Pi\left(L_r\right)/L_r \to \hat{r},\ \left|w_r\left(x_j\right)\right|<\Delta_r,\ r\in \mathrm{P}, \qquad (2)$$

where $\Pi\left(L_r\right)$ is the total deformation energy of the bottom of the drill string from the face to the point of contact L_r with the borehole wall for the r th calculation scheme; $w_r\left(x_j\right)$ is the displacement in the locations of non-contacting SCE for the r th calculation scheme; Δ_r is a radial clearance of non-contacting SCE.

Condition (2) reflects, in fact, the Rayleigh–Ritz Variation Method, which is used as a basis for applying the finite element method.

Let us consider an example of calculating the BHA in the ANSYS software environment with non-gauged SCEs for drilling an inclined well for such initial data α =15.0°, ρ =1140 kg/m^3, G =150 kN, ω =70 min^{-1}. The BHA includes four SCEs, the first from the bit is full-sized, and the rest are non-gauged. Geometric characteristics of BHA are given in Table. 1.

Table 1 – Geometric characteristics of the BHA with non-gauged SCEs

The element of the BHA	*D*, mm	*d*, mm	*l*, m	*q*, kg/m	*δ*, mm
Bit	295.3	80	0.40	400	–
DC	216	80	2.76	245	–
SCE	295.3	80	0.67	400	0
DC	216	80	0.33	245	–
SCE	295.3	80	0.67	400	0.75
DC	216	80	6.83	245	–
SCE	295.3	80	0.67	400	1.00
DC	216	80	5.33	245	–
SCE	295.3	80	0.67	400	1.50
DC	216	80	66.67	245	–

BHA was calculated by static (bit side force, reactions to SCEs, distance from the bit to the point of contact of the bit with the borehole wall) and dynamic (natural frequencies of transverse oscillations) characteristics. Also, there was determined deformation energy of the bottom of the drill string from the bit to the point of contact between the DC and the well wall.

Table 2 shows the results of BHA calculations for four variants. For the first variant, it is assumed that all SCEs contact the well wall, for the second variant – the second SCE does not contact, for the third variant – the third SCE does not contact, and for the fourth variant – the second and third SCEs do not contact. The absence of contacts of non-gauged SCEs are illustrated by the values of the deformations of the elastic axis of the bottom of the drill string at their locations.

Based on the results of calculations (Table 2), the minimum value of the specific strain energy of the BHA is 0.029 MJ/m, which corresponds to the second version of the BHA. Thus, the second non-gauged SCE does not contact the wall of the well and does not fulfill its functional purpose.

BHA selection algorithm

The basis for selecting non-steerable BHAs is the analysis of drilling data in similar geological and technical conditions, and design technological parameters. They form the input data of the model (1), which include, in particular, the class of the ϑ set of permissible alternatives and the system of restrictions $\varphi\left(p^{\nu}\right)$ on the parameters of the BHA.

Table 2 – Results of calculation of multi-supported BHA with non-gauged SCEs

Parameters	Numerical values for BHA variants			
	1	2	3	4
Initial data				
Diameter of the SCE, mm / distance from the bit to the SCE, m:				
the 1st	295.3 / 3.5	295.3 / 3.5	295.3 / 3.5	295.3 / 3.5
the 2nd	293.8 / 4.5	–	293.8 / 4.5	–
the 3rd	293.3 / 12.0	293.3 / 12.0	–	–
the 4th	292.3 / 18.0	292.3 / 18.0	292.3 / 18.0	292.3 / 18.0
Calculated characteristics				
The deflecting force on the bit, kN	-2.89	2.82	-2.81	0.11
Reaction to SCE, kN:				
the 1st	27.43	4.84	22.64	5.19
the 2nd	-20.78	–	-14.84	–
the 3rd	2.31	3.98	–	–
the 4th	9.43	10.02	10.69	10.30
The distance from the bit to the point of contact of the DC with the well wall, m	27.18	27.53	27.28	27.38
Strain energy, MJ	1.49	0.81	1.51	1.52
Specific strain energy, MJ/m	0.054	0.029	0.055	0.056
Natural frequencies, Hz:				
the 1st	$0.59\cdot10^{-4}$	$0.51\cdot10^{-4}$	$0.42\cdot10^{-1}$	$0.55\cdot10^{-4}$
the 2nd	$0.88\cdot10^{-1}$	$0.62\cdot10^{-1}$	5.50	$0.60\cdot10^{-1}$
the 3rd	14.28	10.36	5.72	9.41
the 4th	21.60	13.35	18.34	12.39
the 5th	31.75	24.78	19.62	25.34
the 6th	35.50	30.94	29.82	30.14

In principle, the class ϑ can include alternatives using rotary steerable systems [13]. The main element of rotary steerable systems is the orientation mechanism, which is installed above the bit. Following the mechanism of bit orientation, as a rule, navigation control systems for drilling and other elements are installed, among which there are also SCEs. The location of the SCEs can be justified using the decision-making model (1). Restrictions on the static characteristics of BHA are reasonable to build based on the results of analysis of field data.

To choose the BHA using the model (1), two methodological approaches can be used.

According to the first one, it is believed that there is available a set $A=\{a_i\}$, $i=\overline{1,m}$ of acceptable alternatives of BHA for such drilling conditions, based on the analysis of field data. It is necessary to choose the layout option a^*, corresponding to the minimum risk condition, from this set for the given drilling conditions (1).

The procedure for choosing the BHA is implemented in the sequence as follows.

1. To generate the set $A=\{a_i\}$, $i=\overline{1,m}$ of alternative BHAs variants based on the analysis of the industry data.

2. To build the estimates of the static and dynamic characteristics of the alternatives A for the given drilling conditions.

3. To form a subset of equivalent $A_e \subset A$ BHAs variants that correspond to the conditions of the problem, based on the analysis of static and dynamic characteristics of variants A model (1).

4. If the subset $A_e=\varnothing$ is empty (i.e. it does not contain alternatives that correspond to the conditions of the problem (1)), then construct a new set A and go to step 2.

5. To build risk assessments $R\left(p^{\nu},a^{\nu}\right)$ for a subset A_e of equivalent BHA variants.

6. To choose the variant a^* of BHA, corresponding to the minimum risk, from the condition (1).

The second approach is based on the design of the BHA for the given drilling conditions using heuristic ideas and methods for planning numerical experiments. Its implementation can be submitted by such procedures.

1. To form the class ϑ of the set of permissible BHAs variants, based on the initial information (diameter of the DC, the number and diameters of the SCEs, etc.).

2. To build a zero $\nu=0$ approximation of the BHA variantin the class ϑ, using heuristic ideas or industrial data.

3. To build the estimates of the static and dynamic characteristics of the ν^{th} BHA variant and perform their analysis for compliance with the conditions of the problem (1).

4. In case the BHA characteristics do not match to the conditions of the problem (1) go to step 7.

5. To build the risk assessment of the BHA variant, using Monte Carlo methods, based on information uncertainty.

6. If the risk satisfies the conditions of the task (1), then the results of the choice of the a^* variant of BHA are to be shown.

7. Using heuristic ideas and methods of experiment planning, to build $\nu+1$ approximation of the BHA variant. Go to step 3.

Illustration of choosing BHA

Let`s consider the choice of BHA for the following data: a bit with a diameter of 295.3 mm; a zenith angle of the borehole distortion α =17°; an axial load on the bit $G=170$–190 kN; the bit rotation frequency is $\omega=$ 70–90 min^{-1}; the density of the drilling mud $\rho_\text{p}=1170$ kg/m^3; the length 203 mm of DC with internal diameter 80 mm $l_{DC}=150$ m; the length of the SCE contact surface $l_k=600$ mm. The class ϑ of the set of admissible variants includes BHAs with three or more full-size SCEs.

To choose the BHA, we use the dynamic stability condition, which reflects the nature of the attenuation of the distribution curve of the transverse oscillations amplitude of the drill string bottom, which are disturbed by the bit operation at the bottom [5, 8, 10]. BHA is considered to be dynamically stable if it provides attenuation of transverse oscillation amplitudes, i.e. $a_{DC}/a_B\le 1$ (and only $a_{DC}/a_B=1$ on the bit), where a_B is the amplitude of transverse displacements on the bit, a_{DC} is the amplitude of transverse displacements of the drill string bottom [5, 8, 10]. Otherwise, BHA is considered to be dynamically unstable. Since it is possible to use three-roller bits and PDC bits with different frequencies of disturbing forces for the drilling of wells, the BHA must meet the dynamic stability condition for these bits.

To ensure the stabilization of the curvature, the transverse force on the bit is assumed to be $[F_B]$=1.4 kN. In order to model the influence of local caverns on the efficiency of the BHA in the problem (1), it is additionally assumed that the dynamic stability is ensured at the bottom and the curvature is stabilized in the absence of one contact (an arbitrary one) of the SCE with the borehole wall [10].

The BHA is chosen according to the second algorithm. The zero approximation of the location of the three SCEs was made using the method of planning numerical experiments for the criterion of the minimum bit side force $|F_B|$ and ensuring the conditions for the dynamic stability of the BHA [5, 8, 10]. Coordinates of the location of the SCE centers are x_1=3.5 m, x_2=9.0 m, x_3=18.0 m. Table 3 shows the calculated values of the static and dynamic characteristics of the BHA.

The risk indicators of alternative BHA variants are built by the method of statistical modeling of inaccurate information (Monte Carlo) in a simple situation. The zenith angle was modeled as a statistically independent normal random variable with a mathematical expectation $m_\alpha=17°$ and a standard deviation $\sigma_\alpha=1°$. The parameters of the drilling mode and the coordinates of the contact points of the SCEs with the borehole wall were modeled as statistically independent uniformly distributed random variables in a given interval of their variation (for contact points $x_i\pm l_i/2$). The local caverns were modeled by the absence (presence) of the contact of one of the SCEs with the borehole wall as a uniformly distributed discrete random variable. The number of statistical experiments equals 100.

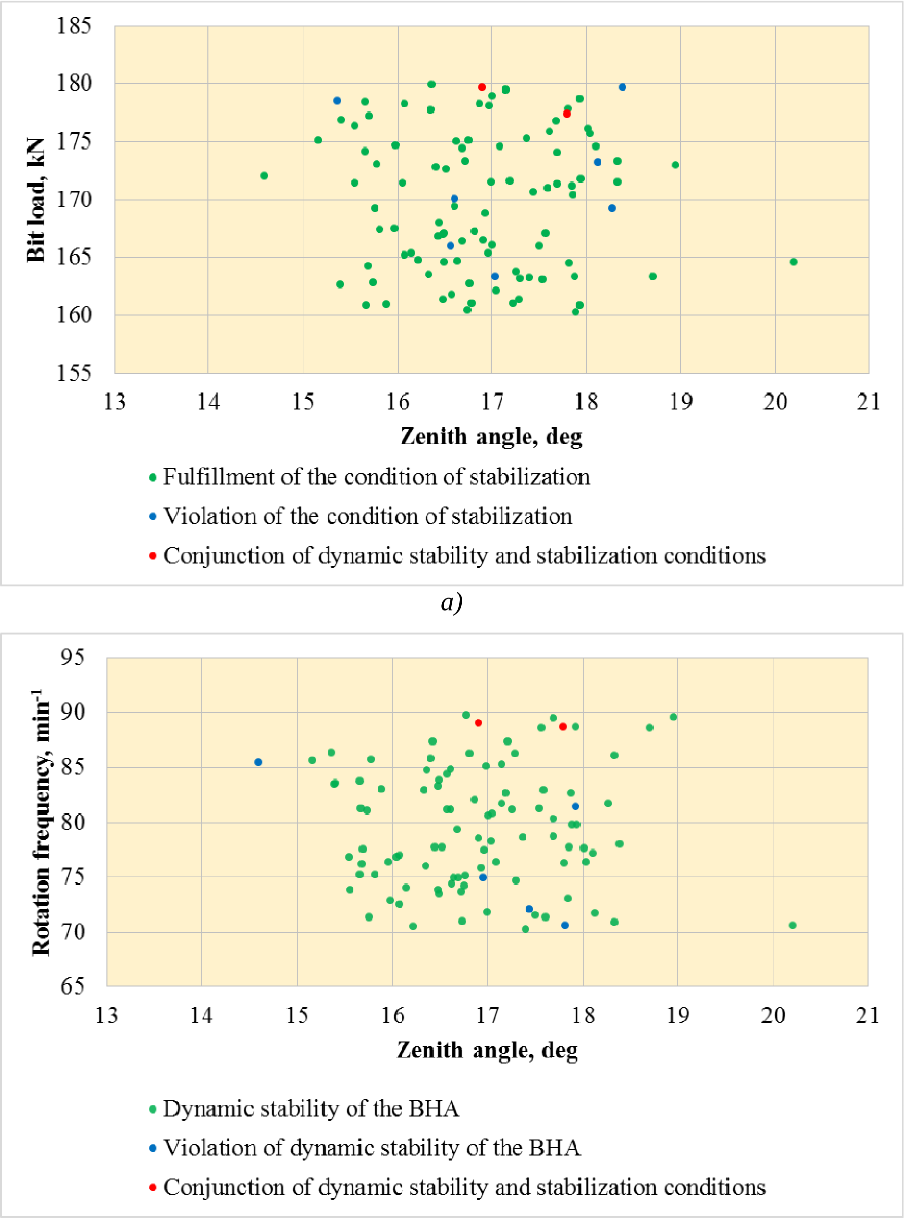
For the given example, the alternative BHA variants are evaluated according to (1) by the indicators of the risks of violation of the conditions of dynamic stability r_d and stabilization of curvature r_s , as well as their conjunction $r_s\wedge r_d$ and disjunction $r_s\vee r_d$. These indicators are important during the procedure for selecting an alternative variant according to (1) and are given in Table 3. Note that the selected BHA with three SCEs has high values of risk indicators and does not satisfy the conditions of problem (1). Clarification of the coordinates of the SCEs location did not provide low levels of risk indicators.

Table 3 – Assessment of characteristics of the BHAs

Characteristics of the BHAs	Number of SCEs		
	3	4	5
Static Characteristics			
F_B , kN	-0.24	0.47	0.01
R_1 , kN	5.69	1.35	2.09
R_2 , kN	-6.39	5.36	-2.06
R_3 , kN	16.35	-1.70	6.49
R_4 , kN	–	14.37	-8.47
R_5 , kN	–	–	17.90
L , m	29.40	35.80	30.50
Dynamic Characteristics			
max (a_{DC}/a_B)	1.0 / 1.0	1.0 / 1.0	1.0 / 1.0
Risk Indicators			
r_s	0.51	0.39	0.09
r_d	0.29 / 0.32	0.34 / 0.14	0.07 / 0.00
$r_s\wedge r_d$	0.20 / 0.04	0.22 / 0.01	0.02 / 0.00
$r_s\vee r_d$	0.60 / 0.79	0.52 / 0.53	0.14 / 0.09

Note. The numerator shows the values of characteristics for the three-roller bit, and the denominator shows that of the PDC bits.

In this case, we increase the number of SCEs and again find the coordinates of their location x_1 =2.0 m, x_2 =7.0 m, x_3 =12.0 m, x_4 =22.0 m. Table 3 shows the characteristics and risk indicators of the BHA with four SCEs, insufficient for the conditions of the problem (1)



a)

b)

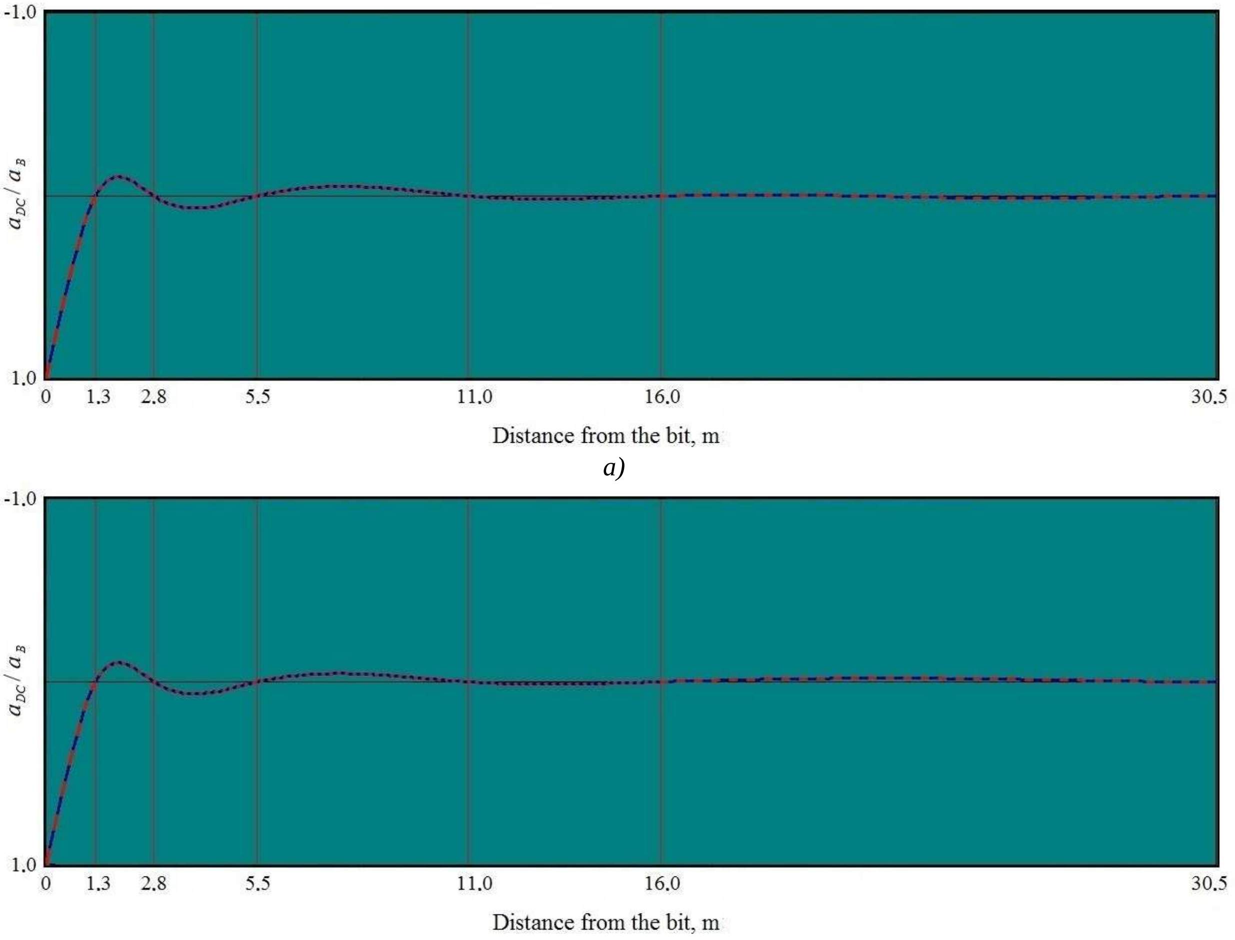
Figure 1 – Diagrams of stabilization of the borehole curvature (*a*) and dynamic stability conditions of BHA (*b*)

(including the results of clarifications of the coordinates of the SCEs location).

Similarly, after clarifications, we choose the coordinates of the location of the five SCEs x_1 =1.3 m, x_2 =2.8 m, x_3 =5.5 m, x_4 =11.0 m and x_5 =16.0 m. The characteristics and risk indicators of BHA are shown in Table 3. Significantly, the BHA chosen, in comparison with the previous versions, has significantly improved characteristics. The risk under the condition of dynamic stability (see Table 3) is sufficiently low 0.07 for the three-roller bits and it equals zero for the PDC bit. Combining the risk indicators for the conditions of dynamic stability of the BHA and stabilizing the bending of the well can satisfy the conditions of the problem (1).

According to the results of statistical modeling, it is shown in Figure 1 the point diagrams of the conditions for the stabilization of the borehole curvature (*a*) and the dynamic stability of the BHA (*b*) in the coordinates, respectively, the zenith angle – the bit load and the zenith angle – the rotation frequency. The diagrams show the risk indicators of the BHA chosen with five SCEs for three-roller bits.

Based on the results of statistical modeling, it is shown in Figure 2 the dynamic characteristics of the BHA chosen for drilling with the PDC bit and the three-roller bit. For the PDC bit, the BHA characteristics are modeled without local caverns, and the three-roller bits are modeled with a local cavern (the first SCE does not contact the borehole wall). The distributions of the amplitudes of the transverse oscillations of the bottom of the drill string for the illustrated BHA (see Figure 2) correspond to the condition of the dynamic stability.



a)

b)

α =17.0°, ρ =1170 kg/m^3, G =180 kN, ω =80 min^{-1}

Figure 2 – Dynamic characteristics of the BHA for drilling with PDC bits *(a)* and three-roller bits *(b)*

Conclusions

There is offered a statistical model of the choice of non-steerable BHA for the conditions of information uncertainty (the zenith angle, parameters of the drilling mode, contact points of the SCE with the well wall, presence of local caverns). The search for the optimal variant is carried out in a certain class of a multi-supporting BHA using the statistical modeling method with the risk minimization condition.

There is also clarified the algorithm for calculating the static and dynamic characteristics of non-steerable BHAs with incomplete SCEs in the software environment ANSYS Mechanical APDL, the implementation of which means to choose a computational model in the class of possible combinations of contacts of incomplete SCEs with the borehole wall.

Based on the analysis of field data, there was substantiated the choice of BHA for drilling of stabilized wellbore drills in similar geological and technical conditions. Using the heuristic ideas and the methods for planning numerical experiments, an algorithm for designing the BHA for the given well drilling conditions was built.

References

[1] Woods, H & Lubinski, A 1960, *Curvature of wells during drilling*, HTII, Moscow. [in Russian].

[2] Griguletsky, VG & Lukyanov, VT 1990, *Designing the bottom-hole assembly*, Nedra, Moscow. [in Russian].

[3] Chen, DCK, Wu, M, 'Maximizing Drilling Performance with State-of-the-Art BHA Program', SPE/IADC Paper 104502 was prepared for presentation at the *2007 SPE/IADC Drilling Conference held in Amsterdam*, The Netherlands, 20–22 February 2007.

[4] Bailey, JR & Remmert, SM, 'Managing Drilling Vibrations Through BHA Design Optimization', Paper SPE 139426 was prepared for presentation at the *International Petroleum Technology Conference held in Doha*, Qatar, 7–9 December 2009.

[5] Myslyuk, MA, Rybchych, IJ & Yaremyichuk, RS 2004, *Wells drilling: Directory*, vol. 3, Interpress LTD, Kyiv. [in Ukrainian].

[6] Derkach, AA 2008, 'Influence of drilling technology on quality of formation of the vertical well hole in hemogenetic adjournment', *Drilling and oil*, no. 2, pp. 30–33. [in Russian].

[7] Bulatov, AI 2015, 'The concept of quality of oil and gas wells drilled', *Drilling and oil*, no. 12, pp. 15–19. [in Russian].

[8] Myslyuk, MA, Stefurak, RI, Rybchych, IJ & Vasylyuk, YuM, *Improving technology of tricone bit run for rotary drilling of wells*, OAO «VNIIOENG», Moscow. [in Russian].

[9] Amorim, D, Hanley, C, Leite, DJ, ‘BHA Selection and Parameter Definition Using Vibration Prediction Software Leads to Significant Drilling Performance Improvements’, Paper SPE 152231 presented at the *Latin American and Caribbean Petroleum Engineering Conference*, Mexico, 16–18 April 2012.

[10] Myslyuk, MA, Dolyk, RM 2016, ‘Technological decision-making when drilling wells inclined sections’, *Construction of oil and gas wells on land and sea*, no. 4, pp. 4–13. [in Russian].

[11] Myslyuk, MA, 2012 ‘Risk assessment of decision making in drilling’, *Construction of oil and gas wells on land and sea*, no. 1, pp. 18–23. [in Russian].

[12] ANSYS® Academic Research Mechanical APDL, Release 18.2.

[13] Levinson, LM, Akbulatov, TO, Levinson, ML & Khasanov, RA 2013, *Construction and navigation of geometrically-complex wells: Tutorial*, Ufa. [in Russian].

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Вибір компоновок низу бурильної колони для буріння стабілізованих стовбурів свердловин в умовах інформаційної невизначеності

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Запропоновано статистичну модель вибору неорієнтованих компоновок низу бурильної колони (КНБК) для буріння стабілізованих стовбурів свердловин, яка ґрунтується на результатах аналізу промислових даних і враховує поліфункціональні вимоги в умовах інформаційної невизначеності. Уточнено алгоритм розрахунку статичних і динамічних характеристик неорієнтованих КНБК із неповнорозмірними опорно-центрувальними елементами. Побудовано алгоритми розв’язку задачі вибору КНБК.

Ключові слова: *інформаційна невизначеність, компоновка низу бурильної колони, опорно-центрувальні елементи, ризики, стабілізований стовбур свердловини, статистична модель прийняття рішень, статичні і динамічні характеристики.*