ЕЛЕКТРИЧНІ МАШИНИ ТА АПАРАТИ

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ENERGY CHARACTERISTICS OF BRUSHLESS MAGNETOELECTRIC MOTORS OF THE RETURN-ROTARY MOTION

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The paper presents the results of studies of the structure of the powers that characterize the state of a specialized brushless magnetoelectric motor of return-rotary motion. The calculated curves of the rotor angular speed, the motor torque and the torques of mechanical resistance, and the curves of the instantaneous values of powers of consumption, useful mechanical load, and losses are given. The frequency dependences of the efficiency factor and power components are obtained based on their calculation. Ref. 7, fig. 5.

Keywords: brushless magnetoelectric motor, return-rotary motion, power, efficiency.

Introduction. One of the areas of research on various electromechanical systems is determining their energy efficiency and calculating the efficiency depending on the changing operating conditions. For the class of return-rotary motion systems under consideration, such studies have their specifics, different from the study of traditional electric drives with the unidirectional rotational motion of the motor shaft.

Return-rotary motion systems based on specialized electromechanical devices [1-4] are designed to control the trajectory of the angular motion of the actuator with a given amplitude and frequency. Features of calculating their energy efficiency are determined by the type of the executive motor, as well as the structures of power converters and mechanical transmissions, if any.

A feature of the brushless magnetoelectric motor (BMM) of return-rotary motion proposed for consideration in this paper [5] is the presence in its structure of an additional permanent magnet in the gap between the coils of a single-phase winding. As a result of the interaction of the rotor magnet with a fixed magnet on the stator, an elastic connection arises between the stator and the rotor, which makes it possible to position the motor shaft in the initial angular position. A noteworthy circumstance is also that in the initial position, the rotor is forcibly oriented so that its poles are located opposite the active parts of the winding. Due to this, when the stator winding is exposed to alternating voltage, direct control of the frequency and amplitude of the mechanical oscillations of the actuating element is provided without the use of any additional mechanical motion trajectory converters, which minimizes the mechanical losses of such an electromechanical system.

The purpose of the paper is to study the frequency dependences of the efficiency factor and the values of the powers that characterize the operating modes of a specialized BMM of return-rotary motion.

The main material and research results. The structure of the BMM under consideration was described in detail in [5, 6]. Here we only note that the BMM of return-rotary motion is a specialized brushless electric machine consisting of a slotless stator with a single-phase winding, a magnetic circuit external to it, and an additional permanent magnet in the gap between the active sections of the winding to implement the effect of the elastic magnetic connection between the sta-

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tor and the rotor. A two-pole permanent magnet and an actuating element are installed on the rotor shaft.

The following equations describe the mathematical model of BMM for controlling the return-rotary motion

$$L\frac{di}{dt}=-Ri-k_m\,\omega\cos\alpha+u\,; \tag{1}$$

$$M=k_m\,i\cos\alpha\,;\qquad M_\omega=k_\omega\,\omega;\qquad M_\alpha=k_\alpha\sin\alpha\,; \tag{2-4}$$

$$M_R=M_B\,sign(\omega);\quad M_L=k_L\,\omega; \tag{5, 6}$$

$$J\frac{d\omega}{dt}=M-M_\omega-M_\alpha-M_R-M_L;\qquad \frac{d\alpha}{dt}=\omega\,. \tag{7, 8}$$

where i, u are current and control voltage of the stator; ω, α are angular speed and angle of rotation of the rotor shaft; M is electromagnetic torque of the motor; M_ω, M_α, M_R, M_L are torques of viscous friction and elasticity, the reactive torque of the bearings, and the load torque, respectively; L, R are inductance and active resistance of the stator winding; k_m is motor torque coefficient; J is rotor moment of inertia; k_ω, k_α are coefficients of viscosity and elasticity of the motor; M_B is the torque of mechanical resistance of the bearings. In this study, it is assumed that the viscosity coefficient of the mechanical load takes into account the parametric disturbance acting on the motor shaft.

The control of the reciprocating-rotary motion motor is carried out by exposing the stator windings to an alternating voltage with controlled amplitude and frequency in the range up to 100 Hz with such variants of its formation [6]

$$u=U_A\sin 2\pi f_O t\,; \tag{9}$$

$$u=U_A\,sign(\sin(2\pi f_O t)), \tag{10}$$

where U_A is stator voltage amplitude; f_O is the frequency of mechanical oscillations of the rotor shaft.

BMM of return-rotary motion is an object with non-linear dependences of input and output parameters. When the stator windings are connected to an AC voltage source, the motor can operate either in the mode of stabilization of the amplitude of the angle α_A of the rotor oscillations or in the mode of limiting the effective value of the stator current I. Stabilization of the oscillation angle at a given level occurs at frequencies not exceeding 20-30 Hz, and in the high-frequency part of the operating range, the maximum current is limited, which is determined by the motor cooling conditions.

As an object for research in this paper, a low-power BMM with an outer diameter of the stator body of 34 mm and a length of 120 mm is adopted. This motor is characterized by the following values of the parameters of equations (1–8): $L=0{,}012\,H$, $R=40\,Ohm$, $k_m=0{,}125\,Nm/A$, $k_\omega=6{,}5\cdot10^{-5}\,Nms/rad.$, $J=2{,}4\cdot10^{-6}\,kgm^2$, $k_\alpha=0{,}0448\,Nm/rad.$, $M_B=2\cdot10^{-4}\,Nm$, $k_L=1{,}7\cdot10^{-4}\,Nms/rad.$

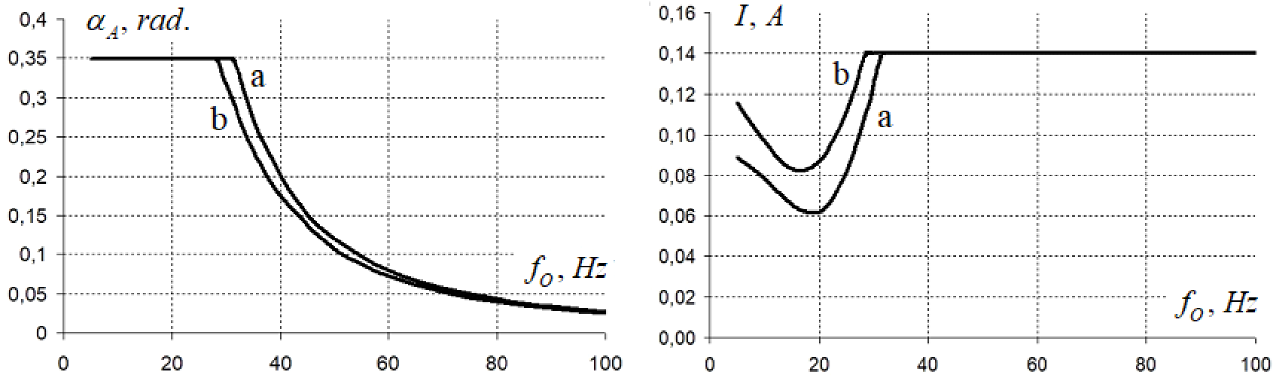
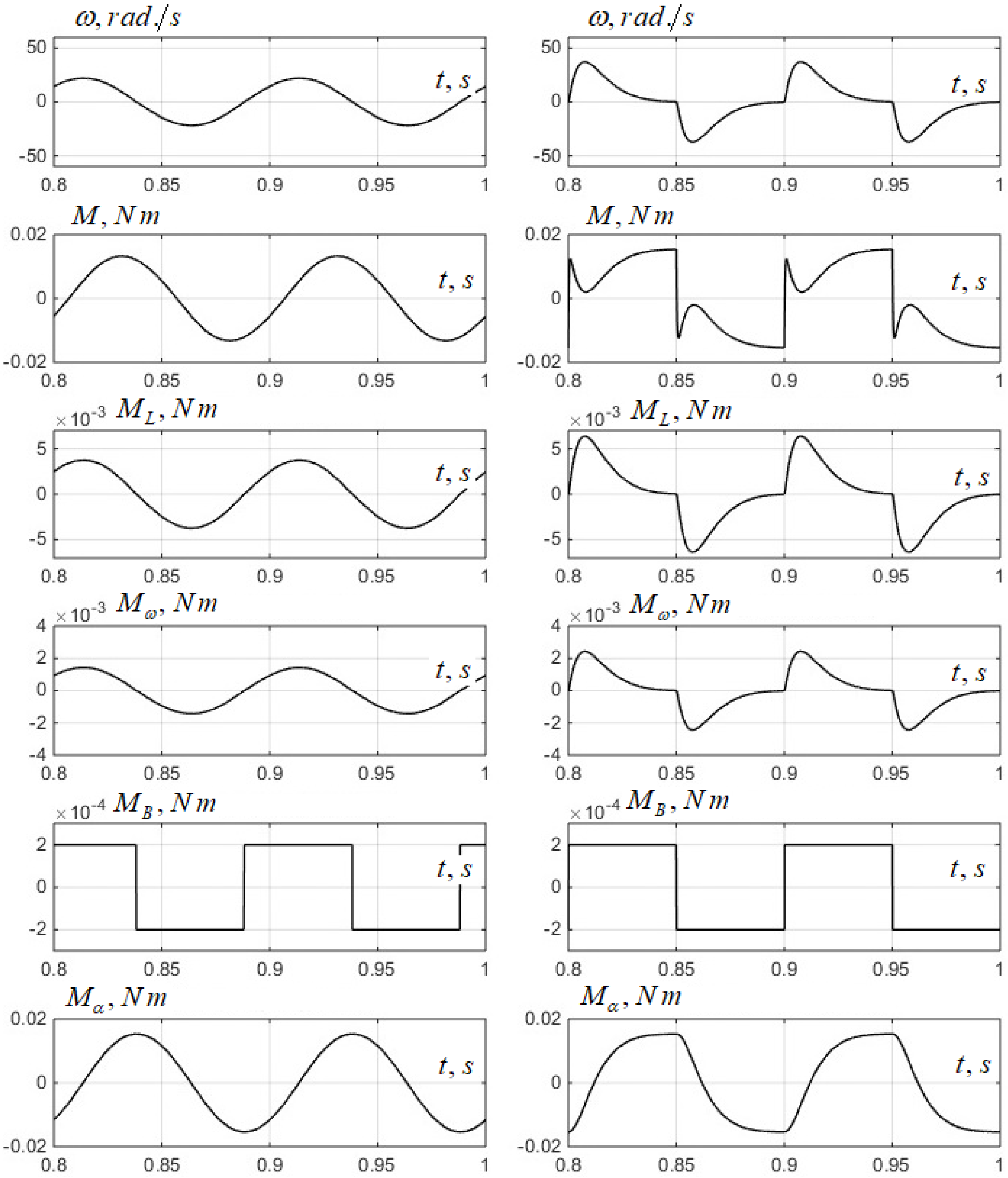


Fig. 1

To illustrate the BMM operating modes, fig. 1 shows the dependence of the amplitude of the angle of rotor oscillations and the effective value of the stator current on the frequency in the range from 1 to 100 Hz. The calculations were performed under the condition of limiting the maximum values of these parameters at the levels $\alpha_3 = \pi/9\ \text{рад.}$ and $I_3 = 0{,}14\ A$. Here, the letters a and b denote the variants of the formation of sinusoidal (9) and rectangular (10) stator voltages.

The study of energy characteristics involves the calculation of the consumed and useful mechanical powers, the determination of the relationship between them, and the analysis of the structure of power losses in the motor. As a result of previous experimental studies [7], the adequacy of the mathematical model (1–8) of the BMM of return-rotary motion was confirmed. In this case, research can be performed based on the specified motor model. In addition, the experimental determination of many parameters and variables of such a specialized motor is difficult or impossible.



a ***b***

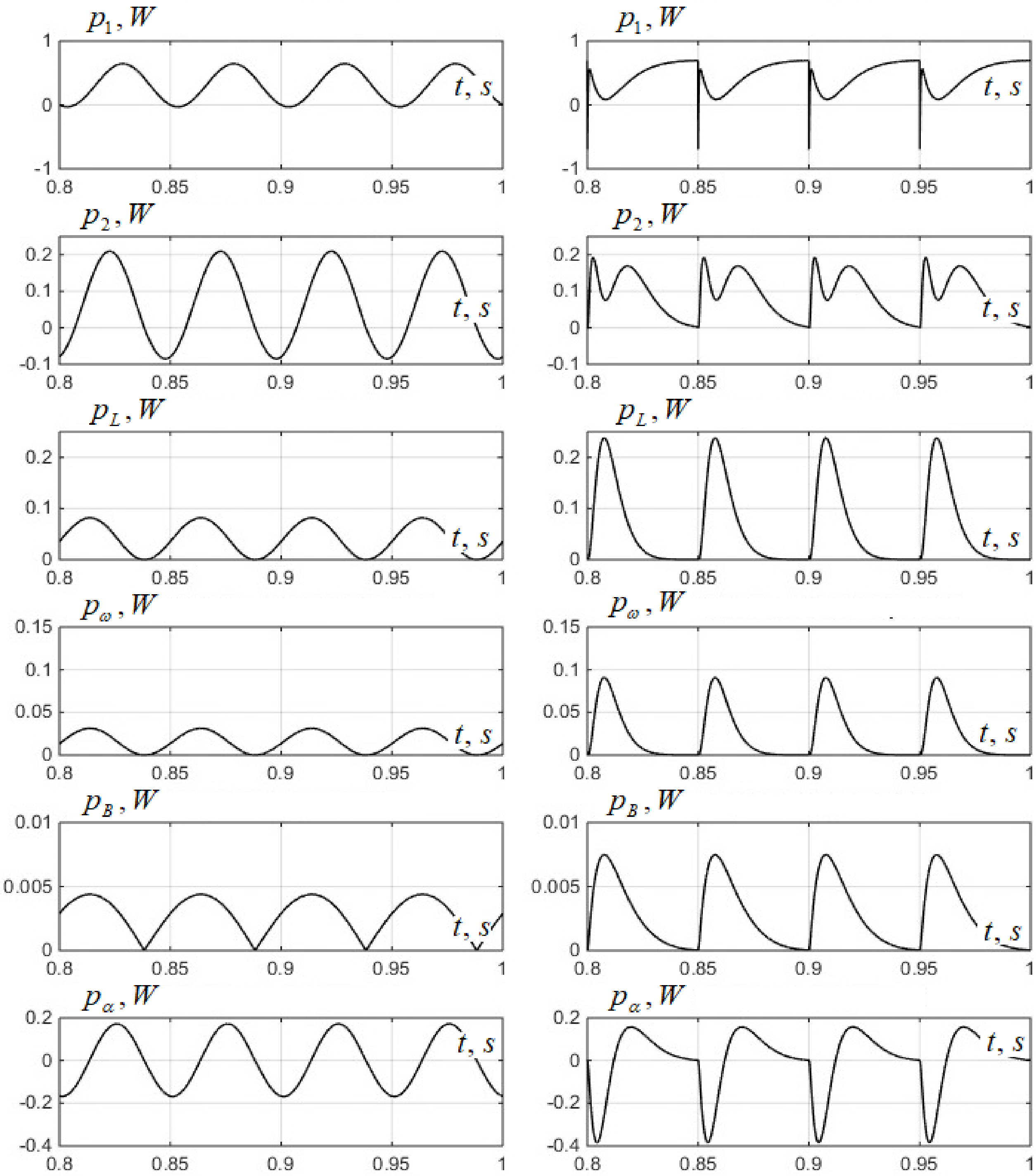
Fig. 2

First, we define the general structure of instantaneous powers, which characterizes the state of the BMM of return-rotary motion

$$p_1 = ui\,;\ p_2 = \omega M\,;\ p_L = \omega M_L\,;\ p_\omega = \omega M_\omega\,; \qquad (11\text{-}14)$$

$$p_B = \omega M_R\,;\ p_\alpha = \omega M_\alpha\,;\ p_A = i^2 R\,, \qquad (15\text{-}17)$$

where p_1 is the power consumed by the stator winding from the power source; p_2 is power on the motor shaft; p_L is the useful power of the mechanical load, which is modeled by introducing the coefficient of viscous friction k_L; p_ω is power, the value of which is determined by the torque of viscous friction of the motor k_ω; p_B is the power expended to overcome the friction of the bear-



a *b*

Fig. 3

ings; p_α is power due to the action of an elastic magnetic connection between the stator and the rotor; p_A is power losses on the active resistance of the stator winding.

Fig. 2 shows graphs of instantaneous values of the angular speed and the number of torques used to calculate the powers. Fig. 3 shows graphs of instantaneous values of powers that describe the state of the BMM of the return-rotary motion at an oscillation frequency value of 10 Hz. The letters *a* and *b* indicate the power supply modes of the motor with sinusoidal and rectangular stator voltage, respectively.

It can be seen that the influence of the elastic magnetic connection between the stator and the rotor does not cause active power consumption; that is, a periodic process of energy accumulation and return is observed.

Based on the formulas for instantaneous powers (11-17), respectively, their average values can be determined

$$P_1=\frac{1}{T}\int_0^T p_1\,dt\,;\;\; P_2=\frac{1}{T}\int_0^T p_2\,dt\,;\;\; P_L=\frac{1}{T}\int_0^T p_L\,dt\,;\;\; P_\omega=\frac{1}{T}\int_0^T p_\omega\,dt\,; \tag{18-21}$$

$$P_B=\frac{1}{T}\int_0^T p_B\,dt\,;\;\; P_\alpha=\frac{1}{T}\int_0^T p_\alpha\,dt\,;\;\; P_A=\frac{1}{T}\int_0^T p_A\,dt\,. \tag{22-24}$$

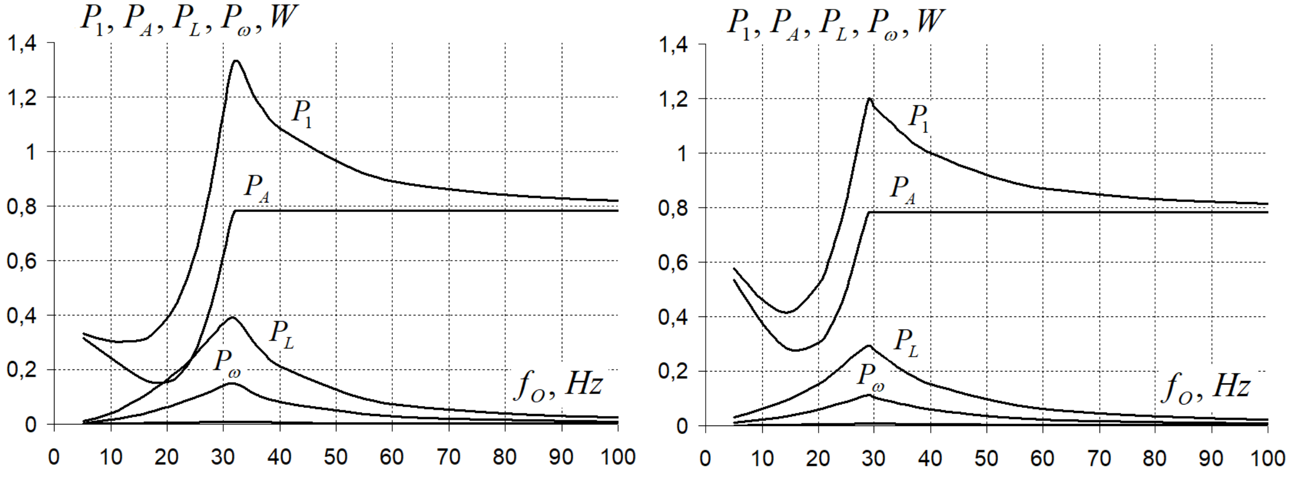
Finally, we can determine some relationships between the average values of the obtained powers

$$P_1=P_2+P_A;\;\; P_2=P_L+P_\omega+P_B;\;\; P_\alpha=0 \tag{25-27}$$

and determine the efficiency as the ratio of useful P_L and consumed P_1 powers

$$\eta=\frac{P_L}{P_1}\,. \tag{28}$$

For two variants of the formation of sinusoidal (***a***) and rectangular (***b***) stator voltage, fig. 4 shows the frequency dependences of the average values of consumption power P_1, losses of power P_A in the active resistance of the stator winding, useful power P_L, and power of viscous friction of the motor P_ω. The dependence of the power P_B consumed to overcome the bearing friction is not shown in the figure due to the smallness of its value.



a ***b***

Fig. 4

Fig. 5 shows the frequency dependences of the efficiency of the motor for the variants of the formation of sinusoidal (a) and rectangular (b) stator voltages.

Conclusion. The BMM of the return-rotary motion under consideration is a low-power device; therefore, the value of the efficiency factor turned out to be relatively small. The motor control mode with a rectangular voltage seems to be inefficient (fig. 5); however, in this case, the forced

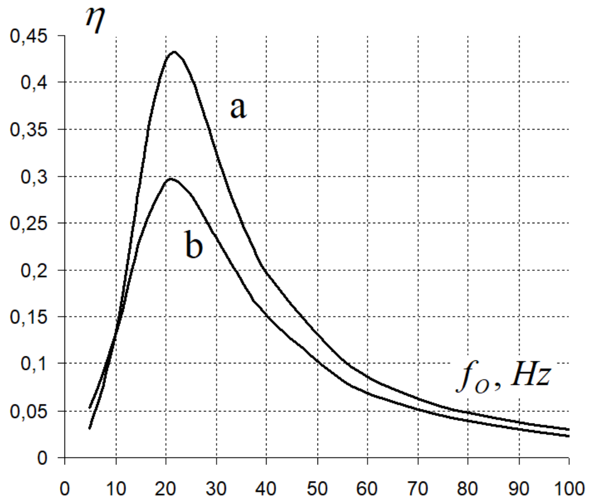


Fig. 5

operation mode of the motor with relatively large values of the amplitude of the angular speed is realized (fig. 2), which in some cases of the motor application provides a technological advantage. It can be seen that the frequency dependences (Fig. 4) reach a maximum under the condition of mechanical resonance, in which case the main operating frequency range of the motor can be selected in this operation mode. The relatively large values of losses in the active resistance of the stator winding are explained by the design limitations of the volume for placing the stator winding. The power expended to overcome the viscous friction of the motor is insignificant, and its reduction seems inappropriate since the feedback with the viscosity coefficient k_ω covers one of the two integrating links (5, 6) with external feedback k_α, thereby contributing to the improvement of the stability of such an electromechanical system.

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ЕНЕРГЕТИЧНІ ХАРАКТЕРИСТИКИ БЕЗКОНТАКТНИХ МАГНІТОЕЛЕКТРИЧНИХ ДВИГУНІВ ЗВОРОТНО-ОБЕРТАЛЬНОГО РУХУ

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У статті представлено результати досліджень структури потужностей, що характеризують стан спеціалізованого безконтактного магнітоелектричного двигуна зворотно-обертального руху. Наведено розрахункові криві кутової швидкості ротора, моменту двигуна та моментів механічного опору, а також криві миттєвих значень потужностей споживання, корисного механічного навантаження та втрат. Отримано частотні залежності коефіцієнта корисної дії та складових потужностей, на основі яких було виконано його розрахунок. Бібл. 7, рис. 5.

Ключові слова: безконтактний магнітоелектричний двигун, зворотно-обертовий рух, потужність, коефіцієнт корисної дії.

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