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Experimental Study on Positioning Accuracy of an Automated Long-Stroke Rodless Pneumatic Actuator

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Abstract

Introduction. In modern industrial processes, pneumatic actuators with long-stroke movements play an important role. However, their use is limited by low accuracy resulting from the difficulties of controlling air flows. These limitations are caused by the compressibility of air and thermodynamic processes, which makes it urgent to improve the accuracy of such systems. The conducted analysis of scientific literature shows that modern research is mainly focused on the use of systems with standard cylinders with a working stroke limited to three meters. At the same time, the issues of development and research of long-stroke systems of rodless pneumatic drives, capable of having a stroke length of up to six meters, remain insufficiently studied. The introduction of advanced control systems in this type of drives involves significant investments in a high-tech electronic base and additional structural elements. In this regard, the development of fundamentally new technical solutions that allow for the efficient operation of mechanisms with a working stroke of more than three meters while maintaining the required technical parameters and economic efficiency, is of particular relevance. In the framework of previous studies, the author proposed a design of a pneumatic drive for long-stroke movements, equipped with a unique control system based on a jet sensor and an external brake mechanism. Its mathematical modeling and theoretical analysis were also performed, which made it possible to identify key factors affecting the accuracy of positioning. To validate the mathematical model and the hypotheses put forward, the objective of this research is to experimentally verify the results of mathematical modeling of a positional long-stroke rodless pneumatic actuator, as well as to confirm the degree of influence of key factors on positioning accuracy.

Materials and Methods. The work involved a stand that was a technical model of a pneumatic drive with an original control system, including a jet sensor and an external brake device. To verify the operability and accuracy of the jet sensor readings, the spillage method was applied using the Camozzi MF4008-10-R-BV-A flow sensor after the element under study, and Camozzi SWCN-P10-P3-2 pressure sensors placed before and after the considered element. The tests conducted on the developed jet sensor showed high reliability and stability of operation in various operating modes. The experimental study of a long-stroke rodless pneumatic actuator included evaluation of the actuator's technical capabilities, analysis of positional cycles, study on the effect of external factors, and comparison of the results of computational and full-scale experiments. The results of computational and full-scale experiments were processed using the Mathcad and MATLAB software packages. The dependences of positioning accuracy on mass and stroke length were constructed.

Results. The reliability of the model was established at the level of the maximum discrepancy between the experimental data and the results of mathematical modeling, which amounted to 18%. That confirmed the adequacy of the developed model for engineering calculations. The effect of the load mass on the accuracy of positioning was experimentally established. With an increase in mass from 10 to 30 kg, the accuracy decreased by 1.47 times, and with a mass of 60 kg, the accuracy deteriorated by another 1.37 times relative to the base mass of 10 kg. In addition, the effect of stop coordinates was studied: the dependence of positioning accuracy on the position of the actuator was established. When moving from 0.1 m to 0.22 m, the accuracy deteriorated by 3.2 times, but with further movement to 0.35 m, it improved by 2.2 times.

Discussion. The conducted experimental studies allowed achieving good results in the development of long-stroke pneumatic drives. Successful verification of the mathematical model confirmed the correctness of both the model itself and the theoretical studies conducted in the author's previous works. The positioning accuracy of the drive of 77 microns at a distance of over three meters was reached. This indicator significantly exceeds the results presented in the studies of other authors, which shows the high potential of the developed design. The economic efficiency of the proposed solution is due to the absence of an electronic component base in the control system. This not only reduces initial production costs, but also significantly simplifies maintenance of the drive under operation. The comparative analysis with existing developments confirms the superiority of the proposed system in terms of cost criteria.

Conclusions. The conducted studies confirmed the efficiency of the developed solutions for a long-stroke rodless pneumatic actuator. Practical significance of the study is determined by the possibility of using the obtained results in creating high-precision long-stroke mechanisms in various industries. The developed design can be used in automated production lines, robotic complexes, and other areas where precise positioning over significant distances is required. Promising areas for further research are the optimization of the control system parameters to reach even higher positioning accuracy, and the development of calculation methods for positional long-stroke pneumatic drives.

Keywords: jet control system for a rodless pneumatic actuator, rodless long-stroke pneumatic actuator, positioning of a pneumatic actuator, pneumatic sensor for a rodless pneumatic actuator

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Оригинальное эмпирическое исследование

Экспериментальное исследование точности позиционирования автоматизированного длинноходового бесштокового пневмопривода

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Аннотация

Введение. В современных промышленных процессах пневматические приводы с длинноходовыми перемещениями играют важную роль. Однако их использование ограничено низкой точностью, вызванной сложностями управления воздушными потоками. Эти ограничения обусловлены сжимаемостью воздуха и термодинамическими процессами, что делает актуальной задачу повышения точности таких систем. Проведённый анализ научной литературы показывает, что современные исследования в основном сосредоточены на применении систем со стандартными цилиндрами, рабочий ход которых ограничен тремя метрами. В то же время вопросы разработки и исследования длинноходовых систем бесштоковых пневмоприводов, способных иметь длину хода до шести метров, остаются недостаточно изученными. Внедрение усовершенствованных систем управления в такие приводы связано со значительными инвестициями в высокотехнологичную электронную базу и дополнительные конструктивные элементы. В связи с этим особую актуальность приобретает разработка принципиально новых технических решений, позволяющих эффективно эксплуатировать механизмы с рабочим ходом более трёх метров при сохранении необходимых технических параметров и экономической эффективности. В рамках предыдущих исследований автором была предложена конструкция пневмопривода длинноходовых перемещений, оснащённая уникальной системой управления на базе струйного датчика и внешнего тормозного механизма; также было выполнено его математическое моделирование и теоретический анализ, что позволило выделить ключевые факторы, влияющие на точность позиционирования. Для подтверждения адекватности математической модели и выдвинутых гипотез целью настоящей работы является экспериментальная верификация результатов математического моделирования позиционного длинноходового бесштокового пневмопривода, а также подтверждение степени влияния ключевых факторов на точность позиционирования.

Материалы и методы. В работе был использован стенд, представляющий собой техническую модель пневмопривода с оригинальной системой управления, включающей струйный датчик и внешнее тормозное устройство. Для верификации работоспособности и точности показаний струйного датчика был применён метод проливки с использованием датчика расхода Camozzi MF4008-10-R-BV-A, установленного после исследуемого элемента, а также датчиков давления Camozzi SWCN-P10-P3-2, размещённых перед и после исследуемого элемента. Проведённые испытания разработанного струйного датчика продемонстрировали высокую надёжность и стабильность работы в различных эксплуатационных режимах. Экспериментальное исследование длинноходового бесштокового пневмопривода включало в себя: оценку технических возможностей привода, анализ позиционных циклов,

изучение влияния внешних факторов и сравнение результатов вычислительных и натурных экспериментов. С помощью пакета прикладных программ Mathcad и Matlab обрабатывались результаты вычислительного и натурального экспериментов, а также были построены зависимости точности позиционирования от массы и длины хода.

Результаты исследования. Достоверность модели была установлена на уровне максимального расхождения между экспериментальными данными и итогами математического моделирования, составившего 18 %, что подтверждает адекватность разработанной модели для инженерных расчетов. Экспериментально установлено влияние массы груза на точность позиционирования. При увеличении массы с 10 до 30 кг точность снижается в 1,47 раза, а при массе в 60 кг точность ухудшается еще на 1,37 раза относительно базовой массы в 10 кг. Кроме того, исследовано воздействие координат остановки: установлена зависимость точности позиционирования от положения исполнительного элемента. При перемещении от 0,1 м до 0,22 м точность ухудшается в 3,2 раза, однако при дальнейшем перемещении до 0,35 м она улучшается в 2,2 раза.

Обсуждение. Проведенные экспериментальные исследования позволили добиться хороших результатов в области разработки длинноходовых пневмоприводов. Успешная верификация математической модели подтверждает корректность как самой модели, так и теоретических исследований, проведенных в предыдущих работах автора. Достигнута точность позиционирования привода 77 мкм на дистанции свыше трех метров. Этот показатель существенно превосходит результаты, представленные в исследованиях других авторов, что свидетельствует о высоком потенциале разработанной конструкции. Экономическая эффективность предложенного решения обусловлена отсутствием электронной компонентной базы в системе управления. Это не только снижает первоначальные затраты на производство, но и существенно упрощает техническое обслуживание привода в процессе эксплуатации. Сравнительный анализ с существующими разработками подтверждает превосходство предложенной системы по критерию затрат.

Заключение. Проведенные исследования подтвердили эффективность разработанных решений для длинноходового бесштокового пневмопривода. Практическая значимость исследования определяется возможностью применения полученных результатов при создании высокоточных длинноходовых механизмов в различных отраслях промышленности. Разработанная конструкция может быть использована в автоматизированных производственных линиях, робототехнических комплексах и других областях, где требуется точное позиционирование на значительных расстояниях. Перспективными направлениями дальнейших исследований являются оптимизация параметров управляющей системы для достижения еще более высокой точности позиционирования и разработка методик расчета позиционных длинноходовых пневмоприводов.

Ключевые слова: струйная система управления бесштоковым пневмоприводом, бесштоковый длинноходовой пневмопривод, позиционирование пневмопривода, пневматический датчик бесштокового пневмопривода

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Introduction. The efficiency of the drives used in modern processing equipment is determined by the speed of movement of the actuating element along the coordinate axes, and the accuracy of positioning the actuators of the drive in real time during the implementation of the required work cycles [1]. These cycles, as a rule, consist of a rapid approach of the actuator, its deceleration to the positioning speed, precise stopping, and rapid withdrawal [2].

Pneumatic drives are characterized by high speed of movement and protection against fire. They also have explosion safety, environmental friendliness, reliability and flexibility in confined spaces [3]. They are effectively used in mechanical engineering, as well as in the food, chemical and woodworking industries, where the combination of speed and positioning accuracy of the power elements of the drive is important [4].

Modern transport and production machines are equipped with various actuators based on pneumatic drives [5]. Such systems are constantly subject to ever higher demands on the speed, accuracy and reliability of their operation [6]. In this context, pneumatic automation offers universal approaches to the control of similar systems.

Most modern industrial drive equipment operates on the basis of automatic pneumatic drives with long-stroke movements of the actuators [7]. These industrial positioning drives guarantee positioning accuracy of about 1% (in some special designs, it can reach up to 0.4%) of the maximum stroke length. This has a negative impact on the accuracy of pneumatic long-stroke drives [8]. Air compressibility and complex thermodynamic processes occurring in air flows have a significant impact on the control of air flows in the drive lines and cavities of the pneumatic cylinder, which limits the positioning accuracy of the drive [9].

Research by D.V. Shilin [10] demonstrated that the implementation of a hybrid control system significantly increased the accuracy of positioning the carriage of a rodless pneumatic cylinder. Experiments made it possible to reduce the error to 0.2% of the stroke length, which was a good result. In [11], the authors proposed a new controller circuit based on fuzzy logic, used to monitor the actuator trajectory following of a robot manipulator with two degrees of freedom.

A promising direction is the development of flexible rodless pneumatic cylinders for long-stroke McKibben-type actuators [12]. Pneumatic cylinders with a self-holding function were tested, providing precise positioning even without applying pressure. Dao The Anh [13] developed and investigated an automated positioning pneumatic actuator with increased accuracy and operating speed, identifying the dependence of the actuator characteristics on the mass of the objects being moved, the deceleration coefficient, relative displacement, and braking force.

Paper [14] presents an adaptive second-order sliding mode tracking control scheme for robotic manipulators. A new control law is proposed that allows for the transition of the robotic manipulator trajectories from all initial conditions to the switching surface of the proportional-integral derivative in a finite time with subsequent retention on this surface.

There is a jet positioning numerical control system [15] based on a cylinder with a piston and a rod connected to a measuring scale. The system uses a “nozzle-receiving channel” sensor to generate a control signal. The device operates on a pneumatic sensor that measures the gap between the sensor and the inclined measuring bar, whose angle is adjusted by a screw. The sensor output is connected to the control input of a threshold device that generates a signal to stop the piston, whose position is adjusted by a throttle [15].

The key drawback of the modern technical solutions under consideration is that they are designed exclusively for the use of standard cylinders [16] with a working stroke not exceeding three meters. When attempting to implement mechanisms with an increased stroke of over three meters, developers encounter a set of serious technical obstacles [17]. The main problem is that to provide the functioning of such systems, it is required to modernize the control system, which causes a significant increase in the costs of manufacturing the end product. The increase in cost occurs in two main areas: the first is associated with the introduction of more complex control electronics, the second is due to the need for additional elements for reliable operation at increased distances [18]. Under such conditions, it is critically important to create an innovative approach capable of effectively solving problems associated with long strokes (more than three meters). At the same time, the new solution must not only provide the required technical characteristics, but also remain economically justified for potential users, while maintaining a high level of operational qualities [19].

This research objective was to experimentally verify the results of mathematical modeling of a positioning long-stroke rodless pneumatic actuator, as well as to confirm the degree of influence of key factors on positioning accuracy.

Materials and Methods. Experimental studies were aimed at validating the results obtained through the mathematical modeling of pneumatic drive systems, which was carried out earlier in paper [8].

During preliminary calculations, the element base of the stand was selected, and its assembly drawing was made, which is presented in Figure 1.

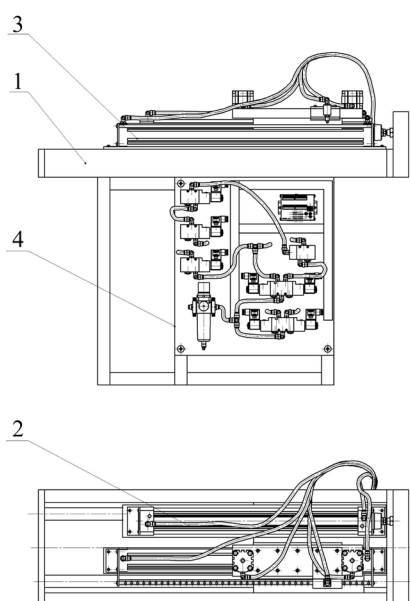


Fig. 1. Assembly drawing of the model stand: 1 — stand frame; 2 — loading pneumatic cylinder; 3 — automated long-stroke rodless pneumatic actuator in assembly; 4 — control panel

The stand, as a technical model of a pneumatic drive for experimental research, assembled on the basis of design documentation, is shown in Figure 2. To study the pneumatic and kinematic characteristics of the drive, an original control system was developed and applied, including a jet sensor and an external brake device [20].

In the course of the development of the experimental setup, a Camozzi 52G2P40A0400 rodless pneumatic cylinder with a working stroke of 400 mm and a piston diameter of 40 mm was mounted on the testing stand. The proposed original control system, developed as part of previous studies, was fixed on the movable carriage of this device [20].

This system included a jet sensor of an original design, consisting of two nozzle elements and a special rack with holes, as well as an external brake device, represented by two Camozzi 31F4A040A005 pneumatic cylinders with friction linings on the rods [8]. Friction linings of Argolon-TX material were selected due to their friction coefficient of 0.4 and linear wear, which is up to 5.5 $\mu\text{m}/\text{brake}$ [13].

Additionally, a standard Camozzi 40M2L050A0400 pneumatic cylinder with a stroke length of 400 mm and a piston diameter of 50 mm was installed on the stand, which made it possible to simulate external loads on the drive. To verify the operability and accuracy of the jet sensor readings, a spillage method was used using a Camozzi MF4008-10-R-BV-A flow sensor located after the element under study, and two Camozzi SWCN-P10-P3-2 pressure sensors placed before and after this element. The tests of the jet sensor showed high reliability and stability of operation in various operating modes.

For the water drawing, a Camozzi MF4008-10-R-BV-A flow sensor was used, which had the following technical characteristics: analog output 0.5–4.5 V; measured value — volumetric flow rate; initial value of the flow measurement range — 0 l/min; final value of the flow measurement range — 10 l/min; accuracy $(1.5+0.2 \cdot \text{FS}/\text{MV}) \%$; operating pressure — 0–5 bar. Camozzi SWCN-P10-P3-2 pressure sensors were also used for the tests, which had the following technical characteristics: maximum measurement pressure — 10 bar; minimum measurement pressure — 1 bar; measurement pressure drop — 0.01 bar; maximum error — no more than 2.01%; scaling factor — 1.543. Additionally, Camozzi M043R-12 pressure gauges were used to provide measurement accuracy and pressure control in various drive units. The experimental stand was equipped with a modern electronic control unit, which included a Giga Device GD32F103VET6 microcontroller. It was responsible for collecting and processing data from all sensors of the pneumatic system, as well as for controlling the pneumatic distributors. To improve the accuracy of the actuator positioning, an encoder of the New Hong OVW6-10-2HC model was used, which had the following technical parameters [21]: power supply — DC 5–12 V, 12–24 V; response frequency — 0–100 kHz; consumption current — 80 mA. All data from the pressure sensors and the encoder were recorded in the system using the Modbus protocol [22]. Information from all measuring devices was collected by a personal computer synchronized with the microcontroller via the W5500 interface.

The DD1 controller interacted with the system, generating control signals for electromagnetic relays via a Unisonic Technologies ULN2003 transistor unit. This provided precise and reliable control of the pneumatic distributor solenoids, as well as maintaining the specified operating parameters of the drive in various operating modes [23].

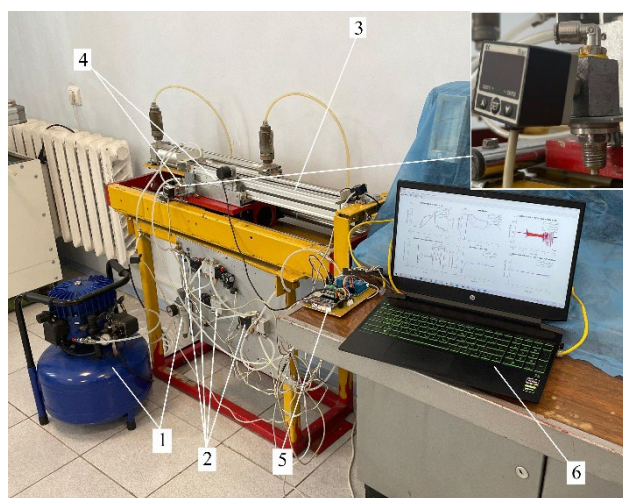
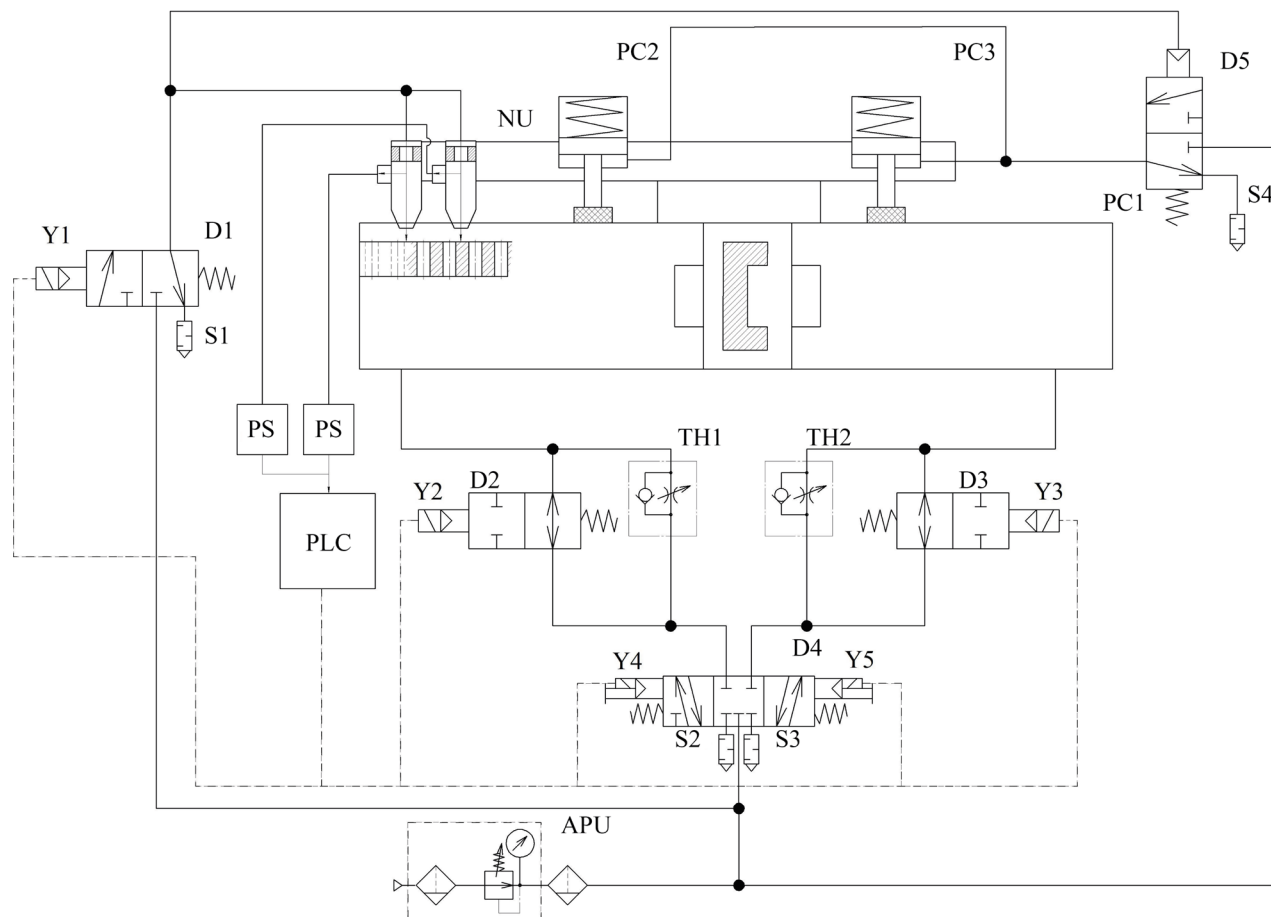


Fig. 2. Research complex: 1 — power subsystem; 2 — drive control devices; 3 — main pneumatic cylinder for long-stroke movements with a loader; 4 — control system in the form of a jet sensor and an external brake device; 5 — electrical subsystem; 6 — personal computer

The external braking device performs the work of fixing the actuator of the pneumatic drive when it is out of operation and precisely stops at a given coordinate. Then the actuator switches to the positioning speed.



Experimental studies were conducted under the following conditions:

- maximum travel speed $V_{\text{max}} = 0.26$ m/s;
- pressure in the drive pneumatic system $p_m = 6$ bar;
- maximum stroke length of a rodless pneumatic cylinder $L = 400$ mm;
- mass of the moved load $M_{\text{np1}} = 10, 30, 60$ kg;
- positioning stop coordinate (working stroke length) $L_{\text{п3}} = 150, 250, 350$ mm;
- positioning speed $V_{\text{п3}} = 0.025\text{--}0.04$ m/s.

- trajectories of the long-stroke pneumatic actuator: acceleration and movement with a steady maximum speed; deceleration of the speed of movement to the positioning speed; movement at the positioning speed and stopping at a given coordinate;

- speed of the long-stroke pneumatic actuator and its components, which includes: acceleration time of the actuator; duration of the positioning stage and determination of the accuracy of reaching the specified final position;
- impact of the external load and the length of movement on the speed and accuracy of positioning.

Research Results. The graphs of the movement of the drive power elements, their speed, as well as the dependence of the air pressure in the drive pneumatic system, in comparison to the graphs of the same drive parameters obtained during the simulation, are presented in Figures 4–6.

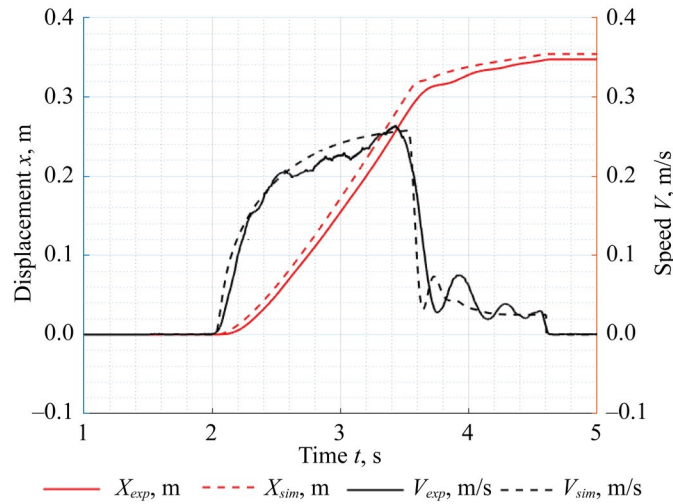


Fig. 4. Graphs of change in time of speed and coordinates of displacement of the actuator of the studied pneumatic drive from time: X_{exp} , V_{exp} — displacement and speed obtained experimentally, respectively; X_{sim} , V_{sim} — displacement and speed obtained during the conducted mathematical modeling, respectively

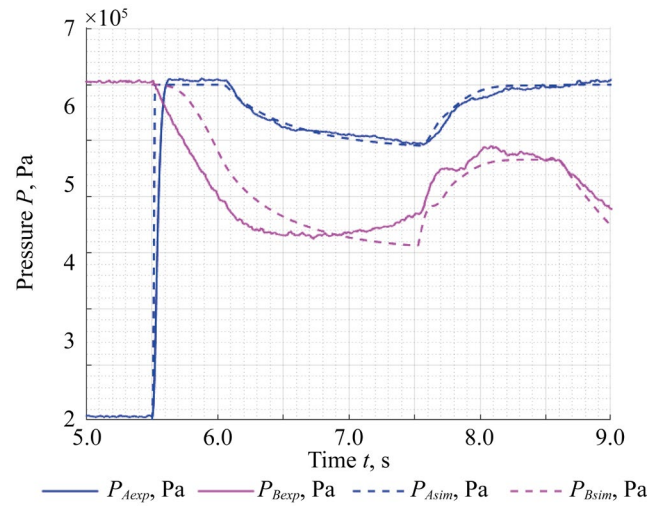


Fig. 5. Graph of change in air pressure in the pressure and drain cavities of the studied pneumatic drive over time: P_{Aexp} , P_{Bexp} — working gas pressure in the pressure and drain cavities, obtained experimentally, respectively; P_{Asim} , P_{Bsim} — gas pressure in the pressure and drain cavities, obtained during mathematical modeling, respectively

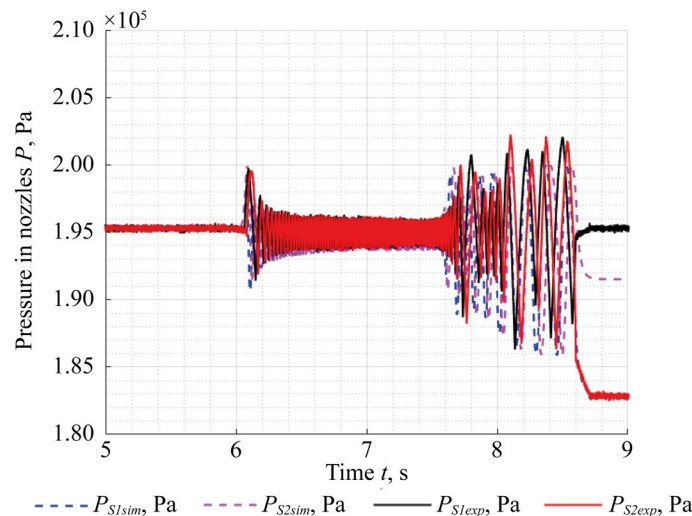


Fig. 6. Graph of the change in gas pressure in the nozzle units of a contactless jet sensor over time: P_{S1exp} , P_{S2exp} — gas pressure in nozzle unit 1 and 2, obtained experimentally, respectively; P_{S1sim} , P_{S2sim} — pressure in nozzle unit 1 and 2, obtained during mathematical modeling, respectively

The maximum discrepancy between the experimental data and the mathematical modeling data (Fig. 4–6) does not exceed 18%, which confirms the reliability of the research results [24].

The discrepancy between the research results was determined for all the data obtained (Fig. 4–6) using the following formula [25]:

$$a = \frac{a_T - a_3}{a_3} \cdot 100 \%, \quad (1)$$

where a_3 — data obtained during the experimental study (displacement, speed, pressure), a_T — data obtained as a result of the theoretical study [26].

In Figures 7 and 8, the captions “ L_{exp} ” and “ L_{mod} ” denote oscillograms obtained as a result of full-scale and computational experiments, respectively.

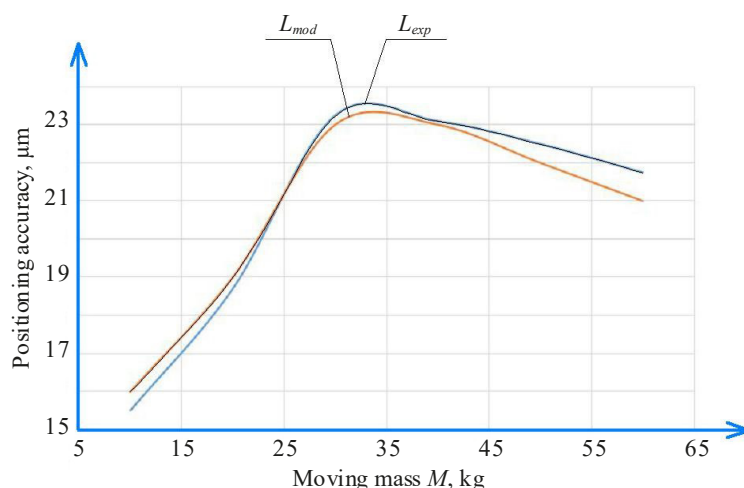


Fig. 7. Effect of mass M of the moving structure on the value of the positioning accuracy of the pneumatic drive:
 L_{exp} — result obtained during a full-scale experiment, L_{mod} — result obtained during mathematical modeling

Figure 7 shows the result of the study on the effect of mass M of the moving structure on the value of the positioning accuracy of the pneumatic cylinder.

The studies have shown that the positioning accuracy of the drive depends on the mass of the moving object. With an increase in mass from 10 to 30 kg, the positioning accuracy decreased by 1.47 times, and with an increase in mass to 60 kg, the accuracy worsened compared to a mass of 10 kg by 1.37 times.

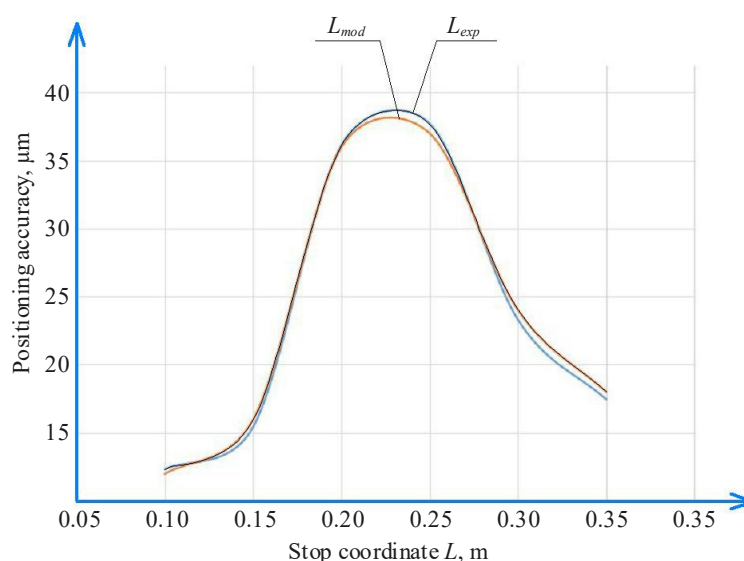


Fig. 8. Effect of working stroke length of the drive on value of its positioning accuracy:
 L_{exp} — result obtained during a full-scale experiment, L_{mod} — result obtained during mathematical modeling

Figure 8 shows the result of the study on the effect of the stop coordinate of the drive actuator on the accuracy of its positioning at the same maximum speed of movement. It was found that the accuracy of the drive positioning depends on the length of its working stroke to a complete stop (stop coordinates): when changing the stop coordinate from 0.1 m to 0.22 m, the positioning accuracy worsened by 3.2 times, and when changing the stop coordinate from 0.22 m to 0.35 m, the positioning accuracy increased by 2.2 times. This is due to the fact that during the operation of the drive, back pressure is created in the air cavity of the pneumatic cylinder when the piston approaches its extreme walls (and the closer to the wall, the greater the pressure) [27]. Back pressure also increases additionally during throttling due to the narrowing of the flow section of the channels of the holes intended for pumping and bleeding gas [28]. The narrowing of the flow sections of the channels causes the deceleration of gas flows [29]. This is observed when the actuator of the drive is moved at the positioning speed [30].

Discussion. The conducted experimental studies allowed obtaining good results in the development of long-stroke pneumatic drives. Successful verification of the mathematical model confirmed the correctness of the theoretical studies carried out in previous works [8, 19].

The obtained positioning accuracy of the drive is 77 μm at a distance of over three meters. This figure significantly exceeds similar results presented in [13, 15], which demonstrates high potential of the developed design, since the economic efficiency of the proposed solution is due to the absence of an electronic component base in the control system [31]. This not only reduces initial production costs, but also significantly simplifies maintenance of the drive during operation [32]. Comparative analysis with existing developments [2, 13] confirms the superiority of the developed system in terms of cost criteria.

Conclusion. The main research results are as follows:

- experimental verification of the results of mathematical modeling of a positioning long-stroke rodless pneumatic actuator was carried out; the maximum error of the research was 18%, which confirmed the adequacy of the mathematical model and its possibility of application for engineering calculations;
- key factors that determine the accuracy of drive positioning were identified: with an increase in the moved mass from 10 to 60 kg, the positioning accuracy decreased by 40%. A significant influence of the position of the pneumatic cylinder piston in the extreme positions on the positioning accuracy was also established, which caused a deterioration in accuracy up to four times in the central positions due to the occurrence of back pressure in the drain cavity when the positioning speed was reached.

The conducted studies confirmed the efficiency of the developed solutions for long-stroke rodless pneumatic actuators.

The practical significance of the study is validated by the possibility of using the obtained results in the creation of high-precision long-stroke mechanisms in various industries [33]. The developed design can be used in automated production lines, robotic complexes, and other areas where precise positioning over significant distances is required.

Promising areas for further research include optimizing the parameters of the control system to obtain even higher positioning accuracy, as well as developing calculation methods for positioning long-stroke pneumatic drives.

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