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Electromechanical wave systems for mineral extraction

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Abstract

The problems of the development of mineral deposits related to the technologies of extraction, transportation and processing of viscous, gaseous and bulk materials, including in mixed fractions, are analysed. To solve the problem of efficient transport technologies, a combination of electromagnetic effects with a bionic approach based on the use of the principles of motion dynamics of dolphins, fish and amphibians with a wave-like swimming method is proposed. The purpose of the study is to develop a structural, object-oriented mathematical model of a channel-type wave electromechanical converter that provides transportation and processing of minerals in liquid, viscous, gaseous and mixed fractions. It is noted that in this case, the existing methods of development and calculation of traditional electric drives are not suitable since the electromagnetic core must have a different spatial arrangement and have a distributed structure, the configuration of which is individual. The construction of a structural bionic model of an electromechanical system is based on the use of a system of travelling wave equations with fixed ends and the principles of the genetic concept in electromechanics. By directional application of genetic and geometric operators to flat and cylindrical forms of electromagnetic field sources, populations of a flow channel and combined structures connected to the ends of a travelling wave are obtained. An object-oriented mathematical model, methodology and algorithm for calculating a multi-motor electromechanical converter integrated into the design of a transport wave system have been developed. The optimal ratios of copper and steel of the electromagnetic core, the geometric dimensions of the flow channel and the number of switched electromagnetic modules providing energetically efficient generation of a travelling wave in the channel are established. The study's theoretical significance lies in the fact that the results obtained can be used in the development of technologies and the design of devices for the transportation and processing of liquid, viscous, gaseous, bulk materials and mixed fractions in the mining industry and in other areas.

Keywords

Transportation and processing, bionic approach, travelling wave, genetic concept, electromechanical converter, mathematical model.

Introduction

The development of mineral deposits requires an increase in the efficiency of extraction, transportation and processing of viscous, gaseous and bulk materials, including in mixed fractions. In the oil and gas industry, this is the extraction and processing of oil and petroleum products in liquid and viscous phases, as well as in a mixture with gas. This problem is especially aggravated with an increase in viscosity at low temperatures. Existing pumping technologies using dynamic and volumetric pumps, especially with heating of petroleum products, are energy-intensive and dangerous in conditions of natural gas fractions (Sokolov, 2017; Beysembetov et al., 2016).

In the mining industry, when draining mines, the problem of mechanisation and automation of the removal of mud and mudflows and groundwater in liquid, viscous and mixed phases, as well as sedimentary materials containing mud and solid fractions, is acute. The standard pumping equipment in these cases works with overload, with reduced productivity and increased wear of the working bodies (Ovchinnikov and Smyslov, 2017; Inshakov and Inshakov, 2018; Eremeev, 2018).

In the cases considered, electromechanical energy conversion technologies are widely used. For a significant historical period of time, electromechanical energy converters have been represented mainly by traditional cylindrical-type rotating machines. The electrical and mechanical parts of such a drive are separate structures connected by a shaft, and a variety of mechanical, hydraulic, electromagnetic and other types of gears and multipliers are widely used to coordinate their performance characteristics (Kuimov et al., 2017; Kuimov and Minkin, 2017).

However, multipliers reduce the efficiency of energy conversion, increase losses, and create noise and vibrations. With the introduction of electromechanics, electronics, computer and digital technologies, it became possible to implement complex types of movement of working bodies, in which intermediate transmissions are eliminated (Moritz, 2014; Salmov and Proshin, 2015). A new method of analytic geometry is offered to calculate the trajectories of mechatronic systems (Bozek, 2016) and CAD/CAM (Peterka, 2014; Vopat, 2014).

At the same time, the possibilities of creating integrated structures have expanded, the distinctive feature of which is the mutual penetration of electrical and mechanical parts into each other. In general, such a converter is a given spatial composition of a mechanical part with an electric machine built into it, containing an electromechanical structure of complex configuration (Afonin, 2001; Shaytor, 2001; Shaytor, 2002).

At the same time, prerequisites are being created for bionic approaches consisting of applying the basic principles of the organisation of structures, properties and functions of living organisms in the creation of effective technical devices and technological systems (Vorobiev and Vorobiev, 2020).

At the same time, the existing methods of calculating traditional electric machines and drives cannot be used in this case; since the electromagnetic core must have a different spatial direction of the magnetic flux and contain a distributed electromechanical and electromagnetic structure, the configuration of which is individual in each case (Vysotsky and Oleinikov, 2020; Skubov and Khodzhaev, 2003; German-Galkin et al., 2014; Afonin et al., 2003).

Therefore, the development of electromechanical systems based on applying the basic principles of the organisation of structures, properties and functions of living organisms capable of transporting and processing liquid, viscous, gaseous and bulk materials and cargo solves an urgent problem.

Currently, more and more attention is being paid to the mathematical modelling of technical systems. This approach is also advisable to apply in this case since, in the process of developing bionic approaches to creating electromechanical systems, a large number of algorithmic problems, including field problems and structural synthesis problems, need to be solved using a mathematical apparatus adapted to solving this class of problems (Shaytor, 2001; Shaytor and Ryaskov, 2017; Kalinin and Khvalin, 2019).

The work aims to create a structural, object-oriented mathematical model of a channel-type wave electromechanical converter that provides transportation and processing of liquid, viscous, gaseous and bulk materials and cargo, including in mixed fractions. To achieve this goal, the principles of movement of dolphins, fish and amphibians with a wave-like way of swimming and movement were used (Slizheuski, 2002; Barsukov, 2005; Antonelli, 2014; Lavars, 2018).

Such methods of displacement can be described by a system of travelling wave equations with fixed ends in the axes x, y (1):

$$\begin{aligned}
&x = L_{\text{в}}\varphi / 2\pi;\ r = 2A\sin\varphi;\ y = r\sin(\varphi - \psi'),\ [\varphi = [0; \pi/2]];\\
&x = L_{\text{в}}\varphi / 2\pi;\ r = 2A;\ y = r\sin(\varphi - \psi'),\ [\varphi = [\pi/2; 3\pi/2]];\\
&x = L_{\text{в}}\varphi / 2\pi;\ r = -2A\sin\varphi;\ y = r\sin(\varphi - \psi'),\ [\varphi = [3\pi/2; 2\pi]];\\
&\alpha = \pm\operatorname{arctg}\left[(2\pi r / L_{\text{в}})\cos\psi'\right],\ [x = 0; y = 0];\\
&\alpha = \pm\operatorname{arctg}\left[(2\pi r / L_{\text{в}})\cos(2\pi - \psi')\right],\ [x = L_{\text{в}}; y = 0],
\end{aligned} \tag{1}$$

where: $L_{\text{в}}$ - wavelength;

r - scope;
φ - distribution range;
ψ' - the angle of the instantaneous position of the wave;
$2A$ - the height of the channel;
α - the angle of rotation of the fixed axis.

The dynamics of the wave at different values of angles ψ' is shown in Figure 1.

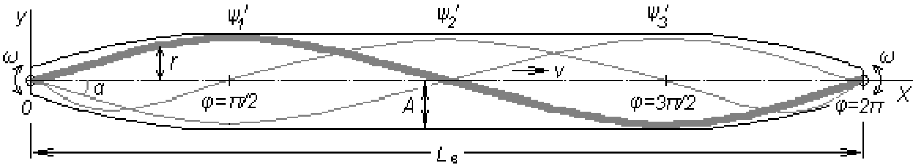

Fig. 1. Dynamics of a travelling wave with fixed ends

To achieve the research goal, it is necessary to solve the problem of structural synthesis and develop an object-oriented mathematical model of an electromechanical converter with a wave working body.

Material and Methods

Structural synthesis of a travelling wave electromechanical system

To solve the problem of structural synthesis, heuristic methods and genetic algorithms were used, sufficient for an approximate solution to the problem of choosing an effective electromagnetic field configuration for an electromechanical converter. At the same time, terminology and classification were used, which were used in electromechanics and proposed by Shinkarenko (2002) and Shumilov (2012).

According to the authors of the genetic concept, the characteristic properties and development trends of electromechanical converters give reason to consider their structural diversity as a unique class of systems of natural and anthropogenic origin, in which the main component - the electromagnetic field - is a specific type of matter, the properties of which are determined by the laws of nature. The genetic concept of the construction and development of electromagnetic structures is based on the fundamental concept of the primary source of the field, the electromagnetic chromosome and the genetic code. Modern ideas about magnetism assume two types of natural sources of the magnetic field - charges and microcurrents of Amperes. They can be called "electromagnetic genes" because they are material carriers of information, and their vector properties are inherited in arbitrary structures of the highest level of development (Kuznietsov and Shinkarenko, 2011).

Electromagnetic structures of the chromosome level are obtained from an arbitrary structure of the primary source of the field (the parent chromosome) by its spatial composition. Structural equivalents of electromagnetic chromosomes in engineering are various types of an electromagnetic nuclei containing electrical and magnetic systems that perform the functions of real field sources in electromechanical systems, Fig. 2. The genetic code is a short form of recording transmitted genetic information of electromechanical structures. The first two letters encode the geometric shape, and the others - the corresponding type of orientation of the field source indicated by the arrow. It is determined by two variants of the orientation of the magnetic field wave relative to the elements of spatial symmetry of a particular source (X – longitudinal and У – transverse). The digital part of the code indicates the number of breaks of the field wave in the direction of propagation (the first digit of the code) and in the orthogonal direction (the second digit) (Gaidaicnko and Shinkarenko, 2011).

Two geometric shapes of electromagnetic field sources are selected to implement the goal function: cylindrical CL and flat PL populations. They are represented by a set of electromagnetic chromosomes - the primary field sources- forming a corresponding magnetic field of cylindrical and flat geometric shapes in space. The targeted application of genetic operators of replication, crossing, mutation, inversion and crossing over to them, together with operators of geometric transformations, make it possible to obtain combined chromosome sets that give the desired electromechanical system (Figiel et al., 2020).

To solve the problem of conditional optimisation, heuristic methods and genetic algorithms were used that are sufficient for an approximate solution to the problem and exclude non-viable options, Fig. 3. Genetic operators are implemented by converting graphical primitives and establishing correspondences and relationships with geometric transformation operators. Geometric operators make it possible to formalise genetic procedures through appropriate spatial transformations. The following pairs of matching genetic and geometric operators are used: replication - doubling; crossing - spatial combination; mutation - spatial deformation; inversion - spatial rotation by an angle of 180 degrees; crossing - parallel transfer (Safin et al., 2018; Zablodskiy et al., 2010).

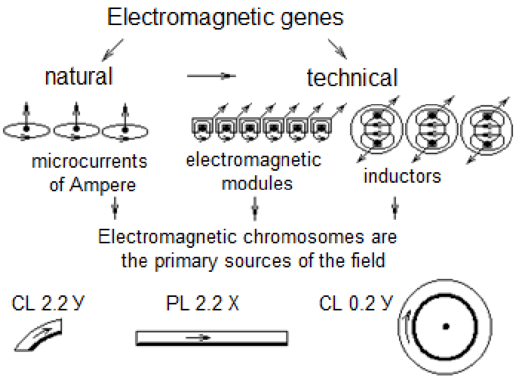

Fig. 2. Synthesis of primary sources of the electromagnetic field

When switching from genetic models to their technical equivalents, it is necessary to take into account the requirements for electromechanical converters in their specific field of application. At the same time, flat shapes should ensure the spatial formation of a flexible working body, and cylindrical shapes should enhance their effectiveness by turning axes rigidly connected to the ends of the working body. This is achieved with the help of an information control system that provides deterministic control signals for switching on electric windings and forming a magnetic field in accordance with the system of equations (1). In addition, the power plant must meet the requirements of reliability and energy conservation, and the power supply system must provide the required operating modes of its elements (Al´per and Terzian, 1970; Rulevskiy et al., 2004; Bozhenov and Shamans, 2012; Franke et al. 2013; Abramov et al., 2015).

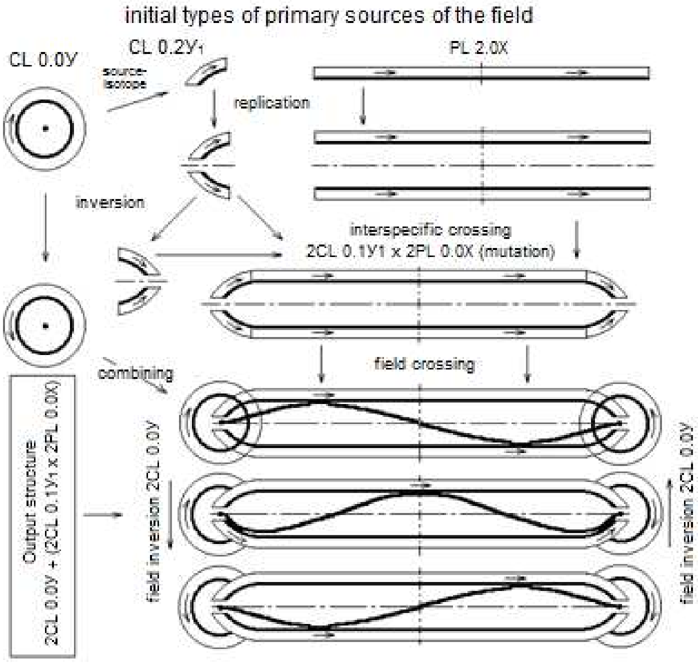

Fig. 3. Structural genetic model of the wave bionic system

An electromechanical energy converter implementing the travelling wave principle is shown in Fig. 4. It consists of a stator 1, inside which electric windings 3 are laid out on U-shaped electromagnetic modules 2. A tightly-durable non-magnetic jacket 4 forms a sealed channel for the pumped liquid, inside which a flexible wave rotor-piston 7 is placed within the axes of rotation of 5 cylindrical asynchronous motors 6, consisting of deformable ferromagnetic elements, and the axes of rotation 5 are rigidly fixed with the ends of the wave rotor 7. The sealed channel in the cross-section has a rectangular shape with a constant width equal to the module's transverse size and the rotor's deformable elements (Fig. 7). To ensure the longitudinal tightness of the rotor, the height of the channel should be determined by the ordinate of the travelling wave crest, that is, the doubled value of the span *r*, in accordance with equations (1), Fig.1. In this case, the height of the channel decreases at its ends, since in the range $\varphi = [0; \pi/2]$, $r = 2A \sin\varphi$ and in the range $\varphi = [3\pi/2; 2\pi]$, $r = -2A \sin\varphi$. In the middle part of the channel, in the range $\varphi = [\pi/2; 3\pi/2]$, the height is unchanged and equal to $2A$.

The requirements of flexibility, elasticity, wear resistance, tightness, and noiselessness are imposed on the wave rotor. It should have good magnetic properties and a low coefficient of friction. Motors 6 are designed to increase the stability and efficiency of wave generation, as well as to increase the drive power by bending the oscillation of the ends of the wave rotor generating the wave.

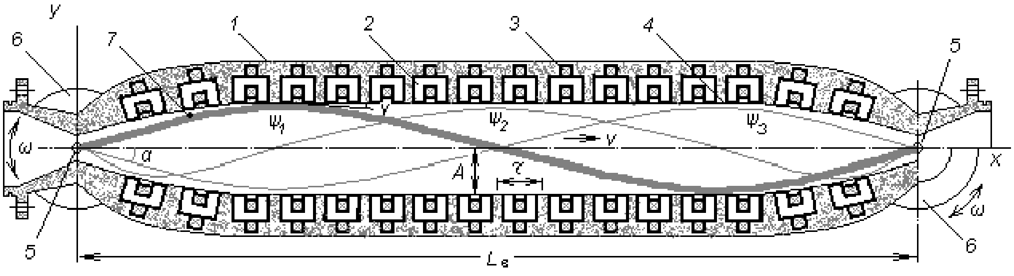

Fig. 4. Electromechanical energy converter with a wave rotor

The formation of a travelling wave in the channel is determined by the switching algorithm of the electric windings 3 located on the stator 1 by the force of a magnetic field on the elements of the wave rotor 7 from the side of the U-shaped electromagnetic modules 2. In this case, two cylindrical motors 6 provide an antiphase counter-directional swing of their rotors on the axes of rotation 5, and the frequency of the swing corresponds to the frequency of the travelling wave of the rotor 7.

The windings are controlled using an electronic switchboard by applying discrete control signals according to a special algorithm that implements the travelling wave equations (1). In this case, a linear travelling magnetic field is created in the stator 1, which acts on the crests of the ferromagnetic wave rotor 7, and electric motors 6 simultaneously generate a wave at its ends. The inversion (reverse) of the wave rotor is achieved by controlling the windings, which ensures simultaneous inversion of the magnetic field of stator 1 and reversal of electric motors 6.

Object-oriented model of a channel-type wave electromechanical system

The object-oriented model of the synthesised structure includes a generalised theoretical model of the genetic level, models of technical equivalents of structural populations, the basic calculation equation and initial conditions (Zablodskiy et al., 2016; Zablodskiy et al., 2016).

The generalised theoretical model is represented by Maxwell's equations:

$$\left.\begin{aligned} &\mathbf{B} = \mu \mu_0 \mathbf{H} \\ &rot\, \mathbf{H} = \mathbf{j} \\ &div\, \mathbf{B} = 0 \end{aligned}\right\}, \tag{2}$$

where: **B** - magnetic induction;
H - magnetic field strength;
j - current density;
μ - relative magnetic permeability;
μ_0 - magnetic permeability of the vacuum.

To account for the saturation of steel, in conditions of a complex configuration of the electromagnetic media section, the calculation of the magnetic field according to the geometry of electromagnetic structures is performed on a computer by the finite element method, by minimising the energy functional (Andreeva et al., 2013; Martyanov and Neustroev, 2014; Belov et al., 2021).

Based on the geometric data of the computational domain, a numerical solution to the field problem was obtained using the standard procedure of the COMSOL FEMLAB 3.0 package. A fragment of the calculation of the magnetic field in the channel between the stator pole and the wave rotor is shown in Fig. 5. The model of the technical equivalent of the channel population (2CL 2.2У x 2PL 2.2X x 2CL 2.2У1) x CL 0.2У contains the equations of electrical equilibrium (3) and electromagnetic forces (4); the latter are calculated by the finite element method on the surface S_p of the wave element, Fig. 6.

$$U = i_{k\,i} R_{k\,i} + d\Psi_{ki} / dt \; ; \tag{3}$$

$$\mathbf{F}_{emm}(x) = \frac{1}{\mu_0}\int_{S_p}[\mathbf{B},\mathbf{n}]\,\mathbf{B} - \frac{1}{2}[\mathbf{B},\mathbf{B}]\,\mathbf{n}\,dS, \tag{4}$$

where: U - voltage;

i_{ki} , R_{ki} , Ψ_{ki} - respectively current; resistance, flow coupling of electric windings of electromagnetic modules.

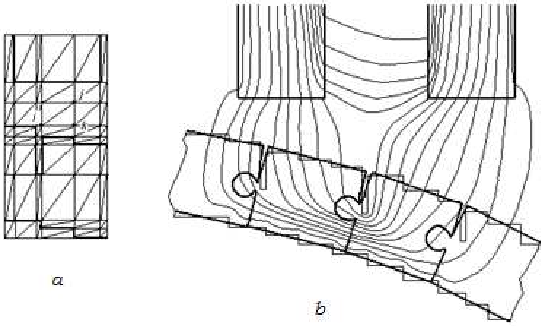

Fig. 5. Calculation of the magnetic field in the channel by the finite element method:
a - triangulation of the calculated area; b - magnetic field of the air gap

The model of technical equivalents of populations of combined structures CL 0.2У and CL 0.2У1 includes, respectively, the equations of electrical equilibrium (5) and electromagnetic moments of the drives (6) axes:

$$U = i_i R_i + d\Psi_i / dt\ ; \tag{5}$$

$$M = \sum d(\Psi_i i_i)/2d\alpha, \tag{6}$$

where: i_i , R_i , Ψ_i - respectively current; resistance, flow coupling of electric windings of cylindrical motors;

α - the angle of rotation of a fixed axis.

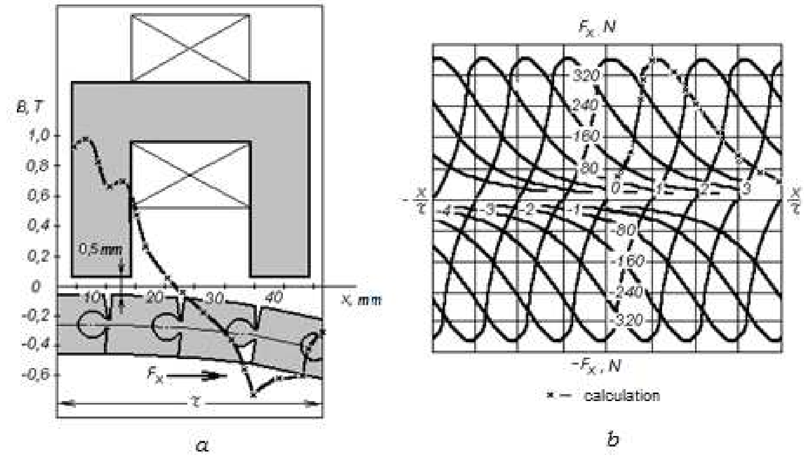

Fig. 6. Calculation of electromagnetic forces on the wave rotor:
a) design area: B - magnetic induction in the gap; x - wave path; *b*) calculation results: F_x - electromagnetic forces on the rotor; τ - pole division

The main calculation equation displays the energy balance in the system. In the left part of the equation, write down the sum of the electrical capacities of the technical equivalents of the populations of the combined structures and the technical equivalents of the channel populations (Kuric et al., 2021; Saga et al., 2014). The right side of the equation contains the sum of the hydraulic power and the power spent on overcoming the moments of inertia of moving masses. The main calculation equation is obtained in the form:

$$2M\omega + \sum F_{em,i} v = F_h v + 2J\omega d\omega / dt\ , \tag{7}$$

where: $\omega = da / dt$ - angular velocity of a fixed axis;

$v = dx / dt$ - the linear velocity of the wave in the channel;

$F_h = \rho\ g\ S_k H_h$ - hydrostatic force;

S_k - the cross-sectional area of the channel;
H_h - hydraulic pressure;
J - the moment of inertia of the technical equivalents of the combined population CL 0.0У.

The solution of equations (2-7) is carried out together with the initial conditions of flow coupling, respectively, of the technical equivalents of the populations of the PL channel $\Psi_{ki}^{p} = f(i_{ki}^{p}, x, y)$, and the combined structures of the CL $\Psi_i^p = f(i_i^p, x, y)$, given by the system of equations (1) of a travelling wave with fixed ends.

The solution of equations (2-7) is carried out in conjunction with the initial conditions (8) for flow connections of the corresponding technical equivalents of channel populations and combined structures

$$\Psi_{ki}^{p} = f(i_{ki}^{p}, x, y); \ \Psi_{i}^{p} = f(i_{i}^{p}, x, y) , \tag{8}$$

by the given equations (1) of a travelling wave with fixed ends.

The solution of the system of equations (1-7), together with the initial conditions (8) determined by the wave equations (1), made it possible to calculate the operating characteristics of the model (Fig.6), perform parametric optimisation and obtain conditions that ensure energetically efficient generation of a travelling wave in the channel.

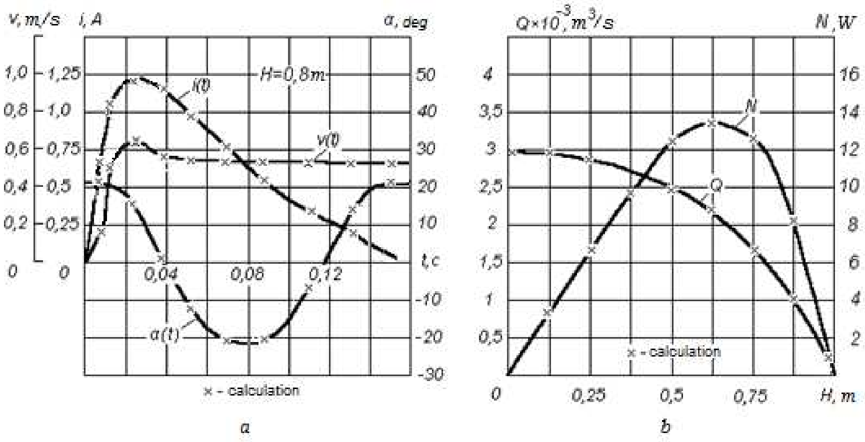

Fig. 6. Operating characteristics of the wave converter: a) electromechanical: v - linear wave velocity in the channel; i - electric current consumption; α - the angle of rotation of the fixed axis; t - time; b) hydraulic: H - pressure; Q - fluid flow; N - power

Results and Discussions

Further research related to parametric optimisation of the technical equivalent is limited to the resulting set of structural elements containing 32 electromagnetic modules, shown in Fig. 4. The initial data for solving the parametric synthesis problem are the channel dimensions, the number and dimensions of electromagnetic modules. The highest developed power *N* in the channel of the resulting design is selected as an optimisation parameter (Fig. 6b). The optimum of the objective function is associated with its maximum and meets the task of obtaining an energetically efficient electromechanical converter (Shaitor et al., 2020).

In the first stage, one-parameter optimisation is performed to obtain optimal ratios of copper and steel based on the main dimensions of the electromagnetic modules *D, a, b_z*, Fig. 7.

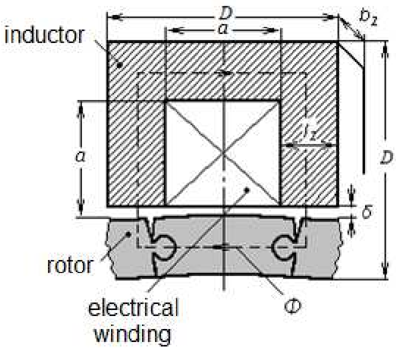

Fig. 7. The main dimensions of the electromagnetic module

This problem is solved based on the required maximum of the magnetic flux Φ created by the magnetomotive force F of the winding. The expression for the magnetic flux in the function of the main dimensions $\Phi = f(D, a)$ is written as:

$$\Phi = \frac{F}{1/\Lambda_\delta + 1/\Lambda} = \frac{1}{C+1}\Lambda F \ ,$$

where: $\Lambda = 0{,}25\mu_0\mu b_z(D-a)/(D+a)$ - magnetic conductivity of steel;

$C = \Lambda/\Lambda_\delta = const$ - the ratio of the magnetic conductivities of steel and the air gap;

$F = jka^2$ - the magnetomotive force of the winding;

j - electric current density;

k - the coefficient of filling the winding with copper.

The expression for the magnetic flux, with the introduction of the size of the module D, a, b_z and the coefficient $C_1 = const$, which includes only constant values, can be rewritten as follows:

$$\Phi = \frac{0{,}25\,\mu_0\mu\ j\,k\,b_z(D-a)\,a^2}{(C+1)(D+a)} = C_1\frac{(D-a)\,a^2}{(D+a)}\,.$$

The study of the function $\Phi = f(D, a)$ at the extremum by taking the derivative $d\Phi/da = 0$ leads to an equation $a^2 + Da - D^2 = 0$ in which the physical meaning has a positive solution $a = 0{,}5D \pm 0{,}5D\sqrt{5}$.

From this, optimal ratios of the main dimensions of the electromagnetic module are obtained $a = 0{,}61\ D$; $l_z = 0{,}5\ (D - a) = 0{,}32a$, and optimal ratios of volumes of copper and steel $a^2 / (D^2 - a^2) = 0{,}59$.

The results were obtained under the assumption of unsaturated electrical steel and are subject to refinement during iterations when solving problems of determining the magnetic field in the calculated region of the electromagnetic core, taking into account saturation (2, 4).

In the second stage, an object-oriented mathematical model of an electromechanical converter with a wave rotor is used, on the basis of which a calculation program is developed. It implements synthesis on an incomplete data set, in the direction from the size and electromagnetic loads to the channel power. The calculation of magnetic characteristics and electromagnetic forces is carried out by the finite element method, taking into account the saturation of the magnetic circuit (Stavinsky et al., 2017; Stavinsky et al., 2017; Shaitor et al., 2021).

In the third stage, numerical experiments are performed using a mathematical model to determine significant factors and an optimisation parameter. As an optimisation parameter, the power developed in the channel of the resulting design is selected. The optimum of the objective function is associated with its maximum and meets the task of obtaining an electromechanical converter with increased energy efficiency. As a result, there is an area of variation in the channel size and electromagnetic loads, which is close to optimal (Kuric et al., 2020; Saga, M., Bulej, V. et al., 2020).

The fourth stage is implemented using an optimisation procedure based on the Box–Wilson gradient method, which allows us to find an even narrower zone of variation of significant factors under which the optimisation parameter satisfies the specified conditions.

Factors are variables that take on certain values at some point in time and affect the optimisation parameter during a numerical experiment. Regarding the problem being solved, the following factors affecting the target function were tested: channel dimensions; induction in the air gap; limiting induction of iron saturation; the number of switched electromagnetic modules (Saga, M., Blatnicky, M. et al., 2020). All other parameters were assigned fixed values determined from the experience of designing electrical machines and selected electrical materials.

Significant factors were used as control actions of parametric synthesis. A factor is considered significant if, when it changes within the scope of determining the factor, the change in the optimisation parameter goes beyond the limits of the accuracy of determining the optimisation parameter. The accuracy of determining the optimisation parameter depends on the adequacy of the model calculation methodology, which is 88 - 92%. Therefore, only those factors were taken into account, the change of which led to a change in the optimisation parameter by more than 12%. The significant factors satisfying these conditions include the number of switched electromagnetic modules and the length to height ratio in the middle part of the channel, $L_b / 2A$.

As a result of numerical studies, it was found that the optimum of the objective function is achieved with the ratio of the length to the height of the channel $L_b / 2A$ in the range of 4:1÷5:1. At the same time, the number of switched electromagnetic modules is in the range of 6÷8 units; that is, it does not exceed 25% of their total number.

With such ratios, an electromechanical converter with a wave rotor develops the greatest power in the channel, has minimal losses in copper and steel, and has the greatest energy efficiency. At the same time, the utilisation rate of electromagnetic modules, iron and copper of the entire structure does not exceed 25%. Therefore, channel-type electromechanical wave converters capable of carrying out the mass transfer of not only liquid but also viscous, gaseous, and bulk materials and their mixed fractions will have increased weight and size indicators compared to traditional electric pumps that do not have universal capabilities.

Conclusion

The result of the theoretical study is the development of a bionic approach to solving engineering problems for the creation of electromechanical wave systems with increased energy efficiency and enhanced functionality of mass transfer.

An object-oriented mathematical model for a channel-type electromechanical wave system based on the equations of a travelling wave with fixed ends, which simulates the movement of bionic prototypes, has been obtained.

Parametric optimisation of an electromechanical converter with a wave rotor is applied using an object-oriented mathematical model. The optimal ratios of copper and steel of the electromagnetic core, the geometric dimensions of the flow channel and the number of switched electromagnetic modules providing energetically efficient generation of a travelling wave in the channel are established.

The theoretical significance of the research lies in the fact that an object-oriented mathematical model can be used in the development of technologies and the design of devices for the transportation and processing of liquid, viscous, gaseous, bulk materials and mixed fractions in mining and other fields.

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