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Computer Simulation of Electro-Pneumatic Drives for Vertical Motion Mobile Robots

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Abstract

This work is devoted to computer simulation of electro-pneumatic drives for vertical motion mobile robots. These robots are equipped with suction pads to move on walls and ceiling. An output highlights a conflict between the main requirements to such robot drives: simultaneous ensuring of high speed and smoothness of movement of robots with a considerable mass of moved objects. The low efficiency of traditional cushion systems of cylinders is shown in development of such kind of robots. New structure of electro-pneumatic drive for applications with considerable inertia load is developed. This structure represents mechatronic system and consists from the set of on-off valves and computer control device that operates the valves and reaches the optimum motion control of the object with required smoothness. This could be achieved due to the multistep braking in the end of stroke. The paper also represents the mathematical model of developed drive with description of throttle elements, friction forces and details of computer control systems. Mathematical model realized in computer program allows to simulate processes of movement of electro-pneumatic drives.
The results of computer modeling show that developed structure and multistep computer control allows to develop effective electro-pneumatic drives for high-quality and high-speed control of massive objects in the part of vertical motion mobile robots. Developed program represents effective analysis instrument, so it can be used in the process of design engineering.

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Keywords: VMMR; electro-pneumatic drive; non-linear mathematical model; computer simulations

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1. Introduction

Vertical motion mobile robots (VMMR) are effectively used for inspection and manipulation of objects, which are complicated or impossible to access. The most common design of these robots consists of two mobile platforms connected with each other. Each platform has its own vacuum pads and pneumatic drives to fix pads on the inspected surface [1]. One of the platforms may have a manipulator or measurement equipment. The robot developed in MSTU "STANKIN" can be an example of such kind of VMMR (Fig. 1).

Suction pads allow platforms to fix on various flat surfaces. While the first platform is attached to the surface, the second makes the movement using the electro-pneumatic drive.

After that the second platform attaches to the surface, the first may move by the means of another electro-pneumatic drive. That construction allows robot to move on walls and the ceiling of investigating object. Using of suction pads requires vacuum ejectors and compressed air despite the fact that it is a very expensive working body [2], therefore it is reasonable to use pneumatic cylinders for platforms movement. Considering task preferences and conditions solved by VMMR the binary (on-off) pneumatic drives are preferred.

The efficiency of VMMR increases dramatically with their speed increase. This is achieved through the speed increase of its pneumatic drives. Total time of VMMR movement consists of acting times of every pneumatic drive, mobile platform drives and pad drives. Therefore the time of mobile platforms movement has the greatest influence on the cycle time. For the average robot speed of 50 mm/sec or more with the stroke of 250 mm the longitudinal cylinders movement time must be not more than 1 sec. This allows calculating the average speed of the cylinders, which is 250 mm/sec. That is 5 times greater than average robot speed.

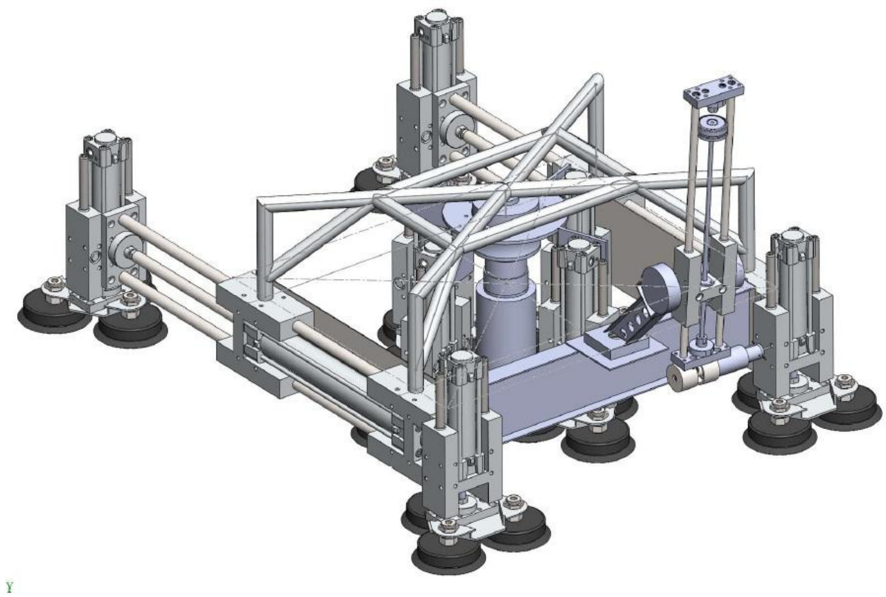

Fig. 1. Example of vertical motion mobile robots.

The first and the most important requirement is to organize the reliable robot fixation. That is why very important to limit dynamic forces, providing smooth starting and braking in the end of the stroke without rebounds and shocks. Ensuring the safe work of the robot requires to limit dynamic forces of one cylinder to 500 N and the speed in the end to 120 mm/sec.

The second requirement is the mobile platform mass minimization. To fulfill this requirement it is important to use cylinders with minimum possible diameter. These cylinders also allow to air economy, which is important not only for mobile robots [2]. Current robot model uses the cylinders with piston diameter of 50 mm thus weight of mobile platforms is 30 kg and 70 kg. The ratio of required movement time (average speed), object mass and the cylinder diameter bring a problem of safe braking in the end of the stroke. It is determined that the speed of massive objects in such tasks makes oscillation while the piston is running [3]. Therefore the dynamic forces in the movement process can be great, so piston with connected object can reach the cap without controlled speed and cause the shock, which could lead the separation of suction pads from the surface and falling of robot. It is visible that the requirements of the increasing and minimizing of dynamic forces are inconsistent. Implementation of drives requirements is difficult in these conditions.

STANKIN experience in using of standard pneumatic cylinders with integrated braking system tells that they aren't match for such kind of tasks in VMMR. These braking systems allow isolating the volume with compressed air in the end of the stroke and exhausting the air through the throttle tight in right way. The disadvantage of such systems consists in appearing of large dynamic and shock loads caused by very intensive braking, especially if the braking direction aligns with the gravity direction.

The conducted researches tells that the solving of such task consists in creating the structure of electro-pneumatic drives as a mechatronic systems, equipped with valves, throttles, sensors and microcontroller. There are two possible approaches to the problem of control of the pneumatic actuator. The first one is based on the use of proportional valves and continuous control laws. The implementation of this approach uses a proportional-integral regulators and may require non-linear control laws and technology of intelligent control [5, 6, 7]. The second approach is based on the use of on-off valves and discrete control laws that implement multistage braking. Its implementation is less expensive, because of on-off valves that are very simple, reliable and cheap [3, 4] in comparison with known solutions that contain proportional valves. Thus, it is obvious that for creation of discrete pneumatic drives of such kind's mobile robots the second approach is more preferable.

These electro-pneumatic drives represent sophisticated non-linear dynamic systems. Developing of such kind of systems requires detailed mathematical models and computer simulating programs that represent the effective instrument for analysis of properties of VMMR. The special attention in this article is paid to computer simulation of high-speed mechatronic electro-pneumatic drives for VMMR. It is necessary to note that these researches were financed by Ministry of Science of Russia Federation within the state task in the sphere of scientific activity.

2. The structure of high-speed mechatronic electro-pneumatic drive for massive objects with high smoothness of movements

It is offered to create the electro-pneumatic drive with computer control and position feedback for high-speed and smooth movement of VMMR's mobile platform. The structure of such drive is shown at Fig. 2. The drive is aligned the principles of mechatronic. This design gives the following advantages:

- high speed of the massive object
- limit dynamic loads in the process of movement by realizing of multistage braking at the end of the stroke

This drive of VMMR is more complex than the standard cyclic drive. But the use of this drive is reasonable for reaching the higher quality values, which can be achieved by fusion of more complex hardware executive part and software of the mechatronic system.

The strength part of the drive consists from two pneumatic cylinders which can act on the mechanical control target (CT - moving platform of VMMR), electro-pneumatic control unit (ECU) and supply pressure device. In ECU consists of following elements:

- Valve V, that can change the direction of movement
- The group of valves V1…VN that can switch-on or switch-off the throttles
- The throttles T1...TN on the exhaust, that determine the speed of the pistons in cylinder and connected CT

The informational part of the drive represented with position sensor that measures the control target position. Position sensor can be continuous or can represent the set of on-off sensors, for example, sealed contacts or Hall sensors. Computer control unit (CCU) is the PLC or another control device that has the ADC converter for the position sensor and the set of digital outputs that can generate signals for on-off valves in the electro-pneumatic control unit.

The number of valves determine amount of the braking stages, the flow rates of throttles determine the intense of braking. These characteristics are chosen according to the features of specific task and drive requirements. The experience in these drives usage shows that for majority of tasks it is enough to have two or three stages braking.

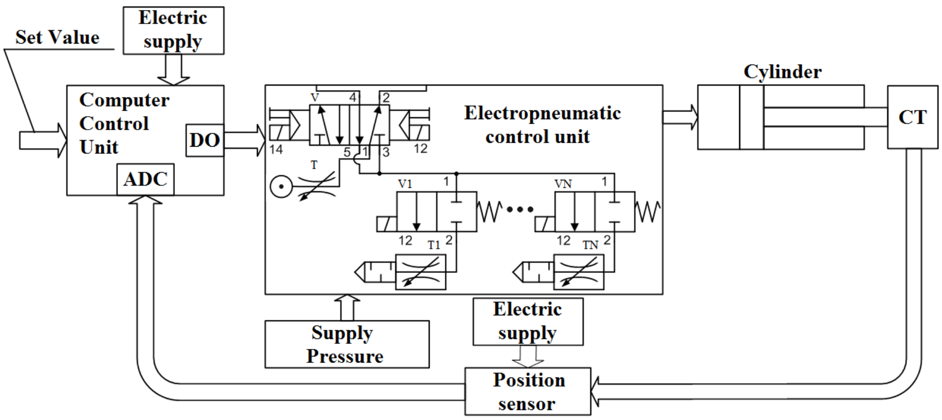

Fig. 2. VMMR drive structure for massive objects movement.

The main role of movement management is assigned to hardware and software parts of computer control unit. This unit executes the algorithm which uses the information from position sensor. The algorithm forms binary signals on valves in real-time. That allows reaching the main goal – high-speed and smooth movement of massive object without shocks and rebounds in the end of movement.

The schematic diagram of the strength part of the drive is represented on Fig. 3.

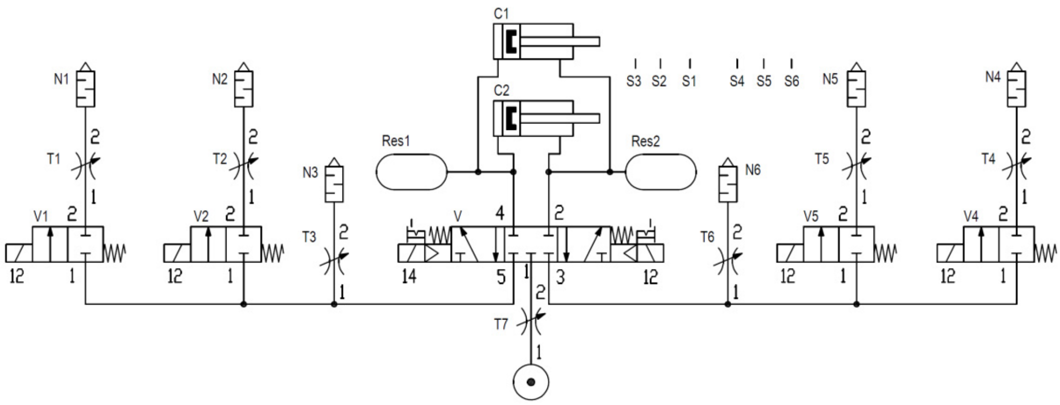

Fig. 3. The schematic diagram of the strength part of the drive.

Where:

- C1 and C2 – pneumatic magnetic cylinders without internal braking systems, that means without damping seal, plug and without screw at the cap.
- S1…S6 – the set of on-off sensors with electric output. These sensors can be integrated in the body of cylinder. Each sensor determine the moment of switching-off the throttle in according valve.
- V – closed centered valve 5/3 structure, that provide changing of direction of pneumatic cylinders and emergency closing of chambers.

- T3 and T6 – throttles, that acting in the second braking stage while moving in and moving out.
- V1, V2, V4, V5 – valves 2/2 structure, that provide switching off the throttles T1, T2, T4, T5 from the exhaust chamber when the signal from sensors S1, S2, S4, S5 is reached. Valves V1 and V2 switching off throttles T1 and T2 on a signal from sensors S1 and S2 when the platform with weight 70 kg is moving (moving in), valves V4 and V5 switching off throttles T4 and T5 on a signal from sensors S4 and S5 when the platform with weight 30 kg is moving (moving out).
- T7 – inlet throttle.

Moving out is provided by generating signals on the valves V4, V5 and left coil of V, so all three throttles – T4, T5, T6 – are connected with the exhaust chamber. When the signal from sensor S4 is reached, throttle T4 is switching off. And when the signal from sensor S5 is reached, throttle T5 is switching off. As a result, piston reaches the front cap with only one connected throttle – T6.

Moving in is provided by generating signals on the valves V1, V2 and right coil of V, so all three throttles – T1, T2, T3 – are connected with the exhaust chamber. When the signal from sensor S1 is reached, throttle T1 is switching off. And when the signal from sensor S2 is reached, throttle T2 is switching off. As a result, piston reaches the front cap with only one connected throttle – T3.

Res1, Res2 – additional volumes in both pneumatic chambers. Using of such kind of additional volumes helps to minimize the dynamic forces in the process of braking and starting.

3. Mathematical model

The mathematical model used for analyze of electro-pneumatic drives for VMMR is based on the research results dedicated to industrial pneumatics [5, 8-10], cyclic and servo pneumatic drives with computer control working in both position and tracking modes [3, 4, 11-13]. This non-linear model considers special internal processes in pneumatic, electric, mechanical and computer parts of the mechatronic electro-pneumatic drive.

This model is based of four differential equations that describe dynamic of pressures in pneumatic chambers and specify the process of movement of the mechanical control target. Below you can see the system of differential equations in standard form:

$$\begin{cases} \dfrac{dx}{dt} = v, \\ \dfrac{dv}{dt} = \dfrac{F}{m}, \\ \dfrac{dP_1}{dt} = n \cdot \dfrac{R \cdot T \cdot G_1 - P_1 \cdot A_1 \cdot v}{V_{01} + A_1 \cdot x}, \\ \dfrac{dP_2}{dt} = n \cdot \dfrac{-R \cdot T \cdot G_2 + P_2 \cdot A_2 \cdot v}{V_{02} - A_2 \cdot x}, \end{cases} \tag{1}$$

where x – coordinate of the piston; v – speed of the piston; P_2, P_2 – pressures in chambers; A_1, A_2 – area of piston in both chambers; m – mass of control target; R – universal gas constant; T – temperature of the compressed air; V_{01}, V_{02} – start volumes of the chambers; n - coefficient of polytropy; F – the force on the output of the special developed algorithm that calculate the acting force on the piston. This algorithm allows the correct description of the Coulomb friction influence on the pneumatic cylinder piston movement and stop processes.

Compressed air mass consumptions G_1 и G_2 are calculated in function of the pressures on the according throttle element inlet and outlet using of non-linear equations:

$$G = \begin{cases} f_{\mathrm{E}} \cdot P_{IN} \cdot \sqrt{\dfrac{2}{R \cdot T} \cdot \dfrac{P_{OUT}}{P_{IN}} \cdot \left(1 - \left(\dfrac{P_{OUT}}{P_{IN}}\right)\right)}, \text{ if } \dfrac{P_{IN}}{2} < P_{OUT} < P_{IN}, \\ f_{\mathrm{E}} \cdot P_{IN} \cdot \sqrt{\dfrac{1}{2 \cdot R \cdot T}}, \text{ if } 0 < P_{OUT} < \dfrac{P_{IN}}{2}, \\ -f_{\mathrm{E}} \cdot P_{OUT} \cdot \sqrt{\dfrac{2}{R \cdot T} \cdot \dfrac{P_{IN}}{P_{OUT}} \cdot \left(1 - \left(\dfrac{P_{IN}}{P_{OUT}}\right)\right)}, \text{ if } P_{IN} < P_{OUT} < 2P_{IN}, \\ -f_{\mathrm{E}} \cdot P_{OUT} \cdot \sqrt{\dfrac{1}{2 \cdot R \cdot T}}, \text{ if } P_{OUT} \geq 2P_{IN}. \end{cases} \tag{2}$$

where G – Compressed air mass consumption through the orifice (valve, throttle etc.); P_{IN}, P_{OUT} – pressures on the inlet and outlet of the orifice; f_{E} – effective square of the orifice. The equations consider the direction of the flow through the orifice and therefore are more suitable for computer modeling.

The mathematical model also considers the delay of the on-off valve, computer control device and the electro-pneumatic control unit, description of time sampling which is typical for computer control devices.

4. Computer simulation program

The developed non-linear mathematical model is realized as computer simulating program. The code is written on the programming language C++ in the Microsoft Visual Studio software. This program is solving the system of non-linear equations, saving and printing results. Program user-friendly interface provides the means of interactive user-machine communication. The main program window allows changing any electro-pneumatic drive parameter. The calculation results are shown in two diagrams: «position in time» and «velocity in time». Fig. 4 shows the program main window example. It includes the input data and the position in time diagram. As an option user can zoom necessary limit of the modeling process and study the process in details. Also the user can find detailed calculations in the saved file in .XLS format. The file stores every variable of a mechatronic system conditions. This data could be used for reports or presentations. User can also change the step of integration and the step of data saving.

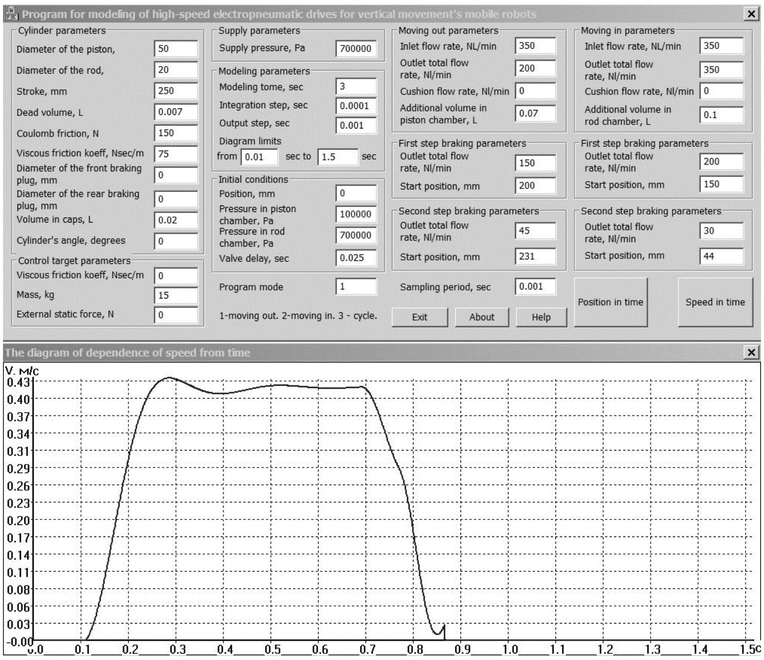

Fig. 4. The main window of the program with basic data and the results of simulation.

This simulation program was tested as a tool for developing the electro-pneumatic drives for different industries. It is noted that using of this program can help to reduce drive development time. Design engineer can examine the wide range of the structures (cylinder with standard cushion system, one stage braking algorithm, multistage braking algorithm) and choose the optimal structure and control algorithm that will help to reach required cycle time or quality of the braking processes. The program helps to adjust required flow rates of the throttles and identify the positions of the sensors.

5. Simulation results

A number of computer simulations using the developed model [12] show following results. First of all, in the process of high-speed movement of massive platforms in VMMR velocity of control target is no longer constant like in classic throttle control. Velocity oscillates and the piston can reach standard braking system with uncontrolled value of the speed. When piston with connected massive object enters standard cushion system pressure in the isolated dumping chamber starts to grow very quickly. It causes the acceleration increase and dynamic forces that are influencing the suction pads. For example two standard pneumatic cylinders with vertical installation in VMMR develop acceleration 16 m/s2 (see Fig. 5). If connected platform mass is 70 kg, dynamic force influencing the suction pads is 1120 N. The conclusion – VMMR can't functional correctly because of force value limits. Besides, there are rebounds and following after that shocks of piston into the cap that can easily damage the cap of the cylinder and connected to it mechanical parts.

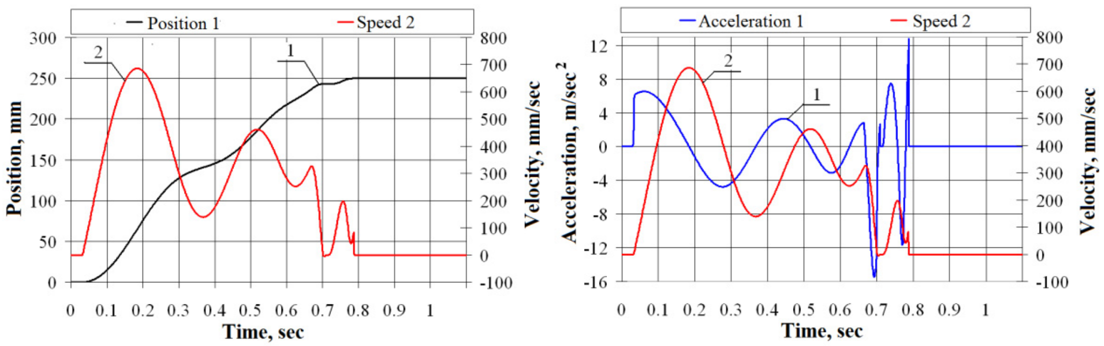

Fig. 5. The diagram of dependence of position + velocity in time (left) and acceleration + velocity in time (right), VMMR is moving up on vertical surface.

Analyzing simulation results show that disadvantages of standard cushion systems are caused by several factors.

First of all standard cushion system contains cushion plug and seal, when plug enters the seal the volume of exhaust chamber isolates and decreases in step way that leads to fast increasing of derivative of pressure at the start of the braking process. Length of the brake plug is insufficient and limited for constructive reasons. In this case using of small cylinder with massive object on high-speed control makes us to tight damping screws hardly to decrease the velocity. The result is processed as in Fig. 5. In this conditions using of minimal diameter and massive object not allowed to achieve necessary pneumatic spring rate and damping in the end of the stroke. That is why using of traditional control methods of pneumatic drives increase the risk of fall of VMMR from vertical surface.

In the process of computer simulation of mechatronic electro-pneumatic drive optimal values of strength and control parts of the drive were achieved. Flow rates of throttles according to fig. 3: T1 – 50 Nl/min; T2 – 105 Nl/min; T3 – 45 Nl/min; T4 – 150 Nl/min; T5 – 170 Nl/min; T6 – 30 Nl/min; T7 – 350 Nl/min. Volumes of reservoirs: Res1 – 70 ml (with connecting tubes); Res2 – 100 ml (with connecting tubes).

Coordinates for sensors: 0 mm – position of sensor S3 that signal that piston is at the left cap; 44 mm – position of sensor S2 that signal about switching off the throttle T2 when cylinder is moving in; 150 mm – position of sensor S1 that signal about switching off the throttle T1 when cylinder is moving in; 200 mm – position of sensor S4 that signal about switching off the throttle T4 when cylinder is moving out; 231 mm – position of sensor S5 that signal about switching off the throttle T5 when cylinder is moving out; 250 mm – position of sensor S6 that signal that piston is at the right cap.

Results of simulation also can be represented in diagrams that are shown on Fig. 6…9. These diagrams correspond to cylinder moving processes with diameter 50 mm, stroke 250 mm, with mass 30 kg (first step of the robot's moving cycle) and with mass 70 kg (second step of the robot's moving cycle) with various orientation of the control target. Each cycle as mentioned before consists from two movements with different masses.

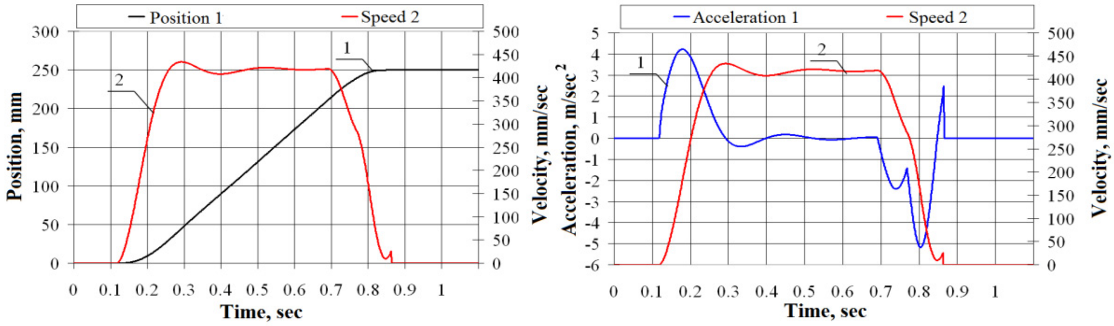

Fig. 6. The diagram of dependence of position + velocity in time (left) and acceleration + velocity in time (right), VMMR is moving on vertical surface in horizontal way (moving out, mass 30 kg).

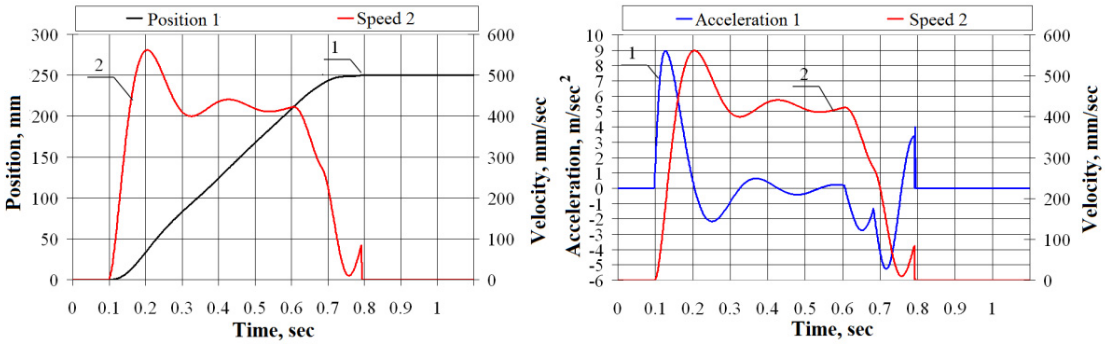

Fig. 7. The diagram of dependence of position + velocity in time (left) and acceleration + velocity in time (right), VMMR is moving on vertical surface in vertical way down (moving out, mass 30 kg).

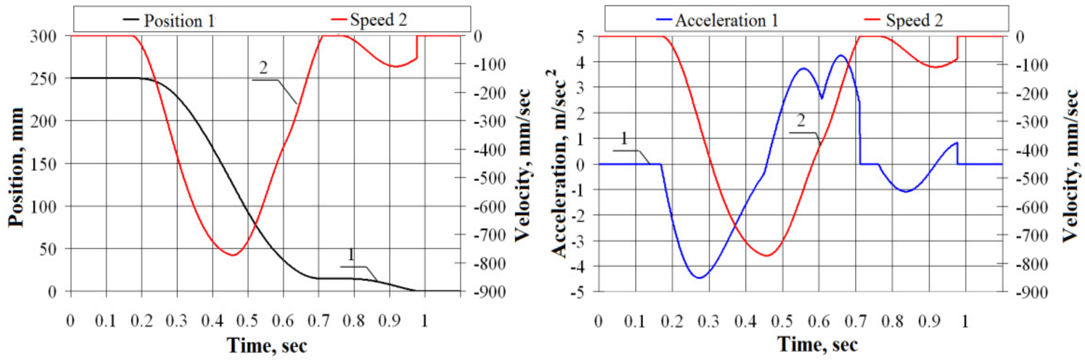

Fig. 8. The diagram of dependence of position + velocity in time (left) and acceleration + velocity in time (right), VMMR is moving on vertical surface in horizontal way (moving in, mass 70 kg).

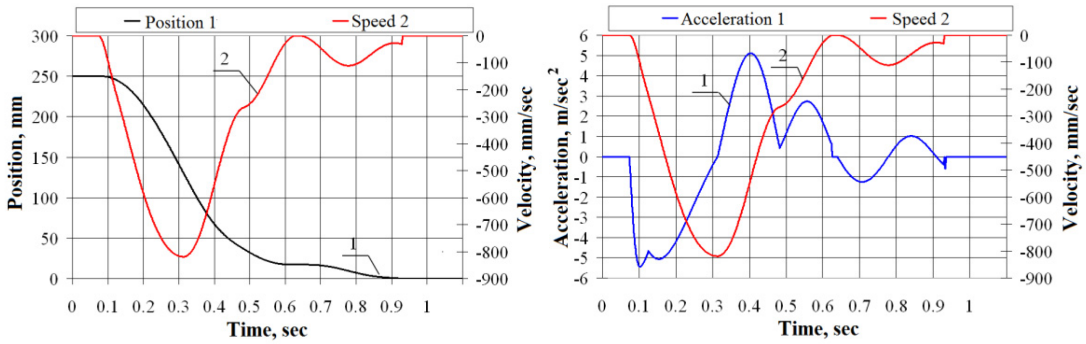

Fig. 9. The diagram of dependence of position + velocity in time (left) and acceleration + velocity in time (right), VMMR is moving on vertical surface in vertical way down (moving in, mass 70 kg).

Fig 9. shows the very specific dependence of acceleration in time at the beginning of the movement (see process on 0,12 sec). This type of acceleration curve explains by inclusion in computer control algorithm special delay to activate throttles T1 and T2 when moving in. After signal generates, valve V is switching to the right position and the air can exhaust from the rodless chamber only through the orifice of throttle T3. After delay in 100 ms throttles T1 and T2 are activated too. Results of computer simulation testifies that including of such kind of delay can decrease dynamic loads at the start of the movement more than twice when the direction of movement coincides with gravity.

It is important to note that application of VMMR means the change of the angle α of axis of pneumatic cylinders concerning the horizon. That causes changing of forces acting on the object connected with rod.

Results of computer simulation with different orientation of mobile platform concerning the horizon represented in Table 1 for different stages of the movement. α – is an angle of orientation of platform and pneumatic cylinders. If $\alpha = 0^{O}$ – it is a horizontal orientation, if $\alpha = 90^{O}$ – vertical orientation, rod upside, if $\alpha = -90^{O}$ – vertical orientation, rod downside. In table 1 we can find the speed of piston when it contacts the cap, maximum dynamic load while the braking process and time of the movement when cylinder is moving in and moving out. Structure, parameters of the drive and adjustments of throttles are invariable.

Table 1. Results of computer simulation with using of cylinder diameter 50 mm and various angles of orientation.

□, ^{O}	Moving out (30 kg)			Moving in (70 kg)		
90	97 mm/sec;	170 N;	0,92 sec.	31 mm/sec;	371 N;	0,93 sec.
60	68 mm/sec;	173 N;	0,92 sec.	38 mm/sec;	343 N;	0,95 sec.
30	30 mm/sec;	173 N;	0,89 sec.	29 mm/sec;	336 N;	0,97 sec.
0	59 mm/sec;	173 N;	0,88 sec.	80 mm/sec;	315 N;	0,97 sec.
-30	88 mm/sec;	177 N;	0,83 sec.	106 mm/sec;	336 N;	1,03 sec.
-60	106 mm/sec;	204 N;	0,80 sec.	59 mm/sec;	343 N;	1,07 sec.
-90	108 mm/sec;	238 N;	0,79 sec.	79 mm/sec;	340 N;	0,91 sec.

If we choose diameter of piston 50 mm the time of one movement is less than 0,92 sec for moving out and 1,07 sec for moving in, dynamic braking load limit in ranges 170 … 371 N, velocity in the moment of contact of piston and the cap is less than 108 mm/sec – that is acceptable for such kind of VMMR.

Thus, results of computer modeling testify the possibility to achieve the high-speed and smooth movement of VMMR drives using the mechatronic electro-pneumatic drive of longitudinal movement. The results of this research were successfully used in the development process of real VMMR sample, which is capable to transfer the object with weight up to 50 kg.

6. Summary and conclusions

We see that the possibility of cushion systems of standard pneumatic cylinders limited. These systems can't provide required absence of shocks in the end of the stroke and smoothness of movements when they integrated in vertical movement's mobile robots (VMMR).

The offered structure and principal diagram must be used for the development of high-speed electro-pneumatic drives for vertical motion mobile robots with high smoothness.

These drives represent mechatronic systems and allow making flexible multistage braking in the end of the stroke; they allow achieving high-speed movement at simultaneous restriction of dynamic braking loads and essential decrease of velocity of the piston at the end of a stroke.

Diameter of the cylinder in such drives must be chosen not only with considering of the weight of mobile platform, but with analyzing of dynamic issues of movement with massive object. For the considered vertical motion mobile robot dynamic braking loads must be less than 500 N – this can be achieve only with using of cylinder with piston not less than 50 mm.

The using of flexible system of throttles for multistage braking together with additional reservoirs and absence of the cushion seal allows reducing the frequency of oscillation of the speed in the braking zone. That provides reducing in several times of dynamic braking loads with comparison with standard cushion (braking) systems integrated in cylinders.

The computer simulation program represents effective means of development of high-speed electro-pneumatic drives for massive objects. It helps to choose the structure and parameters of the drive. It is strongly recommended in the process the VMMR electro-pneumatic drives development for calculating of effective diameter of the piston, number of braking stages, flow rates of throttles, positions of sensors, supply pressure and for testing of computer control algorithms.

The offered structure and principal diagram will be used for the development of the real prototype of the high-speed electro-pneumatic drive for vertical motion mobile robots for making an experimental researches. These experiments will show us the issues of the using of offered math models, methods and computer program. That will help us to modify and improve all of it. The math model is also required detailed description of the friction force and the thermodynamic processes in the compressed air.

The second important part is that the solution, described in this article for vertical motion mobile robots will become the basis for developing of universal method for creation of high-speed electro pneumatic drives for smooth movement of massive objects. Having of such type of method in software realization will dramatically reduce the time of developing of such kind of pneumatic drives.

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