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DRILLING WELLS TAKING INTO ACCOUNT THE DYNAMIC PROPERTIES OF ROCKS

The application of high-frequency vibrations to a drill bit is a promising means of increasing rate of penetration in deep hard formations. The implementation of such drill bit high-frequency vibrations is possible by installing the cavitation hydraulic vibrator in the drill string in front of the rock-cutting tool.

Purpose. Evaluation of resonant modes (frequencies of oscillations) for the dynamic interaction of the mud pressure in the drill string and the drill bit longitudinal vibrations in case of contact with the rock being destroyed while drilling using the cavitation hydraulic vibrator; comparative analysis of the effectiveness of using a high-frequency mechanical vibrator and a cavitation hydraulic vibrator in case of drilling in hard rocks.

Methodology. The research is based on a comparative analysis of the amplitudes and power spectral density of mud pressure oscillations of the mud and vibration accelerations in the drill bit cross section of drill string.

Findings. The results are presented in the form of amplitude spectra and power spectral densities of mud pressure and vibration acceleration, as well as the dependence of the increase in the rate of penetration on the frequency of forced oscillations of the drill bit.

Originality. Taking into account the influence of the cavitation hydraulic vibrator on the drill rig ROP made it possible:

- to determine the resonant frequencies of pressure oscillations of the mud of the drilling tool, for the effective removal of drilled rock at the point of its contact with the drilling tool, and the longitudinal vibration accelerations of the drilling tool, to speed up rate of penetration during the construction of a well;
- to evaluate the effectiveness of using a cavitation hydraulic vibrator in comparison with a high-frequency mechanical vibrator.

For the studied modes of operation of the hydraulic vibrator at values of the cavitation parameter $\tau = 0.19$, the well rate of penetration increases by 40 % compared to the traditional rotary method and by 26 % compared to the vibratory hammer. For the cavitation operating mode of the hydraulic vibrator $\tau = 0.41$, the increase in the rate of penetration is 62 and 37 %, respectively. At the same time, the operating efficiency of the hydraulic vibrator was ensured at the resonant frequencies of the mud pressure with a frequency of 1,580 Hz at $\tau = 0.19$ and 1,980 Hz at $\tau = 0.41$.

Practical value. For a specific design of the cavitation hydraulic vibrator as part of a drill string, by changing the frequency of the drill bit vibration impact on the rock, resonant frequencies are established that ensure the high ROP of the well.

Keywords: *cavitation hydraulic vibrator, drill bit, rock resonant frequency, rate of penetration*

Introduction. The study of the drill string dynamics associated with the imposition of high-frequency longitudinal vibrations on a rock-cutting tool is a current topic of modern research. Scientific work carried out in this direction has important economic benefits and practical guiding value. The extraction of hydrocarbon energy resources at great depths in difficult mining and geological conditions often leads to a dead end situation – low profitability of well construction.

From studies conducted in the former USSR [1], it is known that high-frequency impacts on rocks, namely resonance, impact and cavitation, are the factors that influence the rapid destruction of rock and contribute to the long-term preservation of the working condition of drilling equipment.

In modern conditions, in particular, at Southwest Petroleum University (China), for several years, to overcome the problems associated with the high cost of drilling in the development of the construction of ultra-deep wells (from 2,000 to 6,000 m) in relation to complex geological conditions, they have conducted large-scale research and developed a new drilling tool. A hydraulic pulse generator was installed in it, which implemented a cavitating jet. A description of this tool is given in [2]. At flushing fluid flow rates from 27.5 to 32 l/s, such a device creates oscillations in fluid pressure with a range of $\Delta P \approx 2.1–2.2$ MPa. At the main carrier frequency of these oscillations is 10 Hz. superimposed pressure pulsations with a range of $\Delta P \approx 0.56–0.60$ MPa with a frequency of approximately 80 Hz.

Field drilling tests (with this tool) during the construction of more than a hundred oil wells with a maximum depth of 6,162 m confirmed an increase in the penetration rate [3].

Chinese researchers have also developed a hydraulic oscillator, which is a typical downhole tool that uses self-generated vibration [4].

Construction of wells for hydrocarbon production is one of the most expensive operations in the oil and gas industry. As stated in work [5] 'one of the most important parameters affecting drilling cost is the rate of penetration (ROP)'. Its increase is solved by imposing longitudinal vibrations on the drill bit. This is achieved with the help of mechanical hydraulic hammers operating at frequencies up to one hundred Hz, as well as new cavitation pulse devices developed and implemented in the last decade [1]. Such devices generate shock vibrations in the sonic frequency range and above. At the same time, in certain modes of their operation, the range of oscillations in the mud pressure at the outlet of such devices exceeds the pressure at their inlet.

Literature review. The prospects of the scientific direction for the development of sonic and ultrasonic drilling technologies and the use of vibration loading of drilling tools are confirmed by numerous studies conducted by scientific institutes and organizations in different countries. For example, laboratory studies by Babapour [6] showed the possibility of increasing drilling speed by applying an axial vibration force to the bit using a pulsed cavitation drilling tool. Its design includes a Venturi tube that creates cavitation cavities in the drilling mud. It is argued that the collapse of cavitation bubbles formed inside the tool generates pressure pulsations and oscillatory forces on the bit.

Domestic researchers came to the same conclusion using a Venturi tube that creates a pulsating jet for the efficiency of face cleaning [7].

An analytical model of pulsation pressure characteristics was created in [8]. The results showed that tool design and operating conditions have a significant impact on the frequency and amplitude of bit pressure pulsations. The use of this technology can allow optimization of frequency and amplitude taking into account the lithology of the formations being drilled. This will lead to lower drilling costs and more oil and natural gas fields will become profitable.

The mechanism of rock destruction during impact drilling in deep hard rocks using high-frequency vibrations was studied in [9, 10]. In work [9], based on the mechanics of elasticity and the principles of mechanical vibrations, a model of rock destruction was created. The influence of oscillation frequency on the penetration rate was determined. It has been established that the ROP reaches a maximum when the frequency of shock vibrations is approximately equal to the natural frequency of the rock. Such drilling allows one to increase the service life of the drilling tool and reduce the cost of drilling a well [10].

Experimental and field studies continue to demonstrate that downhole vibrations induced by axial vibration tools in the drill string are the most effective method for reducing friction and improving axial force transmission in high-angle, long-reach wells.

The natural frequency of a number of hard rock samples (hardness is indicated on the Mohs scale), obtained from various sources, is shown in Fig. 1 and is about 37 kHz.

From the above figure, it is clear that the frequency of vibration loading of a rock cutting tool with a hydraulic vibrator, given in [1], is far from the natural frequency of rocks under modern technological conditions.

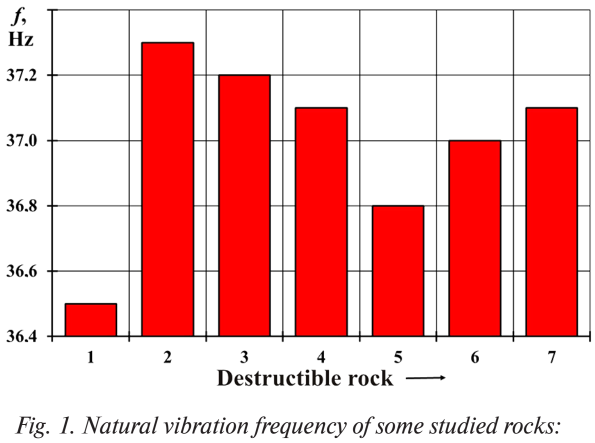

Fig. 1. Natural vibration frequency of some studied rocks:

1 is siltstone with iron additives; 2 is siltstone (hardness up to 6 units); 3 is argillite (up to 2–6 units); 4 is conglomerate (up to 6–7 units); 5 is conglomerate of other compounds (up to 6 units); 6 is granite (up to 7 units); 7 is metamorphic rock (up to 6–7 units)

Such relatively low frequencies of forced vibrations of the drill bit that are most effective in terms of drilling speed in comparison with the frequencies of rock vibrations (Fig. 1) can be explained by the presence of natural heterogeneities of the rock mass and the appearance of differently inclined cracks in the contact zone of the drilling tool and the destroyed material [4].

The work [4] considers the combined crushing of hard rocks by exerting axial and torsional effects on a rock-cutting tool. This technology can significantly increase the speed of well penetration. In this study, the dynamic process and mechanism of rock failure under complex impact are studied and a numerical model is developed. Verification of the effectiveness of the method was confirmed by tests under dynamic impact on sandstone. Finally, the influence of impact parameters and cyclic loads on rock destruction ability was systematically studied. Analysis of the mechanism of rock destruction, laboratory and field tests, and optimization of parameters allowed the authors [4] to develop a new combined impact drilling tool.

Progressive research methods – 3D technologies and high-speed photography allowed the authors of work [12] to obtain new data on the study of the characteristics of a cavitating nozzle. Thus, the influence of the geometric parameters of the nozzle on the dynamic characteristics of the flow realized by it was assessed taking into account the analysis of visualization of the process through image processing. The pressure and volume flow fields were studied as objective functions to assess the influence of the geometric parameters of the nozzle on the dynamics of the process. This study established that 'the optimal values of the throat length and nozzle divergence angle are equal to twice the throat diameter and 40°, respectively'.

Maximizing the ROP due to impact crushing of bottom-hole rock with a bit was experimentally studied in [13]. Dynamic tests when drilling granite samples with different modes of impact were carried out on a stand for rock destruction. The amplitude-frequency characteristics of the dynamic process of rock destruction were determined. Based on the analysis and using the Fourier transform, the spectral characteristics of the impact response of the destroyed rock were obtained. Finally, the optimal modes for effectively increasing the rate of rock destruction were determined. Based on the research results in this work, it is concluded that 'percussive drilling is an important technical method for increasing ROP as it meets the demand for efficient drilling in complex structural wells by using bit impact crushing on bottom rock. The application of vibrational impact rock breaking to increase ROP is especially impressive'. The results obtained in this work are of particular interest for further research into percussion drilling.

The review [14] of the use of sonic and ultrasonic vibrations in mud is based on the study of successful technologies in related industries in recent years. Here, the research results are summarized and the improvement of high-frequency oscillations during cavitation of the mud is considered. The possibility of increasing the magnitude of high-amplitude impacts and achieving resonance of the drilling tool with the destroyed rock was determined. However, as the authors of the review believe that 'at present, the application of ultra-sonic-assisted rock-breaking technology in the oil- and gas-drilling industry still faces some problems and challenges'.

One of these problems is the propagation of high-frequency oscillations in deep-well conditions and the lack of knowledge of the spectrum of frequency and amplitude characteristics.

Thus, summarizing the analysis of recent studies on the influence of the frequency of longitudinal vibration loading of a drilling tool, we can draw the following conclusions:

- the natural frequency of the rock in the zone of its destruction during sonic drilling is approximately an order of magnitude lower than the values shown in Fig. 1. This is explained by the formation of a network of differently inclined cracks in the destroyed rock in the zone of its contact with the drilling tool;

- at the same time, its strength decreases and the rate of penetration increases up to two times [15].

The above frequencies of excitation of drill bit oscillations (from 1,000 to 5,000 Hz) can be achieved by installing a cavitation hydraulic vibrator [1] in the drill string.

The purpose of the presented work is to analyze the resonant dynamic interaction of mud pressure oscillations and the longitudinal vibrations of the drill bit when it comes into contact with the destroyed rock in order to select rational operating modes of the cavitation hydraulic vibrator.

To achieve the goal, the following tasks were solved in the cross-section of the rock-destroying tool of the drill string:

- the amplitude spectra of the mud pressure and vibration acceleration were determined depending on the frequency of their oscillations;
- power spectral densities of mud pressure and vibration acceleration were determined depending on the frequency of their oscillations;
- resonant frequencies of mud pressure and drill bit vibration acceleration have been established;
- a comparative analysis of drilling efficiency using a high-frequency mechanical vibrator and a cavitation hydraulic vibrator was carried out based on the rate of well penetration.

The cavitation hydrovibrator layout diagram. A schematic representation (in 3D projection) of a cavitation hydraulic vibrator is shown in Fig. 2. It consists of a hydraulic vibrator housing (indicated by number *1* in Fig 1), including a cavitation generator (indicated by *2*) as the main element of the hydraulic vibrator, with an input hydraulic channel (indicated by *5*) for leveling the velocity field.

In the hydraulic vibrator housing there is an output flow-through hydraulic channel *3*. To avoid losses of pulse energy, it is made with a diameter equal to the diameter of the generator diffuser at the outlet. The hydraulic vibrator housing also has space for installing a pressure pulsation sensor – indicated by *4* and turnkey milled planes *6* for easy installation of the hydraulic vibrator as part of the drill string. Cavitation generator *2* is a Venturi tube of special geometry and transforms a stationary fluid flow into a periodically stalled cavitation flow.

A simplified layout diagram of the hydraulic vibrator under consideration as part of the drill string is shown in Fig. 3.

As can be seen from the analysis of this layout diagram, the cavitation hydraulic vibrator is located by means of conical threads in the drill string *1* with a rock-cutting tool *3*. When the mud passes through the generator *2* (Fig. 2), as a result of periodic growth, to a certain size and when the cavern is torn off – *5* (Fig. 3), and subsequently carried away by the flow into the flow channel into the high-pressure zone – *6*, its destruction occurs. In this case, high-frequency self-oscillations of shock-type liquid pressure are realized with a range ΔP exceeding the pressure value at the inlet to the generator [1, 2]. Subsequently, the design from the entrance to the hydraulic vibrator to the rock-cutting tool received the name – drilling tool.

As can be seen from the analysis of this layout diagram, the cavitation hydraulic vibrator is located by means of conical threads in the drill string 1 with a rock-cutting tool *3*. During the passage of the flushing fluid through the generator *2* (Fig. 2), the following dynamic processes occur: periodic growth (to certain sizes) and separation of the cavern – *5*

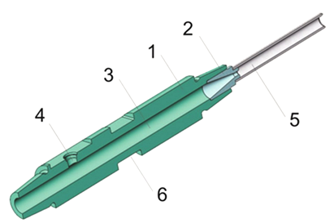

Fig. 2. The 3D diagram of the cavitation vibrator

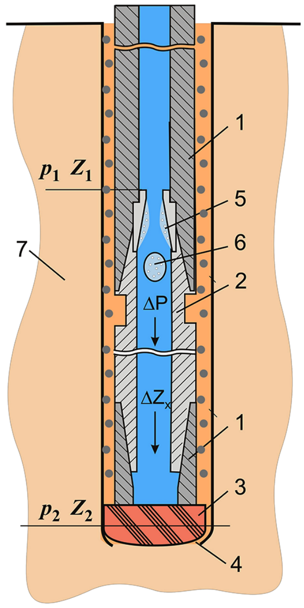

Fig. 3. Layout diagram of the hydraulic vibrator as part of the drill string:

1 is drill pipe; 2 is cavitation hydraulic vibrator; 3 is rock cutting tool; 4 is destroyed rock; 5 is volumetric part of the attached cavity; 6 is volumetric part of the detached cavity; 7 is mud with suspensions of drilled rock

(Fig. 3), subsequent demolition of the cavern by the flow into the high-pressure zone – *6* and destruction of the cavern.

In this case, high-frequency self-oscillations of shock-type liquid pressure are realized with a range ΔP exceeding the pressure value at the inlet to the generator [1, 2]. In further developments, the design from the entrance to the hydraulic vibrator to the rock-cutting tool was called a drilling tool.

The frequency of mud pressure oscillations (the first mode of oscillations) is in the range from 200 to 20,000 Hz and can be adjusted by setting the cavitation mode (i.e., by the cavitation parameter τ). The cavitation parameter τ, as a criterion for the dynamic similarity of the cavitation flow regime [1], is calculated using the formula

$$\tau = \frac{P_2 - P_{cr}}{\rho \frac{v_{cr}^2}{2}},$$

where P_2 is the steady-state total pressure in the flow channel of the hydraulic vibrator; P_{cr} is pressure in the critical part of the generator; v_{cr} is the fluid velocity in the throat section of the generator; ρ is the mud density.

The testing schematic for such drill string, its geometric parameters, and the main test results under various operating modes are given in [16]. In this work, mathematical modeling of the operation of the drilling tool during the interaction of its drill bit with rock (granite) was performed, taking into account its physical and mechanical properties. The adequacy of the developed model is confirmed by satisfactory agreement between the calculated and experimental parameters of mud pressure fluctuations and vibration accelerations in the cross section of the rock-cutting tool, with the exception of the first resonant oscillation operating mode of the hydraulic vibrator.

Later, the mathematical model proposed in [16] was refined in [17] by taking into account the influence of the oscillation amplitude on dissipative losses. This made it possible to obtain acceptable agreement with experimental data over the entire range of operating modes of the drill bit.

The use of a refined mathematical model made it possible to study the time dependences of the hydraulic [17] and mechanical [18] powers of the hydraulic vibrator in the cross section of the rock-cutting tool of the drilling tool.

To determine the amplitude spectra and power spectral density of the mud pressure and vibration acceleration, appropriate sensors were installed in the cross section of the drill bit. Additionally, in the cavitation flow mode at $\tau = 0.19$, to determine the transmission of vibrations 'up' along the drill string, a vibration acceleration sensor was installed in the section of the entrance to the hydraulic vibrator (Fig. 3).

As an example, Fig. 4 shows the time dependences of the dynamic pressure p_2 at the outlet of the hydraulic vibrator (this value can be used to assess the quality of flushing of the drilled rock) and the vibration acceleration of the drilling tool structure Z_2 (this value characterizes the increase in penetration speed) in the drill bit cross section [1]. The same figure also shows the vibration acceleration of the drill string at the entrance to the hydraulic vibrator Z_1.

From the results of the analysis of the time dependences given by Fig. 4, it is clear that the main (first mode) frequency of cavitation pressure oscillations p_2, realized by the hydraulic vibrator, is 397 Hz. Vibration shapes of higher oscillations modes are 'superimposed' on it. The manifestation of high frequencies in the dynamic process under study is associated with the influence of the length of the hydraulic line of the drill string, as well as with such dynamic phenomena as repeated collapses of the detached part of the cavern in the flow channel of the hydraulic vibrator (Fig. 3) and interaction of mud in it with mechanical vibrations of the drilling rig structure.

The frequency of the first mode of the drill bit vibration acceleration oscillations Z_2 in the drill bit cross section can, in certain modes, coincide with the frequency of cavitation pressure oscillations p_2 at the outlet of the hydraulic vibrator. At the same time, high-frequency mechanical vibrations of the structure of higher modes in the cross section of the rock-cutting tool are superimposed on them. This leads to the appearance of resonant phenomena, as will be shown below, and, subsequently, to the development of differently inclined cracks. The destruction of rock occurs before reaching its strength limit.

As for the oscillations above the hydraulic vibrator (section p_1, Z_1), in the work carried out earlier at the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine (V. V. Pilipenko,1989), it was established that cavitation pressure oscillations p_2 upward along the flow are completely "cut off" (suppressed) by the high compliance of the cavitation cavity located behind the critical section of the generator. Mechanical vibrations of the drill string structure in the initial section Z_1 of the cavitation hydraulic vibrator (Fig. 3) amount to no more than 7 % of the structure vibrations in the drill bit section.

Method for processing parameters of a dynamic process and analysis of the results obtained. The new hydraulic oscillator, developed by Chinese researchers [19], taking into account the geological conditions of the field, is a complex hydromechanical device. A study of the vibration frequency spectrum of the design of a rock-cutting tool, as an important characteristic of the dynamic process for optimizing drilling, is also given in [19]. In accordance with the design of this development, fluctuations in drilling fluid pressure are created due to periodic changes in the flow area in the intervalve space of the device. The spectrum of vibration accelerations, calculated using the fast Fourier transform (FFT), indicated the presence of resonance at an oscillation frequency of 12.5 Hz. Note that this frequency is two orders of magnitude lower than the natural frequencies of the rock being destroyed [9].

As part of the vibroacoustic analysis of a drill string with a cavitation hydraulic vibrator, spectral analysis was performed based on experimental data from field tests given in [16], in the frequency range from 1,000 to 12,000 Hz. It is shown in this range that a drilling rig with a cavitation hydraulic vibrator realizes fairly high performance of its dynamic process.

Spectral analysis of the signal from pressure and vibration acceleration sensors was performed on the basis of the amplitude spectrum ASP and power spectral density PSD using standard computational procedures based on the calculation of the complex coefficients of the Fourier series of a periodic signal using the FFT algorithm.

In case of processing cavitation shock vibrations of pressure amplitudes and vibration accelerations due to the significant nonlinearity of the vibration shape, the FFT determines only the harmonic components of the signal. This is especially evident from the pressure amplitude spectrum. However, the oscillation frequencies in a coupled (hydraulic and structure) dynamic system can be analyzed.

Fig. 5 shows the amplitude spectra of *ASP* pressure p_2 in the structure cross section of a rock-cutting tool for values of the cavitation parameter $\tau = 0.19$ and 0.41.

For the cavitation parameter value is $\tau = 0.19$ the dynamic pressure resonances p_2 are observed at the main frequency of cavitation oscillations, equal to 397 Hz, as well as at the second and third natural frequencies, which are 790 and 1,170 Hz. For the case when the cavitation parameter value is $\tau = 0.41$, pressure resonances p_2 are observed, as in the first case, at the main frequency of cavitation oscillations equal to 1,114 Hz. The second and third natural frequencies are 1,980 and 3,520 Hz, respectively. An increase in the oscillation frequency above the values of the third natural frequency, both at $\tau = 0.19$ and $\tau = 0.41$, leads to an intensive decrease in the resonant processes of the drill string.

Amplitude spectra *ASV* of vibration accelerations of structure Z_2 in the drill bit cross section for the same values of the cavitation parameter $\tau = 0.19$ and 0.41 are presented in Fig. 6.

The results presented in this figure make it possible to determine the resonant frequencies of vibration accelerations of the drill structure in the cross section of the rock-cutting tool.

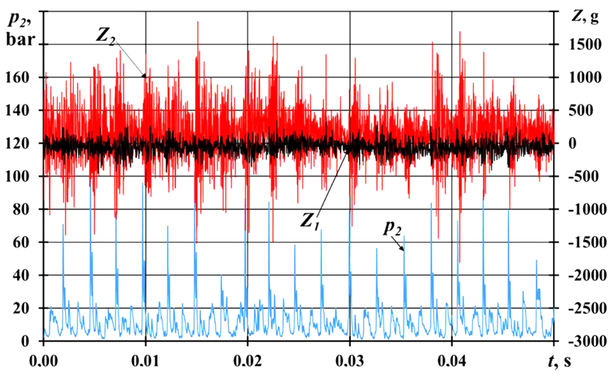

Fig. 4. Time dependences of pressure p_2 and vibration acceleration Z_2 in the drill bit cross section and vibration acceleration at the entrance to the hydraulic vibrator Z_1

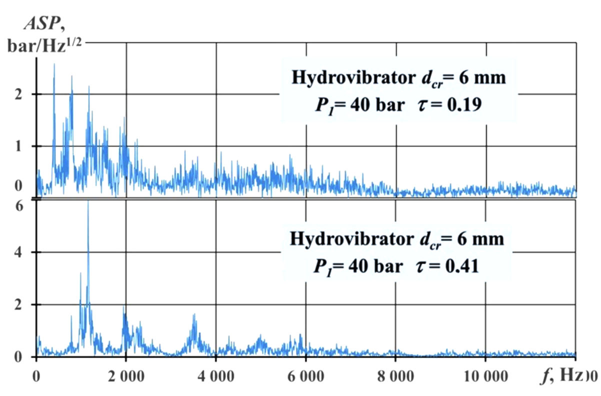

Fig. 5. Amplitude spectrum ASP of dynamic pressure p_2 in the drill bit cross section vs. frequency f

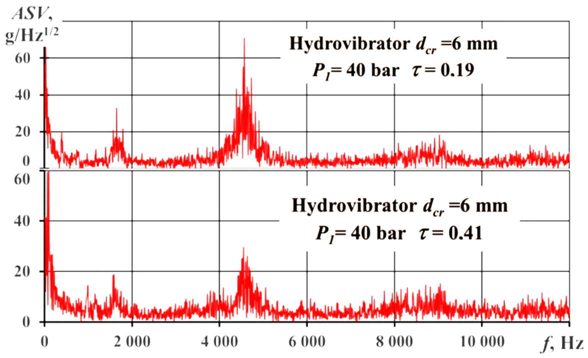

Fig. 6. Amplitude spectrum ASV of vibration acceleration Z_2 of the drill projectile design in the drill bit cross section of vs. the frequency f

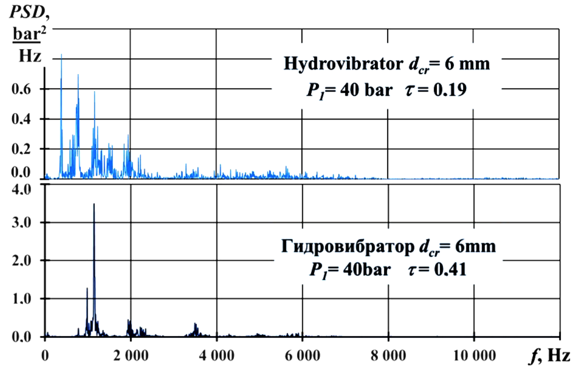

Fig. 7. Power spectral density PSD of vibration-pressure p_2 in the cross section of a rock-cutting tool vs. frequency f

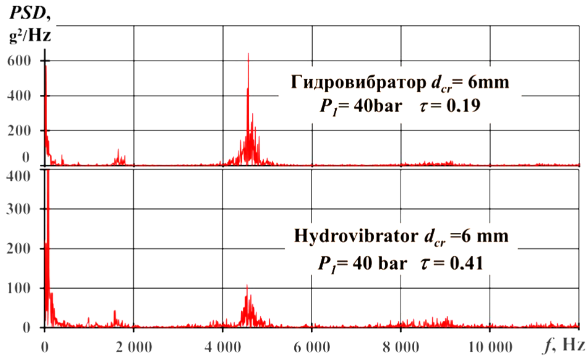

Fig. 8. Power spectral density PSD of vibration acceleration Z_2 in the cross section of a rock-cutting tool vs. on frequency f

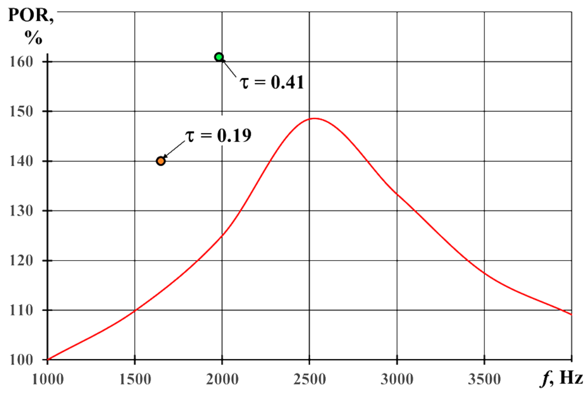

Fig. 9. The ROP increase in rate of penetration vs. the frequency f of the drill bit forced oscillations

For both τ = 0.19 and τ = 0.41, resonant vibration acceleration maxima are observed at frequencies of 1,650 and 4,570 Hz.

Thus, analysis of the amplitude spectra of pressure p_2 and vibration acceleration Z_2 in the cross section of a rock-cutting tool made it possible to establish that the range of resonance frequencies of vibration acceleration Z_2 is five times greater than the values of the resonance frequencies of pressure p_2. The range of values of the resonant frequencies of vibration accelerations corresponds to the increased efficiency of the drilling tool [1].

Power spectral densities *PSD* of dynamic pressure p_2 and vibration acceleration Z_2 in the cross section of a rock-cutting tool are shown in Figs. 7 and 8.

As can be seen from Fig. 7, resonant maxima of the vibration pressure power spectral density p_2 are realized at frequencies of 383, 750 and 1,160 Hz (at τ = 0.19). At the cavitation value of τ = 0.41, resonances of the vibration pressure power spectral density p_2 are observed at frequencies of 1,140; 1,980; 3,490 Hz. The given frequency values correspond to the resonant frequencies determined from the amplitude spectra of pressure p_2 in the cross section of the rock-cutting tool (Fig. 5).

As can be seen from Fig. 7, resonant maxima of the vibration pressure power spectral density p_2 are realized at frequencies of 383, 750 and 1,160 Hz (at τ = 0.19). At a value of τ = = 0.41, resonances of the dynamic pressure power spectral density p_2 are observed at frequencies of 1,140; 1,980; 3,490 Hz. The given frequency values correspond to the resonant frequencies determined from the amplitude spectra of pressure p_2 in the drill bit cross section (Fig. 5).

For case when the drill tool operates in accordance with the spectral power density of vibration accelerations Z_2, the resonant manifestations of the 'drill tool – rock' dynamic system (Fig. 8) can be realized for the considered operation mode at frequencies of 1,650 and 4,570 Hz. These values correspond to the values of the resonant frequencies determined from the amplitude spectra of vibration acceleration Z_2 (Fig. 6).

Fig. 9 shows the dependence of the increase in penetration rate (ROP) during vibro-impact drilling as a percentage relative to the ROP in the traditional rotational drilling method (the value of which is taken as 100 %) on the frequency *f*.

This dependence was obtained from the results of processing experimental data [4] for case of drilling granite rock using a PDC bit.

Experimental data (indicated by dots and corresponding to the operating modes of the cavitation hydraulic vibrator at τ = = 0.19 and 0.41) obtained during field testing of a drilling tool are also presented here [1]. As can be seen from Fig. 9, the drilling rig with a cavitation hydraulic vibrator is more effective compared to the traditional rotary drilling method and for the case of using vibro-impact drilling method. Thus, with the cavitation operating mode of the hydraulic vibrator τ = 0.19, the well penetration rate increases by 40 % compared to the traditional rotary method and by 26 % compared to vibro-impact drilling. For the cavitation operating mode of the hydraulic vibrator τ = 0.41, the increase in the well penetration rate is 62 and 37 %, respectively. In this case, the operating efficiency of the hydraulic vibrator was ensured at the resonant frequencies of pressure p_2 (Fig. 7) with the oscillation frequency of 1,580 Hz at τ = 0.19 and 1,980 Hz at τ = 0.41.

Based on the analysis of the above data, it can be assumed that the greater speed of penetration of the drill string, achieved in case of drilling with a cavitation hydraulic vibrator, compared to drilling using a high-frequency vibratory hammer (under equal vibration operating conditions) is ensured due to effective entrainment of destroyed rock with oscillating mud from the zone of its contact with the drill bit. In addition, an important factor influencing the increase in ROP (using a cavitation hydraulic vibrator) is a decrease in the work of friction forces during the rotational movement of the drill bit with its contact interaction with the rock in the case of intense resonant oscillations of the drilling mud.

Conclusions. Based on the results of the analysis of the amplitudes and power density of pressure oscillations of the mud and vibration accelerations of the structure of the drilling tool with a cavitation hydraulic vibrator in the drill bit cross section, it was established that:

- for the given design of the hydraulic vibrator with the value of the cavitation parameter $\tau = 0.19$, resonances of the amplitude spectrum of pressure p_2 at the outlet of the hydraulic vibrator are observed at the frequency of cavitation oscillations of the first oscillation mode, equal to 397 Hz, as well as at the natural frequencies of the second and third oscillation modes and are 790 and 1,170 Hz. When the cavitation parameter value τ is 0.41, pressure resonances p_2 are observed, as in the first case, at the main frequency of cavitation oscillations equal to 1,114 Hz. The second and third natural frequencies are 1,980 and 3,520 Hz. An increase in frequency above the values of the third natural frequency, both at the cavitation number $\tau = 0.19$ and $\tau = 0.41$, leads to an intensive decrease in resonant processes;

- resonances of the power spectral density of the dynamic pressure p_2 practically coincide with the resonances of the amplitude spectrum of this pressure;

- resonant phenomena of the spectral power density of vibration accelerations Z_2 are realized at frequencies of 1,650 and 4,570 Hz and correspond to the values of resonant frequencies determined from the amplitude spectra of vibration accelerations;

- vibration acceleration resonances Z_2 for the same values of the cavitation parameter $\tau = 0.19$ and 0.41 are observed at frequencies of 1,650 and 4,570 Hz;

- from the results of the analysis of the well drilling carried out in the considered modes in relation to approximately equal rocks, the use of a drilling tool with a cavitation hydraulic vibrator is more effective compared to the traditional rotary drilling method and when using a high-frequency mechanical vibratory hammer. Thus, with the cavitation operating mode of the hydraulic vibrator $\tau = 0.19$, the well penetration rate increases by 40 % compared to the traditional rotational method and by 26 % compared to the vibratory hammer. With the cavitation operating mode of the hydraulic vibrator $\tau = 0.41$, the increase in the well penetration rate is 62 and 37 %, respectively. In this case, the operating efficiency of the hydraulic vibrator was ensured at the resonant frequencies of pressure p_2 with oscillation frequency of 1,580 Hz at the cavitation number $\tau = 0.19$ and 1,980 Hz at $\tau = 0.41$.

The results of the study allow us to select rational frequencies of vibration loading of the drill bit for the specific drill string design to increase the rate of penetration during well construction and avoid restrictions on drilling operating parameters.

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Буріння свердловин з урахуванням динамічних властивостей гірських порід

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Накладання високочастотних поздовжніх коливань на породоруйнівний інструмент є перспективним засобом підвищення швидкості буріння у глибоких твердих пластах. Реалізація таких високочастотних коливань можлива в разі встановлення у буровій колоні перед породоруйнівним інструментом кавітаційного гідровібратора.

Мета. Визначення резонансних режимів (частот коливань) при динамічній взаємодії тиску промивної рідини й поздовжніх коливань породоруйнівного інструменту під час його контакту з породою, що руйнується, при бурінні з використанням кавітаційного гідровібратора; порівняльний аналіз ефективності застосування високочастотного механічного вібратора й кавітаційного гідровібратора під час буріння у твердих породах.

Методика. Дослідження гуртується на порівняльному аналізі амплітуд і спектральної густини потужності коливань тиску промивної рідини й віброприскорень у перерізі породоруйнівного інструмента.

Результати. Подані у вигляді амплітудних спектрів і спектральних густин потужності тиску промивної рідини й віброприскорень, а також залежності зростання швидкості проходки від частоти вимушених коливань бурового інструмента.

Наукова новизна. Урахування впливу резонансної взаємодії породоруйнівного інструменту з гірською породою на швидкість буріння, що запропоноване у цій роботі, дозволяє:

- визначити резонансні частоти коливань тиску промивної рідини бурового снаряда для ефективного видалення розбуреної породи в місці її контакту з буровим інструментом, і поздовжніх віброприскорень бурового інструмента для прискорення проходки при спорудженні свердловини;

- встановити ефективність використання кавітаційного гідровібратора у порівнянні з високочастотним механічним вібратором. Для досліджуваних режимів роботи гідровібратора за значень параметра кавітації $\tau = 0{,}19$ забезпечується зростання швидкості проходки свердловини на 40 % у порівнянні з традиційним обертальним способом і на 26 % у порівнянні з віброударником. За кавітаційного режиму роботи гідровібратора $\tau = 0{,}41$ зростання швидкості проходки свердловини становить 62 і 37 % відповідно. При цьому ефективність роботи гідровібратора забезпечувалася на резонансних частотах тиску промивної рідини з частотою 1580 Hz за $\tau = 0{,}19$ і 1980 Hz за $\tau = 0{,}41$.

Практична значимість. Для конкретної конструкції кавітаційного гідровібратора у складі бурильної колони, за рахунок зміни частоти вібраційного впливу долота на породу, встановлені резонансні частоти, що забезпечують високу швидкість проходження свердловини.

Ключові слова: *кавітаційний гідровібратор, породоруйнівний інструмент, резонансна частота, швидкість проходки*

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