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Investigation of the influence of the length of the intermediate magnetic circuit on the characteristics of magnetic gripper for robotic complexes of the mining industry

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The analysis of the existing systems of mechanical grippers of various operating principles and operating environments, in the design of which both soft and hard magnetic materials are executed. The characteristics of existing prototypes are shown and the results of our own research are presented.

The article presents a study of the effect of the intermediate magnetic circuit length on the characteristics of magnetic gripper, the principle of which is based on the control of the field of a permanent magnet. The gripper based on this principle of action does not require constant energy expenditures to maintain both on and off states.

The description of the magnetic gripper design and the design of the test bench is given, as well as the results of a series of experiments to determine the strength of the release of the gripper at different lengths of the magnetic circuit in the on and off states, followed by statistical processing of the data. The intervals of the ranges in which with a high degree of probability there will be a value of the gripping disengagement force for various lengths of the intermediate magnetic circuit are identified. The nature of the distribution of a random variable, which is the force of decoupling of the gripper, is determined. The dependences of the gripper decoupling force on the length of the intermediate magnetic circuit for each of the gripper states are constructed. It has been established that a decrease in the length of the intermediate magnetic circuit is the cause of a decrease in the gripping adhesion force. Plots of the dependence of the gripper decoupling force were constructed using the modes of the force values varieties to visually display the experimental results. The maximum adhesion force of magnetic pickup – 9.5 kg – was achieved with an intermediate magnetic core length of 50 mm, the minimum with a length of 25 mm – 5.6 kg.

Key words: magnetic gripper; permanent magnet field control

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Introduction. Current trends in the development of the mining industry are aimed at automating production by introducing various robotic systems [1, 2]. One of the important areas of research in the field of robotics is the development of new technical solutions in the direction of gripping systems for interactions between robots, their parts and their operating environment.

The most common technical solution is mechanical grippers. Mechanical gripper requires a drive unit and an executive mechanical subsystem, which requires double energy conversion due to the fact that, as a rule, the battery is the source of energy for the robot. The solution that excludes the mechanical subsystem and does not require double energy conversion is the use of magnetic grippers. This category of grippers can be divided into electromagnetic and permanent magnet based. Electromagnetic grippers require constant energy consumption for maintaining the on state, which is a significant drawback when they are used as a part of autonomous systems. Grippers based on permanent magnets [7] are devoid of this drawback, at the same time they require additional mechanical decoupling systems. A promising area of research is the use of magnetic grippers based on the principle of controlling the field of a permanent magnet. Such systems do not require constant energy expenditures for maintaining the on state and additional gripper decoupling systems.

In the papers [4, 16], a thermomagnetic gripper design was proposed in which local electric heating and cooling are used. The gripper consists of soft magnetic material made of gadolinium (Gd), a thermoelectric generator (TEG), a permanent magnet (NdFeB), and two elastic elements on which the gripper is located, with one rigidly fixed end (CuBe). A temperature below the Curie point changes the properties of gadolinium from paramagnetic to ferromagnetic. A force of magnetic attraction is created between NdFeB and Gd, which subsequently connects the elastic elements to each

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other. After that, a reverse current direct current is applied to the thermoelectric generator to heat the gadolinium. As the temperature rises above the Curie point, gadolinium changes its magnetic properties from ferromagnetic to paramagnetic. Thus, the force of magnetic attraction is eliminated, and the elastic elements of the gripper return to its original position.

A robotic gripper consisting of an electromagnet and an elastic membrane filled with a fluid called MRα, is presented in [11]. MRα fluid is a ferromagnetic fluid with the addition of non-magnetic material to improve its solidification. In an active magnetic field, iron particles align along the lines of magnetic flux and form a column structure, while non-magnetic particles fall into the gap between the iron columns. Silicon rubber is used as the elastic membrane into which the liquid is placed. The maximum grip force is 50.67 N.

Articles [8], [17] discuss the application of the effect of plastic deformation of elastomers when used in magnetic gripper. Such grippers can adapt their shape to the geometry of objects and easily gripper them. The initial shape of the gripper can be restored by turning off the magnetic field. The field-induced plasticity effect of magnetically sensitive elastomers is used to realize a gripper form that is reversible, renewable, and adaptable to various forms of objects.

In [10], a miniature jaw-shaped magnetic grip for manipulating small objects using materials from magnetorheological elastomers based on a silicone rubber matrix made without using a magnetic field is presented. During the experiments, a control coil with a current density of 4.58 A/mm^2 was used. The samples were made of two-component silicone rubber with a 50 % content of carbonyl iron particles with a size of 10 μm. The developed samples were placed in a magnetic field, which varied from 0 to 100 kA/m. Observations of the samples in the presence and absence of a magnetic field show that the magnetic field increases the rigidity of the material. Higher normal stress obtained from 30 % MRE, which is about 5.74 N/mm^2, and the average stress rate belongs to a sample of 50 %. In the gripper tests, an activating coil with a current density of 4.58 A/mm^2 was used. The minimum magnetic field required for gripper is 1.25 kA/m.

A remotely controlled double magneto- and photoreactive soft grip is presented in the source [3]. An uncontrolled soft drive consists of a magnetically sensitive polydimethylsiloxane layer containing magnetic iron powder deposited on the central region of a photosensitive liquid crystal polymer film containing photochromic azobenzene dyes. Light is used to start the drive.

Modular reconfigurable robots with a pneumatic drive, consisting of soft and hard components and materials are presented in [9]. Soft components of these robots are actuators made of silicone elastomers, solid components are structures made of ABS plastic made using 3D printing. Ring magnets (NdFeB) are located inside the soft parts to create and maintain bonds between the grip legs. The reversibility of these magnetic compounds allows you to quickly reconfigure these robots. The combination of magnets with pneumatic control allows you to easily change the design of modular robots in accordance with the requirements of various tasks.

The article [7] discusses the design of magnetic gripper, with the help of which pilotless aircraft can move iron objects. In this design, permanent magnets are used for griping, and a double pulse separation mechanism is used for disengaging. The gripper design consists of several parts made of VeroGrey/Black hard plastic or Tango-Black flexible plastic. Four magnetic pads are located on the base of the gripper, each of which contains four magnets distributed in such a way that each of the magnets has the same pole. There is an isolated plastic separation between the magnets. Each of the magnets is able to provide a lift of about 1 kg. The trip mechanism includes two servos that, when activated, dump the payload. The gripper design allows you to transport up to four iron objects.

The article [14] presents the types of grippers used in known and unknown media, medicine, micro grippers and nano grippers, piezoelectric grippers and adaptable grippers made of soft materials. Grip characteristics such as size, weight, rigidity and simplicity are considered for various designs of robotic grips.

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The design of magnetic grippers for the biped robot HyReCRo (Hybrid Redundant Climbing Robot) is presented in [6]. Magnetic pickup is equipped with three switchable NdFeB magnets with a diameter of 20 mm and a height of 5 mm, located between two polylactide plates (PLA). The magnets are arranged in a circle at an angle of 120° to each other. The lower plate is rigidly connected to the magnets; three motors are located on the upper plate, which actuate the mechanism that switches the state of the magnet. The adhesion force of each magnet is 11 kg.

These studies illustrate various designs of magnetic grippers. The use in dynamic and constant environments and the need to capture objects of different sizes and shapes explain the need for a variety of gripper designs.

In the studies of the authors of [5, 12] a prototype of magnetic gripper based on the principle of controlling the magnetic field of a permanent magnet is presented. The developed experimental specimen had the following characteristics: average gripper disengagement force – 3.7 kg, control pulse voltage – 6 V, current strength – 0.17 A. Next, a cylindrical magnetic gripper was developed that is similar in principle to the experimental specimen. When testing this sample of magnetic gripper, working characteristics were obtained that significantly differ from the characteristics of the experimental sample. The main difference between the samples was the shorter length of the intermediate magnetic circuit. Next, the results of experiments on measuring the adhesion and disengagement of magnetic gripper at different lengths of the intermediate magnetic circuit will be presented and the design and principle of operation of magnetic gripper.

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Magnetic gripper design description. The developed magnetic gripper (Fig.1, *a*) consists of active and passive parts. The active part consists of the magnetic core of the control electromagnet 1, the control electromagnet 2, the permanent magnet (NdFeB) 4 and the intermediate magnetic circuit 3, 5. The passive part of the magnetic gripper includes the magnetic circuit of the passive part 7. The gripper has a pairing plane between the active and passive Part 6. For the study and construction of explicit dependencies, an intermediate magnetic circuit of the following lengths was used: 25 mm, two times longer – 50 mm, and an intermediate value – 35 mm. Figure 1 also shows two grip states – on (1, *b*) and off (1, *c*) and the direction of the magnetic induction lines is shown.

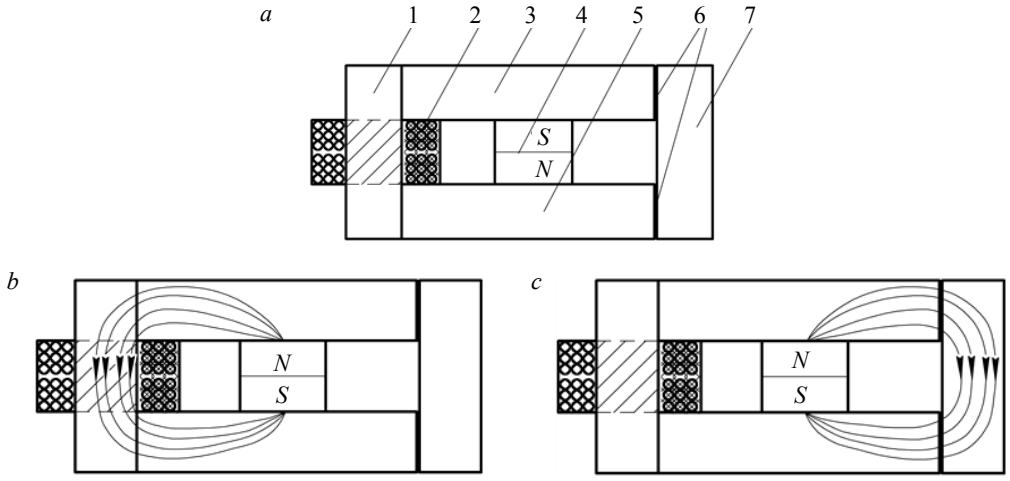


Fig. 1. Magnetic gripper design (*a*), on state (*b*), off state (*c*)

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In the off state, the magnetic field lines pass through the intermediate magnetic wire and the magnetic core of the control magnet. In the on state, the magnetic flux is closed through the magnetic circuit of the passive part of the gripper. The switching of states is carried out by applying a control pulse to the winding of the electromagnet. Depending on the direction of the control pulse current, the flux generated by the electromagnet can be co-directed to the flux of the permanent magnet, which corresponds to switching the gripper to the off state, and oppositely directed, which corresponds to switching the gripper to the on state.

Test bench design description. The experimental part of the study was carried out on a dynamometer stand (Fig. 2). On the base of stand 2, with the help of two bearings 1, 9, two guide shafts 5 are fixed. On the shafts there is a movable carriage 8, driven by a nut-screw transmission 11, 12. Between the support and the transmission nut, a nut-screw to facilitate rotation of the nut the washer 10 is located. The carriage is required for mounting on it a measuring device (dynamometer) 7 connected by means of a damping element 6, which is necessary to smooth out the oscillations of the decoupling force applied to the grip. A magnetic grip is fixed to the support through an adaptive fastener 3 with the possibility of using an intermediate magnetic circuit of various lengths.

The damping element is connected to the magnetic circuit of the passive part through a plastic transition element 4 which is not rigidly fixed to the magnetic circuit, which eliminates the forces applied non-perpendicular to the engagement plane.

A series of experiments was carried out to determine the adhesion and disengagement of magnetic gripper.

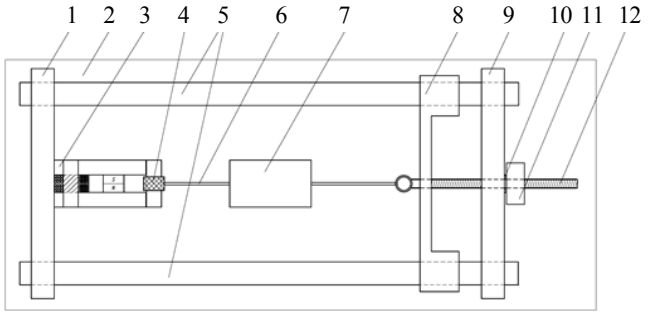


Fig.2. Test bench design

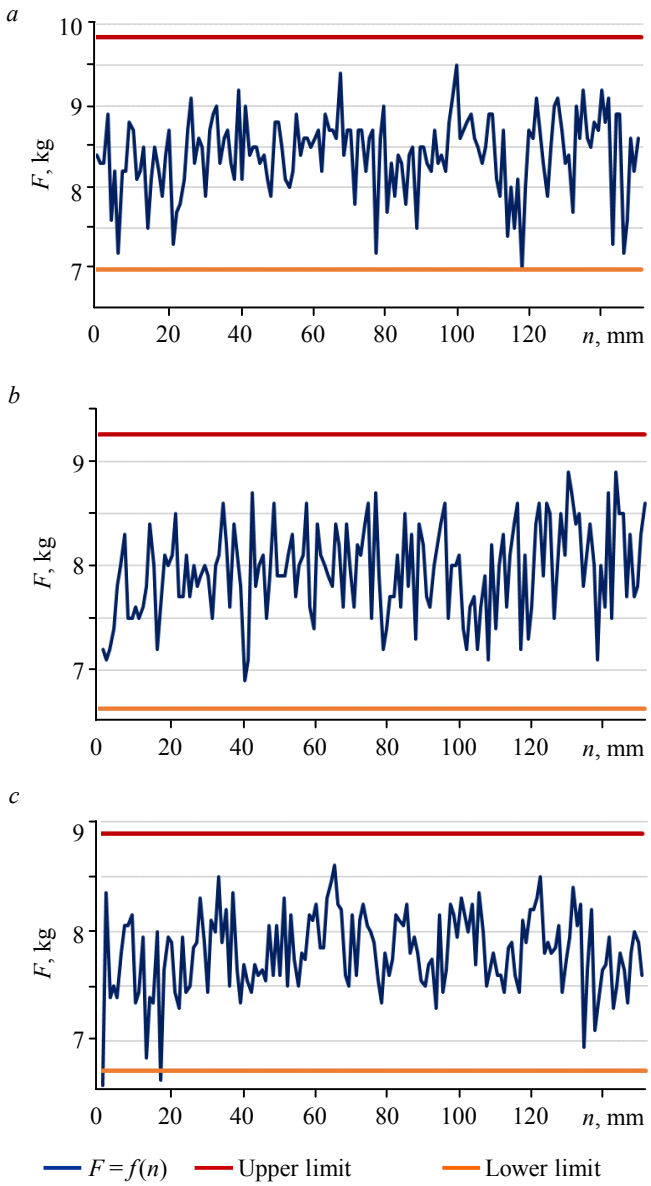


Fig.3. The results of measuring the disengagement force in the on state of gripper with the length of the magnetic circuit: 50 mm (*a*), 35 mm (*b*), 25 mm (*c*)

Experiment 1. Measurement of the release force in the on state of gripper. The experiments were carried out with the same energy of the control pulse equal to 5 J. In total, three experiments were carried out to measure the strength of the release of gripper, each of which used a different length of the magnetic circuit. In each experiment, 150 measurements of the on state gripper disengagement force were performed. The dependences of the decoupling force *F* on different values of the magnetic core length n are shown in Fig.3.

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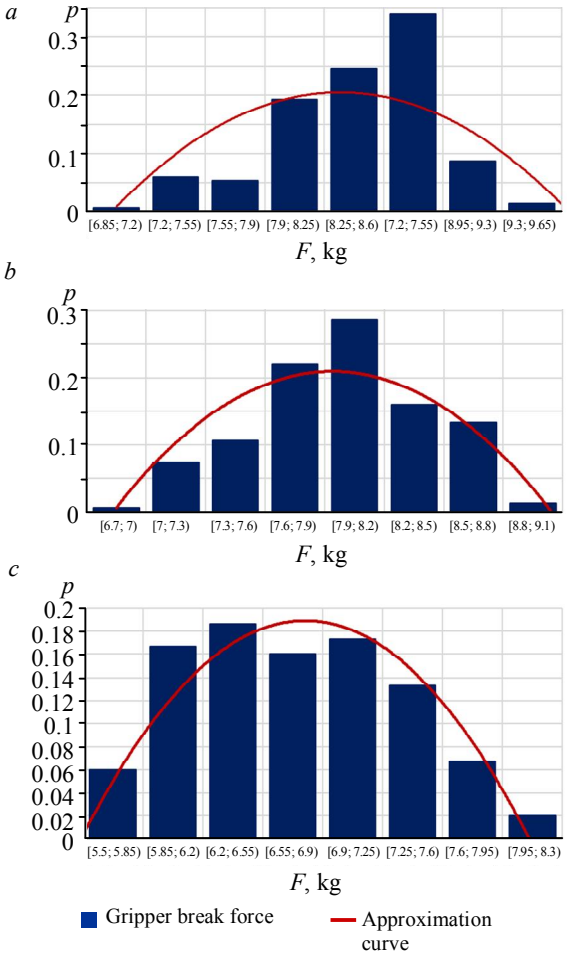


Fig.4. Histograms of experiment results in the on state of gripper with length of magnetic circuit: 50 mm (*a*), 35 mm (*b*), 25 mm (*c*)
p – the probability of the release of the decoupling force in the interval; *F* – the force applied for release of gripper

The upper and lower limits on the graphs show the area in which the values of a random variable can be located with a probability of 0.9973 [13]. The highest value of the tripping force – 9.5 kg – was recorded with a magnetic core length of 50 mm. The smallest value of the decoupling force – 5.6 kg – was noted with a magnetic circuit length of 25 mm. Two values not included in the 3σ interval were discarded in the experiment with a magnetic circuit length of 25 mm. The appearance of such values may be due to possible inaccuracies in the experiment, caused by the appearance of particles of various kinds between the conjugation planes of the active and passive parts of the gripper.

An interval variational series is constructed to determine the most characteristic values of the sample and the spread of data. To construct the interval series, eight intervals k were chosen (Fig.4). This amount was calculated as optimal in accordance with the Sturgess formula [15]

$$k = 1 + \lg(N),$$

where N – sample size.

From the presented histograms, we can conclude in what interval with the highest probability the value of the engagement decoupling force in the on state will be. Intervals of the most likely gripping release force:

Magnetic core length, mm	50	35	25
Force interval of gripper disengagement, kg	[8.6; 8.95)	[7.9; 8.2)	[6.2; 6.55)

For all lengths of the intermediate magnetic circuit, the histograms are unimodal and close to a symmetrical shape. Based on the shape of the approximation curve, it is most likely that the random variable has a normal distribution law.

Experiment 2. Measurement of the force of disengagement in the off state of the gripper. The experiment was carried out with a control pulse energy of 5 J, as well as experiments on the disengagement of gripper in the on state. For each length of the magnetic circuit in the experiments, 50 measurements of the force of release of gripper were performed (Fig.5). The length of the magnetic circuit is identical to the length of the magnetic circuit of the first experiment. To plot the histograms, the sample values were divided into six intervals according to the above formula.

The maximum value of the gripping disengagement force in the off state was 1.3 kg with a magnetic core length of 50 mm. The minimum decoupling force for all experiments was 0.31 kg with a magnetic circuit length of 25 mm. In experiment 2, values that fall outside the 3σ interval are present in experiments with the magnetic core lengths of 35 mm and 25 mm. These values were discarded during the construction of the histogram shown in Fig.6.

From the histograms it follows that the value of the decoupling force is most likely to fall into the interval [1.1; 1.25) with a magnetic core length of 50 mm, [0.94; 1.09) – with the length of the magnetic wire 35 mm and [0.45; 0.55) with a magnetic circuit length of 25 mm.

On-hold average release force:

Magnetic core length, mm	50	35	25
Average disengaging force, kg	8.41	7.95	6.61

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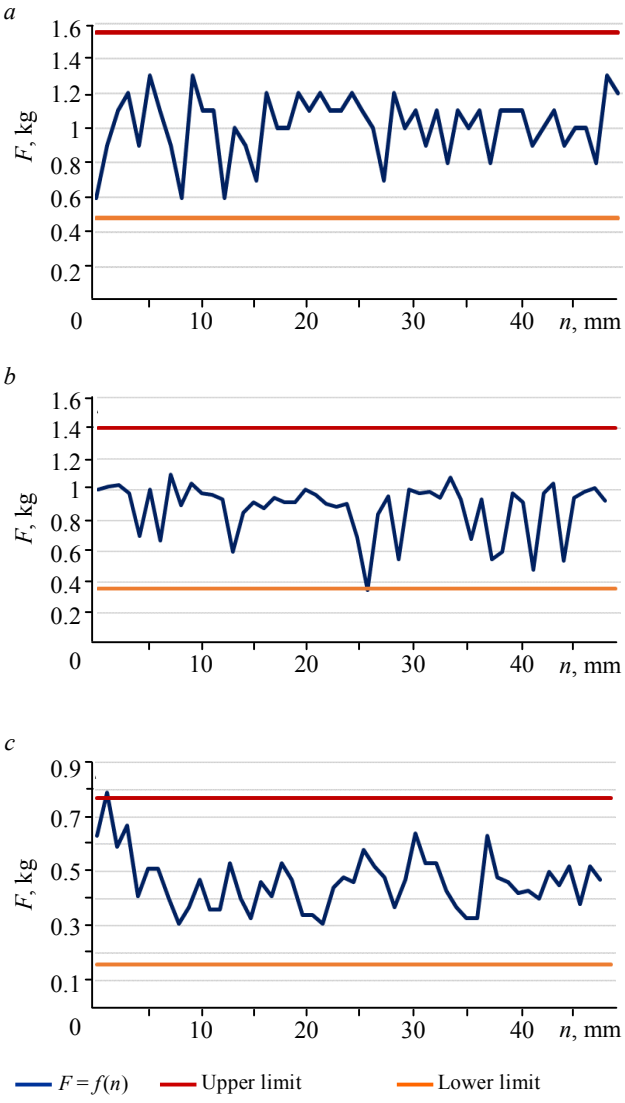


Fig. 5. The results of the measurement of the disengagement force in the off state of gripper with the length of the magnetic circuit:
50 mm (*a*), 35 mm (*b*), 25 mm (*c*)

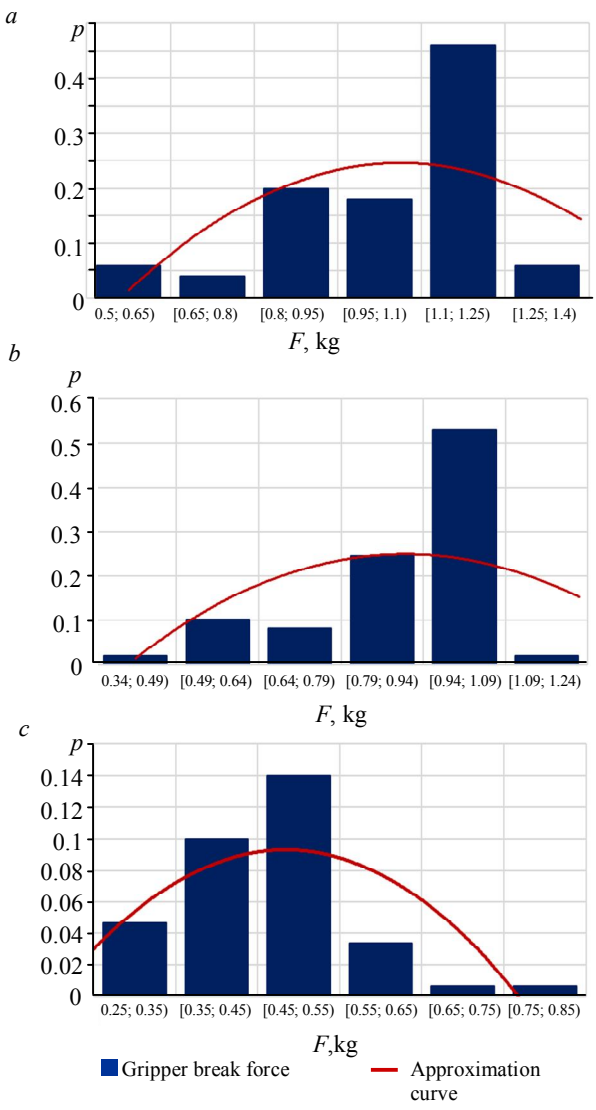


Fig.6. Histograms of the test results in the off state of capture with the length of the magnetic circuit
50 mm (*a*), 35 mm (*b*), 25 mm (*c*)
p – the probability that the trip force falls into the interval;
F – force applied to release the grip

Based on the values, we can conclude that a decrease in the length of the intermediate magnetic circuit reduces the value of the engagement decoupling force.

Gripper disengaging force:

Magnetic core length, mm	50	35	25
Gripper average disengaging force, kg	1.02	0.88	0.46

In the off state, a similar dependence is observed – a decrease in the tripping force with a decrease in the length of the intermediate magnetic circuit. The average disengagement force with the length of the intermediate magnetic circuit is 50 mm, which is approximately two times larger than with a length of 25 mm.

Fig.7 shows graphs plotted according to the modes of the series of values of the engagement decoupling force in the on and off states, since this parameter reflects the most frequent values of the engagement decoupling force.

Conclusion. The study of the influence of the intermediate magnetic circuit length on the strength of the engagement of the gripper in the on and off states. When the length of the intermediate magnetic core is changed two times (from 50 mm to 25 mm), the average value of the de-

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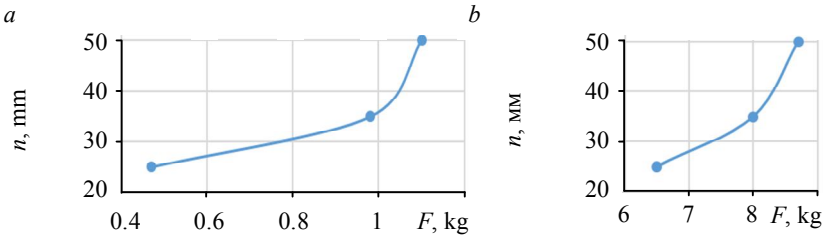


Fig. 7. The dependence of the strength of the engagement of the gripper on the length of the intermediate magnetic circuit in the off (*a*) and on (*b*) states

coupling force in the on state decreases by 21 %, and in the off state – by 55 %. When the length of the intermediate magnetic circuit is 50 mm, the value of the decoupling force in the on state will be in the range [6.85; 9.65], for a magnetic circuit with a length of 35 mm – [6.7; 9.1], with a length of 25 mm – [5.5; 9.65]. The histograms constructed in this work give an idea of the most probable magnitude of the disengagement force for different lengths of the magnetic wire and operating modes. Further research will be carried out in the direction of modeling magnetic fields in a virtual environment and developing methods for calculating the parameters of the presented magnetic gripper.

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