Selecting parameters of air-percussion tunneling facility

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Abstract. The paper discusses vibratory displacement of two-mass vibrating system with air-powered impact force generator. In the first stage of studies, the effect of air leakage between chambers on efficiency of the impact force generator in percussion pricking and ramming, with much short travel of the body of the generator than its piston is analyzed. In the second stage, the influence of clearances on the rate of horizontal self-displacement of the vibrating system with impact force generator is examined at the proportional travels of the body and piston. The effect exerted by compressed air leaks between the work chambers in clearances of swivel joints is evaluated. The research results can be used in design of special pneumatic percussion drive for suction headers.

1. Introduction

In Russia and in the world, trenchless pipeline laying commonly uses vibarion–percussion method and air-driven machines. The process of hole-making is based on the effect of vibro-displacement of a vibrating system under asymmetrical resultant force of internal and external forces. This method needs no equipment for generation of static forces, construction of bearing walls, anchorage, etc. Air-driven machines used as generators of driving force for vibro-displacement of vibrating systems are highly reliable, small in size and allow reduced volumes of preparation, earth works, assembly and reclamation at cut down transportation expenditures [1–3].

Holes with a diameter to 300 mm are made by vibro–percussion pricking, i.e. by soil compaction. Many years-long experience shows that such holes remain stable (do not break down) for a long time (sometimes several years). This allows inserting a carrier pipe and, if necessary, casing directly after completion of hole making [2, 4].

Table 1. Specification of series-produced air hammers.

| Parameter               | IP 4605 | IP 4603 | SO 134 |
|-------------------------|---------|---------|--------|
| Length, mm              | 1500    | 1550    | 1720   |
| Diameter, mm            | 95      | 130     | 152    |
| Weight, kg              | 50      | 100     | 150    |
| Blow energy, J          | 80      | 220     | 500    |
| Blow frequency, Hz      | 5.4     | 6.2     | 4.2    |
| Rated compressed air pressure, MPa | 0.6 | 0.6 | 0.6 |
| Air flow rate, m³/s     | 0.073   | 0.088   | 0.133  |

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Holes with a diameter more than 300 m are made by ramming. In this case, a steel pipe is driven in soil by an air-powered machine and soil plug is taken out of the pipe by self-propelling suction header [1, 2]. The operating device of the suction header is a receiving or bypass core barrel, the drive unit, depending in the size of the pipe to be cleaned from soil, may be one of the series-produced air hammers: IP 4605, IP 4603 SO 134 (table 1).

The feature of the hole-making vibrating systems with the air-powered impact force generator is that these are the self-oscillating systems [5, 6]. Oscillations are sustained by the oscillating elements of the system. Vibratory displacement of such systems with air-powered impact force generators is studied insufficiently.

Compressed air leakage in clearances of swivel joints has considerable effect on vibratory displacement efficiency of oscillating systems and on parameters of the air-powered impact generators: energy $A$ and frequency $f$ of blowing, and on compressed air flow rate $Q$. In this regard, air leaks between chambers should be taken into account in calculations and design of a pneumatic–mechanical mechanism. For instance, neglected air leakage between the power and exhaust chambers in a brand-new pneumatic percussion machine—pulsator [7]—resulted in incomplete clearing of the power stroke chamber—under-exhaust—which destabilized operation of the pulsator and ended with scaling down of investigations aimed to design a very powerful and economic percussion mechanism.

2. An air-driven hammer design and work parameters

The present research focused on influence exerted by air leakage between chambers on energy efficiency of impact force generators in trenchless laying of pipes by the methods of vibropercussion pricking and ramming.

As an impact force generator, we study an air-driven hammer with valve-less air distribution and one controllable chamber. Figure 1 shows the the layout and design model of air hammer IP 4603. The impact force generator has a two-mass oscillating system: $m_1$ is a striking piston, $m_2$ is the generator body rigidly connected with the pipe or core receiver of the suction header. The piston and the body together with an air-distribution element shape the controllable (back stroke) 1, main (instroke) 2 and exhaust 3 chambers. Compressed air is fed from the feed line under pressure $p_f$ via control channels and clearances $S_{1,2}$, $S_{1,3}$, $S_{2,3}$ to the chambers and is released from them to the atmosphere $p_a$. The masses $m_1$ and $m_2$ are affected by the internal active driving forces of cyclic nature governed by the type and setting of the impact force generator. The mass $m_2$ is additionally influenced by the external friction $F_{fr}$.

![Figure 1. Two-mass self-oscillating system.](image-url)
The working chambers of the impact force generator have variable volumes due to mobility of the machine components. Air always leaks in clearances in friction pairs. Clearance is an inherent attribute of a swivel joint. The body of the air hammer is a working tool, its length is approximately 15 times its diameter (table). Clearances between the chambers 1, 2 and 3 (Figure 1) in the air hammer IP 4603 are rather large to eliminate jamming of mobile parts in case of low axial stiffness of the hammer.

The numerical analysis of the effect of air leakages between the air hammer chambers in clearances of swivel joints was implemented at the following assumptions:
— the leakages were evaluated in terms of areas of the joint clearances;
— the clearances were analyzed independently, i.e., the value of air leakage between one pair of the chambers was considered at the constant level of air leakage (areas of clearances) between the other chambers.

The calculations were carried out in two stages. In the first stage, we studied effect of clearances on the impact force generator performance in pricking and ramming. Here, the point is that travel of the hammer body is much shorter than the travel of the piston (less than 3%) [8].

Figure 2 depicts stage I modeling results of the impact force generator performance. The areas of clearances between chambers are given explanatory subscripts, e.g. \( S_{12} \) is the clearance area between the controlled 1 and the main 2 chambers.

![Figure 2](image_url)

**Figure 2.** The work parameters of impact force generator versus value of clearances between chambers.

The calculations involved dimensionless values. The main units were: \( l_e = d_M = 32 \cdot 10^{-3} \) — diameter of the air feed line, m; \( m_e = 37.5 \) — weight of piston, kg; \( S_e = S_f = 103.9 \cdot 10^{-4} \) — area of controlled chamber, m²; \( p_M = 0.7 \) — absolute feed line pressure, MPa; \( T_M = 290 \) — temperature in the main chamber, K; \( R = 8.31 \) J/(mole·K) — universal gas constant; \( t_e = \sqrt{(m_e l_e)/(S_e p_M)} \) — unit time, s; \( A_e = (p_M S_e l_e)/2 \) — unit blow energy, J; \( Q_e = (p_M S_e l_e)/(RT_M t_e) \) — unit air flow rate, kg/s; \( f = Q/(A_N q_N) \) — unit blow frequency, Hz.

It is seen in Figure 2 that the increase in the clearances between the chamber results in higher air consumption and lower blow energy within the whole range of the test parameters. The highest effect on the unit blow energy \( A_e \) and unit flow rate \( Q_e \) is exerted by the clearance \( S_{23} \) between the main and exhaust chambers. It is known that higher blow energy is the critical factor of improvement in the pipe penetration rate, i.e., in enhancement of hole-making efficiency by vibratory percussion [1, 2]. The area of the clearance \( S_{23} \) insufficiently influences the blow frequency \( f \). The influence of the clearances \( S_{12} \) and \( S_{13} \) on \( f \) of the piston is opposite.

In the second stage, we analyzed the influence of clearances on the self-displacement of the vibrating system with the impact force generator represented by the air hammer IP 4603 as well. In this case, the travels of the body and piston of the impact force generator were proportionate. The
external friction force was applied to the body (mass \( m_2 \)) and represented dry friction. The calculations were in dimensional form.

\[
D_f, \text{ m/s} = \begin{cases} 
F_{r1} = 1 \text{ kN} \\
F_{r2} = 0.75 \text{ kN} \\
F_{r3} = 0.5 \text{ kN}
\end{cases}
\]

\[
S_{13} \cdot 10^{-3}, \text{ m}^2
\]

\[
D_f, \text{ m/s} = \begin{cases} 
F_{r1} = 2 \text{ kN} \\
F_{r2} = 2.5 \text{ kN} \\
F_{r3} = 3 \text{ kN}
\end{cases}
\]

\[
S_{13} \cdot 10^{-3}, \text{ m}^2
\]

**Figure 3.** Vibratory displacement rate of impact force generator as function of clearance between working chambers.

The increase in the clearances between the chambers accelerates vibratory displacement of the two-mass system only in the field of insignificant frictions which are less than 30% of recoil of the impact force generator (Figure 3a). This is a signature of this system and is to be taken into account in design and operation of a suction header as in real-time operation, the friction force \( F_r \) of the impact force generator with pipe is low—1 kN, and the generator, instead of advancing in the pipe, will displace backward or even stop. In the field of external frictions exceeding the 30% threshold of the generator recoil, the air leaks between the chambers have insignificant influence of the penetration rate of the vibrating system (Figure 3b).

3. Conclusions

The authors have evaluated influence of compressed air leakage in clearances of swivel joints on performance of valve-less air-powered impact generator with one controlled chamber and on the vibratory displacement rate of the two-mass vibrating system.

The increase in the area of clearances between the working chambers accelerates vibratory displacement of the two-mass vibrating system in the field of insignificant frictions, which are less than 30% of recoil of the impact force generator in the real-time operating conditions. These research findings can be used in design of a special air percussion machine to drive impact force generators.

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