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Effect of recuperative volume parameters on dynamic characteristics of pneumatic drive under braking*

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Влияние параметров рекуперативного объема на динамические характеристики пневмопривода при торможении***

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Introduction. Methods of energy saving in pneumatic drive are considered. The method of braking by creating back pressure in the exhaust cavity of the pneumatic actuator is of interest. Under braking, the compressed air energy is stored in the recuperative volume. It is possible to control the braking dynamics through setting the initial parameters of the recuperative volume. The work objective is to create a mathematical model describing the dynamic processes taking place in the pneumatic drive under braking by backpressure, with a constant mass enclosed in the cavities of the air motor, and considering variation of the initial parameters of the braking volume.

Materials and Methods. A mathematical model is proposed that describes the speed change of the output link, pressures and temperatures in the cavities of the pneumatic drive depending on the initial parameters of the recuperative volume. The solution to the mathematical model is carried out by the numerical integration method.

Research Results. The dependences of the output link velocity, pressures and temperatures in the pneumatic drive cavities on the initial parameters of the recuperative volume are obtained. Adequacy of the built mathematical model is confirmed by Fisher's criterion.

Discussions and Conclusions. The results obtained can be used to solve the problems of energy saving in pneumatic drives under the organization of backpressure braking. The use of recuperative volume increases the technological flexibility of the drive during its readjustment and extends the possibilities of energy saving.

Keywords: pneumatic drive, recuperation, energy saving, backpressure, braking, recuperative volume

Введение. Рассмотрены способы энергосбережения в пневматическом приводе. Интерес представляет способ торможения созданием противодавления в выхлопной полости пневмопривода. При этом энергия сжатого воздуха накапливается в рекуперативном объеме. Задавая начальные параметры рекуперативного объема, возможно управлять динамикой торможения. Цель работы — создание математической модели, описывающей динамические процессы, происходящие в пневматическом приводе при торможении противодавлением, с постоянной массой, заключенного в полостях пневмодвигателя воздуха, и с учетом изменения начальных параметров тормозного объема.

Материалы и методы. Предложена математическая модель, описывающая изменение скорости движения выходного звена, давлений и температур в полостях пневмопривода в зависимости от начальных параметров рекуперативного объема. Решение математической модели осуществлялось методом численного интегрирования.

Результаты исследования. Получены зависимости скорости выходного звена, давлений и температур в полостях пневмопривода от начальных параметров рекуперативного объема. Адекватность полученной математической модели подтверждена по критерию Фишера.

Обсуждения и заключения. Полученные результаты могут быть полезны для решения задач энергосбережения в пневмоприводах при организации торможения противодавлением. Применение рекуперативного объема повышает технологическую гибкость привода при его переналадке и расширяет возможности энергосбережения.

Ключевые слова: пневматический привод, рекуперация, энергосбережение, противодавление, торможение, рекуперативный объем

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Introduction. Pneumatic drives are widely used for automation and mechanization of secondary processes. Energy consumption of the pneumatic equipment may be more than 20% of the total consumption of the enterprise. Therefore, the issues of energy saving in pneumatic drives are urgent problems [1-3]. Such features as compressibility of the working environment and inertia of the output links impede shockless braking, complicate the control and drive design [1, 3, and 4]. It is possible to control the law of pneumatic actuator braking both by affecting a regulator device [1, 2, 5, and 6] and by selecting the most useful technique of braking [7–9].

These above features enable to use compressed air as a brake damper and to accumulate braking energy, which is effectively implemented under braking the pneumatic actuator through back pressure [7]. While changing the switch coordinate for braking, pressure in the brake and injection cavities, connecting additional volume to the exhaust cavity, it is possible not only to provide shockless braking, but also to recuperate the energy of compressed air under braking [2, 7, and 10].

By setting the initial parameters of the regenerative volume, it is possible to affect the braking and energy-speed parameters of the pneumatic drive. However, this issue is not adequately investigated.

Research objective is to create a mathematical model describing the dynamic processes occurring in the pneumatic drive under braking by backpressure, with a constant mass enclosed in the cavities of the air motor, and considering variation of the initial parameters of the braking volume.

Problem Statement. It is required to describe mathematically the dependence of the dynamic characteristics of a pneumatic drive under backpressure braking on the initial parameters of the regenerative volume.

Mathematical Dependences. Consider the backpressure braking by complete overlapping of the pump and exhaust lines. The disadvantage of this method is that when you change the working movement and the external load on the output link, you have to re-set the braking actuation coordinate. An alternative is the connection of a regenerative volume to the brake cavity of the pneumatic motor upon braking. It is possible to affect the final pressure in the brake volume and the braking path of the output link of a pneumatic drive by setting its initial parameters before braking [8].

The following assumptions were made for a mathematical description of the gas-dynamic processes occurring in the cavities of the pneumatic drive [10, 12]: pressure in the lines is assumed constant; thermodynamic processes occurring in the cavities of the pneumatic actuator are considered adiabatic; the working medium in the cavities of the pneumatic drive compressed under braking is taken as an ideal gas.

The backpressure braking is based on the principle of creating a resistance force to the movement of the output link of an air motor. This is achieved by partial or complete overlapping of the pump and exhaust channels. Complete overlap is more efficient because there is no release of pneumatic air from the brake cavity. The dynamics of the pneumatic drive before braking is determined by a known system of equations that considers the subcritical and over-critical discharge regimes [10].

The pneumatic drive parameters are shown in Fig. 1. The working medium parameters are identified as follows: $V_м$, $p_м$, $T_м$ are volume, pressure, and temperature of the air compressed in the channel, respectively; $V_п$, $p_п$, $T_п$, are volume, pressure, and temperature of the air compressed in the head end of the air motor; $V_ш$, $p_ш$, $T_ш$ are volume, pressure, and temperature of the air compressed in the rod or head end of the air engine; $V_{рек}$, $p_{рек}$, $T_{рек}$ are volume, pressure, and temperature of the air compressed in the regenerative volume; $V_{ат}$, $p_{ат}$, $T_{ат}$ are volume, pressure, and temperature of the free air. The air motor geometrics have the following identifiers: $F_п$, $F_ш$ are head and rod useful areas of the air motor; $f_н$, $f_в$ are passage areas of the pump and exhaust lines respectively; x, $x_{0п}$, $x_{0ш}$ are the coordinates of the current displacement, constant head and rod "passive" volumes, respectively; s is maximum driving stroke; P is workload.

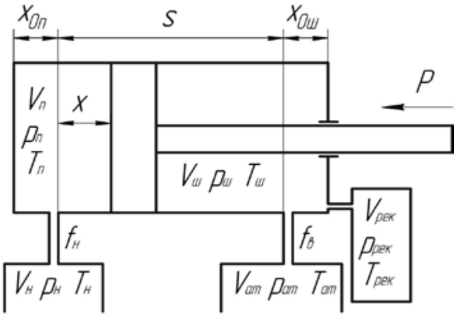

Fig. 1. Pneumatic drive parameters under braking by backpressure in recuperative volume

Under braking, there is a constant amount of the compressed air in the cavities of the pneumatic engine. We consider that heat exchange with the environment is insignificant, therefore, we regard the thermodynamic process to be adiabatic, with the adiabatic index $k = 1.4$ [10]. For braking, the control valve spool will switch to the neutral position and overlap the pump and exhaust lines ($f_н=0, f_в=0$). The switching time of the valve spool is not taken into account, the discharge and exhaust channels are overlapped simultaneously. The connection of the recuperative volume with the rod end of the air motor is considered instantaneous.

Considering the data of the assumptions of the cavity, the working medium pressure in the head end of the air motor will be presented in the following form:

$$p_n=(v_{nm}/v_n)^k\cdot p_{nm}, \tag{1.1}$$

where p_n, p_{nm} are current and initial pressure at the time of switching to braking in the head end of the air motor; v_n, v_{nm} are current and initial specific volumes of the head end of the air motor; k is adiabatic index.

Reduce equation (1.1) dividing it by the area of the air motor piston:

$$p_n=((x_{0n}+x_m)/(x_{0n}+x))^k\cdot p_{nm}, \tag{1.2}$$

where x_{0n}, x_m, x are coordinates: original, brake actuation, and current position of air motor piston, respectively.

At the moment of shifting the distributor on braking, the regenerative and braking volumes are combined; in this case the compressed air parameters will be determined by the following system (1.3):

$$(1.3)\begin{cases} p_{шт}\cdot v_{шт}^k = p\cdot v_1^k & (1.3.1)\\ p_{рек}\cdot v_{рек}^k = p\cdot v_2^k & (1.3.2)\end{cases}$$

where $v_{шт}$, $v_{рек}$ are specific volumes of the air compressed at the start of braking in the rod end and in the regenerative air volume; v_1, v_2 are “conditional” specific air volumes in the rod end and in the recuperative air volume; $p_{шт}$, $p_{рек}$, p are pressures of the air compressed at the start of braking in the rod end, recuperative volume, and in the “combined” volume, respectively.

We express v_1, v_2 specific volumes in the system of equations (1.3):

$$(1.4)\begin{cases} p_{шт}\cdot v_{шт}^k = p\cdot v_1^k \Rightarrow p_{шт}\cdot\left(\dfrac{V_{шт}}{m_{шт}}\right)^k = p\cdot\left(\dfrac{V_1}{m_{шт}}\right)^k \Rightarrow \\ \Rightarrow V_{шт}\cdot\left(p_{шт}\right)^{\frac{1}{k}} = V_1\cdot\left(p\right)^{\frac{1}{k}} & (1.4.1)\\ p_{рек}\cdot v_{рек}^k = p\cdot v_2^k \Rightarrow p_{рек}\cdot\left(\dfrac{V_{рек}}{m_{рек}}\right)^k = p\cdot\left(\dfrac{V_2}{m_{рек}}\right)^k \Rightarrow \\ \Rightarrow V_{рек}\cdot\left(p_{рек}\right)^{\frac{1}{k}} = V_2\cdot\left(p\right)^{\frac{1}{k}} & (1.4.2)\end{cases}$$

where $V_{\text{шт}}$, $V_{\text{рек}}$, are rod and recuperative volumes, respectively, at the time of the start of braking; V_1, V_2 are rod and recuperative volumes connected to the “combined” volume; $m_{\text{шт}}$, $m_{\text{рек}}$ are air mass compressed in the rod and recuperative volume at the time of the start of braking; p is pressure in the “combined” volume.

To determine pressure in the “combined” volume, we sum up the equations (1.4.1) and (1.4.2):

$$p = \left(\frac{V_{\text{шт}} \cdot \left(p_{\text{шт}}\right)^{\frac{1}{k}} + V_{\text{рек}} \cdot \left(p_{\text{рек}}\right)^{\frac{1}{k}}}{V_1 + V_2} \right)^k, \tag{1.5}$$

Using the Clapeyron equation, we can find temperature of the working medium in the “combined” volume:

$$p \cdot v = R \cdot T \Rightarrow T = \frac{p \cdot v}{R} = \frac{p}{R} \cdot \left(\frac{V_{\text{шт}} + V_{\text{рек}}}{\dfrac{V_{\text{шт}}}{v_{\text{шт}}} + \dfrac{V_{\text{рек}}}{v_{\text{рек}}}} \right), \tag{1.6}$$

where T is temperature of the air compressed under braking in the “combined” air volume; R is absolute gas constant.

The final dependence of the air temperature in the brake chamber of the pneumatic actuator on the initial parameters of the regenerative volume will be obtained through determining the values of specific volumes in the equation (1.6) and reducing it to the area of the rod end of the pneumatic motor:

$$T = p \cdot ((s + x_{0\text{ш}} + h_{\text{рек}} - x) \frac{T_{\text{шт}} \cdot T_{\text{рек}}}{(s + x_{0\text{ш}} - x) \cdot T_{\text{рек}} \cdot p_{\text{шт}} + h_{\text{рек}} \cdot T_{\text{шт}} \cdot p_{\text{рек}}})) \tag{1.7}$$

where $h_{\text{рек}}$ is reduced to the rod area of the air motor, recuperative volume; T, $T_{\text{шт}}$, $T_{\text{рек}}$ are absolute temperatures in the “combined”, rod and recuperative volumes, respectively.

$$\left\{ \begin{array}{ll}
m \dfrac{d^2 x}{dt^2} = p_n \cdot F_n - P - p_{\text{ш}} \cdot F_{\text{ш}} & (1.8.1) \\
p_n = \left(\dfrac{x_{0n} + x_m}{x_{0n} + x} \right)^k \cdot p_{nm} & (1.8.2) \\
p = \left(\dfrac{\left(s + x_{02} - x\right)\left(p_{\text{шт}}\right)^{\frac{1}{k}} + h_{\text{рек}}\left(\left(p_{\text{рек}}\right)^{\frac{1}{k}}\right)}{\left(s + x_{02} + h_{\text{рек}} - x\right)} \right)^k & (1.8.3) \\
T_n = \left(\dfrac{p_{nm}}{p_n} \right)^{\frac{k-1}{k}} \cdot T_{nm} & (1.8.4) \\
T = p \cdot ((s + x_{0\text{ш}} + h_{\text{рек}} - x) \dfrac{T_{\text{ш}} \cdot T_{\text{рек}}}{(s + x_{0\text{ш}} - x) T_{\text{рек}} \cdot p_{\text{ш}} + h_{\text{рек}} \cdot T_{\text{ш}} \cdot p_{\text{рек}}})) & (1.8.5)
\end{array} \right. \tag{1.8}$$

The air motor piston movement is described by the equation (1.8.1). The general system of equations for the braking process of a pneumatic device will have the form (1.8).

Here: m is mass of the working body reduced to the air motor rod; $T_н$ is absolute air temperature in the pump line; T_{nm} is initial value of the air temperature in the head end of the air motor at the time of shifting to braking.

The equations (1.8.2) and (1.8.3) describe the pressure variation, and the equations (1.8.4) and (1.8.5) describe the temperature change in the piston and brake chambers of the air motor, respectively.

The simultaneous solution of the system of equations describing the braking dynamics of the pneumatic actuator (1.8) and its acceleration by Runge-Kutta numerical quadrature method [14] enables to study the dependence of the dynamic characteristics of the pneumatic actuator on the initial parameters of the regenerative volume. The bench assessment of the characteristic coincidence of theoretical and practical dependences showed satisfactory convergence [13], which allowed us to test the adequacy of the obtained mathematical model upon the Fisher's variance ratio. For this purpose, a two-factor experiment was conducted. The initial pressure and the value of the regenerative volume were chosen as independent factors. The factors changed according to three levels of variation, which allowed the use of nine combinations of the factors with three-time replication of each experiment.

The mathematical model is adequate to the practical results obtained through the experimental verification, since the calculated value of the Fisher's criterion is 2.67, which is less than the tabulated one (2.7) [15].

The results obtained have enabled to proceed to a computational experiment, which will allow us to determine rational combinations of the initial parameters of the regenerative volume for the given law of pneumatic actuator braking and for maintaining high-speed parameters.

Conclusions:

1. A mathematical model that adequately describes the dynamic processes taking place in the pneumatic drive chambers under backpressure braking with accumulation of the compressed air energy into the recuperative volume is developed.
2. Mathematical dependences of the pneumatic drive parameters on the initial parameters of the regenerative volume under backpressure braking are obtained.

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