Chapter

Sonic Drilling with Use of a Cavitation Hydraulic Vibrator

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Abstract

Sonic drilling is a soil penetration technique that strongly reduces friction on the drill string and drill bit due to liquefaction, inertia effects and a temporary reduction of porosity of the soil. Modern studies to assess the effect of the vibration frequency of the drill bit on the rock fragmentation in experimental and theoretical works on drilling various rocks by the sonic method have shown that vibration frequencies of ~ 1.4 kHz are the most beneficial for ensuring the maximum drilling speed in hard rocks. The above frequencies of excitation of vibrations of the drill bit can be achieved by using a cavitation hydrovibrator. The cavitation hydrovibrator is the Venturi tube of special geometry that converts a stationary fluid (flushing mud) flow into an oscillatory stalling cavitation flow and hydrovibrator structure longitudinal vibrations. The drill bit vibration accelerations are realized in such a drill string, leading to the destruction of rock. Efficient removal of rock particles from the bottomhole is achieved due to high-frequency shock self-oscillations of mud pressure exceeding the steady-state pressure at the generator inlet. The cavitation hydraulic vibrator lacks the main disadvantages of submersible hydraulic hammers.

Keywords: sonic well drilling, high-frequency cavitation hydrovibrator, drill mud oscillations, drill bit longitudinal vibrational accelerations

1. Introduction

Sonic drilling is an effective method for sampling soft soils without disturbance, which can also be used for rapid drilling of bedrocks using vibration shock technology with rotary drilling [1]. Hydraulic hammers are of a dynamic type, operate on the energy of the flushing mud. Their operation principle is based on the effect of a water hammer as a result of interrupting the flow of fluid [2]. The main disadvantages of submersible hydraulic hammers are still:

- their low efficiency, not exceeding 10%;
- increased flow rate of the working fluid, which in some cases contradicts the drilling conditions, for example, leads to erosion of the borehole walls in zones of weak rocks;
- an acceptable operating mode at a liquid pressure drop of less than 6 MPa;
- the presence in their design of rapidly wearing moving parts, springs and rubber cuffs, which significantly reduce the period between inspection and service life;

- negative impact of pressure oscillations to the mud pump, causing increased wear of its parts and deteriorating drilling efficiency due to the unambiguous dependence of the bottomhole power on the pump characteristics [3].

At present, researchers from various countries continue to work on improving the characteristics of hydraulic hammers. For example, in the last decade in the Russian Federation, research has carried out on volumetric hydropercussion machines [3]. The foundations of the theory have been developed and original hydraulic shock and distribution devices have been created. Their peculiarity lies in the presence of a hydraulic accumulator, which complicates the design, especially for significant depth drilling.

Analysis of recent studies and publications indicates the trend of using hydrodynamic cavitation as a source of vibration loading on the drilling tool to increase the drilling speed in hard and super hard formations. Such studies are presented by authors from different countries at conferences on geomechanics and well drilling. So, for example, in the works [4–6] in the process of experimental studies it was found to improve the operational characteristics of the drill bit. This was 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. It was found that for drilling with a cavitation impulse tool more efficient cutting of the rock and transportation of drill cuttings occurs, and friction in the drill string is also reduced.

Possibilities of increasing the profitability of well construction using pulsating jet technologies in future designs of the drill string with the optimization of the frequency and amplitude effects of the bit, taking into account the lithology of drilled rocks, are given in [7]. It was shown, "this could lead to faster and more efficient drilling, which will reduce drilling costs and make more oil and gas wells profitable".

In the last decade, researchers from China have been intensively engaged in the creation of a new cavitating drill bit [8]. This was due to the need to overcome a number of problems in its western region during exploration and construction of superdeep wells with the depth ranging from 2000 m to 6000 m. In particular, the rate of penetration (ROP) of wells and the rate of development of new fields in these difficult geological conditions decreased significantly, and the cost of drilling increased dramatically.

To overcome the above problems, a new drilling tool was developed with the installation of a hydraulic impulse generator of a cavitation jet. Tests of such a generator have shown that at a flow rate of flushing fluid from 32 l/s, it implements fluid pressure oscillations with amplitude range ΔP from 2.1 to 2.2 MPa and a fundamental frequency up to 10 Hz. Field experiments conducted in oil fields throughout China on more than 100 wells with the maximum depth of 6162 m have shown that drilling with this tool increases the ROP by 16 ÷ 104%. This is due to the pulsation of the jet, cavitating erosion and the effect of local negative pressure, as well as an improvement in the cleaning efficiency of the bottomhole [9, 10].

At the same time, studies to assess the effect of the vibration frequency of a drill bit on rock fragmentation in experimental and theoretical works on drilling various rocks by the sonic method showed that vibration frequencies of 1.4 kHz [11] are the most beneficial for ensuring the maximum drilling speed in hard rocks.

At the end of the last century (in the 80 s) the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine (ITM NASU) together with the 'Geotechnika' special design bureau (Russia) created a new scientific direction in the development of submersible percussion machines using the effects of hydrodynamic cavitation [12]. The main goal of this direction was the creation of a new method of dynamic loads on the drill bit, allowing to eliminate the disadvantages of existing hydropercussion machines. This method was implemented in the development of a drill string with a cavitation hydraulic vibrator.

Analysis of the latest publications on the study of promising devices that intensify the technological process of drilling exploration and production wells shows that the drilling technology using the cavitation hydraulic vibrator has a number of advantages. It lacks the main disadvantages of submersible hydraulic hammers [3] and impulse devices [10]. Cavitation hydraulic vibrator does not require additional energy sources and does not contain moving parts, it is easy to manufacture and fits organically into existing equipment without affecting the pump, since drill mud pressure oscillations are not transmitted above the place of the vibrator installation.

2. Drilling rig with a cavitation hydraulic vibrator for intensifying the technological process of well construction

The cavitation hydraulic vibrator (**Figure 1**) is a part of a drill pipe 1 of drilling rig with drill bit 6. The hydraulic vibrator 5 is mounted in the pipe using tapered threads, the structure of the vibrator contains the cavitation generator 2 of flushing fluid pressure oscillations.

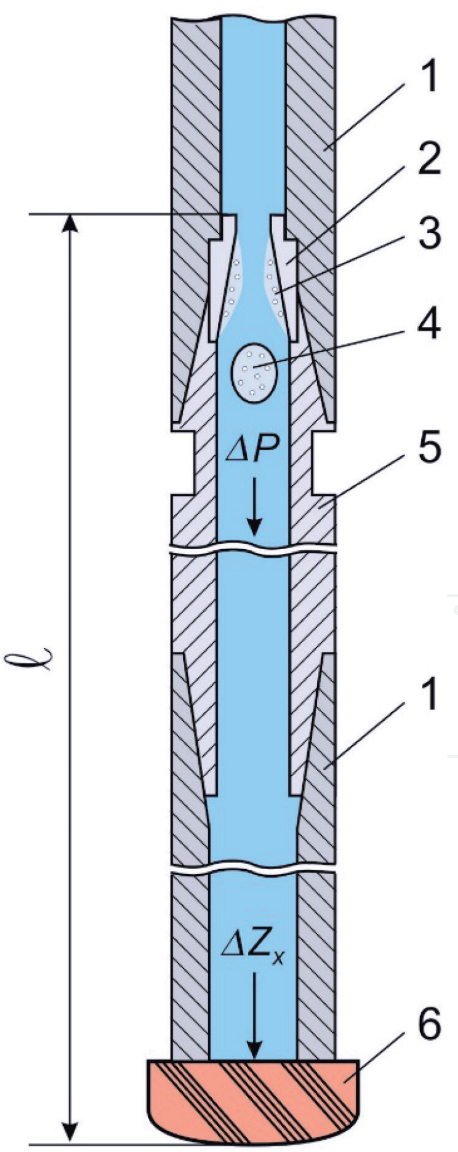

Figure 1.
Layout of a drill string with a cavitation hydraulic vibrator. 1 is drill pipe; 2 is cavitation generator; 3, 4 are the cavity is sedentary and its cavity part that has come off; 5 is hydraulic vibrator; 6 is drill bit.

2.1 Cavitation generator of fluid pressure oscillations and its characteristics

The cavitation generator of pressure oscillations is the Venturi tube of special geometry that converts a stationary fluid flow into a periodically stalling cavitation flow [12]. In this case, high-frequency shock self-oscillations of the liquid pressure are realized, exceeding the pressure at the generator inlet, transforming into axial vibration accelerations of the drill string [13].

A diagram of the cavitation flow in generators of this type with the distribution of pressure and flow velocity along the flow axis and the designation of its dimensions are shown in **Figure 2**.

Cavitation occurs when the local static pressure drops to a critical one, equal to or close to the saturated vapor pressure of the liquid, caused by an increase in the liquid velocity in the cavitation generator throat. In this case, discontinuities of the liquid appear and cavities filled with vapors and gases are formed. It has been established that the most developed cavitation oscillations are observed in the hydraulic system behind a local constriction of the Venturi tube type when the diffuser opening angle $\beta \geq 16°$ [12]. The frequency and amplitude of oscillations in a wide range of their values can be easily controlled by changing the operating parameters of the generator.

The cavitation generator is characterized by the following parameters:

- geometric parameters:

d_{cr} and ℓ_{cr} are the diameter and length of the throat; β is the diffuser opening angle; D and ℓ_d are the outlet diffuser diameter and the diffuser length;

- regime parameters:

P_1, P_2 and Q are total inlet and back pressure and liquid flow rate through the generator; τ is parameter of the mode of the liquid cavitation flow;

- dynamic parameters:

f is self-oscillation frequency; $\Delta P = p_{2max}-p_{2min}$ is the range (peak to peak value) of pressure self-oscillations due to the nonharmonic shapes of oscillations; p_{2max} is the maximum value of the pressure in the pulse behind the generator; p_{2min} is the

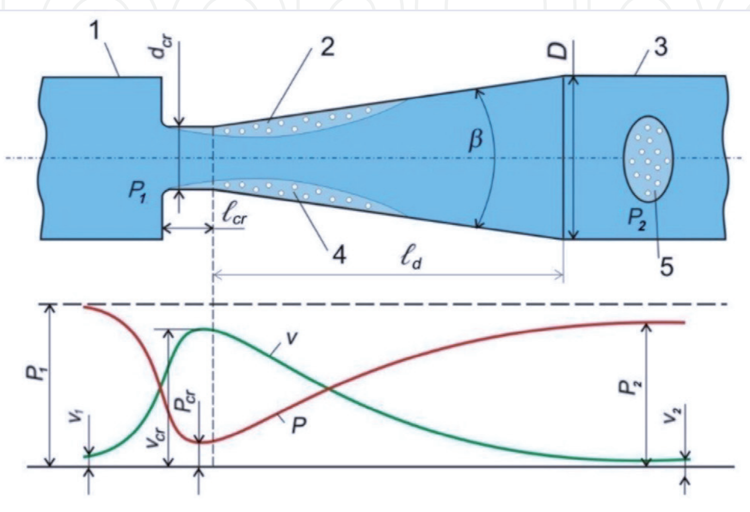

Figure 2.
Scheme of the cavitation flow in the generator with pressure and flow velocity distribution along the generator length. 1 is inlet pipeline; 2 is generator; 3 is outlet pipeline; 4 is cavitation zone with cavity volume V; 5 is detached part of the cavity V_2; P_1 is total pressure at the cavitation generator inlet; P_2 is full back pressure.

minimum value of the pressure in the pulse); ΔQ is the range (peak to peak value) of self-oscillations of the volumetric liquid flow rate.

The cavitation parameter τ is a dimensionless number used in flow calculations. It expresses the relationship between the difference of a local absolute pressure P_2 (at the generator outlet) from the vapor pressure P_{cr} and the velocity head, which is determined by the velocity in the generator throat:

$$\tau = \frac{P_2 - P_{cr}}{\rho \frac{v_{cr}^2}{2}} \tag{1}$$

where v_{cr} is the velocity of the liquid through the generator throat; ρ is the liquid density; P_{cr} is the liquid pressure in the generator throat.

The numerator of this parameter includes the total pressure or head, under the cavity collapses, and the denominator is the flow velocity head, determined by the pressure difference P_2-P_{cr}. The change in pressure on the surface of the body or on the walls of any channel limiting the flow is mainly associated with a change in the flow velocity. Therefore, the velocity head can be considered as a value that determines the pressure drop, as a result of which a cavity can form and expand. From this point of view, the cavitation number is the ratio of the pressure under which the cavity collapses to the pressure under which the cavity appears and grows.

Abnormally high values of liquid pressure in the pulse are observed at the generator diffuser angle of the $16 < \beta \leq 45°$ in the range of values of the cavitation parameter τ from 0.02 to 0.4. As an example, in **Figure 3** shows a fragment of an oscillogram of the time dependence of the pressure $p_2(t)$ and a filmogram of the process of growth and detachment of the cavity volume V. This results were obtained during testing of the hydraulic system with the cavitation generator (the Venturi tube throat diameter of d_{cr} = 6 mm, the diffuser opening angle of β = 20° and outlet diameter of D = 24 mm). In this case, the inlet pressure P_1 and the outlet pressure P_2 were of 20 MPa and of 2.0 MPa (i.e. $\tau \approx 0.1$). In the event of cavitation oscillations in the hydraulic system after the cavitation generator, the pressure P_1 at the inlet to the cavitation generator practically did not contain a dynamic component.

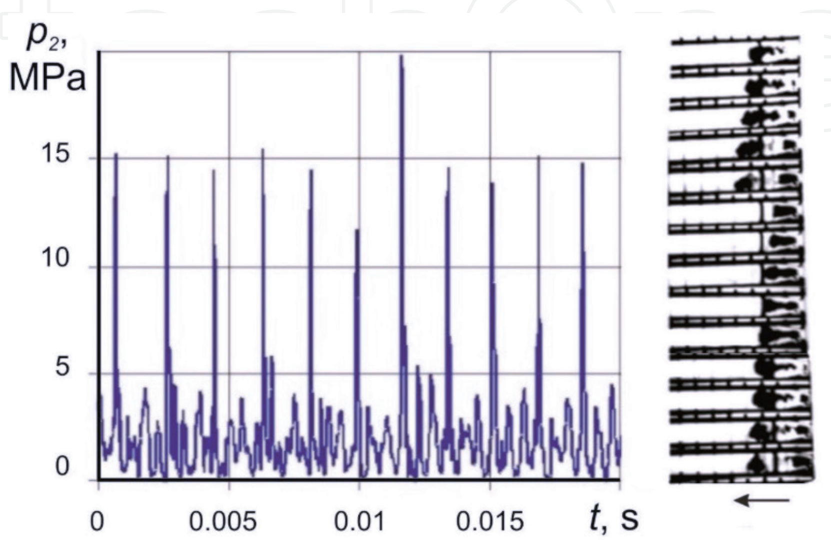

Figure 3.
Fragment of the oscillogram recording the pressure p_2 in time at the cavitation generator output with the critical section diameter d_{cr} = 6 mm at $\tau \approx 0.1$ and a filmogram of the growth and separation of the cavitation cavity in the generator tube (the direction of fluid flow is indicated by an arrow).

The figure shows that when cavitation occurs, the cavity begins at the entrance to the cylindrical section with d_{cr}. The cavity volume V grows over the entire length of the critical section at the fixed pressure value at the outlet of the generator P_2. Then the cavity enters the diffuser and spreads along the walls. When the cavity, at a certain mode, reaches its maximum length, reverse flows along the diffuser wall are observed, which tear off the part of the cavity located in the diffuser. The separation section of the cavity becomes constant and corresponds to the transition of the cylindrical section of the tube into the diffuser [12]. The process of detachment and collapse of a part of the cavity in a certain mode occurs strictly periodically, that is, with a constant frequency of several hundred Hz.

The frequencies of pressure oscillations in the hydraulic system, calculated from the pressure recording oscillograms, and the frequencies of the part of the detachment cavity located in the diffuser, determined from the time marks on the films obtained during the tests of the generator at different values of the cavitation parameter τ, are in satisfactory agreement. This allows us to conclude that the anomalously high periodic pressure impulses of a shock nature behind a local constriction of the Venturi type (see **Figure 3**, curve $p_2(t)$) are caused by the collapse of large-volume cavities in the fluid flow.

The pressure wave from the collapse center propagates along the flow over rather long distances (practically not attenuating in experiments up to 2.0 meters). The pressure wave propagates against the flow, is damped by a new cavity that has grown by this time, as evidenced by the absence of oscillations at the generator inlet, but it takes part in the formation of reverse flows and creates conditions for the separation of the next cavity. Thus, a self-synchronized process of separation and collapse of cavitation cavities is established.

Figure 4 shows the calculated dependences of the swing of pressure oscillations ΔP on the cavitation parameter τ and the experimental data obtained during bench tests. Calculated and experimental data are given for generators with d_{cr}, equal to 8 mm, 6 mm, and 2.5 mm. The inlet pressure values were P_1 = 1 MPa, 10 MPa, 20 MPa, and 30 MPa.

The location of the experimental points relative to the theoretical dependences of the swing ΔP of the pressure oscillations at the generator output on the cavitation parameter τ shows their satisfactory convergence. The relative error of the given results does not exceed 15%. It was found that the regime of periodically stalling cavitation flow is realized in the range of variation of the cavitation parameter τ from 0.01 to 0.8. At a fixed value of τ, an increase in liquid pressure P_1 at the inlet to the experimental sample of the cavitation generator leads to an increase in the magnitude of the pressure oscillation range ΔP. The nature of the established dependences $\Delta P(\tau)$ shows that for all values of pressure P_1, the value ΔP of the oscillatory pressure with increasing τ first sharply increases, reaches its maximum value, and, further, at a certain value of τ decreases.

The dependences of $\Delta P(\tau)$ have the maximums in the range cavitation parameter τ from 0.1 to 0.3 for different values of steady-state pressure P_1. By the increase in the pressure P_1, the maximum ΔP shifts towards lower values of the cavitation parameter τ.

The maximum value of the swing ΔP of the oscillatory pressure value is approximately in 1.2-3.5 times higher than the steady-state pressure P_1 at the generator inlet. In this case, with an increase in the pressure P_1, the ratio $\Delta P/P_1$ decreases. So, at P_1 = 1 MPa $\Delta P/P_1 \approx 3.5$, and at P_1 = 30 MPa the value of is $\Delta P/P_1 \approx 1.2$.

Analysis of the dependencies, presented in **Figure 4**, shows clearly that the amplitude of the oscillatory pressure ΔP is determined by the input pressure P_1 and the cavitation parameter τ. There is no influence of the diameter of the critical section of the generator, and, consequently, of the fluid volumetric flow rate on the values ΔP of the oscillation peaks. So, for example, at P_1 = 30 MPa with a change in d_{cr} from 2.5 mm to 6.0 mm, the value of the fluid volumetric flow rate increased in proportion to the increase in the flow area of the generator by 5.76 times (from 1.12 to 6.46 l/s,), and the swing level ΔP did not change. At first glance, this paradox is associated with the fact that an increase in the volumetric flow rate of liquid through the generator Q leads to an increase in the volume of the detached part of the cavitation cavity. This was recorded by visual studies [12] and by theoretical determination of the amplitude ΔV_c of oscillations of the volume of the detached part of the cavity. It would seem that the collapse of a larger volume of the cavity, with an increase in the flow section of the generator, should lead to an increase in the amplitude of oscillations ΔP. However, as follows from **Figure 4**, this does not happen.

According to the results of the study carried out in [14], it was found that from the physical point of view and from the position of the existing linear mathematical model, the pressure that arises when the cavitation cavity collapses does not depend on its size, but is determined by the speed of its wall movement, which is determined by the difference pressure and discharge pressure.

However, we note that the energy of the discrete-pulse action of a liquid in any technological process is determined not only by the range of pressure fluctuations, but also by the oscillatory component of the volumetric flow rate, which increases with an increase in the generator flow area.

Figure 5 shows the dependences of the theoretical cavitation oscillation frequency f on the cavitation parameter τ for generators with d_{cr} = 2.5 mm, 6 mm, and 8 mm (solid line) and experimental data at fixed values of pressure at the generator inlet P_1 = 1 MPa, 10 MPa, 20 MPa, and 30 MPa.

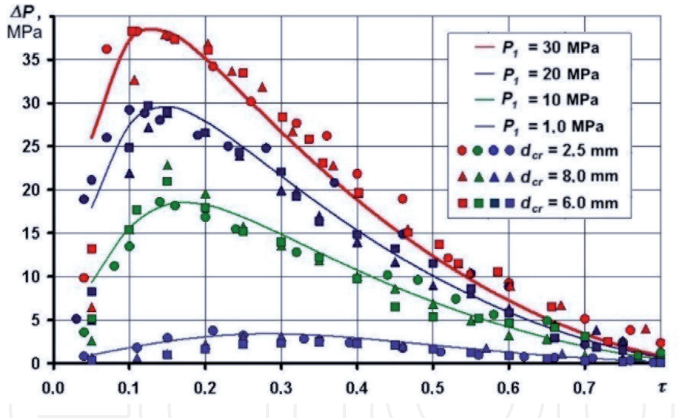

Figure 4.
Theoretical and experimental dependences of the amplitude ΔP of pressure oscillations on the cavitation parameterτ realized by the cavitation generator for case of the inlet pressure P_1 changes from 1 MPa to 30 MPa.

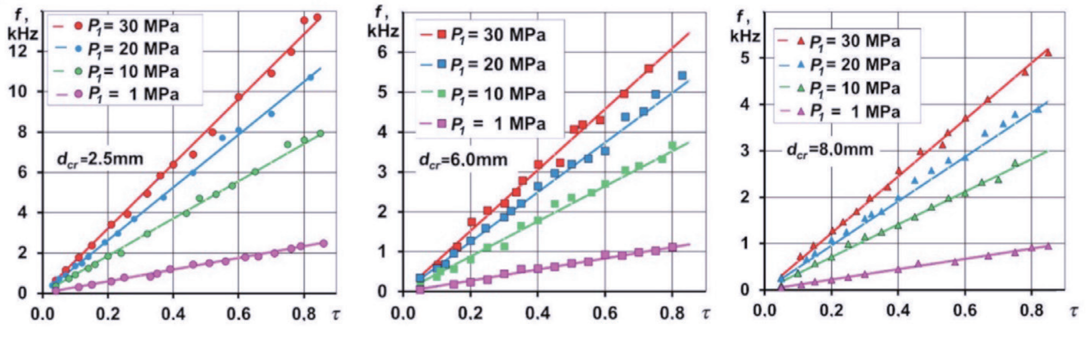

Figure 5.
Theoretical and experimental dependences of the frequency f vs. the cavitation parameter τ for the steady-state inlet pressure P_1 changes from 1 MPa to 30 MPa.

It can be seen from the figure that for all the generators presented, the theoretical dependences $f(\tau)$ obtained by calculations are in satisfactory agreement with the experimental data in almost the entire range of variation of the cavitation parameter τ and are linear. The relative error of the given results does not exceed 10%.

It was found that, at fixed values of the cavitation parameter τ and pressure at the generator inlet, an increase in the diameter of the critical section of the cavitation generator (and, consequently, the volumetric flow rate of the liquid) leads to a decrease in the frequency of cavitation oscillations. So, at the values P_1 = 30 MPa and τ =0.6 increase in the value of the cavitation generator throat diameter from 2.5 mm to 8.0 mm leads to decrease in the frequency of cavitation self-oscillations by about 2.63 times (from 9.74 kHz to 3.71 kHz). An increase in the liquid injection pressure P_1 leads to an increase in the frequency of cavitation self-oscillations. So, with the values of the throat diameter of the cavitation generator 6 mm and the cavitation parameter 0.6, an increase in the fluid inlet pressure P_1 from 1 MPa to 30 MPa leads to an increase in the cavitation self-oscillations frequency from 0.93 kHz to 4.57 kHz.

Thus, it has been established that in a drilling rig with a hydraulic vibrator, that includes the cavitation generator of fluid pressure oscillations, the stationary flow of the process fluid turns into a discrete-pulse flow of increased power. It is realized in the form of high-frequency (from 200 Hz to 20000 Hz) drill bit vibration accelerations [15]. In case of repeated exposure to power impulses from drill bit, the rock destruction takes on fatigue nature. Due to resonance processes in the 'drill string with a hydraulic vibrator – rock' dynamic system and the development of a network of microcracks in the rock, the discontinuity of the rock mass, as a rule, occurs at stresses lower than the ultimate strength of the rock. This leads to an improvement in the removal of the destroyed motive from the zone of its contact with the tool, an increase in the drilling speed, wear resistance of the drilling tool, and an improvement in the stabilization and stability of the operation of the drill string.

It was also found that the magnitude of the pressure pulses and their repetition rate can be controlled by setting the regime parameters of the cavitation flow.

2.2 Dependences of the drill string dynamic parameters on the operating mode of the cavitation hydraulic vibrator

The correctness of the choice of the proposed method of dynamic loading to the drill bit is confirmed by studies of the influence of the operating and design parameters of the cavitation hydrovibrator on the dynamic parameters of the drill string at the drill bit section. Such work was carried out at the ITM NASU hydraulic stand and drilling stands at the 'Geotechnika' special design bureau (Russia).

The most interesting are the results of an experimental study of the dynamic parameters of a drill string in the process of drilling a well. These results and their comparison with the calculated data are given in [15]. The general scheme of testing a drill string in a borehole 87 m deep is shown in **Figure 6** (on the left of the Figure is a photograph of the hydraulic cavitation vibrator of this drill).

The static pressures values at the inlet of the drill string P_1 and at its exit P_2 were calculated using the formulas: $P_1 = (P_d + 0.83)$ MPa and $P_2 = (P_b - 0.87)$ MPa, where P_b is the backpressure (P_d is the pressure of the drilling fluid created by the pump). When carrying out these drill string tests, the I-24.2141 piezoelectric sensors were used to measure fluid pressure pulsations and their frequency. In the same place, vibration accelerations were measured by two ABC-034 sensors. The three tests were carried out for this drill string structure design at differing in pressure of P_d = 3 MPa, 4 MPa and 5 MPa.

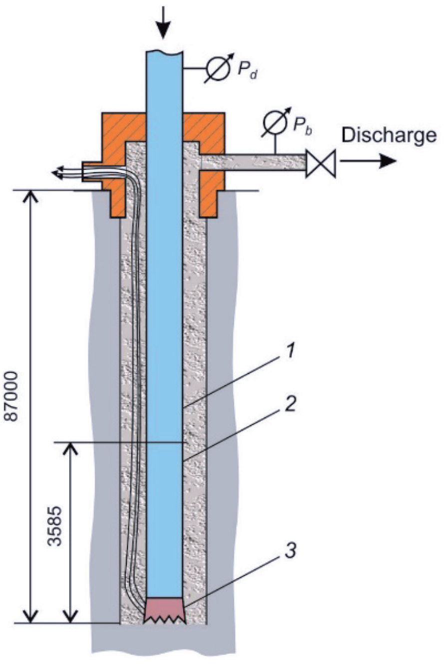

Figure 6.
The schematic of the testing drill string in the well (1 is drill pipe; 2 is drilling rig; 3 is drill bit) and the photographic image of the cavitation hydrovibrator.

Table 1 shows the main geometrical parameters of the drill string and the results of its tests at the pressure of P_d = 4 MPa and the contact of the drill bit with the rock (granite) at the axial static load F of 9.8 kN.

Considering that the oscillation modes of the parameters of the dynamic process in the hydrovibrator differ significantly from the shapes of harmonic oscillations, the analysis of the experimental and theoretical studies was carried out using not the amplitudes, but the peak to peak values ΔP of the fluid pressure and vibration accelerations ΔZ_x in the axial direction. The values of the ranges of these parameters were determined as the difference between their maximum and minimum values. The frequency was calculated based on the analysis of the time dependence of the fluid pressure in the hydrovibrator (the fundamental mode of the fluid oscillations).

Basic geometrical parameters of the drill string		**Test results**			
		τ	**Δ*P*, MPa**	**ΔZ_x, g**	**f, Hz**
throat diameter, d_{cr}	6.0 mm	0.100	4.80	1960	196
length of the throat, ℓ_{cr}	8.2 mm	0.137	6.00	2793	326
outlet diffuser diameter, D	24 mm	0.161	5.90	3201	374
diffuser length, ℓ_d	51 mm	0.184	5.15	2564	423
diffuser opening angle, β	20°	0.200	4.30	1570	508
outlet channel diameter, d_h	24 mm	0.340	3.20	928	793
output channel length, ℓ_h	240 mm	0.415	2.78	1401	995
drill string length, ℓ	3585 mm	0.475	2.55	1027	1188

Table 1.
The basic geometrical parameters of the drill string with and cavitation generator and the results of the drill string dynamic tests at the pump discharge pressure of P_d = 4 MPa and axial static load of F = 9.8 kN.

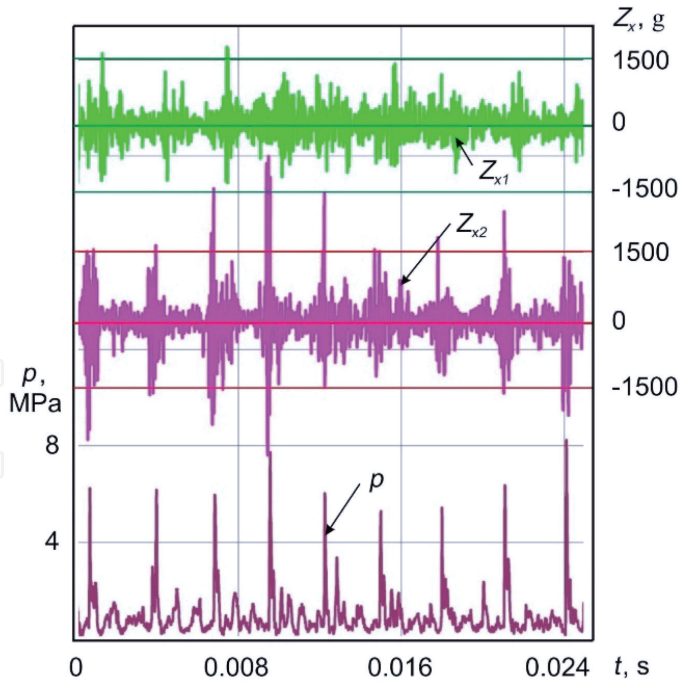

Figure 7.
Waveform recording parameters oscillatory process of the drill string experimental sample: Discharge pressure of P_2, longitudinal vibration accelerations Z_{x1} and Z_{x2} of the drill string structural elements.

As an example, **Figure 7** shows an oscillogram with a real-time recording of the dynamic parameters of the drill string experimental sample: the fluid pressure p oscillations and vibration accelerations Z_{x1} and Z_{x2} in the drill bit section for the pump pressure, equal to the P_d = 4 MPa, and the cavitation parameter of τ = 0.161. The results of this test presented in the Figure describe the dynamic process determined by the development in the generator of the regime of periodically stall cavitation, characterized by the shock shape of pressure oscillations in the hydrovibrator flow channel.

These vibrations propagate along the drill string length and are converted into the drill bit vibration accelerations with average values of $\Delta Z_x \approx 3200$ g and the dominant frequency of cavitation pressure oscillations in the hydraulic vibrator flow path of 374 Hz. The longitudinal vibration accelerations of the drill string structural elements indicated in **Figure 7** by Z_{x1} and Z_{x2}).

As a result of the tests, carried out for different inlet pressure, it was found that an increase in the steady-state pressure p_1 at the hydraulic vibrator inlet leads to the increase in the values of vibration accelerations in the drill bit section from 2280 g (at P_d = 3 MPa) to 4580 g (at P_d = 5 MPa).

2.3 Comparative analysis of the results of theoretical and experimental research of the drill string vibrations by hydraulic vibrator excitation

Mathematical modeling of the oscillatory motion of the drill string with the high-frequency hydraulic vibrator was carried out on the assumption that the drill string structure carries out vibration motion along the flow path longitudinal axis of the fluid flow. This limitation is also due to the axial symmetry of the drill string structure itself and the direction of the total components of the forces acting on the drill string structure [13]. The mathematical model of the 'drill string with a hydraulic vibrator' dynamic system as the coupled hydrodynamic system was proposed in [15]. For various structural elements of the drill string, the model describes the time variation of such system parameters as vibration displacement, vibration velocity, vibration acceleration, as well as pressure and fluid mass flow rate in the flow path of the corresponding drill string structural elements.

Modeling of axial vibrations of the drill string structure was carried out on the basis of its finite element scheme, in which the elements are characterized not only by elasticities and masses, but also by dissipative losses, the magnitudes of which depend on the vibration amplitudes of the structural elements. Thus, the damping coefficients in the equation of motion of the center of mass of the i-th finite element of the drill string

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

were calculated based on the dependences and experimental data [16].

$$b_i = \left(b_i^0 + b_i^a\left(a_i\right)\right)\cdot\frac{\sqrt{c_i \cdot m_i}}{2\pi} \tag{3}$$

where x_i is the displacement of the center of mass of the i-th finite element from the position of dynamic equilibrium; m_i and m_i^p are the distributed mass and concentrated mass of the i-th finite element of the drill string; $c_i = E_i A_i \Delta l_i^{-1}$ is the stiffness coefficient of the i-th finite element; A_i is cross-sectional area of the i-th structural element; Δl_i is longitudinal length of the i-th structural element; E_i is Young's modulus of elasticity of the material of the i-th structural element; b_i^0 is the damping coefficient of the i-th finite element at small structural vibrations; F_i^n is deviation of the force acting on the i-th structural element of the drill string from its steady-state value; $b_i^a\left(a_i\right)$ is the component of the damping coefficient of the mechanical elements, taking into account the damping coefficient increase at 'considerable' nonlinear amplitudes a_i of the drill string structure vibrations.

The time dependences of the displacement, vibration velocity and vibration acceleration of structural elements, fluid pressure and flow rate, the volume of the cavity attached and collapsing in the hydrovibrator flowing part was gotten by numerical integration by the Runge–Kutta method of the system of differential equations describing the drill string longitudinal vibrations for the hydrovibrator steady-state operating mode (at τ = const). These dependences were obtained at the discharge pressure P_d = 4 MPa, the axial static load F = 9.8 kN, and values of the criterion parameter of cavitation τ = 0.12, 0.16, 0.184, 0.2, 0.34, 0.415, 0.475. This data corresponds to experimental studies of the drill sample, the geometric parameters and test results of which are given in **Table 1**.

The calculated time dependences of pressure p, volumetric flow rate Q, vibration acceleration Z, vibration velocity v, vibration displacement x and vibration force F_m in the drill bit section for the value of the cavitation parameter τ = 0.16 are presented in **Figure 8**.

As follows from the given dependences, the oscillatory process is impulsive in nature. For the indicated value of the cavitation parameter the fundamental harmonic frequency of cavitation oscillations is 323 Hz, the range of pressure oscillations is

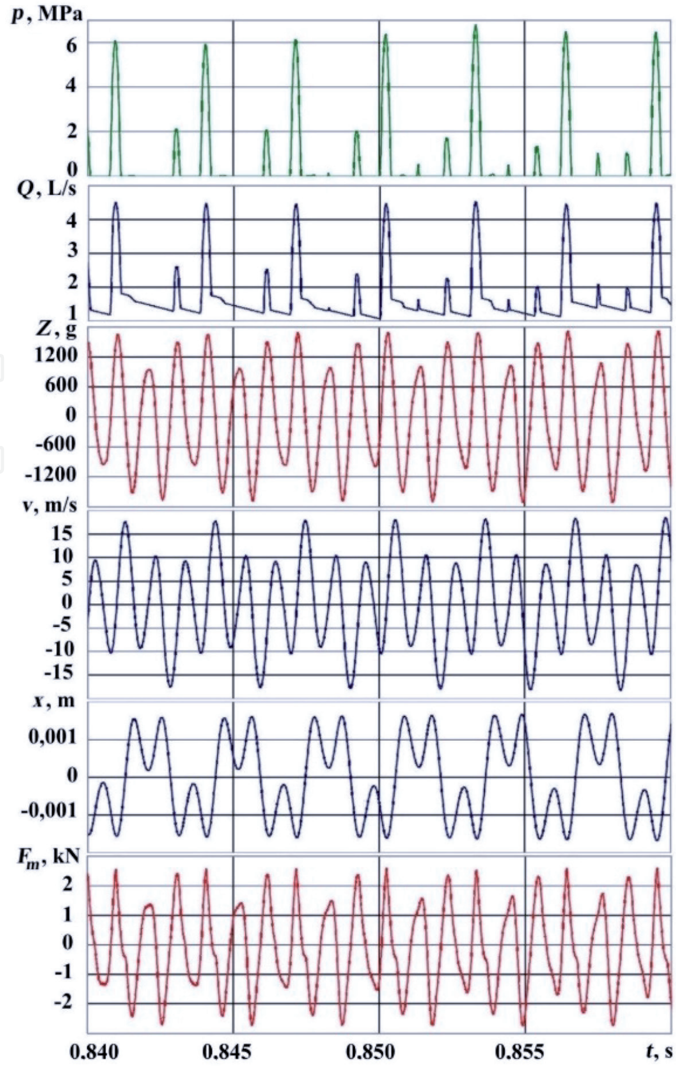

Figure 8.
Calculated drilling parameters vs. time: Pressure p, volumetric flow rate Q, vibration acceleration Z_x, vibration velocity v, vibration displacement x and vibration force F_m at the drill bit section of drill string.

$\Delta P \approx 6.19$ MPa, the volumetric flow rate is $\Delta Q \approx 3.17$ l/s, the vibration acceleration is $\Delta Z \approx 3139$ g, the range of vibration velocity is $\Delta v \approx 28$ m/s, the range of vibration displacement is $\Delta x \approx 3.1$ mm and the vibration force is $\Delta F_m \approx 4.5$ kN. It is seen from the results of the calculations that the frequency of drill string structure vibration (equal to about 970 Hz) is superimposed on the fundamental harmonic of the frequency of cavitation oscillations. This phenomenon occurs due to the dynamic interaction of the drill string structure and the mass of fluid flowing inside the drill pipe.

The calculated and experimental dependences on the cavitation parameter τ of frequency of the cavitation oscillations of the fluid pressure ΔP, as well as the frequencies of hydraulic oscillations f_{cav} in the flow channel of the hydraulic vibrator and the drill string second mode frequency f_{m2} mechanical oscillations are presented in **Figure 9**. It also shows the calculated dependence volume flow rate ΔQ on the cavitation parameter τ.

The nature of the dependences ΔP and ΔQ on τ is nonlinear. The ranges of pressure oscillations ΔP and volumetric flow rate ΔQ increase with an increase in the value of the parameter τ from 0.1 (with an increase in the pump head pressure P_b at P_d = const), reaching the maximum values of 6.19 MPa and 3.17 l/s at $\tau = 0.16$, and then decreases. The maximum value of the oscillatory pressure in the cross section of the sensor installation is approximately in 1.5 times higher than the discharge pressure P_d. Despite the complexity of the processes occurring in the flow channel

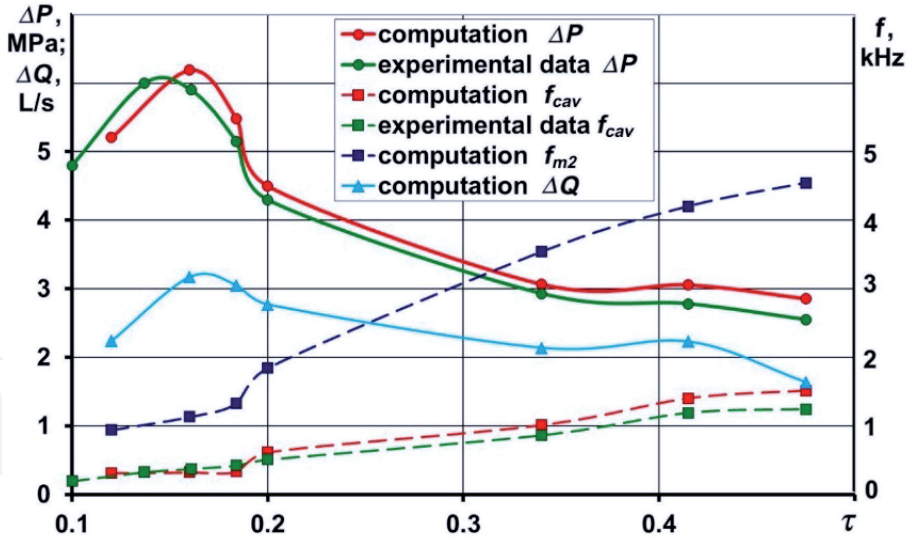

Figure 9.
Calculated and experimental pressure oscillations range ΔP, volumetric flow rate ΔQ and hydraulic oscillations frequency f in the drill bit section vs. the cavitation parameter τ .

of the cavitation hydrovibrator, in the entire range of variation of the value of τ, not only a more qualitative, but also a quantitative (in comparison with work [15]) agreement was obtained for the calculated pressure oscillation ranges with experimental data, including on dynamic system resonant modes.

The experimental and calculated dependences of the frequency f_{cav} of cavitation self-oscillations on the cavitation parameter τ have a character close to linear. Satisfactory agreement is observed between the calculated and experimental frequencies of cavitation vibrations in the investigated range of variation of the cavitation parameter τ. The frequency of the first mode of the forced drill string structure vibrations corresponds to the oscillation frequency of the fluid in the hydraulic vibrator flow channel. This is clearly illustrated in **Figure 8**. As it follows from the figure that the frequency of cavitation self-oscillations of pressure and volumetric flow rate of liquid in the cavitation hydrovibrator flow channel and the first mode of the frequency of forced vibrations of the drill string structure (vibration acceleration, vibration velocity, vibration displacement and vibration force) are equal to 323 Hz. The frequency of the second mode of drill string mechanical vibrations is approximately in three times higher than the first mode frequencies.

The dominant frequency of cavitation oscillations is 1230 Hz at the value of the cavitation parameter $\tau = 0.415$, the second mode of the drill bit mechanical vibrations is approximately in 3.4 times higher and is equal 4202 Hz (see **Figure 9**). This mode caused by repeated collapse of the cavitation cavity and the interaction of the drill bit structure with drill mud in hydrovibrator channel. The swing of pressure oscillations of $\Delta P \approx 3.06$ MPa, the swing volumetric flow rates $\Delta Q \approx 1.83$ l/s and vibration acceleration $\Delta Z \approx 1247$ g. It should be noted that with an increase in the value of the parameter τ from 0.12 to 0.475, the duty cycle of the shock process of changing the parameters of pressure and volumetric flow rate (see **Figure 9**) decreases.

Oscillatory parameters of pressure and volumetric flow rate of the liquid determine the hydraulic power of the cavitation hydraulic vibrator, which characterizes the quality of the removal of the drilled rock from under the drill bit. Vibration acceleration and vibration force refer to the parameters that determine the ROF. The theoretical dependences of the swing of vibration accelerations ΔZ and the swing vibration force ΔF on the cavitation parameter τ and experimental data on vibration accelerations ΔZ at the drill bit are shown in **Figure 10**.

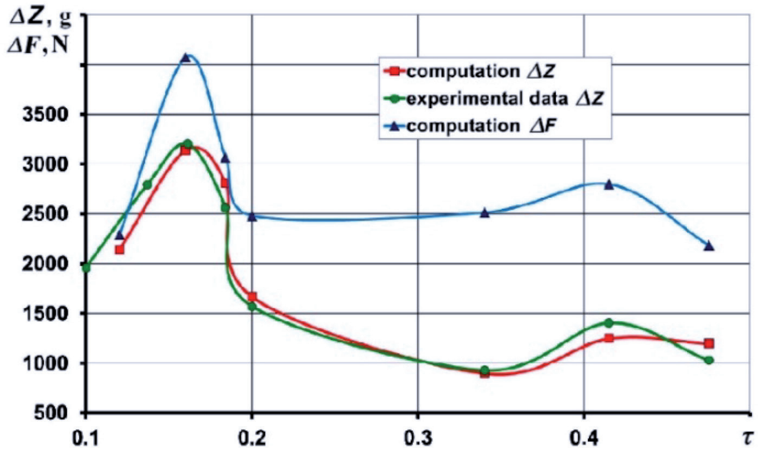

Figure 10.
Calculated dependences of the vibration acceleration peak to peak values ΔZ and the peak to peak values of vibration force ΔF vs. the cavitation parameter τ and experimental data on vibration accelerations ΔZ at the drill bit.

Analysis of the data in this figure shows that an increase in the amplitudes of forced oscillations in the drill fluid pressure at cavitation numbers from 0.1 to 0.16 (see **Figure 9**), leads to an increase in the drill string vibration acceleration and vibration force. The maximum values of the amplitude of vibration acceleration and vibration force on the drill bit for this hydraulic vibrator design are realized at $\tau = 0.16$ and are approximately 3200 g and 4100 N. At the same time, in the research range of the cavitation parameter τ from 0.1 to 0.475, there are two resonant modes of drill string operation. The first resonant mode corresponds to the value of the cavitation parameter $\tau \approx 0.16$, which coincides with the maximum values of the pressure oscillations swing (see **Figure 9**). The second resonant mode manifests itself at $\tau \approx 0.415$ and is a consequence of the convergence of the frequencies of natural vibrations of the drill string structure and the drilling fluid oscillations frequency, caused by the 'operation' of the cavitation generator. Consideration of the theoretical dependences of the swing of vibration accelerations ΔZ on the cavitation parameter τ and experimental data indicates the satisfactory convergence of the results obtained, including in the above resonance modes.

2.4 Evaluation of the efficiency of drill string with a cavitation hydraulic vibrator for geological exploration and construction of hydrogeological wells

On the basis of above theoretical and experimental studies, the new typed BSKG-76 hydrodynamic (with a cavitation hydraulic vibrator) drilling assemblies were created for drilling exploration wells with the following specifications [17]:

- outer tube diameter is 57 mm;
- the length of the hydraulic vibrator is 400 mm;
- the diameter of the generator throat section is 4 mm and 6 mm;
- generator feed pressure from 2.0 to 5.0 MPa;
- flow rate of working fluid from 19 to 200 *l*/min;
- rotational speed of the drill bit is 245 rpm.

The tests of the BSKG-76 type drilling rigs were carried out under the conditions of 'Production Geological Association Stepgeologia' LLP (Kazakhstan) by drilling exploration wells using a drilling rig, including the SKB-5 drilling rig, the ANB-22 pump with a three-stage reduction gear, the RT −1200 turning mechanism. Drill pipes with a diameter of 50 mm of a nipple joint, diamond bits of the 02IZ and A4DP types, and the Shch76k-4 L three-cone bits were used as dril bits.

Water and emulsion solutions were used as a working agent: 3% sulfanol and 3% emulsollenol-32. The tests were carried out in the depth interval from 70 m to 530 m on granites of IX-XI categories in terms of the Protodyakonov drillability scale. The technological parameters of drilling were monitored: the feed force by the load indicator, the flow rate and the fluid pressure by the flow meter and pressure sensor, the power consumption for rotation by the self-recording wattmeter.

The parameters of the well drilling modes in terms of axial load and rotational speed of the drill bit remained identical for the shock-rotational and hydrodynamic methods and alternated after 1-2 runs with the G76VO hydraulic hammer and the BSKG-76 drill string. Comparative analysis of drilling methods was carried out according to the following indicators: ROP, service life of drill bits and power consumption.

For drilling wells by hydrodynamic drilling rig BSKG-76 with coring in comparison with rotary-percussion drilling by the G76VO hydraulic hammer:

- for the 02IZ drill bits an increase in ROP was obtained by from 16–61%; by the resource of the crown by 18%;

- for the A4DP drill bits an increase in ROP was established from 27 to 77%, for a bit resource by 12%;

- for coreless drilling with the Shch76k-4 L roller cone bits an increase in the ROP was obtained by an average of 13.5% and the drill bit resource by 23%.

Analysis of the power consumption for the rotation of the drill bit in all drilling modes showed that for the BSKG-76 drill string is in operation, the power consumption decreases by 30% in compared to the power consumption of the G76VO hydraulic hammer, improves the operation stability of the drill string and drill bit.

A comparative analysis of the BSKG-76 hydrodynamic drill reliability and the G76VO hydraulic hammer reliability during the testing period showed the following: four failures of the hydraulic hammer were noted and ten assemblies were disassembled to adjust and replace the cuffs in the cylinder, O-rings in the splined connector, nozzles and pistons in the striker.

At the same time, during the entire testing period, not a single failure occurred in the operation of the BSKG-76 hydrodynamic drilling rig. The absence of their wear was established by the help of examinations and measurements of the main dimensions of the drill string parts. This indicates that the service life of the hydrodynamic drill string significantly exceeds the service life of the hydraulic hammer.

The drilling rig with a cavitation hydraulic vibrator is characterized by increased reliability and ease of maintenance due to the absence of moving parts, the need for adjustments and assemblies-disassembly with replacement of parts. It does not require additional energy sources other than the energy of the washing solution. A well with a depth of 525 m was drilled by the use of a hydrodynamic drill string and its performance was confirmed to this depth.

To assess the efficiency of large-diameter well drilling by the drill string with the cavitation hydraulic vibrator, it was tested in an industrial environment at the 'Geotechnika' special design bureau (Russia) during the construction of hydrogeological wells.

The geological wells on which the studies were carried out are represented by Quaternary deposits to a depth of 10.5 m and further to a depth of 60 m by limestones and dolomites (weathered in the upper part) of the V-VII category in drillability with interlayers of siliceous and dolomitized limestones with a thickness of no more than 0.5 m each IX- X categories (according to Protodyakonov classification).

The tests were carried out while drilling wells using the hydrodynamic method and rotary drilling was carried out to compare the data in similar geological and technical conditions. The drilling was carried out using an IBA15V drilling rig and an IIGR mud pump with an electric drive. Drill pipes with a diameter of 73 mm sleeve-and-tool joints, heavy weight drill pipes with a diameter of 146 mm and three-ball bits of the "K" type with a diameter of 190 mm were included in the drill string. The experimental model of a hydrodynamic (cavitation) vibrator was built into the central bore of the bit and was closed from above with drill pipes.

The drilling fluid used was water, which was not purified specially.

Technical characteristics of the BSKG-190 hydrodynamic drill string are:

- tube outer diameter is of 73 mm;
- the generator length is 400 mm;
- the diameter of the critical section of the generator is 6 mm;
- generator feed pressure is changed from 1 to 4 MPa;
- the flow rate of the working fluid is from 140 to 260 *l*/min;
- the drill bit rotational speed is 245 rpm.

To determine the effectiveness of the use of experimental hydrovibrator samples, the two wells with a depth of 60 m were drilled by the hydrodynamic method (with the cavitation hydrovibrator) and one well of the same depth by the rotary method (without the cavitation hydrovibrator) in the same area. The axial static load to drill string structure along the compared intervals of depths was identical for both methods and increased with increasing well depths.

The results of a comparative analysis of drilling the hydrogeological well with the diameter of 190 mm by rotary and hydrodynamic methods are given in **Table 2**.

As can be seen from the Table, during the hydrodynamic drill operation, the average increase in ROP reaches 71.5%, compared to the rotary drilling ROP. At the same time, there was a decrease in the wear of drill bits and energy consumption by up to 30%.

According to the research results, it was found that the highest dynamic loads on the bit produced by the hydraulic vibrator are within the range of $0.2 < \tau < 0.5$.

Taking into account the obtained test data, the hydrodynamic drill string was finalized and the experimental sample with the cavitation generator throat diameter of 8 mm was manufactured. Experimental works on the construction of hydrogeological wells with the diameter of 190 mm and the depth of 300 m at a flow rate of flushing fluid of 300 *l*/min and at a pressure of up to 3.0 MPa confirmed that hydrodynamic drill strings are an effective means of increasing the ROP in middle and high strength rocks using serial drilling equipment and tools.

Depth drilling intervals, m	Drilling methods	Time, hour	ROP, m per hour	Increase in ROP, %
10÷23.7	rotary hydrodynamic	0.69 0.36	4.42 9.72	119.9
23.5÷26.2	rotary hydrodynamic	0.22 0.12	9.54 16.67	74.0
25.5÷32.0	rotary hydrodynamic	0.99 0.69	6.69 9.42	40.8
32.0÷35.5	rotary hydrodynamic	0.72 0.6	3.56 5.83	63.8
49.75÷53.55	rotary hydrodynamic	0.47 0.3	5.85 10.0	70.0
52.25÷60.85	rotary hydrodynamic	1.48 0.75	5.51 8.87	61.0
Average indicators	rotary hydrodynamic	4.47 2.82	5.415 8.92	71.5

Table 2.
Results of the comparative analysis of drilling the hydrogeological well with the diameter of 190 mm by rotary and hydrodynamic methods.

3. Conclusions

The sonic drilling technology with the use of a hydraulic cavitation vibrator is an effective means of increasing the penetration rate in rocks of medium and high hardness using commercial drilling equipment and drill bits.

The drilling rig with a cavitation hydraulic vibrator has a number of advantages over other known vibration drilling devices, such as ease of manufacture, the absence of moving parts and the elimination of the transfer of fluid vibrations to the mud pump, which increases its service life. In comparison with the hydraulic hammer drill, the resource of the drill string increases by 5 times, the operating time to failure by 40 times. The cost of one set of a hydraulic vibrator, according to forecast estimates, will not exceed one third of the cost of a set of hydraulic hammer machines (or resonant sonic drill heads).

The cavitation hydraulic vibrator fits organically into the rotary drilling technology, does not require any equipment modifications and allows intensifying the drilling processes at lower specific energy consumption compared to traditional drilling technologies.

Analysis of the results of theoretical and experimental research of the drilling with the cavitation hydraulic vibrator, allows us to draw the following conclusions:

- for borehole drilling in medium and hard rocks using hydrodynamic drilling tools operating in the mode of intermittent-stall cavitation with the fluid pressure oscillations frequency of more than 200 Hz, the increase in the ROP of the exploration wells with the diameters of 76 mm is from 30–50% and for the hydrogeological wells with a diameter of 190 mm is up to 70%,

- the decrease in energy consumption by 25-30% and wear of rock cutting tools by 15-20% was obtained in comparison with traditional drilling methods;

- the drill bit vibrational modes with the basic frequency of cavitation oscillations (rational to achieve the maximum ROP of hard rocks, i.e. from 1.2 kHz to 1.4 kHz) are achieved in the range of values of the cavitation parameter τ from 0.41 to 0.43.

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