Investigation of dynamic characteristics of regenerative pneumatic drive of filling and packing machine

A N Sirotenko, V I Grishchenko, S A Partko and M S Kilina
Don State Technical University, Rostov-on-Don, Russia

Abstract. The article discusses the method of braking by back pressure of the output link of the pneumatic drive and the associated actuator. An increase in energy characteristics is achieved by accumulating compressed air in an additional volume. The mathematical model describes the braking process and includes equations of motion, pressure, and temperature. Preliminary setting of parameters of additional volume controls braking parameters. The solution of the mathematical model planned and conducted a computational experiment and obtained mathematical dependencies for the criteria of speed and energy consumption.

1. Introduction
Pneumatic actuators are widely used for equipment automation [1]. One of the features of application of pneumatic drive is instability of characteristics of its working medium. Another feature of pneumatic drive is its power consumption [2-6].

To reduce power consumption, various methods of controlling the pneumatic drive [5-10] are used, including at the braking stage [1,11-15]. The back pressure braking method has the advantage of reducing the energy consumption of the pneumatic drive. The use of this method allows you to accumulate and use the energy of compressed air during braking [1,11,14,15].

The diagram of the proposed energy-saving drive is shown in Fig.1. At the beginning of the work, all elements are in the positions shown in fig.1. The Pneumatic distributor D4 is a sensor for monitoring the initial position. The pneumatic distributor D1 controls the pneumatic cylinder PC. The D2 pneumatic distributor controls the additional AV volume. The control valve connects / disconnects the additional volume to the brake cavity of the RS pneumatic cylinder. The D5 track pneumatic distributor switches the distributors: D1-to the neutral position; D2 - to the braking position with recovery in the additional volume AV. To reverse the movement of the unloaded PC output link, compressed air recuperated in a large volume is used. The track distributor D6 is set to turn on the main line to continue the reverse. If the reverse is performed without a payload, then the need for D8 disappears and the schematic diagram is simplified.

When braking by back pressure, a significant amount of air is compressed in the brake cavity of the pneumatic cylinder. This makes a simplified mathematical description of the dynamics of a pneumatic actuator very difficult. Taking this feature into account, systems of differential mathematical equations for describing dynamics were compiled and solved [16,17].
2. Methods and materials

The mathematical model was compiled for the following assumptions: the pressure in the lines was considered constant; air cylinder cavities are exhausted and filled with compressed air according to polytropic law; compressed air is an ideal gas [11,17]. Switching the spools of distributors is considered instantaneous.

The dynamics of changes in the characteristics of the pneumatic drive at the acceleration stage are described by a well-known system of equations [17]. These equations are not suitable for describing the braking dynamics. The presented system of equations describes the dynamics of back pressure braking, taking into account the parameters of the additional volume:

\[
\begin{align*}
    m_n \frac{d^2 x}{dt^2} &= p_p \cdot F_n - p_b \cdot F_w \\
    p_p &= \left( \frac{x_{n1} + x_{a1}}{x_{n2} + x} \right)^n \cdot p_{\text{max}} \\
    p &= \left( \frac{(s + x_{n2} - x)p_{\text{max}} \frac{1}{n} + h \left( \frac{p_{\text{at}}}{p} \right)^\frac{1}{n}}{(s + x_{n2} + h - x)} \right)^n \\
    T_p &= \left( \frac{p_{\text{max}}}{p} \right)^{n-1} \cdot T_{\text{max}} \\
    T &= p \cdot ((s + x_{n2} + h - x) \cdot T_{\text{at}} + h \cdot T_{\text{at}} \cdot \frac{p_{\text{at}}}{p})
\end{align*}
\]
where \(m_n\) - reduced mass of moving parts of the pneumatic cylinder, kg; \(F_n, F_a\) - active piston and rod areas of the pneumatic cylinder, respectively, \(m^2\); \(p_a, p_b\) - absolute pressures in atmosphere, pressure line and cavity line, Pa; \(p_{aw}\) - absolute initial pressure in additional volume, Pa; \(p\) - absolute actual pressure in the additional volume and volume of the exhaust cavity of the pneumatic cylinder, Pa; \(x\) - the actual movement, m; \(s\) - maximum stroke of the rod, m; \(x_{01}, x_{02}\) - the unused volumes divided by the area of the piston of a pneumatic cylinder, m; \(t\) - moving time, c; \(P_0\) - external load, H; \(n\) - is the polytrope index, for equations (1.2) and (1.4) \(n = 1+(\frac{p_d}{p_a}(k - 1)\sqrt{\frac{p_d}{p_a}}))\); for equations (1.3) and (1.5) \(n = 1+(\frac{p_d}{p_a}(k - 1)\sqrt{\frac{p_d}{p_a}})); T_p, T_b, T_{aw}, T_n\) - absolute air temperature in the piston of the pneumatic cylinder, absolute air temperature in the rod cavities of the pneumatic cylinder, absolute air temperature in the in the additional volume before connection, absolute air temperature in the additional volume after connection, respectively, K; \(T_{pmn}, T_{pmn}\) - temperature at the beginning of recovery, K; \(p_{pmn}, p_{pmn}\) - pressure in the piston cavity at the beginning of recovery, pressure in the rod cavity at the beginning of recovery, respectively, Pa; \(x_{mn}\) - the coordinate for enabling the additional volume, m; \(h\) - the value of the additional volume divided by the area of the pneumatic cylinder piston, m.

Equations (1.2) and (1.3) describe the change in compressed air pressure in the piston and rod cavities of the pneumatic cylinder. Equations (1.4) and (1.5) describe the temperature variation in the air cylinder cavities.

Joint solution of known [17] and presented system of equations (1) allows to describe dynamic processes in proposed pneumatic drive for all modes of its motion and to estimate efficiency of energy recovery. The proposed system of equations was solved by the Runge-Kutta numerical integration method with automatic pitch selection. The adequacy of the presented mathematical model of braking dynamics was tested on an experimental stand and by the Fisher consent criterion [18]. After confirming the adequacy of the mathematical model, a computational experiment was planned and conducted [19,20]. The purpose of the computational experiment is to determine the effect of the initial parameters of the additional volume on the energy-speed characteristics of the pneumatic drive.

3. Results and discussing
The initial pressure in the additional volume (\(p_{aw}\)) and the geometric value of the additional volume (\(h\)) were taken as experimental factors. Factors varied at three levels. As a criterion of speed (\(Y_1\)) , the time of direct working stroke of the output link was taken. The ratio of the product (\(h p_{aw}\)) to the product of the final pressure in the brake volume of the pneumatic actuator by the value of this volume was considered a criterion for energy consumption (\(Y_2\)). The smaller criteria are the better.

The final stop coordinate at the point of the output link for all experiments remained unchanged. The results of the experiment are shown in Table 1.

| Factors | Criteria |
|---------|----------|
| \(h, \cdot 10^5\)Pa | \(p_{aw}, \cdot 10^{-6}\) m\(^3\) | \(Y_1\) | \(Y_2\) |
| -- | -- | 0,922 | 3,331 |
| -- | 0 | 0,918 | 3,362 |
| -- | + | 0,911 | 3,415 |
| 0 | -- | 0,951 | 2,220 |
| 0 | 0 | 0,934 | 2,239 |
| 0 | + | 0,934 | 2,281 |
| + | -- | 0,968 | 1,879 |
| + | 0 | 0,956 | 1,876 |
| + | + | 0,946 | 1,915 |
After constructing the regression equation and solving them [20], the following dependencies were obtained:

\[ Y_1 = 1.1309h^{0.02424}P_{\text{av}}^{-0.01241} \]  
\[ Y_2 = 1.2122h^{-0.35915}P_{\text{av}}^{0.01513} \]  

The influence of the initial parameters of the additional volume on the speed criterion and the energy intensity criterion of the pneumatic drive is shown in fig. 2.

Figure 2. The dependence of energy-speed criteria on the initial parameters of the additional volume (p; h): a) - speed (Y1); b) - energy consumption (Y2)
4. Consolation

By varying the initial parameters of the additional volume, it is possible to ensure effective energy saving or speed of the pneumatic drive.

When braking with energy recovery, the speed criterion is minimal for the initial parameters of the additional volume: $p_a=5\cdot10^5\text{Pa}$ and $V_a=42\cdot10^{-6}\text{m}^3$. Minimum energy consumption is achieved at initial parameters of additional volume: $p_a=2\cdot10^5\text{Pa}$ and $V_a=210\cdot10^{-6}\text{m}^3$.

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