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TWO- DEGREE-OF-FREEDOM ELECTRIC MACHINE AND ITS OPERATION MODES

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This paper is devoted to the problems of developing an electric machine with two-degrees-of-freedom (2-DOF) of rotor movement and its control system. The structure of the machine with the possibility of rotation of the rotor along two angular coordinates in a limited range of rotation angles is considered. The machine is designed to control the position of the axis of the optical beam along the line and frame trajectories. Based on the electrodynamic state model of the 2-DOF electric machine, a block diagram of the servo system was developed to control the trajectory of the rotor in two coordinates. Relationships between the time constant of the angle controller and the time constants of the high-frequency part of the amplitude-frequency characteristic of an open-loop system are determined. The dependences of the effective values of the currents in the control windings on the frequency of the frames and the duration of the linear part of the triangular signal are obtained. The dependences of the modules of relative accuracy of the rotor movement along a given trajectories on the system tunings are obtained. Ref. 12, fig. 8.

Key words: two-degree-of-freedom electric machine, control system, scanning device, line trajectory, frame trajectory.

Introduction. Devices that control the spatial movement of a radiation beam are known as scanning devices. The range of problems solved with the help of scanning beam systems is quite wide. It includes the issues of control and regulation of parametric fields in thermal objects, for example, in furnaces or special combustion chambers, search and tracking of reference emitters in the process of orientation and navigation, detection and tracking of special objects in military equipment, control of the spatial position of an optical and laser beam in medicine, etc. Despite the fact that scanning devices increasingly use methods for deflecting optical or radar radiation without the use of moving elements, there are technical problems when the use of an electromechanical drive becomes the only possible solution [1]. This is especially true in cases of controlling high-power radiation or when the useful signal is commensurate with the background signal and high resolution is required.

Magnetoelectric drives of scanning devices can be different in their design, but the basic requirements for them remain unchanged, namely: high speed and high electromagnetic torque per unit of energy consumed. This paper discusses the possibility of using a 2-DOF electric machine with permanent magnets to control the spatial position of an optical or laser beam in two spatial angular coordinates and to implement the specified scanning trajectories. In particular, the possibility of implementing the line and frame trajectory of the beam, as the most common [2–4]. The choice of 2-DOF electric machine as a drive for an object of spatial movement is due to its design feature, which consists in the implementation of the function of a two-coordinate spatial turn using one controlled rotor with two-degrees-of-freedom of rotation. 2-DOF electric machine control is carried out using an electromagnetic field generated by a system of windings placed in space. When the winding field interacts with the excitation field of permanent magnets, electromagnetic torques are created along two angular coordinates [5].

The purpose of the paper is to present the experience of developing a 2-DOF electric machine with permanent magnets for controlling the spatial position of the rotor in two angular coordinates and to study the operating modes of such a machine to justify the possibility of implementing a line-frame trajectory of the beam.

2-DOF electric machine structure. Fig. 1 shows the structure of the scanner based on the 2-DOF electric machine (Fig. 1 a) and the appearance of an experimental sample of such a machine, developed at the Institute of Electrodynamics of the National Academy of Sciences of Ukraine (Figure 1b). The movable element of the scanning device is a payload mounting platform 1, which is mounted on a 2-DOF suspension 2 (shown schematically) and rigidly connected to the rotor

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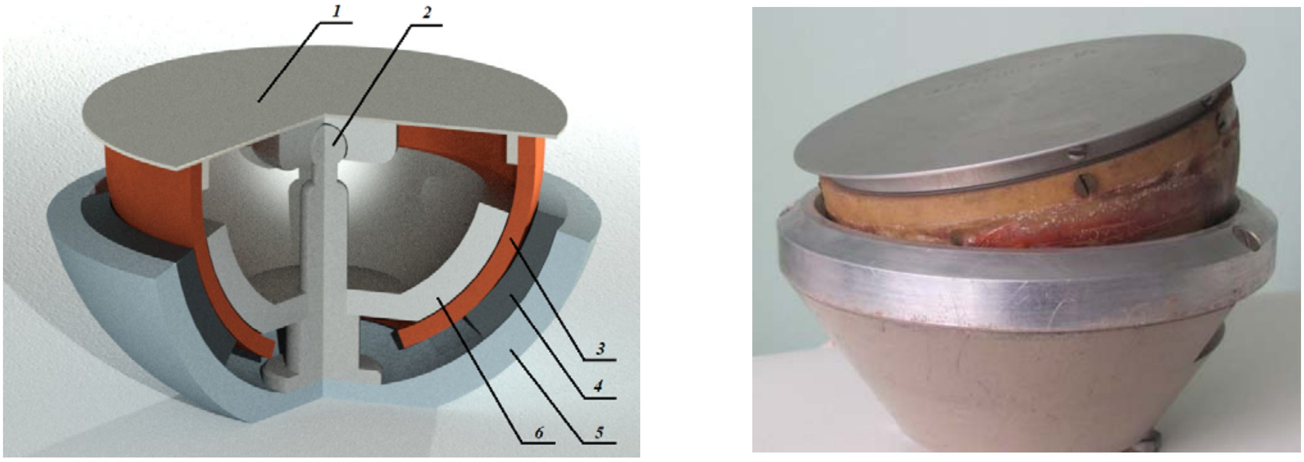
windings 3. An internal two-axis gimbal with angular position sensors mounted on its axes is used as a suspension. The movable rotor is a truncated hollow ball, in which two windings are located, filled with a dielectric compound. One of the windings is wound in the form of a spiral so that its electrical axis coincides with the axis of the machine when the scanning platform is in a horizontal position.



a *b*

Fig. 1

The second winding consists of two coils mounted on the outer surface of the first winding, and the active parts of the turns of the first and second windings located in the working gap of the 2-DOF electric machine magnetic system are mutually orthogonal. Fig. 2 schematically shows one turn of the second winding with current (red arrows) and its location in the working gap.

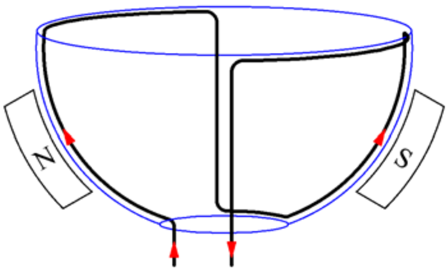


Fig. 2

The stator magnetic system includes one pair of permanent magnets 4, outer 5 and inner 6 magnetic cores rigidly interconnected. Thus, the magnetic excitation system is common for controlling the angular position of the rotor about two mutually orthogonal axes, with the first winding in a more advantageous position in terms of utilization than the second. Structurally, the first winding is closest to the windings used in single-coordinate scanners [6, 7], where everything is subject to achieving the maximum electromagnetic torque with a minimum moment of inertia of the rotor. In the proposed design, the electromagnetic control torque generated by the spiral winding is an order of magnitude higher than that of the coil winding. Therefore, the first winding was used to control the position of the rotor when moving along the line (along the β), as the most intense mode of operation, and the second winding – along the frame (along the α) (Fig. 3).

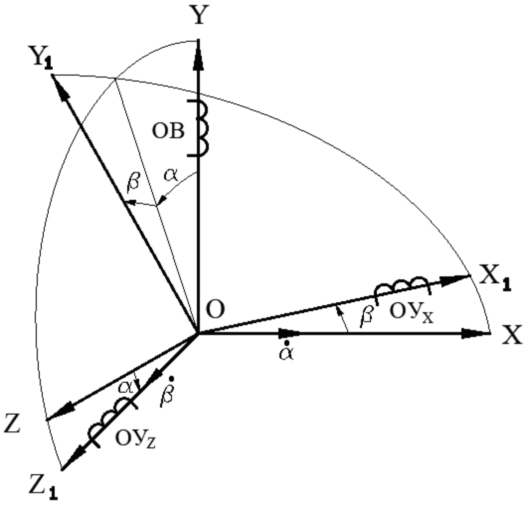


Fig. 3

In accordance with the general theory of electrical machines [5, 8, 9], the 2-DOF machine can be conditionally represented in the form of three current circuits or windings (Fig. 3), one of which is located on the stator (excitation winding (EW)) and is connected to the fixed coordinate system OXYZ, and the other two (control windings OУX and OУZ along the axes OX_1 and OZ_1, respectively) are located on the rotor, connected to the moving coordinate system $OX_1Y_1Z_1$ and have the ability to turn relative to the stator. Both coordinate systems have a common origin, which is located at the intersection of the electrical axes of all three windings and coincides with the center of the gimbal.

By its structure, 2-DOF electric machine is a slotless magnetoelectric motor with possibility of rotor rotation in a limited angular range around two mutually perpendicular axes. To obtain the equations of moments and the electrical balance of the motor, it is necessary to make some assumptions, which will allow describing the electrodynamic state of the machine without taking into account the influence of secondary factors. The generally accepted assumptions in the theory of electrical machines, as well as the assumptions associated with the specifics of the movement of the rotor along two angular coordinates, are:

- lack of saturation of the magnetic circuit, which ensures a proportional dependence of all flux links and EMF from the corresponding currents in the windings;
- the current flowing in the windings remains unchanged throughout their entire length, and therefore, to describe the energy of the electromagnetic field, one can use the lumped parameters of the circuit - active and inductive resistances;
- we will consider 2-DOF electric machine with a two-pole stator and carry out calculations for the first harmonic;
- the use of high coercivity magnets in the excitation system determines the constancy of its magnetic characteristics when the external magnetic field of the rotor windings varies, associated with changes in the currents flowing in them or their spatial position;
- since the physical model of the machine (Fig.1a) does not contain ferromagnetic elements and the magnetic axes of the control windings $ОУ_X$ and $ОУ_Z$ are mutually perpendicular, their mutual inductances are equal to zero;
- The rotor turns center is located at the intersection of the electric axes of all three coils (Fig. 3), which is ensured by the proper execution of the gimbal cardan suspension;
- the center of mass of the rotor coincides with the center of the gimbal and its position remains unchanged when the rotor tilts.

The last point is especially important when placing 2-DOF electric machine on moving objects experiencing multidirectional accelerations. The displacement of the center of mass relative to the center of rotation of the rotor leads to the appearance of a static unbalance of the rotor, which causes an additional load moment. Its direction depends on the trajectory of the object, and the value depends on the overload affecting the object of the installation of the 2-DOF machine. Information about the magnitude and direction of this disturbance can be obtained from acceleration sensors, which in this case must be installed on the object. After processing the signals from the sensors, the motor control system will be able to generate an electromagnetic moment that compensates for the disturbance that has arisen. This is possible only in the case when the parasitic moment does not exceed the moment capabilities of the 2-DOF electric machine. Therefore, in devices with several degrees of rotation, the fulfillment of the requirement to combine the center of mass with the center of suspension is mandatory and is achieved using the methods of static and dynamic balancing of the rotor with the payload.

Thus, 2-DOF electric machine is an electromechanical system, the rotor of which can make a turn around two mutually orthogonal axes. The model of such an electromechanical converter can be considered in the form of interconnected mechanical and electrical parts. The mechanical part is represented by a rotating rotor, the position of which is determined by its geometric coordinates X, Y and Z and the rotation angles α and β. The electrical part is described by currents in the windings i_X, i_Z and i_O. The currents in the windings, as already noted in the assumptions made, are not interconnected and, therefore, do not depend on each other. Thus, the coordinates chosen for consideration are independent, and the electromechanical system is holonomic, which makes it possible to use the Euler-Lagrange equation for its description.

The model of the dynamic state of the 2-DOF electric machine, in which the excitation winding is located on the rotor, and not on the stator, as in our case, was obtained in the monograph [9]. Since the electrodynamic processes occurring in the machine are identical in both cases, we will use these results to compile a mathematical model of the considered drive of the scanning device.

Mathematical model of 2-DOF electric machine and research results. Taking into account the accepted assumptions, the 2-DOF electric machine mathematical model has the form [9]

$$\left(J_X \cos^2 \beta + J_Y \sin^2\right)\frac{d\omega_\alpha}{dt} = M_Z - M_{JX} - M_{\omega\alpha} - M_{L\alpha}; \tag{1}$$

$$M_Z = i_Z k_{mZ} \cos\alpha \cos\beta; \; M_{JX} = 2\omega_\alpha \omega_\beta \left(J_Y - J_X\right)\sin\beta \cos\beta; \tag{2, 3}$$

$$M_{\omega\alpha} = k_\alpha \omega_\alpha; \; M_{L\alpha} = M_B sign\left(\omega_\alpha\right); \tag{4, 5}$$

$$J_Z \frac{d\omega_\beta}{dt} = M_X + M_{JZ} - M_{XZ} - M_{\omega\beta} - M_{L\beta}; \tag{6}$$

$$M_X = i_X k_{mX} \cos\beta; \; M_{JZ} = \omega_\alpha^2 \left(J_Y - J_X\right)\sin\beta \cos\beta; \tag{7, 8}$$

$$M_{XZ} = i_Z k_{mZ} \sin\alpha \sin\beta; \; M_{\omega\beta} = k_\omega \omega_\beta; \; M_{L\beta} = M_B sign\left(\omega_\beta\right); \tag{9-11}$$

$$\frac{d\alpha}{dt} = \omega_\alpha; \; \frac{d\beta}{dt} = \omega_\beta; \tag{12, 13}$$

$$L_X \frac{di_X}{dt} = u_X - R_X i_X - k_{mX} \omega_\beta \cos\beta; \tag{14}$$

$$L_Z \frac{di_Z}{dt} = u_Z - R_Z i_Z - k_{mZ} \omega_\alpha \cos\alpha \cos\beta + k_{mZ} \omega_\beta \sin\alpha \cos\beta, \tag{15}$$

where ω_α, ω_β, α, β are the angular speeds and rotation angles of the rotor shaft around the Z and X axes; J_X, J_Z, J_Y are the axial moments of inertia of the rotor; M_Z, M_X - electromagnetic torques; M_{JX}, M_{JZ} are torques caused by the Coriolis forces; M_{XZ} is electromagnetic torque caused by the influence of the winding with current i_Z; $M_{\omega\alpha}$, $M_{\omega\beta}$ are torques of viscous friction; $M_{L\alpha}$, $M_{L\beta}$ are mechanical torques of resistance of bearings; i_X, i_Z, u_X, u_Z are the currents and voltages of the rotor windings corresponding to the X and Z axes; L_X, L_Z, R_X, R_Z are inductances and active resistances of the rotor windings, respectively, to the X and Z axes; k_{mX}, k_{mZ} are motor torque coefficients, respectively, for the X and Z axes; k_ω is coefficient of viscosity of the motor; M_B is the torque of resistance of the bearings. 2-DOF electric machine (Fig.1) has the following parameters: $J = J_X = J_Z = 5 \cdot 10^{-4}\ kgm^2$, $J_Y = 6{,}7 \cdot 10^{-4}\ kgm^2$, $L_X = 3{,}134 \cdot 10^{-4}\ Hn$, $L_Z = 1{,}658 \cdot 10^{-3}\ Hn$, $R_X = 0{,}96\ Ohm$, $R_Z = 3{,}03\ Ohm$, $k_{mX} = 0{,}0686\ Nm/A$, $k_{mZ} = 0{,}4606\ Nm/A$, $k_\omega = 2{,}7 \cdot 10^{-4}\ Nms/rad$, $M_B = 2 \cdot 10^{-4}\ Nm$.

To implement the line and frame trajectories of the movable rotor, we assume that the signal for setting the rotation angle α should change in accordance with the sinusoidal law

$$\alpha_R = \alpha_A \sin 2\pi f_\alpha t, \tag{16}$$

where α_A, f_α are the amplitude and frequency of the periodic change in the angle α.

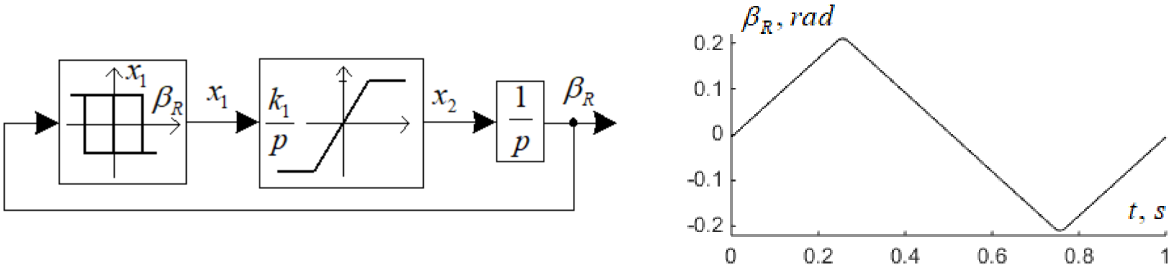
The rotation angle β must change from one extreme angular position to another with constant acceleration. At the same time, in the part of the trajectory, when the acceleration sign changes, in order to improve the energy characteristics of the operating mode, the second derivative of the motion trajectory should be limited. Fig. 4 a shows a block diagram of the generator of a triangular reference signal β_R.

The block diagram of the triangular signal generator is described by the equations and conditions

$$\frac{dx_2}{dt} = k_1 x_1; \text{ if } x_2 > A_1, \text{ then } x_2 = A_1; \text{ if } x_2 < -A_1, \text{ then } x_2 = -A_1; \tag{17-19}$$

$$\frac{d\beta_R}{dt} = x_2; \text{ if } \beta_R > A_2, \text{ then } x_1 = -1; \text{ if } \beta_R < -A_2, \text{ then } x_1 = 1, \tag{20-22}$$

where x_1, x_2 are variables; k_1 is gain of the integrating link; A_1 is the value at which the saturation of the integrating link occurs; A_2 is the value of the angular deviation of the rotor in the linear part of the signal β_R, at which the hysteresis loop relay controller switches.



a *b*

Fig. 4

Based on the given the frequency f_β and amplitude β_A of the triangular signal, as well as the relative duration γ of the linear part of the motion trajectory, it is possible to determine the parameters of the generator

$$A_1 = \frac{8\beta_A f_\beta}{1+\gamma}\,;\ k_1 = \frac{4A_1 f_\beta}{1-\gamma}\,;\ A_2 = \frac{\gamma A_1}{4 f_\beta}\,. \tag{23-25}$$

According to the conditions of the 2-DOF electric machine control problem, the following parameters of the trajectory for changing the rotation angle β are assumed: $f_\beta = 1$ Гц and $\beta_A = 12$ deg Fig. 4b shows a diagram of the generator output signal β_R at a frequency of 1 Hz with a relative duration of the linear working part $\gamma = 0{,}95$, which is defined as

$$\gamma = T_L f_\beta\,, \tag{26}$$

where T_L is the duration of the linear parts on one period of the triangular signal.

For the trajectory of changing the rotation angle α, the signal amplitude $\alpha_A = 1$ deg is assumed, and since the oscillation frequency f_α of the rotor is related to the effective value I_Z of the current in the stator winding, this paper assumes obtaining such a dependence.

To calculate the control system for the angular movements of the rotor, we use a linearized system of equations, which, subject to a limited angular range of rotation, can be obtained with such substitutions $\sin\alpha = \alpha$; $\sin\beta = \beta$; $\cos\alpha = 1$; $\cos\beta = 1$. In addition, we will assume that the insignificant torques M_{JX}, M_{JZ}, M_{XZ}, $M_{\omega\alpha}$, $M_{\omega\beta}$, $M_{L\alpha}$, $M_{L\beta}$ are signal disturbances, which can be ignored in the preliminary calculation of the controller parameters. Then we obtain the linearized equations

$$J\frac{d\omega_\alpha}{dt} = M_Z\,;\ J\frac{d\omega_\beta}{dt} = M_X\,;\ \frac{d\alpha}{dt} = \omega_\alpha\,;\ \frac{d\beta}{dt} = \omega_\beta\,; \tag{27-30}$$

$$L_X\frac{di_X}{dt} = u_X - R_X i_X - k_{mX}\omega_\beta\ ;L_Z\frac{di_Z}{dt} = u_Z - R_Z i_Z - k_{mZ}\omega_\alpha\ . \tag{31, 32}$$

In this case, the mathematical models for the two channels for controlling the rotation angles α and β are structurally identical. Therefore, we present a block diagram (Fig. 6) of the servo system for controlling the value α, taking into account the use of the proposed regulators of the current $W_{iZ}(p)$ and the rotor rotation angle $W_{C\alpha}(p)$, where $\Delta\alpha$ is the unbalance signal; i_{RZ} is output signal of the rotation angle regulator; e_Z is winding EMF; M_{DZ} is torque of disturbances; α_S is output signal of the rotation angle sensor. All further considerations will also be valid for the servo control system of the rotation angle β. When designing a servo system, we refuse to use an internal loop with angular speed feedback [10], since the use of a special angular speed sensor in a low-power electromechanical system is an unacceptable solution.

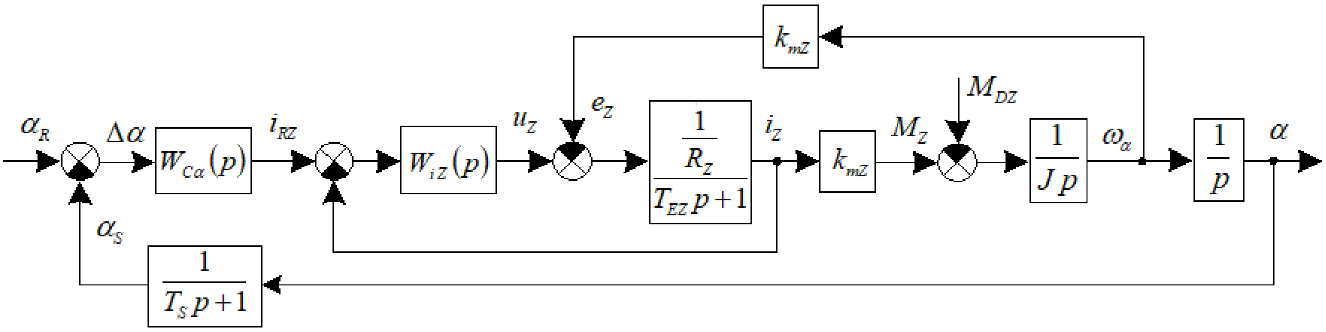


Fig. 5

Fig. 6 also shows the transfer function of the rotor angle sensor realized using the Hall sensor. For such a sensor, the passport value of the response time is 0.000003 s, so its transfer function with the output signal α_S was presented as a first-order aperiodic link with time constant $T_S = 0{,}000001\, s$.

To compensate for the electromagnetic time constant T_{EZ} of the winding, we introduce a current controller with a transfer function into the current control loop

$$W_{iZ}(p) = k_{CiZ}. \tag{33}$$

Without taking into account the influence of internal feedback on the EMF of the motor, we obtain the transfer function of the current circuit in the form

$$\frac{i_Z(p)}{i_{RZ}(p)} = \frac{k_{iZ}}{T_{iZ}p+1}, \tag{34}$$

where i_{RZ} is the current reference signal. The gain and time constant of the current loop are determined by the formulas.

$$k_{iZ} = \frac{k_{CiZ}}{R_Z + k_{CiZ}},\ T_{iZ} = \frac{L_Z}{R_Z + k_{CiZ}}. \tag{35, 36}$$

The purpose of using the current loop is to compensate for the electromagnetic time constant T_{EZ} of the winding, therefore, by setting the desired value T_{DZ} of the current loop time constant, it is possible to determine the value of the current controller gain k_{CiZ}

$$k_{CiZ} = \frac{L_Z - R_Z T_{DZ}}{T_{DZ}}, \tag{37}$$

and then the gain k_{iZ} of the compensated current loop (35). The use of a proportional controller in the current loop does not increase the order of the entire control system and, at the same time, allows to compensate to a large extent the influence of the EMF and the electromagnetic time constant of the winding.

Consideration of the structure (Fig. 6) and its parameters shows that the open-loop system contains two integrating links and two aperiodic links with relatively small time constants of the rotation angle sensor T_S and the compensated current loop T_{iZ}. In this case, to develop a servo control system, a proportional-differentiating controller should be used in the form

$$W_{C\alpha}(p) = \frac{i_{RZ}(p)}{\Delta\alpha(p)} = k_{C\alpha}\frac{T_{C\alpha}p+1}{T_{F\alpha}p+1}, \tag{38}$$

where $k_{C\alpha}$, $T_{C\alpha}$, $T_{F\alpha}$ are the gain and time constant of the PD controller, as well as the time constant of the filter of the non-ideal differentiating link.

Now we can write the transfer function of the open-loop servo system as

$$\frac{\alpha_S(p)}{\Delta\alpha(p)} = k_{C\alpha} k_{iZ} \frac{k_{mZ}}{J} \cdot \frac{T_{C\alpha} p + 1}{p^2 (T_{F\alpha} p + 1)(T_{iZ} p + 1)(T_S p + 1)}. \tag{39}$$

Let's use the approach to tuning the servo control system, which determines the relationship between the time constant $T_{C\alpha}$ of the PD controller and the sum of the time constants of the high-frequency part of the open-loop amplitude-frequency characteristic $T_{F\alpha}$, T_{iZ} and T_S. Developers try to make the last three time constants as small as possible, and their values are limited by the physical feasibility of measurement and control processes.

A convenient parameter that determines the ratio between the time constant $T_{C\alpha}$ and the sum $T_{F\alpha} + T_{iZ} + T_S$ of the time constants is the oscillation index M, which is equal to the ratio of the maximum value of the amplitude-frequency characteristic of a closed system to its initial ordinate [11, 12]. The system with transfer function (39) satisfies the relations

$$T_{C\alpha} \geq \frac{M}{\omega_C (M - 1)}; \; T_{F\alpha} + T_{iZ} + T_S \leq \frac{M}{\omega_C (M + 1)}; \; \omega_C = k_{OLZ} T_{C\alpha}, \tag{40-42}$$

where ω_C is the cut-off frequency; k_{OLZ} is open-loop system gain, which, based on (40-42), is determined as

$$k_{OLZ} = \frac{M(M - 1)}{(T_{F\alpha} + T_{iZ} + T_S)^2 (M + 1)^2}. \tag{43}$$

Next, you can define the parameters of the PD controller

$$T_{C\alpha} = \frac{(T_{F\alpha} + T_{iZ} + T_S)(M + 1)}{M - 1}; \; k_{C\alpha} = \frac{k_{OLZ} J}{k_{iZ} k_{mZ}}. \tag{44, 45}$$

Let us determine the parameters and conditions that are missing for research. The time constants of the high-frequency part of the amplitude-frequency characteristic of open-loop systems are assumed to be values $T_S = 0{,}000001\, s$, $T_{DZ} = 0{,}00001\, s$, $T_{FZ} = 0{,}00002\, s$, $T_{DX} = 0{,}00001\, s$, $T_{FX} = 0{,}0001\, s$. We also determine the ranges of variation of the oscillation index $1{,}025 < M < 1{,}4$, the relative duration $0{,}8 < \gamma < 0{,}975$ of the linear part of the triangular signal β_R, as well as the oscillation frequency f_α of the rotor along the angle α from 20 to 60 Hz. The value of the time constant T_{FZ} is chosen approximately three orders of magnitude less than the value of the signal period (16).

This paper did not set the purpose of achieving a predetermined accuracy of processing given trajectories. On the contrary, we are interested in the dependences of the effective values I_Z and I_X of the currents in the two control windings, as well as the modules of relative errors ε_α and ε_β of processing the angular displacements according to the rotation angles α and β depending on the parameters of the operating modes and the tunings of the regulators, which will allow us to evaluate the energy characteristics of the 2-DOF electric machine and the accuracy of its operation. All further calculations are made on the basis of equations (1-15).

To meet the requirements for the thermal state of the 2-DOF electric machine, it is necessary to determine the dependence of the current effective value I_Z on the frequency f_α of the periodic change in the angle α. Then it will be possible to determine the frequency values f_α at which a long-term operation of the machine is possible or a short-term operation in a forced mode. Since the frequency f_β of the triangular signal is predetermined and equal to 1 Hz, the current value I_X largely depends on the relative duration γ of the linear part of the triangular signal. Fig. 6 shows the dependencies $I_Z(f_\alpha)$, $I_X(f_\alpha)$ and $I_X(\gamma)$. These calculations were performed with the value of the oscillation index $M = 1{,}2$. The results of preliminary studies showed that the value M practically does not affect the effective values of the currents, therefore, based on the dependencies (Fig. 6), it is possible to choose acceptable values for the parameters of the machine operation mode f_α and γ. Obviously, the frequency f_α has practically no effect on the current effective value I_X. Note also that the parameter γ has no effect on the current effective value I_Z.

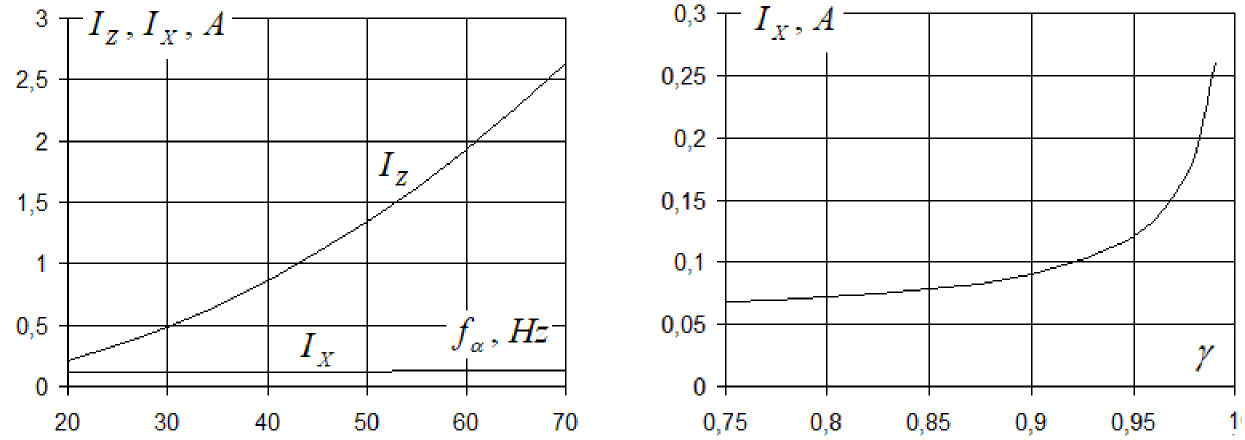


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Fig. 6

Based on the analysis of the research results (Fig. 6), it was determined that for a long-term machine operation mode, it is possible to choose a frequency value $f_\alpha = 40\ Hz$, and for a short-term forced mode, for example, 56 Hz or another frequency value depending on the duration of operation. For further research in the formation of a triangular signal, the value $\gamma = 0{,}95$ was chosen.

Further studies of the influence of the oscillation index M on the accuracy of processing a given trajectory of movement were carried out at $f_\alpha = 40\ Hz$ and $\gamma = 0{,}95$. Fig. 7 shows the dependences of the modules of relative errors ε_α and ε_β on the parameter M. The errors are determined on the interval of the linear part of the triangular signal according to the formulas

$$\varepsilon_\alpha = \frac{\max(\alpha)}{\alpha_A};\ \varepsilon_\beta = \frac{\max(\beta)}{\beta_A}. \qquad (46, 47)$$

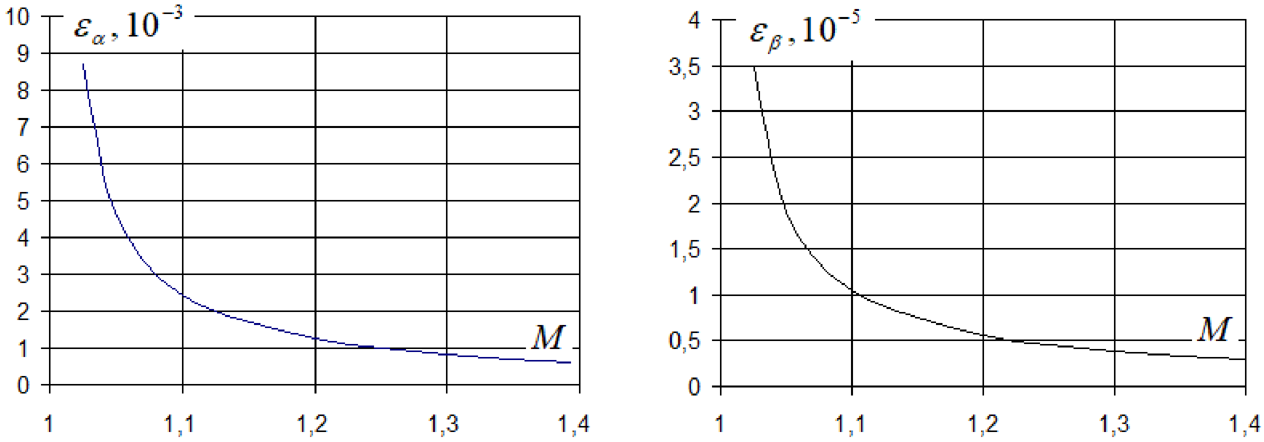

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Fig. 7

Thus, based on the dependencies (Fig. 7), it is possible to choose an acceptable accuracy of the rotor movement along a given trajectory. To illustrate the operation mode of the machine Fig. 8 shows the time dependences of the rotation angles α and β, rotor currents i_X and i_Z, as well as relative values of unbalance signals $\Delta\alpha^*$ and $\Delta\beta^*$, calculated at $f_\alpha = 40\ Hz$, $\gamma = 0{,}95$ and $M = 1{,}2$. The relative values $\Delta\alpha^*$ and $\Delta\beta^*$ are determined as

$$\Delta\alpha^* = \frac{\Delta\alpha}{\alpha_A};\ \Delta\beta^* = \frac{\Delta\beta}{\beta_A}. \qquad (48, 49)$$

Conclusions. The 2-DOF electric machine described in the paper is a structure with fixed permanent magnets and a magnetic circuit on the stator, as well as a rotor moving in a limited angular range with two unequal orthogonal winding systems. The absence of ferromagnetic elements on the rotor and the ability to control the rotor simultaneously in two angular coordinates makes it possible to achieve the minimum moment of inertia of the moving part of the motor and ensure the maximum speed of the drive. In addition, by redistributing the volume allocated for the placement of windings and their design, effective control is achieved of the energy-consuming mode of the high-frequency line trajectory along one angular coordinate and the relatively easy low-frequency mode of changing the second angle when moving along the frame trajectory.

The conducted studies of the operating modes of the 2-DOF control system for the machine rotor substantiate the possibility of implementing the line and frame trajectories of the beam. Based on the obtained dependences of the effective values of the currents and the modules of the accuracy of the processing the movement trajectories on the parameters of the operating modes and the settings of the controllers, it becomes possible to select the system parameters for operation in a long-term or forced short-term mode.

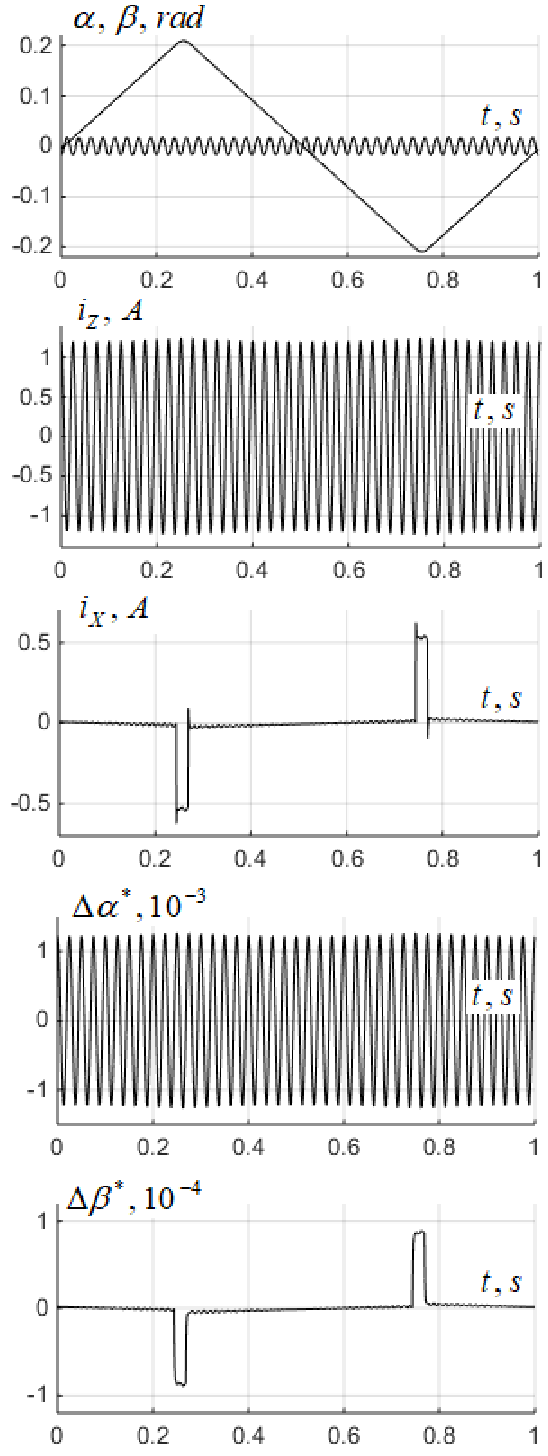

Fig. 8

Фінансується за держбюджетною темою «Розробити наукові засади та принципи побудови керованих n-степеневих магнітоелектричних систем з екстремальними характеристиками» (шифр «Екстремум»), що виконується за Постановою Бюро ВФТПЕ 29.05.2018 р., протокол № 9. Державний реєстраційний номер роботи 0119U001279. КПКВК 6541030.

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ДВОСТУПЕНЕВА ЕЛЕКТРИЧНА МАШИНА ТА РЕЖИМИ ЇЇ РОБОТИ

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Стаття присвячена проблемам розробки електричної машини з двома ступенями свободи руху ротора та системи керування нею. Розглянуто структуру машини з можливістю повороту ротора за двома кутовими координатами в обмеженому діапазоні кутів повороту. Машина призначена для управління положенням осі оптичного променю по лінійній і кадровій траєкторії. На підставі моделі електродинамічного стану машини розроблена структурна схема системи стеження для управління траєкторією руху ротора по двох координатах. Визначено співвідношення між сталою часу ПД-регулятора та сталими часу високочастотної частини амплітудно-частотної характеристики розімкнутої системи. Отримано залежності діючих значень струмів в обмотках управління від частоти кадрової траєкторії та тривалості лінійної ділянки трикутного сигналу. Отримано залежності модулів відносної точності руху ротора по заданій траєкторії від настройок системи. Обґрунтовано можливість реалізації лінійної та кадрової траєкторій руху у тривалому та форсованому режимі роботи двигуна. Бібл. 12, рис. 8.

Ключові слова: електрична машина з двома ступенями свободи, система керування, скануючий пристрій, лінійна траєкторія, траєкторія кадру.

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