Experimental study of pneumatic impact mechanism with three pneumatic chambers

YuV Vanag\textsuperscript{1,2}

\textsuperscript{1}Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
\textsuperscript{2}Novosibirsk State Technical University, Novosibirsk, Russia

E-mail: yuliya.vanag@corp.nstu.ru

Abstract. The problems of preserving the performance of pneumatic impact machines while reducing their weight and dimensions for carrying out the construction works in a confined space were considered. The results of calculating the dynamics of two variants of impact devices with two and three pneumatic chambers were presented. It was shown the reserve for increasing the impact power is a raise the frequency of impacts due to more number of pneumatic chambers at the same radial dimensions and threshold impact energy of the impact devices under consideration.

1. Introduction

The operation of mining, oil and gas factories is linked with the construction and reconstruction of industrial and civil facilities for various purposes, pipeline and communications, which requires a complex of special construction work. The list of such works includes trenchless pipelaying, strengthening the slopes of foundation pits and embankments, the construction of retaining walls and screens, the formation of pales for the foundations of buildings, supports of bridges, overpasses, and power lines. At the same time, technologies based on the boring of horizontal and vertical wells, and percussion immersion of metal profiles into the ground have become widespread [1].

A significant part of construction work associated with the immersion of metal elements in the ground in the existing part of urban development is carried out in cramped conditions or conditions of limited technological space [2]. These include hard-to-reach places of the construction site, work in close proximity to existing buildings and structures, as well as in their basements, where the use of lifting equipment is difficult or impossible. When choosing equipment for the implementation of such works, preference is given to Russian or foreign pneumatic impact machines, for example, pneumatic punches \textit{Grundomat}, IP4605, SO144 or pneumatic hammer “\textit{Taifun}” [3–5].

There are known designs of annular down-the-hole hammer (DTH-hammers) with two and three pneumatic chambers in the air distribution system [6, 7]. They are distinguished by the presence in the design of a through axial channel that together with the inner pipe of a double drill string, forms an exhaust tract, which is simultaneously a pneumatic transport line for carrying out particles of destroyed rock and minerals. The annular DTH-hammers with three pneumatic chambers for driving rod elements into the ground are successfully used [8]. They have a radial compressed air supply and a through axial channel to accommodate the submerged element, and are also equipped with a clamping mechanism through which the impact is transmitted to the rod element through its lateral surface (non-end impact).
2. Theory
A prerequisite for the movement of the submerged element in the soil mass is the achievement by the machines used of the required threshold value of impact energy $E$ [9]. If this does not happen, then a failure occurs due to the impossibility of destroying the internal bonds between soil particles and overcoming the forces of frontal and side resistance. With limited weight and size parameters of impact devices, the preservation of impact power $P$ is carried out by increasing the impacts frequency $f$ [10] and simultaneously reducing the impacts energy and displacement per impact [8]:

$$P = E \cdot f$$

At present, the most widespread machines are machines with a valveless air distribution system and two pneumatic chambers [11, 12] due to their reliability. They are consist of (Figure 1): controlled $F$ (back stroke chamber – BSCh) and uncontrolled $B$ (forward stroke chamber – FSCh) chamber. The peculiarity of such machines is that the intake and the compressed air is exhausted from the controlled chamber $F$ into the chamber $G$ with atmospheric pressure through the channel $H$. The pneumatic punches have such scheme.

An analysis of the dependences of the main parameters shows that an increase in the impact frequency $f$ in the pneumatic impact mechanism scheme occurs due to a decrease in the operating cycle time $T$

$$f = \frac{1}{T}.$$ (1)

Cycle time $T$ is the sum of the forward $t_1$ and back $t_2$ of the striker stroke

$$T = t_1 + t_2.$$ (2)

It follows from expression (3) that in order to reduce the working cycle time, it is necessary to reduce the time of movement of the striker during its back stroke. Reducing the acceleration time on a straight course is possible with an increase in the pre-impact speed of the $v_y$ due to an increase in the cross-sectional area of the striker, which is under pressure on the working stroke. In turn, the reduction in the movement time of the striker during its back stroke is provided by an air cushion that creates back pressure from the side of the forward chamber, which is also associated with the cross-sectional area under pressure, and within the framework of a scheme with one controlled chamber is unattainable. In this case, the equation of motion of the striker has the following form [8]:

$$\frac{dE}{dx} - p_1S_1 + p_2S_2 - mg \sin \Theta = 0,$$ (3)

where $E$ – kinetic energy of striker, $J$; $x$ – displacement of striker, m; $m$ – mass of striker, kg; $g$ – gravity acceleration, $m/s^2$; $p_1, p_2$ – excess air pressures, respectively, in the back stroke and forward stroke chambers of the pneumatic punch, MPa; $S_1, S_2$ – areas of the striker, respectively, from the...
back stroke and forward stroke chambers, $m^2$; $\Theta$ – angle of inclination of pneumatic hummer to the horizon.

It follows from Eq. (4) that at the threshold value of the impact energy, the ratio of the areas of the forward stroke $S_2$ and back stroke $S_1$ chambers has a significant effect on the movement of striker in the forward and reverse directions, which in pneumatic impact machine takes a value from 0.4 to 0.69 [8, 12]. Therefore, in order to increase the frequency of impacts while maintaining the radial dimensions of the impact device, an additional controlled forward stroke chamber must be introduced into its design.

The constructive implementation of such an air distribution system is shown in Figure 2 [11]. Compressed air from the network through channel $A$ in tube 1 constantly enters chamber $B$ (FSCh) located in the striker 2, from where, depending on its position through the inlet channel $C$, through the grooves and $E$, it enters the controlled chamber $F$ (BSCh) or partially when the inlet channels are combined $G$ and $H$ into the annular chamber $K$ of the air cushion – an additional forward stroke chamber – (FSCh2) in the body 3. The exhaust of compressed air from chambers $F$ and $K$ is carried out alternately through the exhaust channel $L$. Changing the design of the device is possible without increasing the number of parts in it, which implies its operational reliability. At the same time, the axial supply of compressed air is retained in the design – channel $A$, and the exhaust from the controlled chambers becomes radial along channel $L$.

On the forward stroke, the entire section of the striker will be under compressed air pressure, this will reduce the forward and reverse stroke time and, accordingly, the working cycle time according to the expression

$$\frac{dE}{dx} - p_1S_1 + p_2S_2 + p_3S_3 - mg\sin\Theta = 0,$$

where $p_3$ and $S_3$ are the excess air pressure and the annular area of the striker from the side of the additional annular forward stroke chamber – FSCh2.

This scheme (Figure 2) is the basis for the development of the studied pneumatic impact mechanism for performing work in conditions of limited technological space.

### 3. Methods of the research

The purpose of mathematical simulation is to calculate the technical characteristics of both variants of impact mechanisms (Figures 1, 2), which makes it possible to compare the prospects of using schemes of impact devices for driving pipes into the ground in conditions of limited technological space. Initial data for modeling:

- $m = 4.4$ – striker mass, kg;
- $\mu = 1$ – flow coefficient;
- $k_v = 0$ – restoration coefficient of impact velocity;
- $T = 300$ – air temperature, K;
- $S_1 = 28.27 \cdot 10^{-4}$;
- $S_2 = 25.44 \cdot 10^{-4}$;
- $S_3 = 2.83 \cdot 10^{-4}$;
- $S_m = 2 \cdot 10^{-4}$ – chamber areas, $m^2$;
- $V_1 = 1.0 \cdot 10^{-3}$,
- $V_2 = 2.5 \cdot 10^{-3}$,
- $V_3 = 0.5 \cdot 10^{-3}$;
- $V_4 = 2.4 \cdot 10^{-3}$ – chamber volumes, $m^3$;
- $S_{12} = S_{24} = S_{a1} = S_{a3} = 3.25 \cdot 10^{-5}$ – total areas of intake and exhaust control channels, $m^2$. 

![Figure 2. Valveless pneumatic impact mechanism: 1 – tube; 2 – striker; 3 – body; A, C, H, G, L – channels; B – forward stroke chambers; F – back stroke chamber; K – an additional annular forward stroke chamber; D, E – grooves](image-url)
Taking into account the generally accepted assumptions, the working process of the pneumatic impact machine was described by a system of equations [13] reflecting the change in the movement of the impactor, pressure and temperature in the $i$-chamber of compressed air. The numerical solution of the equations was carried out in Mathcad.

When deriving dynamic equations that determine thermodynamic processes in compressed air chambers, assumptions are made that are usually used in the calculation of pneumatic systems [14]:

– technical characteristics of air-conducting chokes are perfect and their costs are assumed to be equal to one;
– the movement of the body of the impact device under the action of a single shock pulse is small to the magnitude of the stroke of the striker and it can be neglected;
– air flows through the gaps between the striker and the body, the striker and the nozzle are not taken into account;
– alignment of the air parameters in the working chambers occurs instantly;
– exchange between the air, the striker, the body and the environment (soil) during the cycle is not taken into account due to its insignificance;
– change in the speed of the striker and the body when they collide occurs instantly.

Generalized design model of impact devices are shown in Figure 3, where: 1, 2, 3 – working chambers with volumes $V_1$, $V_2$, $V_3$, accordingly, of which chambers 1 and 3 are controlled. The uncontrolled chamber 2 is constantly in communication with the compressed air line 4. The striker performs the back stroke under the action of the difference in forces arising from the air pressures on the ends of the striker from the side of the BSCh – $V_1$ and FSCh – $V_2$ chambers, the working stroke occurs under the action of the sum of forces from the air pressure in the $V_1$, $V_2$, $V_3$ chambers. Due to this, an increase in impact power can be achieved.

Figure 3. Design model of the impact mechanisms with two (a) and three (b) pneumatic chambers: 1 – back stroke chamber (BSCh); 2 – forward stroke chamber (FSCh); 3 – an additional forward stroke chamber (FSCh2); 4 – line of compressed air; $s_{1a}$, $s_{ia}$ – control channels; $a$ – atmosphere; $p_m$ – pressure in the pipeline.
To achieve the same value of the velocity of striker, the length at the inlet of BSCh was changed. Based on the simulation results, pressure diagrams in the chambers of the considered pneumatic hummer structures (Figure 4) were obtained. In the Table 1, the results of a numerical experiment were presented. Analysis of the pressure diagrams shows that in a device with three pneumatic chambers, a more intensive acceleration of the striker forward, an increase in its speed and a reduction in the cycle time is facilitated by an air cushion of compressed air in the annular forward stroke chamber 3 (Figures 3b).

Table 1. Energy indicators of pneumatic impact devices with a valveless air distribution system

| Specification                                                                 | Estimated characteristics of machines |
|------------------------------------------------------------------------------|----------------------------------------|
| Name                                                                         | 2Ch                  | 3Ch                  |
| The ratio of the areas of the forward stroke and backward stroke chambers $S_1/S_2$ | 0.5       | 1                    |
| length of working stroke $H$, m                                             | 0.067                 | 0.037                |
| Impact frequency $f$, Hz                                                    | 13.0                  | 24.8                 |
| Impact energy $E$, J                                                        | 48                    | 48                   |
| Compressed air flow rate $q$, m$^3$/J                                       | $6.5 \cdot 10^3$      | $6.7 \cdot 10^3$     |

The simulation results show that with the same impact energy in a device with two pneumatic chambers, the striker's stroke length is 1.8 times longer and, as a consequence, the frequency of impacts is 1.8 times less than in a device with three pneumatic chambers. The results of the experiment indicate that an increase in the number of pneumatic chambers allows an increase in the average speed of movement of the striker, which is necessary when developing the device for performing work in a limited technological space.

4. Conclusions

It was found that the frequency of impacts in a device with three pneumatic chambers is 1.8 times higher than in a device with two chambers while maintaining the threshold value of the impact energy. The use of the third chamber makes it possible to reduce the length and total weight of the device by reducing the working stroke of the striker by 1.8 times while maintaining the same body diameter.

Figure 4. Calculated diagrams of pressure in the chambers of pneumatic impact devices with two – 2Ch (a) and three – 3Ch (b) pneumatic chambers; $p_1$, $p_2$, $p_3$ – pressure in BSCh, FSCh and annular FSCh2

Table 1. Energy indicators of pneumatic impact devices with a valveless air distribution system

| Specification                                                                 | Estimated characteristics of machines |
|------------------------------------------------------------------------------|----------------------------------------|
| Name                                                                         | 2Ch                  | 3Ch                  |
| The ratio of the areas of the forward stroke and backward stroke chambers $S_1/S_2$ | 0.5       | 1                    |
| length of working stroke $H$, m                                             | 0.067                 | 0.037                |
| Impact frequency $f$, Hz                                                    | 13.0                  | 24.8                 |
| Impact energy $E$, J                                                        | 48                    | 48                   |
| Compressed air flow rate $q$, m$^3$/J                                       | $6.5 \cdot 10^3$      | $6.7 \cdot 10^3$     |
References

[1] Tishchenko IV and Chervov VV 2014 Influence of energy parameters of shock pulse generator on the pipe penetration velocity in soil Journal of Mining Science Vol 50 No 3 pp 491–500

[2] Sedov DS 2010 Straitened factors of development in towns in the constrained conditions Bulletin of the Moscow State University of Civil Engineering Bulletin MGSU No 4 pp 171–174

[3] Rybakov AP 2006 Fundamentals of trenchless technologies (theory and practice) Moscow Stroyizdat

[4] Kuhn G Scheuble L and Schlick H 1993 Closed laying of impassable pipelines Moscow Stroyizdat

[5] Chervov VV 2019 Application extension of pneumatic hammers with variable structure of percussion power Interexpo GEO-Siberia Vol 2 No 5 pp 103–111

[6] Zhao Z Meng Y Li Y Shi X and Xiang C 2015 Effects of Working Angle on Pneumatic Down-the-hole Hammer Drilling Rock Mech. Rock Eng. Vol 48 No 5 pp 2141–2155

[7] Petreev AM and Primychkin AY 2015 Influence of air distribution system on energy efficiency of pneumatic percussion unit of circular impact machine Journal of Mining Science Vol 51 No 3 pp 562–567

[8] Gurkov KS Klimashko VV Kostylev AD et al. 1990 Pneumatic drills Novostibirsk IGD SB AS USSR

[9] Chervov VV and Smolyanitskii BN 2004 Increase in productivity of pneumatic impact devices for trenchless underground pipeline laying Journal of Mining Science Vol 40 No 2 pp 165–172

[10] Smolyanitsky BN Tishchenko IV Chervov VV al et. 2008 Sources for productivity gain in vibro-impact driving of steel elements in soil in special construction technologies Journal Mining Science Vol 44 No 5 pp 490–496

[11] Abramenkov DE Abramenkov EA Kirillov FF and Kutumov AA 2008 Sliding cylinders of pneumatic mechanisms of impact machines: throttling, fluidic, without spool-type, valveless, combined Tomsk Tomsk State University of Architecture and Civil Engineering Publishing House

[12] Klimashko VV and Vasiliev GG 1990 Express calculation of machines for submerging of pipes, Impulse-forming machine for mining and construction works Novosibirsk IGD SB AS USSR pp 11–24

[13] Vanag YuV and Gileta VP 2009 The choice of parameters of pneumatic impact machines for driving wells in cramped conditions Fundamental problems of the formation of the technogenic geoenvironment pp 230–235

[14] Hertz EV and Kreinin GV 1975 Calculation of pneumatic drives Moscow Mechanical Engineering 272 p