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Article

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INVESTIGATION OF DRILL STRING DYNAMICS USING PROBABILISTIC METHODS

The object of research is a drill string. The work is directed to the study of the drill string dynamics and its influence on the rock, which is drilled using probabilistic methods.

It is shown that the nature of the vibrations of the top of the drill string and the downhole signals are different and have a stationary random character. It is proved that the process at the output of the drill string, taking into account random disturbances, is narrow-band (quasi-harmonic) or close to it. It is found that the energy composition of the spectrum sections and the appearance of resonance peaks and their displacement is directly determined by the physical and mechanical properties of the rocks being drilled, as one of the factors that determines the vibration state of the drill string. Graphs of the spectral density of the power of pitting vibrations are given, showing their amplification at frequencies of 30–40 Hz as the hardness of the rocks being drilled increases. The maximum of the power density bending curve shifts towards low frequencies. There is a «mutual convergence» of the maxima of the power spectral density of the oscillations of the top and bottom of the drill string. It is shown that an important feature of drill string vibrations in the process of drilling with ball bits is that the intensity of vibrations of the top of the drill string passes with frequencies close to low frequencies, and the vibrations of the bottom of the string – to high frequencies.

It is determined that the process at the output of the drill string, taking into account random disturbances, is narrow-band (quasi-harmonic) or close to it. As a result, the assumption of a narrow band at the output of the system, which is the basis of theoretical research, is justified. It is proven that the drill string, as a system with liquid filling under pressure, is more stable compared to a hollow structure. The washing liquid, in this case, plays the role of a dynamic absorber.

Keywords: *drill string, drill string dynamics, impact on rock, nature of oscillations, probabilistic methods.*

1. Introduction

The calculation of the drill string and its elements for static loads has been tested well enough and is almost unquestionable, while their dynamic calculations are time-consuming and not very suitable for practical use.

The methods of calculating the drill string and its elements for dynamic loads can be conditionally divided into three stages:
– calculation for deterministic loads (static or dynamic);
– calculation of random dynamic actions;
– calculation of dynamic loads in conditions of incomplete information about the properties of the loads.

Analogous stages are related to the trajectory of well drilling (directional drilling), as well as methods and geological and technical conditions of drilling. Thus, the properties and structure of the drill string and its elements can be considered as deterministic random with known probable characteristics or random with incomplete information about statistical characteristics. At the same time, various combinations of the listed cases are possible [1–3].

The aim of research is to use probabilistic methods to study the drill string dynamics. This will make it possible to determine the processes occurring at the entrance and exit of the drill string, taking into account random disturbances.

2. Materials and Methods

The research methodology consisted in physical modeling of the mechanical system based on the experimental layout of the drill string. On the basis of the research, a number of experiments have been conducted with the aim of establishing the relationship between downhole disturbances and the vibration state of the drill string based on the level of vibrations of its top, taking into account various mechanical properties of the artificial outcrop. The study of the drill string dynamics and its effect on the rock being drilled has been carried out using probabilistic methods.

Dynamic loads in the drill string and its elements are the main ones. The most characteristic dynamic loads for the drill string and its elements are vibrations (longitudinal,

torsional, bending), which is related to the stability of the structure and the obtained drilling indicators, as well as the strength of its elements. The vibrations of the drill string under the action of such loads will be random, which leads to the application of the mathematical apparatus of the theory of random processes [4–6].

Random fluctuations of drill string elements, as well as its fluctuations in general, are primarily caused by the interaction of the bit with the hole, as well as the elements of the string (for example, arming with centering elements) with the well walls, changes in the trajectory (curvature, geological conditions of drilling, etc.).

Studies of vibrations in the process of deepening a well show that dynamic loads can be considered as stationary random processes, because the transient modes have a sufficiently short duration.

3. Results and Discussion

The recording of vibrations during drilling on an experimental drilling unit is described and analyzed below (Fig. 1).
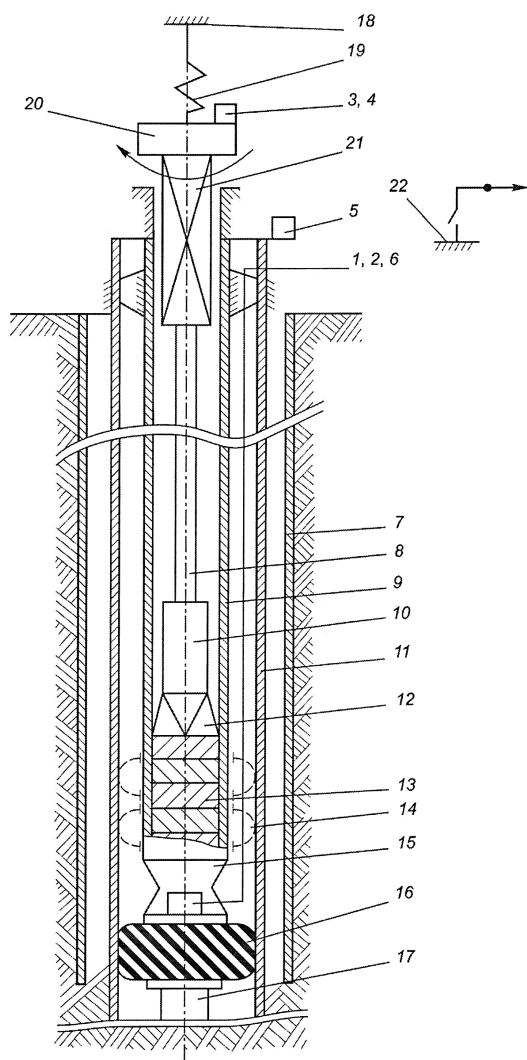
Fig. 1. Scheme of the drilling unit: 1–6 – SV-20 vibration receiver channel; 7, 9, 11 – casing column; 8 – column of drill pipes; 10 – weighted drill pipes (WDP); 12 – chisel B140T; 13 – cement hole; 14 – centralizers; 15 – support; 16 – packer; 17 – lower support; 18 – tower BU75BRE; 19 – thermal system; 20 – moving load of the thermal system; 21 – leading pipe; 22 – penetration level sensor

The task was set as follows: knowing the parameters of the statistical distribution of the random load, determine the appropriate parameters for the values that characterize the reaction of the drill string and its elements to dynamic disturbances during the drilling process (dynamic stresses and displacements). Thus, random processes have been investigated – random functions of time, for example, the order of interaction of the rock bit arming with the rock. A number of experiments have been carried out on the drilling unit, the purpose of which was to establish the mutual relationship between the pitting disturbances and the vibration state of the drill string based on the level of vibrations of its «top» at various physical and mechanical properties of the artificial pitting [1, 7, 8].

The scheme of the experimental layout of the drill string is presented in Fig. 1. An artificial outcrop was drilled – (700-grade cement stone for cold wells) 24 m thick, poured in the form of tiers with different hardening times. The artificial hole was lowered with the casing to a depth of 230 m. The top of the casing, after lowering, was attached to the guide pipe of the well by means of welding. In the lower part of the cement block, a hermetic container with calibrated vibration receivers was cemented, which were connected to the ground equipment with the help of a logging cable. Vibrations on the square rod were recorded by vibration sensors installed on the swivel at the end of the drill string.

Thus, vibrations were recorded through three channels: the drill string, the casing string, and the communication cable line.

Drilling was carried out by the rotary method at a bit rotation frequency of 6.28 s^{-1} and an axial load of 30 kN. The layout of the column: bit B140T, WDP $\varnothing$130 mm, length 4 m, pipes with a diameter of 70 mm and a length of 200 m.

Washing was carried out with water at a pump supply of 24 l/s.

Drilling was conducted with the string completely unloaded at the blowout in order to ensure the loss of stability of the latter and to receive signals from secondary sources of oscillations and, in part, from the interaction of the drill string with the walls of the well.

The passage of signals through the acoustic channels and the activation time of the vibration receivers were controlled by striking the pipes, as well as by sharply landing the tool on the bump. Confirmation of receiving a signal from a hole, fixing it on the surface was carried out using the propagation of an elastic wave in the column based on the difference between the force action and the arrival of a single disturbance pulse, as well as the phase shift of the vibrogram recordings from the hole and surface vibration receivers. The speed of elastic wave propagation is 5030–5070 m/s, which indicates the admissibility of plane wave hypotheses.

Fig. 2 shows typical vibrograms of vibrations recorded by vibration receivers on the pit and receivers installed on top of the column.

Studies of vibrograms obtained through the acoustic channel of the casing showed that its transfer function determined by the envelope process in the zone of the linear characteristic of vibrowashers (from 20 Hz and above) was up to 0.15, the signal decay time was 0.15 s. From these results, the damping characteristics can be determined.

Due to the fact that the drilled intervals of the artificial hole in the intervals are sufficiently uniform in terms of mechanical properties, a coefficient was introduced that takes into account the time it takes for the hole to deepen by 10 cm.
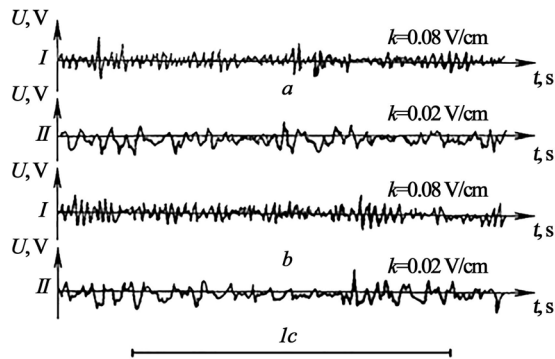
Fig. 2. Characteristic of the voltages from the inductive vibration receiver:
I – near-impact zone; II – drill string top; a – V_M=6.5 m/h;
b – V_M=8.4 m/h

In the future, the coefficient B appears on the graphs of the spectral density, which made it possible to more clearly interpret the results of the experiment. Dimension $|B|$=1 s/cm.

Spectral analysis of the recorded oscillations is shown in Fig. 3, as an example for some vibration records, which makes it possible to qualitatively compare, at the first stage, the nature of the interaction of the bit with the hole when drilling rocks that differ in mechanical properties and vibrations of the top of the drill string.

The given dependencies show that when drilling relatively soft rocks, low-frequency oscillations occur, which were recorded by the upper receivers, caused not only by the pulsation of the pumps and the elasticity of the melt system, but also by components directly related to longitudinal-torsional oscillations. It should be noted that the oscillations on the thalamic system took place with a frequency of about 6 Hz. The peak values of the bit vibrations occur in the range of 20–80 Hz, at the same time

as low-frequency, more powerful vibrations of the top of the drill string are in the range of up to 30 Hz.

Graphs of spectral density in rocks of different hardness are given in Fig. 3.

Considerable attention was paid to the state of the chisel armament. Based on the results of statistical processing of the oscillograms obtained from the vibration receivers in the near-impact zone, graphs of correlation functions were constructed, which can be used to determine the degree of wear of the rock bit weapon.

Expressions [6, 9, 10] can be used to describe the correlation function in our case:

$$R_{YY}(\tau) = R_0 e^{-A\tau} \cos \omega\tau, \qquad (1)$$

where R_0 and A – constants; ω – frequency of oscillations; τ – time.

In this case, the spectral density will be:

$$\Phi_{YY}(\omega) = \frac{1}{\pi} \frac{AR_0}{(\omega-\theta)^2 + A^2} + \frac{1}{\pi} \frac{AR_0}{(\omega+\theta)^2 + A^2}, \qquad (2)$$

where θ – the spectrum shift frequency.

It has maxima in the frequency range $\omega = \pm\theta$.

Fig. 4, 5 shows the curves characterizing the correlation functions of the bit weapon wear.

In the general case, vibrations and stresses that act on the elements of the drill strings are spatial. They can be decomposed into three components along the coordinate axes and consider random vibrations as random functions of one argument – time. The analysis of the vibrations of the drill string and its elements based on random oscillations makes it possible to increase the reliability of determining the vibration reliability of the drill string and its elements.
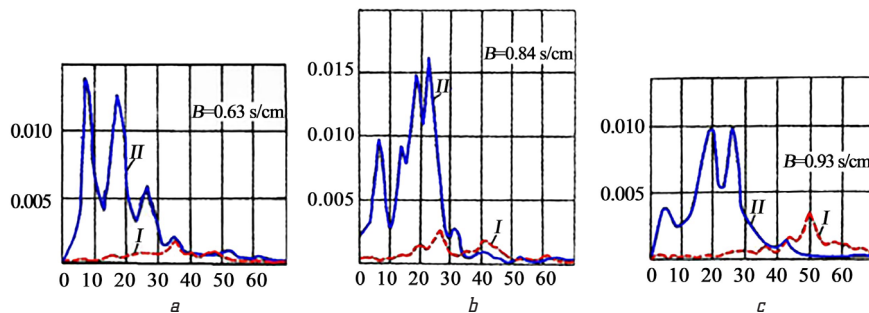
Fig. 3. Graphs of the power spectral density of stresses from vibration sensors in rocks of different hardness: I – near-impact zone;
II – the top of the drill string; a – soft rocks; b – rocks of medium hardness; c – hard rocks
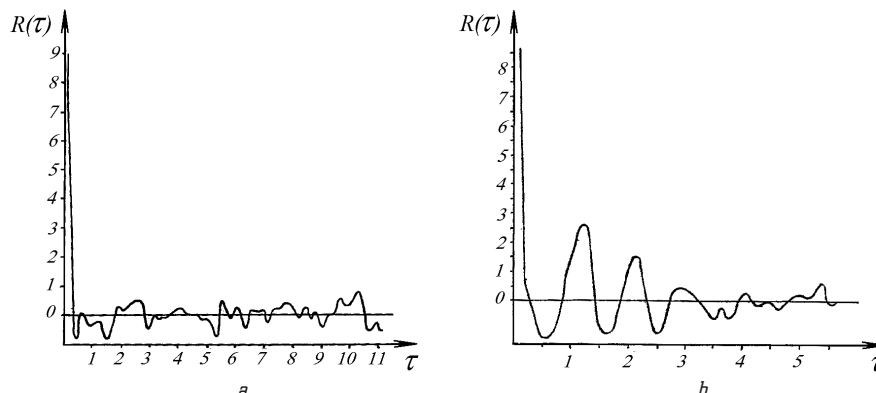
Fig. 4. Autocorrelation functions of the longitudinal oscillations of the chisel bit: a – new bit; b – for 20 % wear and tear of weapons
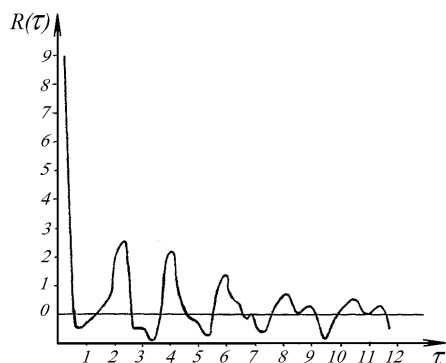
Fig. 5. Autocorrelation function of longitudinal oscillations of the bit at 40 % weapon wear

An important feature of the vibrations of the drill string in the drilling process with square bits is that the intensity of the vibrations of the top of the drill string passes with frequencies close to low frequencies, and the vibrations of the bottom of the string – to high frequencies. The process at the exit of the drill string, taking into account random disturbances, is narrow-band (quasi-harmonic) or close to it. As a result, the assumption of a narrow band at the output of the system, which is the basis of theoretical research, is justified.

The obtained results can be used in the practice of drilling wells to increase the stability of the drill string. On the basis of research, it has been proven that the drill string, as a system with liquid filling under pressure, is more stable compared to a hollow structure, and the flushing fluid, in this case, plays the role of a dynamic absorber.

The conditions and limits of the application of the obtained results are the study of random oscillations of the drill string elements, as well as its oscillations in general, primarily caused by the interaction of the bit with the hole, as well as the string elements with the walls of the well and trajectory changes.

Further research will be aimed at determining the correlation dependences, by which it is possible to determine the degree of wear of the ball bit weapon in deep and ultra-deep wells – with a depth of more than 5000 m.

4. Conclusions

It has been shown that the nature of the vibrations of the top of the drill string and the downhole signals are different and have a stationary random character. The energy composition of the spectrum sections and the appearance of resonance peaks and their displacement have been directly determined by the physical and mechanical properties of the rocks being drilled, as one of the factors that determines the vibration state of the drill string. Graphs of the spectral density of the power of pitting vibrations show their amplification at frequencies of 30–40 Hz as the hardness of the rocks being drilled increases. The maximum of the power density bending curve shifts towards low frequencies. There is a «mutual convergence» of the maxima of the power spectral density of the oscillations of the top and bottom of the drill string. An important feature of the vibrations of the drill string in the drilling process with square bits is that the intensity of the vibrations of the top of the drill string passes with frequencies close to low frequencies, and the vibrations of

the string bottom – to high frequencies. The process at the exit of the drill string, taking into account random disturbances, is narrow-band (quasi-harmonic) or close to it. As a result, the assumption of a narrow band at the output of the system, which is the basis of theoretical research, has been justified. The drill string, as a system with liquid filling under pressure, is more stable compared to a hollow structure. The washing liquid, in this case, plays the role of a dynamic absorber.

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IMPROVEMENT OF THE METHODOLOGY FOR PREDICTING GAS-DYNAMIC PHENOMENA ON THE BASIS OF MODERN SOUND-CAPTURING EQUIPMENT

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The object of the study is the sound accompaniment of the processes of stress redistribution in the bottom part of the coal seam, which precede the release of rock, coal, and gas. Among the hazards of underground coal mining, gas-dynamic phenomena (GDP) are the most complex in nature and the most dangerous in terms of consequences of high dynamic power and the release of a large amount of mechanical energy in the form of fractures and gas in a short period of time. This leads to accidents due to sudden gassing and blockages of workings with coal and rock, as well as explosions of methane and coal dust, destruction of the workings' support, damage to machinery and mechanisms, equipment, and devices. The greatest hazard among GDPs is posed by sudden releases of coal and gas, rock and gas, gas releases with destruction of host rocks and with destruction of the ground of the workings, as well as gas breakthroughs from tectonic fault zones.

Therefore, the accuracy of predicting possible gas-dynamic phenomena significantly affects the level of safety of miners. The acoustic emission (AE) method is used to predict the gas-dynamic activity of a rock massif. The analysis of acoustic emission studies based on archival data in coal seams subject to gas-dynamic activity has made it possible to substantiate the possibility of improving the accuracy of the forecast of emission hazard, which has a social and economic effect. On the basis of exploratory research and production tests, the software for automated calculations of the GDP forecast was improved and an improved Methodology for forecasting gas-dynamic phenomena based on modern sound-capturing equipment was developed. A scientific justification for the reference interval of AE observations in the conditions of a particular longwall was developed.

The developed software and the forecasting methodology were tested in the conditions of the Tsentralna mine of the Toretskugol State Enterprise (Toretsk, Donetsk region, Ukraine). The practical significance of the work is that a method for predicting explosion hazard has been developed, taking into account the modern capabilities of equipment and methods of input data processing, which allows to increase the productivity of mining and tunneling operations in coal seams without reducing the safety of miners.

Keywords: *gas-dynamic phenomena, acoustic emission, signs of gas-dynamic activity zones, manifestations of mining pressure, prediction of GDP.*

1. Introduction

The efficiency and safety of mining operations largely depend on the nature of the manifestation of mining pressure, which is one of the most significant phenomena associated with the development of coal deposits, so many studies have been devoted to it and many methods have been proposed to predict areas of high mining pressure.