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# JUSTIFICATION OF THE PARAMETERS OF ROTARY-VIBRATION DRILLING OF SMALL-DIAMETER BOREHOLES IN ROCKS BASED ON A SUBMERSIBLE CAVITATION HYDROVIBRATOR

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**Abstract.** The article presents the results of laboratory studies of the rotary-vibration drilling method of blast-holes and boreholes of small diameter based on a submersible cavitation hydro-vibrator. A generator that operates in the mode of intermittently stalled cavitation was used as a source of vibration load to the rock-breaking tool. The authors of this article developed and described the design of a submersible cavitation hydro-vibrator at the level of the patent of Ukraine for the invention. In addition, a bench design for laboratory studies of the parameters of a rotary-vibration drilling method was developed and described at the level of a patent of Ukraine for a utility model. It is established that the optimal mode of operation of the cavitation generator is ensured by its cavitation parameter in the range of 0.16-0.2. The geometrical parameters of the cavitation generator in the submersible cavitation hydro-vibrator are determined: the diameter of the critical section is 2.0 mm, the opening angle of the diffuser is 20º, and the outlet diameter is 10.0 mm, and the length of the post-diffuser channel is 200 mm. It is established that under the action of pressure pulses of the washing liquid, which is passed through the cavitation vibrator in the optimal mode, the additional deepening of the rock-breaking tool into the rock sample reaches up to 0.6 mm per rotation. Thus, the drilling speed of small-diameter blast-holes and boreholes (up to 55 mm) with the ЕБГП-1М drilling rig of the Konotop Machine-Building Plant with the optimal mode of the rotation frequency of the rock-breaking tool, which equals 315 min$^{-1}$ (5.25 s$^{-1}$), can be increased by $3 \cdot 10^{-3}$ m/s, from $23 \cdot 10^{-3}$ m/s up to $26 \cdot 10^{-3}$ m/s, which is 13%.

**Keywords:** the rotary-vibration drilling method, cavitation generator, submersible cavitation hydro-vibrator, mining rock.

## 1. Introduction

Drilling boreholes in hard rocks brings about excessive wear of the rock-breaking tool (hereinafter the BT) and low drilling speed, which causes high financial expenses. One of the effective methods of intensifying the borehole drilling process is the transition from the rotary to the rotary vibration-loading method of drilling. But along with the significant effect on the technical performance of drilling, the widespread implementation of piston hydraulic impact tools is restrained by several disadvantages. These include the short service life of springs, rubber seals and parts submerged in water and their low reliability.

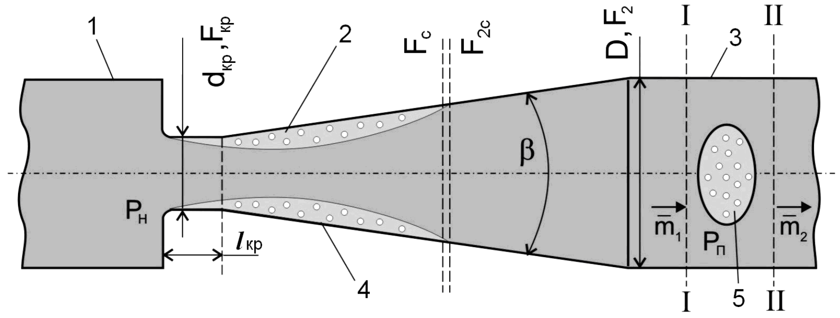
The above drawbacks can be eliminated by using a cavitation generator instead of a hydraulic impact tool, which creates longitudinal dynamic loads to the rock-breaking tool and does not have moving parts. The cavitation generator (hereinafter the GC) is a component of the rock-breaking tool. The specially profiled internal flow channel of such a generator ensures the creation of a mode of intermittently stalled cavitation with fluctuations in the flow pressure of the washing liquid (Fig. 1) [1]. The intermittently stalled cavitation mode allows turning the stationary flow of washing liquid into a pulsed one. The energy of these oscillations is transformed into longitudinal BT accelerations, which intensifies the borehole drilling process.

## 2. Methods

The subject and object of the research and their constructive development. The experimental part of the research. The object of the research is the process of rotary vibro-loading drilling of boreholes and the cinematic parameters of the rock-breaking tool of submersible cavitation hydro-vibrator (hereinafter the SCHV).

The subject of the research is a bench for determining design parameters of the rock-breaking tool of submersible cavitation hydro-vibrator.

The Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine has developed the design of the SCHV for drilling blast-holes and boreholes in hard rock (Fig.2) [2].



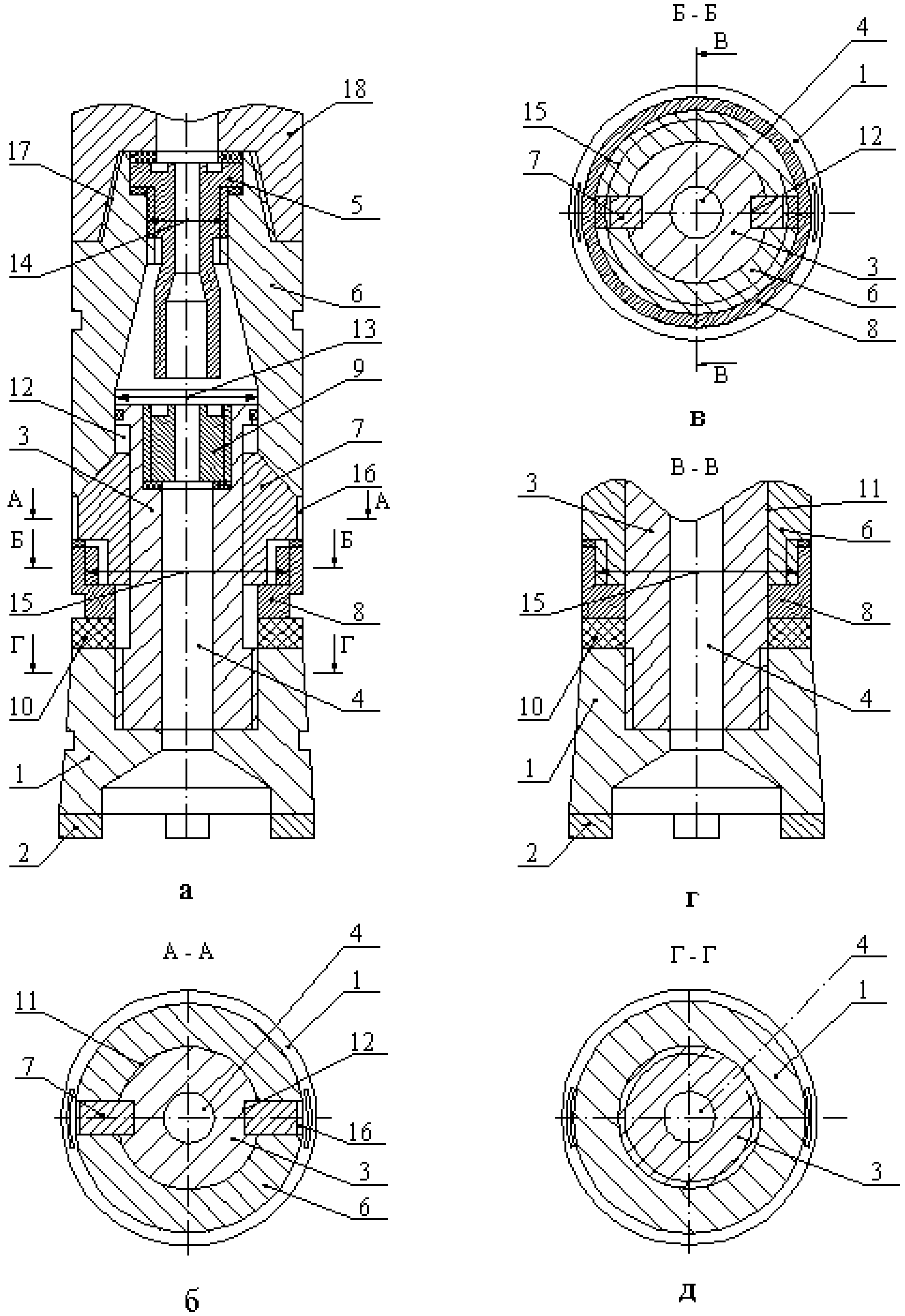

1 - inlet pipe; 2 - Venturi tube; 3 - outlet pipe; 4 - cavitation zone; 5 - part of the broke-away cavern [1]

Figure 1 – Principle scheme of GC

It consists of body 1 with the hard-alloy inserts 2 and the shank 3, where channel 4 is made for passing the flushing liquid, the GC 5, the adapter 6, the sunk keys 7 and the coupling nut 8. The bush 9 regulates the pressure of fluid circulating through the GC 5. The coupling nut 8 rests on the spring washer 10. The longitudinal diametrically opposite grooves 12 are made on the outer cylindrical surface 11 of the shank 3. The adapter 6 has an axial cylindrical through-hole of different diameters: the first 13 equals the diameter of the shank 3 and the second 14 equals the diameter of the GC 5. On the one end of the adapter 6, the thread 15 is cut, in which the diametrically opposite through windows 16 are made through a wall of the adapter 6; on the other end, the outer taper thread 17 is cut for attaching the adapter 6 to the bore rod 18. The coupling nut 8 is pushed onto the shank 3 and connected to adapter 6 by a thread. The sunk keys 7 are mounted in the grooves 12 of the shank 3 so that its windows 16 coincide with the sunk keys 7. The coupling nut 8 is connected to the adapter 6 by the thread 15 so that the sunk nuts 7 cannot move along the adapter 6. The body 1 with the shank 3 can move axially relative to the adapter 6 along the sunk keys 7, located in the grooves 12 of the shank 3 and fixed in the windows 16 of the adapter 6. The GC 5 is rigidly attached to the corresponding through-hole 14 of the adapter 6, and bush 9 is secured in the channel 4 of the shank 3.

The SCHV for drilling blast-holes and borehole operates as follows.

The assembled SCHV is screwed to the bore rod 18 by the taper thread 17 and is advanced towards a borehole bottom till the contact of its hard-alloy inserts 2 with a bottom-hole with the pressing force. For example, for the cutter's diameter of 45 mm, such as the РУ-45 type, the pressing force equals 3.5–4.0 kN. Then a flushing liquid (for example, purified mine water) under pressure (for example, 15.0 MPa) is fed through the bore rod 18. Water is passed through the GC 5. The GC 5 has an inlet channel of reduced diameter, for example, 2.5 mm, and an outlet channel of the bore rod is 18–30.0 mm. In the inlet channel of the GC 5 the pressure of passing through it fluid drops dramatically, and when the liquid enters the diffuser of the GC 5 with an opening angle, for example, 25° then there, under the action of tensile stress, liquid dilution occurs, which results to formation of voids around admixtures – bubbles,




а - axial section, б - sectional view in a plane А-А, в - sectional view in a plane Б-Б,
г - sectional view in a plane В-В, д - sectional view in a plane Г-Г [2]

Figure 2 – The principle scheme of submersible cavitation hydro-vibrator

filled with liquid vapour and gas dissolved in it. Further, the bubbles enter the post-diffuser cylindrical channel of the GC 5 with a diameter, for example, 10.0 mm, where they reach a critical size. Then, while leaving the post-diffuser channel, the bubbles slam and throw micro-streams of the gas-vapour mixture at the pressure of about $10^3$ MPa and the frequency from $10^3$ to $5 \cdot 10^3$ Hz. Under such pressure, the gas-vapour mixture acts on the butt of the shank 3 and forces it to move together with the body 1 along the sunk keys 7 in the direction of drilling.

Simultaneously with the feeding of flushing liquid, torque is being applied to the body 1 by the means of the bore rod 18 through the adapter 6, the sunk keys 7 and the shank 3. Under the action of the axial force of the rod 18, the torque applied to it and the vibro-loading from the action of the gas-vapour mixture on the shank 3 hard-alloy inserts 2 are cutting the mining rock and penetrating into a borehole bottom as well.

The axial force of the rod 18 and its torque are acting constantly, but the gas-vapour mixture can act on the shank 3 with different oscillation frequencies and amplitudes of pressure, depending on the pressure of the circulated liquid at the entrance to the GC 5 and the exit from it. At the inlet of the GC 5 the pressure of circulated liquid is controlled by the starting equipment of a high-pressure installation, and at the exit of the GC 5 the boost pressure is regulated by the use of the bush 9 with a corresponding passing diameter. The fluid passed through the GC 5 and through the bush 9 along the pass channel 4 of the shank 3 gets into the borehole bottom and washes out the broken pieces of rock via the gap between the wall of the borehole and bore rod 18.

Thus, the washing liquid, being passed through the GC 5, creates a hydraulic vibro-loading to the cutter.

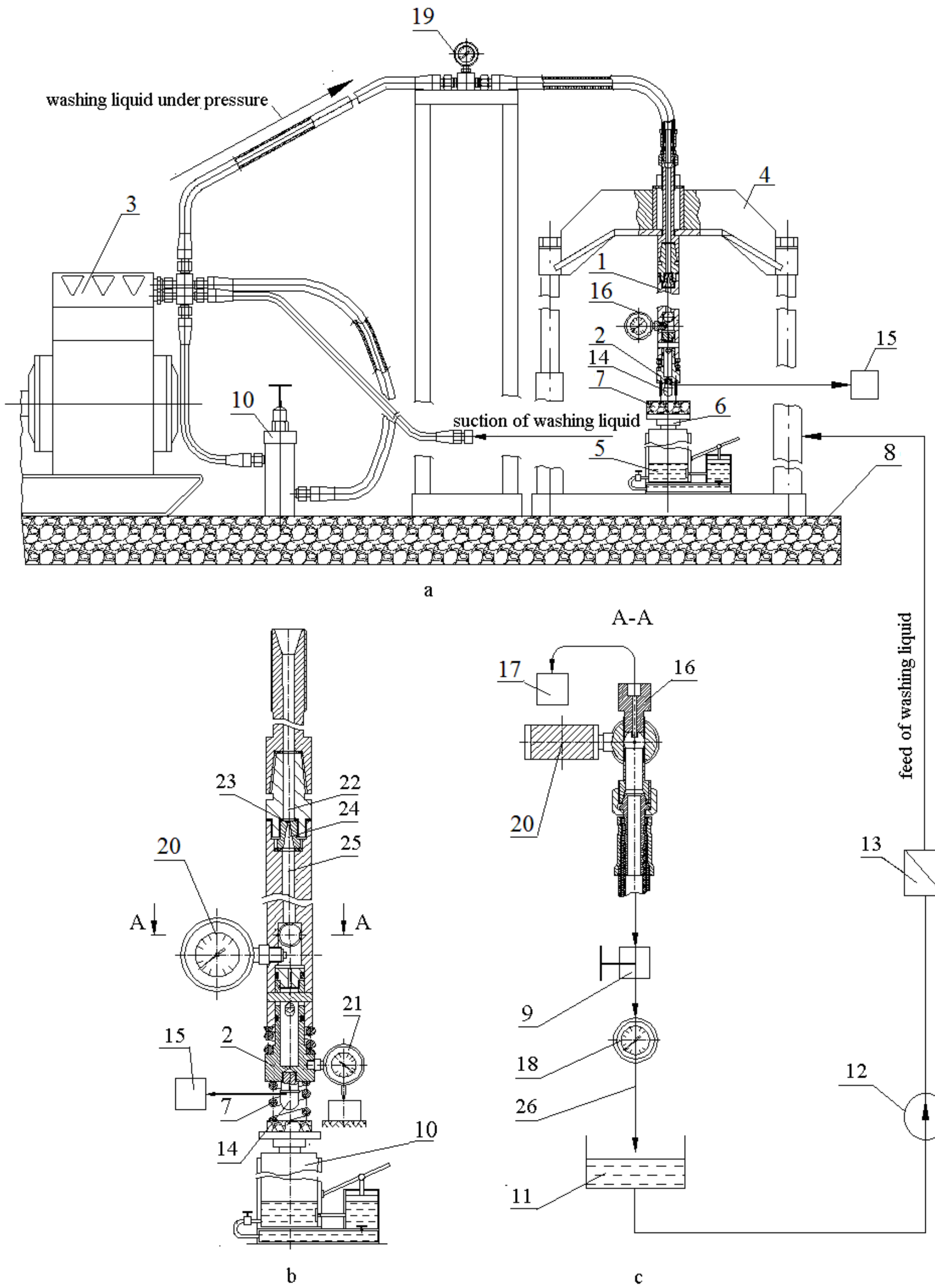
Authors of this article designed and made the test bench for determining parameters of the rotary vibro-loading method of drilling boreholes in hard rock by using the experimental sample of a submersible cavitation hydro-vibrator (Fig. 3) [3, 4].

The test bench consists of SCHV 1 with the rock-breaking tool 2; the high-pressure pump hydraulic installation 3; the rigid rectangular frame 4; the hydro-jack 5 with the piston rod 6 for pressing rock-breaking tool 2 to the sample of mining rock 7 (a support spring to return the rock-breaking tool to its initial position was used as a rock sample); the foundation 8; the regulator 9 (needle valve) of cavitation process mode of SCHV 1; the flow regulator of flushing fluid 10, fed to SCHV 1; tank 11 for collecting flushing liquid; low-pressure hydraulic pump 12 and filter 13.

The test bench is equipped with measuring equipment: the piezoelectric accelerometer 14; the indicator of vibration hydro-loading 15 to the rock-breaking tool 2; the sensor of pressure pulses of circulating fluid 16; personal computer 17 for processing signals from sensor 16; flow meter of flushing fluid 18; the manometers of visual supervision 19 and 20; the depth indicator 21.

The washing liquid is fed under pressure to the experimental sample of SCHV 1. It goes through inlet channel 22 (confuser), narrowed channel 23, expending channel 24 (diffuser), after-diffuser channel 25 and the drain pipe 26 into the tank 11.

The research was carried out on the bench (Fig. 4) with using the rock-breaking tool in the SCHV with a critical diameter of 2.0 mm and cavitation parameter 0.2 (optimal). The bench includes a high-pressure hydraulic installation УН-35 with a flow rate of washing liquid of $0.42 \cdot 10^{-3}$ $m^3/c$, $0.5 \cdot 10^{-3}$ $m^3/c$ and $0.58 \cdot 10^{-3}$ $m^3/c$ and a tared spring with compressive forces from 0 N to 12500 N, a hydraulic jack 10 and a depth indicator 8 with a scale division value 0.01 mm.




a - general view of the bench; b - axial section of the SCHV; c - sectional view in a plane A-A

Figure 3 – The functional scheme of the bench for determination of parameters of vibration hydro-loading to the sample of rock by the SCHV

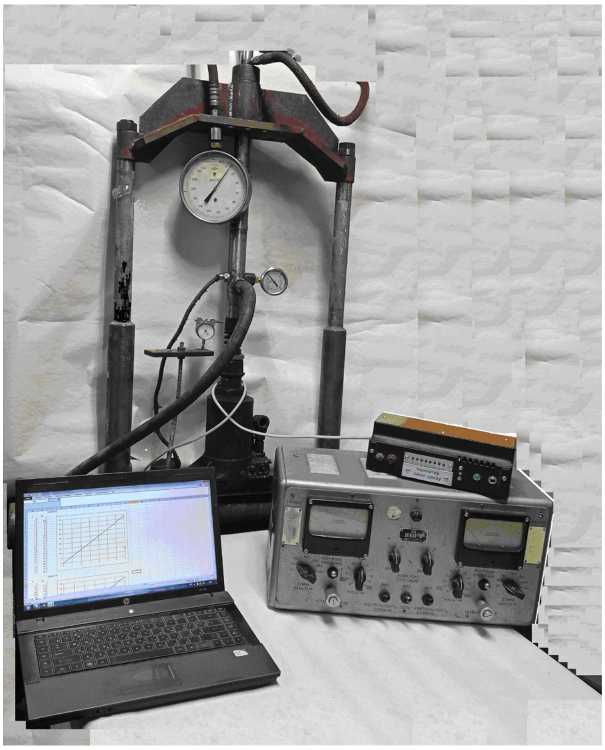


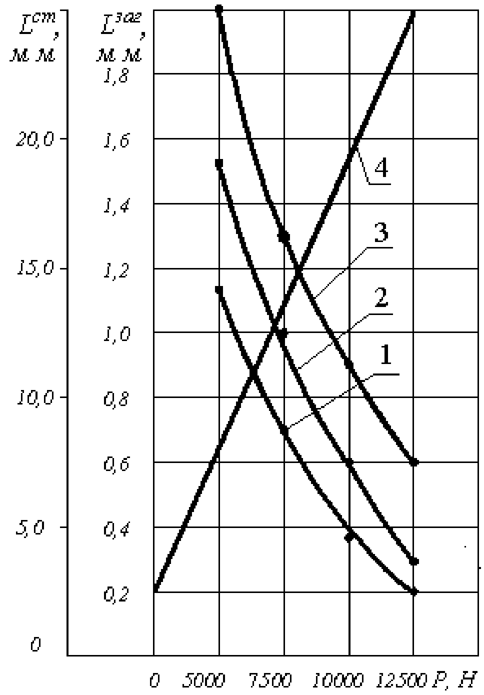
Figure 4 – General view of the bench for determination of parameters of vibration hydro-loading to a rock sample by the SCHV

Figure 5 shows the experimental dependences of the depth of penetration of the rock-breaking tool on the operating mode of the SCHV and the calibration dependence of the compression of the support spring. Curves 1, 2, and 3 have a steeply decreasing shape in terms of pressing forces and the consumption of washing liquid passed through the SCHV.

In advance, physical and mechanical properties of the mining rocks were studied in the laboratory of the Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine according to the known methods [5].

## 3. Results and discussion

The results of the study show that at low flow rates of washing liquid ($0.42 \cdot 10^{-3}$ $m^3/s$ and $0.5 \cdot 10^{-3}$ $m^3/s$), the parameters of the depth are insignificant at the optimal pressure of 12500 N of the rock-breaking tool against the rock sample, (respectively 0.2 and 0.3 mm). Such figures cannot significantly affect the destruction of the rock at the bottom of the blast-hole or borehole. But with the consumption of washing fluid of $0.58 \cdot 10^{-3}$ $m^3/s$, the depth of penetration of the rock-breaking tool reaches 0.6 mm per revolution, which can significantly intensify the drilling process. The calculation shows that with a force of 12500 N pressing the rock-breaking tool to the rock sample and a rotation frequency of 315 $min^{-1}$ (5.25 $s^{-1}$) (correspond to the technical parameters of the ЕБГП-1М drilling machine, serially produced by the Konotop Machine-Building Plant), an additional deepening of the rock-breaking tool by 0.6 mm ($6 \cdot 10^{-4}$ m) per each revolution causes the increase of the drilling speed by $3 \cdot 10^{-3}$ m/s (from $23 \cdot 10^{-3}$ m/s to $26 \cdot 10^{-3}$ m/s), which is 13%.




Curves 1, 2 and 3 correspond to different flow rate of washing liquid:
1– $0.42 \cdot 10^{-3}$ $m^3/s$; 2 – $0.5 \cdot 10^{-3}$ $m^3/s$; 3 – $0.58 \cdot 10^{-3}$ $m^3/s$. Curve 4 – calibration dependence of the compression of the support spring to determine the deepening of GV

Figure 5 – Experimental dependences of the level of the rock-breaking tool on the pressure to GV depending on the operating mode of the SCHV with high-pressure hydraulic installation УН-35 at the constant cavitation parameter of GV 0.2.

**Development of a mathematical model of rotary vibration drilling of small-diameter boreholes in rock based on the SCHV.**

As it is mentioned above, the domestic machine-building plant (Konotop city) serially produces a rotary drilling rig ЕБГП-1М, the technical characteristics of which are listed in Table 1.

Table 1 – The technical characteristics of the drilling rig ЕБГП-1М

| Key parameters | Parameters value |
|---|---|
| Rated power, kW | 2.5 |
| Feed force, N | 10000 - 12500 |
| Depth of feed, m (no more) | 2.2 |
| Speed of feed, m/s | 0 -1.4 |
| Reverse speed, m/s | 5.0 |
| Power consumption, kW | 5.2 |
| Rated consumption voltage, V | 380/660 |
| Rated frequency, Hz | 50 |
| Rotation frequency, $min^{-1}$ | 315 |
| Mass, kg | 130 |
| Rated diameter of boreholes, mm | 50 |

The mathematical model for calculating the speed of the rotary-vibration loading method of drilling small-diameter boreholes (up to 55 mm) with using a submersible cavitation hydro-vibrator can be determined by the formula:

$$V_{dr} = V_r + L_{pen} \cdot n, \quad (1)$$

where $V_{dr}$ – drilling speed, m/s, $V_r$ – rated speed of drilling rig feed, m/s, $L_{pen}$ – the depth of the rock-breaking tool penetration into mining rock with the feed (Table 1), m, $n$ – rated frequency of rotation of the rock-breaking tool of the drilling rig ЕБГП-1М (Table 1), $s^{-1}$.

The results of the bench tests indicate that the depth of penetration into the rock of the rock-breaking tool with the use of SCHV at the force of 12500 N equals 0.6 mm ($6 \cdot 10^{-4}$ m). Furthermore, with the rated rotation frequency of rotation of the rock-breaking tool of the ЕБГП-1М drilling machine (Table 1) 315 $min^{-1}$ (5.25 $s^{-1}$), the drilling speed can increase by $3 \cdot 10^{-3}$ m/s (from $23 \cdot 10^{-3}$ m/s to $26 \cdot 10^{-3}$ m/s), which is use of SCHV according to bench studies (Fig. 5) with rated feed force of the drilling rig ЕБГП-1М 13%.

**The determination of the main parameters of rotary-percussive drilling of small-diameter boreholes in rock based on SCHV.**

Based on experimental works, the following parameters of the experimental sample of the submersible cavitation hydro-vibrator are determined. Geometric parameters: outer diameter of the adapter is 35.0 mm, the inner diameter of the adapter is 25.0 mm, the outer diameter of the rock-breaking tool is 45.0 mm, the outer diameter of the shank of the rock-breaking tool is 25.0 mm. Hydraulic parameters: the diameter of the critical section $d_{cr}$ = 2.0 mm, the opening angle of the diffuser α = 20º, the diameters of the post-diffuser channel $D$ = 5 mm, $d_{cr}$ = 10 mm, the length of the post-diffuser channel $L$ = 20D. Mechanical parameters: feed force is more than 5000 N and the consumption of washing liquid is 0.58·10-3 $m^3$/s.

## 4. Conclusions

Based on the research results it can be concluded that using the cavitation generator in a submersible cavitation hydro-vibrator is reasonable and can be proposed for implementation in the mining industry. The speed of rock drilling at the bottom of a blast-hole or borehole increases by 13% with the following parameters of cavitation generator in submersible cavitation hydro-vibrator: the critical diameter $d_{cr}$ = 2.0 mm, the opening angle of the diffuser α = 20º, cavitation parameter is 0.2, the after-diffuser channel length $L$= 200 mm and the use of a hydraulic high-pressure installation УН-35 with consumption of washing liquid of $0.58 \cdot 10^{-3}$ $m^3$/s.

**REFERENCES**

1. Pilipenko, V.V., Man'ko, I.K. and Zadontsev, V.A. (1998), "Cavitation self-oscillations intensify technological processes", Proceedings of a Fluid Dynamics Panel Workshop, Kiev, Ukraine, Report 827, pp. 1-4.

2. Vasilyev, L.M., Trohimets, N.Ya. and Maltseva, V.Ye, M.S. Poljakov Institute of Geotechnical Mechanics under NAS of Ukraine (2017), Rizets kavitatsiyniy dlya obertal'nogo burinnya shpuriv abo sverdlovyn u girs'kykh porodakh serednyoy mitsosti [Cavitation cutter for rotary drilling of boreholes or wells in rocks of medium strength], State Register of Patents of Ukraine, Kiev, UA,

Pat. № 115203.

3. Maltseva, V.Ye, Ukolova, T.M., and Antonchik, V.Ye. M.S. Poljakov Institute of Geotechnical Mechanics under NAS of Ukraine (2019), Stend dlya vyznachennya parametriv vibrohidronavantazhennya na zrazok girs'koyi porody porodoruynivnym instrumentom zanuryuval'noho kavitatsiynoho gidroudarnyka [Stand for determining the parameters of the vibrohydroload like a rock rock-destroying tool immersion cavitation hydrodrummer], State Register of Patents of Ukraine, Kiev, UA, Pat. № 131902.

4. Zhulay, Yu.A. (2006), "Hydrodynamic cavitation in industrial technologies", *Geotekhnicheskaya Mekhanika* [Geo-Technical Mechanics], no. 64, pp. 142-149.

5. Mineev, S.P. (2009), *Svoystva gazonasyshchennogo uglya* [Properties of Gas-saturated Coal], NMU, Dnepropetrovsk, Ukraine.

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## ОБГРУНТУВАННЯ ПАРАМЕТРІВ ОБЕРТАЛЬНО-ВІБРОНАВАНТАЖНОГО БУРІННЯ СВЕРДЛОВИН МАЛОГО ДІАМЕТРУ В ГІРСЬКИХ ПОРОДАХ НА ОСНОВІ ЗАНУРЮВАЛЬНОГО КАВІТАЦІЙНОГО ГІДРОВІБРАТОРА

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**Анотація.** В статті наведено результати лабораторних досліджень обертально-вібронавантажного способу буріння шпурів або свердловин малого діаметра на основі занурювального кавітаційного гідровібратора (далі ЗКГВ). В якості джерела вібронавантаження на породоруйнівний інструмент (далі ПІ) використано генератор, що працює в режимі періодично-зривної кавітації (далі ГК). Авторами статті на рівні патента України на винахід розроблена і описана конструкція ЗКГВ. На рівні патента України на корисну модель розроблена і описана конструкція стенда для проведення лабораторніх досліджень параметрів обертально-вібронавантажного способу буріння. Встановлено, що оптимальний режим роботи ГК забезпечується параметром його кавітації, рівним 0,16 - 0,2. Визначені геометричні параметри ГК в ЗКГВ: діаметр критичного перетину – 2,0 мм, кут розкриття дифузора - 20$^o$, вихідний діаметр – 10,0 мм, довжина післядифузорного каналу – 200 мм. Встановлено, що під дією імпульсів тиску промивної рідини, яку пропускають через ГК в оптимальному режимі, додаткове заглиблення ПІ в зразок гірської породи за один оберт досягає до 0,6 мм, що при частоті обертів ПІ в оптимальному режимі бурового станка ЕБГП–1М конструкції Конотопського машинобудівного заводу, яка дорівнює 315 хв$^{-1}$ (5,25 с$^{-1}$), швидкість буріння шпурів або свердловин малого діаметра (до 55 мм) може підвищитися на $3\cdot10^{-3}$ м / с з $23\cdot10^{-3}$ м / с до $26\cdot10^{-3}$ м / с, що складає 13%.

**Ключові слова:** обертально-вібронавантажний спосіб буріння, генератор кавітації, занурювальний кавітаційний гідровібратор, гірські породи.

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