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RISK ASSESSMENT OF PACKED HOLEASSEMBLIES FOR ROTARY WELL DRILLING

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Abstract: The main elements of the statistical model of packed hole assemblies (PHA) design for drilling holding sections in conditions of information uncertainty are formalized and described. A constraint system has been given for the angle maintenance conditions of wellbore direction and dynamic stability of bottom hole assembly (BHA) lateral vibrations.

The influence of the information uncertainty of some factors (angle, parameters of the drilling practice, presence of local caverns, etc.) on risk indicators has been analyzed according to the results of the numerical calculations. It has been determined that the risks of angle maintenance disturbance are significantly influenced by the angle and weight on the bit (WOB), and dynamic stability conditions, such as angle and rotation frequency.

Risks of multi-supported BHAs which have been designed for conditions of minimizing bit side force, dynamic stability and include 4–6 stabilizers.

Keywords: information uncertainty, bottom hole assembly (BHA), holding section, stabilizer, risks, statistical decision-making model, static and dynamic characteristics

1. Introduction

Improving the efficiency of the drilling of oil and gas wells requires an integrated approach regarding the choice of technological solutions aimed at ensuring the design parameters and quality of the trajectory, preventing complications and accidents, achieving high technical and economic indicators, etc. In this aspect, one of the important technological solutions is the design of bottom hole assemblies (BHA). The trajectory of the well with maintained angle and shape of well cross-sectionin the form of a circle are considered to be one of the most basic requirements of high-quality casing cementing [1].

2. BHA selection model

Currently in engineering practice BHA design for drilling holding sections is substantiated mainly on the basis of the analysis of static solutions of differential equations of elastic axis equilibrium of drilling string bottom, usually for a plane design scheme [2–5]. Considerable attention is paid to the investigation and design of multi-supported PHA taking into account lateral vibrations and dynamic stability of the drilling string bottom [5–7].

An important direction for BHA design is the use of decision-making models with a flexible choice of optimality criterion and taking into account information uncertainty about input data (angle, parameters of the drilling practice, presence of local caverns, etc.) [8, 9]. The methods of BHA multicriteria efficiency estimation for static and dynamic characteristics are being developed [9] which are determined by technological requirements and the need for field data about the influence of drilling practice on wellbore quality in appropriate well drilling conditions.

In general, the design of PHA is carried out by taking into account the multifunctional requirements that determine BHA effectiveness depending on technical, technological and natural factors. Since the number of factors affecting the angle maintenance and drilling parameters are random, BHA design in some of their class ϑ should be justified by a statistical decision-making model [9]:

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

where:

$R(p^{\nu}, c^{\nu})$ – a risk ν^{th} BHAof class of ϑ layouts,

$p^{\nu} = (p_1^{\nu}, p_2^{\nu}, ..., p_n^{\nu})^T$ – the vector of variable parameter of the ν^{th} BHA with the definition area D^{ν},

$c^{\nu} = (c_1^{\nu}, c_2^{\nu}, ..., c_m^{\nu})^T$ – the vector of known parameters,

$\varphi(p^{\nu})$ – the constraints system for the BHA parameters.

The system defines limitations on drilling practice 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 latter constraints are built on the basis of the field data analysis in similar drilling conditions [9].

The model (1) with constraint system $\varphi(p^{\nu})$ allows a multicriteria assessment of BHA variants and takes into account the information uncertainty of some parameters (angle, drilling practice parameters, presence of local caverns, etc.). The presence of local caverns is simulated by the absence of contact of one (and arbitrary) stabilizers with the wellbore wall. For given geological and technical conditions, alternative variants class ϑ is formed depending on the structural features, geometrical and technical parameters, number and placement of the BHA elements.

Risk function $R(p^{\nu}, c^{\nu})$ indicates the probability of violating the constraint system for static and dynamic BHA characteristics due to inaccurate information of the decision-making model (1).

Static characteristics include bit side force F_B, inclination angle ψ of bit axis to well axis, reaction R_i on stabilizers, contact point coordinate L of drill collar (DC) with wellbore wall and dynamic characteristics – natural frequency, amplitude-frequency characteristics, and others [2–11]. The risks of BHA alternative variants are estimated using the method of statistical simulation (Monte Carlo).

It should be noted that risk management depends on the formalization of the BHA designing task (1), namely, the specification of the constraints system $\varphi(p^{\nu})$, set of permissible alternatives, information uncertainty, etc. Let us consider some of the results of the risk assessment of PHA with full-gauged stabilizers for flat calculation scheme [5, 7] and conditions of angle maintain, dynamic stability.

For the wellbore angle maintenance condition, bit side force F_B limitation will be used:

$$(F_B)^2 - [F_B]^2 \le 0 \tag{2}$$

where $[F_B]$ is the permissible value of bit side force. The fulfillment of dynamic stability condition for lateral vibrations which are generated by bit operation is given in the form of [5, 7]:

$$\left| \frac{a_{DC}}{a_B} \right| \le 1 \tag{3}$$

where a_B, a_{DC} are amplitude of lateral displacements on the bit and at the random BHA coordinate from the bit to the contact point DC with wellbore wall respectively and $a_{DC} = a_B$ only on the bit.

It should be noted that the static characteristics should include the limitation of stabilizer reactions and contact point DC with wellbore wall [2–5, 7]. Condition (3) determines BHA ability to damp lateral vibrations which are generated by the drill bit on the borehole bottom. This has a positive effect on drill bit performance.

Risk analysis of PHAs, designed according algorithm [10] for rotary drilling of vertical and inclined sections by three-cone and PDC bits in order to minimize bit side force and provide dynamic stability (3), was carried out taking into account an influence of different factors (angle, drilling practice, presence of local caverns, etc.) both separately and in combination. The latter used the methods of numerical experiments planning.

In Monte Carlo methods, the simulation of continuous random variables was performed as statistically independent for normal or uniform laws of probability distribution. The presence of local caverns was modeled as a discrete random variable with a uniform distribution of probabilities.

BHA risks were estimated for conditions (2) and (3) (according r_s and r_d), and their conjunction $r_s \wedge r_d$ and disjunction $r_s \vee r_d$. This information is useful for decision making. The calculation was performed using ANSYS Mechanical APDL [12] and software [5].

The analysis of the research results shows that information uncertainty has a significant impact on the BHA risk indicators. The increase in the power of uncertainty intervals contributes to a rise in risk indicators. The risk of a violation of wellbore angle maintenance (2) is significantly influenced by angle α and weight on the bit G while the conditions of BHA dynamic stability (3) are influenced by angle and bit rotation frequency.

Stabilizers in models for the evaluation of characteristics are presented in the form of point support with their fixed location (in the center of the support). Obviously, this inadequately describes the interaction of stabilizers with the wellbore wall. Structural features of stabilizers, in conjunction with local wellbore defects, admit the uncertainty in the traditional task of evaluating static and dynamic BHA characteristics in given drilling conditions [9].

The influence of the calibration surface length of stabilizers on the risk indicators of the designed multi-supported PHA for drilling of inclined sections has been studied. It was found that increasing the calibration of the surface length of the first (from the bit) stabilizer leads to an increase in the risk index (due to the violation of the angle maintenance condition), while changes in the calibration of the surface length of the other stabilizers does not have a significant effect on the risk indicators.

During drilling due to wear, there is a decrease in the stabilizer's diameter and an increase in the clearance between the stabilizer and the wellbore wall. This contributes to the longitudinal bending of a drill string bottom and changes its characteristics. The effect of stabilizer wear on the characteristics of designed multi-supported PHA according to model (1) for drilling vertical and inclined well sections has been investigated. Admissible stabilizer wear was constructed to provide the angle maintenance condition (for the first stabilizer from a bit $\delta_1 = 0$). It has been established that permissible wear of stabilizers does not affect the BHA dynamical stability.

Three-cone and PDC bits have different frequencies of perturbing oscillations, so under other identical conditions, BHAs with these bits can differ only in dynamic characteristics.

The presence of local caverns leads to the contact absence of an arbitrary stabilizer with wellbore wall causing changes in the BHA characteristics. In some cases, changes in characteristics can be significant from the point of view of the limitation system implementation (2) and (3).

Risk study and analysis of multi-supported PHAs shows that the assessment of their effectiveness can be based on the static and dynamic characteristics research for specific drilling conditions in accordance with the decision-making model (1).

3. Example of PHA selection

Consider the PHA design for output data: drill bit diameter 295.3 mm; angle α =17°; weight on the bit 170–190 kN; bit rotation frequency ω = 70–90min^{-1}; drilling fluid density 1170 kg/m^3; DC 203 mm (80 mm inner diameter) length l_{DC} = 150 m; stabilizers contact surface length l_k = 600 mm.

To ensure the angle maintenance condition (2), the limit of bit side force is accepted $[F_B]$ = 1.4 kN. PHA must meet the dynamic stability condition (3) for three-cone and PDC bits. Local cavern formations are possible during drilling, therefore BHA must meet (2) and (3) conditions in the case of one (any) stabilizer contact absence with wellbore wall.

Alternative PHAs variants are proposed according to conditions (2) and (3) which include four (*A*), five (*B*) and six (*C*) full-gauged stabilizers. Their geometrical characteristics are shown in Table 1.

Table 1. Geometric characteristics of BHAs

PHA	Coordinates of stabilizers [m]					
	x_1	x_2	x_3	x_4	x_5	x_6
A	2.0	7.0	12.0	22.0	–	–
B	1.3	2.8	11.0	11.0	16.0	–
C	1.3	2.5	5.5	8.5	11.0	14.0

The risk indexes of alternative variants were built by statistical method of inaccurate information. The angle was modeled as a normal random variable with a mathematical expectation of m_α = 17° and mean square deviation of $\sigma_\alpha = 1°$. The parameters of drilling practice and the coordinates of stabilizer contact points with the wellbore wall were modeled as uniformly distributed random variables in the given range of their changes (for points of contact $x_i \pm l_i/2$). Local caverns were modeled by the absence of one stabilizer contact with the wellbore wall as a uniformly distributed discrete random variable. The number of statistical experiments was 100.

Table 2 presents the results of PHA characteristics and risks: static characteristics – mean ($\bar{F}_B, \bar{R}_i, \bar{L}$) and variances ($\sigma^2_F, \sigma^2_{Ri}, \sigma^2_L$); dynamic characteristics – the boundary values $\max|a_{DC}/a_B|$ for three-cone and PDC bits; risks – index values ($r_s, r_d, r_s \wedge r_d, r_s \vee r_d$) for three-cone and PDC bits.

In Figure 1, PHA static and dynamic characteristics for three-cone bits are shown with 4 and 5 stabilizers (one of which does not have contact with the wellbore wall) based on statistical simulation results.

Static characteristics reflect the elastic axis shape (ratio of lateral displacement to radial clearance between DC and wellbore wall) from bit to contact point DC with wellbore wall and bit side force, reaction on stabilizers (see Fig. 1a, c)

Dynamic characteristics reflect the distribution of ratios of lateral displacement amplitude for drill string bottom (see Fig. 1b, d). Thus, in particular, for the numerical experiment data in Figure 1b PHA is dynamically unstable (increases the lateral vibrations that are generated by drill bit performance on the bottom hole), and for the data in Figure 1d PHA is dynamically stable (reduces lateral vibrations that are generated by the bit).

Table 2. Assessments of characteristics and risks of BHA

Indexes	BHA		
	A	*B*	*C*
Static characteristics			
$\bar{F}_B / \sigma^2_F$, kN / kN²	1.37 / 0.942	0.87 / 0.186	0.20 / 0.024
$\bar{R}_1 / \sigma^2_{R1}$, kN / kN²	4.60 / 7.088	2.80 / 2.982	1.53 / 0.416
$\bar{R}_2 / \sigma^2_{R2}$, kN / kN²	6.00 / 4.663	6.27 / 15.309	1.54 / 0.618
$\bar{R}_3 / \sigma^2_{R3}$, kN / kN²	5.59 / 49.598	7.07 / 9.694	4.02 / 10.115
$\bar{R}_4 / \sigma^2_{R4}$, kN / kN²	13.65 / 0.359	10.31 / 18.562	11.86 / 34.291
$\bar{R}_5 / \sigma^2_{R5}$, kN / kN²	–	16.75 / 3.121	20.36 / 16.887
$\bar{R}_6 / \sigma^2_{R6}$, kN / kN²	–	–	22.02 / 8.788
$\bar{L} / \sigma^2_L$, m / m²	33.97 / 14.816	29.44 / 3.895	28.72 / 1.416
Dynamic characteristics			
$\max |a_{DC} / a_B|$	1.0–37.1 /1.0–11.3	1.0–12.7 / 1.0	1.0 / 1.0
Risks			
r_s	0.39	0.09	0
r_d	0.34 / 0.14	0.07 / 0	0 / 0
$r_s \wedge r_d$	0.22 / 0.01	0.02 / 0	0 / 0
$r_s \vee r_d$	0.52 / 0.53	0.14 / 0.09	0 / 0

Note: For dynamic characteristics and risk indicators, the numerator indicates the use of three cone bits, and the denominator – the PDC bits

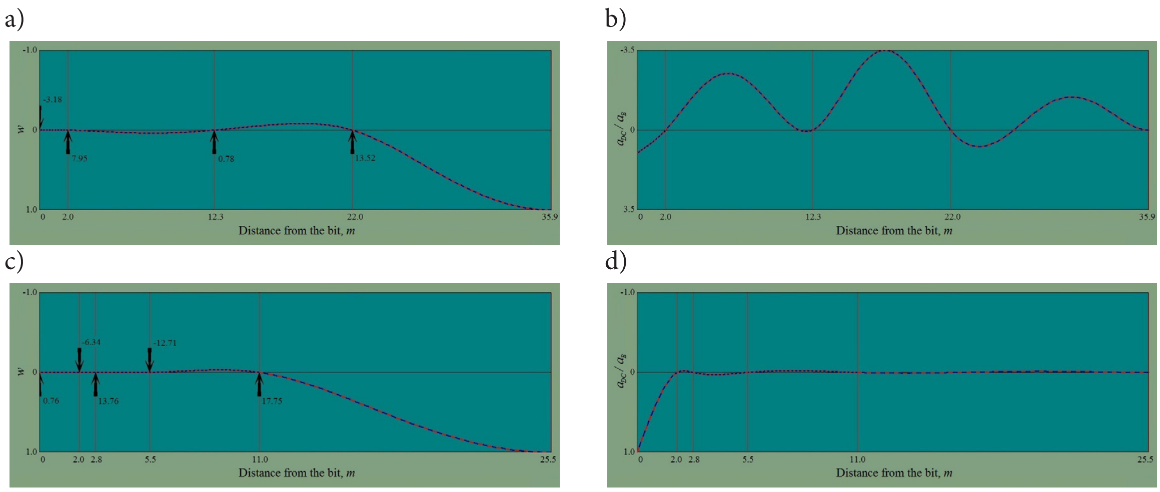

Fig. 1. PHA static (*a, c*) and dynamic (*b, d*) characteristics for three-cone bits with four (*a*, *b*) and five stabilizers (*c*, *d*): *a*, *b* – second stabilizer does not have contact with the wellbore wall (G = 174 kN; ω = 76.8 min⁻¹; α = 17.2 deg); *c*, *d* – fifth stabilizer does not have contact with the wellbore wall (G = 173 kN; ω = 75.1 min⁻¹; α = 16.8 deg)

Modeling of the results of the analysis of characteristics shows that for PHAs with a greater number of stabilizers, the values dispersion indicators of static characteristics and upper boundaries of dynamic indices are reduced. In particular, PHA *B* with PDC bits and *C* with three-cone and PDC bits are dynamically stable.

The simulation results (see Tab. 2) point to high risk ratios for variant *A* using a three-cone bit ($r_s = 0.39$, $r_d = 0.34$, $r_s \wedge r_d = 0.22$, $r_s \vee r_d = 0.52$), which indicates the inappropriateness of using this PHA. It should be noted that the risk indicator for PDC bits is somewhat lower (r_d = 0.14), but the risk indicators combination for conditions of wellbore angle maintenance and dynamic stability ($r_s \vee r_d = 0.53$) is similar to three-cone bits.

Variant *B* is characterized by low risk ratios, and for variant *C*, the risk indicators are zero. It is obvious that these variants can be recommended for use.

Based on the results of statistical simulations, point diagrams of wellbore angle maintenance are shown in Figure 2a, c, e) and dynamic stability (Fig. 2b, d, f) for alternative PHA variants in coordinates angle – weight on the bit and angle – drill bit rotation frequency.

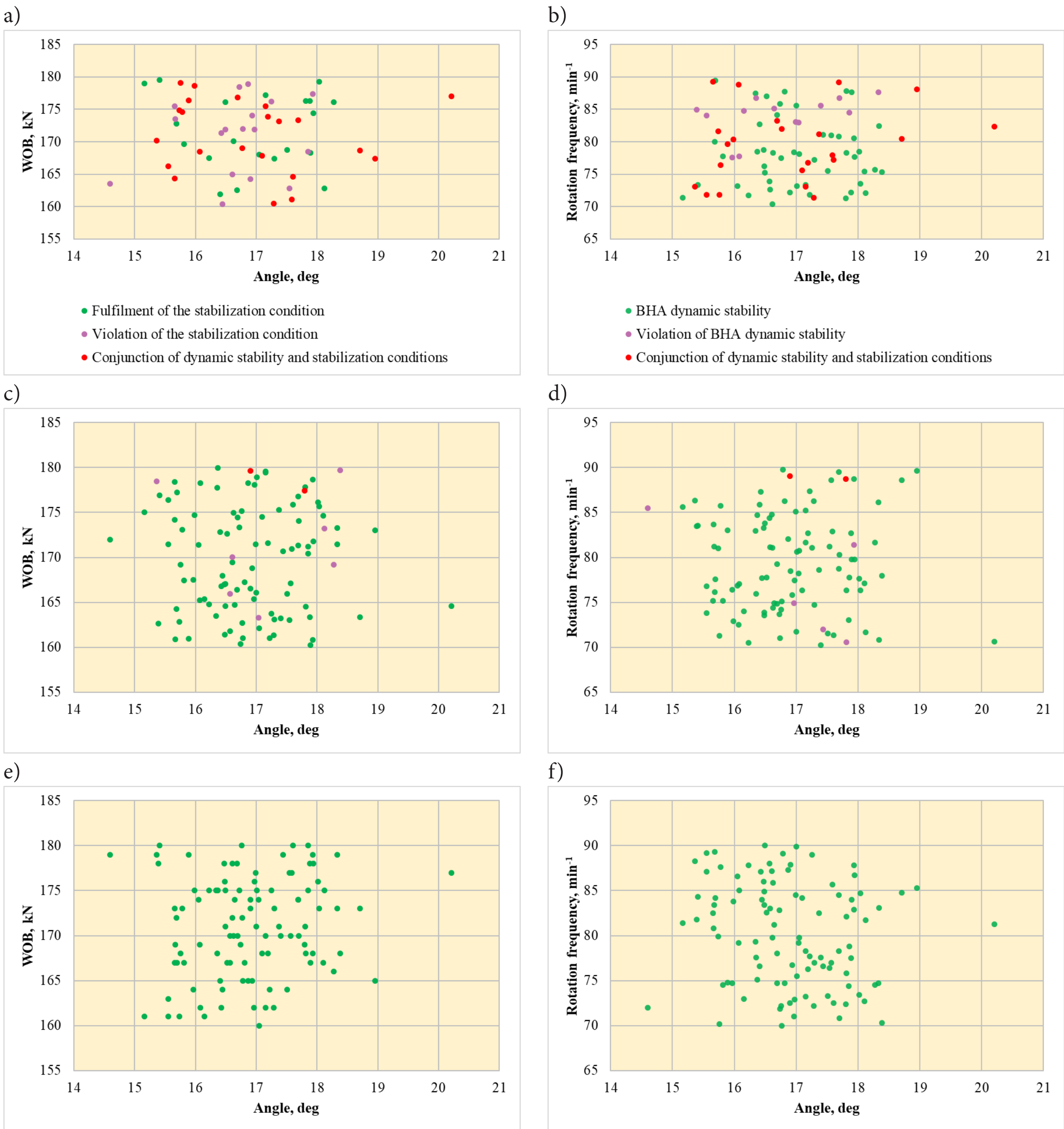

Fig. 2. Diagrams of angle maintenance (a, c, e) and dynamic stability conditions of PHA (b, d, f) with four (a, b), five (c, d) and six (e, f) stabilizers

Diagrams illustrate the distribution of risk indicators for PHA variants due to information uncertainty for three-cone bits.

4. Conclusions

Based on field data about wells quality, a statistical model for PHA design in conditions of information uncertainty (angle, drilling practice parameters, contact point of stabilizer with wellbore wall, presence of local caverns etc.) was substantiated. An optimal variant search is carried out by statistical simulation in a certain class of multi-supported PHA to minimize the risk in the model (1).

The influence of information uncertainty has been analyzed and the directions for the management of BHA risk indicators has been noted. According to the results of the characteristic statistical simulation of PHA alternative variants, including four, five and six stabilizers, the influence of some factors on the risk indicators for the conditions of wellbore angle maintenance and the dynamic stability of drill string bottom have been shown. The increase in the number of stabilizers and their location according to the model (1) reduces BHA risks.

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