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FEATURES AND PRINCIPLES OF THE DEVELOPMENT OF BRUSHLESS MAGNETOELECTRIC SYSTEMS OF THE RETURN-ROTARY MOTION

V.G. Kireyev*, K.P. Akinin, A.A. Filomenko*****
Institute of Electrodynamics of the National Academy of Sciences of Ukraine,
pr. Peremohy, 56, Kyiv, 03057, Ukraine, e-mail: kvg2016@ukr.net

The paper reviews the results of studies of brushless magnetoelectric systems of return-rotary motion, carried out for many years at the Electrodynamics Institute of the National Academy of Sciences of Ukraine. Structures of specialized brushless magnetoelectric motors with elastic magnetic coupling between the stator and the rotor are presented. An example of structural optimization of the motor is given. The electromechanical characteristics of the motors of the return-rotary motion are described and the indexes of their efficiency are proposed. An example of the formation of functional dependences for motor control in an open-loop system is given. Structures of the system for automatic control of the rotor oscillations angle amplitude and stator current limitation, as well as a system for vector control of the auxiliary winding current for active compensation of reactive alternating torque of the main rotor are presented. Examples of calculation of transient responses of the main parameters of the motor are given. References 11, figures 9.
Key words: brushless magnetoelectric motor, return-rotary motion, control system, carrier frequency.

Introduction. There is a special class of actuating electromechanical devices designed to realize the return-rotary motion (RRM) of the instrument in certain types of devices. Such devices are used in special polishing equipment, medical instruments for the treatment of post-operative scars, apparatus cosmetology for lymph drainage, dermotonia and skin micropolishing, in thermal imaging scanners, etc.

The main factor determining the choice of the structure and control method for the electromechanical system of return-rotary motion (RRM) is the range of regulation of the amplitude and frequency of actuator shaft oscillations. For example, when building a RRM system that operates at a constant mechanical load and controlled frequency, it is advisable to use a standard electric drive, at the output of which a special mechanical transducer of rotational motion into return-rotary motion is installed [1, 2]. This solution is determined by the simplicity of implementation and high efficiency of the electric drive, since the rotor of the motor rotates in one direction, and in the motion conversion mechanism, as a rule, there are no parts with a large moment of inertia. There is also a class of devices, the operation of which is based on the use of the resonance effect of the RRM, in which a standard electric motor can also be used, for example an asynchronous [3] or a double-feed motor [4], with a special control system. This solution makes it possible to realize the maximum amplitude of oscillations with a minimum power consumption of the electric drive, however, such RRM system is designed to operate only at the resonant frequency.

The use of a traditional electric drive in combination with various electromagnetic, magnetoelectric, mechanical or other motion converter for simultaneous regulation of the amplitude and frequency of oscillations of the output shaft of the RRM system is not effective and difficult. In this regard, to solve this problem, it is necessary to use special devices that best combine the advantages of both drives with conversion mechanisms and those based on the resonance effect.

The development of specialized electromechanical RRM systems presupposes, on the one hand, the construction of special structures of actuating motors, on the other hand, it is necessary to implement effective methods of controlling their operating modes. This paper examines the structure of an electromechanical system based on a special brushless magnetoelectric motor (BMM), which controls the frequency and amplitude of mechanical oscillations of the actuating element.

The paper is devoted to the research carried out at the Electrodynamics Institute of the National Academy of Sciences of Ukraine in the direction of creating brushless magnetoelectric RRM systems.

ORCID ID: * https://orcid.org/0000-0002-9407-1074 ; ** https://orcid.org/0000-0002-7830-2311 ;
*** https://orcid.org/0000-0003-4289-8579

Features of magnetoelectric systems of the RRM. The considered class of magnetoelectric systems is characterized by the following features:

– BMM of the RRM is the structure [5] shown in Fig. 1, *a*, where the body *1* contains a cylindrical slotless magnetic circuit *2* and two bearings *3*, in which the rotor shaft *4* with a bipolar permanent magnet *5* and a actuating element *6* is installed. On the inner surface of the magnetic circuit *2* there are two coils *7* and *8* of the stator winding, and an additional permanent magnet *9* is installed in the space between the coils to realize the effect of elastic magnetic coupling between the stator and the rotor;

– control of BMM of the RRM is carried out by acting on the stator windings with alternating current with controlled amplitude and frequency in the range up to 100 Hz;

– the main output controlled parameter of the system is the amplitude α_A of the oscillations angle of the main rotor relative to the device body;

– the controlled coordinate of the system is the stator current effective value I under the conditions of motor cooling;

– regulation of the oscillations angle amplitude of the main rotor is carried out in the range of no more than 40 degrees;

The principle of engine operation is as follows. In the initial state, the rotor is in a stable equilibrium position and is forced to orient itself when its poles are positioned opposite the active parts of the winding. When the winding of the stator is connected to the power supply, an electromagnetic moment occurs which takes the rotor out of the stable equilibrium position. The greater the angle of the rotor deflection under the action of the control electromagnetic moment, the greater the force of the elasticity, so that with some of the rotor deflection angle the electromagnetic moment is equalized by the moment of the magnetic spring. At this point, the signal of the electromagnetic moment is forced to change and the rotor moves backwards.

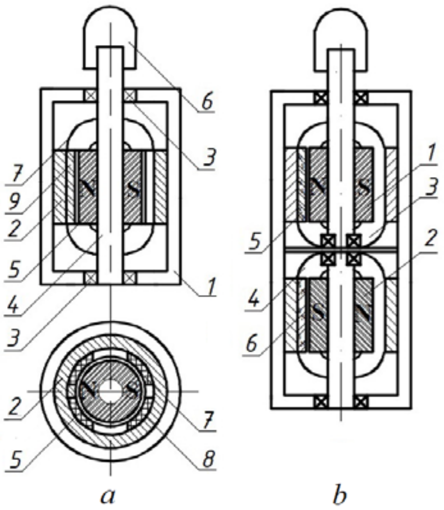


Fig.1

During operation, the oscillations of the rotor cause an undesirable reaction of the housing of the device to the operator's hand, therefore an additional structurally identical drive system can be introduced in the composition of the device in order to compensate for the occasional alternating moments of the BMD, The rotor of which oscillates synchronously, but is counterphase to the first rotor. On Fig. 1, *b* shows the total type of instrument consisting of main *1* and compensating *2* rotors, windings of main *5* and additional *6* stators, and two additional permanent magnets *3* and *4*.

Optimization of parameters of motor structural elements. The art of designing electric machines with permanent magnets lies mainly in the selection of such ratios between the dimensions of the elements of the magnetic system, at which the maximum of the motor torque per unit of power input is achieved. In other words, it is necessary to solve the problem of structural optimization of the BMM magnetic system in order to identify the maximum of the electromagnetic torque, which is an objective function of several variables. Such variables can be both the geometric dimensions of the individual components of the magnetic system, and their relative position.

We will show the procedure for solving the optimization task using the example of one of the variants of the BMM of the RRM, the cross section of the magnetic system of which is shown in Fig. 2. The electromagnetic part of the motor includes the magnets of the rotor *1* and stator *2*, two stator coils *3* and an external magnetic circuit *4*.

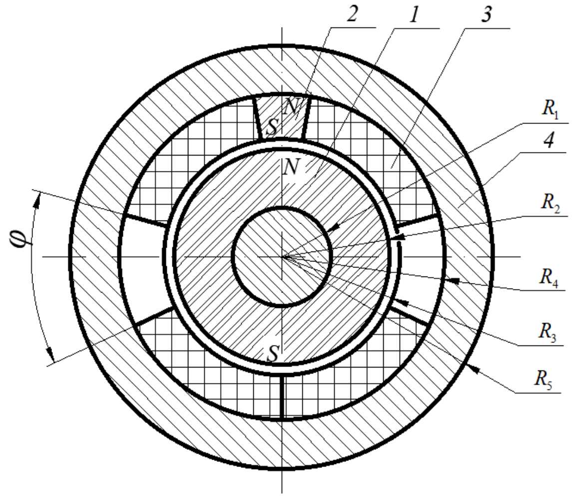


Fig. 2

It is known that the electromagnetic torque of the motor depends on the magnetic flux density amplitude distributed in the air gap, as well as on the volume of the current circuits in it and their location relative to the rotation rotor axis

$$M = pB_\delta I w l_a R_m, \tag{1}$$

where M is the electromagnetic torque; p is the number of pole pairs; B_δ is the value of the radial magnetic flux density component in the air gap; I is the current in the stator winding; w is the number of winding turns; l_a is the active length of the winding conductors; R_m is the average radius of the force application arm, which in accordance with Fig. 2 is equal to $0,5(R_3 + R_4)$.

We will search for the maximum torque under the following conditions and restrictions: the power P supplied to the motor from the power source is constant and for the task being solved it is equal to 5 W; the number of pole pairs $p = 1$; the overall radius of the magnetic system is fixed and equal to 13.5 mm; the maximum magnetic flux density in the external magnetic circuit does not exceed 1.2 T; the gap between the rotor and stator is constant and equal to 0.5 mm; diameter $2R_1$ of the shaft is equal to 6 mm; we will consider the mode of formation of the starting torque, in which energy dissipation occurs only in the conductive conductors of the stator windings; in order to reduce the number of variables, we restrict ourselves to considering one length of the active part of the winding l_a = 22 mm.

As the arguments of the objective function, we select the radial thickness of the winding $h = R_4 - R_3$ and the size of the coil window, determined by the angle φ, that is, those parameters that determine the amplitude and distribution law of magnetic flux density B_δ in the gap of the BMM, as well as the cross-sectional area of the stator winding coils. Based on the stipulated conditions, with a constant input power, the current in the winding and its resistance should also remain unchanged. To do this, it is necessary to vary the cross-section and the number of coil conductors so that their resistance remains unchanged, this will be the condition for the constancy of the dissipated power [7]. Let us express the length l_m of the average turn and the number w_C of coil turns through the geometric dimensions of the magnetic system

$$l_m = 2l_a + (2R_3 + h)(0,5\pi + \varphi); \qquad w_C = \sqrt{\frac{US_C}{I\rho l_m}}, \tag{2), (3}$$

where U is the voltage of the power source; S_C is the cross section area of one half of the coil; ρ is the specific resistance of the coil conductor material.

After substitution of expressions (2, 3) into (1) and some transformations, we obtain

$$M = pB_\delta \sqrt{\frac{PS_C}{\rho l_m}} l_a (R_3 + 0,5h). \tag{4}$$

The solution of the extremal task for (4) was carried out using the Comsol software package in a three-dimensional formulation to take into account the influence of scattering fields from the surfaces of the rotor magnet end. The developed calculation algorithm made it possible to find the law of variation of the function $M(h, \varphi)$ and find its maximum (Fig. 3).

The calculation showed that for the given initial data, the maximum torque is achieved at $h = 2,1$ mm and $\varphi = 44$ deg. The solved problem illustrates a optimization technique BMM of the RRM, which can be applied not only for other initial data, but also for other structures of brushless electric machines with permanent magnets.

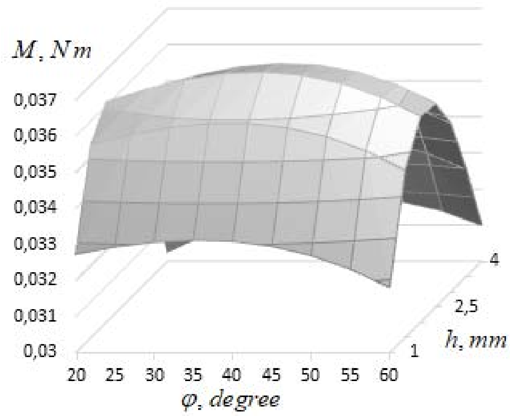


Fig.3

Mathematical model and operating modes of BMM of the RRM. The mathematical model of BMM is described by the equations [8]:

$$L\frac{di}{dt} = -Ri - k_m\,\omega\cos\alpha + u; \quad M = k_m\, i\cos\alpha; \quad M_\omega = k_\omega\,\omega; \quad M_\alpha = k_\alpha \sin\alpha; \tag{5)-(8}$$

$$M_R = M_B\, sign(\omega); \quad M_L = k_L\,\omega; \quad J\frac{d\omega}{dt} = M - M_\omega - M_\alpha - M_R - M_L; \quad \frac{d\alpha}{dt} = \omega, \qquad (9)\text{-}(12)$$

where ω, α are angular speed and angle of the rotor shaft oscillation; *L*, *R* are inductance and active resistance of the stator winding (in a motor with a slotless stator and a surface-mounted permanent magnets on the rotor, the inductance *L* can be assumed to be a constant value [9]); *i*, *u* are current and control voltage of the stator; k_m is motor torque coefficient; *J* is rotor moment of inertia; M_ω, M_α, M_R, M_L are torques of viscous friction and elasticity, reactive torque of bearings and torque of loading, respectively; k_ω, k_α are viscosity and elasticity coefficients; M_B is bearing friction torque; k_L is viscosity coefficient of the motor load.

In the study of the characteristics of the PMM of the RRM, such variants of the formation of the stator alternating voltage were assumed

$$u = U_A \sin 2\pi f_O t; \qquad (13)$$

$$u = 0{,}5\, U_A \left(sign\left(\sin 2\pi f_O t - 0{,}5\varphi_1\right) + sign\left(\sin\left(2\pi f_O t + 0{,}5\varphi_1\right)\right)\right), \qquad (14)$$

where U_A is the stator voltage amplitude; f_O is the carrier frequency of rotor shaft oscillations; φ_1 is angular length of the zero shelf of a rectangular form voltage; *t* is time.

BMM is an object with nonlinear dependences of input and output parameters. At the same time, BMM of the RRM can operate in one of two modes:

– in the mode of limiting the amplitude of the rotor oscillations angle at a given level in the low-frequency range of operation (up to 20-30 Hz);

– in the mode of limiting the effective value of the stator current at values of the oscillations frequency more than 20-30 Hz, and the current effective value is limited according to the conditions of motor cooling.

Efficient operation of BMM of the RRM is achieved by ensuring the maximum of one of two parameters – the performance index $k_1 = \alpha_A / I^2$ of the operation mode of the BMM, taking into account the given frequency and amplitude with a minimum value of losses in the stator winding or the amplitude of the angular speed ω_A of rotor oscillations.

There are two possible approaches to controlling BMM of the RRM:

– in an open-loop system by forming functional frequency dependences of the value of the amplitude and the form parameter of the control alternating voltage of the stator, which can be formed on the basis of the electromechanical characteristics of the BMM, taking into account the given performance indexes of its operating mode [8];

– in a closed-loop control system for the amplitude of the rotor oscillations angle and limiting the stator current effective value [9], while it is necessary to form the corresponding feedback signals, which significantly complicates the hardware part of the system.

Electromechanical characteristics of BMM of the RRM. Fig. 4 shows the electromechanical characteristics of the BMM in the form of frequency dependences of the shaft oscillations angle amplitude α_A, the stator current effective value *I*, the proposed performance index k_1 and the angular speed amplitude ω_A of the rotor oscillations. The characteristics are determined in the frequency range up to 100 Hz, subject to the specified limitations of the oscillation angle amplitude and the stator current effective value $\alpha_{AO} = \pi/9\, rad.$ and $I_O = 0{,}14$ A. Number 1 denotes a variant of the formation of a sinusoidal voltage (13). Numbers 2, 3 and 4 designate variants for rectangular voltage (14) with three parameter values φ_1 - 0, 80 and 160 el. degrees. Calculations are performed for equations (5–12) with the following parameter values: $L = 0{,}012\, Hn$, $R = 40\, Ohm$, $k_m = 0{,}125\, N m / A$, $k_\omega = 6{,}5 \cdot 10^{-5}\, Nms / rad$, $J = 2{,}4 \cdot 10^{-6}\, kg\, m^2$, $k_\alpha = 0{,}0448\, N m / rad$, $M_B = 2 \cdot 10^{-4}\, N m$, $k_L = 2{,}1 \cdot 10^{-4}\, Nms / rad$.

Formation of functional dependences. To control the BMM of the RRM in an open-loop system, a method has been developed for the formation of functional frequency dependences of the control voltage parameters, in which for each value of the carrier frequency f_O the stator voltage parameters are determined, at which the maximum of the selected performance index is ensured. The dependences of the stator voltage parameters $U_A(f_O)$ and $\varphi_1(f_O)$, as well as the corresponding dependences of the performance indexes $k_1(f_O)$ and $\omega_A(f_O)$ are shown in Fig. 5. The letters A and B designate respectively the variants of the formation of sinusoidal and rectangular voltages.

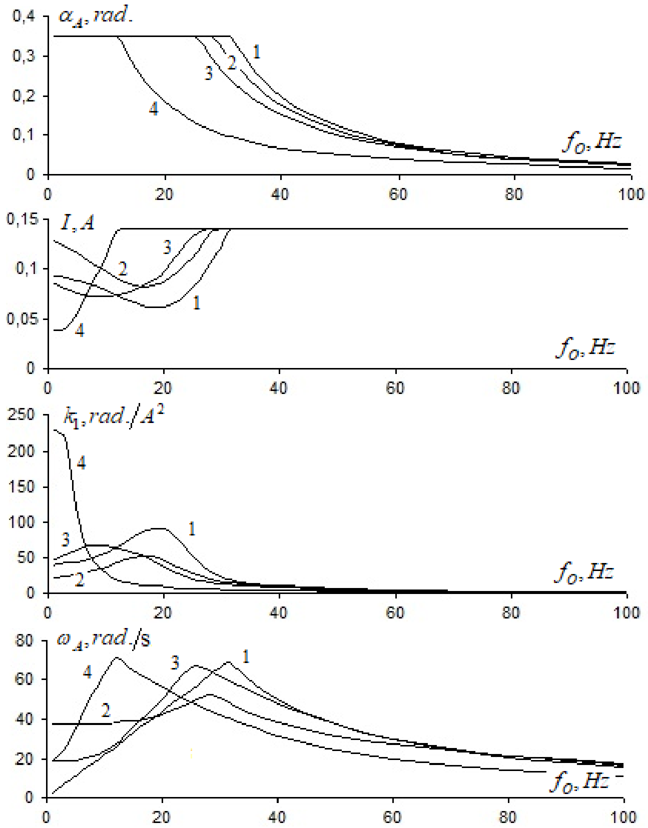


Fig.4

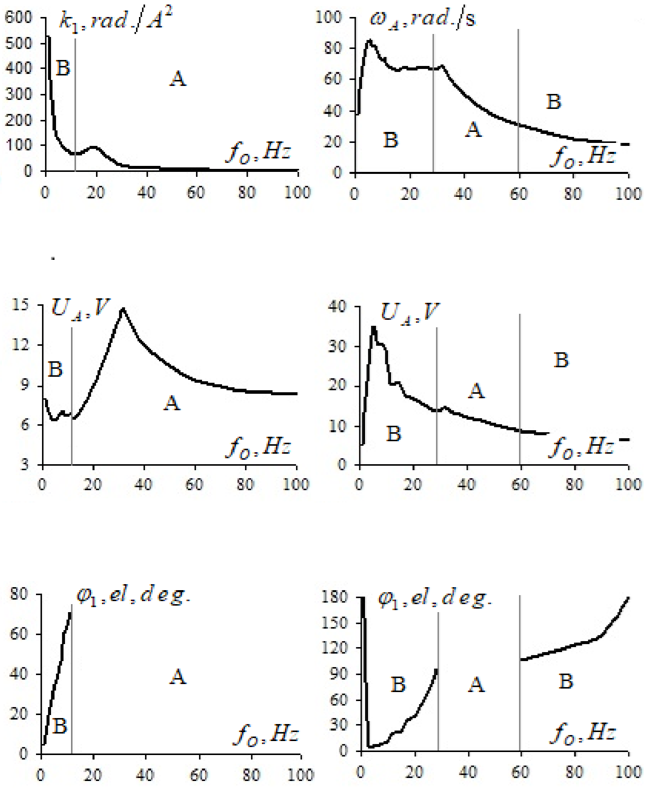


Fig.5

System for automatic regulation of rotor oscillations amplitude and stator current limitation. For automatic control of the rotor oscillations angle amplitude α_A and limiting the stator current effective value *I*, the structure of the control system is developed [10], shown in Fig. 6, where *C* is a controller of the oscillations angle amplitude with nonlinearity of the saturation type; *F* is a filter of the output signal of the nonlinear link; U_C, U_F are output signals of the controller and filter; $x_O(\omega_O t)$ is carrier periodic signal, where $\omega_O = 2\pi f_O$; $\max(|\alpha|)$, $RMS(i)$ are the procedures for determining the amplitude of the modulus of the rotor shaft oscillations angle and the stator current effective value at each half-period of the alternating stator voltage, the values of which are maintained for half the period of the carrier signal.

The calculation of the system parameters is carried out on the basis of the frequency characteristics of the BMM of the RRM and the controller. In this case, the controller of the rotor oscillations amplitude is calculated at a given value of the carrier frequency f_O, provided that a given phase stability margin γ is provided [8, 9], which is determined by the formula

$$\gamma = \pi + \varphi_\alpha(\omega_C) + \varphi_P(\omega_C), \qquad (15)$$

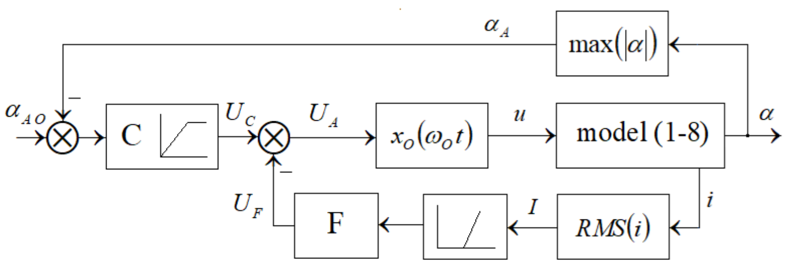


Fig.6

where $\varphi_\alpha(\omega_C)$, $\varphi_P(\omega_C)$ are the values of the phase shifts of the output signals of the BMM and the controller at a given value of the cut-off frequency ω_C, the value of which is chosen less than the carrier frequency $\omega_C = \omega_O / n$. At given values ω_O, ω_C and γ the parameters of the controller are determined from the condition that the amplitude frequency characteristic of the open-loop system is equal to unity

$$A(\omega_C) = A_\alpha(\omega_O) A_P(\omega_C) = 1, \qquad (16)$$

where $A_\alpha(\omega_O)$, $A_P(\omega_C)$ are the values of the amplitude frequency characteristics of the BMM and the controller at the values of the carrier frequency and cut-off frequency.

The transfer coefficient of the I-controller, as well as the parameters of the PI-controller is determined by the formulae [10]

$$k_I = \frac{\omega_C}{A_\alpha(\omega_O)}, \quad T_{PI} = \frac{1}{\omega_C} tg\left(\gamma - \frac{\pi}{2} + \varphi(\omega_C)\right), \quad k_{PI} = \frac{\omega_C}{A_\alpha(\omega_O)\sqrt{1+T_P^2 \omega_C^2}}. \qquad (17)\text{-}(19)$$

The transfer coefficient and time constant of the first-order filter in the current limiting loop in the high-frequency part of the range is also determined taking into account the frequency characteristics

$$k_F = \frac{A_I(\omega_O) U_{\max} - I_O(1+\varepsilon)}{A_I(\omega_O) I_O \varepsilon}; \qquad T_F = \frac{20}{f_O}, \qquad (20), (21)$$

where $A_I(\omega_O)$ is the value of the current amplitude frequency characteristics of the BMM; ε is the relative accuracy of limiting the current effective value; I_O is the reference value at which the stator current starts to be limited; $U_{\max}$ is the maximum value of the output signal of the oscillations angle amplitude controller.

Fig. 7, *a-d* shows the graphs of transient responses of regulation of the oscillation angle amplitude

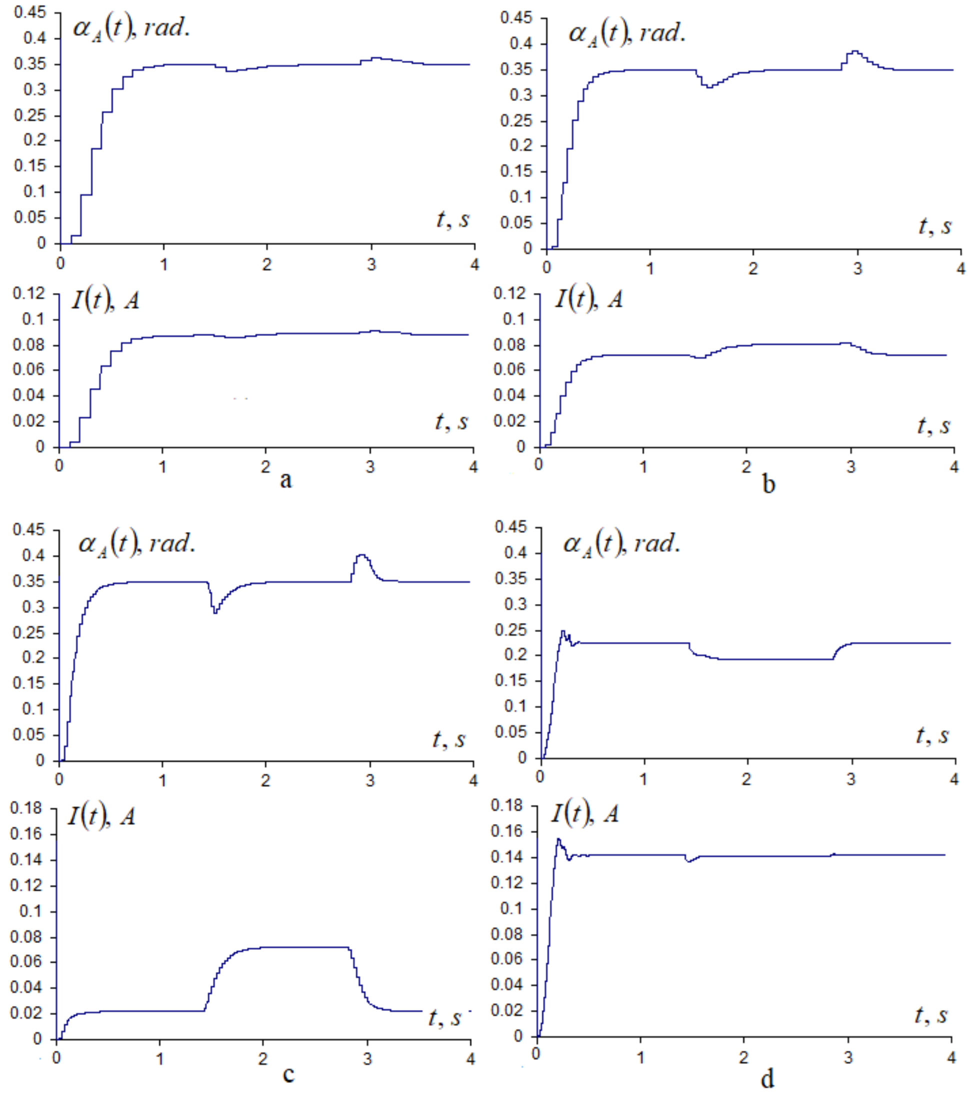


Fig.7

α_A and the current effective value *I* at the values of the carrier frequency f_O 5 (*a*), 10 (*b*), 20 (*c*) and 40 (*d*) Hz in the modes of starting the motor and changing the load. The calculations were carried out for a given sinusoidal stator voltage and a current limiting accuracy of 1%.

Active compensation of reactive torque of the main rotor. Let us define the features, conditions and principles of building a control system for a two-rotor BMM of the RRM [6] (Fig. 1, *b*).

The main and compensating systems are structurally identical and are described by equations (6)-(12). The difference is that the compensating rotor is unloaded, and the moments of inertia of the two rotors can be different.

The condition for the compensation of the reactive torque on the device body is defined as the achievement of the minimum values of the amplitude of the oscillation angle of the body around the axis of rotors rotation, while the dynamics of body oscillations is described by the equations

$$J_3 \frac{d\omega_3}{dt} = M_{D2} - M_{D1} - M_{\omega 3} - M_{\alpha 3}; \qquad \frac{d\alpha_3}{dt} = \omega_3, \qquad (22, 23)$$

where J_3, ω_3, α_3 are axial moment of inertia, angular speed and angle of rotation of the body around the axis of the rotors; M_{D1}, M_{D2} are dynamic torques on the shafts of the main and compensating rotors; $M_{\omega 3}$, $M_{\alpha 3}$ are the torque of viscous friction and the torque of elasticity, determined by the influence of the human hand on the device body. From the consideration of equation (22) it is seen that compensation is achieved under the condition of equality of dynamic torques $\Delta M = M_{D2} - M_{D1} = 0$.

Since it is difficult to directly measure the body rotation angle α_3, the difference between the variable periodic oscillations of the two rotors is taken as the output compensated parameter as a feedback signal of the closed control system

$$\Delta\alpha = \alpha_1 - \frac{J_2}{J_1}\alpha_3. \qquad (24)$$

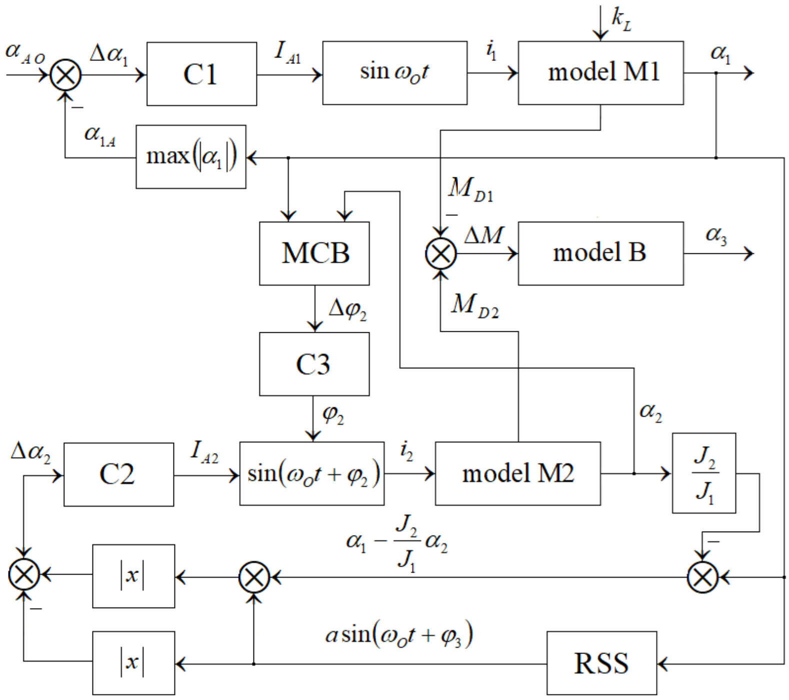
The currents of the stator windings corresponding to the main and compensating rotors is assumed

$$i_1 = I_{1A}\sin 2\pi f_O t; \qquad i_2 = I_{2A}\sin\left(2\pi f_O t - \varphi_2\right), \qquad (25), (26)$$

where i_1, i_2 are alternating currents of stator windings; I_{1A}, I_{2A} are amplitudes of currents; φ_2 is the phase shift of the current of the compensating winding.

To ensure compensation of the body response, it is necessary to develop a vector control system for the motion of the compensating rotor [11], that is, it is necessary to implement a system for regulating the amplitude I_{2A} and phase shift φ_2 of the stator current i_2 of the compensating system (26) relative to the main stator current i_1. For this, it is necessary to generate mismatch signals at the inputs of the current amplitude and phase shift controllers based on measurements of the angular variables of the main and compensating rotors α_1 and α_2. The general structure of the control system for a two-rotor BMM [10] with active compensation of reactive torque is shown in Fig. 8, where C1, C2, C3 are controllers of the oscillations amplitudes of the first and second rotors, as well as the controller of the phase shift φ_2 of the current of the compensating system; BCM is the block for calculating the phase shift mismatch $\Delta\alpha_2$ of variables α_1 and α_2; RSS is the reference signal shaper; M1, M2, B are designations for the models of the first and second motors, as well as the device body.

Fig. 9 shows the graphs of transient responses of the current amplitude I_{1A} of the main stator winding, the oscillations angle α_1 of the main rotor, the amplitude I_{2A} of the current of the compensating stator winding, the mismatch signal $\Delta\alpha_2$ in the amplitude of the compensating winding current, the signal of the phase shift mismatch $\Delta\varphi_2$, the phase shift φ_2 of the stator current i_2 of the compensating system and the rotation body angle α_3 at a carrier frequency of 10 Hz.



C1
sin ωₒt
model M1
max(|α₁|)
MCB
model B
C3
C2
sin(ωₒt + φ₂)
model M2
|x|
RSS

Fig.8

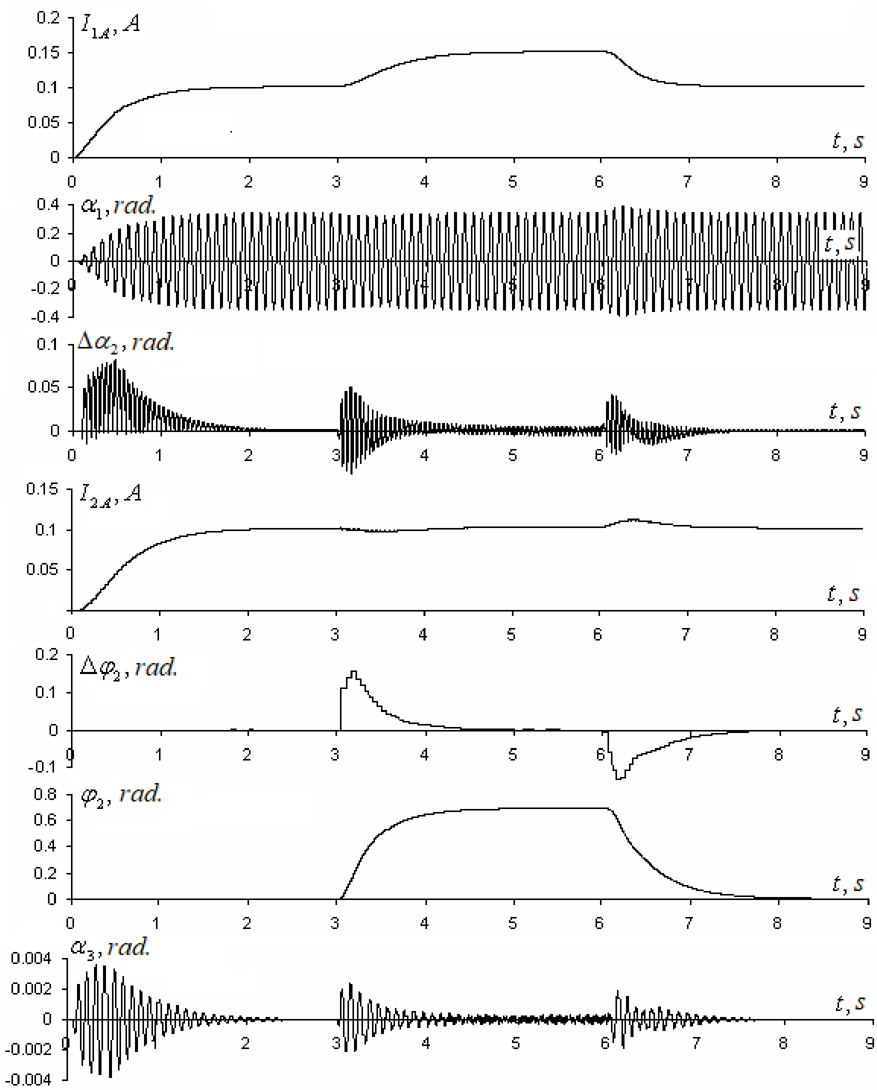


Fig.9

Fig. 9 shows the graphs of transient responses of the current amplitude I_{1A} of the main stator winding, the oscillations angle α_1 of the main rotor, the amplitude I_{2A} of the current of the compensating stator winding, the mismatch signal $\Delta\alpha_2$ in the amplitude of the compensating winding current, the signal of the phase shift mismatch $\Delta\varphi_2$, the phase shift φ_2 of the stator current i_2 of the compensating system and the rotation body angle.

Conclusion. The described electromechanical structures are specialized low-power systems that provide direct effective control of the RRM of the actuating element without the use of additional mechanical transmissions. The proposed structures can be the basis for the creation of various hand tools. The described open and closed control systems make it possible to choose a rational structure of the electromechanical device as a whole. The implementation of the principle of active compensation of reactive alternating torque in devices containing an electric drive of return-rotary motion, by creating an controlled torque, the value of which at each moment of time corresponds to the torque of the main motor, and is directed in the opposite direction, allows solving the problem of vibration protection of a person working with a power hand tool.

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ОСОБЛИВОСТІ ТА ПРИНЦИПИ ПОБУДОВИ БЕЗКОНТАКТНИХ МАГНІТОЕЛЕКТРИЧНИХ СИСТЕМ ЗВОРОТНО-ОБЕРТАЛЬНОГО РУХУ

В.Г. Кіреєв, канд. техн. наук, **К.П. Акинін**, докт. техн. наук, **А.А. Філоменко**
Інститут електродинаміки НАН України,
Пр. Перемоги, 56, Київ, 03057, Україна. **E-mail: kvg2016@ukr.net**

Ввиконано огляд результатів досліджень безконтактних магнітоелектричних систем зворотно-обертального руху, що проводяться в Інституті електродинаміки НАН України. Представлено структури спеціалізованих безконтактних магнітоелектричних двигунів з пружним магнітним зв'язком між статором та ротором. Наведено приклад структурної оптимізації двигуна. Описано електромеханічні характеристики двигунів зворотно-обертального руху та запропоновано критерії ефективності їхньої роботи. Наведено приклад формування функціональних залежностей для керування двигуном у розімкненій системі. Представлено структури системи автоматичного керування амплітудою кута коливань ротора та обмеження струму статора, а також системи векторного керування струмом допоміжної обмотки задля активної компенсації реактивних знакозмінних моментів основного ротора з виконавчим елементом. Наведено приклади розрахунку перехідних процесів основних параметрів двигуна. Бібл. 11, рис. 9.

Ключові слова: безконтактний магнітоелектричний двигун, зворотно-обертальний рух, система керування, несуча частота.

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