AADE-05-NTCE-26

High-frequency downhole hydrovibrator for enhancing the effectiveness of drilling in hard and super hard formations

V.V.Pylypenko, I.K.Manko, L.G.Zapol'sky, S.I.Dolgopolov, O.D.Nikolayev

Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the National Space Agency of Ukraine

This paper was prepared for presentation at the AADE 2005 National Technical Conference and Exhibition, held at the Wyndam Greenspoint in Houston, Texas, April 5-7, 2005 This conference was sponsored by the Houston Chapter of the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individuals listed as author/s of this work.

Abstract

The extremely harsh conditions during drilling in hard and super hard formations and its cost call for novel drilling techniques featuring higher effectiveness and reliability. For this purpose, a cavitation hydrovibrator for imposing high-frequency impact loading at the bit-rock interface has been developed and studied. The hydrovibrator is of a radically new design; it has no moving or rotating parts and requires no special energy supply.

The experimental prototype hydrovibrators, which differ by the expense of washing liquid was conducted, were tested on a hydraulic bench in the range of drilling mud flow rates required for bottom hole cleaning when drilling boreholes 36 mm to 250 mm in diameter, the hydrovibrator inlet pressure lying in the range 11 to 301 bars. In this range of operating conditions, fluid pressure oscillations of frequency 100 to 7,300 Hz occurred in the flow passage of the drilling assembly with different hydrovibrators. Their maximum peak-to-valley amplitude was 1.5 to 4 times as high as the steady pressure at the hydrovibrator inlet. Testing these hydrovibrators as a part of preprototype core and full-hole drilling assemblies has shown that the maximum peak-to-peak amplitude of vibration acceleration pulses on the rock-cutting tool is 50 to 15,000 times the gravitational acceleration depending on the drilling assembly design and operating conditions.

The proposed hydrovibrator provides a basis for the development of novel techniques of flush rotary-percussion drilling, which offer higher drilling rate and reduced tool wear in core and full-hole drilling of deep exploratory and oil wells.

These works are conducted within the framework of implementation of project 1132the Science and Technology Center in Ukraine (STCU). This Center has been created by Ukraine, Canada, Sweden and USA with the purpose of seeking an economically viable alternative utilization of the scientists and engineers professional knowledge related to the development and production of weapons. Collaborator on this project there was senior scientist at Brookhaven National Laboratory USA Dr. Upendra. S. Rohatgi.

Introduction

To drill deep wells through hard rocks, it is customary to use rotary diamond or hard-alloy drilling. In this case, rock destruction can be intensified by providing operating conditions such that the strength and cutting characteristics of the materials the rock cutting tool is tipped with are used most efficiently and power consumption for its wear is minimized [1]. This is achieved by setting up dynamic loads on the rock cutting tool. Both research into the application of vibration facilities to drilling and its practice show that if longitudinal vibration accelerations of required power are imparted to the rock cutting tool, the drilling process is intensified, the life of the rock cutting tool is prolonged and the energy intensity of the process is reduced [2].

Thus for many rocks the efficiency of their destruction can be substantially increased by replacing rotary drilling with vibration-rotary drilling, rotary-percussion drilling or percussion-rotary drilling [3-5]. This is especially true for brittle rocks. In the past twenty years small-size hydraulic hammers for drilling small wells 76 and 59 mm in diameter have been developed. This has made it possible to use hydro percussion drilling in combination with diamond drilling and conventional hard-alloy drilling depending on the physicomechanical properties of the rock thus opening up new avenues for increasing the efficiency of diamond drilling. However, along with considerable improvement in drilling indices, the use of hydraulic hammers involves some difficulties. Among these are operation complexity (due to the necessity of adjustment according to drilling depth), inadequate reliability (which is mainly due to the presence of moving parts, springs and rubber seals, higher wear of the pump because its hydraulic part is affected by pressure oscillations, dependence of the downhole power input and the efficiency of the machine on the parameters of hydraulic waveguide passages and low frequency of shock pulses

(20 – 70 Hz). One of the most promising ways of efficient destruction of hard rocks is vibration-rotary drilling. Its essence consists in additionally setting up high-frequency and high-intensity longitudinal vibrations on the rock cutting tool. The advantage of this method consists in the fact that it combines the advantages of vibration drilling and rotary drilling. In combined methods of rock destruction, the rock is acted upon not only by static forces, but also by dynamic shock pulses (short-time loads). Under the action of these forces, the rock not only is broken and chipped off under the rock cutting tool when struck, but also is cut off or chipped off due to the rotation and axial static loading. We propose a radically new hydrovibrator without any moving or rotating parts which will impart longitudinal vibration accelerations to the rock cutting tool using the energy of the flow of the drilling mud pumped to the borehole to remove rock chips.

Paper Headings

For a number of years the investigations on self-oscillation regimes in hydraulic systems with cavitating local hydraulic resistances have been conducted at the Institute of Technical Mechanics of NAS of Ukraine [6,7]. In studying the cavitation phenomena in local hydraulic resistances liquid flow regimes have been revealed under which in the channel of the local hydraulic resistance of the venturi - nozzle type large cavitation formations periodical nucleation and their growth to certain sizes take place. On reaching the maximum sizes in accordance with the given flow regime the cavitation formation break-off occurs that is followed by its further carry-over and collapse as a whole in a pressure zone that involves a pressure pulse in the flow. A flow regime of this kind has been called by us a "periodically stalled'' cavitation regime [6,7].

When sizeable cavities collapse in the fluid flow, extremely high pressures are generated. The pressure wave runs downstream from the collapse center to considerable distances with little or no damping (as long as 2.0 m in the experiments) while the pressure wave running upstream is damped by a new cavity that has grown by then as evidenced by the absence of oscillations at the Venturi nozzle inlet, but it takes part in the initiation of reverse flows and sets the stage for the detachment of the new cavity. In such a manner, a self-synchronizing process of cavity detachment and collapse is set up.

Thus the phenomenon of periodically detached cavitation revealed by the project team previously provides strong grounds for developing a hydrovibrator without any rotating or moving parts. The hydrovibrator will have the appearance of a part of a drill string, and its specially shaped flow passage will realize the regime of periodically detached cavitation in the drilling mud flow. It can be installed at a considerable distance from the rock cutting tool (for example, over the core barrel), and it will transform the steady-state fluid flow into a pulsating one in the frequency range ≈ 100 – 7300 Hz. The pressure oscillations will act on the part of the drill string between the hydrovibrator and the rock cutting tool thus imparting longitudinal vibrations to the rock cutting tool. The regime of periodically detached cavitation will be sustained to suit the well depth by setting up the proper pressure at the hydrovibrator inlet. Because the pressure oscillations generated in the regime of periodically detached cavitation do not propagate upstream, this will facilitate the operation of the mud pump [8].

Thus the proposed hydrovibrator will eliminate the drawbacks typical of existing hydraulic hammers and vibrators.

A pioneer theoretical study of the mechanism of transformation of fluid pressure oscillations in the flow passage of a drilling assembly into the longitudinal vibration accelerations of the rock cutting tool has been conducted. According to this study, this mechanism is attributable to the longitudinal forces that represent the force action of the oscillating fluid on the hydrovibrator drilling assembly structure as a whole. These forces are due to the longitudinal components of the pressure forces acting on the drilling assembly elements, fluid medium inertia (stemming from the acceleration of the drilling assembly structure) and fluid medium oscillations with the vibratory motion of the variable flow area elements of the drilling assembly. Besides, the longitudinal vibration accelerations of the rock cutting tool may also be responsible for the Poisson interaction between the fluid and the drilling assembly structure.

The pioneer mathematical model of the longitudinal vibrations of a drilling assembly with a high-frequency cavitation hydrovibrator without any rotating or moving parts provides not only qualitative, but also quantitative agreement between the calculated and experimental fluid pressure oscillation parameters and vibration accelerations of the drilling assembly structure at different sections thereof. According to this model, the vibratory motion of the high-frequency cavitation hydrovibrator drilling assembly structure caused by its dynamic interaction with the fluid flowing in its flow passage is described by a system of differential equations of order 830. By convention, this system can be divided into two blocks of equations.

The first block describes the vibratory motion of the drilling assembly structure, and the second block describes the oscillatory motion of the fluid in the flow passages of the hydrovibrator and drilling assembly elements downstream of the hydrovibrator under cyclic variation of the volume of the cavity in the hydrovibrator diffuser. The mathematical simulation of the system used the assumption that the drilling assembly structure executes a vibratory motion only along the axis of the fluid flow in the flow passage of the hydrovibrator, i.e., only the longitudinal vibrations of the structure were considered. This follows from the axial symmetry of the structure itself and of the forces acting on the drilling assembly structure. For convenience, a relative system of coordinates fixed to the center of mass of each structural element was used; i.e., the oscillatory motion of the fluid was assumed to be executed relative to the walls of the flow passage of the drilling assembly structure.

The system of differential equations used in the simulation of the oscillatory motion of the fluid in the diffuser of the hydrovibrator cavitator and in the hydrovibrator flow passage downstream of the diffuser is written in the variables "pressure–flow rate–cavity volume". To simulate the fluid oscillations in the drilling assembly flow passage in the frequency range 50 to 20,000 Hz to sufficient accuracy, about 220 finite elements are used.

In the mathematical model developed, the dynamic interaction between the elements of the drilling assembly and the fluid in its flow passage is accounted for by including in the equations of motion of the drilling assembly structure the force action of the pressure of the oscillating fluid on the drilling assembly walls and the inertia force of the moving fluid which arises when the drilling assembly structure executes an accelerated motion. The force action on a structural element involves the forces that are due to the product of the area times the fluid pressure at the end sections of the element and the fluid inertia forces caused by the acceleration of the drilling assembly structure and by fluid mass flow oscillations in the drilling assembly flow passage.

Fig. 1 shows the calculated time dependence of the vibration acceleration (a) and vibration speed (b) of the hydrovibrator structure (at the vibration acceleration transducer mounting section) and the volume (c) of the cavity collapsing in the flow passage of hydrovibrator E11.G.2002.01.00.00.

The quantitative analysis of the variation of these parameters in the vibratory motion of the drilling assembly may be of use when considering the features of one or other drilling assembly design with the aim to optimize the drilling process.

Thus the proposed mathematical model of the longitudinal vibrations of a drilling assembly with a high-frequency cavitation hydrovibrator provides not only qualitative, but also quantitative agreement between the calculated and experimental parameters of fluid pressure oscillations and the longitudinal vibration accelerations of the drilling assembly structure at different sections thereof.

The mathematical simulation of the "high-frequency cavitation hydrovibrator drilling assembly" dynamic system performed by this model has made it possible to compute the longitudinal stresses produced by high-frequency fluid pressure oscillations in the drilling assembly structure, in particular at a rock cutting tool section close to the rock cutting tool–rock contact zone.

The layouts of preprototype hydrovibrators without any moving or rotating parts have been designed, the geometry of the flow passages of these preprototypes has been decided on, and these flow passages have been dimensioned. Design documentation for three preprototype hydrovibrators that differ in the throat diameter of the converging-diverging section of the flow passage thus providing different fluid flow rates at the same inlet pressure has been drawn up, and these preprototypes have been made. In the inlet pressure range 11 to 301 bars, the three preprototype hydrovibrators provide drilling mud flow rates of 30 to 157 dm^3/min, 67 to 354 dm^3/min and 120 to 629 dm^3/min, respectively. These drilling mud flow rates are required in drilling boreholes of diameter 36 to 76 mm, 93 to 150 mm and 151 to 250 mm, respectively.

The preprototype hydrovibrators have a hollow body with a male metric thread cut on its both ends.

The flow passage of the cavitator is converging-diverging in shape. The throat diameter of the converging-diverging passage is rated at a specific flow rate at a steady-state inlet pressure. The inlet pipe of the converging-diverging passage is a pipe with a specific length-to-diameter ratio which serves to equalize the velocity field of the fluid flow at the inlet of the converging-diverging passage of the cavitator. Because the cavitator converging-diverging passages differ in throat diameter which governs the cavitator dimensions, the preprototype hydrovibrators differ in design only in body and inlet pipe dimensions. The structural layout of preprototype hydrovibrator is shown in Fig. 2.

The test results for preprototype indicate that a drilling hydrovibrator with throat diameter *dcr* = 4 mm in the steady inlet pressure range Đ1 = 11- 301 bars is capable of providing fluid flow rates *Q* = 30 – 157 dm3/min, respectively.

As an illustrative example, Fig. 3 shows the frequency *f* of cavitation oscillations of the pressure *P2* at the preprototype hydrovibrator outlet versus cavitation parameter τ at different pressures Đ1.

Here, the cavitation parameter τ is the ratio of the difference of the total pressure at the Venturi tube outlet and the vapor pressure to the velocity head determined by the throat velocity

$$t = \frac{P_2 - P_{cr}}{\dfrac{r\,\bar{\dot{m}}^2}{2\left(rmF_{cr}\right)^2}}, \tag{1}$$

where $\bar{\dot{m}}$ is the mass flow rate through the Venturi tube, *r* is the liquid density, *m* is the flow coefficient of the Venturi tube, F_{cr} is the throat area of the tube, P_2 is the total pressure at the tube outlet and P_{cr} is the throat pressure.

As seen from the figure, the pressure P_2 at the preprototype hydrovibrator outlet exhibits oscillations in the cavitation parameter range τ = 0.05 – 0.78. In this range of τ, the oscillations of the pressure $Đ_2$ are due to the cavity collapse, their frequency *f* lying in the range 80 to 7300 Hz. At a fixed pressure P_1 at the preprototype hydrovibrator inlet, the oscillation frequency *f* of the pressure P_2 increases with cavitation parameter τ, nearly linearly. At a fixed cavitation parameter τ the oscillation frequency f of the pressure P_2 increases with hydrovibrator inlet pressure P_1

Shown in Fig. 4 is the peak-to-valley amplitude ΔP_2 of the pressure at the preprototype hydrovibrator outlet versus cavitation parameter τ for different pressures P_1. As seen from the figure, at all values of the pressure P_1 with increasing . the peak-to-valley pressure amplitude ΔP_2 sharply increases, reaches its maximum at some value of τ and then decreases. For different values of the pressure P_1, the ΔP_2 vs. τ relationship has a maximum in the cavitation parameter range τ = 0.10 – 0.36. As the pressure P_1 increases, the maximum value of ΔP_2 shifts in the direction of decreasing cavitation parameter.

The maximum value of the peak-to-valley pressure amplitude ΔP_2 is about 1.2 – 2.18 times as high as the pressure $Ð_1$ at the preprototype hydrovibrator inlet. The ratio $\Delta Ð_2/Ð_1$ tends to decrease with increasing pressure P_1.

At the same time, throughout the entire range of the pressure P_1 the experimental dependences of the peak-to-valley pressure amplitude ΔP_2 on the cavitation parameter τ differ from those calculated.

The experimental studies conducted have shown that the fluid pressure pulses generated by the hydrovibrator impart to the hydrovibrator body longitudinal vibration accelerations propagating along the length of the structure whose amplitude depends on the hydrovibrator inlet pressure and operating conditions and can be as high as more than 15,000g. As an example, Fig. 5 shows a time oscillograms of the hydrovibrator parameters during bench tests at an inlet pressure of P_1= 101 bars.

Shown in Fig.6 the photograph of general view of experimental type hydrovibrator is resulted for the use at the vibratory-rotary drilling method in drilling deep holes 36 to 250 mm in diameter, as at the core method of the rotators drilling so at the boring drilling by a drilling bits.

The developed experimental standard of hydrovibrator has next basic performance specifications:
Borehole diameter - 36–250mm, drilling depth – 4000m, rock drill ability index -IV-XII, hydrovibrator length no more than 1000mm, mass, no more than 40kg, working substance: industrial water, clay drilling mud or emulsion drilling mud, mean life, no less than 2000h.

Conclusions

It has been shown that in the inlet pressure range 11 to 301 bars the hydrovibrators without any rotating or moving parts are capable of generating fluid pressure oscillations at the outlet in the cavitation parameter range 0.05 to 0.8. In this cavitation parameter range, the frequency of oscillations generated in the regime of periodically detached cavitation varies from 74 and 7300 Hz according to the pressure at the inlet.

The maximum peak-to-valley pressure amplitude is, depending on the inlet pressure, 1.2 to 2.72 times as high as the pressure at the hydrovibrator inlet.

Thus the operation of the cavitation generator of the hydrovibrator produces sizeable pulsed longitudinal vibration accelerations on its body which are transmitted to the rock-cutting tool with little or no decay.

This high-frequency hydrovibrator differs from conventional hydraulic hammers in that it doesn't have any rotating or moving parts. Besides, it doesn't use any additional energy sources other than the stream energy of the drilling mud pumped to the borehole for bottom hole cleaning in conventional drilling. This simplifies its design and servicing and offers far higher reliability and smaller mass and overall dimensions. All these advantages will make it possible to use the vibratory-rotary drilling method in drilling deep holes 36 to 250 mm in diameter.

This hydrovibrator may be used as a part of both core and noncore drilling assemblies. When testing preprototype drilling assemblies at a hydrovibrator inlet pressure of 10 to 301 bars, which corresponds to a drilling depth of 100 to 4,000 m, the rock cutting tool developed longitudinal vibration accelerations in the frequency range of 100 to 7,300 Hz. Depending on the inlet pressure, the vibration acceleration peak-to-peak amplitude ranged from 500 to 150,000 m/s^2. As the hydrovibrator inlet pressure increases with drilling depth, the vibration acceleration frequency and peak-to-peak amplitude will increase too.
Preliminary developmental work and drilling experience have shown that with a magnetostriction vibrator the cutting speed of vibratory-rotary roller-bit drilling is 3.2 to 4.3 times higher and the first-sharpening life of the bit is 5 to 8 times longer in comparison with rotary drilling.

Acknowledgments
V.Pilipenko - is scientific guidance by works, I.Manko - is manager of project, development of construction of hydrovibrator, S.Dolgopolov, O.Nikolayev - development of mathematical models, L.Zapol'sky - is conducting of experimental researches, development of technology of the boring drilling with hydrovibrator.

References

1. N.N.Strabikin and Ko-Tya-Khva. Intensification of rotary drilling by setting up impulse loads on the tool tip (in Russian). Mechanization of Mining. Collected volume. Kemerovo, Kuz. PTI. 1984, No 16, pp. 110-116.

2. V.G.Kardysh, A.T.Kiselev and Yu.A.Melamed. Hydropercussion drilling using roller drill bits (in Russian). Novel Facilities for Exploration Drilling. Collected volume. Leningrad, 1989, No 6, pp.91-98.

3. Yu.A.Melamed, N.V.Ilyina and A.A.Shalimov. Rotary-percussion drilling of deep wells using hogh-frequency hydraulic hammers (in Russian). Improvement and Development of Boring Tool for Advanced Drilling Methods. Collected volume. Leningrad, 1986, pp.31-45.

4. A.B.Kuleshevich, D.I.Karabash and A.P.Rep'ev. Study of the feasibility of hydraulic hammers for intensifying the drilling of hydrogeological wells (in Russian). Ibid., pp. 64-70.

5. A.AKozhevnikov and A.T.Kiselev. Theoretical estimation of the efficiency of rotary-percusion drilling (in Russian). Izvestiya Vuzov. Geologiya i Razvedka. 1989, No 3, pp.124-126.

6. On High-frequency Pressure and Flow Oscillations in a Hydraulic System past Cavitating Venturi-Tube/ V.V. Pilipenko, V.A. Zadontsev, I.K. Man'ko, N.I. Dovgot'ko// Proceedings, XIII ALL Union Meeting on Hydraulic Automation/ June 24-26, 1974, t. Kaluga/. – Kaluga: Publish. House of the – Inst. Of Contr. Probl. AS USSR, 1974, pp. 199-201. (In Russian).

7. Pilipenko V.V., Zadontsev V.A., Man'ko I.K., Dovgot'ko N.I. Studies of High-Frequency Self-Excited Oscillations in Hydraulic System With Venturi Tube / Cavitation Self-Excited Oscillations in Pump System. – Kyiv: Naukova Dumka, 1976, - p.2, p.p. 104-113. (In Russian).

8. V.V.Pilipenko, I.K.Man'ko, L.G.Zapols'ky "USE HYDRODYNAMIC CAVITATION FORINCREASE OF FFICITNCY OF PROCESS OF WELL DRILLING" CAV-2003-OS-2-3-004, Fifth International Symposium on Cavitation (CAV 2003), Osaka, Japan, November 1-4, 2003.

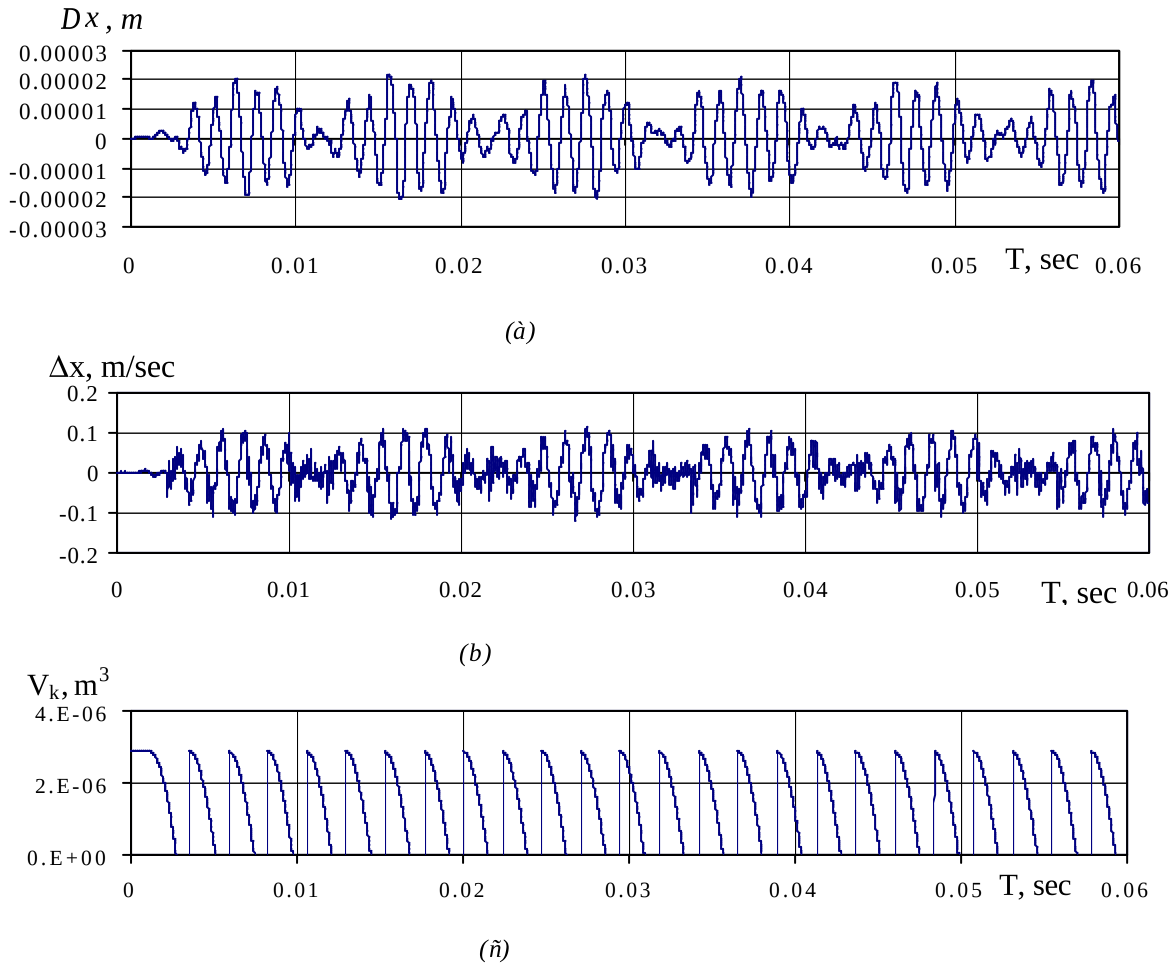

Fig. 1 - Calculated time dependence of the displacements (a), vibration accelerations (b) and cavity volume (ñ) for hydrovibrator E11.G.2002.01.00.00.

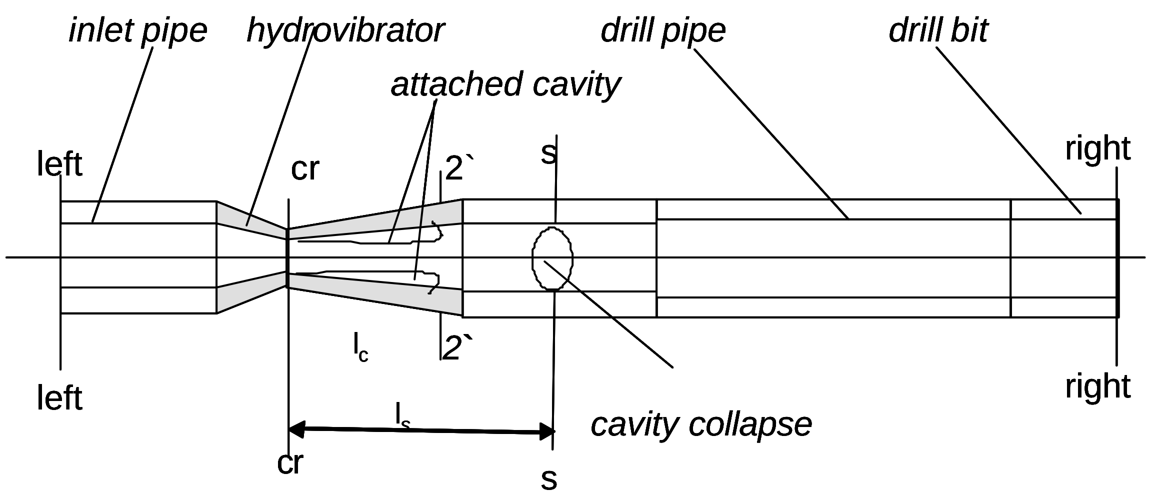

Fig.2 The structural layout of preprototype hydrovibrator.

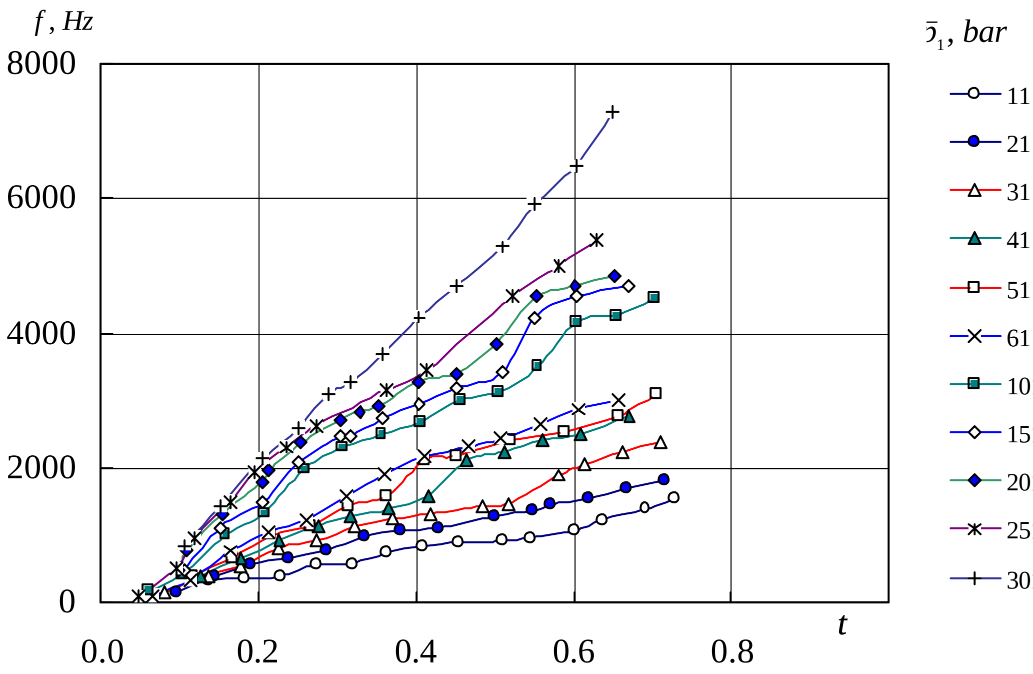

Fig. 3 Frequency *f* of cavitation oscillations of the fluid pressure P_2 at the outlet of preprototype hydrovibrator versus cavitation parameter at different values of the inlet pressure P_1

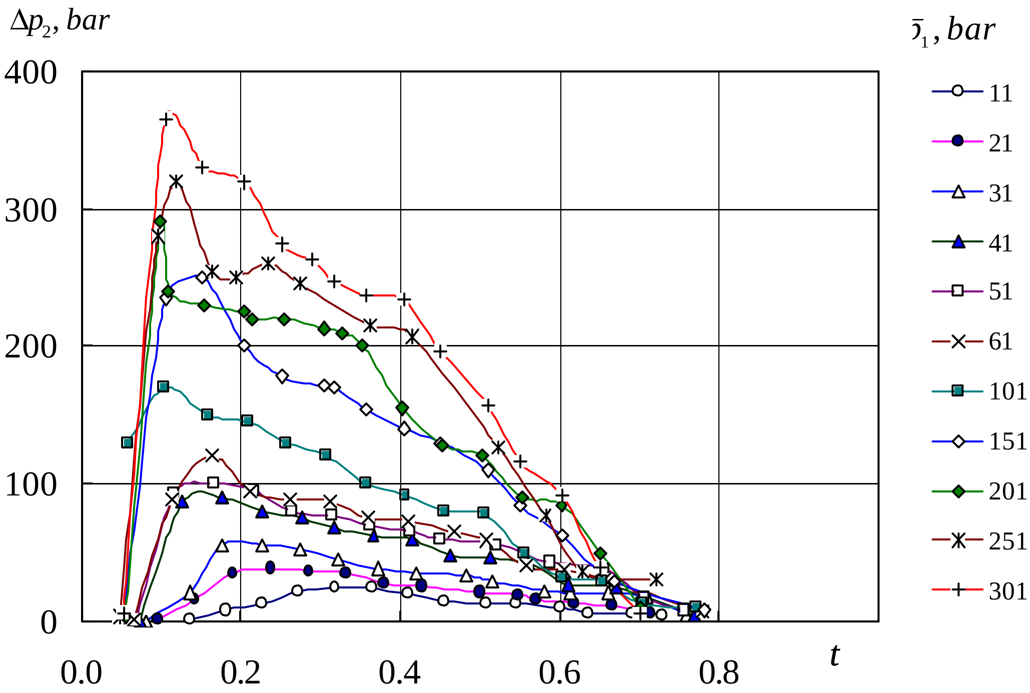

Fig. 4 Peak-to-valley amplitude DP_2 of pressure oscillations at the outlet of preprototype hydrovibrator versus cavitation parameter τ at different values of the inlet pressure P_1

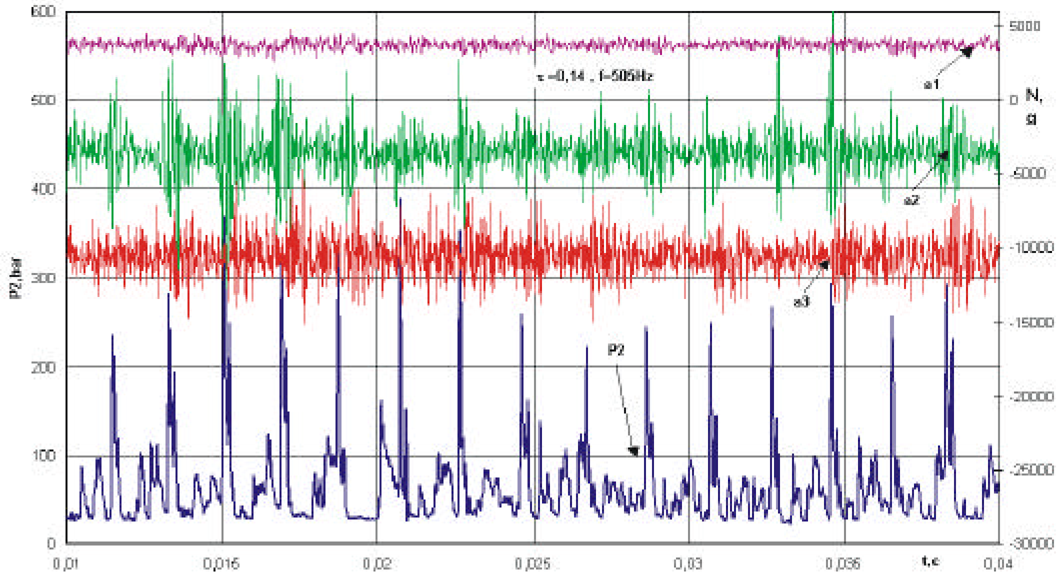

Fig.5 Fragment of a time oscillogram of the hydrovibrator parameters at an inlet pressure of P_1=101 bars and cavitation parameter τ = 0.14.
Vibration acceleration: a1– upstream of the hydrovibrator; a2– on the hydrovibrator; a3– downstream of the hydrovibrator

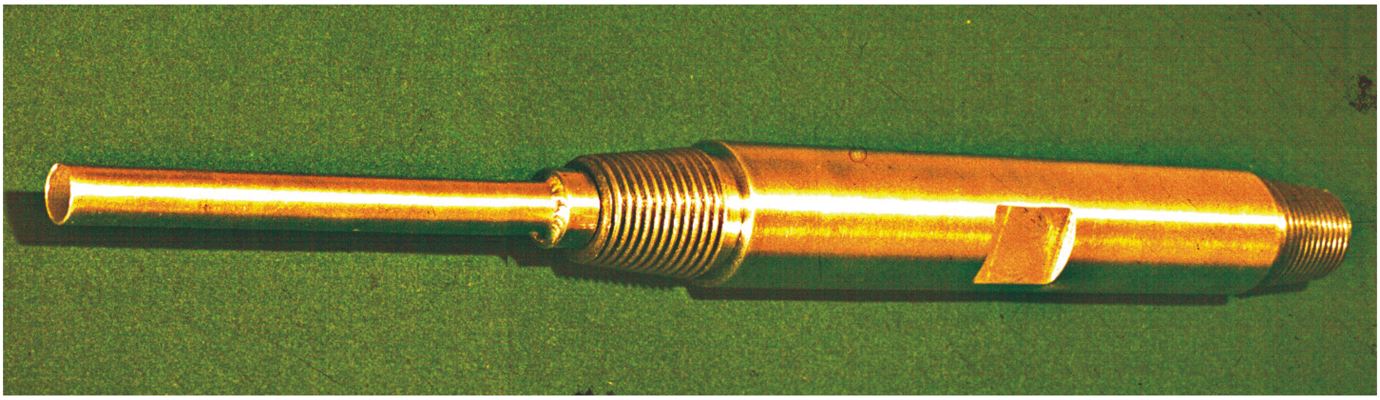

Fig.6 Photo of the high-frequency cavitation hydrovibrator