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Modeling and research of a magnetoelectric converter for hydro and pneumo actuators

Purpose. *Presentation of the results of modeling and practical implementation of a magnetoelectric converter for hydraulics and pneumatics systems of the aerospace industry.* ***Methodology.*** *Calculations of three-dimensional magnetic fields are carried out with the Finite Element Method by JMAG program. The solution of the differential equations connecting the input voltage, current, magnetic flux and torque is performed by numerical integration.* ***Results.*** *As a result of calculations, the converter configuration was obtained. Tests of the prototype model of the converter confirmed the principle workability of the adopted design and design solutions in its development.* ***Practical value.*** *Tests of the converter prototype sample confirmed the fundamental performance of the adopted design and constructive solutions.* References 9, tables 3, figures 14.
Key words: **magnetoelectric converter, three-dimensional magnetic field, mechanical characteristic, prototype sample.**

Наведено результати моделювання та практичної реалізації магнітоелектричного перетворювача для гідро- та пневмоприводів аерокосмічної галузі. На основі серії проектних розрахунків при різноманітній конфігурації магнітної системи перетворювача обрано варіант з чотирма зубцями на полюсі статору і отримані його основні характеристики. Результати розрахунків зіставлені з результатами експерименту на макетному зразку магнітоелектричного перетворювача. Бібл. 9, табл. 3, рис. 14.
Ключові слова: **магнітоелектричний перетворювач, тривимірне магнітне поле, механічна характеристика, макетний зразок.**

Introduction. In modern aircraft control systems, guidance and tracking systems, hydraulic and pneumatic drives are widely used, the component of which is a contactless magneto-electric converter (MEC) [1-3]. The MEC is designed to convert the input electrical signal (current) supplied to the control winding into a proportional angular displacement of the output shaft.

The first and currently the only theoretical work devoted to the development of MEC in Ukraine is the work [4]. Regarding the development of similar devices abroad, any information is missing or unavailable in open sources.

Currently, MECs for aviation and space technology are not produced in Ukraine. In this regard, the development and introduction into production of domestic MECs is urgent. This goal is solved within the framework of scientific and technical cooperation between State Design Office «Pivdenne» (Dnipro) and Ltd. «Electrical Engineering – New Technology» (Odesa).

According to the design of the magnetic system, MECs can be performed with electromagnetic excitation and excitation from permanent magnets. The MECs type MP-220B with permanent magnets of the UNDK brand became the most popular. The design of this MEC is based on the principle of a double polarized relay (Fig. 1) [5].

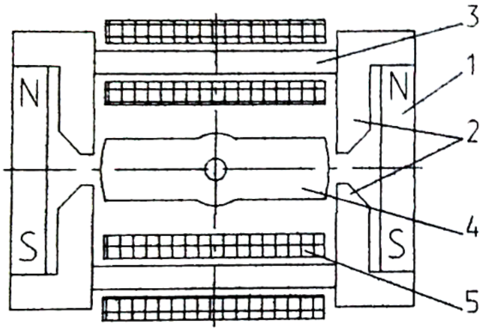

Fig. 1. MEC type MP-220B: 1 – permanent magnet; 2 – pole tips; 3 – core; 4 – armature; 5 – control winding

The design of this type ensures a stable neutral position, as well as the occurrence of a torque proportional to the angular deviation from the neutral position and directed in the direction opposite to this deviation (magnetic spring effect).

At the same time, MECs in this design have a number of disadvantages associated with the structural and technological difficulty of their manufacture [4].

The influence of the above-mentioned shortcomings can be eliminated by changing the topology of the MEC magnetic circuit from a rectangular to a concentric one, while preserving the principle of interaction of the excitation and control magnetic fluxes [4].

To solve this problem, it is proposed to implement the magnetic system of the MEC similar to the magnetic system of the hybrid stepper motor [4, 6, 7]. This implementation of the MEC magnetic system, in comparison with the MP-220B magnetic system, is characterized by a much better use of the volume of the active space, specific mass-dimensional indicators and adaptability to the use of rare earth magnets [4]. For the first time, the study of the MEC with such a topological structure of the magnetic system was carried out in [4] on the basis of magnetic substitute circuits, followed by the determination of magnetic conductivities by the modified method of probable paths of the magnetic flux. Without questioning the results obtained in [4], it should be noted that the method of probable magnetic flux paths has low accuracy and limitations in use [8]. Considering the fact that in the design of the MEC, which is built similarly to the magnetic system of a hybrid stepper motor, the complex path of closing the magnetic flux in the volume of the active part, in this case it is necessary to solve the problem of calculating the magnetic field in a 3D formulation using one of the modern numerical methods.

The goal of the article is to develop 3D mathematical models and analyze the characteristics of a magnetoelectric converter, the magnetic system of which is made similar to the magnetic system of a hybrid stepper motor.

Basic technical requirements for the electromechanical parameters of the MEC.

1. The MEC must ensure the linearity and necessary rigidity of the mechanical characteristics at different currents in the control winding. The mechanical characteristic is the dependence of the torque M created by the MEC on the angle of rotation of its shaft θ, i.e. $M = f(\theta)$.

2. The MEC must ensure the linearity and necessary rigidity of the mechanical characteristic $M = f(\theta)$ when the control current in its windings is equal to zero (characteristic of the magnetic spring). The slope of this mechanical characteristic determines the stiffness of the magnetic spring, which must be at least 0.0106 Nm/degree.

3. With the nominal control current I = 50 mA and the zero position of the shaft, the torque on the MEC shaft should be at least 0.0624 Nm, and when loaded by an external spring with stiffness of 0.0236 Nm/degree and shaft rotation angle of 1.5°, the torque should be not less than 0.0354 Nm.

Description and principle of operation of the selected MEC design. By analogy with the hybrid stepper motor, the magnetic system of the developed MEC consists of toothed stator and rotor (Fig. 2). Stator 1 is made in the form of a salient pole structure with coils 4 on toothed poles. Rotor 2 is divided into two parts, between which there is a cylindrical permanent magnet magnetized in the axial direction. The upper and lower parts of the rotor 2 are offset relative to each other by 90° and have tooth zones with gaps, which distinguishes them from the tooth zones of a stepper motor, which are performed without gaps. To eliminate magnetic hysteresis, the MEC magnetic core is made of permalloy grade 50N.

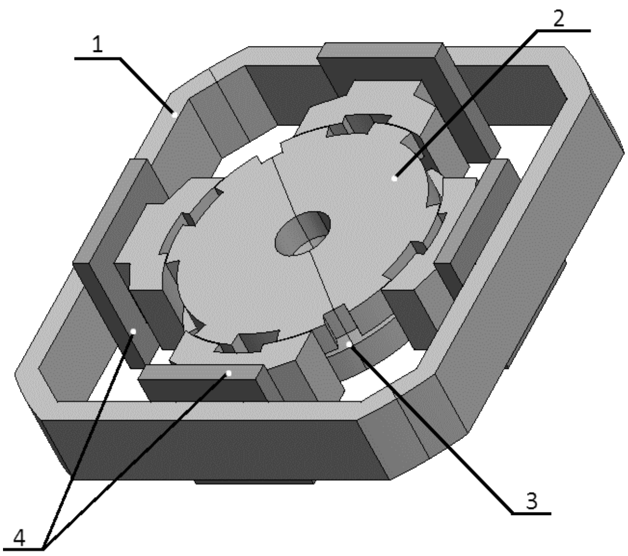

Fig. 2. Active part of the MEC: 1 – stator; 2 – rotor; 3 – permanent magnet; 4 – winding

The principle of operation of the MEC under consideration is as follows. In the absence of current in the excitation winding, the magnetized rotor occupies the zero position, in which half of the upper and lower rotor teeth are symmetrically located opposite the stator teeth.

When the rotor deviates from the zero position, the overlapping area between the stator teeth and the teeth of the upper and lower parts of the rotor changes (for example, it decreases from above, increases from below depending on the direction of rotation of the rotor) and the magnetic flux in the corresponding air gaps changes. At the same time, magnetic attraction forces tend to return the rotor to a stable zero position. Thus, the MEC magnetic system has the properties of a mechanical spring.

When the current flows in the control winding, a magnetomotive force is created, which leads to a change in the distribution of the magnetic flux in the air gap between the stator and the rotor halves. As a result, electromagnetic forces and torque arise which tend to deviate the rotor from the central position.

The design of the MEC of this type can be completed with a different number of teeth and poles on the stator and rotor. For example, a design with two teeth on the stator pole is shown in Fig. 2, and with three and four teeth – respectively in Fig. 3, 4.

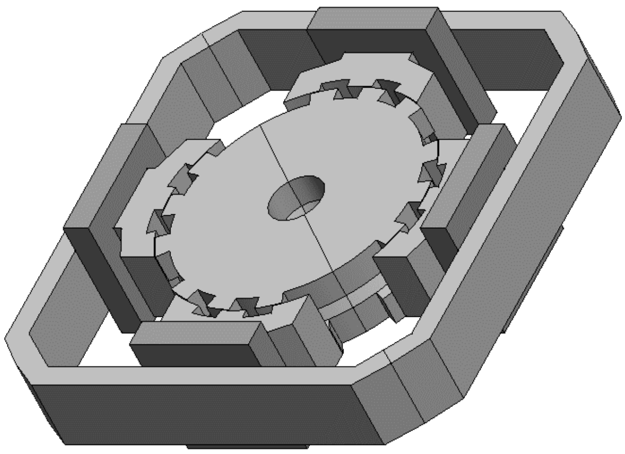

Fig. 3. Active part of the MEC with three teeth on the stator pole

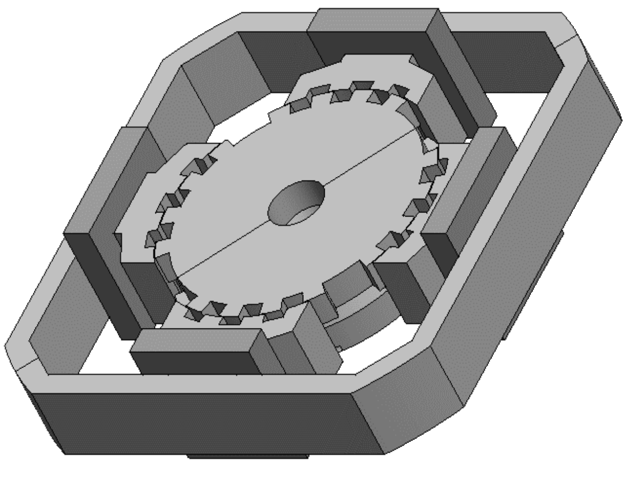

Fig. 4. Active part of the MEC with four teeth on the stator pole

To choose a constructive implementation of the active part of the MEC, presented in Fig. 2–4, and to calculate the characteristics of the selected design, it is necessary to conduct simulation of the magnetic field for each of the variants of the active part of the MEC.

Field models of MEC and results of design calculations. Calculations of the 3D magnetic field were carried out using the Finite Element Method for four variants of the four-pole active part of the MEC with two, three, four and five teeth on the stator pole. In all calculation variants, the number of elements of the finite element mesh of the 3D model was on average 240,000. With such a number of mesh elements, a sufficiently detailed approximation of the geometry of the MEC is achieved.

As an example, Fig. 5 shows the 3D field mathematical model of the MEC with three teeth on the pole, which was developed in the license program JMAG-Designer [9], and in Fig. 6 – the results of calculating the magnetic field in the form of magnetic lines of force.

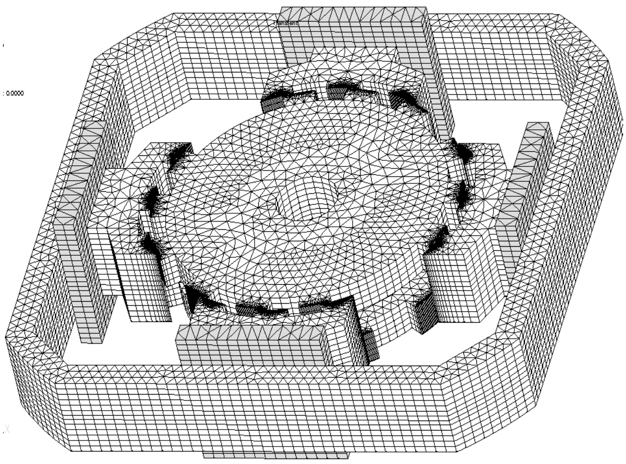

Fig. 5. 3D finite element model of the active part of the MEC with three teeth on the stator pole

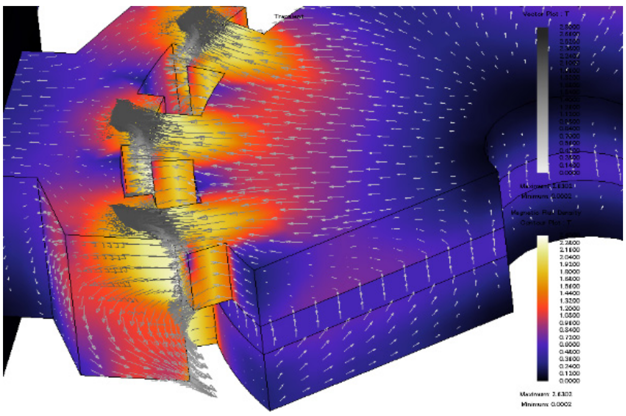

Fig. 6. Lines of force of the magnetic field in the active part of the MEC with three teeth on the stator pole

Based on the results of a series of calculations of the magnetic field of the considered four-pole variants, a family of characteristics of magnetic springs and mechanical characteristics of the MEC was obtained. The analysis of the obtained characteristics showed the following:

- with an increase in the number of teeth, the stiffness of the magnetic spring increases;
- the torque at the nominal current and the zero position of the rotor practically does not depend on the number of teeth on the stator pole;
- the slope of the mechanical characteristics increases as the number of teeth on the stator pole increases.

The results of the calculations are summarized in Table 1.

Table 1

Results of MEC calculations

Number of teeth on the stator pole	Stiffness of the magnetic spring, Nm/degree	Torque at zero position of the rotor, Nm
2	0,00059	0,055
3	0,0063	0,0617
4	0,0117	0,067
5	0,0183	0,0676

From the data in the Table 1, it can be seen that the version of the active part of the MEC with four teeth on the stator pole and a high coercive permanent magnet of the NdFeB brand fully meets the basic technical requirements for the electromechanical parameters of the MEC, and its manufacture is more technological than the manufacture of the active part of the MEC with five teeth on the stator pole.

The construction of the proposed MEC is shown in Fig. 7. The main geometric dimensions and materials of the active part of the selected version of the MEC are given in Table 2.

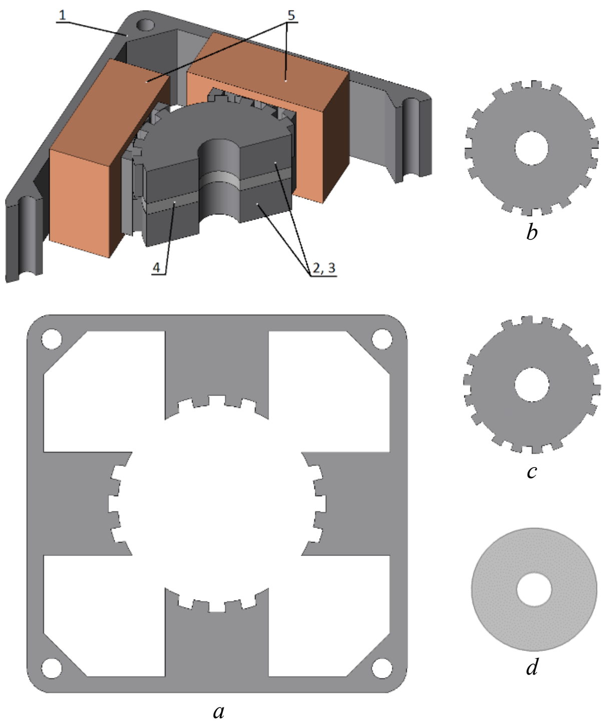

Fig. 7. Structural elements of the active part of the MEC:
a – general view (1 – magnetic core of the stator, 2, 3 – magnetic cores of parts of the rotor, 4 – permanent magnet, 5 – coils of the control winding) and section of the magnetic core of the stator;
b, *c* – cross-section of parts of the magnetic core of the rotor;
d – cross-section of the permanent magnet

Table 2

Geometric dimensions and materials of the active part of the MEC

Name	Value
Overall dimensions of the active part, mm	46×46×14
Internal diameter of the stator, mm	24
Length of the active part, mm	14
Air gap, mm	0,1
Magnet thickness, mm	2
Material of the magnetic core of the stator and rotor	Permalloy 50N
Permanent magnet material	N38EH
Magnetomotive force of the coil, A	20
Operating range of rotor rotation angles, mech. degrees	±2
Number of coil turns	200

Taking into account the symmetry of the constructive implementation of the active part of the MEC when solving the 3D field problem, the boundary conditions of the periodicity of the change of the magnetic vector potential were adopted, which made it possible to limit the calculation area to half of the 3D model of the MEC and reduce the time of magnetic field analysis.

Figure 8 shows a 3D finite element model of the MEC with four teeth on the stator pole, and Fig. 9 – distribution of the magnetic field in its active part.

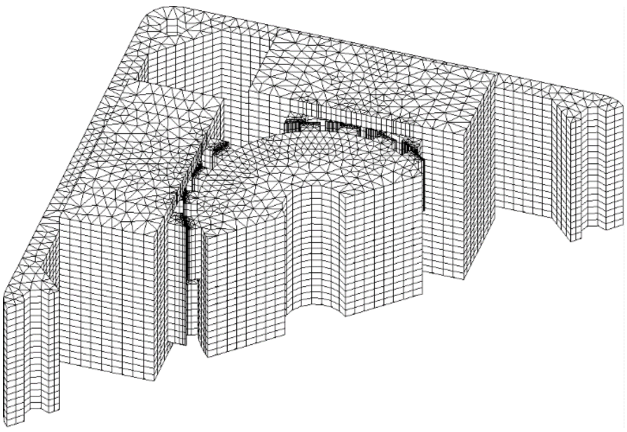

Fig. 8. 3D finite element model of the active part of the MEC with four teeth on the stator pole

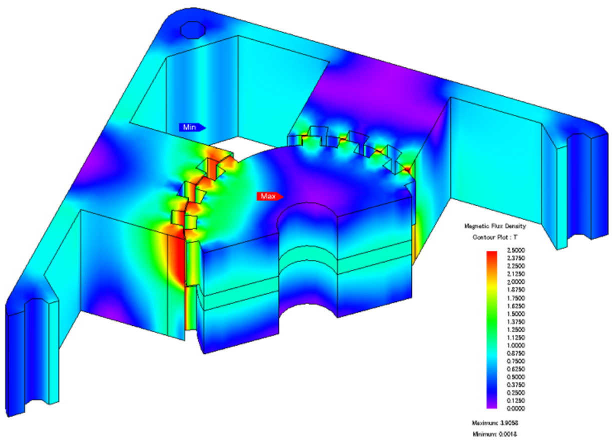

Fig. 9. Distribution of magnetic flux density in the active part of the MEC with four teeth on the stator pole

As a result of a series of calculations of the magnetic field, a family of mechanical characteristics of the MEC was obtained (Fig. 10).

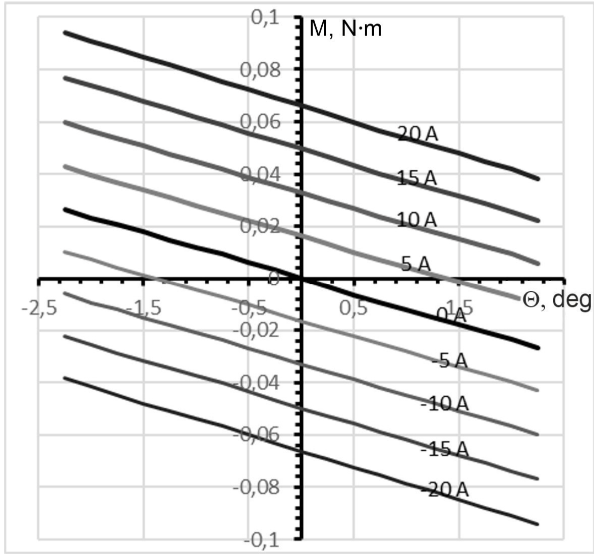

Fig. 10. Mechanical characteristics of the MEC with four teeth on the stator pole

The mechanical characteristics were calculated when the MMF of the coils of the control winding was changed from 0 to 20 A. Here, the MMF of the coil of 20 A corresponds to the nominal MEC control current of 50 mA.

Figure 10 shows that the mechanical characteristics of the MEC are linear. With nominal control current of 50 mA and a shaft braked in the zero position, the torque developed by the MEC is 0.067 Nm, which meets the requirements (not less than 0.0624 Nm). When rotating the rotor by 1.5°, the MEC torque is 0.0476 Nm, which also meets the requirements (not less than 0.0354 Nm). The stiffness of the magnetic spring is 0.0117 Nm/degree. (0.668 Nm/rad) and meets the specified requirements (at least 0.0106 Nm/degree).

The calculation of the characteristics of the selected design of the active part of the MEC with four teeth on the stator was also performed, using instead of the permanent magnet of the NdFeB brand, a permanent magnet of the SmCo brand, which has a higher temperature limit of operation, but somewhat worse magnetic and energy characteristics. Figure 11 shows the mechanical characteristics of the compared MEC variants. From the given data, it can be seen that the MEC with a permanent magnet of the SmCo brand has a lower stiffness of the magnetic spring and a lower torque at the zero position of the rotor and nominal control current of 50 mA.

A comparison of the calculated characteristics of the proposed MEC with the characteristics of the MP-220B prototype was also carried out (Fig. 12).

It can be seen that the compared characteristics are close to each other. However, if total magnetomotive force of 300 A is required to control the MP-220B in the nominal mode, then for the MEC proposed in this article only 80 A, that is, the power consumption of the MEC under development is significantly less than in the prototype.

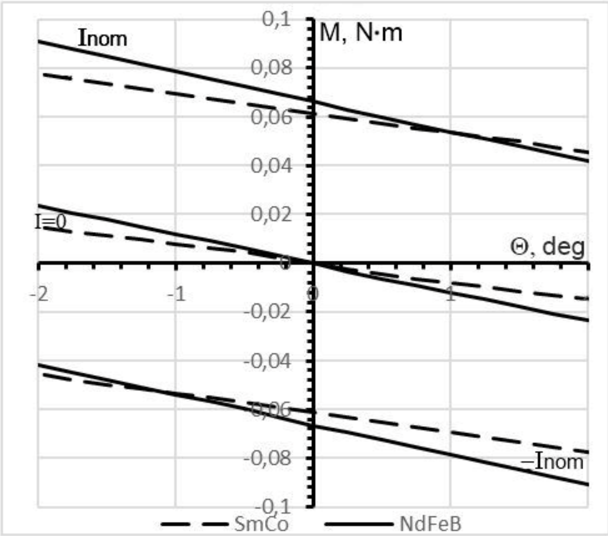

Fig. 11. Mechanical characteristics of the MEC with four teeth on the stator pole with SmCo and NdFeB magnets

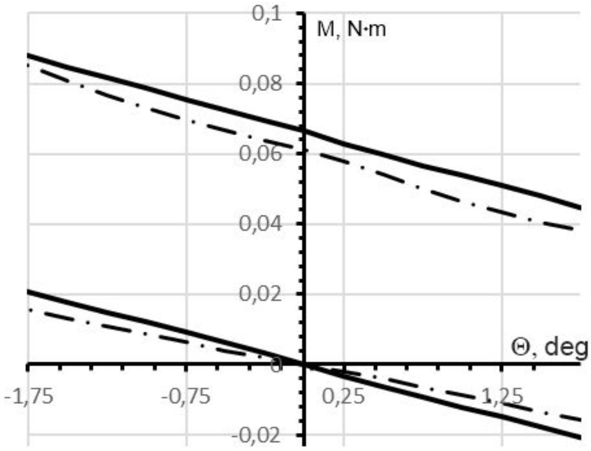

Fig. 12. Comparison of the calculated mechanical characteristics of the proposed MEC (———) with four teeth on the stator pole and MEC MP-220B (– · – · –)

Thus, based on the analysis of the results of the obtained calculations, the construction of the active part of the MEC was adopted in the form of a four-pole magnetic system with four teeth on the stator pole, the main geometric dimensions and materials given in Table 2.

MEC layout. In order to confirm the functionality and the possibility of implementing the main technical characteristics, a mock-up sample of the MEC was made, the external view of which is shown in Fig. 13.

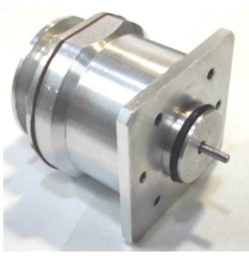

Fig. 13. External view of the MEC mock-up sample

The following were evaluated when prototyping the MEC Indicators:

1. Stiffness of the magnetic spring.
2. Torque at the zero position of the rotor.
3. The rotation angle of the rotor at a load torque of 0.0354 Nm.

A test stand was developed to evaluate the above-mentioned MEC indicators (Fig. 14).

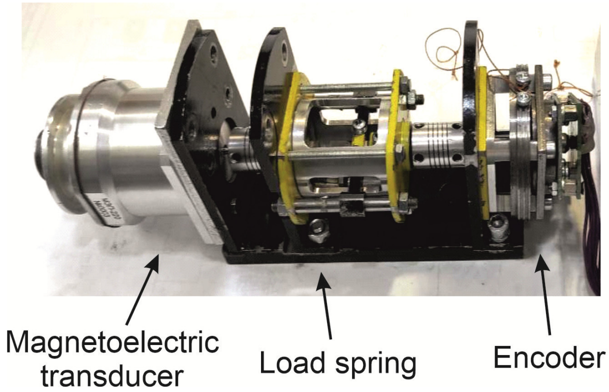

Fig. 14. MEC test stand

The stand consists of two units mechanically connected to the MEC shaft: a loading spring and an encoder. The loading spring is designed to create a load on the MEC shaft as a function of its angle of rotation. The magnetic encoder implemented on the AEAT-6600 sensor is designed to measure the MEC shaft rotation angle. The resolution of the encoder is 16 bits, which allows to determine the position of the shaft with an accuracy of 1 arc minute.

The results of tests of the MEC mock-up sample are shown in Table 3.

Table 3

Results of MEC tests

	Stiffness of the magnetic spring, Nm/degree	Torque at the zero position of the rotor, Nm	Angle of rotation of the rotor at the moment of loading 0,0354 Nm, degree
MEC layout	0,0115	0,064	1,7
Technical requirements	not less than 0,0106	not less than 0,0624	1,5

Conclusions.

1. The possibility of creating an MEC with the necessary technical characteristics and parameters is shown. On the basis of design calculations carried out on the basis of magnetic field modeling in a 3D formulation, the construction of the active part of the MEC in the form of a four-pole magnetic system with four teeth on the stator pole is substantiated.

2. The mechanical characteristics of the developed MEC are linear in the given range of the rotor rotation angle change. With nominal control current of 50 mA and the shaft braked in the zero position, the calculated torque developed by the designed MEC is 0.064 Nm, which satisfies the technical requirements (not less than 0.0624 Nm). The stiffness of the magnetic spring is

0.0115 Nm/degree and corresponds to the value specified in the technical requirements (not less than 0.0106 Nm/degree).

3. Tests of the mock-up sample of the MEC confirmed the basic efficiency of the adopted design and construction decisions.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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