GEOTECHNICAL AND MINING MECHANICAL ENGINEERING, MACHINE BUILDING

Yu. O. Zhulay[1],
orcid.org/0000-0001-7477-2028,
O. D. Nikolayev[2],
orcid.org/0000-0003-0163-0891

1 − Institute of Transport Systems and Technologies of the National Academy of Sciences of Ukraine, Dnipro, Ukraine, e-mail: zhulay@westa-inter.com
2 − Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine, Dnipro, Ukraine

EVALUATION OF HYDRAULIC POWER OF DRILLING STRING WITH A CAVITATION HYDROVIBRATOR

Purpose. To develop a method for assessing the drill string hydraulic energy based on mathematical modeling of dynamic processes at the 'drill string with a hydraulic vibrator − rock' system, taking into account the nonlinear dependence of system dissipative losses on the drill string vibration amplitudes at drill operating modes.

Methodology. Methods are based on experimental and theoretical studies on the drill string dynamic parameters and the evaluation of efficiency of converting stationary fluid flow into pulsating flow.

Findings. The results are presented in the form of calculated and experimental dependences of pressure, volumetric flow rate, vibration accelerations and hydraulic vibrational power in the section of the rock cutting tool on the criterion parameter of cavitation τ.

Originality. Taking into account the influence of the string elements' vibration amplitude on dissipative losses, made it possible to obtain an acceptable agreement with the drilling experimental data as well as:

- to determine the peak to peak (from 43.5 to 9.8 kW) and average (from 9.8 to 2.35 kW) values of hydraulic oscillatory power at the cavitation parameter range τ = 0.12−0.475;

- to evaluate the efficiency of converting the drilling fluid stationary flow power at the inlet to the hydraulic vibrator into the oscillatory power (for the oscillation period) on the rock cutting tool. Within the investigated range of the drilling operation parameter, the maximum calculated value of the efficiency was approximately 76 % with the value of the cavitation parameter τ equal to 0.16, and the minimum efficiency value was 19 % at τ = 0.475.

Practical value. Practical value of the results obtained is that the improved mathematical model of the 'drill-rock' dynamic system allows establishing a rational mode of cavitation hydraulic vibrator operation at the drill string design stage to implement acceptable levels of hydraulic power on the drill bit.

Keywords: *mathematical modeling, drill string, cavitation hydraulic vibrator, drill bit, hydraulic oscillation power*

Introduction. Percussion-rotary method for drilling wells using submersible percussion machines is one of the directions to accelerate drilling operations [1].

The submersible percussion machines running on air (pneumatic hammers) became widespread in the USSR in the 50s and in the 60s they began to be used in foreign practice. Basically, hammers are used in construction for the construction of shallow wells up to 200 meters in the range of diameters of 60−500 mm.

The main disadvantage of pneumatic hammers is the low efficiency coefficient of 6−8 %. And an increase in the compressed air pressure of more than 1.8 MPa to expand the technological capabilities for the drilling depth, as practice has shown, is not economically profitable.

Simultaneously in the 50s, with the improvement of pneumatic hammers, another type of submersible percussion machines began to be developed − dynamic type hydraulic hammers operating on the energy of the flushing fluid. Their principle of operation is based on the effect of a water hammer in case of the flow of liquid is interrupted. However, the possibility of creating hydropercussion machines for drilling in hard and super-hard rocks with an efficiency exceeding 50 %, declared by SKB Geotechnika, was not confirmed [2]. During bench tests simulating drilling at a depth of 2000 m, the efficiency of the hydraulic hammer, created by SKB, did not exceed 8 %.

The main disadvantages of submersible hydraulic hammers still include:

- low efficiency, not exceeding 10 %;

- increased flow rate of the working fluid, which in some cases contradicts the drilling conditions (for example, it leads to erosion of the borehole walls in zones of weak rocks);

- the ability to work only on clean water;

- an acceptable operating mode in case of pressure drop of less than 6 MPa [2];

- the presence of quickly wearing out moving parts, springs and rubber cuffs in the construction design, which significantly reduce the period between inspection and service life;

- pressure oscillations' negative impact on the pump, causing increased wear out of its parts and deteriorating drilling efficiency due to the unambiguous dependence of the bottomhole power on the pump characteristics.

However, it should be noted, that work to improve the characteristics of hydraulic hammers is currently being carried out. So, in the last decade, research has been carried out in the Russian Federation on volumetric hydropercussion machines. The foundations of the theory have been developed and original hydropercussion and distribution devices have been created [2, 3]. Their peculiarity involves the presence of a hydraulic accumulator, which complicates the design, especially in case of vertically downward wells at significant drilling depths.

The engineering and research of submersible hydropercussion systems with a higher efficiency are being developed quite intensively abroad. This is evidenced by a large number of currently performed research works on this problem and new patents, for example, [4, 5].

In the 80s, the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine (ITM NASU) under the leadership of Academician of the National Academy of Sciences of Ukraine Pilipenko V. V. together with the 'Geotechnika' SKB created a new direction in the development of submersible percussion machines. The main goal was to create a new method of dynamic loading on the rock-cutting tool, eliminating the disadvantages of existing hydropercussion machines. This method was implemented in the development of a drill string with a cavitation hydraulic vibrator [6].

The layout of the drill string with the cavitation hydraulic vibrator is shown in Fig. 1.

It consists of a drill pipe − 1 with a rock cutting tool − 6, a hydraulic vibrator − 5, in the vibrator flow path is mounted the cavitation generator of fluid pressure oscillations (hereinafter referred to as a generator) − 2.

It is the Venturi tube of special geometry that converts stationary fluid flow into periodically stalling cavitation flow. As a result of periodic detachment of the cavity − 3, its drift by the fluid flow into the hydrovibrator flow channel in the zone of increased pressure − 4, cavity collapses. In this case, high-frequency shock oscillations of the fluid pressure are realized, exceeding the pressure at the generator inlet. The repetition rate of pressure pulses in the range of 200−10 000 Hz can be controlled by setting the cavitation flow mode. Shock pressure oscillations transmitted to the drilling tool are transformed in the form of vibration accelerations [6].

The cavitation hydrovibrator does not feature the main disadvantages of submersible hydraulic hammers. It does not require additional energy sources, is easy to manufacture and fits organically into existing equipment without affecting the pump, since pressure fluctuations are not transmitted above the place of the hydrovibrator installation.

The correctness of the choice of the proposed method of drill bit vibration loading is confirmed by studies on the dynamic parameters of the drill string on the hydraulic and drilling stands of the 'Geotechnika' SKB in Podolsk (Moscow region, Russia) and pilot tests during the wells construction of in the Astana region, Kazakhstan (N. A. Dzoz).

It has been established that in case constructing wells in hard rocks, the use of such drill string leads to an increase in the drilling speed and in the drill bit wear resistance, to improvement in stability of the drill string operation.
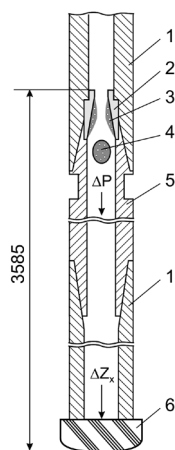

Fig. 1. Layout of the drill string:

1 − drill pipe; 2 − generator; 3, 4 − attached cavity and cavity come off; 5 − hydraulic vibrator; 6 − rock-cutting tool

Literature review. Hydrodynamic cavitation, as a source of vibration loading on the drill bit to increase the drilling speed in hard and superhard formations, has been considered by researchers from different countries at international conferences on geomechanics and well drilling. For example, in the work [7] through experimental studies, improvement of the operational characteristics of the drilling tool was found. In this case more efficient rock cutting and less friction in the string occur. This is achieved by intensifying the removal of crushed material from the contact zone between the surfaces of the bit cutters and the rock during drilling due to cavitation effects in the high-pressure flow of the drilling fluid in the bit nozzle. In [8], using a new tool for rotary drilling with the imposition of vibration, the increasing drilling capacity due to the microcracks was investigated. 'The greatest effect of vibrations during drilling is achieved when the bit vibration frequency approaches the resonant frequency of the drilled substrate' [9].

The increasing profitability of well construction using cavitating nozzles such as Venturi tubes that create vibrations on the drilling tool is given in [10]. This translates into faster and more efficient drilling and reduced oil and gas well construction costs.

In the last decade, the drilling science researchers from China have been intensively engaged in the creation of a new drilling cavitating tool [11]. This was due to the need to overcome a number of problems in the construction of superdeep wells (2000−6000 m). In particular, the rate of drilling of wells and the rate of development of new deposits in these difficult geological conditions has significantly decreased, and the cost of drilling has increased greatly [12].

To overcome the above problems, a new drilling tool by the installation of a hydraulic pulse generator of cavitation jet was developed [13]. This tool creates pressure pulses by interrupting the flow of drilling fluid with a rotating impeller. The pulsating flow of the drilling fluid is amplified in the resonant cavitation chamber, and is transformed on the rock cutting tool as string vibration accelerations.

The tests of such generator showed that at the flushing fluid flow rate ~32 l/s, it implements fluid pressure oscillations with a range of $\Delta P \approx 2.1 - 2.2$ MPa and fundamental frequency of 10 Hz.

Field experiments conducted in oil fields throughout China on more than 100 wells with a maximum depth of 6162 m have shown that drilling by use this tool increases the penetration rate by 16−104 %. The generator run time ranged from 230 to 520 hours. In addition, the hydraulic pulse generator was successfully used for the construction of more than 10 offshore wells with a diameter of 311 and 216 mm. In this case the ROP increased by more than 25 %. According to the authors of [13], this is due to the pulsation of the jet, cavitating erosion and the effect of local negative pressure, as well as the improvement of the bottom hole cleaning efficiency.

We should also be noted the significant contribution of scientists from Dnipro University of Technology (formerly called the National Mining University of Ukraine). Here, at the Department of Technology for Exploration of Mineral Deposits, a new technology was developed − drilling with impulse bottomhole washing. Pulse flushing, as in the drilling string, was provided by the mode of periodically stall cavitation. By the experimental implementation of this technology, the increase in the ROP has been demonstrated [14]. To increase the durability of the drill bit, the work [15] studied one of the reasons for its premature wear − overheating. It also considered the problem of determining the rational parameters of the impulse supply of drilling mud to prevent overheating of the drilling tool.

In theoretical terms, the first mathematical model of longitudinal vibrations of the drill string (as applied to bench tests) was developed at the ITM NASU by I. K. Manko and O. D. Nikolayev.

To describe mathematically the longitudinal vibrations of the mechanical part of the drill, they used the equation of the dynamics of the launch vehicle structure of Gladky V. F. and the equation of the force action on the structural element in

accordance with the mechanism for converting high-frequency oscillations of the drilling fluid into longitudinal vibration accelerations of the rock-cutting tool. The equations describing the process of oscillatory fluid motion in the flow channel of cavitation generator were obtained in the works by V. V. Pilipenko, O. V. Pilipenko, and Yu. A. Kvasha.

Further improvement of the mathematical model of the drill string longitudinal vibrations, taking into account the dynamic impact of the rock and the drilling tool, was carried out in [6]. The results of calculating the drill string dynamic parameters given in this work are in satisfactory agreement with the experimental data (with the exception of the resonant operating modes of the cavitation generator).

However, as the analysis of recent studies has shown, the assessment of the energy efficiency of devices using the mode of periodically stall cavitation as a source of vibration load on the drill bit has not been carried out.

In connection with the above, the development of a method for assessing the energy efficiency of a drill string using the mathematical model [6] is an urgent scientific and technical problem.

This is due to the fact that at the design stage during the development of the drill string, the optimization of the operation of a hydraulic vibrator is based not only on estimates of the drill bit vibration loading, but also on its energy efficiency.

The purpose of this paper is to develop a method for assessing the hydraulic energy efficiency of the drill string based on the mathematical model of the 'drill string with the hydraulic vibrator − rock' dynamic system taking into account the influence of the string vibration amplitudes on dissipative losses of the drill string elements.

The following tasks were solved to achieve this goal:
- the mathematical modeling of longitudinal vibrations of the drill string structure based on structure finite element scheme, in which the elements are characterized not only by vibration frequencies and masses, but also by dissipative losses depending on the structural element vibration amplitudes;
- the calculation of the drill string vibrational parameters (pressure, flow rate and vibration accelerations) at the section of the drilling tool, taking into account the strength, elastic and dissipative characteristics of the destroyed rock and forces acting in the longitudinal (axial) direction on the drilling string structure and comparison the results with experimental data;
- the calculation of the drill string hydraulic power at drill bit section.

Correction of the mathematical model of the 'drill string with the hydraulic vibrator − rock' dynamic system. In [6], the mathematical model of the 'drill string with the hydraulic vibrator − rock' dynamic system describes changes in time of such parameters as longitudinal vibration displacement, vibration velocity, vibration acceleration, as well as pressure and mass flow rate of fluid in the flow path of the corresponding elements of the drill string. Mathematical modeling of the longitudinal vibrations of the drill string was carried out by integrating a system of differential equations describing the dynamic processes of the structure and the fluid in its flow path using the finite element method.

In this paper, it is proposed to model the longitudinal vibrations of the drill string structure on the basis of its finite element scheme, in which the elements are characterized not only by vibration frequencies and masses, but also by dissipative losses, whose magnitude depends on the vibration amplitude of the element. Such a model, even for a one-dimensional case, when vibrations in one (longitudinal) direction are considered, is more meaningful and informative than the traditional model of longitudinal vibrations of a drill string structure in normal coordinates. It allows studying the dynamic interaction of the elements of the drill string and more accurately determining the parameters of its oscillations at resonance modes. However, taking into account energy dissipation for modeling of drill string longitudinal vibrations, in turn, is a problem, since there are still no sufficiently accurate models describing energy losses during elastic vibrations of such structures, and the available

experimental data of influence of dissipation on the magnitudes of these oscillations are very scarce [16].

Thus, the main difference between the mathematical model of the 'drill string with the hydraulic vibrator − rock' dynamic system proposed in this work and the one given in [6] is that in the equation of motion of the center of mass of the ith finite element of the drill string

$$(m_i + m_i^p)\frac{d^2\Delta x_i}{dt^2} + c_i(\Delta x_i - \Delta x_{i-1}) +$$
$$+ b_i(\frac{d\Delta x_i}{dt} - \frac{d\Delta x_{i-1}}{dt}) + + c_{i+1}(\Delta x_i - \Delta x_{i+1}) + \quad (1)$$
$$+ b_{i+1}\left(\frac{d\Delta x_i}{dt} - \frac{d\Delta x_{i+1}}{dt}\right) = \sum_n \Delta F_i^n,$$

to determine the damping coefficients b_i in the equations of the end elements, it is proposed to use the expressions [16].

$$b_i = (b_i^0 + b_i(a_i)) \cdot \frac{\sqrt{c_i \cdot m_i}}{2\pi}, \quad (2)$$

and in the equations of intermediate elements

$$b_i = (b_i^0 + b_i(a_i))\frac{\sqrt{(c_i + c_{i+1})m_i}}{2\pi}, \quad (3)$$

where Δx_i is deviation of the coordinate of the center of mass of the ith finite element from the position of dynamic equilibrium; m_i and m_i^p are mass of the ith finite element and mass added to the ith finite element of the drill string; $c_i = E_i A_i \Delta l_i^{-1}$ is stiffness coefficient of the ith finite element; A_i is cross-sectional area of the ith structural element; Δl_i is longitudinal length of the ith element; E_i is Young's modulus of elasticity of the material of the ith structural element; b_i^0 is dissipative coefficient of vibrations of the ith finite element at small amplitude string structural vibrations; ΔF_i^n is deviation of the force acting on the structural element of the drill string from its steady-state value; $b_i(a_i)$ is a component of the decrement of vibrations of mechanical elements of a dynamic system, taking into account the increase in the amplitude at 'considerable', essentially nonlinear, vibrations of the drill string structure.

Thus, as can be seen from the above equation (1), each finite element, based on the separation scheme of the drill string structure of the simulated, was described by mass (m_i), elastic (c_i) and dissipative (b_i) characteristics. Decrements of vibrations b_i^0 of the ith finite elements were set on the basis of the values of these quantities, for a specific type of connection of parts of the drill string and the material used in its design, and varied within 0.06−0.2 [6].

As a result of numerical integration by the Runge-Kutta method of the system of differential equations describing the drill string longitudinal vibrations in a steady state (τ = const), the time dependences of the movement process, vibration velocity and vibration acceleration of drill string structural elements, pressure and fluid flow rate, volumes of the cavity attached and collapsing in flowing part of the hydrovibrator. In this case, the 450 finite elements were used to describe the dynamic properties of the hydrovibrator structure and the fluid in the vibrator flow path. This made it possible with a sufficient degree of reliability to simulate the longitudinal oscillations of such a dynamic system in the frequency range from 50 to 20 000 Hz. These dependences were obtained at a discharge pressure P_d = 4 MPa, axial load F = 9.8 kN and values of the criterion cavitation parameter τ = 0.12, 0.16, 0.184, 0.2, 0.34, 0.415, 0.475. This corresponds to tests of an experimental drill sample in industrial conditions [6]. The geometrical parameters of this drill string are given in Table 1.

As an example, in Fig. 2 for the value of the cavitation parameter τ = 0.16 the calculated time dependences of pressure, volumetric flow rate and vibration acceleration in the drill bit section are presented.

As follows from the given time dependences, the oscillatory process is impulsive in nature. At the value of the cavitation parameter $\tau = 0.16$, the fundamental harmonic of the frequency of cavitation vibrations was 323 Hz. The peak to peak values of pressure fluctuations are about $\Delta P \approx 6.19$ MPa, peak to peak values of volumetric flow rate are $\Delta Q \approx 3.17$ l/s and peak to peak values of vibration acceleration are $\Delta Z \approx 3139$ g. The calculation results show that the frequency of the drill string vibration accelerations (equal to 970 Hz) is superimposed on the fundamental harmonic of the frequency of cavitation vibrator pressure oscillations. This is due to the dynamic interaction of the drill string structure and the liquid medium in the hydrovibrator flow path.

The dominant frequency of cavitation oscillations increased up to 1402 Hz along with increasing in the value of the cavitation parameter to $\tau = 0.415$. The level of oscillation ranges decreased: the pressure values to $\Delta P \approx 3.06$ MPa, — volumetric flow rate values to $\Delta Q \approx 1.83$ l/s and drill string vibration accelerations to $\Delta Z \approx 1247$ g. The experimental and calculated dependences of the frequency f on the cavitation parameter τ at the investigated range, are close to linear, and vary from 0.2 to 1.5 kHz. The frequencies of higher modes are superimposed on the fundamental harmonic of the frequency of cavitation vibrations, caused by the repeated collapse of the cavitation cavity and the dynamic interaction of the structure of the drill string with the liquid medium in its hydraulic channel. It should be noted that the duty cycle of the shock process decreases with the increase in the value of the parameter τ from 0.12 to 0.475.

The processing of the results of numerical simulation of the oscillatory process of the drill string in the section of the drilling tool makes it possible to perform a comparative analysis with the previously obtained results and experimental data.

The processing results are presented in Table 2. The peak to peak of oscillatory values of pressure ΔP, volumetric flow rate ΔQ and vibration acceleration ΔZ are determined at cavitation parameter ($\tau = 0.12–0.475$) range, which corresponds to experimental studies.

This table also shows the parameters of the oscillatory process obtained in [6].

Fig. 3 shows the calculated dependences of the ranges of pressure fluctuations ΔP at the rock cutting tool section on the cavitation parameter τ in the range of its variation from 0.1 to 0.475. Experimental data borrowed from work [6] are also presented here.

The nature of the presented dependences is non-linear. The increase in the value of the parameter τ from 0.1 (with an increase in the back pressure at P_d = const) leads to increase in the amplitude range of pressure fluctuations and reaches a maximum value of 6.19 MPa at $\tau = 0.16$, and then decreases. The maximum peak to peak values of the oscillatory pressure in the cross section of the sensor installation is approximately 1.5 times higher than the discharge pressure P_d.

In the entire range of the τ variation, not only a better quality, but also a quantitative agreement, in comparison with work [6], of the calculated values of the pressure fluctuation range with experimental data was obtained.

Consideration of the theoretical dependences of the amplitude of vibration accelerations ΔZ_x on the cavitation parameter τ and experimental data (Fig. 4) indicates a satisfactory convergence of the results obtained.

An analysis of the data in this figure shows that an increase in the amplitudes of forced fluctuations in the pressure of the drilling fluid at cavitation numbers of 0.1–0.16 leads to an increase in vibration accelerations. The maximum value of the amplitude of vibration accelerations on a rock cutting tool for this design was obtained at $\tau = 0.16$ and is approximately 3200 g. At the same time, we note that, in the investigated range for the cavitation parameter $\tau = 0.1–0.475$, there are two

Table 1

Basic geometrical parameters of the drill string

Geometrical parameter	size
Generator throat diameter, mm	6
Generator critical section length, mm	8.2
Diffuser diameter at the generator outlet, mm	24
Generator diffuser length, mm	51
Opening angle of the generator diffuser, °	20
Hydrovibrator channel diameter, mm	24
Hydrovibrator channel length, mm	420
Drill pipe diameter, mm	76
Drill length, mm	3585

Table 2

The results of processing the numerical simulation of the drill string oscillatory process

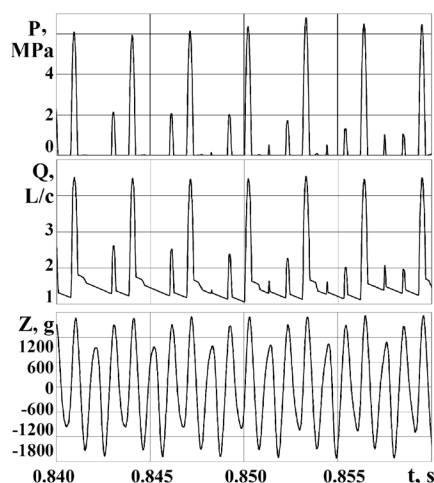| τ	This paper			The paper [6]		
	ΔP, MPa	ΔQ, l/s	ΔZ, g	ΔP, MPa	ΔQ, l/s	ΔZ, g
0.120	5.21	2.24	2140	6.32	2.59	2810
0.160	6.19	3.17	3139	5.09	4.71	3140
0.184	5.48	3.05	2807	4.07	2.52	2446
0.200	4.50	2.77	1667	3.72	2.34	1197
0.340	3.37	2.14	898	3.59	1.99	987
0.415	3.06	1.83	1247	3.15	1.97	1585
0.475	2.86	1.64	1196	2.99	1.85	1128

Fig. 2. The calculated time dependencies of pressure, volumetric flow rate and vibration acceleration at the drill bit section of the drill string at $\tau = 0.16$

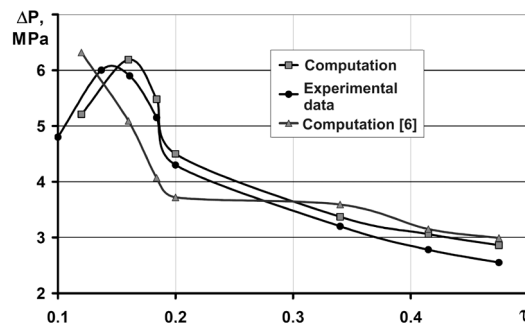*Fig. 3. Calculated and experimental peak to peak values of dependences of pressure at the rock cutting tool section on the cavitation parameter τ*

resonant modes of the drilling string operation. The first one is when the value of the cavitation parameter is $\tau \approx 0.16$, which corresponds to the maximum values of the swing of the oscillatory pressure value (Fig. 3). The second one, at $\tau \approx 0.415$, is a consequence of the convergence of the natural vibration frequencies of the drill string structure and the vibration frequency of the drilling mud, caused by the "operation" of the cavitation generator. This is confirmed by both experimental and theoretical dependences $\Delta Z_x = f(\tau)$.

Of particular interest is the consideration of the combined theoretical dependences of the oscillatory values of the fluid volumetric flow rate in the drill hydraulic channel at the section of the rock cutting tool on the cavitation parameter τ, obtained in this work and in [6]. They are shown in Fig. 5 and indicate a noticeable discrepancy in the volumetric flow rate ranges in the hydraulic channel of the drill, especially in the range of $\tau = 0.12-0.18$. So, at the value $\tau = 0.16$, the range of the volumetric flow rate of the liquid, determined according to [6], is approximately by 1.5 times higher than its value calculated using the corrected model.

Computation of the oscillatory power realized by the hydraulic vibrator at the drill bit of the drill string. The study on the mechanical specific energy used to quantify the drilling efficiency and maximize the penetration rate in impulse drilling of oil and gas wells is given in [17, 18]. In this work, the evaluation of the hydraulic oscillatory power was carried out on the basis of calculating the oscillatory power released into the liquid after the collapse of the cavity at the section of the rock cutting tool of the drill

$$N = \frac{1}{T_{im}} \int_0^T \delta P(t) \cdot \delta Q(t) dt, \qquad (4)$$

where $\delta P(t)$ and $\delta Q(t)$ are the deviations of the current values of pressure and volumetric flow rate of the liquid from their stationary values; T_{im} is the pulse duration.
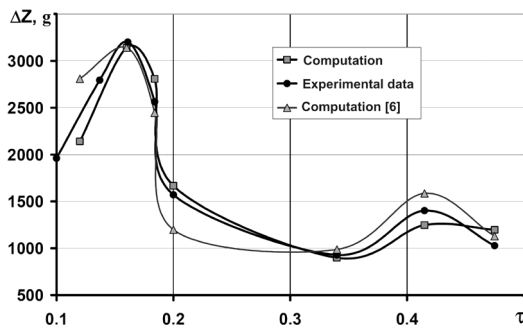

Fig. 4. Calculated and experimental dependences of the amplitude of oscillatory accelerations on a rock cutting tool on the cavitation parameter τ
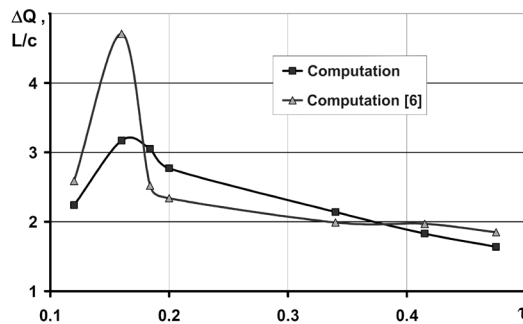

Fig. 5. Calculated dependences of the peak to peak values of drilling fluid volumetric flowrate of in the drill string hydraulic channel in the section of the rock cutting tool on the cavitation parameter τ

The process of variation in time of the hydraulic oscillatory power N_h, calculated by the formula (4) for the values of the criterion cavitation parameter of $\tau = 0.12$, 0.16, 0.184, 0.2, 0.34, 0.415, 0.475 is shown in Fig. 6. Consideration of the dependences $N_h = f(t)$, shown in Fig. 6, shows that in the entire range of values of the cavitation parameter τ, the time process of changing the hydraulic oscillation power is of the shock nature.

In this case, the maximum peak values of the hydraulic oscillatory power at the drill bit section of the drill string follow on with the frequency corresponding to the fundamental frequency of cavitation oscillations realized by the generator.

Table 3 shows the results of processing the above time dependences $N_h = f(t)$. Here N_{him} and N_{hm} are the maximum peak value in the hydraulic power impulse and the average value over the oscillation period.

Table 3 also shows the calculations of the average values of the hydraulic vibrational power according to the results of the studies carried out in [6], and according to the experimental data given in this paper.

At the same time, taking into account that at the time of the test of the experimental drill string model, there were no measuring instruments for rapidly changing flows, the values of the volumetric flow rate ranges ΔQ were determined in accordance with (Angelovskiy, A. A., 2015).

From the analysis of the presented dependences, it follows that at the fixed value of the pressure at the inlet to the hydraulic vibrator by an increase in the cavitation parameter τ from 0.12 to $\tau = 0.16$, the peak to peak values of oscillatory power both in the
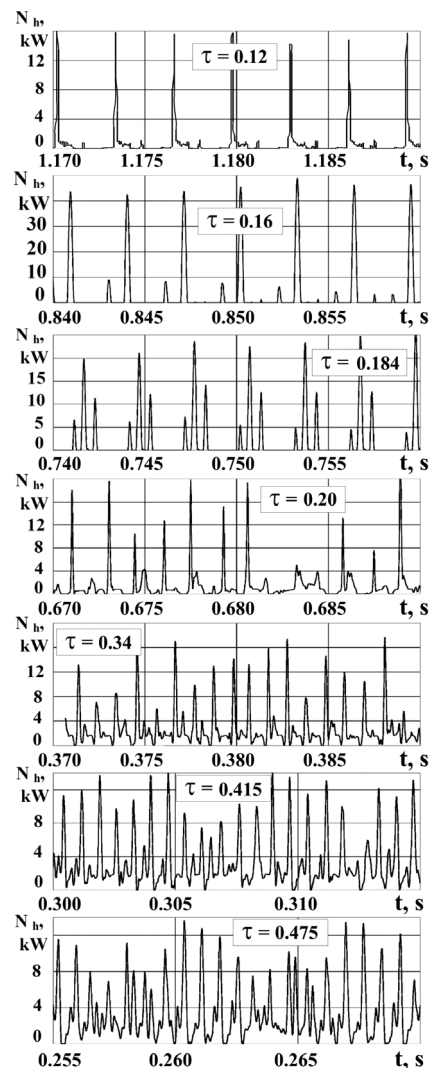

Fig. 6. The process of hydraulic oscillatory power N_h vs. time

pulse N_{him} and the average N_{hm} increase sharply, reaching the power of 43.5 and 9.8 kW accordingly. The further increase in the cavitation parameter τ (from a value of 0.16 to $\tau = 0.2$) leads to a sharp decrease in the level of the ranges of oscillatory energies N_{him} and N_{hm} occurs, followed by a gradual decrease.

Data processing of time dependences $N_h = f(t)$ made it possible to establish the change in the maximum peak in the pulse N_{him} and average N_{hm} values of hydraulic oscillation power depending on the cavitation parameter τ. The dependences $N_{him} = f(\tau)$ and $N_{hm} = f(\tau)$ are shown in Fig. 7.

Comparison of the theoretical dependences and experimental data of the average values of the vibrational power of the fluid flow on the cavitation parameter τ in the section of the rock cutting tool is shown in Fig. 8. The value of the stationary flow power at the inlet to the hydrovibrator N_{h1} is also shown here.

It can be seen that in the entire range of variation of the value of τ, not only a qualitative, but also a quantitative agreement was obtained between the calculated values N_{hm} of the fluid flow oscillatory power N_{hm} and the experimental data N_{hexp}. At the same time, the calculated values of the oscillatory power of the pulsating liquid flow N_{hm}, obtained from the results of [6], have some discrepancy with the experimental data in the range of variation of the cavitation parameter $\tau = 0.12–0.3$. So, near the resonant operating mode of the generator at a value of $\tau = 0.16$, the average value of the vibrational power N_{hm}, determined from the results of studies carried out in [6], exceeds N_{hexp} by about 26 %.

In the entire investigated range of variation of the cavitation parameter τ, the numerical average values of the fluid flow oscillatory power (both theoretical and experimental) do not exceed the power of the mud stationary flow at the inlet to the hydrovibrator, which is defined as

$$N_{h1} = P_1 \cdot Q_{cr}, \qquad (5)$$

where P_1 is pressure at the inlet to the hydraulic vibrator, taking into account the liquid column $P_1 = (P_p + 0.83) \cdot$ MPa; Q_{cr} is volumetric fluid flow rate of liquid through the generator, equal to 2.64 l/s.

The oscillatory power, related to the power of the stationary flow at the inlet to the hydraulic vibrator, determines the efficiency of converting the stationary fluid flow into a pulsating flow. Fig. 9 shows the theoretical and experimental dependences of this ratio as a percentage on the cavitation parameter τ at the section of the rock cutting tool.

Consideration of the above theoretical $N_{hm}/N_{h1} = f(\tau)$ and experimental $N_{exp}/N_{h1} = f(\tau)$ dependences indicates their satisfactory convergence both in terms of their behavior and in quantitative terms. These dependences make it possible to calculate the efficiency of converting the power of the drilling fluid stationary flow at the inlet to the hydraulic vibrator into the oscillatory power in the section of the rock cutting tool.

In the investigated range of the cavitation parameter τ, the maximum calculated value of the efficiency in the considered case was approximately 76 % for the value of the cavitation pa-
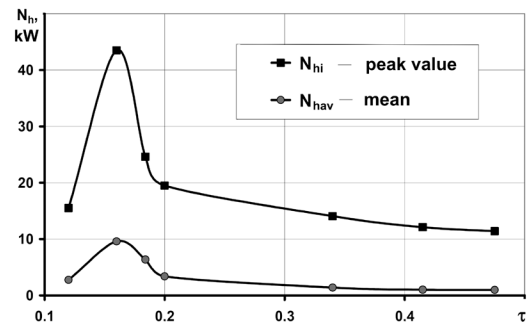

Fig. 7. Dependences of the maximum peak in impulse N_{him} and average N_{hm} values of hydraulic power on the cavitation parameter τ
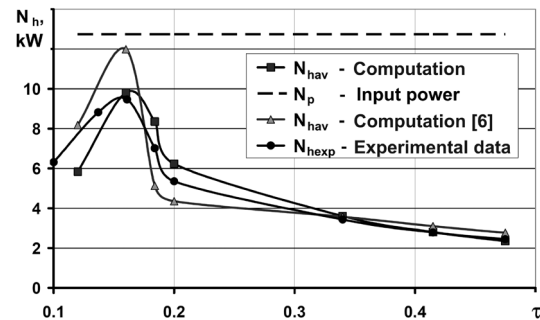

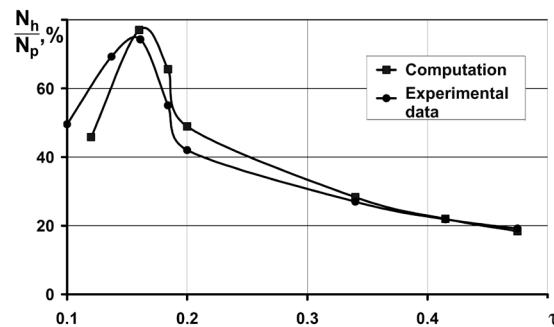*Fig. 8. Dependencies of mean values of hydraulic oscillatory power from the cavitation parameter τ*

Fig. 9. Dependences of the relative oscillatory power at the drill bit section on the cavitation parameter τ

rameter τ is equal to 0.16, and the efficiency minimum is 19 % at $\tau = 0.475$.

Thus, taking into account the influence of the oscillation element amplitudes on dissipative losses, proposed in this work, made it possible to obtain quite acceptable results for determining the average values of the mud flow oscillatory power. This made it possible to determine the efficiency of converting the power of the stationary flow of the drilling mud at the inlet to the hydraulic vibrator into the oscillatory power in the section of the rock cutting tool.

Conclusions. The analysis of results of the mathematical modeling of the longitudinal vibrations of the drill string as coupled 'string structure with cavitation hydraulic vibrator – rock' dynamic system characterized by the system finite elements dissipative losses depending on the drill string vibration amplitudes, found that:

- the proposed mathematical modeling is more meaningful and informative for the given design of the hydrovibrator than the traditional model of longitudinal vibrations of the drill string structure;

- the model allows studying the dynamic interaction of the string structural elements and determining the parameters of its oscillations in resonance modes more accurately.

Table 3

Results of processing the time dependences of the hydraulic oscillatory power of the drill

| τ | this paper | | paper [6] | Experimental data | |
	N_{him}, kW	N_{hm}, kW	N_{hm}, kW	τ	N_{hexp}, kW
0.120	5.21	2.24	2140	6.32	2.59
0.160	6.19	3.17	3139	5.09	4.71
0.184	5.48	3.05	2807	4.07	2.52
0.200	4.50	2.77	1667	3.72	2.34
0.340	3.37	2.14	898	3.59	1.99
0.415	3.06	1.83	1247	3.15	1.97
0.475	2.86	1.64	1196	2.99	1.85

The use of this mathematical model to the study on the time dependences of the hydraulic oscillatory power of the hydraulic vibrator at the drill bit section of the drill string made it possible:

- to calculate the peak to peak (from 43.5 to 9.8 kW) and average (from 9.8 to 2.35 kW) values of the hydraulic oscillatory power in the range of variation of the cavitation parameter $\tau = 0.12-0.475$;

- to establish the efficiency of converting the power of the drilling mud stationary flow at the inlet to the hydraulic vibrator into the hydraulic oscillatory power at the drill bit section. In the studied cavitation parameter range the maximum calculated value of the efficiency in the considered case was approximately 76 % for the value of the cavitation parameter τ equal to 0.16 and the minimum 19 % at $\tau = 0.475$.

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Оцінка гідравлічної потужності бурового снаряду з кавітаційнім гідровібратором

Ю. О. Жулай[1], *О. Д. Ніколаєв*[2]

1 — Інститут транспортних систем і технологій Національної академії наук України, м. Дніпро, Україна, e-mail: zhulay@westa-inter.com

2 — Інститут технічної механіки Національної академії наук України і Державного космічного агентства України, м. Дніпро, Україна

Мета. Розробка методу оцінки гідравлічної енергоефективності бурового снаряду на підставі математичної моделі системи «буровий снаряд з гідровібратором — гірська порода» з урахуванням впливу амплітуди коливань елемента на дисипативні втрати.

Методика. Заснована на експериментальному й теоретичному дослідженні динамічних параметрів бурового снаряду та ефективності перетворення стаціонарного течії рідини в пульсуючий потік.

Результати. Представлені у вигляді розрахункових і експериментальних залежностей тиску, об'ємної витрати, віброприскорень і гідравлічної коливальної потужності в перетині породоруйнівного інструменту від параметра кавітації τ.

Наукова новизна. Облік впливу амплітуди коливань елемента на дисипативні втрати, запропонований у даній роботі, дозволив отримати прийнятне узгодження з експериментальними даними та:

- визначити пікові (від 43,5 до 9,8 кВт) і середні (від 9,8 до 2,35 кВт) значення гідравлічної потужності в діапазоні зміни параметра кавітації τ = 0,12−0,475;

- встановити ефективність перетворення потужності стаціонарного потоку промивної рідини на вході до гідровібратора в коливальну потужність у перерізі породоруйнівного інструменту. У досліджуваному діапазоні зміни значення параметра кавітації розрахункове значення ефективності в розглянутому випадку становило приблизно 76 % при значенні параметра кавітації τ рівному 0,16, а мінімальне 19 % при τ = 0,475.

Практична значимість. Практична значимість отриманих результатів полягає в тому, що скоригована математична модель системи «бурової снаряд — гірська порода» дозволяє на стадії проектування встановити раціональний режим роботи кавітаційного гідровібратора для реалізації прийнятних рівнів гідравлічної потужності на породоруйнівному інструменті.

Ключові слова: *математичне моделювання, буровий снаряд, кавітаційний гідровібратор, породоруйнівний інструмент, гідравлічна потужність*