NATIONAL TECHNICAL UNIVERSITY OF UKRAINE
"IGOR SIKORSKY KYIV POLYTECHNIC INSTITUTE"

Faculty of Electrical Engineering and Automation
(full name of institute, faculty)

Department of Electromechanics
(full name of the department)

"Admitted to defense"

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"___"_____________20__ year

Thesis

for a bachelor's degree

in specialty 141 – Electric power engineering, electrical engineering and electromechanics
(code and name)

on the topic: Electromagnetic wave drive based on permanent magnets

4th year student , group ___________________ E M-g62-1 ________
(group code)

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(surname, first name, patronymic) (signature)

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(position, academic degree, academic title, surname and initials) (signature)

Consultant ___________ ________________________________ _________
(section name) (position, academic title, academic degree, last name, initials) (signature)

Reviewer ___________, Candidate of Technical Sciences, Associate Professor, Buryan Serhiy Oleksandrovych
(position, academic degree, academic title, academic degree, surname and initials) (signature)

I certify that this thesis does not borrow from the works of other authors without appropriate references.
Student _____________
(signature)

National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"

Faculty of Electrical Engineering and Automation
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Department of Electromechanics
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Level of higher education – first (bachelor's)
Specialty 141 – Electrical Power Engineering, Electrical Engineering and Electromechanics
Specialization – Electrical machines and devices

APPROVE
Head of the Department
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(signature) (initials, last name)
"___"_____________20__ year

TASK
for a student's thesis
To Viacheslav Aleksandrovich Lykhohub
(last name, first name, patronymic)

1. Project topic Electromagnetic wave drive with permanent magnets
Project manager: Mykola Oleksandrovych Reutsky, Ph.D. (Technology), Assoc. Prof.
(surname, first name, patronymic, academic degree, academic title)

approved by the order of the university dated "___"_________ 20__ No. _____
2. Deadline for student project submission : 14.06.20
4. Contents of the explanatory note: Contents. Introduction. 1. Patent search. 2. Description of the proposed design 3. Electromagnetic calculation 4. Mechanical calculation 5. Construction of drive characteristics. Conclusions. List of literature.
5. List of graphic material (indicating mandatory drawings, posters, presentations, etc.) Drawings of an electromagnetic wave drive on permanent magnets.

6. Project Section Consultants*

* The thesis supervisor cannot be named as a consultant.

Section	Consultant's last name, initials and position	Signature, date	
		the task was given	accepted the task

7. Date of issue of the task 10.09.2019

Calendar plan

No. of the company	Name of the stages of completing the thesis	Project milestones deadline	Note
1	Patent search	10.11.2019	
2	Design description	20.12.2019	
3	Electromagnetic calculation	15.03.2020	
4	Mechanical calculation	01.05.2020	
5	Construction of machine characteristics	15.05.2020	
6	Graduation thesis preparation	01.06.2020	

Student ______________ V. O. Lykhohub

(signature)(initials, last name)

Project Manager ______________ M.O. Reutsky

(signature)(initials, last name)

ABSTRACT

The thesis contains: pages – 38, figures – 38, tables – 2, drawings on A1 sheet and 4 references to scientific works.

The purpose of the thesis is to design a permanent magnet wave drive in accordance with the requirements determined in the patent search.

During the writing of the thesis, the following calculations were made: two-dimensional electromagnetic calculations of three variants of electromagnetic systems, three-dimensional calculation of the optimal electromagnetic system using parameterization, mechanical calculations of kinematic schemes of wave transmissions at different power parameters, and calculation of a simplified model of a flexible element in the transition zone.

As a result of the calculations above, a wave drive design was obtained, which has a number of innovative qualities, namely: the possibility of creating multi-wave mechanical systems, position fixation when power is removed.

On the topic of the thesis, together with Reutsky M.O., an article was published in the international scientific and technical journal of young scientists, postgraduates and students "Modern Problems of Electrical Power Engineering and Automation".

WAVE ELECTROMAGNETIC DRIVE, TORQUE MOTOR, FINITE ELEMENT METHOD CALCULATIONS, ELECTROMAGNETIC CALCULATION, MECHANICAL CALCULATION.

SUMMARY

Thesis contains: page - 38, figure - 38, table -2, drawing on sheet A1 and 4 references to scientific works.

The goal of the diploma project is to design electromagnetic strain wave drive with permanent magnets in accordance with requirements that are set by patent search.

During the writing of the diploma the following calculations were made: two-dimensional electromagnetic calculations of three variants of electromagnetic systems, three-dimensional calculation of the optimal electromagnetic system using parameterization, mechanical calculations of kinematic schemes of strain wave drive at different power parameters and calculation of a simplified model of a flexible element.

As a result of calculation, construction with unique characteristics were designed: ability to create multi-wave mechanical system and fixing position after disconnection from supply.

In cooperation with MO Reutskyi, an article related to the diploma project in the international scientific and technical journal of young scientists and students "Modern problems of electrical engineering and automation" was published.

ELECTROMAGNETIC STRAIN WAVE DRIVE, ELECTROMAGNETIC HARMONIC DRIVE, TORQUE ENGINE, FINITE ELEMENTS ANALYSIS, ELECTROMAGNETIC CALCULATION, MECHANICS CALCULATION.

CONTENT

INTRODUCTION

The relevance of the problem lies in the fact that a large number of modern systems, in particular in the fields of robotics, aviation, space systems, place high demands on electromechanical converters. If it is necessary to obtain high torque at low speeds, the result is achieved by transmitting high-speed rotational motion to the gearbox. Compared to systems where the rotational motion is transmitted directly to the executive body of the system, such systems have lower reliability and larger mass-dimensional indicators. On the other hand, the use of torque machines significantly complicates control systems that generate a system of low-frequency voltages in accordance with the feedback signal.

A possible step in optimizing the systems described above is to combine the principles of rotational motion reduction with the principles of electromechanical energy conversion. This solution can eliminate intermediate elements of the systems, which will increase their reliability and reduce energy losses.

This paper will describe and calculate an engine that combines the principle of wave reduction and electromechanical energy conversion.

The principle of wave reduction was chosen because it has a number of advantages that are extremely important for technology, namely: ensuring a high gear ratio, high efficiency, no backlash, compactness, high reliability, and the ability to carry significant torque.

Torque in wave transmission is created by waves of elastic material (Fig. 1, 2) that mesh with a fixed element (Fig . 3) [2]. Waves can be created mechanically, hydraulically, pneumatically, electrostatically, and electromagnetically.

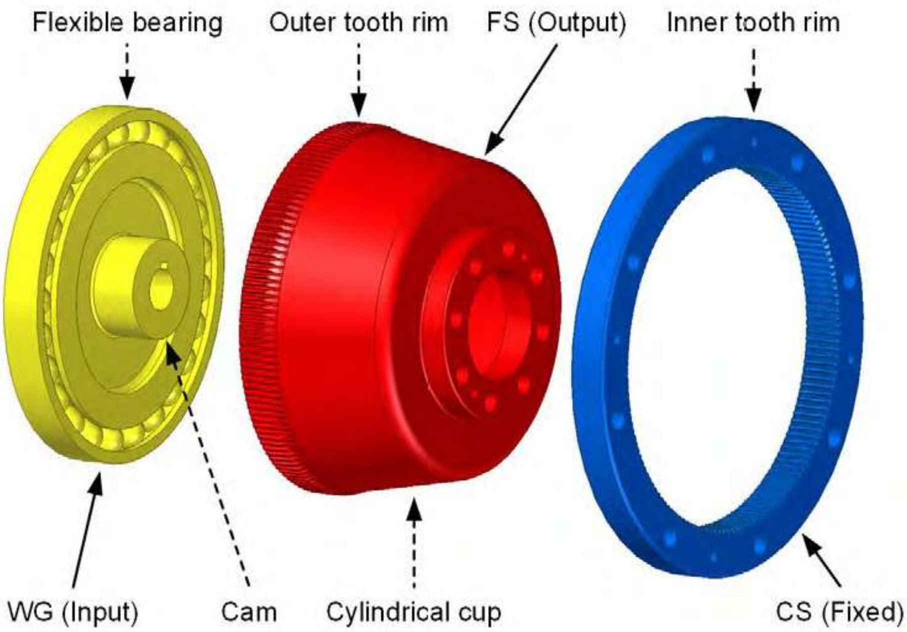

Fig. 1. Main components of wave transmission

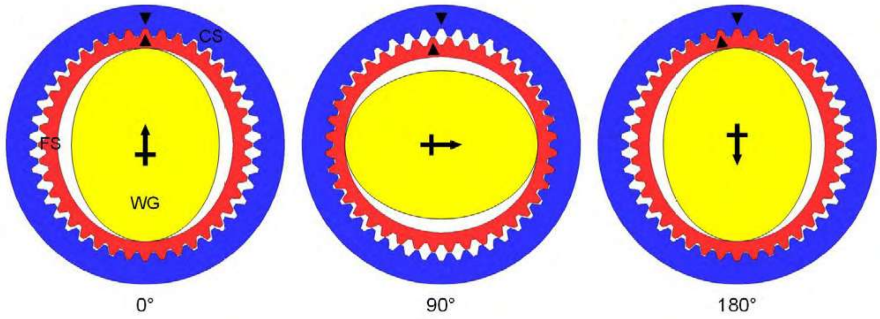

Fig. 2. Dependence between the coupling period and the rotation period of wave transmission

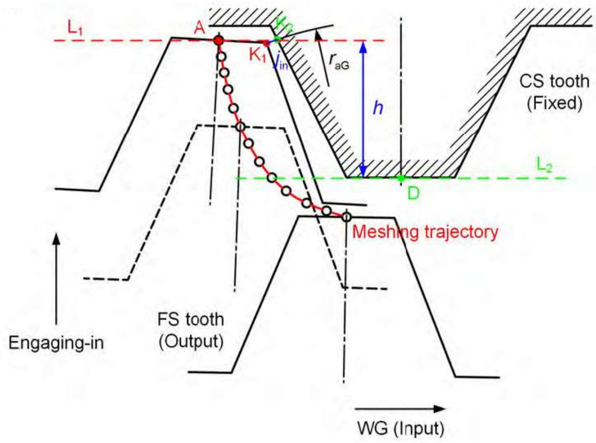

Fig. 3. Relative movement of the teeth of the flexible element relative to the teeth of the fixed gear

When using electromagnetic and electrostatic methods to obtain rotational motion, wave transmission consumes exclusively electrical energy and can be used as an electromechanical converter capable of providing high torque at low rotational speed. [1] .

1 PATENT SEARCH

1.1 Objective search function $F_{ц1}$

The purpose of the patent search is to study works on the topic of combining the principle of wave reduction and electromechanical energy conversion, analyze research results, and identify shortcomings.

Search criteria:

- Using the principle of strain wave drive.
- Consumption of electrical energy only.
- Obtaining a rotational motion at the output with a rotation frequency lower than the speed of rotation of the magnetic field.

1.2 Patent search result by objective search function $F_{ц1}$

The principle of operation of the wave motor is described in detail in patent US3169201A (USA) from 1965 [3]. A sketch of the invented machine is shown in Fig. 1.

The invention described in the patent includes a flexible annular element and a reaction element that interact with each other, an electromagnetic wave generator with a control system that causes the deformation wave movement of the annular element, as a result of which the output shaft is driven.

The wave generator is a group of coils distributed in a circle around the reaction element with a certain gap. The control system must ensure that the coils are energized, which ensures the deformation of the reaction element into an elliptical shape. When an external input signal is applied, the deformation wave must move in a given direction.

The reaction element transfers its own deformations to a flexible element with external teeth. When the flexible element acquires an elliptical shape, the teeth come into contact with a rigid element of a larger radius with internal teeth. The number of teeth of the rigid element is slightly greater than the number of teeth of the flexible element. The flexible element is mounted on the output shaft.

, the teeth of the flexible element run over the teeth of the rigid element and the flexible element rotates. The speed at which the output shaft rotates is determined by the formula (1. 1).

$$\omega_o = \omega_f \cdot \frac{Z_I - Z_o}{Z_o} \quad (1.\ 1)$$

where ω_o is the angular velocity of the output shaft, ω_f is the angular velocity of the magnetic field, Z_I is the number of teeth of the internal gear (flexible element), Z_O is the number of teeth of the external gear (rigid element).

Since the number of teeth on the internal gear is less than the number of teeth on the external gear, the angular velocities of the output shaft and the magnetic field have different signs.

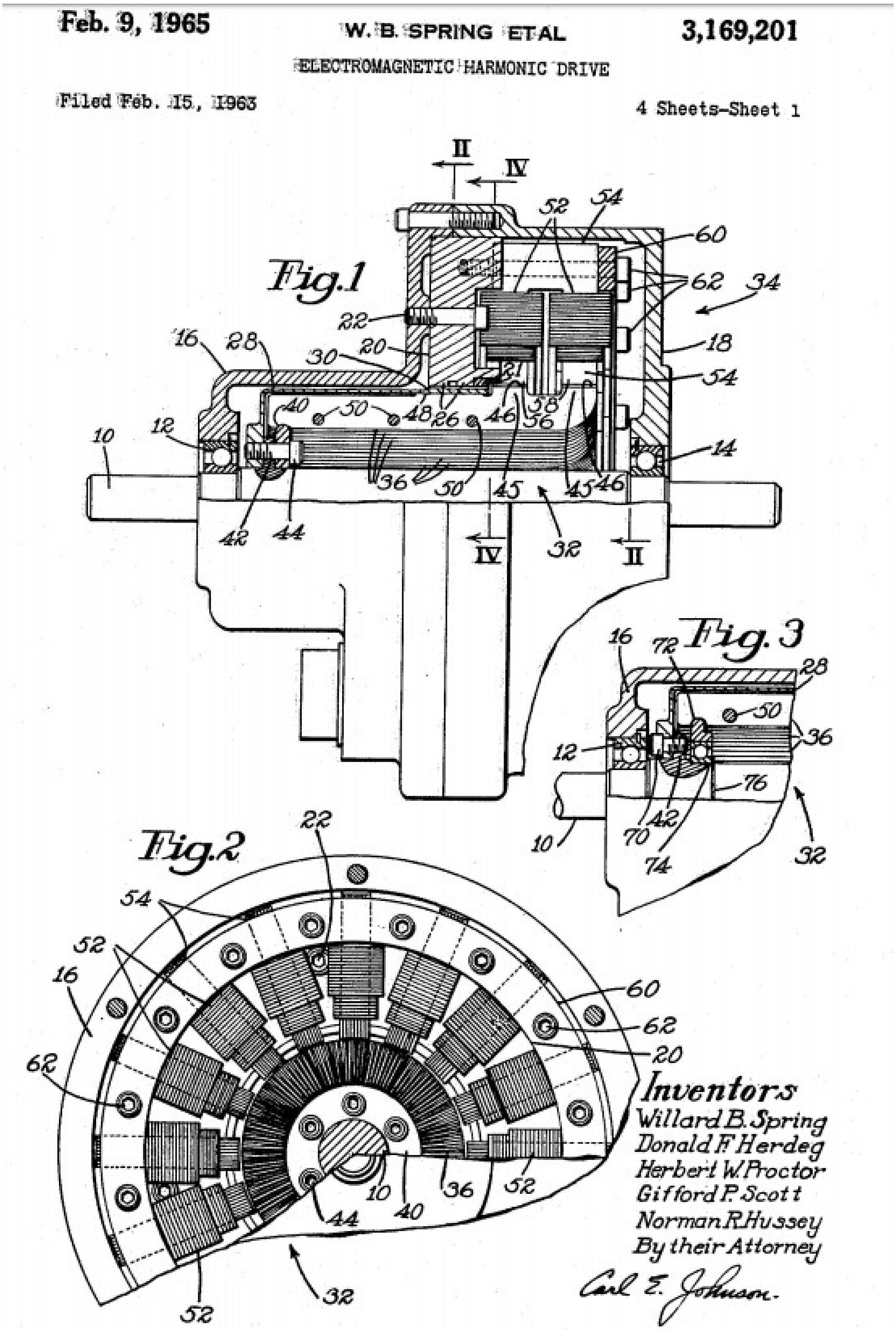

Fig. 1of the wave motor described in patent US3169201A

1.3 Patent analysis US3169201A

Compared to the classic drive design using a motor-gearbox scheme, the design given in patent US3169201A has a number of advantages:

- Smaller weight and dimensions with the same power and efficiency.
- Significantly lower moment of inertia due to the absence of rapidly rotating parts.
- Simplicity and reliability of the design.

Despite all the advantages listed above, this implementation of the drive has adopted some of the design shortcomings of classic wave gearboxes, namely:

- Large extension of the flexible element beyond the contact zone to ensure the transmission of rotational motion to the rigid output shaft, which increases the dimensions and reduces the rigidity of the position.
- The flexible element is unable to push away from the poles, forming depressions, which reduces the specific power and limits the maximum number of mechanical waves to three.

New design flaws have also appeared related to the implementation of the wave generator and the reaction element:

- Lack of position fixation when removing voltage.
- Rapid wear of the varnish layer on the electrical steel sheets and rubber tubes on the reaction element.

1.4 Objective search function $F_{ц2}$

Given the design shortcomings listed in section 1.3we will conduct a patent search with specified criteria.

Search criteria:

- Using the principle of strain wave drive.
- Consumption of electrical energy only.
- Obtaining a rotational motion at the output with a rotation frequency lower than the speed of rotation of the magnetic field.

- Transmission of rotational motion from a flexible element without significant deflection.
- Ability to generate more than 3 mechanical deformation waves.
- Fixing the position of the output shaft when removing the supply voltage.

1.5 Patent search result by objective search function $F_{ц2}$

In the processed patent databases, no information was found about systems with more than 3 waves and the ability to fix the position when the supply voltage is removed, therefore it is advisable to remove these criteria from further search.

1.6 Objective search function $F_{ц3}$

Search criteria:

- Using the principle of strain wave drive.
- Consumption of electrical energy only.
- Obtaining a rotational motion at the output with a rotation frequency lower than the speed of rotation of the magnetic field.
- Transmission of rotational motion from a flexible element without significant deflection.

1.7 Patent search result by objective search function $F_{ц2}$

Patent “Wave Electric Motor” No. 75744 (Ukraine) from 2006 [4] describes a design that does not have the problem of a large deflection of the flexible element due to the combination of the reaction element and the flexible element into one whole.

The flexible magnetosensitive element is made in the form of a radially bent single-layer ferromagnetic strip with axial pins arranged in an orderly manner in the radial direction, the end sections of which, protruding beyond the edges of the ferromagnetic strip, are located with the possibility of movement in the grooves of the power disks, which are installed and fixed on the electric motor shaft adjacent to the ends of the stator core.

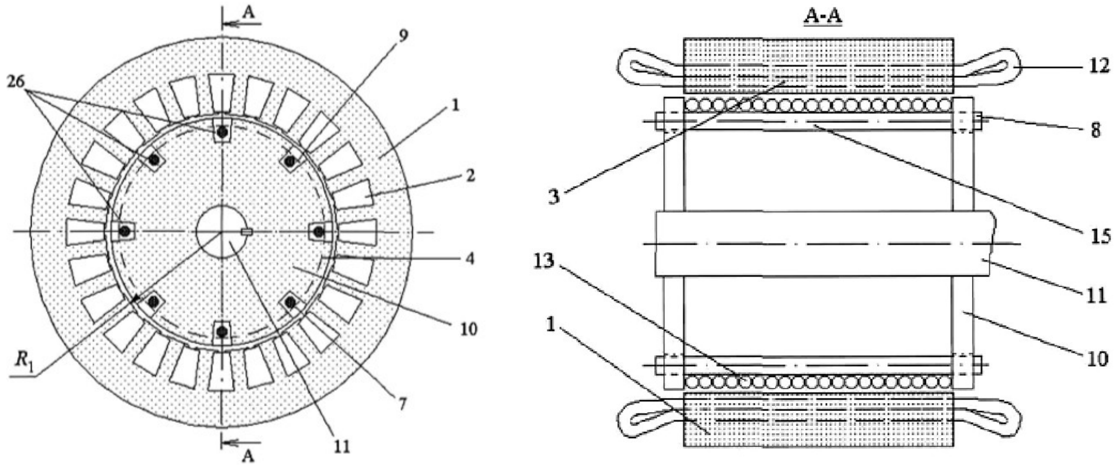

Fig. 1of the design proposed in the patent "Wave electric motor" No. 75744 (Ukraine) from 2006

Conclusion to the chapter

The patent search revealed technical solutions that could be used to implement the proposed idea, showed which useful qualities of wave engines had not yet been realized, and therefore opened up a promising direction of research.

2 DESCRIPTION OF THE PROPOSED CONSTRUCTION

2.1 General overview

The object of this work is an electromagnetic wave drive with permanent magnets, which is designed for electromechanical energy conversion, which will provide low-speed movement of the output shaft with the ability to obtain high torque.

To obtain the desired result, the principle of wave reduction and electromechanical energy conversion was combined. The proposed design consists of a group of coils wound on a core made of composite electrical steel, a reaction element, a flexible element, a rigid gear and a housing.

Based on an analysis of the shortcomings of existing designs that were studied during the patent search, the desired characteristics for the electric machine being created were established, namely:

- Using the principle of strain wave drive.
- Consumption of electrical energy only.
- Obtaining a rotational motion at the output with a rotation frequency lower than the speed of rotation of the magnetic field.
- Transmission of rotational motion from a flexible element without significant deflection.
- Ability to generate more than 3 mechanical deformation waves.
- Fixing the position of the output shaft when removing the supply voltage.

2.2 Description of the electromagnetic part of the drive. Formulation of the problem of designing an electromagnetic system

Providing such features as the ability to form more than 3 mechanical waves and fixing the position of the output shaft when the supply voltage is removed requires a fundamentally new approach to creating the interaction force between the electric coils and the reaction element compared to existing designs.

When passing the magnetic flux created by the stator poles through the soft magnetic material located on the reaction element, the domains orient themselves in the direction of the external magnetic field, creating their own magnetic field. The interaction of these two fields generates the attraction of the flexible stator to the poles. When changing the direction of the magnetic flux created by the coil on the stator, the magnetic field in the soft magnetic material also changes its direction, and as a result, the direction of the mechanical force remains unchanged.

To ensure repulsion, it is necessary to place an independent magnetic field source on the reaction element. This can be either an electromagnet or a permanent magnet.

Placing permanent magnets on the flexible element will increase the force of attraction and provide repulsion, which will increase the specific power of the electromechanical converter. Also, this design does not require stacking of the flexible element, which will significantly increase reliability.

Using an electromagnet will provide an equal increase in both the force of attraction and the force of repulsion. Although this option is the most complex in terms of manufacturing, it provides the best characteristics and the smallest weight and dimensions.

The ability to provide interaction in both directions allows for greater force to be applied to deform the flexible element and create more than 3 mechanical waves, which expands the range of gear ratios.

In this paper, we will consider a design that uses permanent magnets as a source of an independent magnetic field on the reaction element, due to the fact that only with the help of this option is it possible to ensure position fixation when the supply voltage is removed.

The task of designing an electromagnetic system is to create a structure that would provide equal attraction and repulsion of the reaction element relative to the coil with the core, with sufficient force , and in such geometric dimensions that allow it to be placed in the actuator housing.

2.3 Description of the mechanical part of the drive. Formulation of the problem of designing a mechanical system

The mechanical part of the wave drive consists of a flexible element, external and internal rigid gears. The external gear has internal teeth with the number Z_1. The flexible element has both external and internal teeth with the number Z_2 and Z_3, respectively. The internal gear has external teeth with the number Z_4. All teeth in the system have the same geometric dimensions. For this arrangement of teeth, the condition (2. 1)

$$Z_1 > Z_2 > Z_3 > Z_4 \qquad (2.1)$$

Due to the differences in the number of teeth on different gears, the rotation speed is reduced.

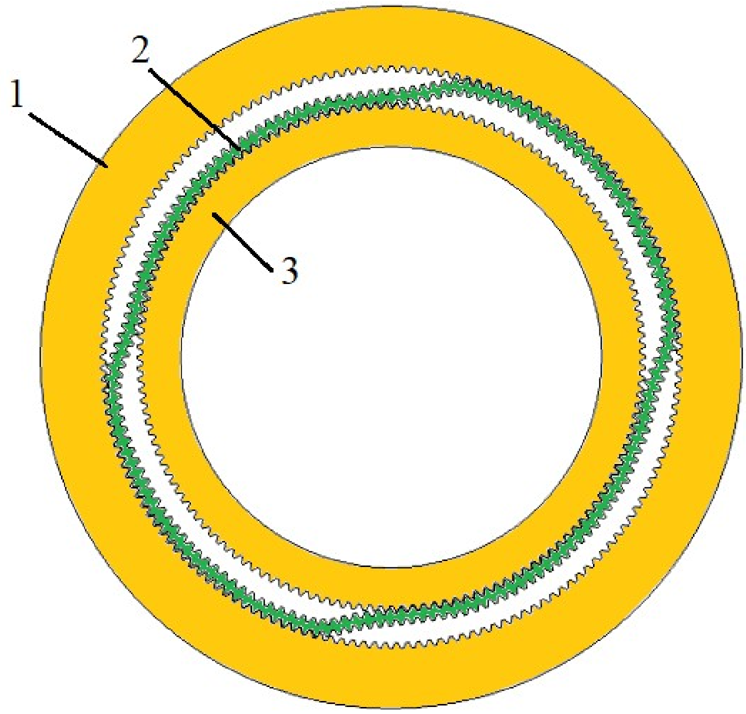

Fig. 21. Sketch of 1mechanical system of the electromagnetic wave drive.

1 – external gear, 2 – flexible element, 3 – internal gear.

Increasing the number of mechanical waves increases the number of contact points of the teeth of the flexible element with the teeth of the fixed gear, distributing the forces between the teeth. This allows you to reduce the tooth modulus, and therefore reduce the difference in diameters of the flexible element and the fixed gear, which in turn reduces the deformation of the flexible element and reduces the air gap between the coil with the core and the reaction element, which must cross the magnetic flux.

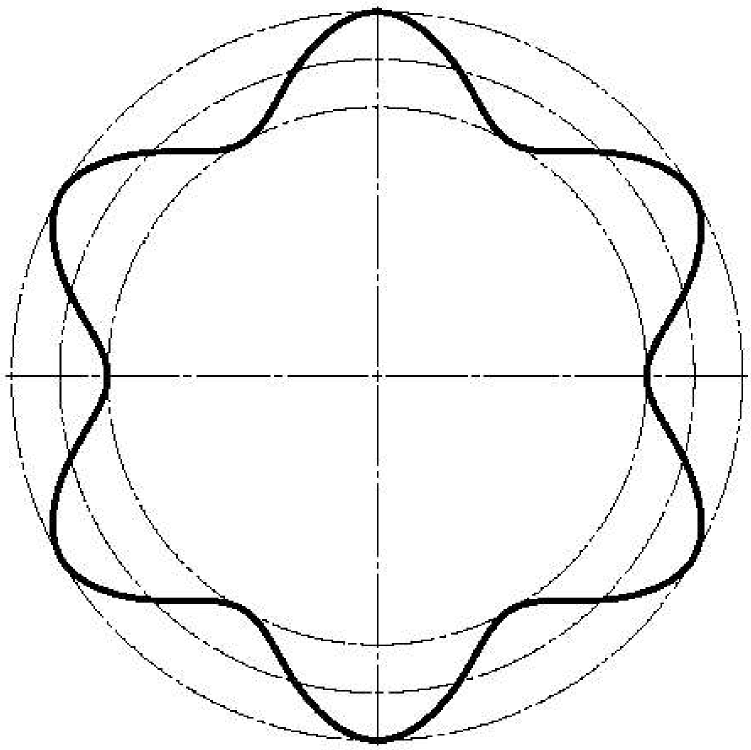

Fig. 22. 2

The task of designing a mechanical system is to create a structure that will provide the possibility of wave reduction of the rotation speed, the ability to work with a different number of mechanical waves, reliable fastening with the reaction element and its minimum stroke.

The minimum travel of the reaction element is necessary to reduce magnetic resistance by minimizing the air gap to the coil with the core.

Conclusion to the chapter

This section describes the proposed design of a permanent magnet wave drive, which will be investigated and optimized in the course of further work. Problems for electromagnetic and mechanical calculations were formulated, which determined clear goals for further work.

3 ELECTROMAGNETIC CALCULATION

3.1 Choice of pole geometry and operating principle

To create a design that would provide equal degrees of both attraction and repulsion of the reaction element relative to the coil with the core, it is necessary to use a source of independent magnetic field on the reaction element, which in this work will be a permanent magnet for the reasons described in section 2.2.

Analytical methods for calculating the magnetic field and the mechanical force it creates do not allow working with systems of complex geometry and greatly complicate the calculation when taking into account the saturation of the magnetic core, therefore, numerical methods will be used to calculate this machine.

The packages COMSOL Multiphysics 5.4 and Matlab 2020a were chosen as the calculation packages.

To obtain an electromagnetic pole system that meets the task, it is necessary to choose an effective method of interaction of the magnetic field of the coil with the magnetic field of the permanent magnet.

The parameters of the models are given below:

- maximum coil power – 2000 A
- permanent magnet force – 0.3 T
- relative magnetic conductivity of magnetic cores – 2000 rel.

The most difficult moments of the pole operation are the attraction of the reaction element at the maximum air gap and the repulsion of the reaction element at the minimum air gap. With this in mind, the following will provide drawings of the distribution of magnetic induction in these modes.

When the magnitude of the force created by the magnetic field is specified, the rule of signs is chosen as follows: the sign "+" denotes repulsion of the reaction element (upward movement), the sign "-" denotes attraction of the reaction element (downward movement).

Option 1

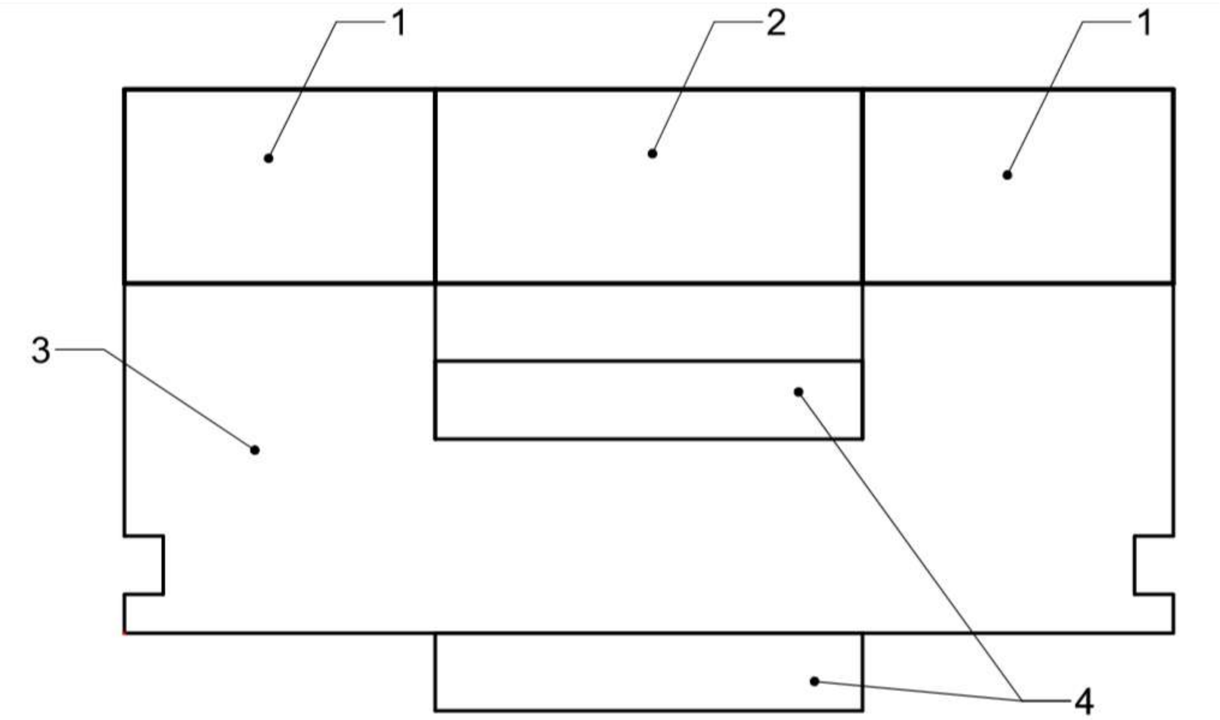

Fig. 3of the pole. Option 1.
1 – magnetic circuits adjacent to the permanent magnet, 2 – permanent magnet, 3 – magnetic circuit, 4 – coil.

Fig Fig. 3two magnetic cores at the ends of the magnet. The permanent magnet with the magnetic cores attached to it are movable and represent a reaction element.

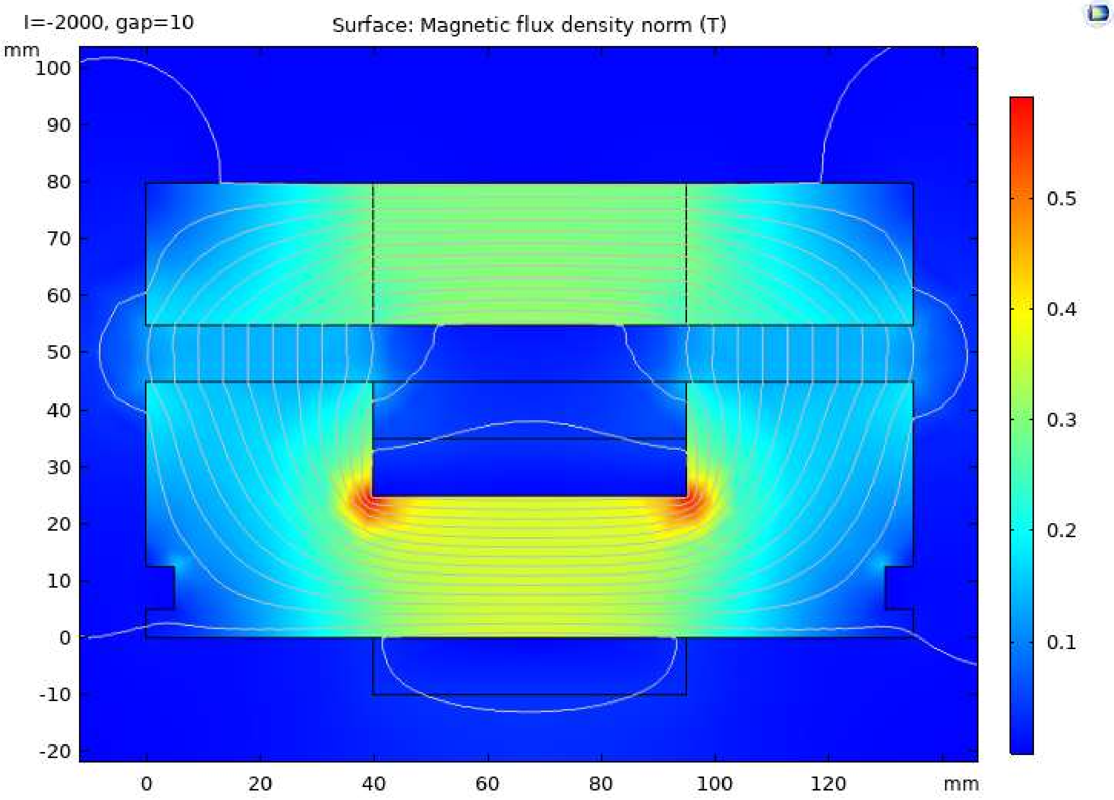

Fig. 32. Distribution 1magnetic induction. Air gap – 10 mm. Current to attract the reaction element

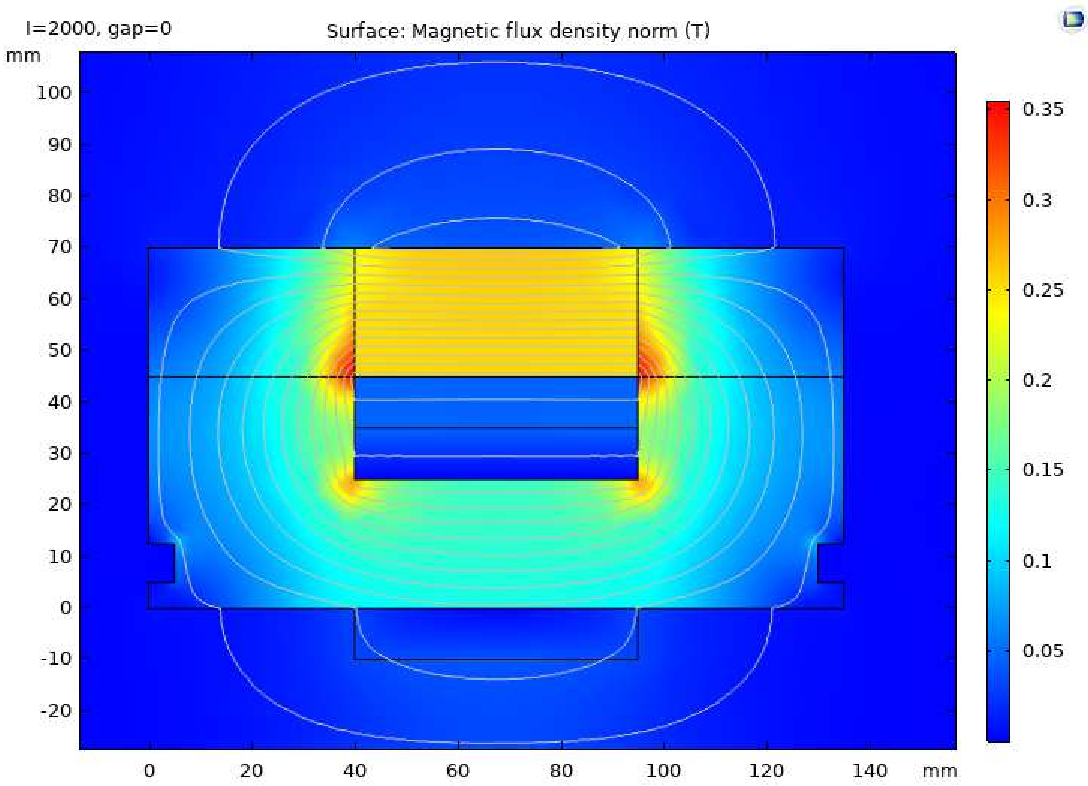

Fig. 3of magnetic induction. Air gap – 0 mm. Current for repulsion of the reaction element.

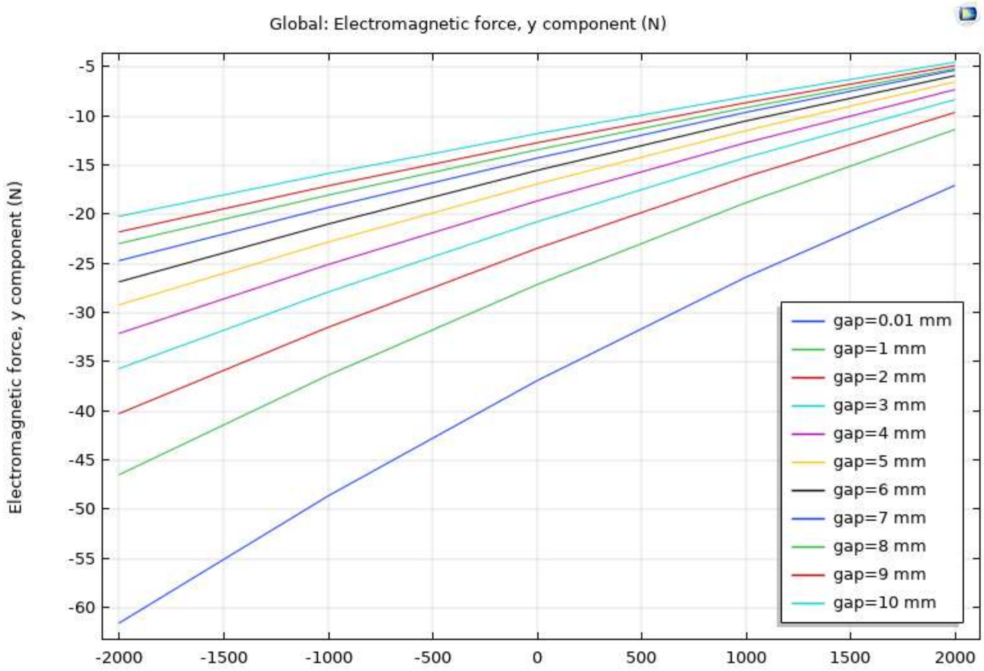

Fig. 34. Graph 2the dependence of the interaction force on the current strength at different air gaps.

As can be seen from Fig. 34. Graph 2the reaction element in the given range of coil force values.

Let's perform the calculation with an increased coil force range.

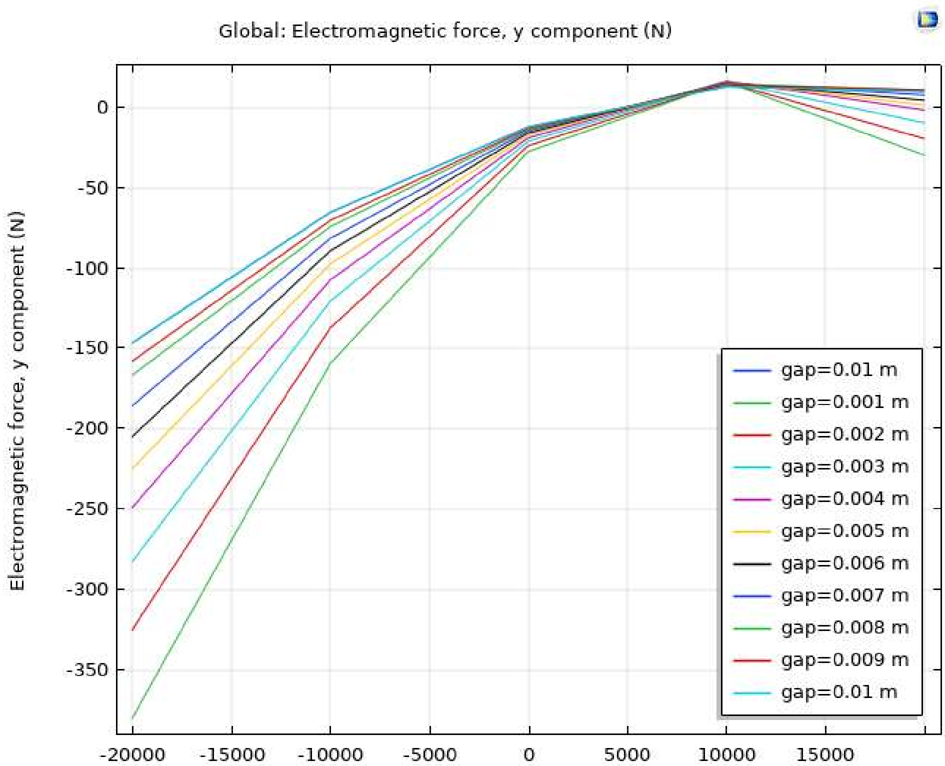

Fig. 35. Graph 3the dependence of the interaction force on the current strength at different air gaps (enlarged range).

As can be seen from Fig. 35. Graph 3repulsion occurs, but with a further increase in current, the sign of the force changes sign again.

Given the significant asymmetry of the power characteristic relative to zero, the need for very large currents, and the provision of a small repulsive force, the design is considered unsuccessful.

Option 2

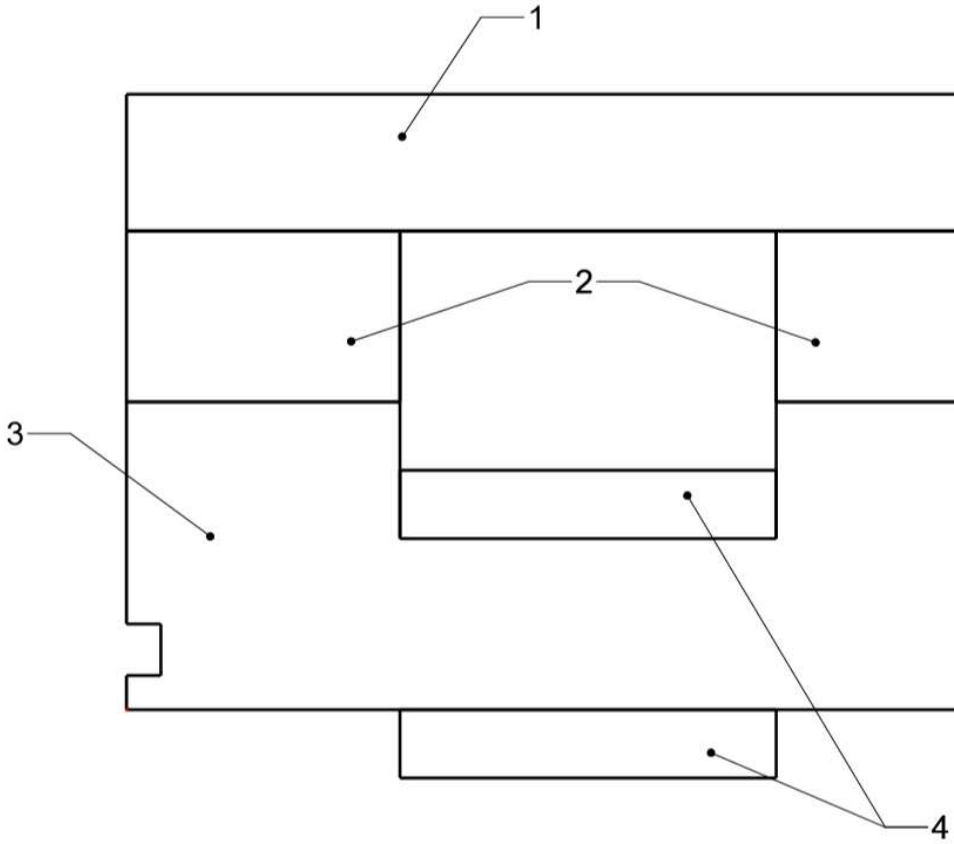

Fig. 36. Sketch 4the pole. Option 2.
1 – magnetic core adjacent to permanent magnets, 2 – permanent magnets, 3 – magnetic core, 4 – coil.

Fig Fig. 36. Sketch 4a magnetic core connecting 2 magnets. The permanent magnets with the magnetic core attached to them are movable and represent a reaction element. The magnets are magnetized along the vertical axis and have opposite directions of magnetization.

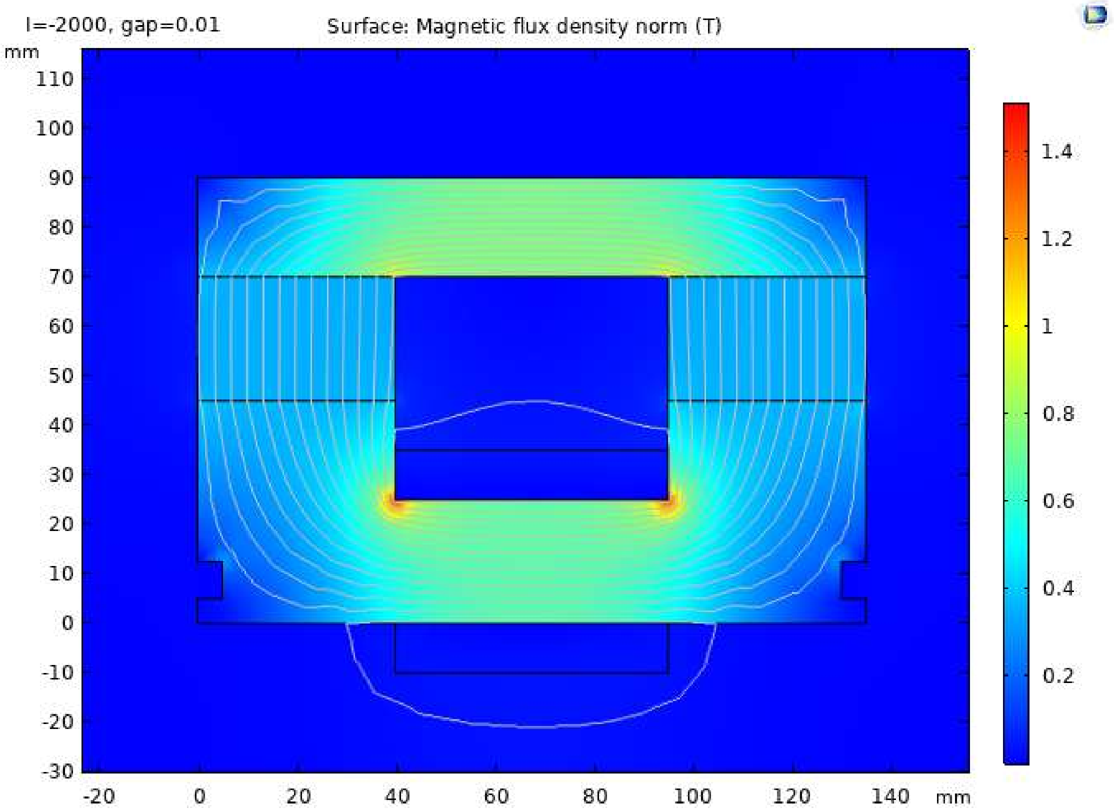

Fig. 37. 5

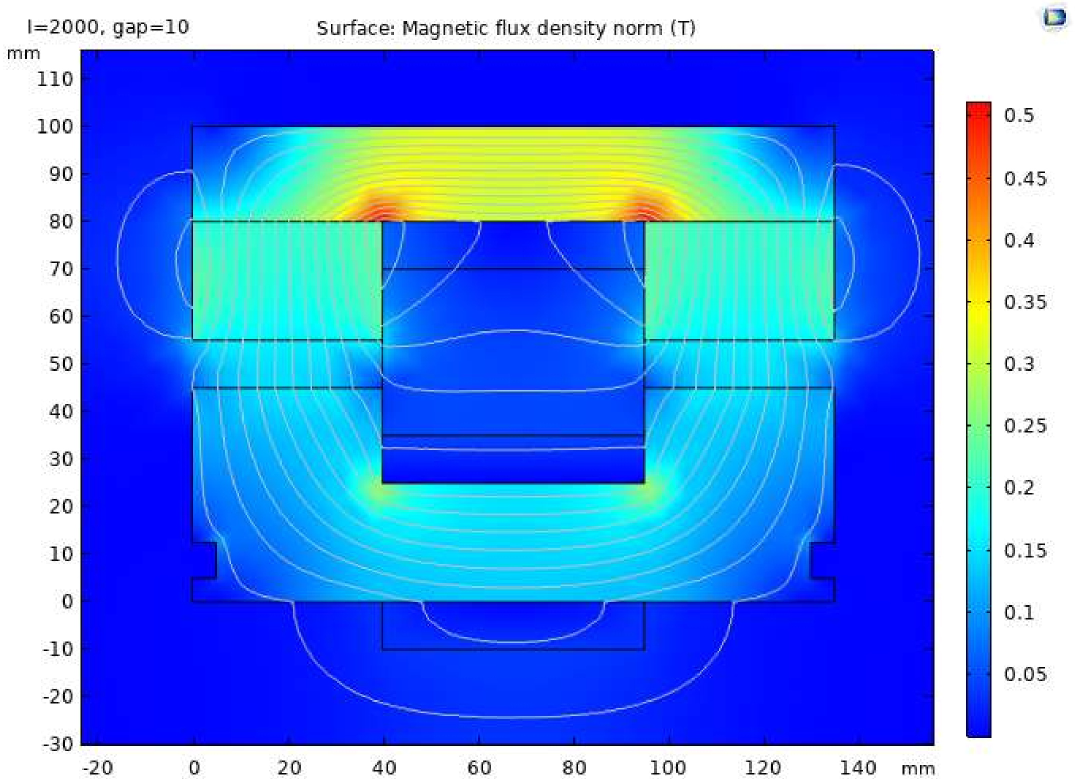

Fig. 38. Distribution 6magnetic induction. Air gap – 0 mm. Repulsion current of the reaction element.

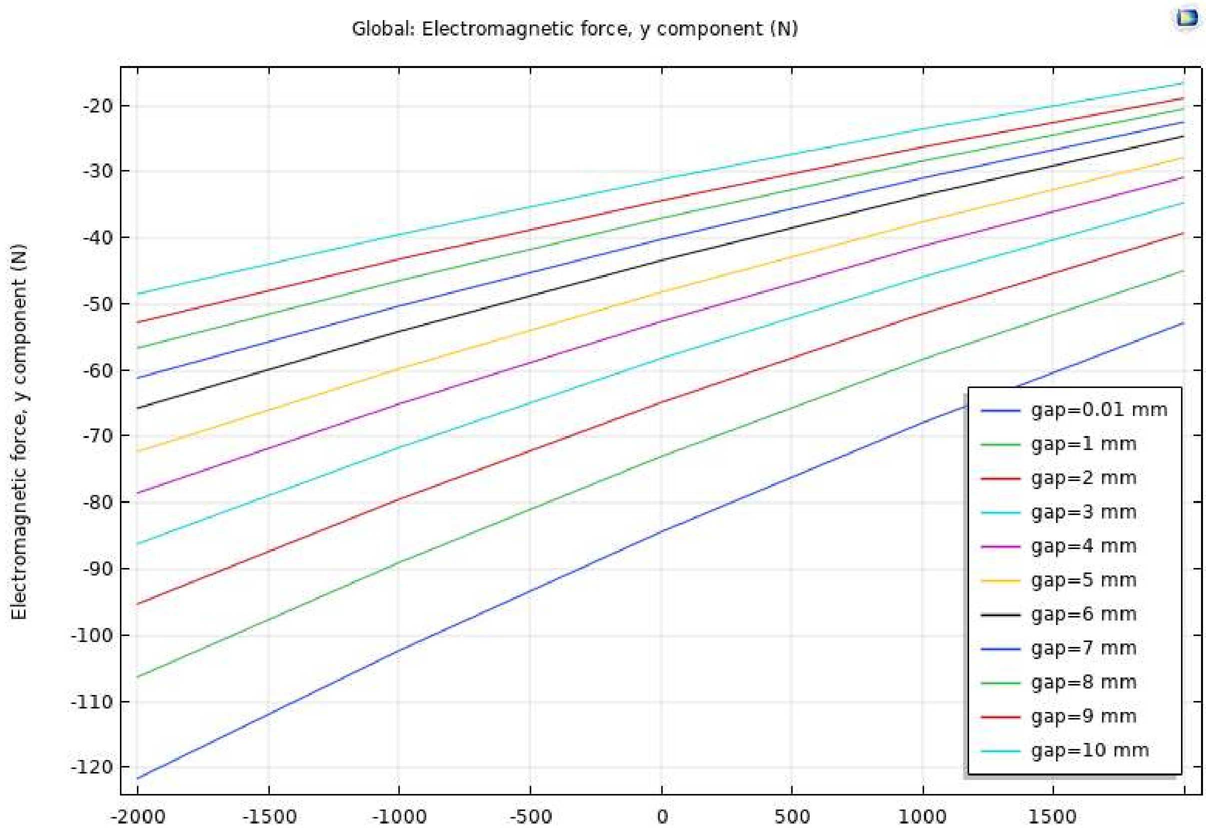

Fig. 39. Graph 7the dependence of the interaction force on the current strength at different air gaps.

As can be seen from Fig. 39. Graph 7

We can conclude that repelling the reaction element from the core coil by creating a counter magnetic flux is ineffective.

Option 3

Taking into account the mistakes made in options 1 and 2, it was decided not to create a counter magnetic flux to the permanent magnet flux, but to control it by closing this flux.

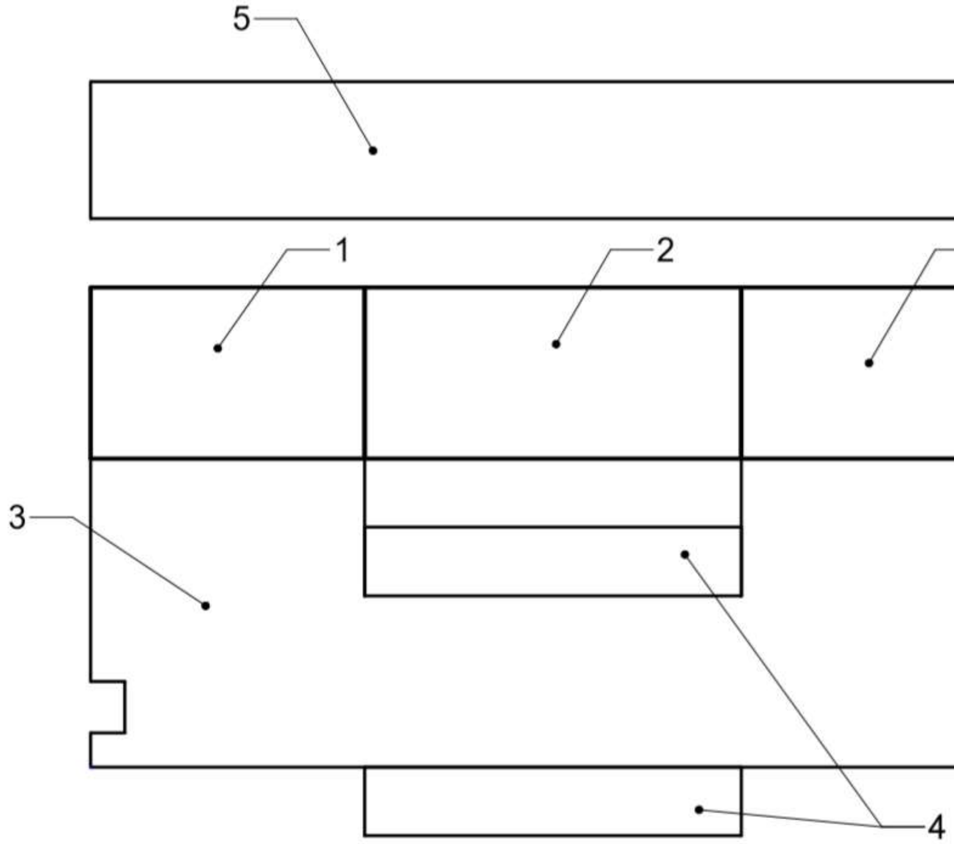

Fig. 3of the pole. Option 3.
1 – magnetic core adjacent to the permanent magnets, 2 – permanent magnets, 3 – magnetic core, 4 – coil, 5 – upper magnetic core.

Fig Fig. 3and the upper fixed magnetic core. The permanent magnet with the magnetic cores attached to it are movable and represent a reaction element.

The principle of operation of this circuit is that using the current in the coil, it is possible to control through which magnetic circuit (main or upper) the magnetic flux of the permanent magnet will be closed, and therefore to which magnetic circuit the reaction element will be attracted.

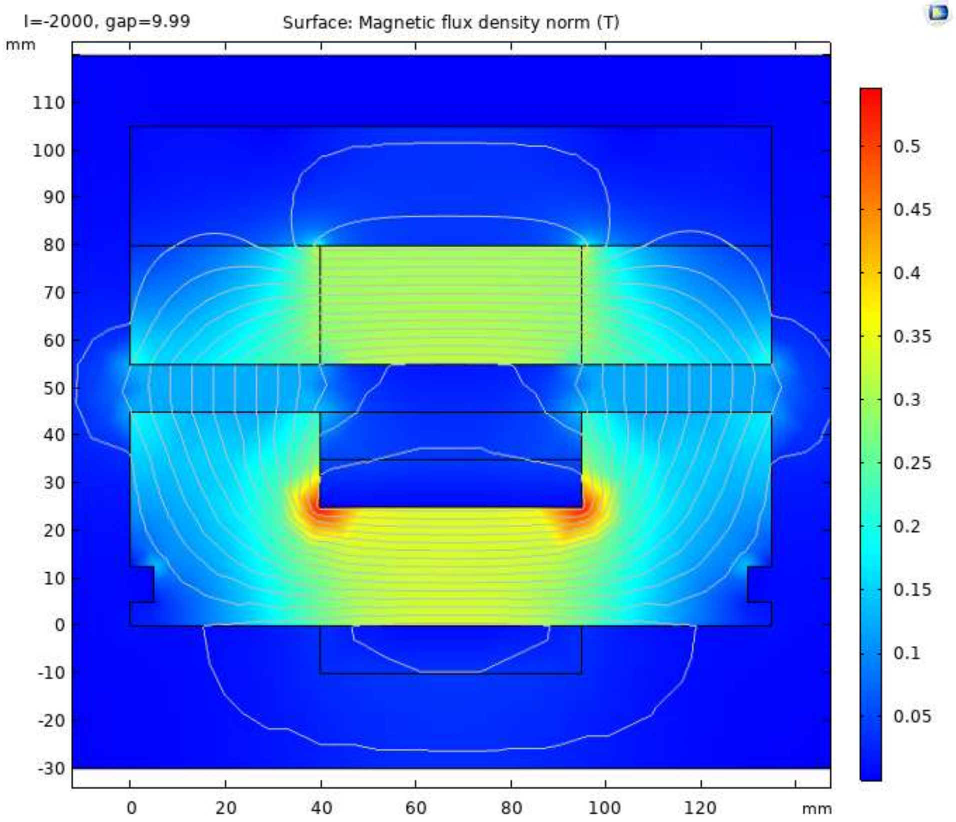

Fig. 3of magnetic induction. Air gap – 10 mm. Current to attract the reaction element.

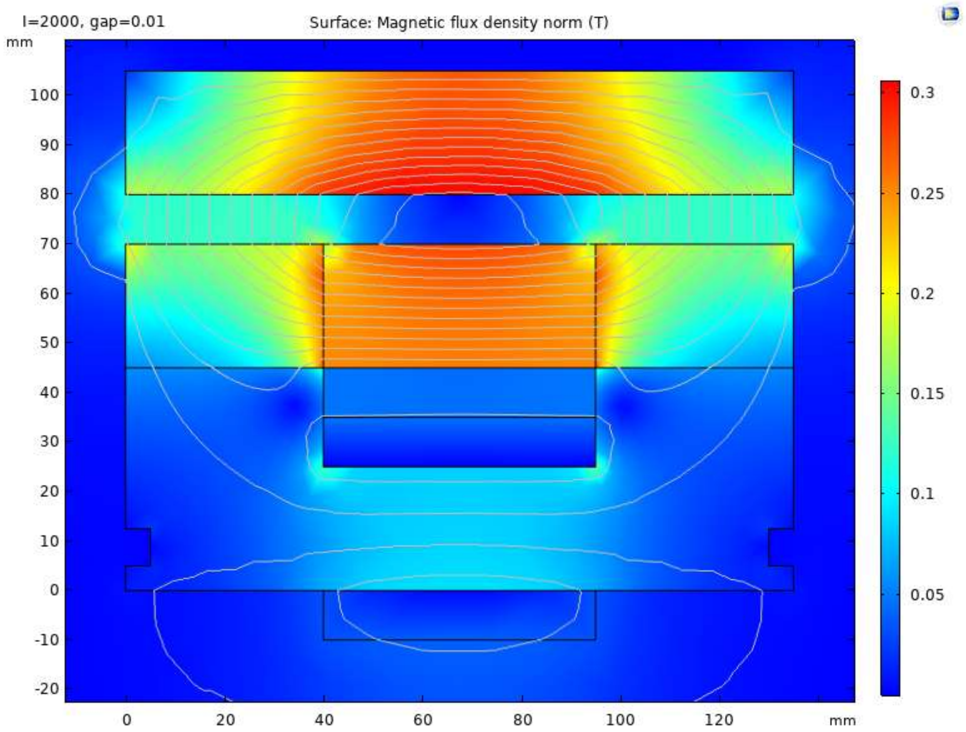

Fig. 3of magnetic induction. Air gap – 0 mm. Repulsion current of the reaction element.

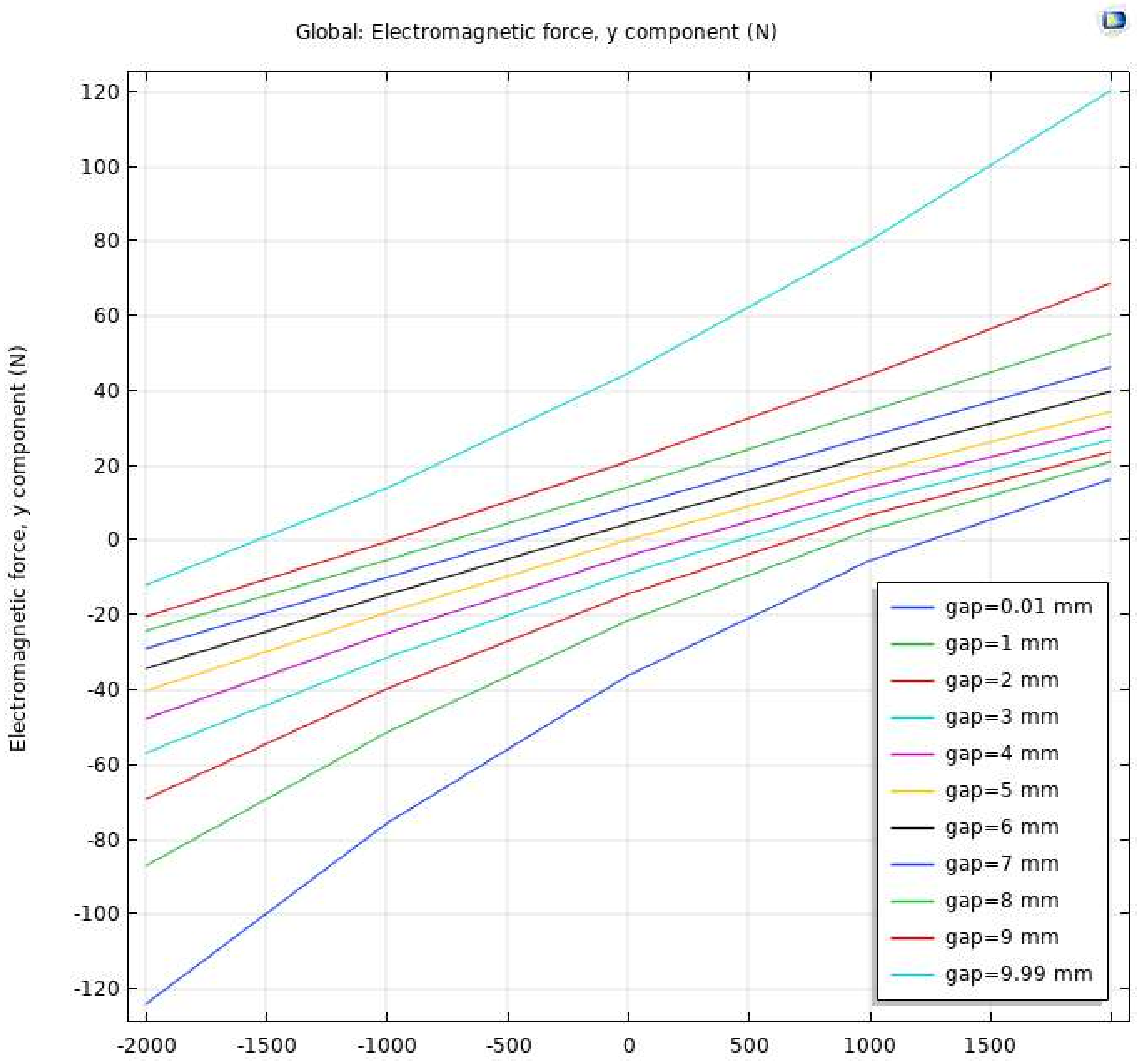

Fig. 313. Graph 8the dependence of the interaction force on the current strength at different air gaps.

As can be seen in Fig. 313. Graph 8the force characteristics lie on different sides of the horizontal axis, which means that both attraction and repulsion are possible. The characteristics are approximately symmetrical about the origin, from which we can conclude that approximately the same current is required for repulsion and attraction.

A sign of the system's operability is that all points corresponding to the maximum positive current lie in the positive half-plane, and points corresponding to the maximum negative current lie in the negative half-plane. This feature is more clearly seen in the dependence of the force on the air gap at different currents (**Error! Reference source not found.**The angle at which the internal wheel rotates, depending on time, with the number of waves waves = 2 and the angular velocity of the mechanical wave 31.4 rad/ s9calculation of these characteristics when formulating a complete two-dimensional problem taking into account the exact geometry of the elements of the mechanical system (REF _Ref41665036 \h Fig. 5.1) turned out to be impossible due to the high nonlinearity of the mathematical model.

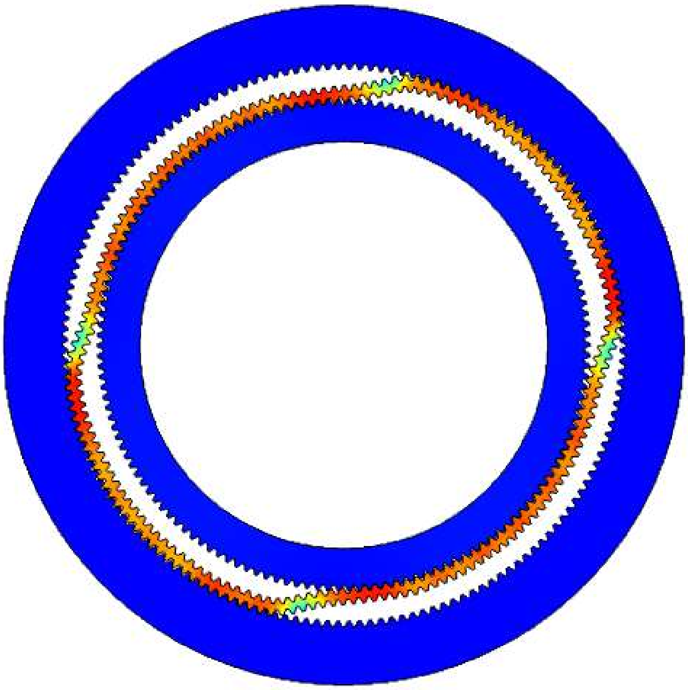

Fig. 31. 10

The creation of mechanical torque occurs when the coil switches and the segment of the flexible element moves from one gear to another. If this process is simulated, it is possible to obtain the value of the mechanical force that is created.

To do this, we will create a simplified model that would describe this process in the COMSOL Multiphysics package using the Multibody Dynamics module in the form of a two-dimensional truss (Fig. 32. 11. 5.2) .

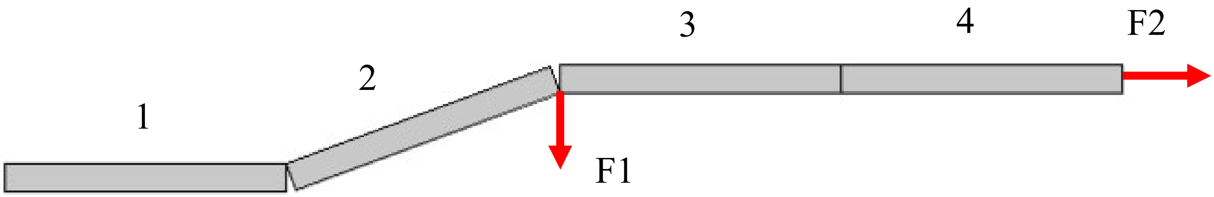

Fig. 32. 11

Fig Fig. 32. 11each other by a hinge. Segment 1 is rigidly fixed, segment 4 is able to move freely horizontally, but is unable to move vertically.

This diagram describes a flexible element made of rigid segments in the transition zone. Segment 1 corresponds to the part of the flexible element that is engaged with the internal gear, segment 4 to the external gear, segments 2 and 3 correspond to the part of the flexible element that changes its position.

The geometry of the simplified scheme was obtained by analyzing the results obtained when trying to take into account the full geometry of the mechanical part (Fig. 31. 10). The physical properties of the segments take into account the masses of real structural elements.

The hinge connection between segments 1 and 2 is constrained such that segment 2 is unable to deviate from the horizontal downwards, which describes the reaction of the internal gear support.

Two forces are applied to the system, which Fig. 32. 11shown by red arrows in Fig. 5.2 .

$_1$ is applied vertically downwards , which is created by the interaction of the reaction element with the magnetic field of the coil with the core. The magnitude of this force depends on the current in the coil and the position of the reaction element. This dependence is implemented by interpolation of the results obtained in section **Error! Reference source not found.**. During the movement of the point to which the force is applied, the magnitude of the force changes automatically. The coil force is assumed to be 2000 A.

$_2$ is applied to the right edge of segment 4 , which characterizes the load moment on the machine shaft.

The purpose of the experiment is to find the maximum force F_2 at which the force F_1 is able to tip segment 2 to the lower position.

The video file "Movment 1.avi" shows the movement of the system at a force F_2 = 410 N, which is the maximum force at which segment 2 can move to the lower position. On

Fig. 33. Dynamics of motion 12

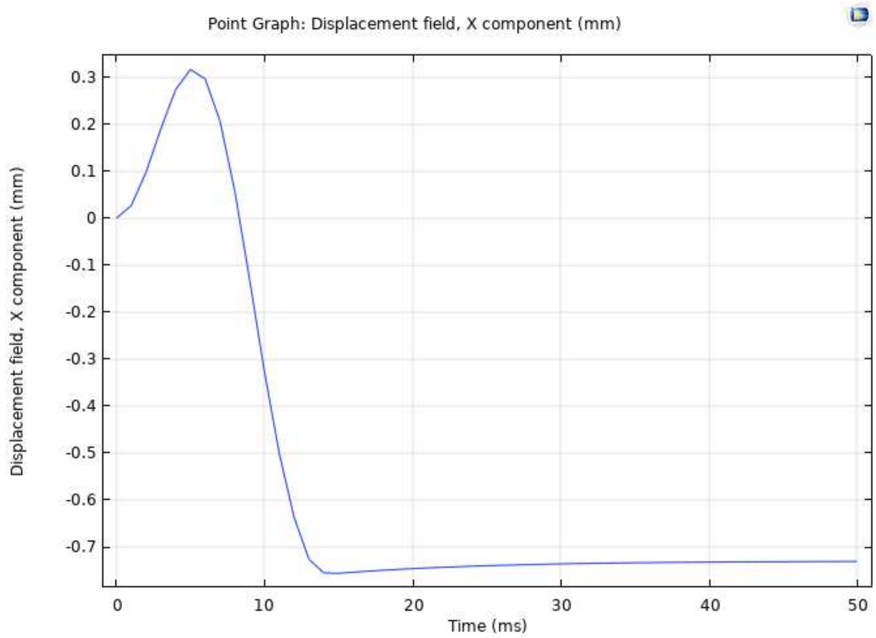

Fig. 33. Dynamics of motion 12segment 4 at force F_2 = 410 N

The video file "Movment 2.avi" shows the movement of the system at a force F_2 = 420 N. Fig. 34. Dynamics of motion 13shows the dynamics of the movement of segment 4. This figure shows that the system is unable to take a stable position, which indicates the impossibility of engine operation .

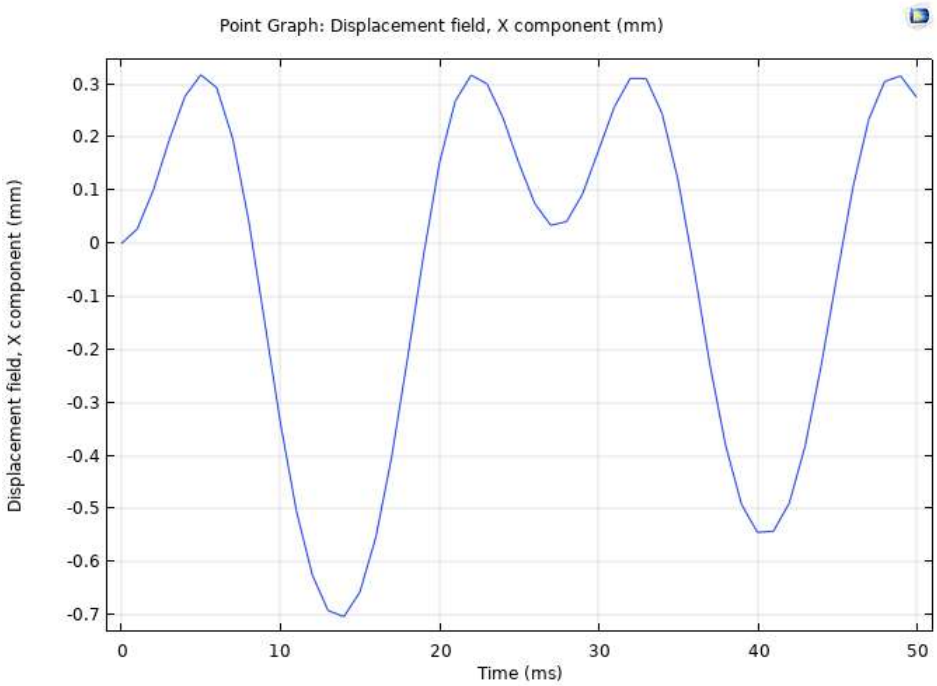

Fig. 34. Dynamics of motion 13segment 4 at force $F_2 = 420$ N

Determination of the maximum total moment

Having the maximum value of the force F_2 and the radius of the flexible element R_f, we can calculate the equivalent moment created by 1 crest of a mechanical wave (3. 1).

$$M_w = F_{2max} \cdot R_f = 410 \cdot 0.049 = 20.09 \text{ H} \cdot \text{m} \qquad (3.1)$$

Since each wave has 2 transitions, we can write down the maximum total torque, taking into account the number of mechanical waves W, which can create a drive (3. 2).

$$M_{max} = 2 \cdot F_{2max} \cdot R_f \cdot W \qquad (3.2)$$

The design that was calculated can have no more than 4 waves, therefore the dependence of the maximum moment on the number of waves has a range of definition from 2 to 4 inclusive and will be a linear dependence, as shown in Table 1.

Table 1

Number of mechanical waves W	Maximum moment M_{max}, , N · m

2	80.36
3	120.54
4	160.72

Determining the step size

When switching 1 group of coils, the output shaft is shifted by a fixed angle. As can be seen from Fig. 33. Dynamics of motion 12. 5.3 , the gear surface is shifted by 0.73 mm, from which we can calculate the angular (3. 3).

$$\alpha = \frac{\Delta x}{R_f} = \frac{0.73}{49.7} \cdot \frac{180}{\pi} = 0.8536° \qquad (3.3)$$

Determining maximum rotation speed

The rotation speed is limited by the time required to change the position of the flexible element segment.

As can be seen from Fig. 33. Dynamics of motion 12α = 0.8536 ° , from which we can calculate the maximum speed (3. 4).

$$n_{max} = \frac{\alpha \cdot 60 \cdot c}{t_s \cdot 360°} = \frac{0.8536° \cdot 60}{0.015 \cdot 360°} = 9.484 \frac{\text{об}}{\text{хв}} \qquad (3.4)$$

Determining drive power

An important indicator used for comparison with analogues is the useful power on the shaft. With this design, the power of the machine depends on the number of waves, so it is appropriate to determine the dependence of the maximum power on the shaft on the number of waves. For this, we will use the formula (3. 5).

$$P_{max} = n_{max} \cdot \frac{\pi}{30} \cdot M_{max} \qquad (3.5)$$

The calculation results are shown in Table 2.

Table 2

Number of mechanical waves W	Maximum power P_{max}, W
2	79.81
3	119.72
4	159.62

Conclusion to the chapter

In this section, the machine parameters were determined for the geometry shown in the drawing (Appendix 1) by creating a simplified model of a flexible element in the transition zone.

CONCLUSIONS

The work showed the process of developing an electromagnetic drive based on permanent magnets, which included a patent search, electromagnetic and mechanical calculations, and determination of machine parameters.

The calculated drive can provide the following indicators:

- torque 160 N · m
- rotation speed 9.48 rpm
- step 0.85 °

Considering the specifics of the obtained indicators, we can conclude that this machine behaves in many ways similarly to a stepper motor and can be useful in systems where it is necessary to obtain high torque at low rotation speed, position fixation when the power is turned off, and precise positioning without a feedback loop.

A number of calculations performed in the COMSOL Multiphysics package showed the possibility of implementing an electromagnetic wave drive of the proposed design, however, further research is needed for its implementation. To improve the parameters of the machine, it is necessary to optimize the mechanical system, which at the moment is the main obstacle to increasing the specific power, as it requires a significant stroke of the flexible element, and therefore a large air gap, which must be passed by the magnetic flux. There is also a need for further research into the behavior of multi-wave systems.

LIST OF LINKS

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4Markov Oleksandr Mikhailovich, "Wave Electric Motor", Limited Liability Company "TETRA, LTD", UA75744, Ukraine