Method for determining the loads on the deflection module of the push-the-bit rotary steerable system

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Abstract. The article presents a method for calculating the loads on the blades - elements of the deflecting module of the push-the-bit rotary steerable system for directional drilling of oil and gas wells, affecting its reliability. It is shown that the reliability of rotary steerable systems is of particular importance as the development of unconventional oil fields expands - a high-cost process that increases attention to specific factors of reliability of drilling equipment. A feature of the method for calculating the loads on the deflecting blades proposed by the authors is the representation of the rotary steerable system as an absolutely elastic rod, which is acted upon by a complex of forces arising from the directional wells with horizontal wavy segments. As a result of calculations, conditions were determined under which the interaction of forces acting on the deflecting blades will create a load close to the maximum permissible values, which increases the risk of failure of the entire bottomhole assembly of the rotary steerable system. The key condition was the change in the drilling segments of directional wells from ascending to descending when drilling a horizontal section with a wave profile, as a result of which there is a multiple load drop on the deflecting blades. Based on the calculated data, with an increase in the axial load, it is recommended to adjust the drilling mode to reduce the risk of failure of the push-the-bit rotary steerable system.

1. Introduction

Directional drilling is widely used for various types of mining. It is used for oil and gas production, for drilling wells for advanced degassing of coal seams, for the development of geothermal deposits. Rotary steerable systems are widely used in the oil and gas industry for the construction of directional wells with complex profiles. It was possible to truly evaluate the potential of the technology when drilling long sections with a large azimuthal curvature [1-2]. Via this technology, at the well design stage, it becomes possible to create more complex trajectories for more successful field development [3-4].

One of the technologies that brought about the shale revolution was rotary steerable systems. They not only allow the development of unconventional oil fields, but also, together with other modern stimulation technologies, are able to extend the life of wells in conventional fields relative to other drilling methods [5-7]. Rotary steerable systems have shown themselves to be more effective in comparison with the traditional downhole motor inclination [8-10], since it provides high quality of the wellbore, requires fewer tripping operations, which affects the drilling speed.
An important factor affecting the advantages of a rotary steerable system is its reliability. There are risks such as sticking of the casing, weakening of circulation of the drilling fluid in the well, which can negatively affect the benefits of the technology [11].

There are two sides of the reliability of drilling systems. The first is technological, associated with their use [12-13]. The second facet is constructive. It depends on design features of systems, the quality of its assembly and materials, as well as maintainability [14-15]. Factors of technological reliability include axial load, zenith, hardness and rock formations, tool speed, etc.

The constructive factors of the reliability of the rotary steerable system are related to the loads that the elements of the mechanism are responsible for changing the zenith. In the point-the-bit rotary steerable system, anti-rotation levers and eccentric rings perform this function. As for the push-the-bit rotary steerable system, deflecting blades are responsible for inclination, which ensure the deviation of the bottomhole assembly by moving out of the tool body in the opposite direction from the direction of inclination. So they are having maximum loads.

A small number of researchers are working on the issues of loading of drilling equipment [16-18]. Researchers of rotary steerable system loads are studying the problems of quality control of drilling using rotary systems, the effect of vibrations on their reliability, as well as problems when drilling deep geothermal wells [19-21].

2. Materials and Methods

The subject of the study is the effect of loads on the reliability of the deflecting module of push-the-bit rotary steerable systems, represented by the blades, during directional drilling. We consider the Schlumberger PowerDrive X5, X6 models; Halliburton iCruise, etc.

The zenith change, axial load on the bit, wellbore depth were used as the design parameters of the loads on the blades of deflecting module. Geological conditions (composition and hardness of rocks) are taken as mutual for all variations of the initial drilling parameters using the push-the-bit rotary steerable system.

By the reliability of the rotary steerable system, we mean the property of a tool to keep within the established limits the values of all parameters affecting the system's performance. The loss of this ability is a system failure. Its reliability depends on the reliability of the articulated shaft rotating in the support units, the deflection module blades, the blade drive, the drilling mode and the properties of the rocks being drilled. Loads on blades and their drives are common for both push-the-bit systems and combined ones (for example, Schlumberger Archer). Therefore, the blades are one of the most specific elements of the deflection module due to the multiaxial loads that affect the reliability of the bottomhole assembly.

The objective of eliminating failures of rotary steerable system modules can be reached by simulating the system operation under certain downhole conditions and under certain drilling modes. The load on the deflecting blades is related to the reaction force arising on it.

Since the deflection module of push-the-bit rotary steerable system undergoes serious loads due to its design, it is necessary to calculate them. To do this, we create a model according to which a rotary steerable system is an absolutely elastic rod, for which the action of the drilling fluid and rotation is taken into account in the form of a change in the friction force. Fig. 1 shows our model in a segment of an inclined wellbore.
Figure 1. Model of forces distribution acting on the push-the-bit rotary steerable system when drilling an inclined segment of the wellbore.

The bottom hole is point D, the deflecting blades is represented as B, the resulting reaction $R_B$ is equal to the required load on the blades extended to the maximum distance of an inch, which deviates BHA to 0.3°. To find the reactions, we compose reaction force projections equations on the X and Y axes, and the moments of force equation at point D:

$$
\Sigma F_X = Q + G \times \cos(\theta + 0.3^\circ) - R_{DX} = 0
$$

(1)

where $F_x$ – bottom hole resulting force projection on X axe kN.

$Q$ – axial load on rotary steerable system, kN;

$G$ – RSS weight, kN;

$\Theta$ – zenith, degrees;

$R_{DX}$ – bottom hole reaction force projection on Y axe проекция на ось Y силы реакции опоры забоя, kN.

$$
\Sigma F_Y = -G \times \sin(\theta + 0.3^\circ) + R_B - R_{DY} = 0
$$

(2)

where $F_y$ – bottom hole resulting force projection on Y axis, kN;

$AD$ – rotary steerable system length, m;

$R_B$ – reaction force – blades load, kN;

$$
F_{MD} = -G \times \frac{AD}{2} \times \sin(\theta + 0.3^\circ) + R_B \times BD = 0
$$

(3)

where $F_{MD}$ – bottom hole moment of force resulting $BD$ – interval between blades and bottom hole.

The set of forces that form the load on the deflecting blades with increasing zenith is described by the following formulas (2-3):
When the zenith exceeds 90°, the distribution of forces acting on the rotary steerable system changes. The diagram of the effect of forces during drilling the rising segment of the well is shown in Fig. 2.

\[ R_{DX} = Q + G \times \cos(\theta + 0.3°) \]  
\[ R_B = G \times \sin(\theta + 0.3°) + R_{DY} = \frac{G \times AD \times \sin(\theta + 0.3°)}{BD} \]  

When the zenith exceeds 90°, the distribution of forces acting on the rotary steerable system changes. The diagram of the effect of forces during drilling the rising segment of the well is shown in Fig. 2.

**Figure 2.** Modal of forces distribution acting on the push-the-bit rotary steerable system when driving the rising segment of the wellbore

Reaction RA occurs in A point as a result of the redistribution of the axial load. At the bottom hole point, the reaction RD is uniaxial to RA.

The equation of moments at point A is described by equation (6):

\[ F_{MA} = G \times \frac{AD}{2} \times \sin(\theta + 0.3°) - R_B \times AB + R_{AY} \times AD = 0 \]  

where \( F_{MA} \) – resulting moment of force at point A, kNm;  
\( R_{AY} \) – resulting force projection of the hole wall at point A on the Y axe kN.

When calculating the load on the deflecting blades with setting the zenith over 90°, it is important to take into account the reaction force RA in the point A, for which we have transformed formula (6), presenting it in the following form:

\[ R_{AY} = \frac{R_B \times AB}{AD} - \frac{1}{2} G \times \sin(\theta + 0.3°) \]  

The calculation of the load on the deflector blades when drilling the rising segment of the wellbore was carried out with a step of changing the angle (10), in the range of 90-179° (Fig. 4).

3. Results

The presented calculation of the deflection blades loads was performed for the rotary steerable system Schlumberger PowerDrive X5 675. The parameters used for the calculation included: bottomhole assembly length– 4.11 m; diameter - 215.9–250.8 mm; weight - 2463 kg; maximum inclination intensity, deg / 30 m - 6.5; maximal weight on bit - 800.68 kN. The performed calculation makes it possible to determine the nature of the increase in the loads when the technological
parameters of drilling change as they approach the maximum values, which directly determines the risk of system failure. The values of the load on the deflecting blades, calculated from equations (1-7) for different azimuths, are shown in Fig. 3 - in the segment of the inclined, Fig. 4 - rising wellbore.

![Figure 3. Load on the deflecting blades depending on zenith on the descending segment of borehole.](image)

To take into account the influence of the axial load on the deflecting blades, it is assumed that the total load on the deflecting blades of the rotary steerable system is determined as the sum of the load calculated above and the friction force.

![Figure 4. Load on the deflecting blades depending on zenith on the ascending segment of borehole.](image)

Fig. 5 shows the calculation of the axial load on the blades for the adopted drilling mode (Q = 60 kN) and for the recommended axial load limitation for the rotary steerable system Schlumberger PowerDrive X5 675 (Q = 290 kN), for different segments of directional drilling.
4. Discussion
As a result of the analysis of the obtained values of the calculations of the load on the deflecting blades of the bottomhole assembly of the rotary steerable system Schlumberger PowerDrive X5 675, the following regularities were determined, which make it possible to judge the influence of the technological parameters of drilling on the reliability of the system.

First, when analyzing the load in the case of zenith growth up to 30\(^\circ\) (Fig. 3), there is a direct proportionality between the actual axial load and the instantaneous load on the deflecting blades; further, a slowdown in the increase in load is observed. This is evidenced by the increase in the effort to overcome the resistance forces from the side of the borehole, since we state that at the zenith of up to 30\(^\circ\), the roughness of the borehole walls and the angle of inclination of the wellbore have an uncritical effect on the increase in friction forces. When zenith is exceeded above the critical value of 30\(^\circ\), the influence of friction forces increases sharply. Whereas, for the rising section of the well (Fig. 4), there is a drop in the load on the blades with an increase in zenith. Compared to the situation with an increase in the angle from 0\(^\circ\) to 90\(^\circ\), in this case there is a decrease in the loads on the deflecting blades of the rotary steerable system due to the distribution of the load to overcome the friction forces. Based on this, if the weight of the system and the axial load are similar in magnitude, then in the case of the construction of an upward trajectory (zenith is about 180\(^\circ\)) there is a risk of the tool hanging.

Second, from the analysis of the graphs in Fig. 3 and we state that at the moment of zenith growth to 90\(^\circ\) (horizontal wellbore), the load drop acting on the deflecting blades is more than five times. When drilling undulating horizontal sections in which multiple passes of this mark occur, using the push-the-bit rotary steerable system, it can cause negative fatigue loads on its elements.

Thirdly, according to the graph of the dependence of the loads on the axial load Fig. 5, the axial load plays a significant role in the formation of loads acting on the deflecting blades. Based on this, in areas of intense zenith change, a change in drilling parameters leads to a greater increase in loads, which can approach the maximum. This follows from the increasing reaction force of the support under conditions of increasing zenith.

Fourthly, the obtained values of the load acting on the deflecting blades are far from the critical value. The axial load of 60-290 kN is not the maximum for the rotary steerable system existing today, incl. Schlumberger PowerDrive family. With a maximum axial load of 800 kN (Schlumberger PowerDrive X6 675), the deflection blades load is estimated to reach 345 kN. However, in the future, as the depth of drilled wells increases, technologies and tools for directional drilling develop, the
requirements for its reliability will increase. In this case, the loads on the deflecting module will also increase, which increases the risk of system failure and requires further research.

5. Conclusions
The analyzed loads on the push-the-bit rotary steerable system deflecting module were considered using the example of the well-proven model Schlumberger PowerDrive X5 675. The bottomhole assembly of the rotary steerable system was presented as an absolutely elastic rod for two segments of the zenith change, namely 0°-90° and 90-180°, also working and limit values of axial load. We considered the loads on the deflection blades as a special factor that can lead to failure of push-the-bit systems, as well as an important factor for the development of combined rotary steerable systems (Schlumberger Archer, etc.), directly affecting their reliability.

After analyzing the results obtained, we noted that the loads on the deflecting blades increase in the segment of the zenith change from 0 to 30°, and then decrease until reaching 90°. When the direction of the wellbore is changed from rising to falling when drilling horizontal undulating wells, there is a 5-times load drop on the deflecting blades. This leads to a decrease in the reliability of the push-the-bit rotary steerable system. We also established a linear dependence between the axial load and the load on the deflecting blades, which dictates the need for further studies of the effect of various kinds of deformations on the reliability of the rotary steerable system with increasing drilling depth and the number of undulating sections. In addition, we recommend controlling the drilling mode to avoid the loads on the deflector blades close to the maximum when driving undulating profiles.

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