Dynamics of mechatronic function modules drives of flow technological lines in food production

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Keywords:

Functional
Module
Packing
Electro-pneumatic
Actuator
Accuracy

Article history:

Received 14.01.2018
Received in revised form 22.05.2018
Accepted 27.12.2018

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DOI: 10.24263/2304-974X-2018-7-4-16

Abstract

Introduction. The tasks were considered, which are related to the working bodies for the artificial food products movement according to the specified movement law and their positioning in the intermediate positions of the kinematic cycle.

Materials and methods. The actuators dynamics characteristics and control system of power part of positional electro-pneumatic actuators were researched. The methods of mathematical and computer modeling, and methods of solving ordinary differential equations and partial differential equations and method of correlation analysis were used.

Results and discussion. The analytical dependences for determining the kinematic parameters of the artificial product movement with the mechanism of collision, which is based on the pneumatic actuator, are obtained. The dynamical model of the actuator is mathematically tested and the movement law of the collision mechanism, which is approximated to the optimal speed, is obtained. To analyze the loading process of the working link of the positional actuator, the model of a generalized control system is used, which is limited by the one full cycle of operation of the functional mechatronic module of the packing machine. Such a model allows to describe the overload process, both in the case of full and partial filling of the working cycle. This is important when packing products in different geometric shapes of consumer packaging, which is typical of modern packaging machines. The simulation model of the actuator is theoretically substantiated and confirmed, which has a number of advantages, unlike the existing structures of positional drives in packaging machines. Calculated difference, during mathematical modeling, of the value of the working time of the output stage of the functional mechatronic module for the processing of the kinematic cycle of the operation of the packaging machine was for the various input parameters of the limit to 7%. The results of the mathematical modeling of dynamics for a positional pneumatic actuator, with the condition of changing the cross section of the exhaust hole, gave the opportunity to obtain the kinematic characteristics of the drive.

Conclusions. The results of mathematical modeling for positional pneumatic actuators with the condition of changing the section of the exhaust hole allowed to track all the kinematic characteristics of the actuator.

Introduction

In recent years, a rather complicated process of optimal control of actuators of technological equipment for food production has been studied by many authors [1-4]. The authors took the various assumptions in order to simplify the mathematical description of the work of tracking and positional actuators [3, 4]. For a long time, this approach was justified, but over time, the productivity of mechatronic functional modules as part of technological equipment has increased significantly. In this connection, many control models of positional actuators with rational kinematic and dynamic parameters have become unacceptable for practical use [19]. Therefore, modulation of the moving process of artificial products by pusher on the basis of a position pneumatic actuator taking into account the real boundary conditions, as well as dynamic processes in the pneumocylinder, is relevant.

The main ways of packing artificial products in polymer films are revealed: the placement of the product in a pre-made package and fastening it with clips; the placement of the product in the sleeve, which is formed from roll packaging material; the placement of the product between two films and the formation of a package with four seams; the wrapping of the product with a polymeric film [8].

The analysis of the existing equipment for the packaging of artificial and small artificial foods, showed the priority of using polymeric packaging materials for a number of economic, environmental and protective parameters [5–7]. There are modules with linear displacement actuators in the composition of the collision mechanisms in the studied packaging machines (PMs), the most common mechatronic functional modules (MFMs) feeding the food product to the packaging area. The main ways of packing artificial products in polymer films are: placing the product in a pre-made package and fastening it with clips; placement of the product in the sleeve, formed from roll packaging material; placement of the product between two films and the formation of a package with four seams; wrapping the product with a polymeric film [8]. FMM layouts, which are using for the packaging of artificial and small artificial products, use commonly-designed functional devices (FDs) with pneumatic or electro-pneumatic actuators for pushing products [9,10]. It should be noted that in some cases, technological operations in packaging machines (movement of artificial products, the formation of a layer of artificial products, delivery of the package) carry out by using a pneumatic actuator [11]. It does not allow using of the single piston motion law when moving artificial products due to their different physical and mechanical properties. The strikes, which arise in the final position in the movement of artificial products, cause loss of their product appearance or the destruction of group units [12]. First of all, it is necessary to take into account, the possibility of practical implementation of this law by a pneumatic actuator, what means the possibility of ensuring a smooth change of all its parameters, when choosing the law of moving an artificial product [13].

The criterion, characterizing the operations of forming the structural elements of the package, can be the law of motion, selected by the condition of the required productivity, which is the most common in MFM packaging machines. It is connected with the work of packing machines, which have their own productivity, and locates at the earlier stages of the technological chain [14,15].

The *aim* is expanding the functionality of food packaging equipment provides the searching for ways to improve the drives of the functional mechatronic modules.

The *tasks* of the study:

- the modeling of piston movement law of the pneumocylinder with an initial difference in air pressure, approximating to the optimal speed. In this case, the loads movement on the fixed flat is considered a collision mechanism with a positional pneumatic actuator.

- using the mathematical modeling to study the cases of smoothing the acceleration function at the moment of disengagement of the driving force, which allows to change smoothly the working parameters of the positional pneumatic actuator.
- creation of the simulation model of the positional actuator, with taking into account the cases of functions smoothing of the of the analogue of speed and analogue of acceleration.
- description of the method of choosing the initial movement stage (in the coordinate x), with taking into account the possible reduction of the actuating mechanism productivity.
- the study of optimal kinematic parameters of the packaging process of artificial food products in packaging machines.
- the development of the mathematical analysis method of the positional electro-pneumatic actuator for working out the modes of operation of the different functional mechatronic modules in a packing machine for artificial food products of the horizontal type.

In addition, it is necessary to set the value of the initial stage of the movement (x coordinate), choosing it in such a way that the initial stage does not have a significant effect on the productivity reduction of the executive mechanism. According to the author, the initial stage should not exceed 10% of the total displacement time of the piston (product), which allows the practical realization of a given law of motion without major errors.

Materials and methods

Materials

The materials were chosen the positional actuators of packaging machines. The aim of the study was chosen the dynamics of electro-pneumatic positional actuators. The analysis of the working bodies motion laws of the initial kinematic link of the collision mechanisms was carried out for the technological schemes of the MFM movement of artificial products and the group (layer) of artificial products into the formed sleeve of the packaging material.

MFM formation characteristics of artificial products packaging

The operations of forming the artificial products packaging are connected to the work of the MFM elements according to the laws of motion, which determine the required productivity of the packaging machine. As an researched positional actuator, for the given layout of Figure 1, MFM was chosen on the basis on pneumo actuator of positional type.

At Figure 1b there is shown with use of the graphs the generalized characteristics of displacement, speed, acceleration for the working output of the MFM. The mathematically illustrated graphs are described in the work [16]. According to the recommendations, we accept the initial conditions for the study of the technical system of the MFM (Figure 1a):

- The collision system, provided by the FMM, works according to the linear modified [17] law;
- The stage of acceleration is limited by the conditions $0<t<0{,}25T$:

$$x = 2x_0\left(\frac{t}{T}\right)^2;\ \dot{x} = 4x_0\frac{t}{T^2};\ \ddot{x} = \frac{4x_0}{T^2}. \qquad (1)$$

Deceleration:

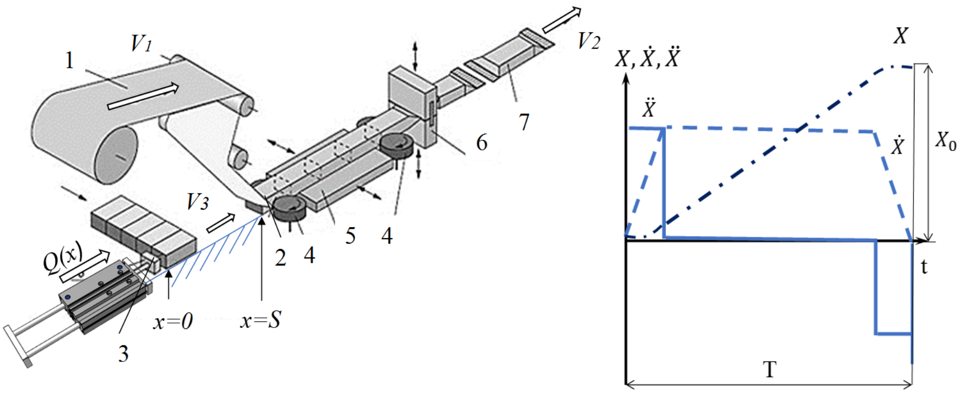
$$0{,}75T<t<T;\ x = \frac{4x_0 t}{T} - x - 2x_0\left(\frac{t}{T}\right)^2$$

$$\dot{x} = \frac{4x_0}{T}\left(1-\frac{t}{T}\right);\ \ddot{x} = -\frac{4x_0}{T^2}.$$

Constant motion: $0{,}25T<t<0{,}75T$;

$$x = \dot{x}t;\ \dot{x} = \frac{x_0}{T};\ \ddot{x} = \mathrm{const}; \qquad (2)$$

$$\ddot{x} = \frac{6x_0}{T^2}\left(1-\frac{2t}{T}\right).$$



a **b**

Figure 1. Technological scheme of PM for packing in a three-seam package with the work schedule of the output kinematic link MFM:
1 – FMM supply of packaging material; 2 – FD formation of the semi-sleeve; 3 – FD package formation; 4 – artificial product based on corex; 5 – MFM the formation of the longitudinal seam; 6 – MFM the formation of the longitudinal seams; 7 – FMM forming of welding transverse seams; 8 – FD cutting off surplus shrinkable packaging material; 9 – transport system of withdrawal of finished packaging; 10 – MFM moving products into the sleeve.

The given descriptions of the movement laws of the technological machines [16] of working bodies do not allow us to describe in detail the change in the kinematic characteristics of the working bodies in the arrangement with the electro-pneumatic actuator. Therefore, taking into account Figure 1 (b) and work [16,18], we can formulate research tasks with additional parameters. For such parameters we accept the processes of changing the pressure in the power part of the positional pneumatic actuator. MFM research with taking into account the inertial processes of the power part of the electro-pneumatic actuator is due to the need to supplement information on the operation of the executive mechanisms of automatic machine [16], in particular the packaging machine for the packaging of artificial food products. Well-formed structure of the control system, which also needs to be taken into account in the studies, allows to coordinate the work of all the components of the MFM.

Research methods

Methods of mathematical and computer modeling, methods of solving ordinary differential equations and differential equations in partial derivatives were used to study the dynamics of compressed air in the cavities of the pneumocylinder. In the study of the layout of MFM packaging machines, the theory of automated control of electropneumatic position drives is used.

Results and discussion

The first stage requires the analysis of classical methods for describing the work of the MFM output working links. The graph (Figure 1, B) show the 3 stages of changes in kinematic parameters of the output link. At the real technical systems, according as that the control module is taken into account, the similar graphs can be divided into 4 stages:

- the time of the preparatory period of the forward stroke t_{I};
- the time of the working stroke of the piston t_{II};

- the time of the preparatory period of the reverse stroke t_{III}, which is connected with the time of receipt of the control signal for the operation of the pneumocycler rod;
- the time of piston motion in the reverse direction t_{IV} is determined by a common solution of equations (3) – (5) with the help of the ECM.

The second stage consists of studying the movement of the stem of pneumocylinder, it is the MFM output links. We have chosen the law of the stem movement due to the necessary productivity. This is a special case of the optimal speed of the process of load movement, which allows to achieve maximum productivity of the actuator.

In the implementation of the studied of movement law of the working output link of the MFM (Figure 2), the inertia of the positional electro-pneumatic actuator control system is taken into account. The structure of control of the system (Figure 3) is analyzed, with the condition – to ensure the presence of the driving force Q (acceleration $\ddot{x}$) in the initial stage of motion.

To compile a mathematical model of the MFM output link, the assumptions are made:

- taking into account the external force on the piston rod until the resistive force Q(x), (Figure 2), does not increase to the value corresponding to the required acceleration $\ddot{x}$.
- the change in the value of acceleration of the piston and the rod of the pneumocylinder from the maximum to the minimum value is considered at the moment of disengagement of the driving force. It requires an instantaneous increase in pressure in the exhaust flat.

The classic graphs of the movement laws of the working links (Figure 1b) do not take into account the transitional stages of the work of the technical system as part of the control module. Therefore, we have chosen to compile a mathematical model of the work of the initial working link, it is the combined law of the movement of the rod into the electro-pneumatic positional actuator. The graph (Figure 2) describes the working and idle movement of the piston rod in the operation of control elements, it is electromagnetic relays of the control system, the scheme of which is shown on (Figure 4).

Thus, the solution of the problem is reduced to the solution of the optimization problem with initial conditions, that are not equal to zero, followed by smoothing the discontinuous function at the time of switching off the driving force. The movement of the piston of the positional pneumatic actuator (Figure 2) consists of four stages:

Stage I is initial. The using a control signal from electromagnetic relays of an electropneumatic distributor – and the driving force increases ($Q \leq Q(x) \leq Q_{max}$). The movement law of a piston pneumoscilinder acquires a parabolic form. The work of the working link begins.

Stage II is intensive acceleration. It finishes with the disappearance of the signal of the control electromagnet (first solenoid). The driving force is constant$Q_{max} = const$). The stage condition: Q_{max}- is the maximum driving force, developing by pusher, does not cause deformation of the artificial product.

Stage III is transitional. The using of the electromagnetic relay of the electropneumatic distributor (second solenoid).Driving force decreases ($Q_{max} \geq Q(x) \geq Q$) as a result of the resistance of the compressed air of the rod chamber of the pneumocycler.

Stage IV is characterized by a reverse movement of the rod, which is under the influence of intense deceleration. The stage is completed when the control signal from the second solenoid is turned off.The driving force is zero (Q = 0). It is necessary to ensure the integrity of the load from the pusher. The boundary conditions in this problem are as follows:

$$t = 0;\ \ddot{x} = 0;\ \dot{x} = 0;\ x = 0;\quad \ddot{x} = \ddot{x}_{IV};\ \dot{x} = 0;\ x = S.$$

where S is the value of the movement of cargo from the initial position to the final; $\ddot{x}_{IV}$ is the value of the load acceleration at the stage of intense deceleration.

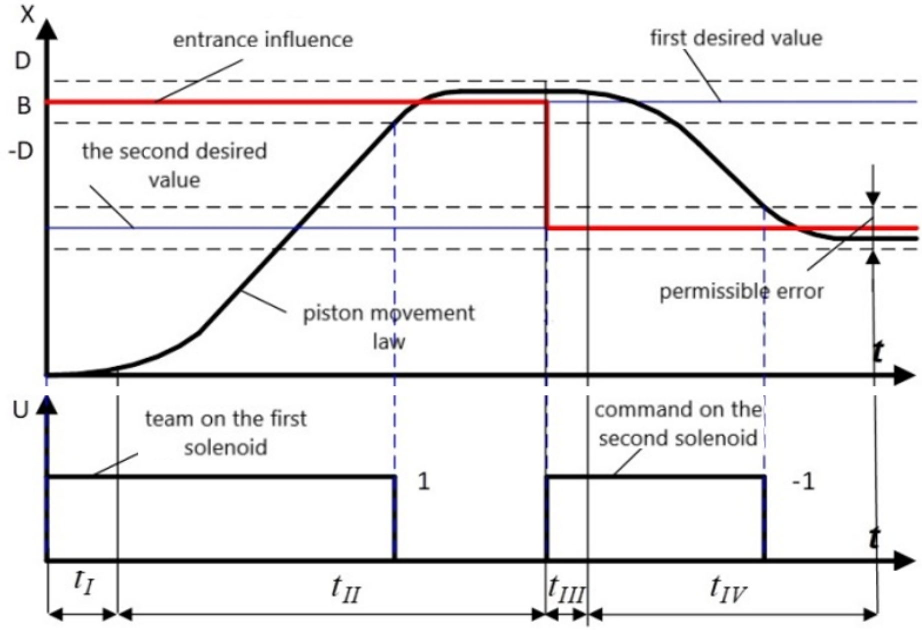


Figure 2. Combined law of motion of the driving link in the MFM positional actuator with taking into account the receipt of control signals from electromagnetic relays of the electropneumatic distributor

According to the equation (4.1), there is no time in final conditions for which the load is moved. This is explained by the fact that during a four-stage mode, the time of movement is determined during the task execution. The variable quantities are set depending on the parameter x, the equation of the piston motion of the pneumatic actuator of two-way action will have the form:

$$m\ddot{x} = p_1(x)F_1 - p_2(x)F_2 - P(x) \quad (3)$$

where m – the mass of the product; p_1, p_2 – pressure of the piston and stomach cavity, $F_{1,2}$ – square of the piston pneumocycline.

We obtain expressions, which characterize the change in pressure as a function of displacement, respectively, for the working and exhaust cavities

$$\frac{dp_1}{dx} = \frac{k}{x_{01}+x}\left[\frac{f_1^{e} K p_m \sqrt{RT_m}}{F_1}\varphi(\delta_1)\cdot\frac{1}{\dot{x}} - P_1\right] \quad (4)$$

$$\frac{dp_2}{dx} = \frac{k}{S+x_{02}-x}\left[\frac{-(f_2^{e} K p_2^{\frac{3k-1}{2k}}\sqrt{RT_m})}{F_2 p_m^{(k-1)/2k}}\cdot\frac{1}{\dot{x}}\varphi\left(\frac{\delta_a}{\delta_2}\right) + P_2\right] \quad (5)$$

where k – air adiabatic coefficient, x_{01}, x_{02} – initial and final coordinate of the piston movement, R – gas constant air, T_m – air temperature, p_m – pressure of the pneumatic line; $\varphi(\delta_1)$ – is cost characteristic of the section.

According equation (5), the pressure in the exhaust cavity is:

$$P_2(x) = (P_1(x)F_1 - m\ddot{x} - P(x))/F_2 \quad (6)$$

After differentiating the P_2 (x) function by the variable x, we have:

$$\dot{P}_2(x) = (\dot{P}_1(x)F_1 - m\dddot{x} - \dot{m}\ddot{x} - \dot{P}(x))/F_2 \quad (7)$$

According equation (4.4) the effective area of the exhaust hole is

$$f_2^e = \frac{\left[P_2 - \frac{dp}{dx}\frac{S + x_{02} - x}{k}\right]\dot{x}F_2 p_m^{(k-1)/2k}}{kp_2^{(3k-1)/2k}\sqrt{RT_m}\,\varphi\left(\frac{\delta_a}{\delta_2}\right)} \tag{8}$$

Thus, having the equations (3-8), which are describing the parameters of the positional pneumatic drive depending on the variable x, we can proceed to the definition of the equations characterizing the movement of the moving load on a fixed flat (Figure 3).

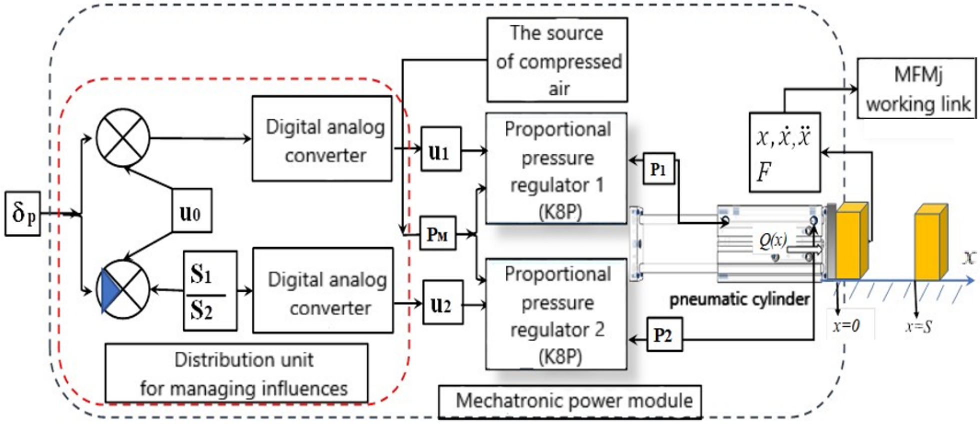


Figure 3. The generalized scheme of the load movement on a fixed flat in the layout with the structural scheme of tracking the piston movement of the pneumocylinder

Figure 3 shows the circuit diagram of the electro-pneumatic positioning actuators of the packing machine. Actuators are built by combining into a single module a pneumocylinder, reliable and inexpensive serial electro-pneumatic distributors of discrete action, precision piston position sensors and a controller that implements the algorithm of digital relay control.

To stop the object at different points, feedback from the continuous action sensor is used that measures the current state of the piston relative to the base value. The pneumomechanical subsystem consists of a piston with a rod, a mechanical control object and equivalent pneumatic springs in the cavities of the pneumocylinder. The control effects, u1 and u2, are on the two pressure control modules, which are implemented programmatically by using the control distribution control block. To achieve high speed drive and obtain the maximum range of force control is advisable to provide a consistent change of effects u1 and u2 in accordance with the equation:

$$\begin{cases} u_1 = u_0 + \delta_p\,, \\ u_2 = (u_0 + \delta_0)\cdot\frac{S_1}{S_2}. \end{cases} \tag{9}$$

This equation is used the input action of the mechatronic FD δ_p and the reference value u_0, which sets the pressure in the cavities of the pneumocylinder at zero input action, taking into account the difference in the piston area from the rod cavity S_1 and the piston-free cavity S_2. The presence of a MFM with a positional actuator is a distinctive feature of the proposed new structure of the mechatronic FD.

Consider the law of movement of the leading link as a part of the mechatronic FD. It requires:

– to find the time T_{on} of load movement in the optimal speed of the two-stage mode to set the required value of x_{Ik} of load movement at the first stage I in a four-stage mode;

- to determine the equations on the basis of the obtained value x_{Ik}, describing the kinematic parameters of the moving load at first stage in the four-stage mode, and also the final conditions for this stage;
- to consider the load movement as a three-stage and to determine the shutdown time of the driving force and the total time of movement. In this case, the final coordinates for the stages I and III of the three-stage mode of motion coincide with the final coordinates for stages I and IV of the four-stage mode of movement;
- to determine the equations describing the load movement at II and IV stages, and then at III stage for a four-stage mode of motion.

This sequence of tasks is connected with determining the initial and final coordinates of the load movement for each stage and with the searching for integration constants.

The time T_{on} of the load movement at optimal speed in two-step mode (Figure 4, 8, a) is determined by the method [9].

$$T_{on} = \sqrt{\frac{2S}{gf(1-m_c gf/Q)}} \quad (10)$$

where S is value of load movement (piston stroke); m_c is load weight; f is the coefficient of friction between the bearing surface of the load and the displacement flat.

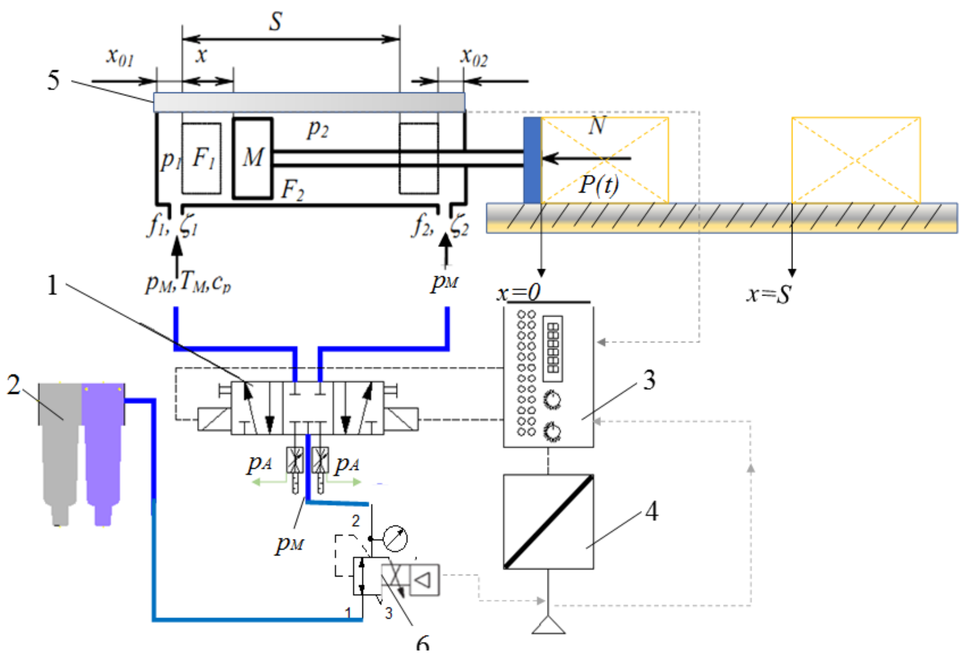


Figure 4. The structured control scheme of the power part of the positional pneumatic actuator with dynamic load:
1 – control divider 5/3 with closed lines in the central position, 2 – air preparation unit, 3 – controller, 4 – control signal converter of the automated control system.

In the Table 1, for ease of use, the equations, describing the kinematic parameters of a moving product (piston) in a four-stage mode, when T and Q_{max} are known.

The changing of parameters of the movement product process on a fixed flat and the operating parameters of the positional actuator when Q_{max} = 20 H; weight of artificial product m_c =0.5 kg; f = 0.3; S = 0.2 m; F_1 = 4,9·10^{-4} m^2; F_2 = 3.77·10^{-4} m^2;

f_1^e is variable, depending on the diameter of the main pipeline; $P_m=5\cdot10^5$ Pa; $m=m_{gr}+m_p$= 0,5+1,5=2 kg, where m_p= 1,5 – the mass of moving parts of the pneumocylinder; $P_{d.tr}$ = 20 N – is the dynamic load of the pneumocylinder is shown in Figure 5.

Table 1

Calculation formulas for determining the kinematic parameters of the moving load by a collision mechanism with a pneumatic actuator in the implementation of the motion law approximating to the optimal velocity

Stage	Calculation formulas
I	Initial conditions: $t = 0;\ x = 0;\ \dot{x} = 0; \ddot{x} = 0$. $\ddot{x}_I = A_1 \cdot \sin(a_1 x)\ \ , a_1 = \frac{\pi}{2x_{I\text{к}}};$ $A_1 = \ddot{x}_{II} \cdot \dot{x}_I = \sqrt{2 \cdot \frac{A_1}{a_1} \cdot (1-\cos(a_1 \cdot x))}$ $t_1 = \int_0^{x_{I\text{к}}} \frac{dx}{\sqrt{2\frac{A_1}{a_1} \cdot (1-\cos(a_1 \cdot x))}}$ Final conditions: $t_{I\text{к}} = t_I;\ \ddot{x}_{I\text{к}} = \ddot{x}_{II};\ x = \ddot{x}_{I\text{к}};\ \ddot{x} = x_{I\text{к}}.$
II	Initial conditions: $t_{II\text{н}} = t_1;\ \ddot{x}_{II\text{н}} = \ddot{x}_{II};\ \dot{x}_{II\text{н}} = \dot{x}_{I\text{к}};\ x_{II\text{т}} = x_{I\text{к}}.$ $\ddot{x}_{II} = \frac{Q}{m} - g \cdot f;\qquad \dot{x}_{II} = \sqrt{\dot{x}^2{}_{I\text{н}} + 2 \cdot ((\frac{Q}{m} - g \cdot f) \cdot (x - x_{II\text{н}}))};$ $t_{II} = \frac{\dot{x}_{II\text{к}} - \dot{x}_{II\text{н}}}{\frac{Q}{m_c} - g \cdot f}$ Final conditions: $t_{II\text{к}} = t_I + t_I;\ \ddot{x}_{II\text{к}} = \ddot{x}_{II};\ \dot{x} = \dot{x}_{II\text{к}};\ x = x_{II\text{к}}$
III	Initial conditions: $t_{III\text{н}} = t_{II\text{к}};\ \ddot{x}_{III\text{н}} = \ddot{x}_{II\text{к}};\ \dot{x}_{III\text{н}} = \dot{x}_{II\text{к}};\ x_{III\text{н}} = x_{II\text{к}}$ $\ddot{x}_{III} = B_3 + A_3 \cdot \sin(q_3 \cdot x + b_3)$ $A_3 = \frac{\lvert\ddot{x}_{II}\rvert + \lvert\ddot{x}_{IV}\rvert}{2};\ B_3 = \frac{\lvert\ddot{x}_{II}\rvert + \lvert\ddot{x}_{IV}\rvert}{2};\ b_3 = \pi - a_3 * x_\tau$ $a_3 = \frac{0.45 \cdot (p_{2n} + p_{2k}) \cdot k \cdot F_2 - \dot{p}_1 \cdot F_1(s + x_{02} - x)}{(s + x_{02} - x) \cdot m \cdot A_3}$ $\dot{x}_{III} = \sqrt{2 \cdot (B_3(x - x_{III\text{н}}) - \frac{A_3}{a_3} \cdot \cos(a_3 \cdot x + b_3) + \frac{x_{II\text{н}}{}^2}{2}}$ $t_{III} = \int_{x_{3\text{к}}}^{x_{3\text{н}}} \frac{dx}{2 \cdot (B_3 \cdot (x - x_{III\text{н}}) - \frac{A_3}{a_3} \cdot \cos(a_3 \cdot x + b_3) + \frac{\dot{x}_{III\text{н}}{}^2}{2}}$ Final conditions: $t_{III\text{к}} = t_I + t_{II} + t_{III};\ \ddot{x}_{III\text{к}} = \ddot{x}_{IV};\ \dot{x} = \dot{x}_{III\text{к}};\ x = x_{III\text{к}}$
IV	Initial conditions: $t_{IV\text{н}} = t_{III\text{к}};\ \ddot{x}_{IV\text{н}} = \ddot{x}_{IV};\ \dot{x}_{IV\text{н}} = \dot{x}_{III\text{к}};\ x_{IV\text{н}} = x_{III\text{к}}$ $\ddot{x}_{IV} = -g \cdot f\ ;\qquad \dot{x}_{IV} = \sqrt{2 \cdot g \cdot f(s - x)};\qquad t_{IV} = {}^{\dot{x}_{IV\text{н}}}/_{g \cdot f}$ Final conditions: $t_{IV\text{к}} = T_r; \ddot{x}_{IV\text{к}} = \ddot{x}_{IV};\ \dot{x}_{IV\text{к}} = 0; x = s$

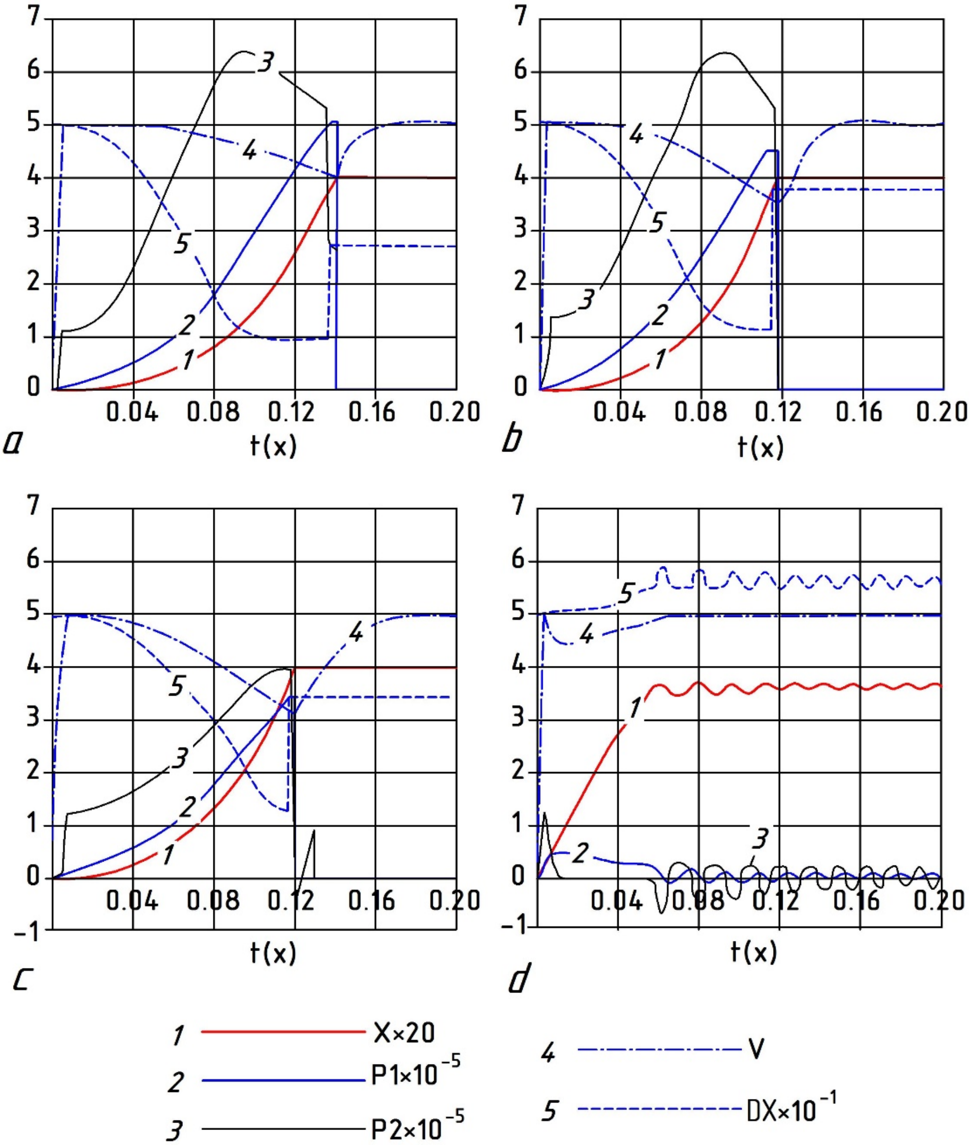


Figure 5. The generalized results of the modeling of the kinematic load and the pressure variation of the working position pneumatic actuator (without taking into account h – the coefficient of viscous friction of the piston in the pneumatic cylinder) with the minimization of the movement time of the artificial product:

a – the diameter of the pipeline is 10mm, $f_1^e = 7.854 \cdot 10^{-5}$ m^2,
b – the diameter of the pipeline is 8 mm, $f_1^e = 5.027 \cdot 10^{-5}$ m^2,
c – the diameter of the pipeline is 6mm , $f_1^e = 2.827 \cdot 10^{-5}$ m^2,
d – the diameter of the pipeline is 4mm , $f_1^e = 1.257 \cdot 10^{-5}$ m^2;

x – the coordinate of the piston movement (m); V – the speed of piston movement (m/s); Dx – the acceleration of piston movement; P_1 – pressure in the piston chamber of the pneumocylinder (Pa); P_2 – the pressure in the rod end of the pneumocylinder (Pa); t – time movement (s).

Thus the resultant of all resistance forces at I, II and III stages of the kinematic links movement:

$$\boldsymbol{P(x) = P_{friction\,force} + (m_c + m_n)\ddot{x} + m_c g f + p_a(F_1 - F_2)} \quad (11)$$

The resultant of all resistance forces at stage IV:

$$\boldsymbol{P(x) = P_{friction\,force} + m_n\ddot{x} + p_a(F_1 - F_2)} \quad (12)$$

Figure 5 shows the graphs of the dependence of kinematic parameters from the time of movement of an artificial product in the implemented mode and the pressure change in the working cavities of the pneumocylinder (the power part of the position actuator).

Conclusion

The output link movement of the experimental MFM, the pneumo-cylinder rod of the electro-pneumatic positional actuator are implemented and mathematically described. The conditions of the initial difference of air pressure are taken into account. The mathematical description of the rod movement law, which is optimal for the speed of action, is obtained. In the obtained results, it is clearly observed that when the exhaust section of the working cylinder of the positional pneumatic actuator is narrowed, the value of the inertial component at stage 4 (deceleration) increases. In addition, given the complexity of the working environment, – compressed air – it is necessary to apply the additional parameters: viscous friction coefficients of the working kinematic pair of piston-rod, resistance coefficients in the exhaust section in the implementation of the fourth stage of motion.

The movement of products on a fixed reference flat by a mechanism of collision with an electro-pneumatic positional pneumatic actuator with consideration of the control system is researched.

The proposed analytical dependences allow:

- to set the working body the law of translational motion, approximating to the optimal speed, without exceeding the maximum permissible dynamic load for the moving load;
- to move the artificial product from the initial position to the final in the shortest possible time for the pneumatic actuator;
- to analyze the existing structures of operating actuators with pneumatic actuators.

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