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MODELING OF DRILLING TOOL VIBRATION IN THE PROCESS OF DRILLING BLAST WELLS

Purpose. To determine the characteristic features and model bit vibration during its interaction with rock in the process of drilling technical (blast) wells in open pit mines.

Methodology. The following methods were used in the work: analysis of scientific and practical solutions; statistical methods for processing the results of experimental studies; methods of analytical synthesis; computer modeling methods for synthesis and analysis of mathematical models.

Findings. The process of interaction between a drill bit and a rock was analyzed. The conditions and causes of vibration of drilling equipment are determined. The spectral analysis of the vibration signal, the formation and analysis of the map of the order of rotation of the rotating parts of the drilling rig during the drilling of technical (blast) wells were performed to identify the bit in the frequency domain of the measured concomitant integrated vibration signal as a source of high-amplitude vibration. The modulated signal measured in the time domain at the specified frequency carries information about the physical and mechanical characteristics of the drilled rock and the state of the bit. The analysis of the experimental studies and modeling of the process of interaction of the bit with the rock allows us to conclude that the obtained statistical indicators of the accompanying vibration signal really adequately characterize the process of well drilling.

Originality. A method for determining the characteristics of the interaction of a drill bit with rock in the process of drilling technical (blast) wells based on measuring the parameters of the accompanying vibration signal is proposed. The method differs from the known ones in the fact that in the process of changing the operating mode of the drive of the rotating parts of the drilling rig, an order map is formed over the entire range of its revolutions, the frequency of high-amplitude vibration of the bit is determined, which corresponds to a certain peak order of revolutions, and at this frequency the statistical parameters of changes are measured.

Practical value. This approach to the process of drilling wells in open pit mines makes it possible to quickly determine the physical and mechanical characteristics of the drilled rock and adjust the process parameters accordingly to increase its productivity and energy saving.

Keywords: *mine working*, *well drilling, chisel, vibration, parameters, modeling*

Introduction. Vibration of drilling equipment is one of the factors limiting the maximum drilling productivity. Vibration oscillations during drilling also cause damage to the bit, excessive torque of the drill string joints, torsional fatigue, etc. [1].

The sources of vibration excitation are the interaction of the well bore and drill string and the interaction of the well bore with the drill bit. Real-time analysis of the rig dynamics is becoming a necessity to optimize drilling parameters and reduce vibration-related problems. It is very difficult to develop a model of the drilling process due to the presence of many variables characterizing this process. This article presents an approach based on the separation of vibrations arising from the interaction of the bit with the bottom hole, in order to use the parameters of this process to determine the physical and mechanical characteristics of the rock.

Literature review. Rotary drilling is a standard method used in the mining industry for exploration and production of mineral resources. Drilling rigs currently in use vary greatly in their design, purpose, and capabilities. However, the main components of any drilling rig are: a drive power unit with a transmission – A, a drill string (rod) – B, and a drilling tool unit – C (Fig. 1).

Achieving high rates of penetration (ROP) is one of the main goals of drilling process control. ROP primarily depends on changes in a bit of load (WOB) and a bit rotation speed (RPM). Taking into account the entire possible operating range of WOB and RPM changes, this relationship is nonlinear [2]. This is due to the patterns of interaction between the bit and the rock and its changing physical and mechanical characteristics.

The bit is a kind of mechanism that converts the rotation of the drill string into longitudinal (axial), torsional, and, under certain conditions, transverse (lateral) vibrations in the process of interaction with the bottom hole [3]. Fig. 1 shows the

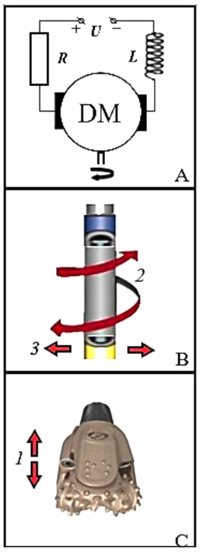

Fig. 1. Types of drilling rig vibrations:

1 – longitudinal; 2 – torsional; 3 – transverse

main types of vibrations that occur in a drilling rig during its operation.

Strong vibrations during tool operation can lead to the destruction of drilling rig elements, an increase in the well diameter, premature bit wear, and a decrease in the mechanical drilling rate. When vibrations increase and in the absence of control over their level, resonance may occur, which in most cases leads to catastrophic destruction of the elements of the drilling rig [4].

Vibration oscillations are of a wave nature. They depend on the respective characteristics of the drill string (rod) and bit, physical and mechanical properties of the drilled rocks, and drilling operating parameters [5].

These types of vibration lead to specific movements of the drilling tool: reverse vortex, catch-slip, bit jump, lateral vibrations or run out [6].

In general, oscillatory motion is caused by the process of intermolecular collision in a medium, such as air or a solid. The necessary conditions for oscillatory motion are elasticity and inertia. Elasticity is the ability of a body to return to its equilibrium position after it is displaced. Inertia allows the transfer of momentum neighboring elements of the environment. Oscillatory motion can be characterized in terms of wave propagation, which, in turn, forms modes. Thus, the dynamics of mechanical vibrations can be studied in terms of both wave propagation and modal analysis. Oscillatory motion causes pressure fluctuations in air and displacements in solids. Thus, the resulting mode shapes are pressure and displacement patterns for air and solids, respectively [7].

Paper [8] states that the main diagnostic parameters of vibration signals are time characteristics – the correlation function $R(\tau)$ and dispersion $D[\xi(t)]$ of the process (1), as well as its spectral characteristics – frequencies f_k of its harmonic components and dispersion σ_k^2 of their random amplitudes γ_k.

In [9, 10], the process of propagation of vibrations in rock is considered ξ, with a wavelength of λ, whose amplitude depends on the size and number of ore inclusions. The variance of this value is determined by the expression

$$D\xi = M\xi^2 - \langle\xi\rangle^2,$$

where $M\xi^2 = \sum_{k=0}^{\infty} M\left(\frac{\xi^2}{k}\right)F(k)$; $M\xi$ – mathematical expectation of a random variable ξ; $M(\xi/k)$ – conditional mathematical expectation for a fixed number of ore inclusions k; symbol $\langle\ \rangle$ – averaging over fluctuations in their size and number.

It is shown that the relative value of

$$S = \frac{\sqrt{D\xi}}{\langle\xi\rangle},$$

characterizes the size of heterogeneity in the rock.

In addition to these characteristics, the envelope of the correlation function, capstral characteristics, and, in multichannel systems, mutual correlation and spectral characteristics are also used as diagnostic features [11].

Purpose of the article. To determine the characteristic features and model bit vibration during its interaction with rock in the process of drilling technical (blast) wells in open pit mines.

Methods. Rock destruction in the process of well drilling has a pronounced dynamic nature of energy-intensive contact interaction, during which each bit element is a source of high-amplitude vibroacoustic vibrations that characterize this process in aggregate.

When drilling wells, the physical and mechanical properties of rocks change randomly. To ensure optimal drilling conditions, it is necessary to adequately regulate the axial force and rotation speed of the drill bit when the rock strength changes. It is proposed to solve the problem of prompt determination of the physical and mechanical characteristics of rocks during well drilling by analyzing the vibrations of the bit that occur during this process.

Fig. 2, as an example, shows the texture and structure of iron ore deposits in the Kryvyi Rih basin.

Thus, we can note the diversity of minerals and their aggregations in iron ore, which have their own special physical and mechanical characteristics. Accordingly, the complex mineralogical composition and textural and structural features of iron ore deposits also determine the special characteristics of the accompanying vibration signal in the process of contact interaction between the drill bit and the rock.

The drill bit is the main tool used in drilling; it has a destructive effect on the rock during well drilling. Choosing the best bit and its operating conditions is one of the tasks that determines the efficiency of drilling.

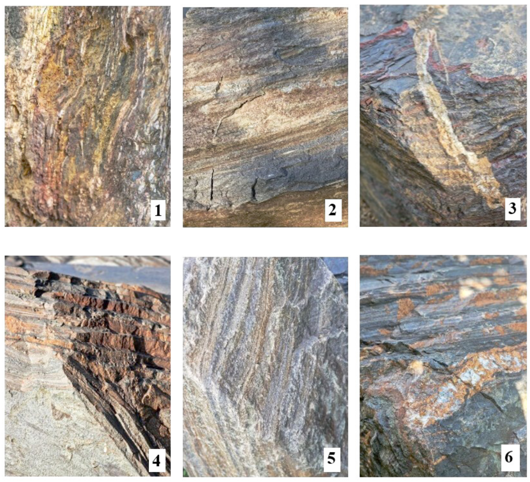

Fig. 2. Texture and structure of iron ore deposits in the Kryvyi Rih basin:

1 – Southern Mining and Processing Plant (MPP), sixth iron horizon. Siderite-limonite-hematite-martite quartzites, wide-ranging; 2 – Inhuletskyi HZK, fourth iron horizon. Quartzites are magnetite, thinly laminated, sulphurous-faceted; 3 – Tsentralnyi HZK, Glievatskyi open pit, fourth ferruginous horizon. Hematite-magnetite quartzites, red-banded, broadly laminated; 4 – Tsentralnyi HZK, Artemivsk open pit, fourth ferruginous horizon. Magnetite quartzites are thin-layered, gray-banded; 5 – Inhuletskyi HZK, fourth iron-ore horizon. Hematite-magnetite quartzites, thin-layered, red-striped; 6 – Pivnichnyi HZK, Pervomaiskyi open pit, sixth iron horizon. Medium-layered magnetite quartzites

There is a wide range of drill bits that can be used; however, for rotary drilling, they are mainly divided into two categories: roller cutter bits and bits with fixed cutters, such as polycrystalline diamond bits – PDC (Polycrystalline Diamond Compact).

A roller cone bit is a structure consisting of several axial elements (usually three) on which roller cones rotate on roller or ball bearings. There are pin bits with teeth in the form of carbide pins with a wedge or spherical working surface and toothed bits made of the same material as the roller. The drill bits have one rotational degree of freedom relative to the body, so that the drill bit rolls during drilling and each tooth periodically comes into contact with the rock.

The contact interaction of a roller cutter bit rock involves a combination of dynamic and static forces, and the vibrations that occur during drilling consist of three components: periodic, shock, and random, which are determined by the structure and texture of the material of contact. Considering the space occupied by the contact between the drill bit and the rock at a given time t, as a discrete bounded area Ω, the mathematical model of the contact interaction "drill bit-rock" can be represented as follows [12].

$$m\ddot{u} = p(t) + c(u,\alpha) - f(u,\beta),$$

where m is mass matrix; $\ddot{u}$ – acceleration vector; t – time variable; p – external force vector; c – contact force and friction vector; f – internal voltage vector; u – moving an object; α – a variable related to the properties of the contact surface; β – a variable related to the constitutive ratio of the material.

As a result of this process, vibrations of varying amplitude and frequency are formed both in the bit itself and in the rock mass.

Polycrystalline diamond (PDC) bits are believed to provide a higher rate of penetration (ROP) than conventional conical bits with a roller cone. At the same time, their shear effect on the rock usually leads to strong vibration, whereas the bit movement includes periodic phases: sticking, when the bit stops rotating, and slipping, when it acquires a higher than nominal angular velocity when leaving the sticking phase.

The phenomenological model proposed by Detournay and Defourny [13] takes into account the fact that the cutting action of a friction PDC bit consists of both a cutting process and a friction process. It is believed that the components of the torque on the bit TOB and the load on the bit WOB act on each cutter of the bit. When drilling through rock, the average cutting force T_c and the average weight carried by the cutting surface, W_c are the cutting components of TOB and WOB, respectively, and the friction force T_f and the contact surface W_f are the corresponding friction components. The rock-bit interaction model uses WOB and bit angular velocity as input data w_b, and the torque is on the bit T_b; friction-related torque T_f; weight due to friction W_f; torque associated with cutting T_c; weight associated with cutting W_c, are the outputs.

Equation for torque on the bit T_b (reflecting the nonlinear friction moment caused by the interaction of rock and bit) undergoing intermittent slippage [13].

$$T_b = D_b W_b [\mu_{cb}(w_b) + (\mu_{sb} - \mu_{cb}) e^{-\lambda |w_b|}],$$

where μ_{cb} and μ_{sb} are static, dry and coulomb friction coefficients; λ – attenuation coefficient equal to 0.9; w_b – angular velocity of the bit.

As mentioned above, the main causes of drilling rig vibrations are: the abrupt nature of rock fracture; well bore bottom hole dislocation, which in turn depends on the impact of the drill string on the bottom hole during its longitudinal and torsional vibrations, abrupt and frequent changes in drilling mode parameters, heterogeneity, fracturing and sharp variations in the hardness of the drilled rocks, pressure differences under different bit teeth, etc.

Usually, a distinction is made between low-frequency and high-frequency vibrations of a drilling rig. For example, for the SBSh-250 drilling rig, which is widely used in the drilling of exploration and production wells, high-frequency vibrations have an amplitude of 0.01–0.03 mm and a frequency of 20–60 Hz, and low-frequency vibrations, respectively: 0.1–2 mm and 2–12 Hz [14].

When modeling the vibrations of a drilling rig, its model can be represented as a set of connected elementary basic oscillatory blocks consisting of a spring k (means for storing potential energy), mass m or inertia J (means for storing kinetic energy), and a damper c (means by which energy is gradually lost) (Fig. 3).

Periodic force $F(t)$, acting on the above system, can be expressed in terms of harmonic functions using the Fourier series as follows [15].

$$F(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos nwt + b_n \sin nwt).$$

Then the stationary solution for the above scheme can be written as

$$x_p(t) = \frac{a_0}{2k} + \sum_{n=1}^{\infty} \frac{a_n/k}{\sqrt{(1-r_n^2)^2 + (2\zeta r_n)^2}} \cos(nwt - \psi_n) + \sum_{n=1}^{\infty} \frac{b_n/k}{\sqrt{(1-r_n^2)^2 + (2\zeta r_n)^2}} \sin(nwt - \psi_n).$$

During the drilling process, the damping parameters change (interaction of the drill bit with the rock, friction of the drill string against the borehole walls, movement of interconnected parts of the drilling rig), which leads to changes in the parameters of the system response to the applied force. In Figs. 4, 5 show the dependence of the phase angle and the dimensionless value of the response to a harmonic signal on the frequency ratio r for different values of the damping coefficient ζ from 0.1 to 1.0

$$r = \frac{w}{w_n}.$$

In this case, the value of the dimensionless response is set as a bandwidth [15, 16].

$$\frac{|X(iw)|}{A} = \left[\frac{1 + \left(\frac{2\zeta w}{w_n}\right)^2}{1 - \left(\frac{w}{w_n}\right)^2 + \left(\frac{2\zeta w}{w_n}\right)^2}\right],$$

where A is the amplitude of the harmonic effect; ζ – the damping coefficient.

Phase angle ϕ is defined by the expression

$$\phi(w) = \tan^{-1}\left[\frac{2\zeta\left(\frac{w}{w_n}\right)^2}{1 - \left(\frac{w}{w_n}\right)^2 + \left(\frac{2\zeta w}{w_n}\right)^2}\right].$$

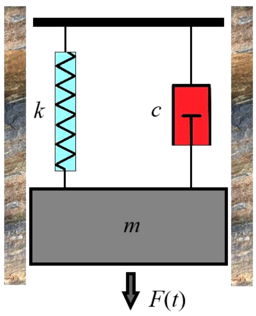

Fig. 3. Model of the basic oscillating unit

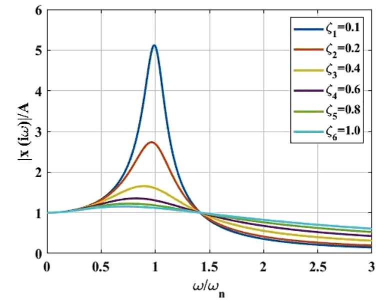

Fig. 4. Dependence of the dimensionless response of an oscillatory system to a harmonic signal on the frequency ratio r

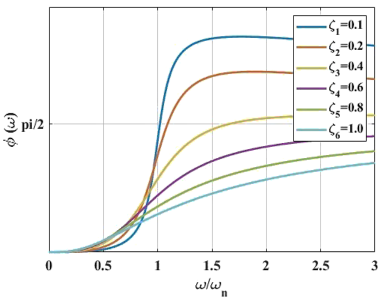

Fig. 5. Dependence of the phase angle of response to a harmonic signal on the frequency ratio r

Thus, the use of the above approach allows modeling the parameters of the drilling tool vibration in the process of interaction with the rock, which are the characteristic features of this process.

Vibrations occurring on the bit during well drilling represent a complex oscillatory process

$$X(t)=\sum_{k=1}^{\infty}A(t)\cos[kw_0(t)+\varphi_k(t)]+\xi_w(t).$$

It includes the superposition of a quasi-poly harmonic process – in the low and medium frequencies, a random broadband stationary process $\xi_w(t)$ – in the high frequency region [14, 17].

Relevant information on the interaction of the bit with the rock during well drilling is contained in the high-frequency random component of the vibration signal. The extraction of this useful information and the determination of characteristic features for identifying the physical and mechanical characteristics of the rock is carried out using spectral analysis. The Fourier transform determines the spectral power density of this signal [18].

$$S_T(w)=\frac{1}{T}[H_T(jw)]^2,\quad 0<t<T,$$

where $H_T(jw)=\int_{-\infty}^{\infty}\eta(w)e^{-jwt}$ is frequency representation of the signal.

From this signal, a narrow band component was distinguished $\xi_\Delta(t)$ with the highest capacity [14, 19].

$$\xi_\Delta(t)=A[1+mB(t)\cos(\omega_\Delta t+\varphi_0)],$$

where $0<m<1$ is the modulation depth.

In this expression

$$B(t)=\sum_{k=1}^{n}C_k\cos(k\Omega t+\varphi),$$

i. e., represents an amplitude-modulated process of the form

$$\xi(t)=A\left[1+\sum_{k=1}^{n}m_kC_k\cos(k\Omega t+\varphi)\right]\cdot\cos(w_\Delta t+\varphi_0),$$

where m_k is the partial modulation coefficient; Ω is the angular frequency of modulation.

The main issue in this procedure is to determine the signs by which the $\xi_\Delta(t)$ is distinguished. This determines how much information about the process of interaction of the bit with the rock is protected from the influence of various interferences (vibrations of other parts of the drilling rig, external processes in the rock mass, etc.). To solve this problem, the formation, and analysis of the map of the rotational order of the rotating parts of the drilling rig is performed.

The idea of the proposed method is to use the formation and analysis of the map of the order of rotation of the rotating parts of the drilling rig during the drilling of technical (blast) wells to identify the bit in the frequency domain of the measured concomitant integrated vibration signal as a source of high-amplitude vibration. Measurement of the characteristic parameters of oscillations in the time domain at a certain frequency corresponding to the peak value of the order on the generated map allows reducing the influence of disturbing factors arising in the process of well drilling and being potential sources of undesirable components of the measured vibration signal for analysis on the results of assessing the characteristics of the interaction of the drill bit with the rock. The modulated signal measured in the time domain at a specified frequency carries information about the physical and mechanical characteristics of the drilled rock and the state of the bit. The information on ore characteristics obtained at the stage of extraction allows optimizing further technological operations (crushing, grinding, classification, benefaction, etc.) to prepare it for metallurgical processing [20]. It is also useful for improving the quality of modeling of these operations [21].

Order analysis is the study of vibrations in rotating systems that result from the rotation itself. The frequency of these vibrations is often proportional to the rotational speed. The constants of proportionality are the orders.

Rotational speed is usually measured independently and varies with time under most experimental conditions. Proper analysis of rotational oscillations requires resampling and interpolation of the measured signal to achieve a constant number of samples per cycle.

This process converts signal components whose frequencies are constant multiples of the rotational frequency into constant tones. The conversion reduces the blurring of spectral components that occurs when the time-tone changes rapidly over time.

There are various methods for tracking the order of the rotating machines. For example, the method for tracking the order using analog devices is based on measuring vibration parameters with the simultaneous generation of a signal proportional to the speed of the rotating machine shaft. This allows for selective selection of information (angular domain sampling) followed by its analysis using the Fast Fourier Transform (FFT), which results in an order spectrum. Currently, this method is of limited use due to the low accuracy and complexity of its hardware implementation.

The following methods are widely used, mainly for detecting malfunctions of machines and mechanisms: the computed order tracking (COT) method, the method based on the Vold-Kalman filter (VKF-OT) and the method using the Gabor transform.

COT essentially consists of converting a time domain signal sampled by the Shannon-Nyquist sampling theorem into an angular domain signal. The equipment collects the axis velocity pulse signal at the same time interval to calculate an equal angular time, then an interpolation algorithm is used to interpolate and fit the resampling time to obtain the final angular domain signal [22].

The limitation of this method is the finite order resolution. This causes problems when orders do not fall on spectral lines.

The VKF-OT method relies on data equations and a structural equation. The data equation of the second-generation

Vold-Kalman filter for single-order filtering is defined as [23].

$$y(n) = x(n)e^{j\Theta(n)} + \eta(n),$$

where $y(n)$is measured data; x(n) – complex envelope of the filtered signal; $e^{j\Theta(n)}$ – complex carrier wave; $\Theta(n) = \sum_{i=1}^{n} w(i)\Delta t$; $w(i)$ – discrete angular frequency; $\eta(n)$ – random noise and other order components, or errors.

The structural equation ensures the smoothness of the sequential digital points of the filtered data by fitting a low-order polynomial to the sequence $x(n)$.

This method allows for the extraction of close and overlapping orders in systems with multiple shafts, and has a higher frequency and order resolution than conventional methods. However, since the VKF-OT method requires a longer calculation time, it is not well suited for real-time processing.

When extracting signal order based on the Gabor transform, the center frequency is usually determined by linear interpolation. On this basis, the filter pass band is determined by the equal-frequency or equal-order method. If q- and the center frequency $f_q(t)$ and equal frequency bandwidth Δf is a constant, the filtering neighborhood can be represented by equation [24].

$$f_q(t) \pm \frac{\Delta f}{2} = \left[f_q(t) - \frac{\Delta t}{2}, \quad f_q(t) + \frac{\Delta t}{2} \right].$$

Then, using a masking algorithm, the Gabor coefficient of the corresponding order in the signal is obtained.

The method based on the Gabor transform requires less time to implement compared to the VKF-OT method, but is inferior in accuracy.

Other methods for tracking the order of the rotating machines are also known, each of which has its advantages and disadvantages [25].

Obviously, the choice of a particular one depends on the specifics and conditions of the task at hand.

Results. Fig. 6 shows a block diagram of the order analysis algorithm using Matlab functions based on the WTO method with the use of signal resampling to increase its resolution [26].

The following operations are performed sequentially:

1. Download of the vibration signal synchronized with the data of the drilling rig drive speed.

2. Estimation of the phase angle as a time integral of the rotational speed using the function suntraps

$$\varnothing(t) = \int_0^t \frac{RPM(\tau)}{60} d\tau.$$

3. Upsampling and low-pass filtering of the signal using the *resample*.

4. Linear interpolation of the signal to a uniform grid in the phase domain using the function *interp1*.

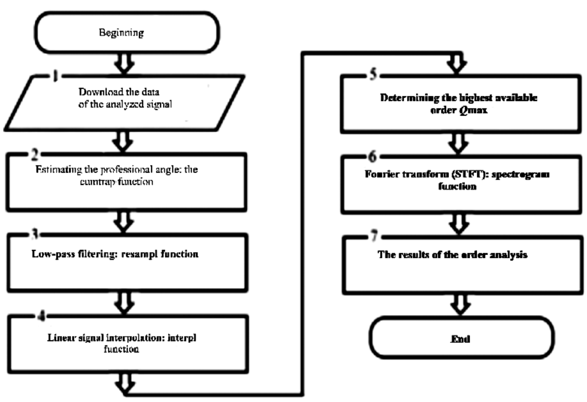

Fig. 6. Order analysis algorithm using Matlab functions

5. Determination of the highest available order in the measurement, which is recorded by the sampling rate and the highest rotational speed achieved by the system

$$O_{\max} = \frac{f_s/2}{\max\left(\frac{RPM}{60}\right)}.$$

To obtain better results, we resample by an additional factor of 4. The resulting sampling frequency in the phase domain f_p is

$$f_p = 4 \cdot 2O_{\max} = 4 \cdot 2 \frac{f_s/2}{\max\left(\frac{RPM}{60}\right)}.$$

6. Calculation of the short-term Fourier transform (STFT) of the interpolated signal using the function *spectrogram*. The function divides the signal into L sampling segments and flat-topped windows of each of them

$$N_{overlap} = \min\left(\left\lfloor \frac{p_{overlap}}{100} \cdot L \right\rfloor, \quad L-1 \right),$$

where $p_{overlap}$ is overlap between adjacent segments (50 %).

Resolution depends on the sampling rate and segment length

$$r = \frac{f_p}{L} \cdot ENBW,$$

where $ENBW$ is the equivalent noise bandwidth of the window, which is calculated using the function *enbw*.

7. The results of the order analysis are used to distinguish the component of the total vibration signal in the time domain at the bit rotation frequency during all operating modes of the drilling rig.

In accordance with the above algorithm, an rpm map was formed from the vibration data in the process of changing the operating mode of the drilling rig (increasing the drive speed from 500 to 2,150 rpm within 40 seconds (Fig. 7). The amplitude of the map represents the root-mean-square (RMS) value of the vibration signal.

Fig. 8 shows the results of the spectral analysis of the total vibration signal (1) and the isolated ordinal signal directly on the drill bit (2).

Figs. 9, 10 show the results of separating the ordinal component on the bit from the total vibration signal in the time domain during a change in the operating mode of the drilling rig.

Table 1 shows the statistical characteristics of the line-by-line signals on the bit corresponding to the three types of iron ore: Mean – mean value; Median – median value; RMS – root mean square value; STD – standard deviation; VAR – variance).

The analysis of the experimental studies and modeling of the process of interaction between the bit and the rock allows us to conclude that the obtained statistical indicators of the accompanying vibration signal really adequately characterize the process of drilling wells.

It should be noted that the characteristics of the obtained vibration signals depend on the content of iron oxides Fe_2O_3 + FeO. Thus, the data presented in Table correspond to iron ore with Fe_2O_3 + FeO content of 42.2, 23.5, 16.5 (%), and the overall correlation of RMS of the obtained signals with this indicator is 81–85 for ores with different mineralogical composition. This can be explained by the predominant hardness and strength of these components over others. At the same time, given the diversity of the mineral composition and textural and structural features of iron ore, the use of only the above parameters of the vibration signal is not sufficient to reliably determine its mineralogical and technological varieties.

Conclusions. A method for determining the characteristics of the interaction of a drill bit with rock in the process of drilling technical (blast) wells in open pit mines based on measur-

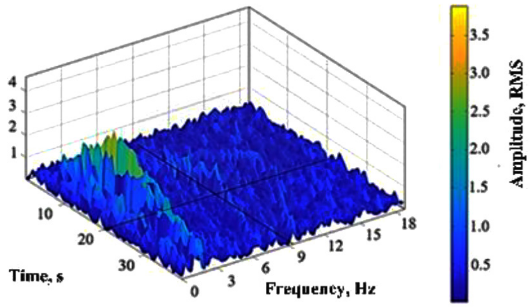

Fig. 7. Vibration data map of rotating parts of the drilling rig

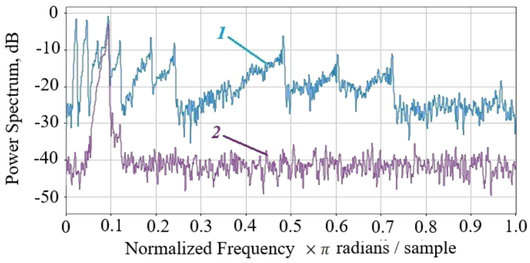

Fig. 8. The results of spectral analysis of the total vibration signal (1) *and the isolated ordinal signal directly on the drill bit* (2)

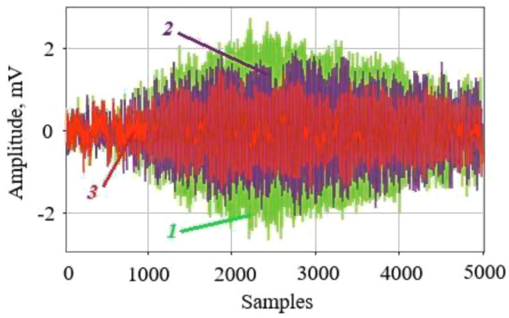

Fig. 9. Sequence signals on the bit corresponding to three types of iron ore

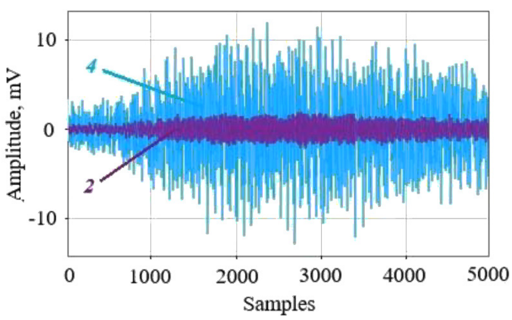

Fig. 10. An ordinal signal on the bit against the background of the general vibration signal

Table

Parameters of the analyzed drilling rig vibration signal in the time domain

Parameter	Mean	Median	RMS	STD	VAR
Signal 1	1.334	1.3701	1.4556	0.6072	0.3687
Signal 2	0.9736	0.9996	1.0716	0.4477	0.2004
Signal 3	0.6180	0.6155	0.6819	0.2881	0.0830

ing the parameters of the accompanying vibration signal has been investigated, which differs from the known ones in the fact that in the process of changing the operating mode of the rotating parts of the drilling rig, an order map is formed in the entire range of its revolutions, the frequency of high-amplitude vibration of the bit is determined, which corresponds to a certain peak order of revolutions, and at this time the statistical parameters of changes in the amplitude of the measured signal are measured. This makes it possible to improve the quality of assessment of the physical and mechanical characteristics of the drilled rocks by reducing the influence of disturbing factors**.**

The obtained results are used as one of the characteristic features in determining the technology and mineralogical types of iron ore in the process of drilling technical (blast) wells. This approach makes it possible to quickly determine the physical and mechanical characteristics of the drilled rock and adjust the process parameters accordingly to increase its productivity and energy saving. In addition, based on the information obtained, a geological scheme of the deposit and the corresponding blasting technology for its exploration and exploitation are formed.

The direction of further research is to determine the best combination of the characteristic features of the well drilling process and intelligent methods for processing the information received to optimize its technological and economic performance.

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Моделювання вібрації бурового інструменту у процесі буріння вибухових свердловин

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Мета. Визначення характеристичних ознак і моделювання вібрації долота при його взаємодії з гірською породою у процесі буріння технічних (вибухових) свердловин на відкритих гірничих виробках.

Методика. У роботі використані такі методи: аналіз наукових і практичних рішень; статистичні методи для оброблення результатів експериментальних досліджень; методи аналітичного синтезу; методи комп'ютерного моделювання для синтезу та аналізу математичних моделей.

Результати. Виконано аналіз процесу взаємодії бурового долота з гірською породою. Визначені умови та причини виникнення вібрацій бурового устаткування. Виконано спектральний аналіз вібраційного сигналу, формування та аналіз карти порядку обертів обертових частин бурової установки у процесі буріння технічних (вибухових) свердловин для ідентифікації долота у частотній області вимірюваного супутнього інтегрованого вібраційного сигналу як джерела високоамплітудної вібрації. Виміряний у часовій області на зазначеній частоті модульований сигнал несе інформацію про фізико-механічні характеристики гірської породи, що буриться, і стан долота. Аналіз виконаних експериментальних досліджень і моделювання процесу взаємодії долота з гірською породою дозволяє зробити висновок про те, що отримані статистичні показники супутнього вібраційного сигналу дійсно адекватно характеризують процес буріння свердловин.

Наукова новизна. Запропоновано метод визначення характеристик взаємодії долота бурової установки з гірською породою у процесі буріння технічних (вибухових) свердловин на основі вимірювання параметрів супутнього вібраційного сигналу. Метод відрізняється від відомих тим, що у процесі зміни робочого режиму приводу обертових частин бурової установки формують карту порядку в усьому діапазоні його обертів, визначають частоту високоамплітудної вібрації долота, яка відповідає визначеному піковому порядку обертів, і на цій частоті вимірюють статистичні параметри змін амплітуди виміряного сигналу.

Практична значимість. Зазначений підхід до процесу буріння свердловин на відкритих гірничих виробках дозволяє оперативно визначати фізико-механічні характеристики гірської породи, що буриться, і відповідним чином корегувати параметри процесу для підвищення його продуктивності та енергозбереження.

Ключові слова: *гірничі виробки, буріння свердловин, долото, вібрація, параметри, моделювання*

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