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FREQUENCY CHARACTERISTICS OF BRUSHLESS MAGNETOELECTRIC MOTORS OF RETURN-ROTARY MOTION

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In this paper, the frequency characteristics of a special brushless magnetoelectric motor of return-rotary motion with sinusoidal and rectangular forms of the carrier signal are investigated. The method of generating a feedback signal on the amplitude of the rotor shaft oscillations angle has been improved by fixing the value of the signal at the moment of reaching its amplitude. The method of calculating the control system of the oscillations angle amplitude is investigated based on the frequency characteristics of the open-loop system by setting the phase stability margin. Examples of the calculation of transient processes of regulation of the oscillations angle amplitude and the effective value of the stator current when starting the motor and changing the mechanical load are given. Ref. 9, fig. 6, tables 2.
Keywords: brushless magnetoelectric motor, return-rotary motion, control system, carrier frequency, frequency characteristic.

Introduction. The development of specialized electromechanical systems of return-rotary motion (RRM) 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 condition.

The implementation of RRM systems can be based on different physical principles, for example, with the help of special mechanical transmissions [1, 2], controlled electric drives based on induction motors [3], or doubly-fed motors [4]. The use of such electric drives in combination with various electromagnetic, magnetoelectric, mechanical, or other motion transducers for the simultaneous regulation of the amplitude and frequency of oscillations of the motor output shaft is ineffective and difficult.

In this paper, we considered an electromechanical structure based on a special brushless magnetoelectric motor (BMM) without the use of any transmission mechanisms [5]. In this case, the actuating element of the device is installed directly on the motor shaft, so that it is possible to directly control the frequency and amplitude of its mechanical oscillations by changing the parameters of the current in the stator winding.

The purpose of the paper is to investigate the frequency characteristics of BMM when specifying a carrier periodic signal of an arbitrary form as a basis for the synthesis of the control system of the amplitude of rotor mechanical oscillations and the effective value of the stator current. This research is the development of the approach described in [6].

The main material and research results. In [6], the frequency characteristics of the BMM of RRM were investigated with a sinusoidal input action on the stator winding. Based on the obtained frequency characteristics, a system for controlling the parameters of the RRM was developed. At the same time, it is shown in [7] that the generation of a rectangular stator alternating voltage allows increasing the amplitude of the motor shaft oscillations angular speed. Therefore, it is of interest to consider the frequency characteristics of the BMM of RRM also with non-sinusoidal carrier signals.

The proposed BMM is an electromechanical structure consisting of a slotless stator with a single-phase winding, an external magnetic circuit, and an additional permanent magnet on the stator to implement the effect of a magnetic spring, as well as a rotor with a two-pole permanent

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magnet and an actuating element mounted on its shaft [5]. The mathematical model of such a motor is described by the equations [7]:

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

$$M = k_m\, i\cos\alpha\,; \quad (2)$$

$$M_\omega = k_\omega\,\omega\,; \quad (3)$$

$$M_\alpha = k_\alpha \sin\alpha\,; \quad (4)$$

$$M_R = M_B\, sign(\omega)\,; \quad (5)$$

$$M_L = k_L\,\omega\,; \quad (6)$$

$$J\frac{d\omega}{dt} = M - M_\omega - M_\alpha - M_R - M_L\,; \quad (7)$$

$$\frac{d\alpha}{dt} = \omega\,, \quad (8)$$

where ω, α are angular speed and angle oscillations of the rotor shaft; L, R are inductance and active resistance of the stator winding; 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.

The considered BMM of RRM is a system operating at a carrier frequency in the range up to 100 Hz. The input action is the alternating stator voltage of arbitrary form

$$u = U_A\, x_O(\omega_O t)\,, \quad (9)$$

where U_A is amplitude of the stator voltage; $x_O(\omega_O t)$ is carrier alternating signal of arbitrary form with unit amplitude; $\omega_O = 2\pi f_O$; f_O is carrier frequency; t is time.

The main output parameters of the system are the amplitude α_A of mechanical oscillations of the rotor and the effective value of the stator current I, the values of which are determined at each half-period of the carrier signal. The block diagram of a BMM with a voltage modulator, which operates at the carrier frequency f_O, is shown in fig. 1, where $\max(|\alpha|)$, $RMS(i)$ – are the procedures for determining the amplitude of the modulus of the rotor shaft angle α_A and the effective value of the stator current I at each half-period of the carrier alternating signal.

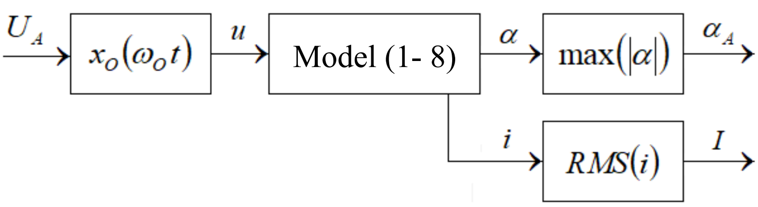


Fig. 1

In this research, we assume that the carrier alternating signal $x_O(\omega_O t)$ can have a sinusoidal or rectangular shape with a zero shelf. Then the stator voltage is described by two variants of the following

$$u = U_A \sin 2\pi f_O t\,; \quad (10)$$

$$u = 0{,}5\,U_A\left(sign\left(\sin 2\pi f_O t - 0{,}5\phi_1\right) + sign\left(\sin\left(2\pi f_O t + 0{,}5\phi_1\right)\right)\right). \quad (11)$$

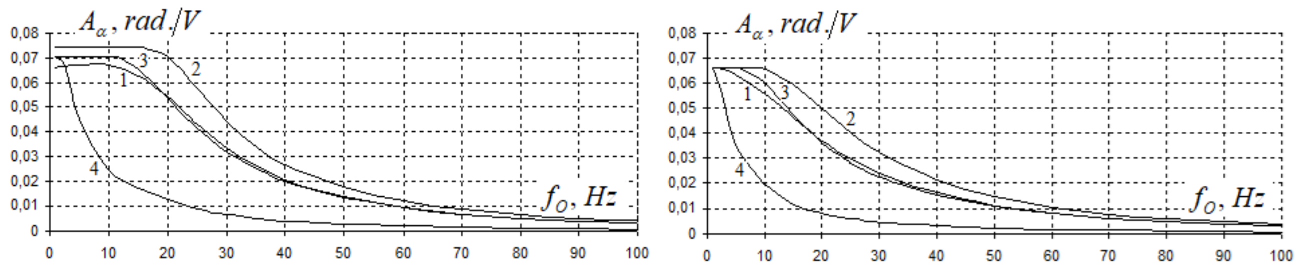
where ϕ_1 – angular length of the zero shelf of the rectangular form voltage.

Based on the structure (fig. 1), the frequency characteristics of the amplitude of the angle of motor shaft oscillations $A_\alpha(\omega)$ and the effective value of the stator current $A_I(\omega)$ can be obtained, which are determined as

$$A_\alpha(\omega) = \frac{\alpha_A}{U_A} \quad (12)$$

$$A_I(\omega) = \frac{I}{U_A}. \quad (13)$$

Figures 2 and 3 show graphs of frequency characteristics $A_\alpha(\omega)$ and $A_I(\omega)$ of BMM on no-load (*a*) and on load mode (*b*). Here and below, the numbers 1, 2, 3, and 4 denote, respectively, variants of the formation of input actions of the form (10) and (11) for three values of the parameter ϕ_1 – 0, 80, and 160 el. degrees. The calculations were performed for the system (1–8) with the following parameter values: $L = 0.012\ Hn$, $R = 40\ Ohm$, $k_m = 0.125\ N\,m/A$, $k_\omega = 6.5\cdot10^{-5}\ N\,m\,s/rad.$, $J = 2.4\cdot10^{-6}\ kg\,m^2$, $k_\alpha = 0.0448\ N\,m/rad.$, $M_B = 2\cdot10^{-4}\ N\,m$, $k_L = 2.1\cdot10^{-4}\ N\,m\,s/rad.$. A feature of the study is that the calculation of these characteristics is performed at the nominal values of the amplitude of the rotor oscillations $\alpha_{AO} = \pi/9\ rad.$ and the stator current effective value $I_O = 0.14\ A$.



a **Fig. 2** *b*

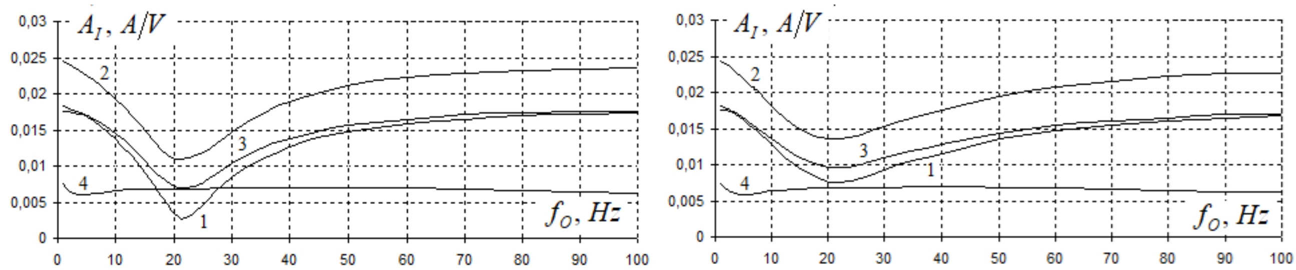


Fig. 3
a *b*

Concerning the determination of the phase-frequency characteristics of the system operating at the carrier frequency, the indicated main parameters of the RRM (α_A and I) are determined at each half-period of the carrier signal, and then are fixed and stored as feedback signals during the next half-periods, which determines the delay effect in the control loop. In [6], the study of the system (1–8) was carried out, which indicated that for an input amplitude-modulated signal of the form $U_A(t) = 1 + 0.5\sin\Omega t$ (where $\Omega = \frac{\omega_O}{n}$; $n > 2$ is the whole number), the phase shift of the output variable quantized signal $\alpha_A(t)$ concerning the input envelope $U_A(t)$ is approximately determined by

$$\phi_\alpha = \frac{\pi}{n}. \quad (14)$$

This does not take into account the effect of delay due to fixation and preservation of the signal value for half the period.

In [6], a method was considered for the synthesis of an RRM control system based on the amplitude and phase-frequency characteristics of the controller and BMM. The choice of the parameters of the regulator of the rotor oscillations angle amplitude can be carried out at a given value of the carrier frequency f_O based on the frequency characteristics under the condition of ensuring a given phase stability margin γ [8, 9], which is determined by

$$\gamma = \pi + \phi_\alpha(\omega_C) + \phi_C(\omega_C), \tag{15}$$

where $\phi_\alpha(\omega_C)$, $\phi_C(\omega_C)$ are values of the phase shifts of the BMM and controller signals at a given value of the cut-off frequency ω_C, the value of which is chosen less than the carrier frequency

$$\omega_C = \frac{\omega_O}{n}. \tag{16}$$

At given values of the phase stability margin γ and cut-off frequency ω_C, the parameters of the regulator with its known structure are determined under the condition that the amplitude-frequency characteristic of the open-loop system is equal to unity

$$A(\omega_C) = A_\alpha(\omega_O) A_C(\omega_C) = 1, \tag{17}$$

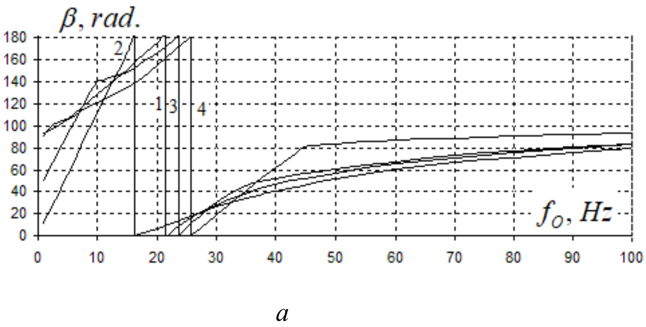
where $A_C(\omega)$ is the amplitude-frequency characteristic of the regulator.

Note that the amplitude-frequency characteristic $A_\alpha(\omega)$ of the BMM is determined by the value of the carrier frequency f_O (Fig. 2), while the phase-frequency characteristic $\phi_\alpha(\omega)$ depends on the value of the parameter n according to (14).

Considering that no special requirements are imposed on the dynamics of control by BMM, we will restrict ourselves to considering the I–controller, the amplification factor of which is determined by [6]

$$k_{C1} = \frac{\omega_C}{A_\alpha(\omega_O)} = \frac{\omega_O}{n\,A_\alpha(\omega_O)}. \tag{18}$$

Researches have shown that in the low-frequency range, the amplitude value α_A can be fixed at the moment of determining the oscillations angle amplitude, and not at the beginning of the next half-period of the carrier signal [6]. In this case, the value of the phase shift turns out to be somewhat less than the value determined by (14). Fig. 4 shows graphs of phase-frequency characteristics of BMM without load (*a*) and with load (*b*), obtained based on model (1–8) for the above-mentioned four variants of the carrier signal.



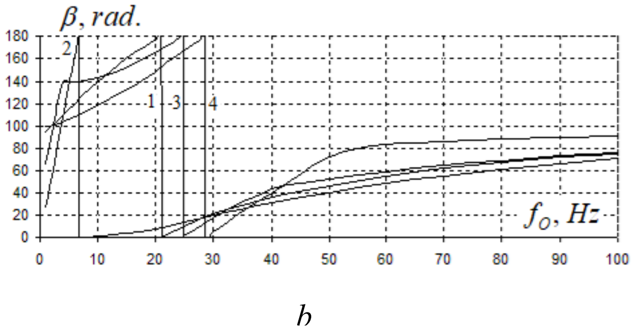


Fig. 4

As shown in fig. 4 parameter β determines the angular length of the interval from the beginning of the half-period of the variable $\sin 2\pi f_O t$ to the moment of fixing the amplitude of the rotation angle. In this case, the phase shift of the quantized signal $\alpha_A(t)$ relative to the input envelope $U_A(t)$ will be approximately determined by

$$\phi_\alpha = \frac{\beta}{n}. \qquad (19)$$

Then the amplification factor of the I–controller, taking into account (15), is determined by

$$k_{C2} = \frac{\omega_O\left(0,5\pi - \gamma\right)}{\beta\, A_\alpha\left(\omega_O\right)}. \qquad (20)$$

Note that using (20) is possible in the operating low–frequency range when the parameter β does not exceed 180 el. degrees.

Table 1 shows the calculating results of the amplification factor of the I–controller of the oscillation angle amplitude and the performance indexes of the transient responses of feedback signals $\alpha_A(t)$ of a closed-loop system, which consists of the controller and BMM (Fig. 1) with a step input signal $U_A(t)$, where t_P is control time determined by the time of reaching the output signal of a five percent zone of the steady-state value; σ is overshooting as a relative value of the maximum deviation of the output signal; N is the number of the variant of the formation of the carrier signal. Table 1 shows the characteristics of the 1st version of the system, defined by (16, 18), and the 2nd version, calculated following (19, 20). Based on the studies described in [6], we assume $n = 8$.

Table 1

N	BMM parameters			1st version			2nd version		
	f_O, Hz	$A_\alpha, rad/V$	β, rad	$k_{C1}, V/rad$	t_P, s	σ, %	$k_{C2}, V/rad$	t_P, s	σ, %
1	5	0.0668	106.8	58.76	0.4597	0.0819	99.00	0.2611	0.0708
	10	0.0668	128.6	117.5	0.2359	0.3275	164.5	0.1859	0.6212
	20	0.0539	174.2	291.3	0.1242	0.5372	301.0	0.1242	0.5482
2	5	0.0741	55.86	52.97	0.5311	0.5849	180.0	0.2315	6.861
	10	0.0741	111.5	105.9	0.2316	0.7311	171.0	0.1332	2.516
3	5	0.0705	94.16	54.06	0.4528	0.2730	106.4	0.2534	1.573
	10	0.0707	141.1	111.0	0.2392	0.0407	141.6	0.1893	0.0296
	20	0.0534	166.0	295.1	0.1230	0.6347	318.8	0.1230	0.5763
4	5	0.0448	106.9	87.81	0.4594	0.4432	147.6	0.2593	0.1043
	10	0.0244	121.0	324.4	0.2336	0.6461	478.7	0.1836	0.4797

Analysis of the research results confirms the possibility of calculating the I–controller based on the frequency characteristics of the BMM with non–sinusoidal input signals. The appearance of overshooting in the 2nd version is explained by the deviation of the parameter value β from the calculated value in the dynamic mode.

Fig. 5 shows the graphs of transient responses for the first and second versions of the formation of feedback signals of the rotor oscillations angle amplitude $\alpha_A(t)$ when the BMD is switched on with a step input signal. The calculation performs at 5 Hz for four variants of the carrier signal, respectively *a* = 1.1, *b* = 1.2, *c* = 2.1, *d* = 2.2, *e* = 3.1, *f* = 3.2, *g* = 4.1, *h* = 4.2 (first and second numbers mark the formation variant of the carrier signal and the version of the feedback signal formation, respectively). The obtained graphs demonstrate the effect of improving the dynamics of the regulation when using the second method of forming feedback. The positive effect is manifested to the greatest extent precisely in the low–frequency part of the BMM operation range.

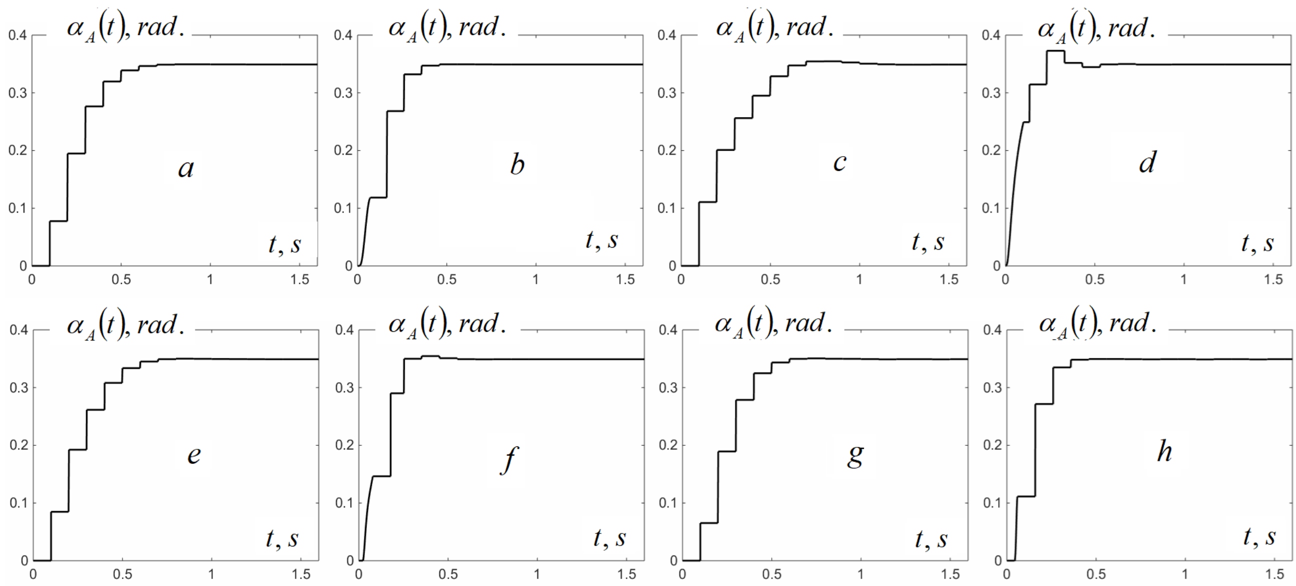


Fig. 5

Based on the BMM model (1–8) and the model of the control system given in [6], the transient responses of regulation of the rotor oscillations angle amplitude α_A and limitation of the current effective value I at a carrier frequency of 40 Hz in the modes of motor start and changing load were calculated. In this case, the amplification factor and the filter time constant in the current limiting loop in the high–frequency part of the operating range are determined based on the frequency characteristics (fig. 3)

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

$$T_F = \frac{20}{f_O}, \quad (22)$$

where ε is relative accuracy of limitation of the effective current value; I_O is the task value at which the stator current starts to be limited; $U_{\max}$ is the maximum value of the output signal of the angle amplitude regulator. Table 2 shows the main parameters of the control system at $\varepsilon = 0.01$.

Table 2

N	$k_{P1}, V/rad$	$U_{\max}, V$	$k_F, V/A$
1	709.3	15.0	2761
2	534.0	10.0	1855
3	752.4	12.5	2104
4	457.3	24.5	3071

Fig. 6 shows the graphs of the transient responses of feedback signals of the angle amplitude $\alpha_A(t)$ (first version) and the stator current effective value $I(t)$ for four variants of the formation of the carrier signal, respectively $a = 1$, $b = 2$, $c = 3$, $d = 4$.

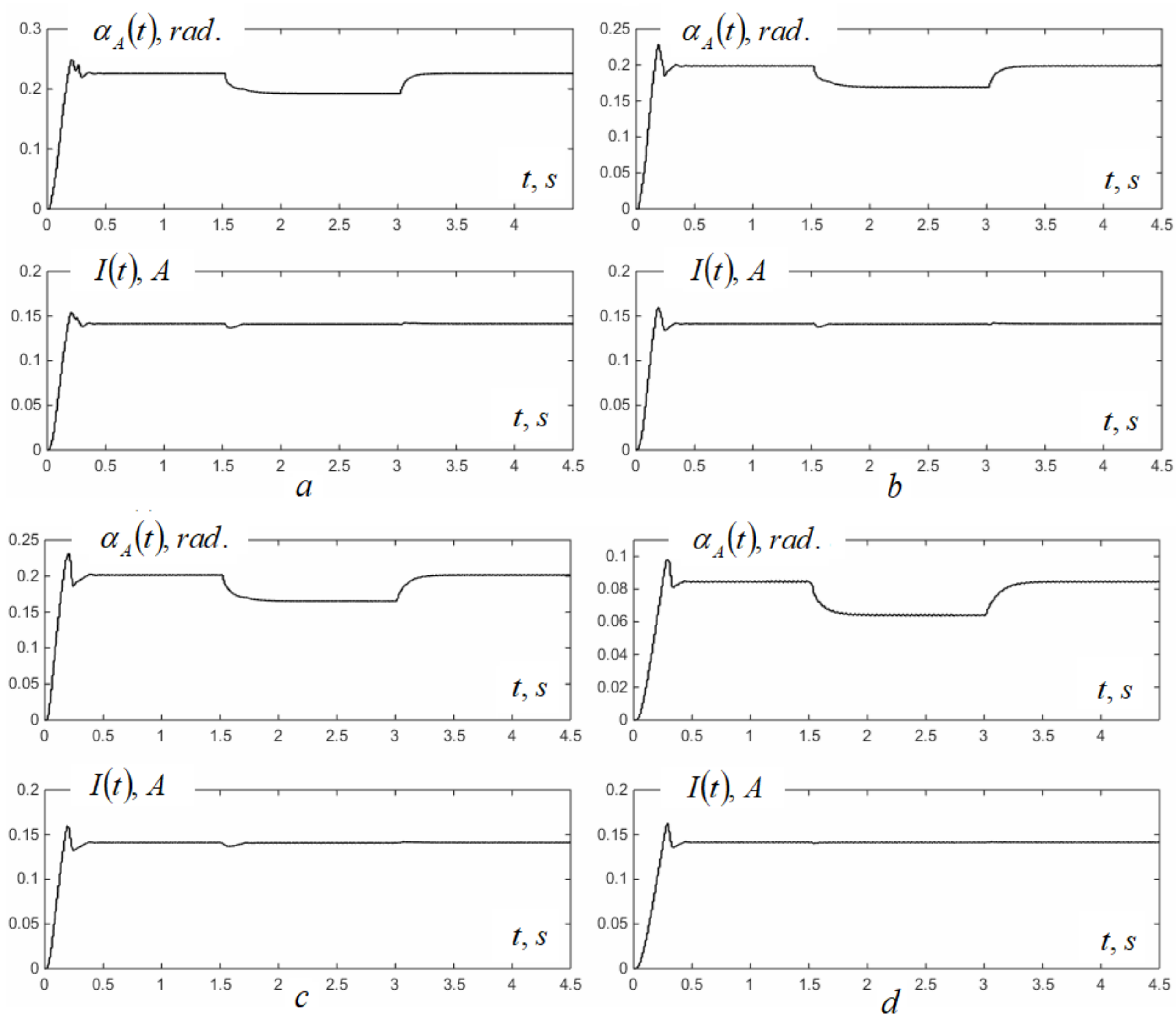


Fig. 6

Conclusions. The described studies have confirmed the possibility of analytical calculation of the parameters of the regulator of the rotor oscillations angle amplitude and the system for limiting the effective value of the stator current based on the frequency characteristics at an arbitrary form of the alternating carrier signal. Calculation of the amplitude and phase-frequency characteristics must be carried out at the given values of the amplitude of the rotor oscillations angle and the effective value of the stator current. The use of the second version of the formation of the feedback signal of the oscillations angle amplitude is possible in the low–frequency operating range up to 20 Hz.

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ЧАСТОТНЫЕ ХАРАКТЕРИСТИКИ БЕСКОНТАКТНЫХ МАГНИТО-ЭЛЕКТРИЧЕСКИХ ДВИГАТЕЛЕЙ ВОЗВРАТНО-ВРАЩАТЕЛЬНОГО ДВИЖЕНИЯ

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В статье исследованы частотные характеристики бесконтактного магнитоэлектрического двигателя возвратно-вращательного движения при формировании синусоидального и прямоугольных несущих сигналов. Усовершенствован способ формирования сигнала обратной связи по амплитуде угла колебаний вала двигателя путем фиксации значения сигнала в момент достижения максимального значения угла поворота. Исследован метод расчета системы управления амплитудой угла колебаний вала ротора на основании частотных характеристик разомкнутой системы, при котором задается запас устойчивости по фазе. Приведены примеры расчета переходных процессов регулирования амплитуды угла колебаний и действующего значения тока при пуске двигателя и изменении механической нагрузки. Библ.9, рис.6, табл.2.
Ключевые слова: бесконтактный магнитоэлектрический двигатель, возвратно-вращательное движение, система управления, несущая частота, частотная характеристика.

ЧАСТОТНІ ХАРАКТЕРИСТИКИ БЕЗКОНТАКТНИХ МАГНІТО-ЕЛЕКТРИЧНИХ ДВИГУНІВ ЗВОРОТНО-ОБЕРТАЛЬНОГО РУХУ

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У статті досліджено частотні характеристики безконтактного магнітоелектричного двигуна зворотно-обертового руху під час формування синусоїдального та прямокутних сигналів носіїв. Удосконалено спосіб формування сигналу зворотного зв'язку за амплітудою кута коливань валу двигуна через фіксацію значення сигналу у момент досягнення максимального значення кута повороту. Досліджено метод розрахунку системи керування амплітудою кута коливань валу ротора на основі частотних характеристик розімкненої системи, за якого задається запас стійкості за фазою. Наведено приклади розрахунку перехідних процесів регулювання амплітуди кута коливань та діючого значення струму під час пуску двигуна та зміні механічного навантаження. Бібл.9, рис.6, табл.2.
Ключові слова: безконтактний магнітоелектричний двигун, зворотно-обертовий рух, система керування, несуча частота, частотна характеристика.

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