Model of the Pneumatic Positional Unit with a Discrete Method for Control Dynamic Characteristics

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Abstract. At present, it appears that systems of pneumatic units with discrete and analog control, in which the required analog law of motion of the output member is provided with the help of discrete switchgear, offer a promising potential. When developing the schemes of positional hydraulic-pneumatic units, the parameters of the movement of the hydraulic-pneumatic unit are studied, namely: the value of displacement, speed, and acceleration of its output member. To carry out the simulation, a design based on discrete switchgear was taken as the basis for the pneumatic positional unit. Solving the inverse problem, i.e., with the law of motion of the output member of the pneumatic unit (specifying the positioning function) known, we determine the mandatory law of change in the effective areas of the control line and represent each equation of the dynamic model as block diagrams. A mathematical model of the system of pneumatic positional units with program control was developed. It considers the features of the system of pneumatic units and consists of mathematical models of the actuator, a real-time control line model, and a real-time control system. The proposed algorithm for analysis of dynamic characteristics using the MATLAB simulation environment confirms the adequacy of the mathematical models describing the operation of a positional pneumatic unit implemented on discrete pneumatic equipment. The developed algorithm is advisable to analyze the operation of the existing one and for designing new technological equipment.

Keywords: Dynamic model · Discrete switchgear · Positioning function · Block diagram · Process innovation

1 Introduction

The basic requirements for hydropneumatic positional units are known. They ensure the specified technical characteristics determined by the technological process, ease of manufacture and cost-effectiveness; high reliability and trouble-free operation; the ability to reprogram the control system quickly.

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When developing pneumatic positional units, designers are faced with the problem of a limited choice in the range of manufacturers of pneumatic valves with proportional electric control. Therefore, at present, the most promising are systems of pneumatic units with discrete and analog control, i.e., those in which the required analog law of motion of the output member is provided using discrete switchgear. Due to the discreteness of choice in the controlled parameters, the interconnection with digital control devices is facilitated. These systems focused on regulating the working environment in the cavities of the hydraulic and pneumatic motor, allowing to expand of the functionality of hydraulic units. The apparent advantage of such systems is that they can be relatively easy to implement [1–3]. The effectiveness of these control methods is determined by the constant improvement of the control system, which is currently based on microprocessor-based computer technology, allowing applying complex control algorithms [4–6].

2 Literature Review

Recently, digital hydraulic and pneumatic units have been widely used in the industry [7, 8]. These systems are logically integrable in the spirit of the Industry 4.0 strategy, according to which these systems can be combined into one network [9], communicate with each other in real-time, self-adjust, and learn new behavior models [10, 11].

The active implementation of digital pneumatic units into the industry is facilitated by the relative simplicity of design and operation, long service life, reliable operation in a low-temperature range in high humidity, dustiness, radiation of the environment, and fire and explosion safety. Digital hydraulic units allow us to increase the positioning accuracy of actuators and increase the system's energy efficiency [12, 13].

When developing the schemes of positional hydraulic-pneumatic units, the parameters of the movement of the hydraulic-pneumatic unit are studied, namely: the value of displacement, speed, and acceleration of its output member. Studies [14–16] show that the main tasks of developers of systems of controlled hydraulic-pneumatic units are associated with the fulfillment of the requirements for the movement of the output member, which led to a variety of methods for controlling the motion parameters of the systems of positional parts [17–19].

The purpose of this work is to develop an algorithm for analyzing the positioning function, which allows you to provide the specified technical characteristics of the pneumatic positional unit by describing the necessary law of change in the effective areas of the control line of the pneumatic positioning unit, implemented on discrete/digital switchgear.

3 Research Methodology

A design based on discrete switchgear was taken as the basis for the positional pneumatic unit [20, 21]. The diagram of the pneumatic unit is shown in Fig. 1.

The pneumatic unit consists of the following elements (Fig. 1): 1 - position sensor; 2, 3 - pneumatic valves; 4 - pneumatic throttle valve; 5 - pneumatic cylinder.

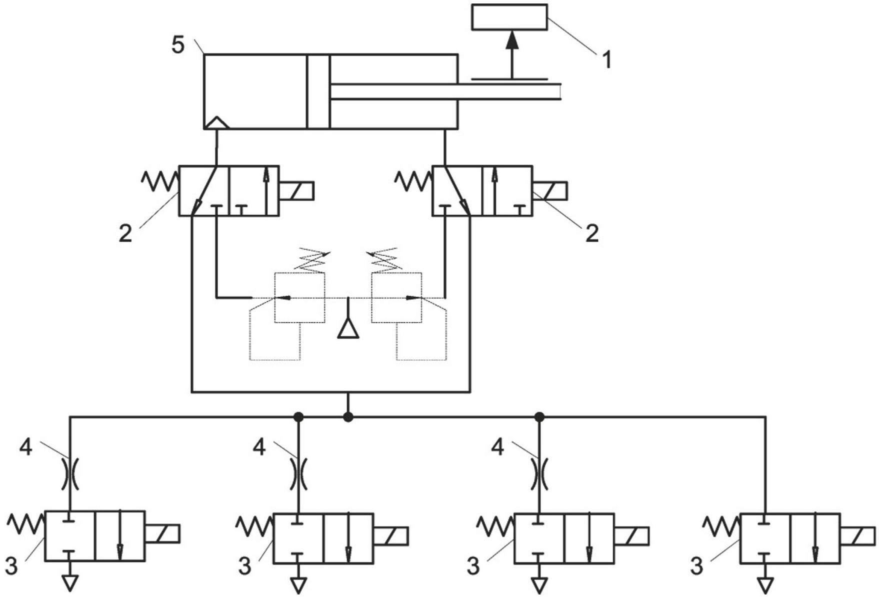

Fig. 1. Diagram of positioning pneumatic unit.

Based on differential equations describing the dynamic characteristics of the pneumatic unit during operation and calculation [22], a dynamic model of the pneumatic unit was created. The designations of the variables used in the dynamic model are shown in Table 1.

System of differential equations describing a dynamic model:

$$\left.\begin{array}{l} \dot{p}_1 = \frac{k}{F_1x+V_{10}}\left(f_1^eK_G^1 - p_1F_1\dot{x}\right) \\ \dot{p}_2 = \frac{k}{F_2(S-x)+V_{20}}\left(f_2^eK_G^2 - p_2F_2\dot{x}\right) \\ m\ddot{x} = p_1F_1 - p_2F_2 - p_a(F_1 - F_2) - F_c \end{array}\right\}, \quad (1)$$

where at p1 = pm and p2 = pa values of K_G^1 and K_G^2 become:

$$K_G^1 = \mu_1 \mathrm{p}_m\sqrt{2RT}\phi\left(\frac{p_1}{p_m}\right); K_G^2 = -\mu_2 \mathrm{p}_2\sqrt{2RT}\phi\left(\frac{p_a}{p_2}\right).$$

Solving the inverse problem, i.e., the law of motion of the output member of the pneumatic unit (specifying the positioning function) known, we determine the required law of change in the effective areas of the control line. In the case of the extension of the actuator, the effective area in the pressure line f_1^e is set and constant. Then there is the need to determine the change law in the effective area of the discharge line. Thus,

Table 1. Designations of variables used in the dynamic model.

No.	Description	Designation	Metric units
1	Mass of inertial load	m	kg
2	Piston area in bottom end of pneumatic cylinder	F_1	m^2
3	Piston area in rod side of pneumatic cylinder	F_2	m^2
4	Resistance force	F_c	N
5	Effective areas of lumped resistances	f_1^e, f_2^e	m^2
6	Piston stroke	S	m
7	Piston movement	x	m
8	Piston movement speed	$\dot{x}$	m/s
9	Piston acceleration	$\ddot{x}\ddot{x}$	m/s^2
10	Pressure in bottom end	p_1	Pa
11	Pressure in rod side	p_2	Pa
12	Atmospheric pressure	p_a	Pa
13	Line pressure	p_m	Pa
14	Initial volume of bottom end	V_{10}	m^3
15	Initial volume of rod side	V_{20}	m^3
16	Discharge coefficient	μ_1, μ_2	–
17	Gas constant	R	J/(kg·K)
18	Air temperature in line	T	K
19	Ratio of specific heats	k	–
20	Discharge function	K_G^1, K_G^2	–

the system of differential equations becomes:

$$\left.\begin{aligned} \dot{p}_1 &= \frac{k}{F_1 x + V_{10}}\left(f_1^e K_G^1 - p_1 F_1 \dot{x}\right) \\ f_2^e &= \frac{\dot{p}_2 (F_2 (S - x) + V_{20})}{k \cdot K_G^2} - \frac{p_2 F_2 \dot{x}}{K_G^2} \\ p_2 &= \frac{m\ddot{x} + p_1 F_1 - p_a (F_1 - F_2) - F_c}{F_2} \end{aligned}\right\}. \tag{2}$$

4 Results

We represent each equation of the dynamic model as block diagrams [23]:

1. A block diagram for solving the inverse problem of the dynamics of the positional pneumatic unit (system of differential Eqs. (2)) is shown in Fig. 2.

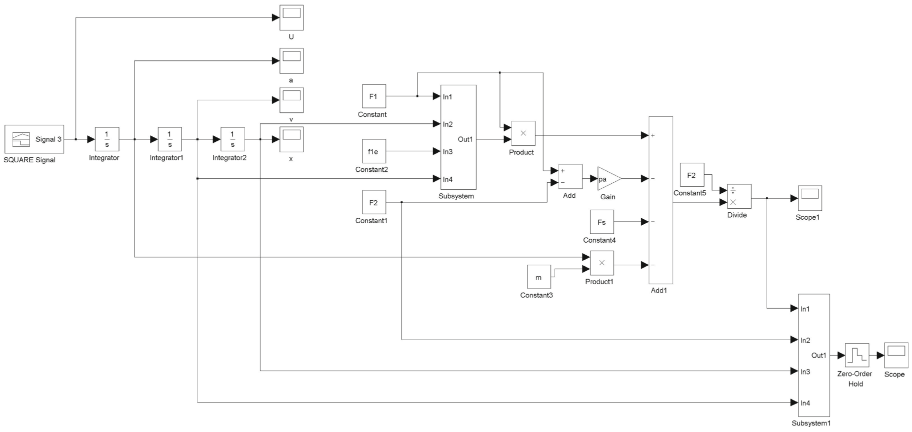

Fig. 2. Block diagram for solving the inverse problem of the dynamics of a pneumatic positional unit.

Positioning function U is shown in (Fig. 3).

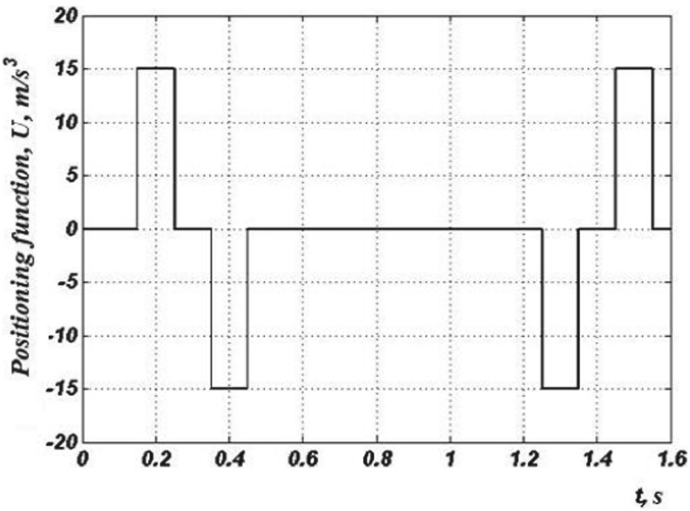

Fig. 3. Positioning function U.

Acceleration a, speed V and movement x of the output member are shown in (Fig. 4).

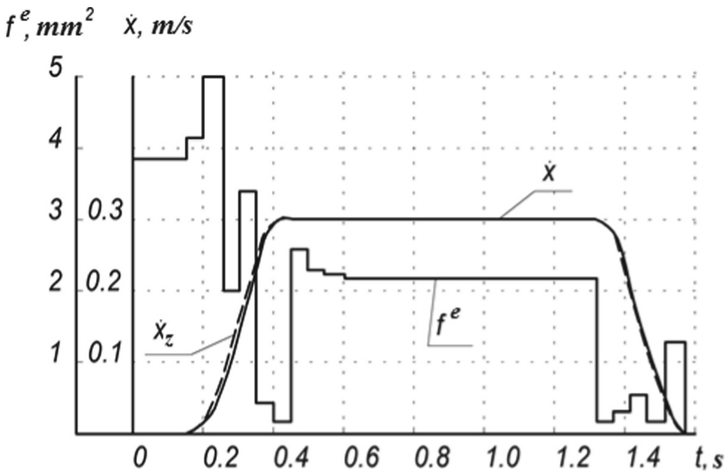

Fig. 4. Values of the effective area in the control line at the outlet f_2^e to obtain the required law of motion of the output member; $\dot{x}_z$ - specified speed of movement; $\dot{x}$ - an obtained speed of movement.

The results show high accuracy of coincidence of the specified and actual speeds.

2. The block diagram for calculating the pressure p1 from the dependence $\dot{p}_1 = \frac{k}{F_1 x + V_{10}}\left(f_1^e K_G^1 - p_1 F_1 \dot{x}\right)$ is shown in Fig. 5.

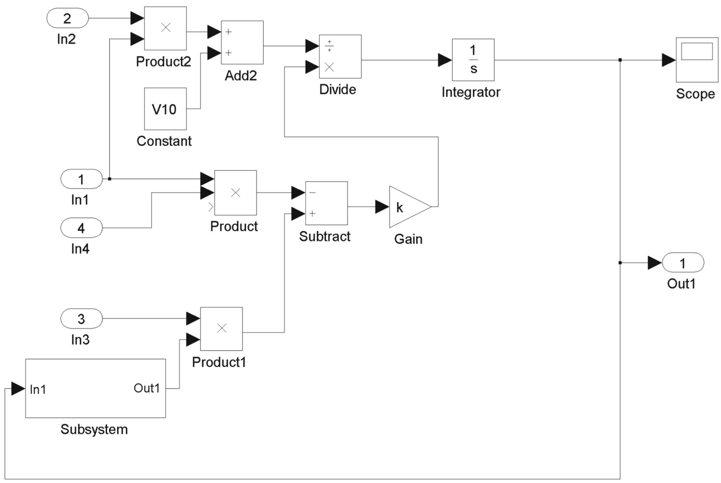

Fig. 5. Block diagram for calculating the pressure p_1.

3. The block diagram for calculating the coefficient K_G^1 from dependence $K_G^1 = \mu_1 p_m \sqrt{2RT}\phi\left(\frac{p_1}{p_m}\right)$, taking into account the connection diagram of the pneumatic cylinder is shown in Fig. 6.

4. The block diagram for finding the effective area in the control line at the outlet f_2^e from dependence $f_2^e = \frac{\dot{p}_2(F_2(S-x)+V_{20})}{k \cdot K_G^2} - \frac{p_2 F_2 \dot{x}}{K_G^2}$ is shown in Fig. 7.

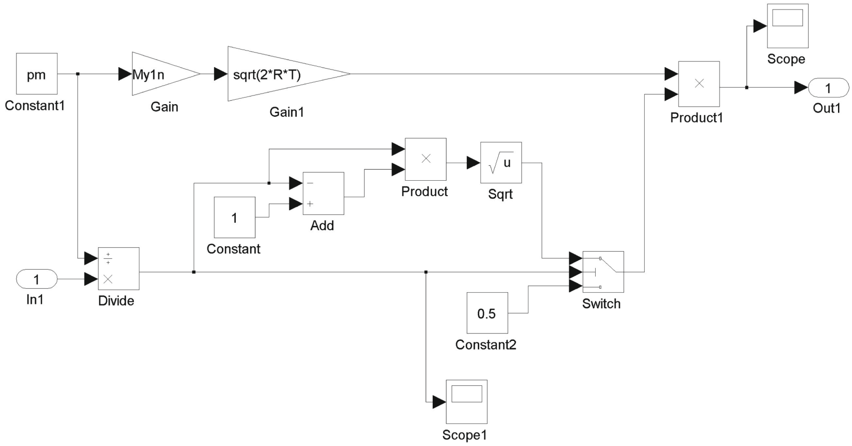

Fig. 6. Block diagram for calculating the coefficient K_G^1.

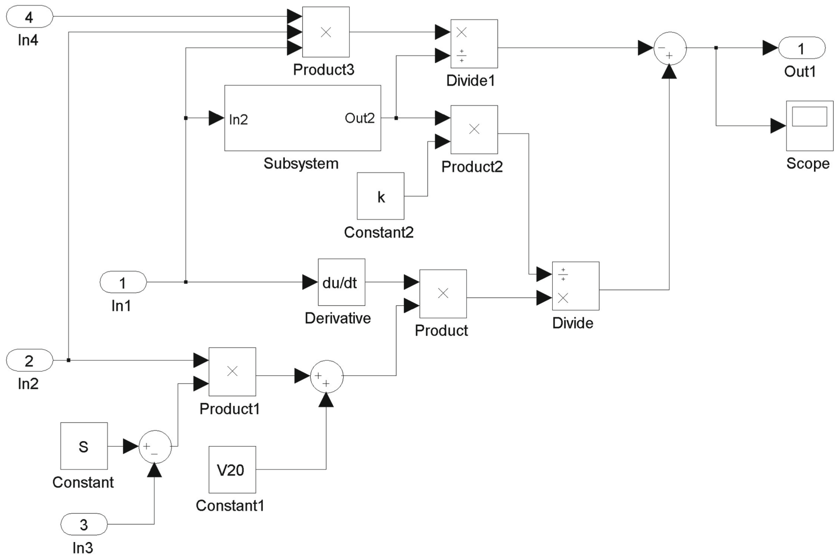

Fig. 7. Block diagram for calculating the effective area in the control line at the output f_2^e.

5. The block diagram for calculating the coefficient K_G^2 from dependence $K_G^2 = -\mu_2 p_2 \sqrt{2RT} \phi\left(\frac{p_a}{p_2}\right)$ considering the connection diagram of the pneumatic cylinder is shown in Fig. 8.

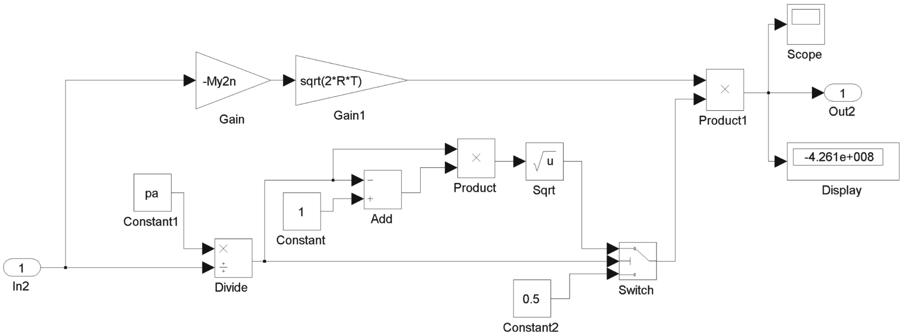

Fig. 8. Block diagram for calculating the coefficient K_G^2.

5 Conclusions

The developed mathematical model of the positional pneumatic unit system with program control allows considering the characteristics of the pneumatic unit system. It includes calculation models of the simulator, real-time control line mode, and real-time control mode system.

The proposed algorithm of analysis of dynamic characteristics using the MATLAB simulation environment confirms the adequacy of the mathematical models describing the operation of the positional pneumatic unit implemented on discrete pneumatic equipment. The developed algorithm is advisable to analyze the operation of the existing and new technological equipment design.

The laws of motion of the positional pneumatic unit output member are obtained. They are based on the developed algorithm of analysis of the positioning function and implemented in the MATLAB environment. Research results can provide the specified technical characteristics for a smooth acceleration of the pneumatic unit output member. Besides, formulated laws of motion allow movement at a steady speed and smooth braking with a stop at the positioning point.

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