ЕЛЕКТРИЧНІ МАШИНИ ТА АПАРАТИ

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STUDY OF THE INFLUENCE OF CHANGING THE PARAMETERS OF BRUSHLESS MAGNETOELECTRIC MOTORS OF THE RETURN-ROTARY MOTION ON THEIR CHARACTERISTICS

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The paper presents the results of studies on the influence of changing the parameters of a specialized brushless magnetoelectric motor on its characteristics in the mode of return-rotary motion. The frequency dependencies of the amplitude of the rotor oscillation angle, the effective value of the stator current, the efficiency index of the motor operation mode, the amplitude of the angular speed of the rotor oscillations, the amplitude of the stator voltage, the total value of losses in the motor are given. The dependences of the resonant frequency of mechanical oscillations on the changing values of the elasticity coefficient, the moment of inertia, and temperature-dependent parameters are determined. The dependence of the maximum value of the efficiency of the return-rotary motion motor on the viscosity coefficient of the mechanical load is obtained. It is shown that the most economical mode of operation of the motor is provided under the condition of resonance of mechanical oscillations. Ref. 11, fig. 5.

Keywords: brushless magnetoelectric motor, return-rotary motion, frequency characteristic, motor parameters, resonant frequency.

Introduction. One of the tasks arising in developing various electromechanical systems is the study of the influence of changes in the parameters of executive electric motors on their characteristics. Reasons for changing the parameters may be different. Firstly, these can be parametric disturbances due to temperature changes or the influence of some other factors. Secondly, the range of variation of some parameters can be determined by the developer himself in optimizing the device or its mode of operation. Naturally, the specificity of such studies is determined by the properties and features of the executive motor, as well as the mode it is controlled.

This paper is focused on studying the influence of changing parameters on the characteristics concerning systems of return-rotary motion based on electric motors [1-4], designed to control the trajectory of the actuating element with a given frequency and angular amplitude. An essential feature of such systems is their inherent effect of mechanical resonance, which appears in a specific range of changes in the oscillation frequency of the actuating element.

Here, the authors propose a specialized brushless magnetoelectric motor (BMM) of return-rotary motion in a limited range of changes in the angle of rotation of the shaft [5]. A feature of such a motor is installing an additional permanent magnet into its structure in the gap between the winding coils to realize an elastic magnetic coupling between the stator and the rotor, which allows positioning the motor shaft in the initial angular position. A noteworthy circumstance is also that by affecting the stator winding to alternating voltage, direct control of the frequency and amplitude of the mechanical oscillations of the actuating element is provided without the usage of mechanical transducers of motion trajectories.

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The purpose of the paper is to study the influence of changing the parameters of the specialized BMM of a return-rotary motion on its frequency characteristics, as well as to determine the dependencies of the mechanical resonance frequency on those parameters that affect it.

The main material and study results. The structure of the considered BMM was described in detail in [5]. Here we only briefly 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 ensure the elastic magnetic coupling between the stator and the rotor, on which a bipolar permanent magnet and an actuating element are installed.

The mathematical model of BMM for the return-rotary motion control is described by the equations [6]:

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

$$M = k_m\, i\cos\alpha\,;\ M_\omega = k_\omega\,\omega\,;\ M_L = k_L\,\omega\,; \tag{2–4}$$

$$M_\alpha = k_\alpha \sin\alpha\,;\ M_R = M_B\, sign(\omega)\,; \tag{5, 6}$$

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

where i, u are current and control voltage of the stator; ω, α are angular speed and angle of the rotor shaft oscillation; 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 the total moment of inertia of the rotor and load; k_ω, k_α are coefficients of viscosity and elasticity of the motor; M_B is the torque of resistance of the bearings. In this study, it is assumed that the mechanical load viscosity coefficient k_L takes into account the parametric disturbance acting on the motor. The adequacy of the presented mathematical model (1–8) of the BMM of the return-rotary motion was confirmed as a result of previous experimental studies [7].

Considering the mathematical model (1–8), let's analyze the structure of the motor parameters.

The values of inductance L, active resistance R of the stator winding, and, to some extent, the torque coefficient k_m are determined by the structure and geometry of the stator winding, as well as the magnetic system of the motor. In addition, the magnitude of the torque coefficient is determined by the properties of magnetic materials [8].

The total moment of inertia J on the rotor shaft is determined by the values of two components - the moments of inertia of the motor rotor and the actuator, and the parameters of the latter can be different depending on its size and weight.

The motor viscosity coefficient k_ω is determined by the magnetic circuit's eddy current losses and the stator winding's copper conductors. The value of this coefficient can be influenced by dividing the winding conductors into several parallel conductors of a smaller cross-section and using a magnetic circuit made of laminated or amorphous iron [9] or powder material [10]. In addition, it was shown above (4) that in our case, the mechanical load is modeled by introducing an additional viscosity coefficient k_L, which does not change the structure of the model (1–8), but leads to an increase in the overall value of the motor viscosity coefficient $k_\omega + k_L$.

The value of the motor elasticity coefficient k_α is determined by the parameters of the additional permanent magnet in the gap between the active sections of the stator winding and, of course, the structure and parameters of the magnetic motor system. The influence of this coefficient's value on the motor's characteristics is also to be studied in this paper.

Note that the values of the active resistance R of the stator winding, the torque coefficient k_m , and the coefficient of elasticity k_α of the motor depend on temperature changes [11]

$$R=\left(1+a_T\left(T_T-T_{T0}\right)\right)R_0\,;\; k_m=\left(1-b_T\left(T_T-T_{T0}\right)\right)k_{m0}\,;\; k_\alpha=\left(1-b_T\left(T_T-T_{T0}\right)\right)k_{\alpha 0}\,, \tag{9–11}$$

where T_{T0}, R_0, k_{m0} $k_{\alpha 0}$ are initial temperature, active resistance, torque coefficient, and coefficient of elasticity of the motor; T_T is motor temperature; a_T, b_T are temperature coefficients of the winding conductor (for copper) and reversible changes in magnetic induction (for modern high-coercivity permanent magnets based on the NdFeB intermetallic composition). In this paper, we assume $b_T=0{,}0012\;\;1/C^o$.

Thus, temperature and load viscosity changes determine the parametric perturbations affecting the return-rotary motion motor.

The return-rotary motion motor is controlled by effecting its stator windings to an alternating voltage with controlled amplitude and frequency. We restrict ourselves to studying the characteristics of the motor with a sinusoidal variant of the formation of the stator voltage and a frequency range from 1 to 100 Hz

$$u=U_A\sin 2\pi f_O t\,, \tag{12}$$

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

Operating modes of BMM of return-rotary motion are characterized by several parameters [6]:

- amplitude α_A of the rotor oscillation angle;
- an effective value I of the stator current;
- performance index $k_1=\dfrac{\alpha_A}{I^2}$ of the BMM operation mode with a given frequency and amplitude;
- amplitude ω_A of the angular speed of the rotor oscillations;
- the total value of losses in the motor $P=P_A+P_\omega+P_B$, while taking into account losses in the active resistance P_A of the stator winding, losses to overcome the torque of viscous friction P_ω , and the torque of resistance of the bearings P_B [12]. The indicated losses are determined by the formulas $P_A=\dfrac{1}{T}\int\limits_0^T i^2R\,dt$, $P_\omega=\dfrac{1}{T}\int\limits_0^T \omega M_\omega\,dt$, $P_B=\dfrac{1}{T}\int\limits_0^T \omega M_R\,dt$;
- efficiency η, defined as the ratio of useful power P_L, consumed to overcome the mechanical load, and the consumed power P_1

$$\eta=\frac{P_L}{P_1}\,, \tag{13}$$

where $P_L=\dfrac{1}{T}\int\limits_0^T \omega M_L\,dt$ and $P_1=\dfrac{1}{T}\int\limits_0^T u\,i\,dt$.

If we analyze the operation of the motor in a wide frequency range of mechanical oscillations from 1 to 100 Hz, then two main modes should be noted:

- stabilization of the amplitude of the rotor oscillation angle α_A in the low-frequency range of operation (up to 20-30 Hz);
- limitation of the effective value of the stator current I at oscillation frequencies of more than 20-30 Hz according to the conditions of the thermal state of the motor.

In this study, we assume such maximum specified values of the amplitude of the rotor oscillations angle $\alpha_3 = \pi/9\, rad$ and the effective value of the stator current $I_3 = 0{,}14\ A$. We also assume the basic values of the motor parameters: $L = 0{,}012\ Hn$, $R = 40\ Ohm$, $k_m = 0{,}125\ N\,m/A$, $k_\omega = 6{,}5\cdot 10^{-5}\ N\,m\,s/rad$, $J = 2{,}4\cdot 10^{-6}\ kg\,m^2$, $k_\alpha = 0{,}0448\ N\,m/rad$, $M_B = 2\cdot 10^{-4}\ N\,m$. The given values of the parameters characterize a low-power BMM with an outer diameter of the stator body of 34 mm and a length of 120 mm.

This paper is supposed to study the operating modes of the BMM of return-rotary motion for given basic values of the motor parameters and change only one parameter or several of them. Figures 1-4 show the study results in the form of families of frequency dependences. As a result of numerical modeling, families of frequency dependences of the main indicators of motor operation modes were obtained according to the accepted values of the variable parameters: elasticity coefficient k_α (Fig. 1), total moment of inertia J (Fig. 2), motor temperature T_T and parameters dependent on it (Fig. 3), as well as the sum of the viscosity coefficients k_ω and k_L (Fig. 4). The table shows the values of all variable parameters that were used in the calculations, where N is the characteristic number.

N	k_α, $N\,m/rad$	J, $kg\,m^2$	T_T, ^oC	R, Ohm	k_m, $N\,m/A$	k_α, $N\,m/rad$	k_ω, $N\,m\,s/rad$	k_L, $N\,m\,s/rad$
1	0,0138	$1{,}2\cdot 10^{-6}$	–60	27,5	0,137	0,0491	$1{,}625\cdot 10^{-5}$	0
2	0,0249	$2{,}4\cdot 10^{-6}$	+20	40,0	0,125	0,0448	$3{,}25\cdot 10^{-5}$	0
3	0,0448	$3{,}6\cdot 10^{-6}$	+120	55,6	0,11	0,0394	$6{,}5\cdot 10^{-5}$	0
4	0,0806	–	–	–	–	–	$6{,}5\cdot 10^{-5}$	$6{,}5\cdot 10^{-5}$
5	0,1452	–	–	–	–	–	$6{,}5\cdot 10^{-5}$	$1{,}95\cdot 10^{-4}$
	Fig. 1	Fig. 2	Fig. 3				Fig. 4	

All figures show families of graphs of frequency dependences of the rotor oscillation angle amplitude $\alpha_A(\omega)$ (a), the effective value of the stator current $I(\omega)$ (b), the performance index $k_1(\omega)$ of the motor operation mode (c), the amplitude $\omega_A(\omega)$ of the angular speed of the rotor oscillations (d), the amplitude $U_A(\omega)$ of the stator voltage (e), the total value of losses in the motor $P(\omega)$ (f). In addition, all figures marked with the letter g show families of dependences of the amplitude of the rotor oscillation angle $\alpha_A(\omega)$, calculated under the condition of limiting the effective value of the stator current at $I_3 = 0{,}14\ A$. Fig. 1, 2, and 3 (h) show the dependencies of the resonant frequency f_R on the changing values of the elasticity coefficient k_α, moment of inertia J, and temperature T_T, respectively. Fig. 4 (h) shows the frequency dependencies of the efficiency $\eta(\omega)$ calculated for 4 and 5 calculation variants, that is, for those cases when a mechanical load is simulated on the motor shaft. All characteristics in the figures are numbered with numbers corresponding to the number N indicated in the table.

Fig. 5 shows the dependence of the maximum value of the efficiency $\eta_{\max}$ on the viscosity coefficient k_L of the mechanical load, through which the parametric perturbation affecting the motor is taken into account. The maximum value of the coefficient $\eta_{\max}$ was determined based on the frequency characteristics $\eta(\omega)$ (Fig. 4 h). The dependence is calculated at a fixed value of the motor viscosity coefficient $k_\omega = 6{,}5\cdot 10^{-5}\ N\,m\,s/rad$.

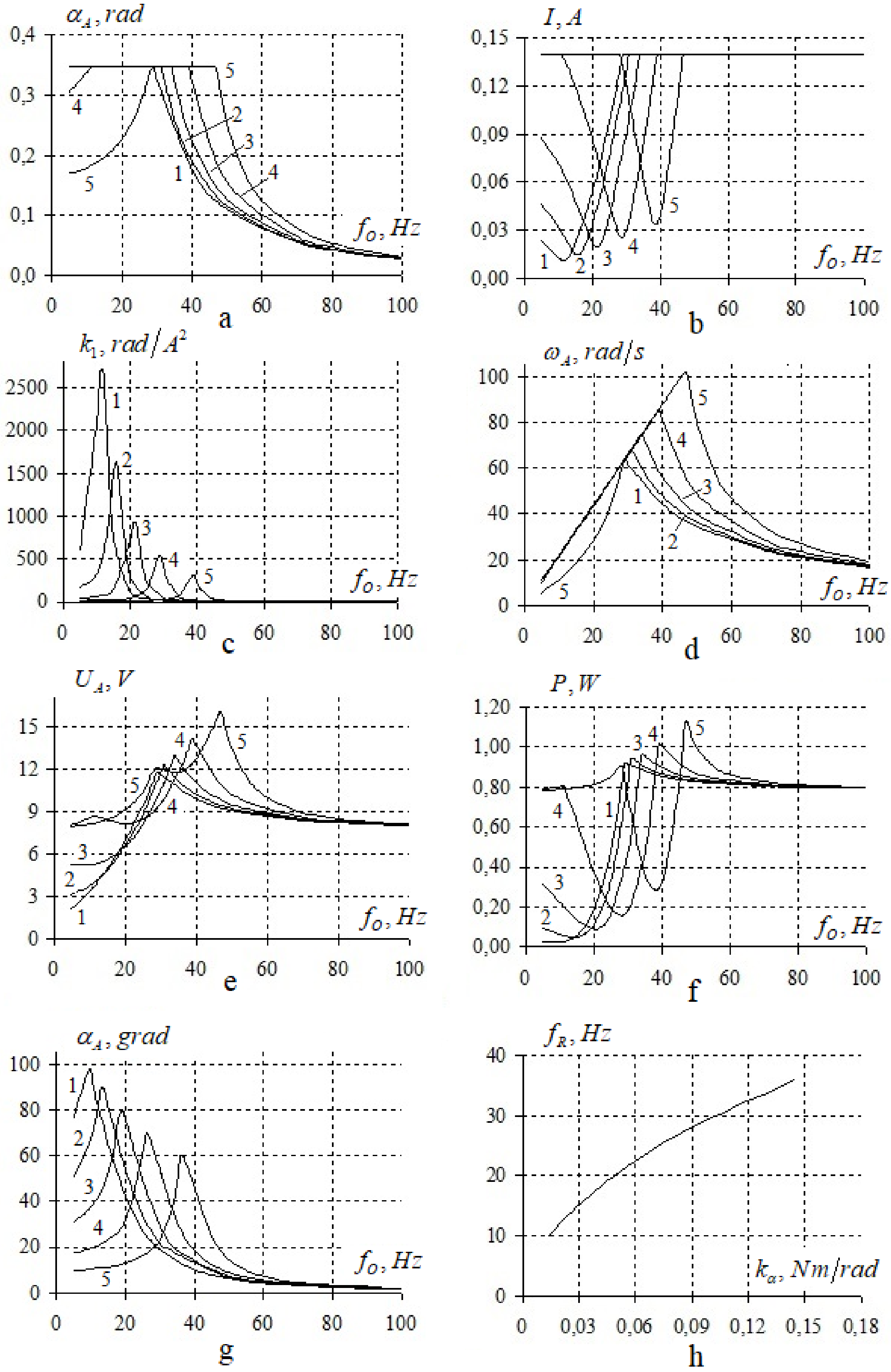

Fig. 1

Conclusions. Considering the obtained characteristics, it follows that changes in the elasticity coefficient k_α and the total moment of inertia J on the motor shaft significantly affect the magnitude of the resonant frequency f_R (Fig. 1, 2 b, c, and g). And if the value of the moment of inertia is determined by the dimensions and mass of the actuating element installed on the shaft, that is, it is a given value, then the elasticity coefficient is a parameter whose value can be set when develop-

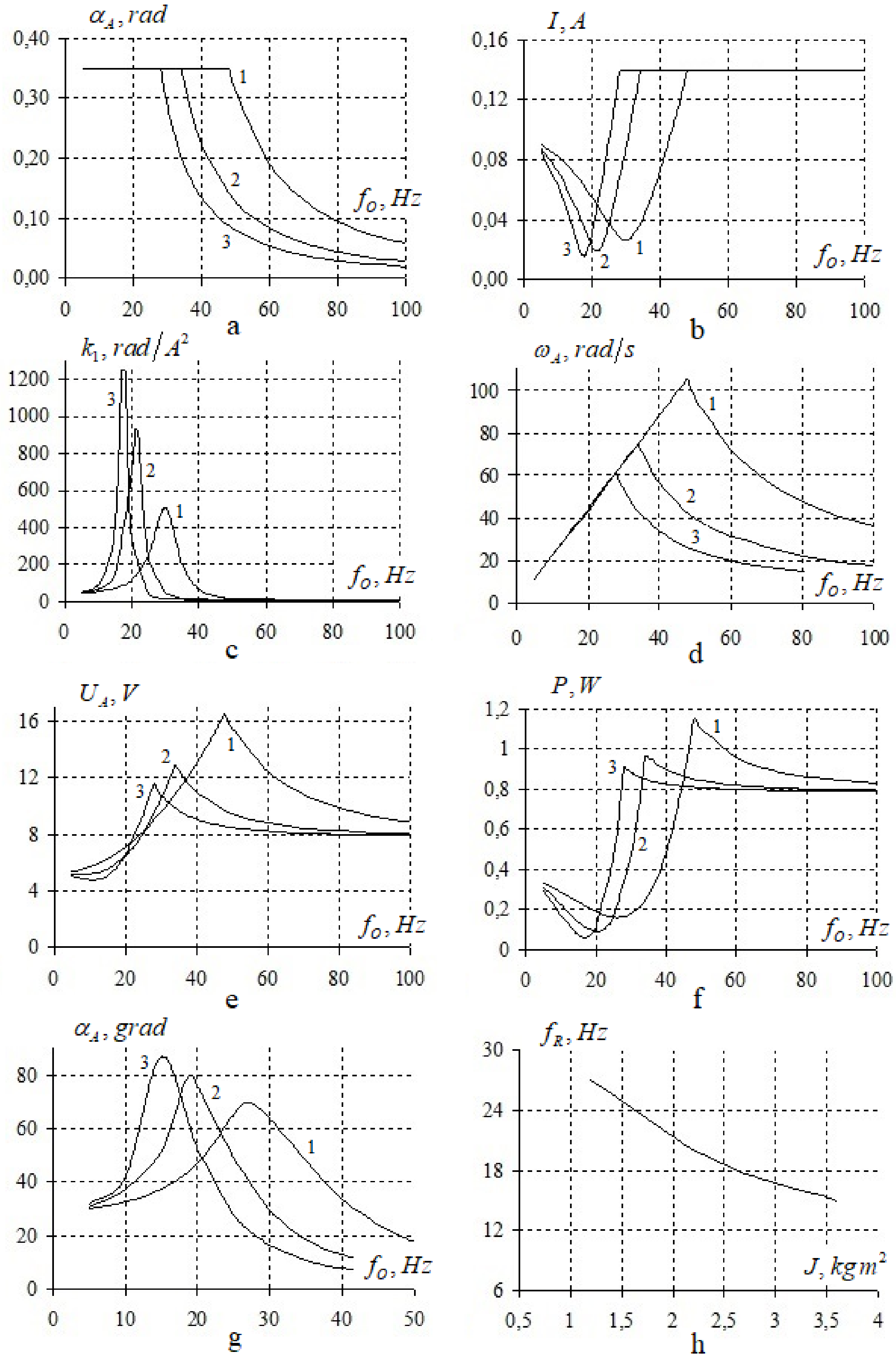

Fig. 2

ing the motor. The latter is an essential circumstance since, in the vicinity of the resonant frequency, the motor is characterized by the best energy performance (Fig. 1, 2 c and f), and it is under the condition of mechanical resonance that it is advisable to set the main operating mode of the return-rotary motion motor.

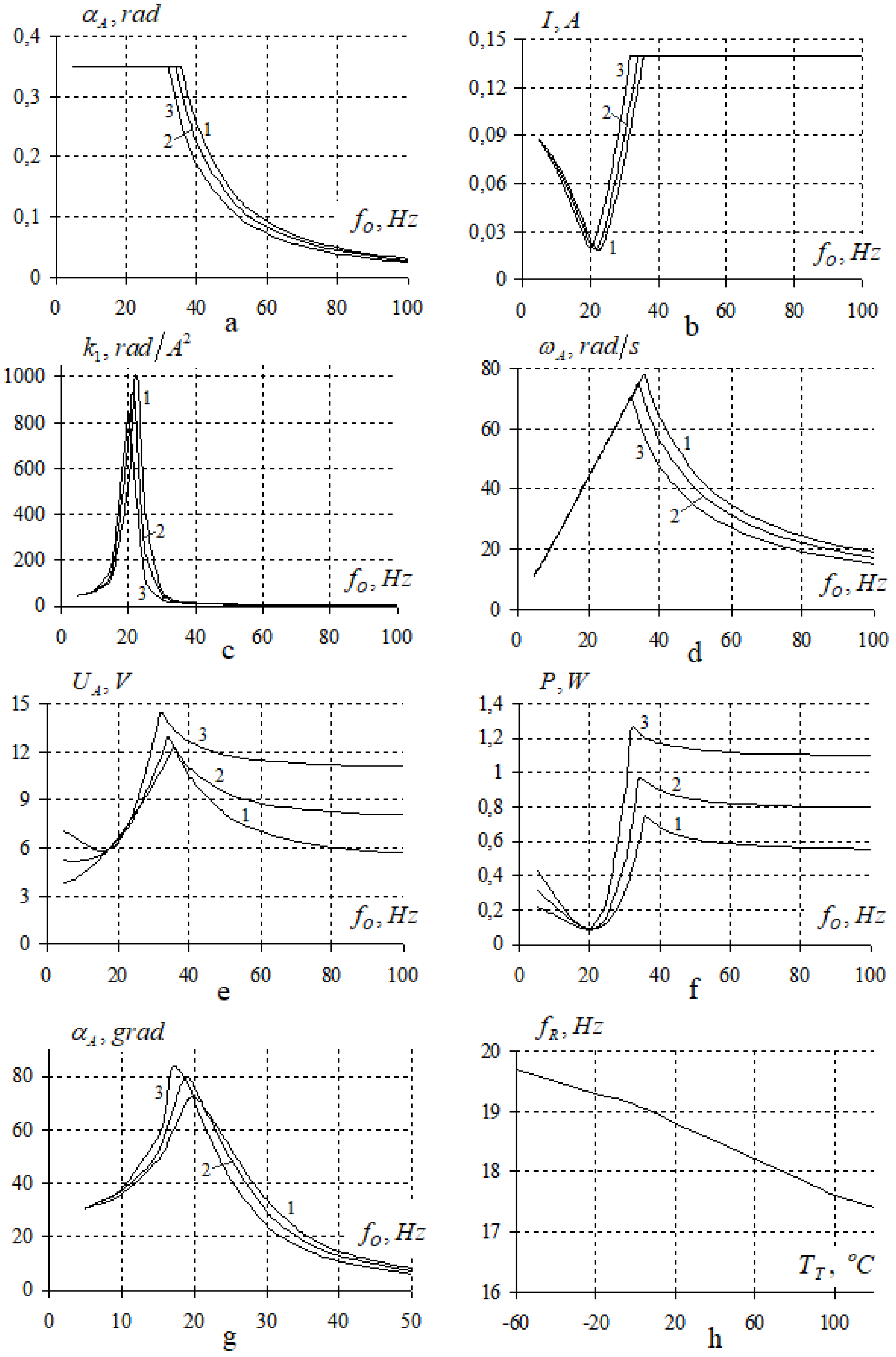

Fig. 3

The temperature change T_T has practically no effect on all the presented in Fig. 3 dependences, except for the frequency dependences of losses in the motor, which is due to a significant change in the active resistance R of the stator winding (Fig. 3 e), as well as frequency dependences of the stator AC voltage amplitude U_A (Fig. 3 f).

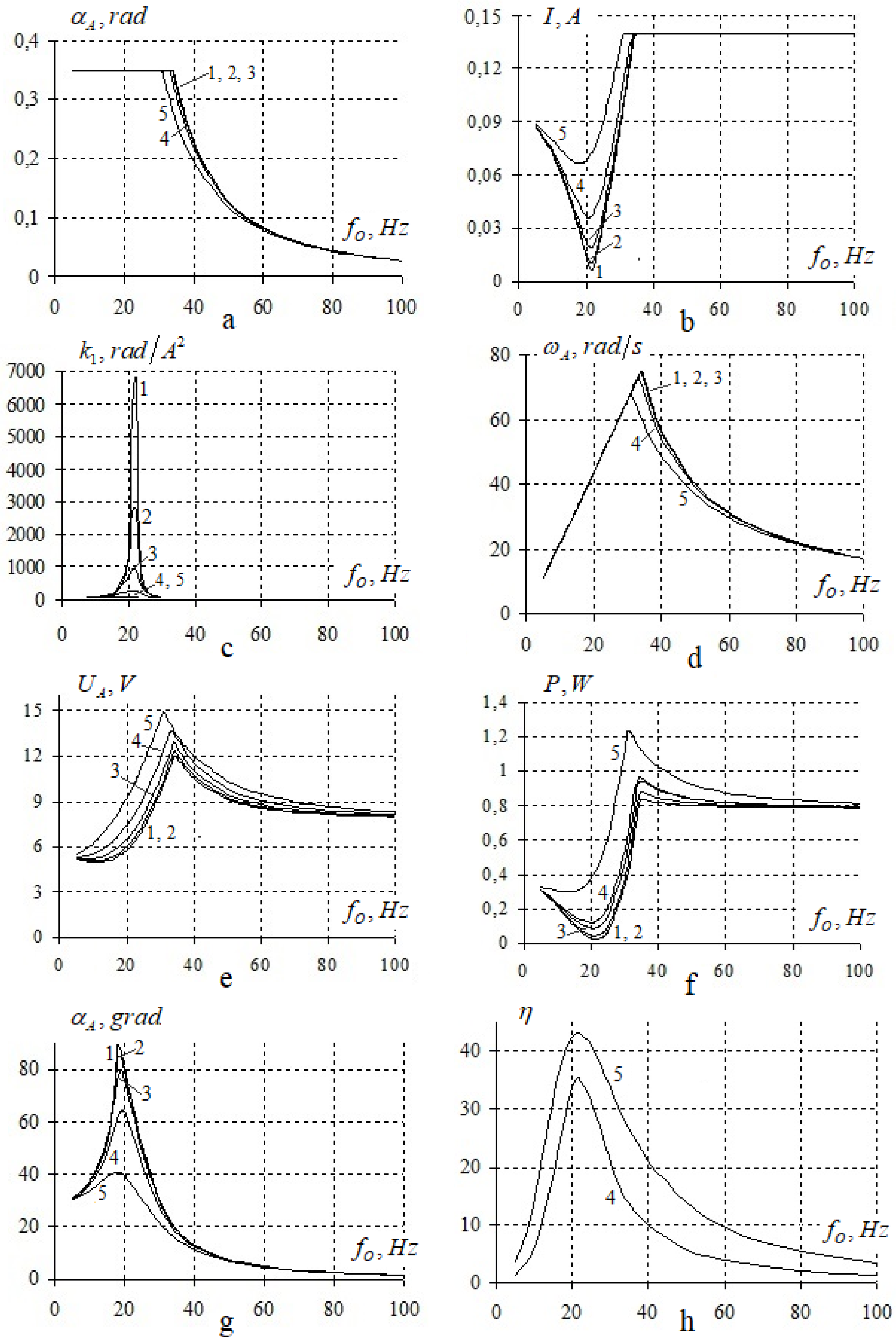

Fig. 4

Changing the overall value of the viscosity coefficient $k_\omega + k_L$ of the motor does not affect the value of the resonant frequency. However, with an increase in this coefficient, a significant weakening of the resonant effect is observed (Fig. 4 b, c, and g). The dependence $\eta_{\max}(k_L)$ (Fig. 5) shows that the maximum value $\eta_{\max}$ of the efficiency of the return-rotary motion motor remains at a relatively high level of about 40% in a wide range of changes in the mechanical load on the motor shaft, modeled by introducing an additional viscosity coefficient k_L.

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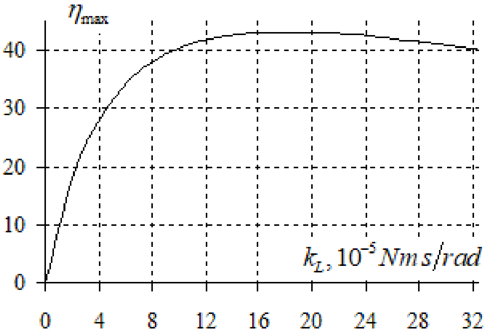

Fig. 5

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ДОСЛІДЖЕННЯ ВПЛИВУ ЗМІНИ ПАРАМЕТРІВ БЕЗКОНТАКТНИХ МАГНІТОЕЛЕКТРИЧНИХ ДВИГУНІВ ЗВОРОТНО-ОБЕРТАЛЬНОГО РУХУ НА ЇХНІ ХАРАКТЕРИСТИКИ

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У статті представлено результати досліджень впливу зміни параметрів спеціалізованого безконтактного магнітоелектричного двигуна на його характеристики в режимі зворотно-обертального руху. Наведено частотні залежності амплітуди кута коливань ротора, значення струму статора, показника ефективності режиму роботи двигуна, амплітуди кутової швидкості коливань ротора, амплітуди напруги статора, сумарної величини втрат у двигуні. Визначено залежності резонансної частоти механічних коливань від змінюваних значень коефіцієнта пружності, моменту інерції, а також параметрів, що залежать від температури. Отримано залежність максимальної величини коефіцієнта корисної дії двигуна зворотно-обертального руху від коефіцієнта в'язкості механічного навантаження. Показано, що найбільш економічний режим роботи двигуна забезпечується за умови резонансу механічних коливань. Бібл. 11, рис. 5.

Ключові слова: безконтактний магнітоелектричний двигун, зворотно-обертальний рух, частотна характеристика, параметри двигуна, резонансна частота.

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