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STUDY OF APPROACHES TO THE DEVELOPMENT OF A SCANNING DEVICE BASED ON A BRUSHLESS MAGNETOELECTRIC MOTOR OF RETURN-ROTARY MOTION

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The paper presents the results of studies of approaches to the development of a scanning device based on a specialized brushless magnetoelectric motor of return-rotary motion. The structures are described and a comparison is made of servo systems with motors both with an elastic magnetic coupling between the stator and the rotor, and without such coupling. The dependences of the accuracy of a given sawtooth signal processing and the stator current effective value on the parameters of the servo systems, the values of the coefficients of elasticity and viscosity of the motor, as well as the relative value of the duration of the linear interval of the reference sawtooth signal are determined. It is shown that the reduction of the stator current effective value is achieved by introducing an elastic magnetic coupling between the stator and the rotor, as well as limiting the second derivative when forming the process of resetting the reference sawtooth signal. References 8, figures 9, tables 3.
Keywords: brushless magnetoelectric motor, return-rotary motion, servo system, scanning device.

Introduction. Optical scanning devices or, as they are also called, deflectors, due to their ability to reflect and deflect a light beam, have found wide application in such areas of technology as medicine, instrumentation, information input-output devices in computer technology, search and tracking systems in space and military technology, robotics and other areas. In some of the first optical scanning devices, an electromechanical drive was used to control the position of the mirror, which at that time was an obvious and easily implemented solution [1]. Despite the fact that in some applications optical-mechanical devices have been replaced by scanners of other types with high speed, the electromechanical drive of mirrors remains in demand to this day. So, for example, in the case of controlling a high-energy beam, the decision to use mirrors to control its spatial position remains uncontested today. This is due to the fact that the mirror has minimal optical losses, works well in a wide range of radiation wavelengths - from ultraviolet to infrared, and the deflection angles of the light beam do not depend on the wavelength [2]. Therefore, the development of optical-mechanical scanning devices is still an urgent task, especially since the use of a magnetoelectric drive, realized using modern high-coercivity magnetic materials, significantly increases the speed of scanners, and in combination with modern electronics, allows you to implement a variety of trajectories of mirror.

The purpose of the paper is to study approaches to the development of a scanning device based on a specialized brushless magnetoelectric motor (BMM) of the return-rotary motion [3]. In [4], the results of studies of the operating modes of such a motor are presented by exposing its stator winding to an alternating voltage without using a rotor angular position sensor. This paper will consider the mode of forming the rotor return-rotary motion trajectory with a linear operating interval by realizing a closed-loop control system with feedback on the angular position of the rotor.

The reliability of the proposed research is substantiated by the fact that the adequacy of the mathematical description of the BMM of the return-rotary motion was confirmed experimentally in [5], and when developing the servo control system for the trajectory of the return-rotary motion, the principles of the theory of automatic control are used [6, 7]. General approaches to the development of systems for processing the input signal are known. This is, first of all, an increase in the astatism of the system, an increase in the value of the gain of an open-loop system, or the development of a combined system. When choosing the servo system controllers, we will proceed from the equations structure and parameters of the motor. Here we do not set the task of achieving any pre-specified one value of the accuracy of the angular trajectory processing. We

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will be interested in the dependence of the achievable values of this accuracy on the parameters of the controller and the motor.

The main material and research results. Let's define the operating conditions and principles for development of a scanning device:

– development of a servo system with feedback on the rotor shaft rotation angle;

– formation of a reference sawtooth signal of the rotor rotation angle with a linear operating interval at an oscillation frequency of 25 Hz in the range of the rotation angle of 10 degrees;

– the structure of the executive motor is brushless with a slotless single-phase stator with a surface installation of permanent magnets on the rotor, as well as with an additional permanent magnet on the stator to implement an elastic magnetic coupling between the stator and the rotor, which allows positioning the motor shaft in its initial position [4];

– to compensate for the electromagnetic time constant of the stator winding, an additional current circuit is formed;

– the main parameters of the servo system are the accuracy of a input sawtooth signal processing on the linear operating interval, the stator current effective value, which characterizes the thermal state of the motor, and the duration of the time interval of the linear part of the sawtooth signal.

In the paper, we will also compare the modes of processing the reference sawtooth signal of the rotor rotation angle in systems that use BMM with and without elastic magnetic coupling between the stator and rotor. When implementing the mode of return-rotary motion of the rotor in a limited angular range, the presence of an elastic magnetic coupling between the stator and the rotor provides some advantages. Firstly, the motor shaft is positioned in its initial position, and secondly, the accumulation of energy in the elastic element of the electromechanical system makes it possible in some cases to reduce the energy consumption of the motor. We will also consider servo systems for controlling the rotor angular position without using an internal loop with feedback on the angular speed [8], since the use of a special angular speed sensor in a low-power electromechanical system is unacceptable.

The structure of the BMM of the return-rotary motion is described in detail in [4]. The mathematical model of such a motor is described by the equations:

$$L\frac{di}{dt} = -Ri - e + u\,; \qquad e = k_m\,\omega\cos\alpha\,; \quad M = k_m\,i\cos\alpha\,; \quad M_\omega = k_\omega\,\omega\,; \quad M_\alpha = k_\alpha\sin\alpha\,; \qquad (1\text{-}5)$$

$$M_R = M_B\,sign(\omega)\,; \quad J\frac{d\omega}{dt} = \Delta M\,; \quad \Delta M = M - M_\omega - M_\alpha - M_R\,; \quad \frac{d\alpha}{dt} = \omega\,, \qquad (6\text{-}9)$$

where i, u are current and voltage of the stator; ω, α are angular speed and angle of rotation of the rotor shaft; ΔM is dynamic torque; M is electromagnetic torque of the motor; M_ω, M_α, M_R are the torques of viscous friction and elasticity, as well as the reactive torque of the bearings; L, R are inductance and active resistance of the stator winding; k_m is motor torque coefficient; J is the moment of inertia of the rotor; k_ω, k_α are coefficients of viscosity and elasticity of the motor; M_B is the torque of resistance of the bearings.

Since the operating range of the rotation angle is limited to 10 degrees, trigonometric dependencies in formulas (2, 3, 5) can be neglected. In this case, based on the mathematical model (1-9), taking into account the use of the proposed controllers of the stator current $W_{Ci}(p)$ and the rotor rotation angle $W_{C\alpha}(p)$, it is possible to develop a structure of the servo system, which is shown in Fig. 1.

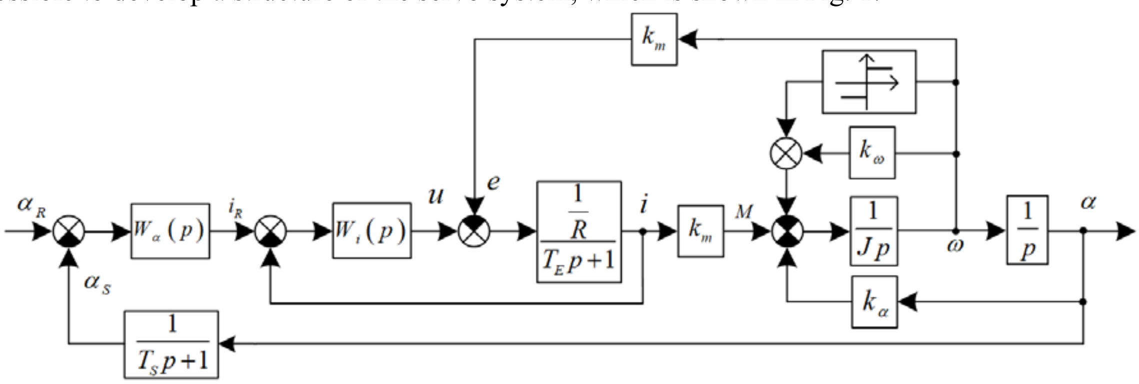


Fig. 1

From the consideration of the structure (Fig. 1), it can be seen that a link with an elasticity coefficient k_α forms an internal loop with feedback on the rotor position angle, while a link with a viscosity coefficient k_ω closing one of the integrating links makes it possible to form a structurally stable link of the second order. Neglecting the influence of the friction torque of the bearings, we write the transfer function of such a motor:

$$\frac{\alpha(p)}{i(p)}=\frac{k_m/k_\alpha}{\frac{J}{k_\alpha}p^2+\frac{k_\omega}{k_\alpha}p+1}. \tag{10}$$

Let us represent the denominator of the transfer function of the oscillatory link in the form $T_1^2p^2+2\xi_1T_1p+1$, where $T_1=\sqrt{J/k_\alpha}$ is the time constant; $\xi_1=0{,}5k_\omega/\sqrt{Jk_\alpha}$ is damping factor.

In the absence of an elastic magnetic coupling between the stator and the rotor, equation (5) is not used, that is, in the structure (Fig. 1) there will be no link with an elasticity coefficient k_α In this case, this structure contains an integrating link covered by feedback with a viscosity coefficient k_ω, with a transfer function:

$$\frac{\omega(p)}{\Delta M(p)}=\frac{1/k_\omega}{\frac{J}{k_\omega}p+1}. \tag{11}$$

For a system (Fig. 1) with an elastic magnetic coupling between the stator and the rotor, the value of the viscosity coefficient k_ω affects only the value of the damping coefficient ξ_1, which is not critical when tuning the rotor angle controller parameters. In the absence of elastic magnetic coupling, in the open-loop structure of the control object there is an aperiodic link (11), and its gain and time constant are determined by the value of the viscosity coefficient k_ω. Given that when designing the motor, the exact calculation of this coefficient or its experimental determination is difficult, the calculation of the rotation angle controller will not be accurate. A decrease in the value of viscous resistance in the BMM, caused by the presence of eddy currents during motor operation, is possible due to a decrease in the cross section of the winding conductors by connecting them in parallel, the use of tape and powder magnetic cores, and the use of amorphous iron in their pro-duction. The implementation of such approaches is an expensive and not always justified solution.

To compensate for the electromagnetic time constant T_E of the stator winding, we introduce a current controller with a transfer function into the stator current control loop:

$$W_i(p)=k_{Ci}. \tag{12}$$

Without taking into account the influence of the EMF feedback of the motor, we obtain the transfer function of the current loop in the form:

$$\frac{i(p)}{i_R(p)}=\frac{\frac{k_{Ci}}{R+k_{Ci}}}{\frac{RT_E}{R+k_{Ci}}p+1}=\frac{k_i}{T_ip+1}, \tag{13}$$

where i_R is the reference current signal; k_i, T_i are the gain and the time constant of the current loop.

Assuming, for example, the current controller gain $k_{Ci}=100$, we obtain $k_i=0{,}99$ and $T_i=T_E/100$, that is, the electromagnetic time constant of the current loop can be compensated. 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 you to largely compensate for the influence of the stator EMF *e*.

The basic values of the parameters of the motor are as follows: $R=25\,\text{Ohm}$, $k_m=0{,}125\,\text{N m/A}$, $k_\omega=6{,}5\cdot10^{-5}\,\text{N m s/rad}$, $J=3{,}6\cdot10^{-6}\,\text{kg m}^2$, $k_\alpha=0{,}044413\,\text{N m/rad}$, $M_B=2\cdot10^{-4}\,\text{N m}$. Features of determining the parameters of the return-rotary motion motor were described in [5]. To study the influence of the elasticity coefficient on the performance indexes of the servo system, we set the minimum and maximum values of the range of change of this parameter $k_{\alpha\min}=0{,}011103\,\text{N m/rad}$ and $k_{\alpha\max}=0{,}177653\,\text{N m/rad}$. Let us write down the values of the time constants and the damping coefficient of the dynamic links of the system. For three given values of the elasticity coefficient $k_{\alpha\min}$, k_α and $k_{\alpha\max}$ for the above value of the viscosity coefficient k_ω, we have $T_{1\min}=0,018063\,\text{s}$, $T_1=0,0090032\,\text{s}$, $T_{1\max}=0,0045016\,\text{s}$, $\xi_{1\min}=0,3251$, $\xi_1=0,0813$ and $\xi_{1\max}=0,0406$, respectively, and for the time constant of the corrected current loop (13) – $T_i=0,000003\,\text{s}$.

Fig. 1 also shows the transfer function of the rotor position angle sensor, realize using a Hall sensor. For the sensor used in the BMD, the passport value of the response time is 0.000003 s, so its transfer function can be approximately represented as a first-order aperiodic link with time constant $T_S=0,000001\,\text{s}$:

$$\frac{\alpha_S(p)}{\alpha(p)}=\frac{1}{T_S p+1}. \tag{14}$$

where α_s is the output signal of the sensor.

Analysis of formulas (10, 13, 14), taking into account the values of the motor parameters, shows that the control object contains a low-frequency oscillatory link, the time constant T_1 of which is much greater than the time constants of the current loop T_i and the rotation angle sensor T_S, i.e. $T_1 >> T_i > T_S$.

Neglecting the effect of internal EMF feedback, based on the above, we write the transfer function of the control object in the presence of an elastic coupling between the stator and the rotor:

$$\frac{\alpha_S(p)}{i_R(p)}=k_i\frac{k_m}{k_\alpha}\cdot\frac{1}{\left(T_1^2p^2+2\xi_1T_1p+1\right)\left(T_ip+1\right)\left(T_Sp+1\right)}, \tag{15}$$

as well as without elastic coupling and in the absence of a torque of viscous friction:

$$\frac{\alpha_S(p)}{i_R(p)}=k_i\frac{k_m}{J}\cdot\frac{1}{p^2\left(T_ip+1\right)\left(T_Sp+1\right)}. \tag{16}$$

For the first variant of development of the servo system with a control object (15), we use the PID controller of the rotor rotation angle in the form:

$$W_{\alpha1}(p)=\frac{i_R(p)}{\Delta\alpha(p)}=k_{C\alpha2}\left(\frac{A_1p}{T_Fp+1}+A_2+\frac{1}{p}\right)=k_{C\alpha2}\frac{T_2^2p^2+2\xi_2T_2p+1}{T_Fp+1}, \tag{17}$$

where $k_{C\alpha2}$, T_2, ξ_2 are the gain, time constant and damping factor of the PID controller; T_F is the time constant of the filter of the real differentiating link; $A_1=T_2^2-\left(2\xi_2T_2-T_F\right)T_F$, $A_2=2\xi_2T_2-T_F$ are PID controller gains.

For this case, we write the transfer function of an open-loop servo system for controlling the rotor rotation angle:

$$\frac{\alpha_S(p)}{\Delta\alpha(p)}=k_{C\alpha2}k_i\frac{k_m}{k_\alpha}\cdot\frac{T_2^2p^2+2\xi_2T_2p+1}{p\left(T_1^2p^2+2\xi_1T_1p+1\right)\left(T_Fp+1\right)\left(T_ip+1\right)\left(T_Sp+1\right)}. \tag{18}$$

The condition for tuning the parameters of the PID controller is the equality of the denominator of the control object (15) and the numerator of the controller (17):

$$T_1^2p^2+2\xi_1T_1p+1=T_2^2p^2+2\xi_2T_2+1. \tag{19}$$

In this case, the transfer function of an open-loop servo system has the form:

$$\frac{\alpha_S(p)}{\Delta\alpha(p)}=k_{C\alpha2}k_i\frac{k_m}{k_\alpha}\cdot\frac{1}{p\left(T_Fp+1\right)\left(T_ip+1\right)\left(T_Sp+1\right)}. \tag{20}$$

The fulfillment of condition (19) makes it possible to compensate for the inertia of the control object in the form of a second-order oscillatory link (15). Then the only adjustable parameter of such a control system is the open-loop system gain:

$$k_1=k_{C\alpha2}k_ik_m/k_\alpha. \tag{21}$$

The value of this gain coefficient is chosen according to the conditions for ensuring the stability margin of the servo control system.

Let us study the dynamics of the servo system for two values of the time constant of the filter of the real differentiating link of the PID controller: $T_{F1}=0,00001\,\text{s}$ and $T_{F2}=0,0001\,\text{s}$. When comparing the time constant values of the current circuit T_i, the angle of rotation sensor T_S and the filter T_F of the real differentiating link, it can be seen that the latter value T_F is the largest among the time constants of the dynamic links in the high-frequency part of the amplitude-frequency characteristic of an open-loop system, i.e. $T_F > T_i > T_S$. Then for the transfer function of an open-loop system (20), the value of its gain k_1 can be approximately determined by the formula:

$$k_1 = \omega_C , \qquad (22)$$

where ω_c is the cut-off frequency. Formula (22) is valid under the condition $\omega_C \le \omega_F = 1/T_F$, since at frequency ω_F the slope of the logarithmic amplitude-frequency characteristic changes.

For the second variant for development of the servo system with a control object (16), we use a PD controller in the form:

$$W_{\alpha 2}(p) = \frac{i_R(p)}{\Delta\alpha(p)} = k_{C\alpha 3}\left(\frac{T_D p}{T_F p + 1} + 1\right) = k_{C\alpha 3}\frac{T_3 p + 1}{T_F p + 1}, \qquad (23)$$

where $k_{C\alpha 3}$ is the gain of the PD controller; T_D is the gain of the differentiating link; $T_3 = T_D + T_F$ is the time constant of the PD controller.

For this case, we obtain the transfer function of an open-loop servo system in the form:

$$\frac{\alpha_S(p)}{\Delta\alpha(p)} = k_{C\alpha 3} k_i \frac{k_m}{J}\cdot\frac{T_3 p + 1}{p^2 (T_F p + 1)(T_i p + 1)(T_S p + 1)} . \qquad (24)$$

Recommendations for tuning the controller for this case are given in [7], and their essence is to ensure the stability margin of the system by choosing the ratio between the time constant T_3 of the PD controller and the time constants of the high-frequency part of the amplitude-frequency characteristic of the open-loop system T_F, T_i and T_S, and also choosing the value of the cut-off frequency under the condition:

$$1/T_3 < \omega_C \le \omega_F = 1/T_F < 1/T_i < 1/T_S . \qquad (25)$$

In this case, the gain k_2 of the open-loop servo system (24), depending on the cut-off frequency ω_c and the time constant T_3 of the PD controller, is determined by the formula:

$$k_2 = k_{C\alpha 3} k_i \frac{k_m}{J} = \frac{\omega_C}{T_3} = \frac{1}{n\, T_3\, T_F} , \qquad (26)$$

where n is a dimensionless parameter, the value of which shows how much the cut-off frequency of an open-loop system is less than the frequency ω_F.

Another task in development of the scanning device based on an executive electric motor is the formation of a reference sawtooth signal, which has a linear and reset intervals. Preliminary studies have shown that special requirements are imposed on the time interval for resetting such a signal. Therefore, it was proposed to form a sawtooth signal under the condition of limiting the second derivative on the reset interval. Fig. 2 shows a block diagram of the sawtooth signal generator.

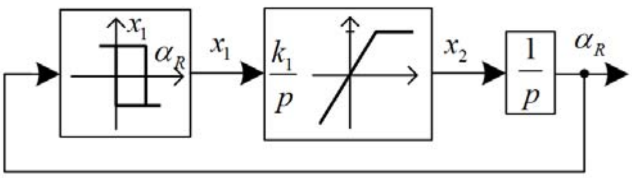


Fig.2¶

The block diagram of the sawtooth signal generator is described by the equations:

$$k_3 \frac{dx_2}{dt} = x_1 ; \qquad \text{if } x_2 > A_3 , \quad \text{then } x_2 = A_3 ; \qquad \frac{d\alpha_R}{dt} = x_2 ; \qquad (28\text{-}30)$$

$$\text{if } \alpha_R > \alpha_{\max} , \quad \text{then } x_1 = -1 ; \qquad \text{if } \alpha_R < 0 , \text{ then } x_1 = 1 , \qquad (31, 32)$$

where x_1, x_2 are variables; k_3 is gain of the integrating link; A_3 is the value at which the saturation of the integrating link (28) occurs; $\alpha_{\max}$ is the maximum value of the angular deviation of the rotor in the linear interval of the sawtooth signal relative to its neutral position. In this paper, the value $\alpha_{\max} = \pi/18 = 0{,}174533$ rad is taken.

Fig. 3 shows diagrams of signals at a frequency of 25 Hz with a relative duration of the linear operation interval $\tau = 0{,}8$, and the relative duration τ of the linear interval is defined as

$$\tau = T_L / T , \qquad (33)$$

where T_L, T are the duration of the linear interval and the period of the sawtooth signal.

Analysis of curves in fig. 3 showed that in order to obtain formulas for calculating a sawtooth signal, it is sufficient to consider one, for example, a positive half-wave, which must be divided into three time intervals. In table 1 for three time intervals, their durations are determined, signals $x_2(t)$ and $\alpha_R(t)$ are described, values B_n are obtained that the variable $\alpha_R(t)$ reaches at the end of each of the three time intervals, where T_1 is the duration of half of the linear interval of the sawtooth signal; T_2 is time interval from the completion of the linear section to the maximum value of the sawtooth signal; T_3 is the time interval at which the sawtooth signal is reset from the maximum value to zero. In this case, the condition $2(T_1+T_2+T_3)=T$ must be fulfilled.

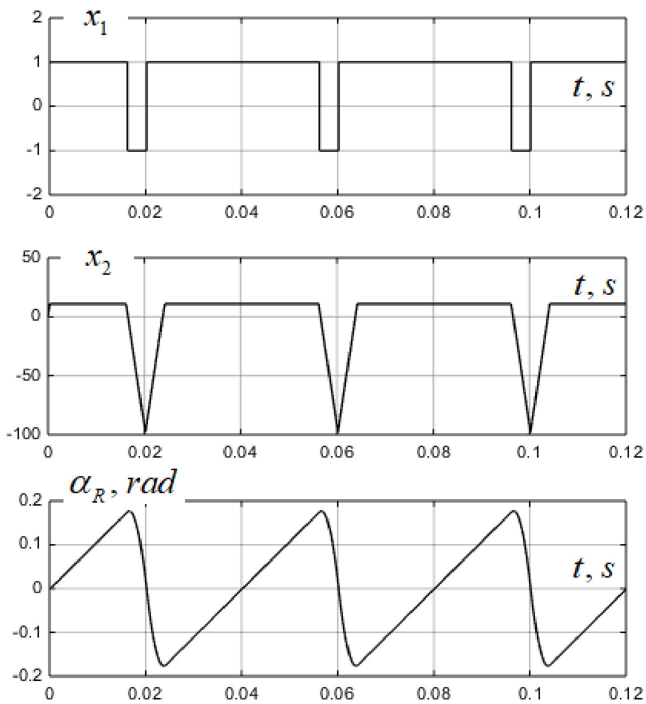


Fig. 3

Note that for three values of the parameter B_n, we can write the relation:

$$B_1+B_2=B_3\,, \tag{34}$$

whence after substitutions we get:

$$A_3T_1+0,5A_3(T_2-T_1)=0,5A_3(T_3-T_2)^2/(T_2-T_1)\,. \tag{35}$$

From this relation, we determine the values A_3 and k_3:

$$A_3=\frac{\alpha_{\max}}{T_1};\; k_3=\frac{\alpha_{\max}T}{T_1(0,5T-T_1)^2}\,. \tag{36, 37}$$

Table 1

№	time interval	$x_2(t)$	$\alpha_R(t)$	B_n
1	$0<t<T_1$	A_3	A_3t	A_3T_1
2	$T_1<t<T_2$	$A_3-A_3t\cdot(T_2-T_1)^{-1}$	$A_3t-A_3t^2\cdot 0,5(T_2-T_1)^{-1}$	$0,5A_3(T_2-T_1)$
3	$T_2<t<T_3$	$-A_3t\cdot(T_2-T_1)^{-1}$	$-A_3t^2\cdot 0,5(T_2-T_1)$	$-0,5A_3\cdot(T_3-T_2)^2\cdot(T_2-T_1)$

Table. 2 shows the parameters that describe the sawtooth signal at a frequency of 25 Hz and different relative values of the length of the linear interval.

Table 2

τ	T_1	A_3	k_3
0,9	0,018	9,69626	96962,6
0,85	0,017	10,26663	45629,5
0,8	0,016	10,9083	27270,75
0,75	0,015	11,63552	18616,83
0,7	0,014	12,46663	13851,81

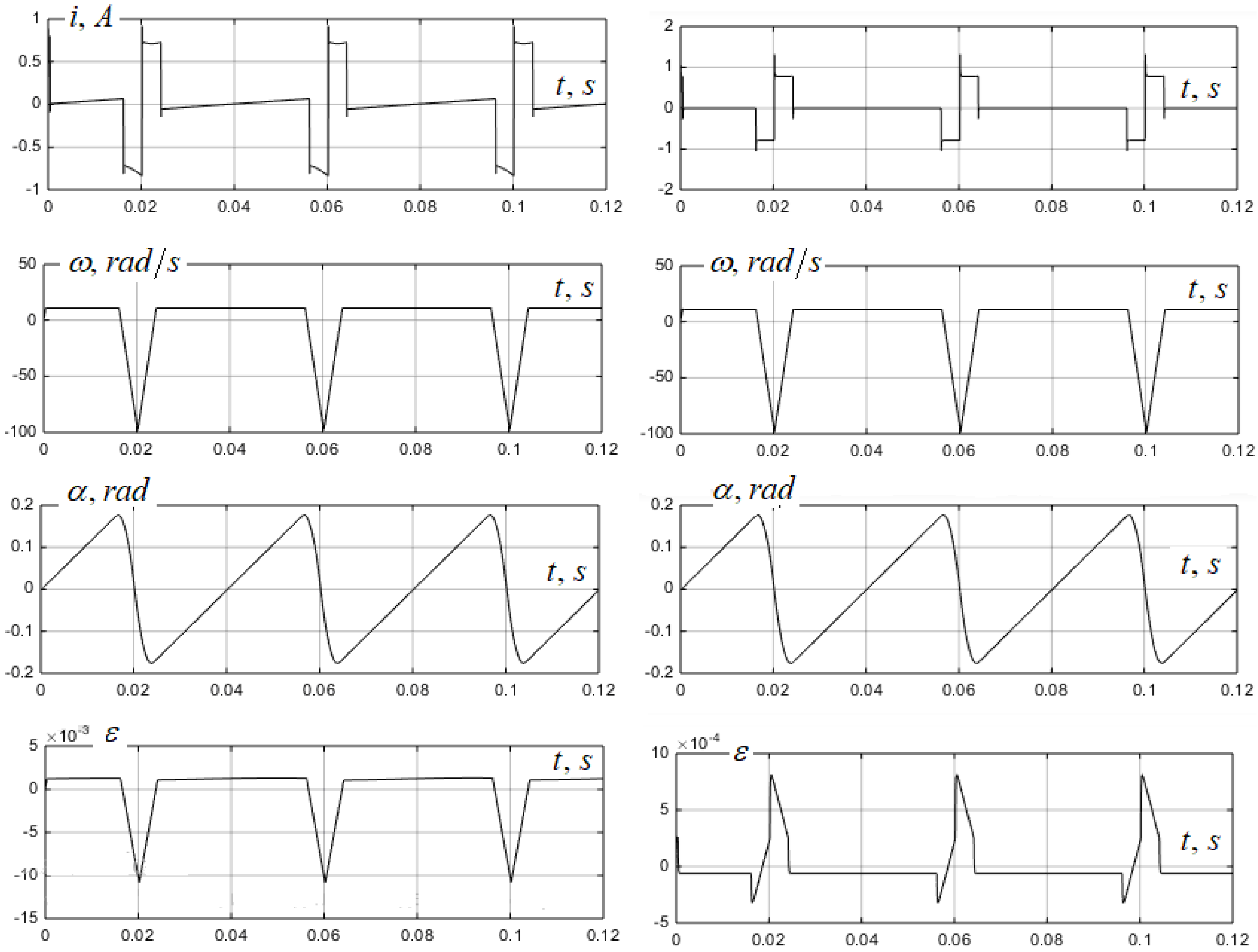
Fig. 4, *a* shows the timing diagrams of variable signals that describe the operation mode of the servo system with an elastic coupling between the stator and the rotor for the system parameter variants at $k_\alpha=0,044413$ N m/rad, $T_F=0,00001$ s and $k_1=50000$, that is, at $\omega_C=1/2T_F$. Fig. 4 also shows graphs of changes in the relative error of reference sawtooth signal, which is defined as

$$\varepsilon=(\alpha-\alpha_R)/\alpha_{\max}\,. \tag{38}$$

Fig. 4, *b* shows the timing diagrams of the same variable signals, only for the servo system without an elastic coupling for the system parameters: $T_F=0,00001$ s, $T_3=0,0001$ s and $\omega_c=1/2T_F$.

Comparison of two calculation variants was carried out for the same values of the cut-off frequency ω_c of two open-loop systems. Already here we can make preliminary remarks on the nature of the processes in these two systems. In the first and second cases, we have servo systems with astatism of the first and second orders, respectively. Therefore, in the first case, a steady-state error *ε(t)* with a non-zero value is observed on the linear interval of the reference sawtooth signal. In a system with second-order astaticism, the steady-state value of this error is practically zero.

Noticeable is also the difference in the curves of the change in stator currents. In the first case, in the linear interval of the reference sawtooth signal, a linear change in the magnitude of the stator current is observed in proportion to the change of the resistance torque of the elastic coupling between the stator and the rotor. In the second case, the process of changing the current is determined only by the torque of resistance of the bearings, the value of which is relatively small. Due to the fact that in the first case there is a gradual accumulation of energy in the elastic system, and in the process of releasing the sawtooth voltage, this energy is consumed relatively quickly, a decrease in the consumed current is observed compared to the current in the BMM without an elastic coupling.



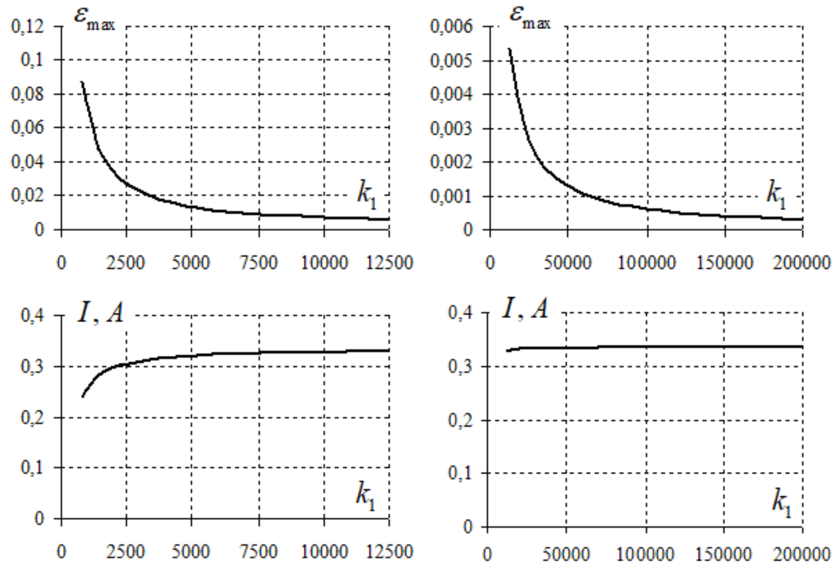
a ***b***

Fig. 4

The most important parameters that characterize the quality of the servo system operating in the return-rotary motion mode with a reference sawtooth signal are the maximum relative error ε_{max} in the linear interval of the sawtooth signal and the stator current effective value I. The maximum error ε_{max} in the operating interval T_L is determined by the formula:

$$\varepsilon_{max} = \left(\max\left[\alpha - \alpha_R\right]\right) / \alpha_{max} . \qquad (39)$$

First, we will study the first variant of the servo system with an elastic coupling between the stator and the rotor. Figures 5 and 6 shows the dependences of the maximum relative error $\varepsilon_{max}(k_1)$ and stator current $I(k_1)$ on the open-loop system gain, calculated with the elasticity coefficient $k_\alpha = 0,044413$ N m/rad and, respectively, for two values of the filter time constant of the real differentiating link $T_F = 0,00001$ s and $T_F = 0,0001$ s. Moreover, Fig. 5, *a* and 5, *b* shows these dependences for two sub-ranges of change in the open-loop system gain k_1.



a *b*

Fig. 5

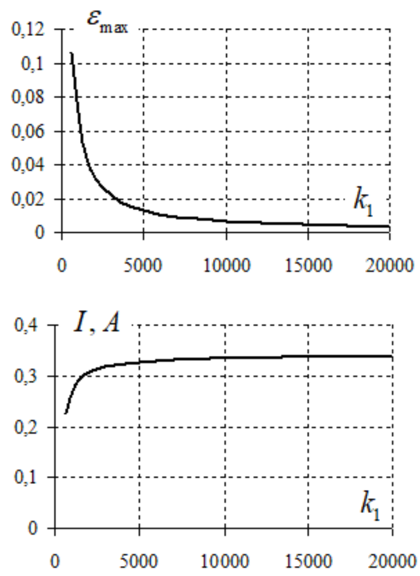


Fig. 6

Fig. 7 and 8 presents the results of a study of the influence of changes in the elasticity k_α and viscosity k_ω coefficients of the motor on the values of the maximum relative error $\varepsilon_{\max}$ and the stator current effective value I. Fig. 9 show the dependences of the maximum relative error $\varepsilon_{\max}$ and the effective value of the stator current I on the relative value τ of the duration of the linear interval of the sawtooth signal (33). These dependences were calculated for $T_F = 0{,}00001\,\text{s}$ and $k_1 = 6250$ as well as for the accepted basic values of the motor parameters, with the exception of the characteristics (Fig. 7 and 8), for each of which the value of one of the coefficients k_α or k_ω was changed, respectively.

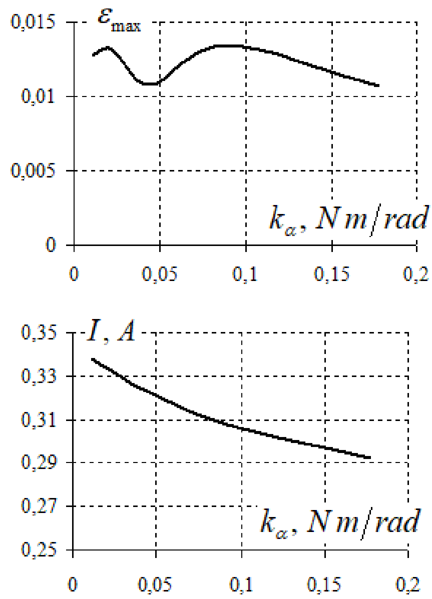


Fig. 7

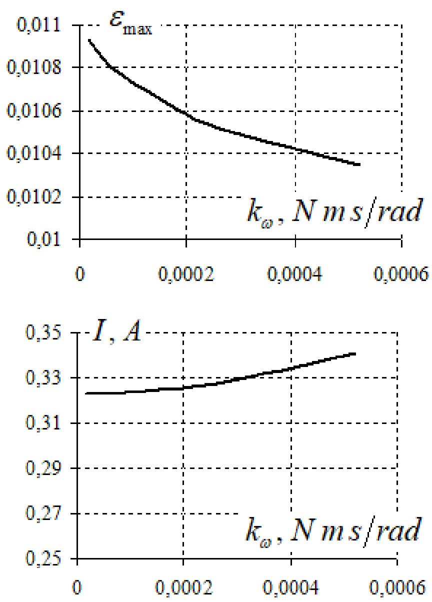


Fig. 8

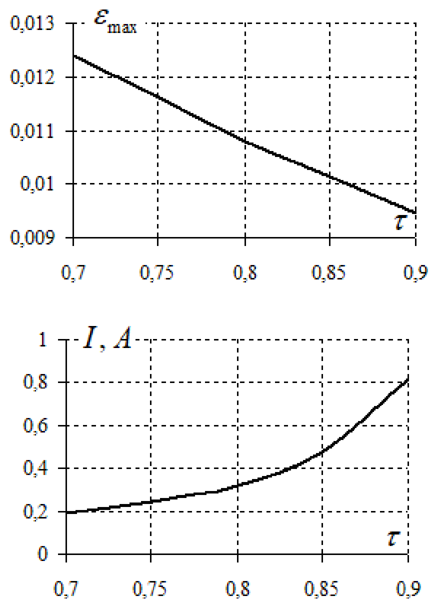


Fig. 9

Unlike the first variant, in a servo system without an elastic coupling between the stator and the rotor, when choosing the parameters of the PD controller, two parameters can be varied – the time constant T_3 of the controller and the cut-off frequency ω_C of the open-loop system, taking into account conditions (25) and (26). In the course of preliminary studies, it was noticed that with some settings of the regulators, processes were observed when the error curve $\varepsilon(t)$ did not reach its steady-state value. Therefore, the results of the research are presented in Table 3, which shows the parameters that determine the controller tuning T_3, T_F

and n, as well as the performance indexes ε_{max} and I, and in addition, the steady value ε_s of the error and the time t_C it takes to reach this steady value from the moment of the begin of the linear interval α_R (Fig. 3). In cases where the error signal $\varepsilon(t)$ has not reached a steady value, the column ε_s shows the value that the signal $\varepsilon(t)$ reached at the end of the linear interval. Dashes in the column t_C mean that the signal $\varepsilon(t)$ never reached its steady state value.

Table 3

T_3, s	T_F, s	n	ε_{max}	ε_S	I, A	t_C, s
0,0001	0,00001	1	0,000093	-0,000062	0,3537	0,00006
0,001			0,00145	-0,000058	0,3533	0,0028
0,01			0,00168	(0,000049)	0,3523	-
0,1			0,000808	(0,00064)	0,3519	-
0,0001		2	0,000254	-0,0000617	0,3541	0,00008
0,001			0,00298	-0,000054	0,3536	0,0035
0,01			0,00341	(0,000161)	0,3517	-
0,1			0,00166	(0,00138)	0,3511	-
0,0001		4	0,00057	-0,0000603	0,3555	0,0001
0,001			0,00604	-0,000045	0,3548	0,0042
0,01			0,00687	(0,000382)	0,3509	-
0,1			0,00336	(0,00283)	0,3497	-
0,0001		8	0,0012	-0,000059	0,3585	0,0014
0,001			0,0122	-0,000028	0,3572	0,0047
0,01			0,0137	(0,000828)	0,3495	-
0,1			0,00678	(0,00573)	0,3471	-
0,001	0,0001	1	0,0153	-0,000019	0,3661	0,00325
0,01			0,0182	(0,00104)	0,3551	-
0,1			0,0094	(0,00713)	0,352	-
0,001		2	0,031	0,0000238	0,3729	0,00353
0,01			0,0357	(0,00214)	0,3515	-
0,1			0,0178	(0,0144)	0,3454	-
0,001		4	0,0634	0,00011	0,387	0,0043
0,01			0,0693	(0,0043)	0,3435	-
0,1			0,0341	(0,00289)	0,3319	-
0,001		8	0,0149	0,000282	0,4242	0,0066
0,01			0,0132	(0,0085)	0,3229	-
0,1			0,0671	(0,058)	0,3031	-

Conclusions. The reliability of the studies is based on the fact that the adequacy of the mathematical description of the specialized BMM of the return-rotary motion was confirmed experimentally in [7], and also on the fact that in the development of a servo system, the principles of the automatic control theory were used. In particular, the electro-magnetic time constant of the stator winding was compensated by using a proportional controller and current feedback. The inertia of the oscillatory link of the second order of the control object was compensated with the help of a PID controller, which made it possible to obtain an astatic control system of the first order. In the absence of an elastic magnetic coupling between the stator and the rotor, a system with second-order astatism is realized.

The studies have confirmed the possibility of development of the scanning device based on a specialized BMD of return-rotary motion. It is shown that the most energy-consuming is the mode of resetting the sawtooth signal and transferring the rotor shaft from one extreme angular position to another. The formation of an elastic magnetic coupling between the stator and the rotor of the motor made it possible to reduce the stator current effective value by 10-15% or more compared to using a traditional BMM without such a coupling. This is explained by the fact that the energy in the elastic element of the electromechanical system accumulates gradually at a low value of the stator current in the linear interval of the sawtooth signal. The accumulated energy is consumed over a short time interval when the sawtooth signal is reset and the rotor position changes from positive values of the amplitude of the rotor position angle to negative. In addition, the limitation of the second derivative of the sawtooth signal at the reset interval contributes to the reduction of the stator current effective value.

The study of the influence of changes in the values of the coefficients of elasticity and viscosity of the motor, as well as the relative value of the duration of the linear interval of the sawtooth signal on the characteristics of the operating mode of the servo system showed that the stator current effective value is most susceptible to change, which allows to some extent to optimize the thermal state of the executive motor.

The dependences of the accuracy of processing the input sawtooth signal on the parameters of servo systems are determined. The possibilities for ensuring this accuracy are limited by the influence of the time constant T_F of the filter of the real differentiating link.

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ДОСЛІДЖЕННЯ ПІДХОДІВ ДО ПОБУДОВИ СКАНУЮЧОГО ПРИСТРОЮ НА ОСНОВІ БЕЗКОНТАКТНОГО МАГНІТОЕЛЕКТРИЧНОГО ДВИГУНА ЗВОРОТНО-ОБЕРТОВОГО РУХУ

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Наведено результати досліджень підходів до побудови скануючого пристрою на основі спеціалізованого безконтактного магнітоелектричного двигуна зворотно-обертального руху. Описано структури та проведено порівняння слідкуючих систем з двигунами як з пружним магнітним зв'язком між статором і ротором, так і без такого зв'язку. Визначено залежності точності відпрацювання заданого пилкоподібного сигналу і діючого значення струму статора від параметрів слідкуючих систем, значень коефіцієнтів пружності та в'язкості двигуна, а також відносної величини тривалості лінійної робочої ділянки пилкоподібного сигналу завдання. Показано, що зниження діючого значення струму статора досягається шляхом введення пружного магнітного зв'язку між статором і ротором, а також обмеження другої похідної при формуванні процесу скидання пилкоподібного сигналу завдання. Бібл. 8, рис. 9, табл. 3.
Ключові слова: безконтактний магнітоелектричний двигун, зворотно-обертовий рух, слідкуюча система, пристрій сканування.

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