ELECTROPNEUMATIC DRIVE FOR INDUSTRIAL ROBOTS

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Abstract: This scientific article presents the design of a newly developed electropneumatic drive for robots and robotic systems, the diagram of its operating principle, and the graphs of output shafts moving at different speeds and directions that are independent of each other.

The proposed drive provides an opportunity to create intelligent modules for robots. The drive consists of electromagnets and pneumatic cylinders and, through the control system, ensures the movement of the output shafts at various speeds and steps.

The proposed scientific article can be used by researchers and doctoral students conducting studies in the field of robotics.

Keywords: Electropneumatic drive; industrial robot; pneumatic cylinder; electromagnet; multi-output module; stepwise motion; positioning accuracy; controlled working grippers (CWG); output rod; thermal analysis; finite element method (FEM).

SANOAT ROBOTLARINING ELEKTROPNEVMATIK YURITMALARI

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Annotatsiya: Mazkur ilmiy maqolada robotlar va robototexnika tizimlari uchun yangi yaratilgan elektropnevmatik yuritma, uning konstruktsiyasi, ishlash prinsipi sxemasi va chiqish vallari turli tezliklar va bir-biriga bogʻliq boʻlmagan yoʻnalishlarda harakatlanishini koʻrsatadigan grafiklar taqdim etilgan.

Taklif etilayotgan yuritma asosida robotlar uchun intellektual modullar yaratish imkoniyati mavjud. Yuritma elektromagnitlar va pnevmosilindrlardan tashkil topgan boʻlib, boshqaruv tizimi orqali chiqish vallari turli tezliklar va qadamlar bilan harakatlanishini ta’minlaydi.

Ushbu ilmiy maqola robototexnika sohasida tadqiqot olib borayotgan ilmiy xodimlar va doktorantlar uchun foydali boʻlishi mumkin.

Kalit soʻzlar: Elektropnevmatik yuritma; sanoat roboti; pnevmosilindr; elektromagnit; koʻp chiqishli modul; qadamli harakat; pozitsiyalash aniqligi; boshqariladigan ishchi qisqich (CWG); chiqish vali (sterjen); issiqlik tahlili; chekli elementlar usuli (FEM).

ЭЛЕКТРОПНЕВМАТИЧЕСКИЙ ПРИВОД ДЛЯ ПРОМЫШЛЕННЫХ РОБОТОВ

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Аннотация: В данной научной статье представлен новый электропневматический привод для роботов и робототехнических систем, включая его конструкцию, схему принципа работы и графики движения выходных валов, движущихся с различными скоростями и в независимых друг от друга направлениях.

Предлагаемый привод обеспечивает возможность создания интеллектуальных модулей для роботов. Система состоит из электромагнитов и пневмоцилиндров и через систему управления позволяет выходным валам двигаться с различными скоростями и шагами.

Данная научная работа может быть использована исследователями и аспирантами, занимающимися изучением робототехники.

Ключевые слова: Электропневматический привод; промышленный робот; пневмоцилиндр; электромагнит; многовыходной модуль; шаговое перемещение; точность позиционирования; управляемые рабочие захваты (УВЗ/CWG); выходной шток; тепловой анализ; метод конечных элементов (МКЭ).

INTRODUCTION

In recent years, the demand for industrial robots has been rapidly increasing in manufacturing, logistics, and process industries, where high productivity, repeatability, and flexible automation are required. The performance of such robotic systems is largely determined by the capabilities of their drive units. Industrial robot drives must ensure reliable operation, high positioning accuracy, structural simplicity, and a wide range of controllable speeds. At the same time, modern robotic applications increasingly require compact intelligent modules capable of generating different motion laws, adapting to changing loads, and operating efficiently in intermittent duty cycles.

Linear motion drives are widely used in robotic mechanisms because they can directly produce translational movement without complex kinematic transformations. However, many conventional solutions—electric, hydraulic, or purely pneumatic—face practical limitations. Electric drives often require gear transmissions or ball-screw assemblies to obtain high force at low speeds, which increases size, cost, and mechanical wear. Hydraulic systems can provide high power density but are associated with leakage risks and maintenance issues. Pure pneumatic systems are attractive due to simplicity and low cost, yet they may suffer from limited positioning accuracy and difficulty in implementing fine stepwise motion without additional feedback and locking devices.

To address these challenges, this paper proposes a new electropneumatic drive for industrial robots and robotic systems. The drive combines a pneumatic cylinder and a disk-type electromagnetic actuator with controlled working grippers to transmit reciprocating motions to output rods. Such a hybrid structure enables autonomous movement of multiple output shafts with different velocities, directions, and step sizes that are independent of each other. The coarse motion is generated by the pneumatic part to achieve high-speed displacement over long strokes, while the electromagnetic part provides small-step motion for precise positioning and improved control near the target point. By adjusting the magnetic gap and coordinating the gripper switching logic, the system can realize different step lengths and achieve the required positioning accuracy across the entire travel range.

The paper presents the design and operating principle of the proposed electropneumatic drive, including the functional scheme, the switching sequence of electromagnet windings and controlled working grippers, and motion diagrams illustrating the coordinated movement of the output rods. In addition, a thermal analysis of the electromagnetic subsystem is performed using a quadrilateral finite element approach to verify that the temperature rise remains within permissible limits under intermittent operating conditions. The obtained results confirm the feasibility of creating intelligent multi-output modules based on the proposed drive concept for advanced robotic applications.

MATERIALS AND METHODS

Recently, linear motion drives have been widely used in robots and robotic systems [2, 3]. The main requirements imposed on industrial robot drives are reliability, positioning accuracy, simplicity of design, and a wide range of speed control.

The proposed electropneumatic drive makes it possible to move the output shafts (rods) of the drive autonomously with different speeds and step lengths. Based on the proposed drive, it is possible to create intelligent multi-output modules for robotic systems [1, 4].

The drive [5] consists of two parts — pneumatic and electromagnetic. The pneumatic part is made in the form of a pneumatic cylinder, whose piston is connected to one rail, while the electromagnetic part is made in the form of two magnetic cores with windings and a disk-shaped armature connected to another rail. The rails are equipped with controlled working grippers (CWGs), by means of which the reciprocating motions of the piston and the armature are transmitted to the output shafts.

The drive performs stepwise movements of the output shafts with different step sizes.

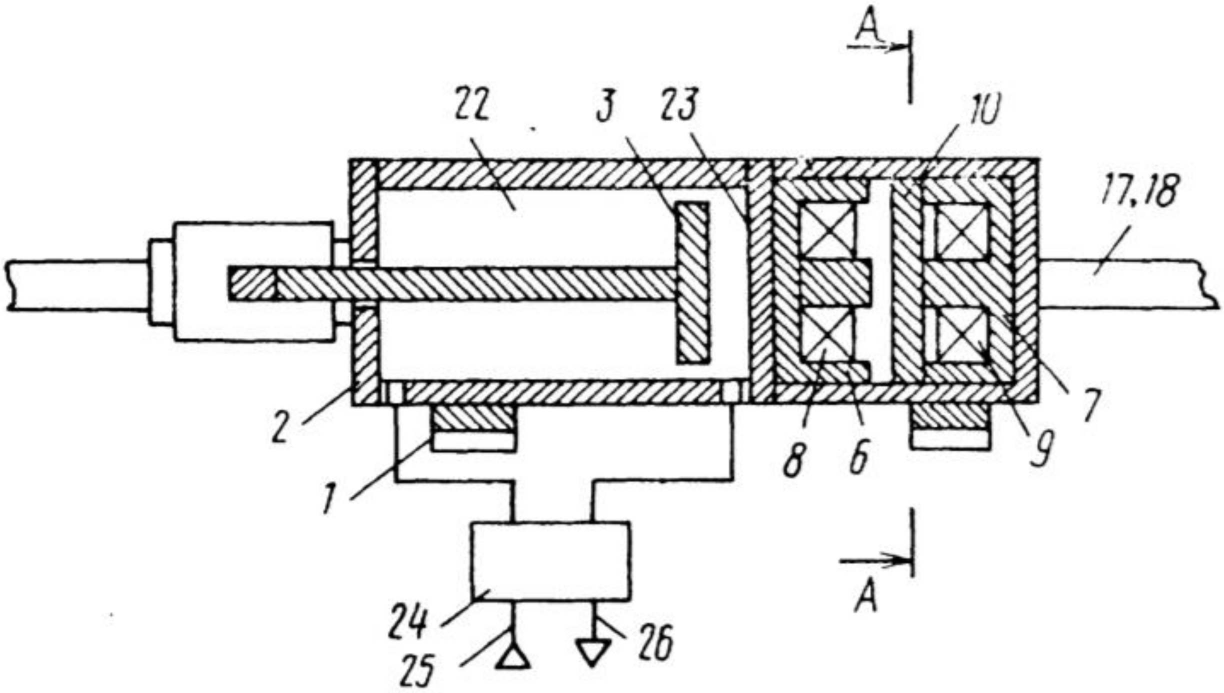

Fig. 1. The electropneumatic drive consists of the following elements (Figs. 1 and 2): A pneumatic cylinder 2 rigidly mounted on the base 1 with a piston 3 fixed to a rail 4 through a rod, and two disk-type electromagnets made in the form of magnetic cores 6 and 7 with excitation windings 8 and 9 and a common armature 10. The armature 10 is rigidly connected (Fig. 3) to a guide 11 by means of a rail 12.

On rails 4 and 12, the main and auxiliary controlled working grippers 13–16 are installed, by means of which the reciprocating motions of the piston 3 of the pneumatic cylinder 2 and the armature 10 of the electromagnet are transmitted to the double-sided rods 17 and 18. In addition, the drive is equipped with controlled working grippers 19 and 20 rigidly connected to the housing 1 by means of a rail 21.

The controlled working grippers 13, 14, 15, 19, and 20 are made in the form of electromagnetic powder clutches (not shown in the figures). By adjusting the gap between the magnetic cores 6 and 7 and the armature 10, different step lengths ΔX_e and positioning accuracy can be obtained.

The working chambers 22 and 23 of the pneumatic cylinder 2 are connected via the corresponding pneumatic distributor 24 to the high- and low-pressure lines 25 and 26. Between the armature 10 and the guide 11, shielding bushings 27 are installed, which serve to reduce magnetic flux leakage. The guide 11 moves freely relative to the housing 28 on balls 29.

The drive operates as follows. The control unit (Fig. 5) generates control signals for the pneumatic distributors 24, the excitation windings 8 and 9, and the grippers 13, 14, 15, 16, 19, and 20 depending on the required travel X of the drive. Using the pneumatic cylinder 2 and grippers 13 and 14, the rods 17 and 18 are moved with a step ΔX_p equal to the piston stroke 3. Using the disk electromagnets and grippers 15 and 16, the rods 17 and 18 are moved with a step ΔX_e equal to the armature stroke 10.

The control unit calculates the number of steps N_p for the pneumatic cylinder 2 and the number of steps N_e for the electromagnets according to the following relations: $N_p = INT(K)$, where INT denotes the integer part. First, the drive executes N_p steps, then N_e steps.

Variants are possible in which the drive performs movements with step ΔX_p at the beginning, and in the middle or at the end of the stroke with step ΔX_e for the rods 17 and 18, depending on the requirements imposed on the drive. Such a need arises when it is necessary to move an object quickly to a target point and then continue its movement with a small step and a high tractive force.

Let us explain the principle of operation in the case when rod 17 moves to the left (according to the drawing), first with steps ΔX_p and then with steps ΔX_e, while rod 18 moves to the right with a constant step ΔX_p. The control unit calculates the numbers of steps N_p and N_e from the above relations for both rods 17 and 18 depending on their travels X_1 and X_2.

Assume that in the initial position piston 3 is in the rightmost position (in the drawing), and armature 10 is also in the rightmost position attracted to magnetic core 7. By means of the corresponding pneumatic distributor 24, chambers 22 and 23 are connected to lines 25 and 26 so that piston 3 makes one step to the left. This movement is transmitted to rod 17 by alternately switching on and off grippers 13 and 19, and rod 17 moves one step to the left.

After that, the pneumatic distributor 24 is set to its initial position, grippers 19 and 13 are switched off, and piston 3 returns to its initial state. This cycle is repeated N_p times. After completing N_p steps, control of the pneumatic cylinder 2 via distributor 24 is stopped and gripper 13 is switched on. Then signals are generated to control windings 8 and 9 of magnetic cores 6 and 7 and gripper 15 in order to move rod 17 with small steps N_e.

Figure 4 shows a graph illustrating the motion of rods 17 and 18. During the time interval t_{p1}, rod 17 moves to the left with steps ΔX_p, and during the time interval t_{e1} it moves with steps ΔX_{e1}. The motion of rod 18 begins in the opposite direction with a delay of t_pause, moving by X_{p2} during the time interval t_{p2}.

Thus, rods 17 and 18 simultaneously perform motions in opposite directions.

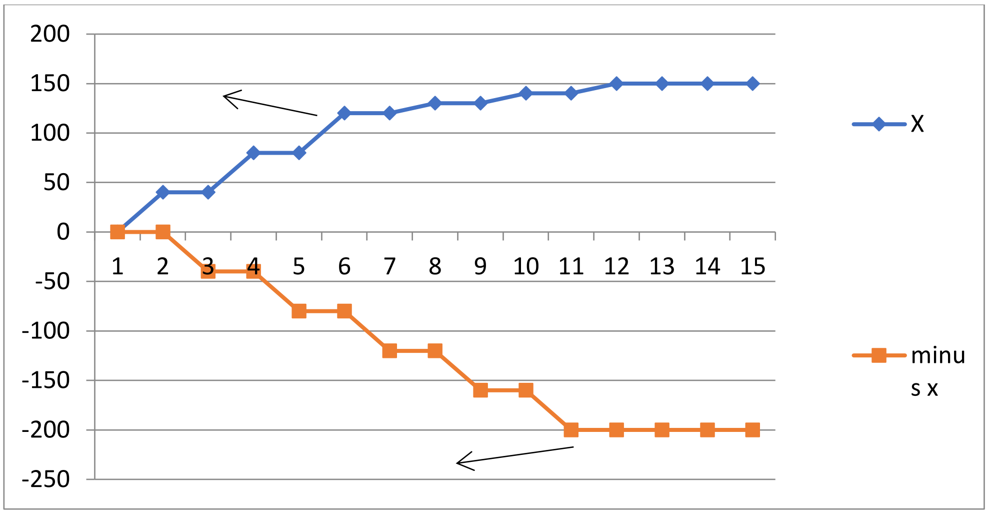

Fig. 2. Operating diagram of the electropneumatic drive: where 1 – curve illustrating the motion of rod 17, 2 – curve illustrating the motion of rod 18.

Table No. 1. Switching of the electromagnet windings and the controlled working grippers (CWGs).

№	**ЭМ$_{22}$**	**ЭМ$_{23}$**	**ЭМ$_{9}$**	**УВЗ$_{13}$**	**УРЗ$_{19}$**	**УРЗ$_{15}$**	**УРЗ$_{14}$**	**УРЗ$_{20}$**	**УРЗ$_{16}$**
1	-	+	-	+	+	-			-
2	+	-		-	+	-	+	-	-
3	-	+	-	+	+	-	-	+	-
4	+	-	-	-	+	-	+	-	-
5	-	+	-	+	-	-	-	+	-
6	+	-	-	-	+	-	+	-	-
7	-	-	-	-	-	+	-	+	-
8	+	-	+	-	+	-	+	-	-
9	-	-	-	-	-	+	-	-	-
10			+	-	+	-	-	-	-
11	-	-	-	-	-	+	-	-	-

Assume that rod 18 begins to move to the right at the moment when rod 17 starts moving to the left with steps ΔX_{p1}. Then, during the leftward movement of rod 17, winding 8 and CWG 15 are switched on, while winding 9 and CWG 19 are switched off. Rod 18 remains stationary because the armature 10 is moving to the left. At the same time, the locking gripper 20 is switched on and the working gripper 16 is switched off.

Next, when the corresponding winding 8 and the locking gripper 20 are switched off, winding 9 and the working gripper 16 are switched on. In this case, rod 18 and the armature 10 together make one step ΔX_{p2} to the right. At this moment, gripper 19 is switched on and gripper 15 is switched off, so rod 17 remains stationary.

Then, with the corresponding winding 9 and the working gripper 16 switched off, winding 8 and the locking gripper 20 are switched on. The armature 10 is attracted to magnetic core 6, rod 18 is stationary, and rod 17 moves one step to the left. Thus, the cycle is repeated until the drive completes N_{p1} steps for rod 17 and N_{e1} steps for rod 18.

In a similar way, rods 17 and 18 can be moved N_{p2} steps in opposite directions or simultaneously in the same direction. Thus, the device makes it possible to fix rods 17 and 18 with a заданной точностью (specified accuracy) at any positioning point over the entire travel range.

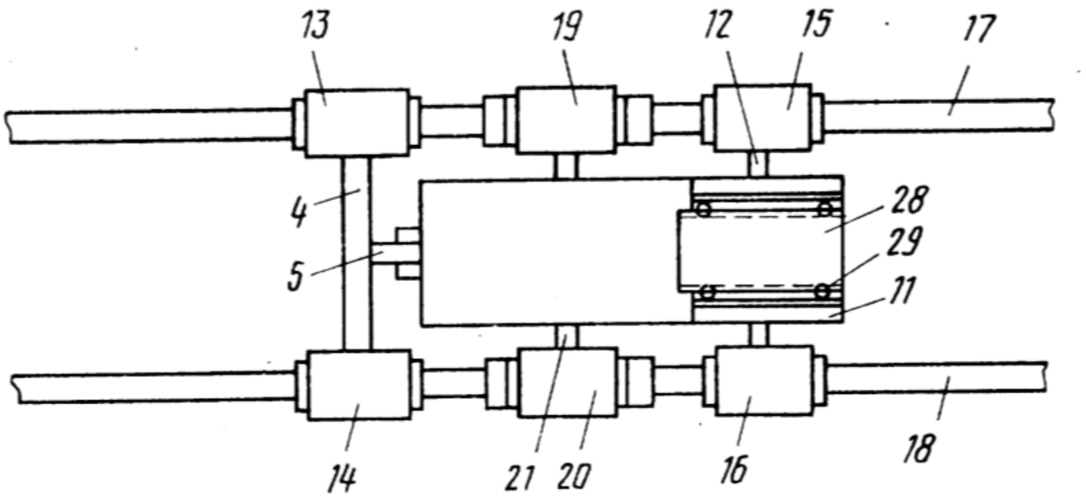

Fig. 3.

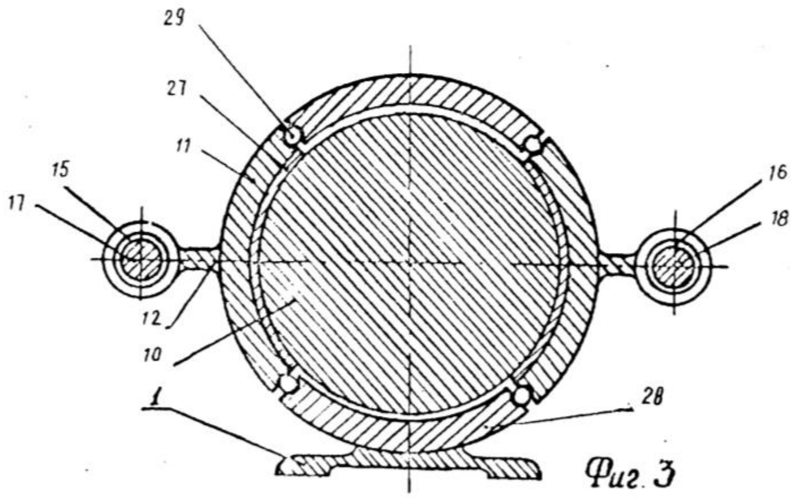

Fig. 4.

Here is the English translation: The control unit of the electropneumatic drive (Fig. 5) makes it possible to move the output shafts according to different motion laws and ensures reliable operation with high positioning accuracy.

For the electromagnetic part of the drive, a thermal analysis was carried out using the method of quadrilateral finite elements. Recently, in solving problems of thermal and magnetic field calculations, quadrilateral finite elements with quadratic approximation of the sought functions within each element have found increasing application [6]. Due to the higher accuracy of approximation, the use of quadrilateral finite elements makes it possible to employ a smaller number of elements and reduce the number of approximation nodes when dividing the computational domain into elements. This leads to a reduction in computation time and the amount of computer memory required to store intermediate results.

To calculate the thermal field pattern of the developed device, the method of N. V. Savin was used. This method consists in the analytical evaluation of integrals and the combination of the integration results into so-called base matrices, which allows a radical reduction in computation time and a rationalization of the computational process on a computer.

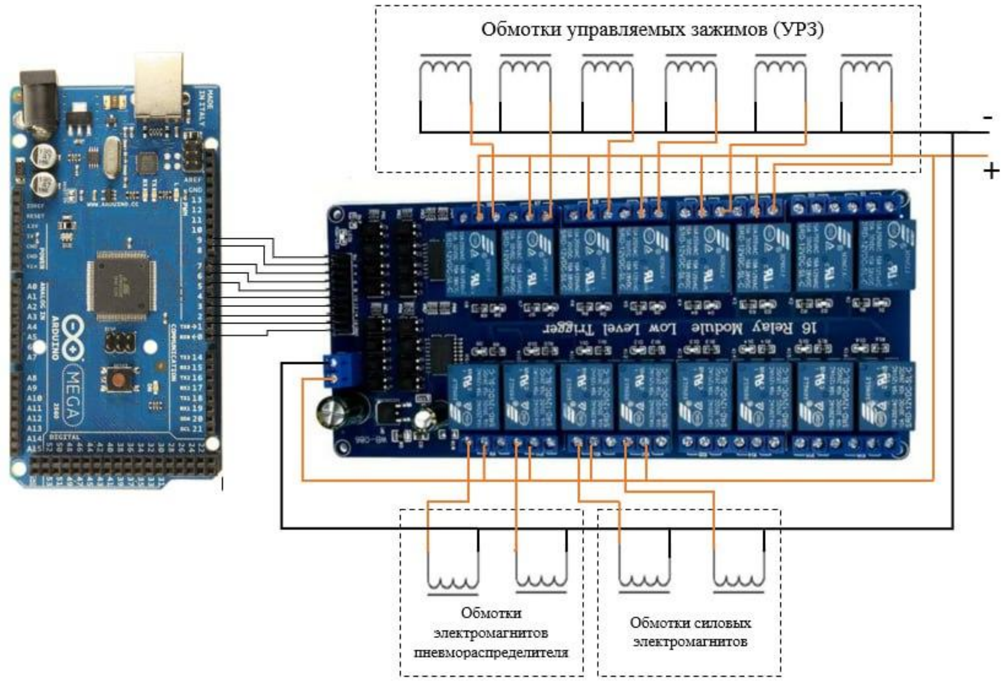

Fig. 5. Control unit of the electropneumatic drive

As is known, the mathematical essence of the problem of calculating the thermal field by the finite element method is reduced to solving a system of linear algebraic equations with respect to the values of the vector thermal potential at the element nodes.

$$([K] + j\omega\,[M])\cdot\{\dot{T}\}_{\mu} = \{R\},$$

where the elements of the coefficient matrices [K][K][K], [M][M][M] and the right-hand side vector {R}\{R\}{R} are expressed for each finite element through the components of the thermal conductivity tensor λx,λy\lambda_x, \lambda_yλx,λy and the coordinate functions Ni,NjN_i, N_jNi,Nj; the latter depend only on the type of finite elements used and on the distribution of the approximation nodes.

Taking into account the base matrices, the computational formulas for determining the coefficients and the free terms of the system take the following form:

$$K_{ij}^{(e)} = \frac{1}{\lambda_y}\frac{b}{a}\cdot C_{ij} + \frac{1}{\lambda_x}\frac{a}{b}d_{ij};$$

$$m_{ij}^{(e)} = g\,\frac{a\cdot b}{4}\,g_{ij};$$

$$r_i^{(e)} = \frac{a\cdot b}{4}\delta\cdot Z_i + \alpha_x\cdot\frac{a}{2}Pi + \alpha_y\frac{b}{2}qi;$$

where Cij,dij,Zi,Pi,qiC_{ij}, d_{ij}, Z_i, P_i, q_iCij,dij,Zi,Pi,qi are the base matrices; χ\chiχ denotes the Neumann boundary conditions on the horizontal and vertical sides of the finite element; aaa and bbb are the lengths of the finite element along the axes, respectively; qqq is the heat generation density, and λ\lambdaλ is the thermal conductivity of the material.

Thus, with the use of base matrices, the integration operation is replaced by simple multiplication by the corresponding matrix elements. Using this method, two-dimensional temperature fields in piecewise-homogeneous anisotropic rectangular objects with internal heat generation—such as the EMUS—were calculated under third-kind (Robin) boundary conditions.

The electromagnetic part of the drive (Fig. 6) is considered, where it is placed in a Cartesian coordinate system X,YX, YX,Y and divided into finite elements by straight lines parallel to the coordinate axes. The numbering of the computational domain is carried out from left to right from 1 to IxI_xIx (along the X-axis) and from top to bottom from 1 to IyI_yIy (opposite to the Y-axis direction). Next, the components of the thermal conductivity tensor are specified for the base material (the core) and for elements modeling inhomogeneous inclusions. The interval numbers along the X and Y axes into which the specified elements fall are determined.

Internal heat generation and the corresponding numbers for the elements that act as heat sources are assigned. The heat transfer coefficients at the object boundaries are specified. The system of equations is solved by the Cholesky decomposition method (square-root method).

The program consists of two subroutines, POLE and GRAFIK, which are used for visual presentation of the calculation results. The POLE subroutine prints the field topology, and the GRAFIK subroutine plots temperature distribution graphs along the coordinate axes for various cross sections of the object, which are given in the appendices.

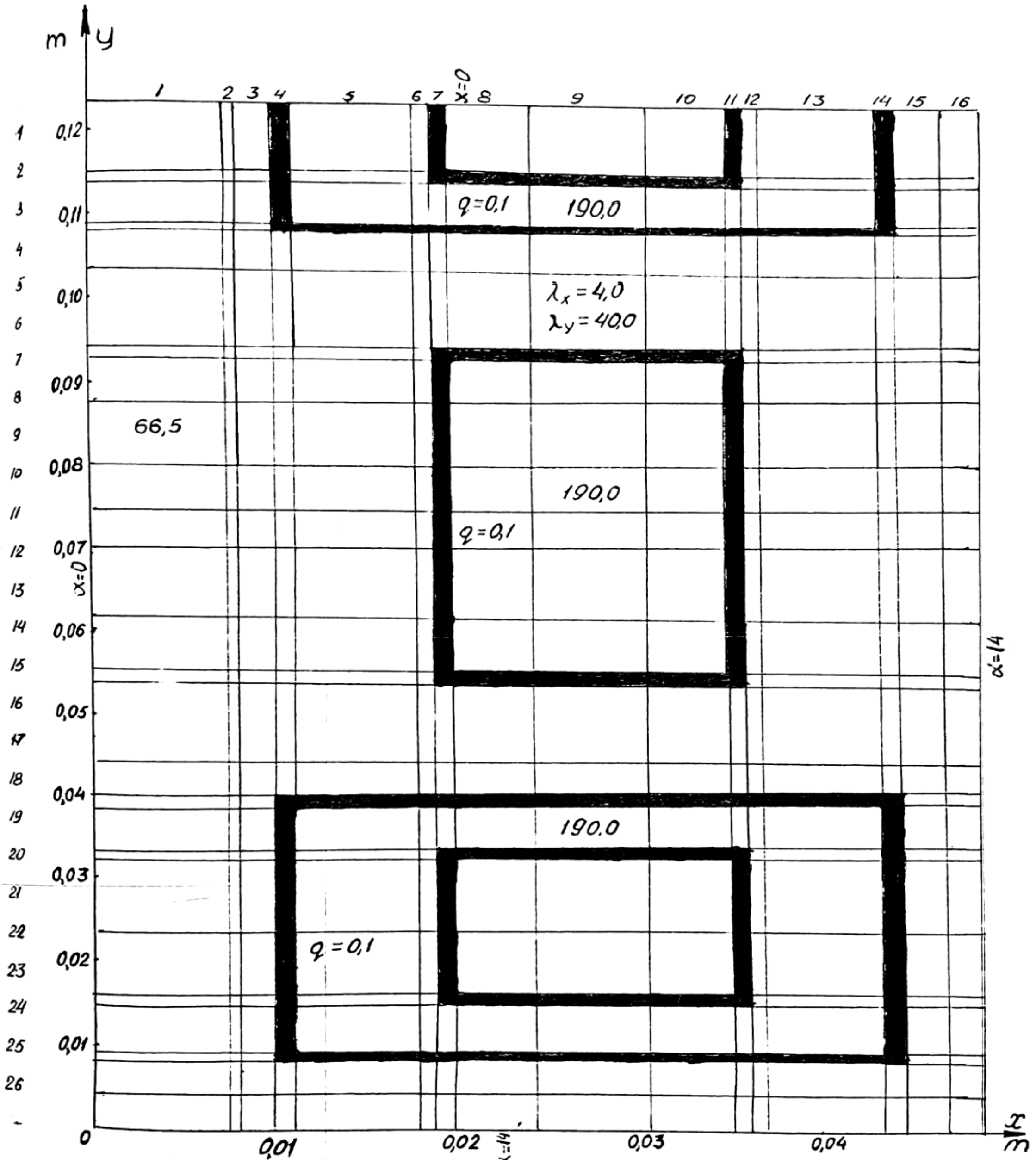

Fig. 6. Electromagnetic part of the drive

Thus, the temperature distribution curves along the coordinate axes made it possible to determine the temperature field distribution over the entire electromagnetic (EM) region, which must be taken into account to determine the operating mode and to assess the performance of the EM.

An analysis of the temperature field pattern showed that the temperature rise ttt throughout the EM region remains within permissible limits.

Considering that the electropneumatic drive operates in an intermittent (repeated short-time) duty cycle, the following condition must be satisfied [6]:

Tmax=Tcont. allowT_{\max} = T_{\text{cont. allow}}Tmax=Tcont. allow

where Tcont. allowT_{\text{cont. allow}}Tcont. allow is the permissible temperature rise under continuous operation, and TmaxT_{\max}Tmax is the maximum temperature rise in the quasi-steady-state mode, for full utilization of the materials and for ensuring reliable operation.

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