Effect of elastic valve characteristics on pneumatic impact ring machine capacity

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Abstract. The paper presents a case-study of the effect exerted by a ring-shaped elastic valve as a promising lock-and-control element of air distribution on the performance of a pneumatic impact ring machine. The design model of the machine is presented. The authors determine the blow energy and frequency of the machine, as well as the compressed air flow rate versus the preload of the valve and the elasticity modulus of the valve material. The recommendations on design of the elastic air distribution elements for pneumatic percussion machines subject to their operational conditions are given.

1. Introduction

Many special construction works are connected with driving of various rods of low axial stiffness in soil to serve as ground electrodes, anchors, dowel bars, probes, well points, injectors, etc. An efficient method of driving such rods in soil is ramming by portable pneumatic impact ring machines designed at the Institute of Mining, SB RAS. The advantages of this approach are high-rate mechanization, mobility, elimination of auxiliary hoisting equipment and applicability in a confined area.

Efficiency of the pneumatic impact ring machines is governed by two properties. The first is the ability to be fastened to a rod and to transfer impact load to the rod in its any cross-section, including small distances to bottom hole, which eliminates instability of the driven element. The second is the ability to move upward from the bottom hole along the rod to a new point of force application at command from an operator.

Though structurally different, the machines are functionally similar. They are composed of a pneumatic impact assembly and a clamp fixture which includes an impact load transfer unit and a recoil intake unit.

The promising route of improvement of pneumatic percussion machines is inclusion of a ring-shaped elastic lock-and-control valve in the air distribution system. The undeniable advantages of the valve are simplicity and small size. The valve can control large flow areas while performing small displacements [1].

2. Pneumatic percussion machines test results

One of the most popular models of pneumatic ring impact machines is KUM42-1K (Figure 1). It is meant for injection of soil foundations and nail reinforcement of soil slopes. The Institute of Mining, SB RAS has manufactured and sold more than a dozen of such machines under economic agreements. The machines have been operating in many regions in Russia and in Kazakhstan for more than 5 years.
As compared with the earlier modifications of the machine, model KUM42-1K is advantageous for high specific capacity, low consumption of compressed air, small weight and long service life. These advantages are governed by introduction of the ring-shaped elastic valve introduced in the machine design to control air exhaust from the backward stroke chamber.

The capacity of the machine [2, 3] depend on the effective areas of piston 1 from the sides of the power and backward stroke chambers, the front chamber volume Vo, travel l14 of the piston until opening of exhaust holes 5 in housing 2, value of the opening of channels 6 in pipe 3, as well as the opening and closure actuation times of elastic valve 4.

For the machines with an elastic element, it is important to select appropriate parameters of the elastic valve which governs the capacity and efficiency of the machine [4]. Efficiency of air distribution depends on the active forces, friction and on the elastic force conditioned by the elasticity modulus of elastomeric material and by preload of the valve on the piston.

Thus, it is required to study the effect of the preload and material properties of the valve on the impact machine capacity.

The fast and economically beneficial method of air distribution analysis in pneumatic percussion machines is computer modeling as it allows experimentation without a full-scale prototype of a machine [5–7]. The problem is that the archives of computational software products contain no structural element to simulate operation of an elastic valve.

In ITI SimulationX we constructed a model of pneumatic ring machine KUM42-1K with the elastic valve in the air distribution system (Figure 2). The model included the main parameters of the machine, namely, the volumes of the working chambers, valve timing, the weight and effective areas of the piston from the sides of the power stroke and backward stroke chambers. The built-in preliminary developed model of the elastic valve describes the valve cycle, i.e. control of the flow area depending on the pressure difference and elastic forces on the valve [6]. The valve model takes into account the action of the resultant force of air pressure (source 3), preload (source 7), maximum travel length (endStop2), friction (rigidFriction1), and elasticity modulus of material (spring2).

First, we estimated the influence of preload of the elastic valve on the pneumatic impact ring machine capacity, including the unit blow energy (A), blow frequency (n), energy source flow rate (Q) and impact power (P). The modeling results obtained with the elastic valve made of elastomeric
material with the elasticity modulus $E = 6 \text{ MPa}$ are graphically presented in Figure 3.

Modeling has found that the machine operates steadily at the elastic valve preload of less than 2%. This is explained by insufficient elastic forces for the reliable compressing of the ring-shaped element after the piston passes the exhaust holes. In this case, during the power stroke, the valve overlaps the clearance between the piston and the housing, an air cushion is generated in the backward stroke chamber, and the pre-blow velocity and, consequently, blow energy drop.

Figure 2. Design circuit of pneumatic impact ring machine KUM42-1K.

Figure 3. Blow energy $A$, blow frequency $n$, energy source flow rate $Q$ and impact power $P$ versus elastic valve preload $\varepsilon$. 
In the range of the preload from 2 to 6%, percussion machines in the rated mode, at the maximal blow energy and impact power of 171 J and 1.77 kW, respectively, at the minimal energy source flow rate of 2.5 m³/min and at the blow frequency of 10.4 Hz. When the preload is higher than 6%, the blow energy and impact power decrease while the blow frequency and air flow rate increase. The dependences of capacity characteristics on preload are sufficiently accurately approximated by linear functions:

\[
A = A_0 \left[1 - 0.03(\varepsilon - 6) \right], \\
P = P_0 \left[1 - 0.018(\varepsilon - 6) \right], \\
n = n_0 \left[1 + 0.2(\varepsilon - 6) \right], \\
Q = Q_0 \left[1 - 0.064(\varepsilon - 6) \right],
\]

where \(\varepsilon\) is the preload of ring-shaped elastic valve, \(6 \leq \varepsilon \leq 20\); \(A_0, P_0, n_0, Q_0\) are the rated values of blow energy, impact power, blow frequency and compressed air flow rate, respectively.

After increasing the preload of the elastic valve over 20%, no changes in the characteristics of the impact machine capacity are observed. In this case, the elastic forces exceed the air pressure, and no stretching of the elastic valve takes place—the machine switches to valveless mode of operation.

Thus, from the research, the preload of the ring-shaped elastic valve to ensure steady-state autooscillation regime of the pneumatic percussion assembly is \(\varepsilon = 2\)–5%. Elastomeric materials feature yielding and stress relaxation ability which range as 1–3% [9]. For this reason, in design of air distribution systems for pneumatic percussion machines with elastic valves, it is expedient to assume the valve preload in a range from 3 to 8%.

At the second research stage, we determined the influence of the valve elasticity modules on the pneumatic impact ring machine capacity in terms of the unit blow energy \(A\), blow frequency \(n\), energy source flow rate \(Q\) and impact power \(P\) versus elastomer elasticity modulus \(E\).

![Graphs showing the dependence of blow energy \(A\), blow frequency \(n\), energy source flow rate \(Q\) and impact power \(P\) on elastomer elasticity modulus \(E\).](image.png)
source flow rate $Q$, and the impact power $P$. Modeling was performed for the elastomers with the elasticity modulus from 3 to 15 MPa. The modeling results at the valve preload $\varepsilon = 5\%$ are shown in Figure 4.

This stage modeling data qualitatively agree with the first stage results, and this is valid as the elasticity forces aimed to compress the elastic valve during its operation obey the Hooke law: $F_{el} = kx$. The stiffness ratio is governed by the elasticity modulus of a material, and the preload is deformation.

Design of the air distribution systems with a ring-shaped elastic valve should ensure sufficient value of the elastic forces such that unprevent total extension of the valve in the backward stroke of the piston and ensure compression of the valve after exhaust without any air cushion risk [10].

For the test valve with a cross-section $15\times15$ mm to control compressed air exhaust in pneumatic impact ring machine KUM42-1K, the elasticity force for the steady-state operation of air distribution system should be within a range from 30 to 80 N. This is achievable through various combinations of the valve elasticity modulus and preload. However, it is difficult to vary the valve elasticity. For this reason, it is better to select a material and use its physical and mechanical properties to determine the required preload of the elastic valve for the steady-state operation of pneumatic percussion machine.

3. Conclusions
1. In design of air distribution systems of pneumatic percussion machines with elastic valves, it is advisable to set the preload of the valve in the range from 3 to 8%. It is also necessary to take into account climatic service conditions of the machines: the preload should be assumed nearer the upper limit of the range in case of high temperatures and nearer the lower limit of the range in case of low temperatures.
2. It is recommended to make elastic valves from elastomeric materials (rubber or polyurethane) with the elasticity modulus from 4 to 8 MPa, and with the stress relaxation ability not higher than 1.5%.

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