Influence of shock-vibration loads of drilling equipment on the drilling indicators of oil and gas wells

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Abstract. When drilling oil and gas wells, downhole and drilling wellhead equipment is subject to the influence of significant vibration processes of different directions with different amplitude-frequency characteristics. The paper describes the main sources of vibration of drilling equipment, which have a downhole origin. In this paper an amplitude-frequency characteristic of oscillatory processes of a drill string and their influence on drilling performance are given. In addition to the sources of fluctuations of the bottomhole nature of origin, sources of the wellhead nature can also be distinguished. Thus drilling mud pump is a generator of pulsations and beats of the pressure of drilling fluid, which in turn leads to the increase in the dynamics of the drilling tool, the appearance of torsional vibrations of downhole motors and bits. We established the negative influence of vibrations of the bottomhole assembly and drilling mud on the stability of the operation of hydraulic downhole motors, penetration on the bit, durability of the elements of the string and energy indicators of drilling. The proposed device allows reducing the amplitude of pressure fluctuations of the drilling fluid and drilling tool.

1. Introduction

Modern conditions for the operation of drilling companies impose more and more high demands on the technical and economic indicators of drilling. Firstly this circumstance is reasoned by more complex profiles and the increase in well depths. Secondly, in recent years, there has been a tendency to reduce the cost of oil on the international market, and, as a consequence, the requirement to reduce the cost of the development of oil and gas fields despite the aggravating nature of the first factor. The paper gives the amplitude-frequency characteristic of the oscillatory processes of the drill string and their influence on the drilling performance. The influence of fluctuations in the flow rate and pressure of the flushing fluid on the stability of the downhole motor is shown.

2. Purpose and tasks of the research:
- to conduct an analytical study of the entire set of reasons for the oscillatory processes during drilling;
- to classify the vibrations of the drilling tool and drilling fluid, taking the frequency range of vibrations as a classification criterion;
- to propose a design of a downhole device that allows reducing the amplitude of tool vibrations, as well as the pressure of the drilling fluid.
3. Materials and methods

One of the most effective technologies, such as radial drilling, was taken as the object of research. The analysis of the advantages and disadvantages of the method was carried out. The results of application of radial drilling in field conditions were presented.

4. Content of the method and assessment of its effectiveness

As we know, in the process of drilling, oscillations of wellhead and downhole drilling equipment occur, which differ both in direction in space and in magnitude.

Depending on the direction of movement of the drilling tool, the following types of its oscillations can be distinguished (Figure 1):

a) axial (longitudinal) vibrations, which is a cyclic movement of the bottomhole assembly along the wellbore and caused both by the processes occurring during the interaction of the rock cutting tool at the bottomhole and by the operation of drilling mud pumps [1]. The latter are particularly capable of rocking the entire drill string at a frequency of approximately 1 Hz and causing significant fatigue stresses;

b) torsional vibrations caused by periodic changes in the speed of the bottomhole assembly (BHA). Accordingly, there are BHA fading moments in time. This type of vibration increases with the increase in the length of the drill string due to a change in the elastic properties of the entire string. When the moment of resistance on the bit changes, the latter tends to sharply increase its speed after periods of fading;

c) lateral vibrations resulting from significant bending stresses and representing the movement of the BHA from one borehole wall to another. An extremely dangerous manifestation of lateral vibrations is the periodic impact of the assembly against the borehole walls, occurring with significant acceleration.

Let us consider in detail the description of the factors causing vibration processes during drilling and carry out their classification. Let us choose the frequency range of oscillations as a classification criterion and, in accordance with it, distinguish a group of infra-low frequencies, a group with a low frequency range of oscillations, as well as groups with a spectrum of medium and high frequencies [2].

In the first group of conventionally designated frequencies, we include oscillations occurring in the frequency range up to 1 Hz. Periodic pressure beats during parallel operation of two drilling pumping units, manual mode of feeding the tool to the bottomhole, as well as vibrations caused by the effect of wind load on the tower and elastic properties of the soil are among the sources of vibrations in the arrangement of the tool and drilling fluid. It is necessary to note that the fluctuations of this group mainly occur due to the processes occurring at the wellhead and are not able to significantly affect the drilling performance.

The next group includes those oscillatory processes that lie in the range from 1 to 70 Hz.

Speaking about the sources of oscillations of this frequency group, first of all it is necessary to note the mud pump, which, due to its design features, leads to the appearance of high-amplitude oscillations of the pumped drilling fluid inside the drill string with a frequency of about 1 Hz [3, 4]. Taking into account that the actual drilling conditions presuppose the setting of the average pressure at the level of 10 MPa and above, the unevenness of the drilling fluid supply by the pumps causes not only high-amplitude fluctuations in the fluid pressure, but also the swinging of the entire drill string [5].
Drilling mud pumps also generate drilling mud pressure pulses in the 4–5 and 50–60 Hz frequency ranges [6]. The reason for the appearance of these vibrations is the operation of the valve mechanisms. However, their amplitude is much less than the above mentioned vibrations with a frequency of 1 Hz.

In the group of low-frequency vibrations, we also include those that arise as a result of elastic deformations of the tackle system.

Downhole hydraulic motors can also generate pressure pulses in the drilling fluid column. They are especially pronounced during the operation of downhole drilling motors. In view of the fact that the latter is a representative of the volumetric type of the hydraulic motor for each change in the moment of resistance on the bit, it immediately responds with pressure surges of the drilling fluid moving up towards the mud pump [7].

Sources of vibrations in the tool and drilling fluid can be drill hoses, which act as a link between the drilling mud pump and drill string. Among the distinctive features of the drill pipe from hose, it seems important to highlight its elastic properties in the research. Taking into account this circumstance, in combination with a wide variety of applied drilling modes, it can be assumed that resonance may occur in the hydraulic system of the drilling rig and, as a consequence, a significant increase in the amplitudes of oscillatory processes.

Now let us turn to downhole sources of vibrations. First of all, it is a rock cutting tool that is in direct contact with the rock. Vibrations arising in the process of interaction between the bit and the rock being drilled are transmitted to the drill string rigidly connected to the bit. With the help of a special set of instruments and sensors, it is possible not only to record their amplitude-frequency characteristics, but also to read such parameters as the bit rotation frequency, the number of PDC bits blades and the degree of its wear, the condition of hydraulic motors, the dynamic component of the axial load and the moments of bit bouncing at the bottomhole.

Despite the complexity of the oscillatory motion of the BHA as a result of the interpretation and analysis of its amplitude-frequency characteristics, the obtained data can be used to adjust the drilling mode and, accordingly, increase the technical and economic indicators of drilling [8].

Cone roller bits make it possible to relatively effectively drill out rocks in various ranges of hardness. The are still used (mainly for drilling directions) at the present time. The destruction of the rock occurs when rolling bits along the bottom and introducing into the rock a large number of teeth located on the cones. Due to the reaction of the bottomhole to stresses coming from the side of the bit, the latter is forced to oscillate.

The interaction of rock cutting tools with the bottomhole leads not only to the appearance of a
time-varying torque on the bit, the frequency of rotation of the shaft of the downhole motors, but it is also transmitted to the entire string. Thus, for example, with the reciprocating movement of the shaft of a hydraulic motor such as a turbodrill, pressure pulses appear in the column of the drilling fluid. The speed of propagation of pressure waves is influenced by such parameters as the bulk modulus of the drilling fluid, as well as its density.

The rotational speed of the hydraulic motors used today, as well as the top power drives, is usually in the range from 100 to 300 rpm. Accordingly, the vibration frequency of the BHA, generated during the rotation of the rock cutting tool in the specified frequency range, will be in the range of 1.6–5.0 Hz. In the case of the use of tricone bits, in case that there is no bit slip in contact with the rock, the frequencies of the oscillations generated by it will triple and will be in the range from 4.8 to 15 Hz, respectively.

It is necessary to note that the use of roller cone bits, in contrast to PDC bits, causes a lower torque of resistance to bit rotation. This circumstance is explained by the fact that the cutters roll along the bottom and encounter less resistance to movement. Thus, during the operation of roller cone bits, it is the axial vibrations of the tool that predominate, which can be expressed by a cyclical change in the value of the axial load.

In the third group of oscillatory processes of medium frequency, we include the oscillations arising from the introduction of PDC cutters of bits and teeth of roller cone bits into the rock in contact with them and, accordingly, having a downhole nature of occurrence. Oscillations of this particular group can also be recorded by special equipment and subsequent interpretation of the results and lie in the frequency range 100–500 Hz [10].

The described spread of the vibration frequency range of the rock cutting tool, in addition to the large variation of the designs used for drilling bits and drill heads (for example, the bit diameter, the number of cones and teeth on each of them, the geometric ratio of these parameters, as well as the number of blades, the number and diameter of cutters on each blade, the height of the profile of PDC bits) is explained by the difference in the speed of rotation of the bottomhole motor determined by the drilling mode.

In the last group, we include oscillations with a frequency of more than 500 Hz. The vibrations of the drilling tool and drilling fluid of such high frequencies have insignificant amplitudes and quickly attenuate in the drill string and for these reasons they are the most difficult to register. This spectrum of vibrations of the tool and drilling fluid occurs for example during the use of drilling hard rocks, diamond bits and core bits [10].

After the amplitude-partial characteristic of the oscillatory processes occurring during the drilling of oil wells, let us turn in more detail to the fluctuations in the flow rate and pressure of the drilling fluid and the drilling equipment, generated during the operation of mud pumps.

Mining-geological and technological drilling conditions in certain cases presuppose the operation of two pumping drilling units operating on one manifold and connected in parallel. This can result in the appearance of so-called pressure beats in the circulation system of the drilling rig. These phenomena generally occur when two periodic oscillations of a parameter with approximately the same frequencies and similar amplitudes are added. The difference in the frequencies of fluid pressure fluctuations generated by mud pumps can be explained by the difference in the tension of the V-belt transmission connecting the electric motors to the pumps, as well as by the relative slippage on the pulleys. As a result, at those moments when these oscillations occur in phase, the total amplitude will be maximum and at the moment when they are in antiphase, their mutual damping occurs [9].

As an example we consider the recorded values of the drilling fluid pressure on the high pressure manifold (Graph 1), axial load (Graph 2), as well as the mechanical speed (Graph 3) when drilling well No. 7063 of the Kholmovskaya area by Tatburneft (Figure 2). When interpreting the graphs of this figure, we can see that the value of the pressure of the drilling fluid during the passage of the drilled rocks varies in a wide range. In particular, the analysis shows that at a working pressure of the solution of 9 MPa, the swing amplitude of the oscillations can be up to 5 MPa or 40% of the working pressure.
A common thing is the failure of the rubber diaphragms of pneumatic compensators of reciprocating mud pumps due to excessive pressure increase in the hydraulic system and its fatigue wear. As it is known, the principle of operation of a pneumatic compensator consists in periodic compression and expansion of gas in the above-diaphragm space. In accordance with the laws of physics, rapidly alternating increases and decreases in the temperature of the gas and the diaphragm in contact with it occur. As a result, the diaphragm material is susceptible to fatigue failure. A more detrimental effect of pressure surges in the drilling fluid can occur during the passage of the Serpukhovsko-Oka horizon, represented by fractured rocks.

Thus, when these types of rocks pass through, periodic rock falls and the resulting BHA wedge and plugging of drilling bit flushing channels can be attributed to quite common phenomena. The mud pump continues to pump the fluid, however, due to the lack of rotation of the bottomhole motor, the fluid suddenly encounters an obstacle in its path at the motor. This circumstance causes the appearance of a powerful shock wave of water hammer, tending upward from the bottom to the drilling wellhead equipment. As a result, the diaphragm of the mud pump more often fails and even more often the safety devices of the pump are triggered. All this requires additional non-productive costs for repairs and a forced shutdown of the drilling process, which negatively affects the technical and economic indicators.

The pulsation of pressure and flow rate of drilling fluid can lead to such negative consequences as loss of drilling fluid, collapse of the borehole walls, especially when drilling weakly stable rocks. For example, it can occur during such rocks as limestones, sandstones, dolomites with interlayers of clays, siltstones and marls, clays, etc. Therefore, when drilling unstable intervals, it is necessary to pay special attention to the reduction of the oscillatory processes of the drilling tool, flushing fluid and the selection of drilling fluids with certain technological properties.

In addition to the above-mentioned negative consequences, the fluctuations in the pressure and flow rate of the drilling fluid affect the unevenness of the rotational speed of the bottomhole motors, as a result of which there is a continuous change in their operating mode and oscillations in the drill string occur, changing the load on the bottomhole. Let us consider the influence of fluctuations in the flow rate and pressure of the drilling fluid on the operation of bottomhole motors.
Figure 2. Recorded drilling parameters for well No. 7063 in the intervals: a) 355-570 meters; b) 570-850 meters; c) 850-1120 meters; d) 1120-1410 meters.

As we know, the effective torque is determined by the dependence [5]:

$$ M_{ef} = M_0 P D e t, $$

where $M_0$ – the specific torque is a function of the rotor overhang and a parameter representing the ratio of the radius of the engagement tooth to the eccentricity; $D$ — design diameter equal to the diameter of the stator initial circle; $e$ – eccentricity; $t$ – stator pitch.

The engine pressure drop, in turn, is determined by the following relationship:
where \( Q \) – flushing fluid flow through the engine; \( \alpha_p \) – proportionality factor between flow and pressure.

The flow rate of the flushing fluid of the circulating system, due to the uneven flow of the mud pump, is determined by:

\[
Q = Q_{\text{aver}} + A_q \sin \omega t,
\]

where \( A_q \) and \( Q_{\text{aver}} \) – respectively, the amplitude of fluctuations in the flow rate of the flushing fluid and the average flow rate;

\( \omega = 2\pi f \) – circular frequency.

Substituting (3) and (4) in (2) we obtain

\[
M_{ef} = M_0\alpha_p (Q_{\text{aver}} + A_q \sin \omega t)^2 \text{Det.}
\]

In the expression (4) we see that the effective torque on the motor shaft is in a quadratic dependence on the average flow rate and the amplitude of fluid oscillations, which creates conditions for the appearance of oscillatory processes during well drilling.

The dynamism of the engine operation enhances the oscillation of the friction torque of the spindle, which depends on the fluid flow rate:

\[
M_s = \mu r_{\text{aver}} P_n = \mu r_{\text{aver}} (P_b - P_h)
\]

where \( \mu \) – friction factor; \( r_{\text{aver}} \) – average friction radius of the spindle of the motor screws; \( P_n \) – axial load on the spindle; \( P_b \) – axial load on bit; \( P_h \) – hydraulic load on the motor spindle.

Substituting in (5) the dynamic load of the bit and the screw motor, we obtain:

\[
M_s = \mu r_{\text{aver}} \left[ P_{st} + A_p \sin \omega_p t - \alpha \gamma (\alpha_p Q_{\text{aver}} A_q \sin \omega t) - G \right].
\]

According to the obtained dependencies, we see that such parameters of the operation of the bottomhole motor as the torque on the shaft and the rotational speed are very sensitive to the unsteady nature of the fluid flow in the drill string. The instability of its rotation can cause an increase in vibration loads on the BHA, a decrease in the engine life, the occurrence of axial, transverse and, above all, torsional vibrations of the entire drill string.

Taking into account the above mentioned aspects, we can conclude that, despite the diaphragm compensators installed in modern pumping drilling rigs, the latter do not provide the required reduction in the amplitudes of fluctuations in the flow rate and pressure of the fluid.

In order to increase the service life of bottomhole motors and bits, as well as to damp pressure fluctuations and hydraulic shocks occurring at the bottomhole and propagating up the column of drilling fluid to the wellhead equipment, a bottomhole compensator was developed [10] (Figure 3).

The design of the damping device includes a housing 1 with a projection 2, a casing 3 with a threaded connection, holes 4 and a seal 5. An annular piston 6 is mounted in the space between the casing and the casing, sealed with rubber elements 7 and 8. The piston is a separator of the increased cavities 9 and reduced 10 pressures. In the area above the piston there is a spring 16 that prevents the piston from moving upward.

The device provides the ability to communicate with the annulus above the piston area, through hole 4. To enhance the damping effect, metal shavings 11 are provided within the area of increased pressure. This area communicates through radial channels 12 with an area 13 inside the housing. The compensator is mounted in the assembly at the bottom of the drill string by means of connecting threads on nipple 14 and sleeve 15.
An uneven flow of drilling fluid by means of radial channels rushes into the area of increased pressure. It is damped by passing through the metal shavings, presses on the piston, forcing the spring to be compressed [11]. When the piston moves upwards, the fluid is displaced in the annulus between the drill string and the borehole wall. This is how the pressure fluctuations of the drilling fluid are damped. For the most efficient operation of the device, it is advisable to install it in the BHA above the bottomhole screw motor, reducing not only the vibration of the bita and fluid pulsations, but also increasing the uniformity of the engine speed [12].

5. Results
Thus, the drilling equipment in the process of drilling performs complex oscillatory movements, including axial, torsional and lateral vibrations. This leads to premature failure of the drill string elements, which occurs, in particular, due to the prolonged action of fatigue stresses. Taking into account the wide range of vibration frequencies of the tool, it can be easily calculated that the number of stress cycles that lead to fatigue failure of assembly elements can exceed a million even for a short period, for example, 5 hours. The vibrations of the BHA are significant in amplitude and breaking force when passing rocks with intermittent hardness. The rock cutting tool in this case literally periodically hits the bottom and, first of all, reduces the resource of PDC bits, which are very sensitive to shock loads.

6. Conclusion
Taking into account the high degree of negative influence of oscillations of the drilling tool and the pressure of the drilling fluid on the performance of the wellhead and bottomhole drilling equipment, as well as on the technical and economic indicators of well construction, the development of equipment and technology for damping oscillations while drilling wells is an urgent task.

Figure 3. Bottomhole compensator design
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