

Characteristics of Electromechanical Clamping Mechanism with Asynchronous Electric Motor

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Abstract—The study investigates certain operating characteristics of the developed electromechanical actuator of a clamping mechanism for a lathe. The research was conducted using a previously designed special computer program which displays results in the form of graphs. The time dependencies of investigated characteristics have been found and analysed. The theoretical research results facilitate clarification of the peculiarities in operation and creation of the clamping mechanisms with an asynchronous motor. In particular, they contribute to defining appropriate adjustments for specified operating conditions and optimal parameters for structural elements of mechanisms of this type.

Keywords—*electromechanical actuator of a clamping mechanism, time dependencies, asynchronous motor, characteristics of the clamping process*

I. INTRODUCTION

The quality and productivity of machining on automatic lathes largely depends on the characteristics of fixation of a workpiece in the clamping mechanism (CM). The use of maximum machining modes is limited by the amount of effort that keeps the workpiece from moving under the action of cutting forces, i.e. the forces acting during machining of the workpiece [8]. Furthermore, the CM as a mechanism containing moving parts and located on the machine spindle has a significant influence on the dynamic characteristics of the spindle assembly. Features of a CM design determine the possibility of high-precision balancing of the spindle assembly and maintaining a balanced state for a specified period of operation [2]. Thus, the CM design has a restrictive effect on the maximum spindle speed, which, as a consequence, also determines the machining productivity and surface quality after processing. When spindle assembly is rotated with high frequency, large centrifugal inertia forces act on the elements of CM [4]. Such features have an effect on the efficiency of CM and cause deterioration of the workpiece fixation characteristics when the spindle speed increases during processing. The speed of clamping and unclamping of a workpiece on mass production lathes also affects the overall machining productivity. The largest structural element of the CM, which determines the parameters of its power characteristics, is the actuator of the clamping mechanism (ACM). That is, ACM is one of the main components of the CM and has a significant impact on the technical and economic indicators of its operation. The power characteristics of the ACM have an effect on the maximum intensity of the cutting modes, as well as stability and reliability of clamping, which determines the possibility and quality of workpieces processing; energy consumption, etc. [3]. Mechanical ACM with geometrical locking (locking of power flow in mechanism) is one of the most common types which are used in automatic lathes. This principle of operation is embodied in numerous ACM designs, starting

with the first semiautomatic lathes [3]. In ACM of this type, the magnitude of forces required for reliable fixation of a workpiece during processing is maintained by locking the mechanism in the final stage of the clamping. This is achieved by force interaction in links with a surface of a special profile which contains areas on which the force interaction between the links can lead to the transmission of movement in only one direction. As a rule, these are cam mechanisms or mechanisms with wedge-shaped elements. This principle of operation eliminates the need to bring energy to the ACM from the outside while the workpiece is held in a clamped state during the machining process, and determines the number of advantages of ACM designs of this type. Compared to other types of ACM that require a constant supply of energy from the outside in the form of a pressurized working medium (liquid or gas), geometrically-locked ACM provides a more secure hold of the workpiece in the event of uncontrolled changes in characteristics of energy supply or its loss. This reduces the probability of a machining defect and increases safety of the equipment. It also eliminates the need to use bulky external power supplies, such as hydro and pneumatic power pump station, that actively consume energy throughout the whole workpiece machining cycle.

II. RESEARCH PROBLEMS

Significant spreading of ACM structures with geometrical locking (Fig. 1a) is due to many advantages of this operation principle in comparison with other types of ACM. However, there are a number of disadvantages to these ACM. One of the main disadvantages that are characteristic of mechanical systems with geometrical locking is that the instability of the size of one of the links in the system causes the instability of the total deformation of all units when the mechanism is locked. Such an element having an unstable size in the CM system is a workpiece which is clamped. Its actual size is within a certain tolerance field. In this way, uncontrolled changes in the amount of workpiece clamping force result in reduced productivity and quality of machining, reliability of equipment, increased energy expenditure, etc. The use of calibrated workpieces leads to a significant increase in the price of the workpiece.

There is a need for additional external or internal machine subsystems to supply power to the existing types of ACM. These can be hydro and pneumatic stations or camshafts and other types of mechanical gears for power supply of mechanical ACM (Fig. 1b). This complicates the design of lathes, increases the number of energy converters and leads to additional energy losses. It also imposes significant restrictions on the possibility of upgrading the CM by making changes to the ACM design, since it requires alignment of the parameters of new alternative ACM designs with existing power sources and control systems.

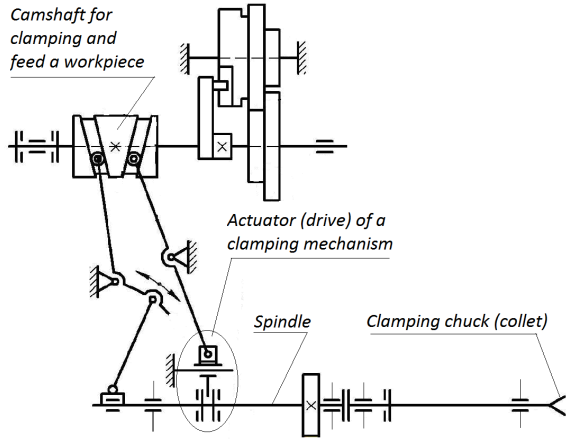
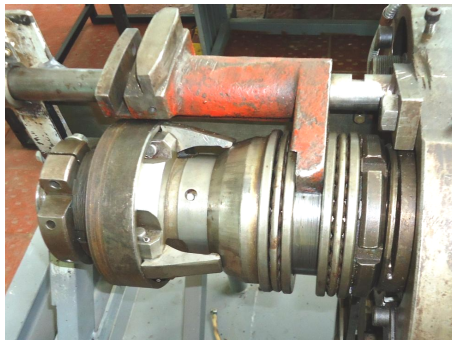


Fig. 1. Mechanical ACM mounted on a lathe spindle: a - general appearance; b - the fragment of the kinematic scheme of the supply system with a camshaft.

A general analysis of the creation and development of ACM designs has shown that this is mainly done by optimizing the parameters of their separate elements while maintaining the typical structure and technical solutions. As a result, only some of the technical parameters of the new ACM designs get improved. Such an approach aimed at preserving the typical designs of machine tool units for a long time does not contribute to the active innovative development of machine tools. The most effective and common way of supplying technological equipment by energy is to use electric energy. There is also a tendency to expand the sphere of usage of electromechanical units in technological equipment, including replacement of their existing mechanical analogues, in order to reduce the number of types of energy converters and energy loss. This makes it possible to assume that the use of electromechanical actuators for CM of metalworking machines is promising [3]. For the preliminary assessment of the feasibility of usage and the possibility of further experimental exploration of electromechanical actuators for CM, it is necessary to conduct theoretical research of their characteristics.

III. MAIN RESEARCH

One of the simplest electromechanical ACM designs under the Ukrainian patent [5] which is based on asynchronous electric motor was chosen for the research. It is necessary to determine the characteristics of electromechanical ACM in order to further analyse the feasibility of usage and ways of improving these designs. The electromechanical ACM (Fig. 2) works as follows. To start the workpiece clamping process, a current is supplied to the windings of the stator 2 which is based on the machine body 1. As a consequence, the torque occurs on a rotor 3.

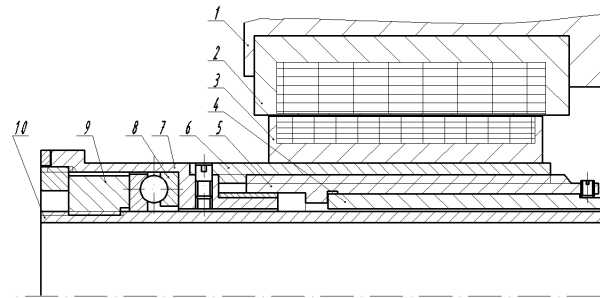


Fig. 2. Longitudinal section of electrical ACM under the patent [5]

The rotor 3 is fixed to the bushing 6 with an internal threaded surface screwed onto the bushing 5 with the outer threaded surface. Since the bushing 5 is fixed to the spindle 4, the rotation of the rotor 3 relative to the spindle 4 leads to the axial movement of the bushing 6 relative to the spindle 4 to the left. The axial force which appears as a result of the interaction in threaded connection of the bushings 6 and 5 is transmitted to the tie rod 10 through a nut 9, the thrust bearing 8 and the bushing 7. The axial force arising on the tie rod 10 is transmitted to the clamping chuck (collet) located at the front end of the spindle (not shown in the picture).

The workpiece clamping process continues until the required clamping force is reached, which depends only on the parameters of the current supplied to the stator windings 2. The force does not depend on the magnitude of the deviation of the radial dimensions of a workpiece. The translational-rotational motion of the rotor 3 (the clamping process) is terminated arbitrarily if the required clamping force is achieved and, as a consequence, the force that counteracts its axial movement. The end of the clamping process (rotor stop) can be detected by the characteristics of the current in the windings of the stator 2. After completion of the clamping process, the current supply to the windings of the stator 2 is terminated. The clamping force is supported by self-braking in the threaded connection of bushings 5 and 6. This design of the electromechanical ACM provides the ability to adjust the amount of clamping force during the rotation of the spindle.

On the basis of the proposed structure, a prototype of electromechanical ACM was made (Fig. 3) and adapted for assembling on a spindle of an automatic lathe on the test stand. A preliminary assessment of the effect that the changes in the ACM design have on the dynamic characteristics of the spindle assembly can be made based on a comparison of the geometric-mass parameters of the moving parts of the typical mechanical (Fig. 1a) and new electromechanical (Fig. 3a) ACM. The dimensions and mass of the rotating part of the new electromechanical ACM are smaller than the mechanical ACM of the classical design by approximately 20% and 50%, respectively. The design of the electromechanical ACM contains fewer movable elements that can change their position uncontrollably in the radial direction due to gaps that appear in the mechanism due to wear. This change can significantly degrade the balancing accuracy of the spindle assembly and as a consequence its performance at high speeds [2].

For the analysis of the characteristics of ACM in this work, a mathematical model [6] was used, which intended to calculate some basic electromechanical dependencies. The mathematical model of an asynchronous motor used to create the computer program [7] is designed to analyze the

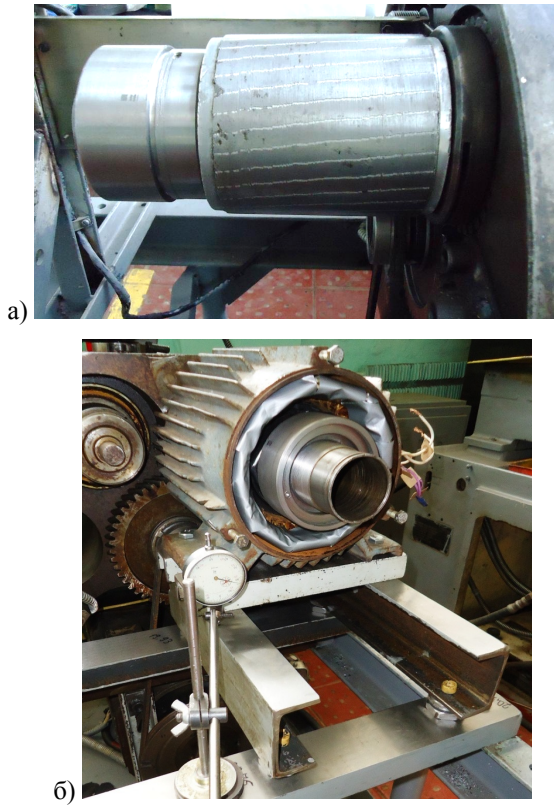


Fig. 3. The electromechanical ACM: a) rotational part (without stator); b) general appearance

performance of an engine, both autonomously and as an element of a complex system such as ACM. The differential equations of a three-phase asynchronous motor in the nonorthogonal (affine space) coordinate system written in the normal Cauchy form were taken as the basis [7]:

$$\frac{dI_S}{dt} = A_S (U_S - r_S I_S) + A_{SR} (\Omega \Psi_R - r_R I_R)$$

$$\frac{dI_R}{dt} = A_{RS} (U_S - r_S I_S) + A_R (\Omega \Psi_R - r_R I_R)$$

where I_S , I_R – the columns of stator currents and converted rotor currents; U_S – the column of the source voltage; Ψ_R – the column of full flux-linkage rotor windings; r_S , r_R – resistive resistors of stator and rotor windings; V_R – the column of rotor winding voltage; A_S , A_{SR} , A_{RS} , A_R – the matrix of coefficients. The analysis was based on the following assumptions generally accepted in the electrical theory: temperature fields are not taken into account; the magnetic field of the machine is conventionally divided into the working field and the dissipation field; magnetic iron loss is not taken into account. These assumptions make it possible to determine electromagnetic connections in saturated devices, to present a system of differential equations in the normal Cauchy form, and to model transients in electromechanical systems without reducing the adequacy of mathematical models.

Inductive and active resistance was calculated especially and particularly for an electrical engine type 4A112MA8 of the ACM. The magnitudes of stator's L_S and rotor's L_R inductance were determined by calculation, which is based on the passport's data [1] of the engine of the ACM and the parameters of substitution scheme. Nominal phase's current $I_{ph.nom}$ calculated from the nominal parameters of: power of

the engine P_{nom} , phase's voltage $U_{ph.nom}$, relative coefficient of efficiency η_{nom} , and power factor $\cos \varphi_{nom}$.

$$I_{ph.nom} = \frac{P_{nom}}{3 \cdot U_{ph.nom} \eta_{nom} \cos \varphi_{nom}} = \frac{2200}{3 \cdot 220 \cdot 0.765 \cdot 0.71} = 6.137 \text{ A}$$

Calculation of absolute values of resistances is done by using parameters R_1' , R_2'' , X_1' , X_2'' , and X_m presented in relative units selected from the directory [1] for a substitution scheme of the prototype engine:

$$r_1' = R_1' \cdot \frac{U_{ph.nom}}{I_{ph.nom}} = 0.093 \cdot \frac{220}{6.137} = 3.334 \text{ Ohm}$$

$$x_1' = X_1' \cdot \frac{U_{ph.nom}}{I_{ph.nom}} = 0.11 \cdot \frac{220}{6.137} = 3.92 \text{ Ohm}$$

$$r_2'' = R_2'' \cdot \frac{U_{ph.nom}}{I_{ph.nom}} = 0.083 \cdot \frac{220}{6.137} = 2.975 \text{ Ohm}$$

$$x_2'' = X_2'' \cdot \frac{U_{ph.nom}}{I_{ph.nom}} = 0.17 \cdot \frac{220}{6.137} = 6.094 \text{ Ohm}$$

$$x_m = X_m \cdot \frac{U_{ph.nom}}{I_{ph.nom}} = 1.5 \cdot \frac{220}{6.137} = 53.772 \text{ Ohm}$$

Magnitudes of inductance resistance of dissipation of phases of stator windings were calculated in accordance with [1]:

$$x_{\sigma 1} \approx \frac{2x_1' x_m}{x_m + \sqrt{x_m^2 + 4x_1' x_m}} =$$

$$= \frac{2 \cdot 3.92 \cdot 53.772}{53.772 + \sqrt{53.772^2 + 4 \cdot 0.11 \cdot 53.772}} = 3.912 \text{ Ohm}$$

Other resistances were calculated in accordance with [1]:

$$r_1 = \frac{r_1'}{m_T} = \frac{3.334}{1.38} = 2.415 \text{ Ohm}$$

$$r_2' = \frac{r_2''}{m_T (1 + \tau_1)^2 \cdot (1 + \rho_1^2)} = \frac{2.975}{1.38 (1 + 0.066)^2 \cdot (1 + 0.058^2)} = 1.891 \text{ Ohm}$$

$$x_1 = \frac{x_1'}{1 + \tau_1} - r_1 \rho_1 = 3.537 \text{ Ohm}$$

$$x_2' = \frac{x_2''}{(1 + \tau_1)^2 \cdot (1 + \rho_1^2)} = \frac{6.094}{(1 + 0.066)^2 \cdot (1 + 0.058^2)} = 5.345 \text{ Ohm}$$

where m_T – reduction factor of active resistance to calculated work temperature [1], which depends on the insulation class of heat resistance (for class F and H , $m_T = 1.37 \dots 1.38$). Stator resistance coefficient $\rho_1 = r_1 m_T / x_1 + x_m = 0.058$, stator's dissipation factor $\tau_1 = x_1 / x_m = 3.537 / 53.772 = 0.066$. Accordance with [1] $x_1 / x_2' \approx 0.7 \dots 1$ and in this case $x_1 / x_2' = 3.537 / 5.345 = 0.66$, which is acceptable with taking into account approximations in calculations.

Before the presented theoretical studies were conducted, the real ACM prototype (Fig. 3) had been created. It made it possible to realize preliminary practical tests and define some mass-geometrical parameters of ACM which are necessary to know for carrying out theoretical calculations

by using the specially created computer program. The computer program [7] had been created for determining the characteristics of the electromechanical ACM. It detected the dependence on time: the rotor rotation frequency n , the magnitude of the current I on stator's winding, the electromagnetic torque M_a on the rotor, the movement X_T of the output unit of ACM. These characteristics were determined accordingly to the following magnitudes of the initial data that is corresponding to the characteristics of the prototype. Data which must be entered in the program for calculation of characteristics of the electromechanical ACM are presented in Table I.

TABLE I. BASIC DATA FOR CALCULATION OF CHARACTERISTICS OF THE ELECTROMECHANICAL ACM

Parameters	Values	Symbols
Maximum voltage stator windings	310	V
The angular frequency of supply voltage	314	s ⁻¹
Active resistance of the stator winding phase	2.415	Ohm
Active resistance of the rotor winding phase	1.891	Ohm
Inverted value of inductance of dissipation (leakage inductance) of the stator phase	88.77	H
Inverted value of inductance of dissipation (leakage inductance) of the rotor	58.7	H
The main inverted value of the inductance of the magnetic circuit (magnetization branches)	5.84	H
Moment of inertia of the rotor	0.07	kg·m ²
Number of pole pairs of the electric motor	4	
The torque of resist which counteracts rotor rotation during clearance adjustment (eliminating gaps on the first stage of motion)	5	Nm
The maximum axial workload on the output link, determined by the required amount of force to clamping the workpiece	40000	N
The time constant	3	
The thread diameter of the screw gear	0.089	m
The thread pitch of the screw	0.002	m
Reduced angle of friction in the screw gear	4	°

The output links of ACM in the real case are loaded as a result of counteraction of input link of the clamping chuck. In the theoretical researches conducted using the computer program the exponential rate of increase of the ACM output link workload to its maximum preset value is controlled by changing the time constant [7]. The results of the calculations are presented in the form of graphs (Figs. 4, 5) of dependencies on time: the rotation speed n of the rotor, the magnitude of current I of the stator's winding, the electromagnetic torque M_a on the rotor, the movement X_T of the output link of ACM at the maximum axial workload 40 kN (Fig. 4) and 30 kN (Fig. 5).

Analysing the plot in Fig. 4 and Fig. 5, it is apparent that the initial phase of work of the ACM is accompanied by large transient processes. Their duration reflect the approximate value of the operating lag at switching on and are related to the characteristics of a particular mechanism, such as mass-geometrical parameters, sizes of technological and adjustable backlashes (gaps). Adjustment of the ACM can also affect the degree of using inertial forces. The power characteristics of the presented mechanism can be affected by changing the magnitude of the free rotor run which

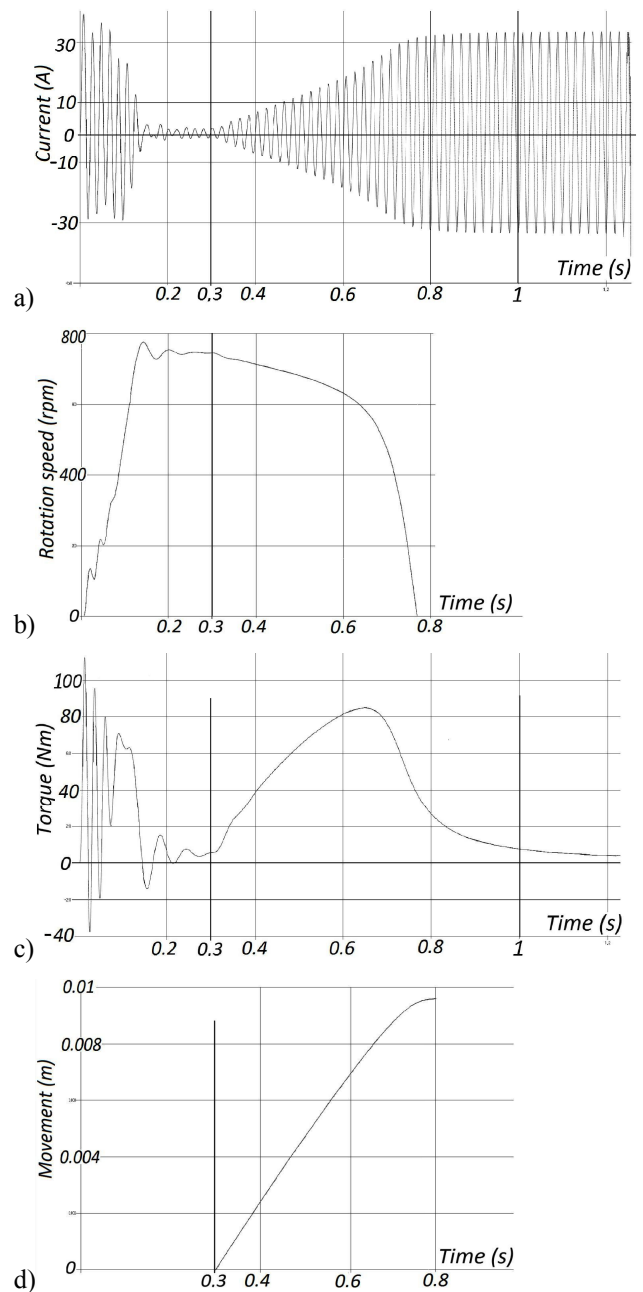


Fig. 4. The time dependencies: a) the frequency n of rotation of the rotor; b) the values of the current I of the stator winding; c) the electromagnetic torque M_a of the rotor; d) movement X_T of output link of the ACM with the workload 40 kN

influences the amount of the rotor kinetic energy at the end of the initial phase. In this case, the duration of the initial phase and the operation lag at switching on is assumed to be equal $t_0 = 0.3$ s as the time during which the rotor is accelerating (Figs. 4b, 5b) before operating in a steadystate and the process of taking up backlashes takes place. The presence and value of the operation lag at switching on of the ACM can be important to take into account to create and configure an effective control system of the clamping process especially when the lathe should work in a fast automatic mood.

The finish of the transients processes and start of the second period of work is reflected as a beginning of the output link movement (Figs. 4d, 5d) and the systematic increases in the magnitudes of the electromagnetic torque of

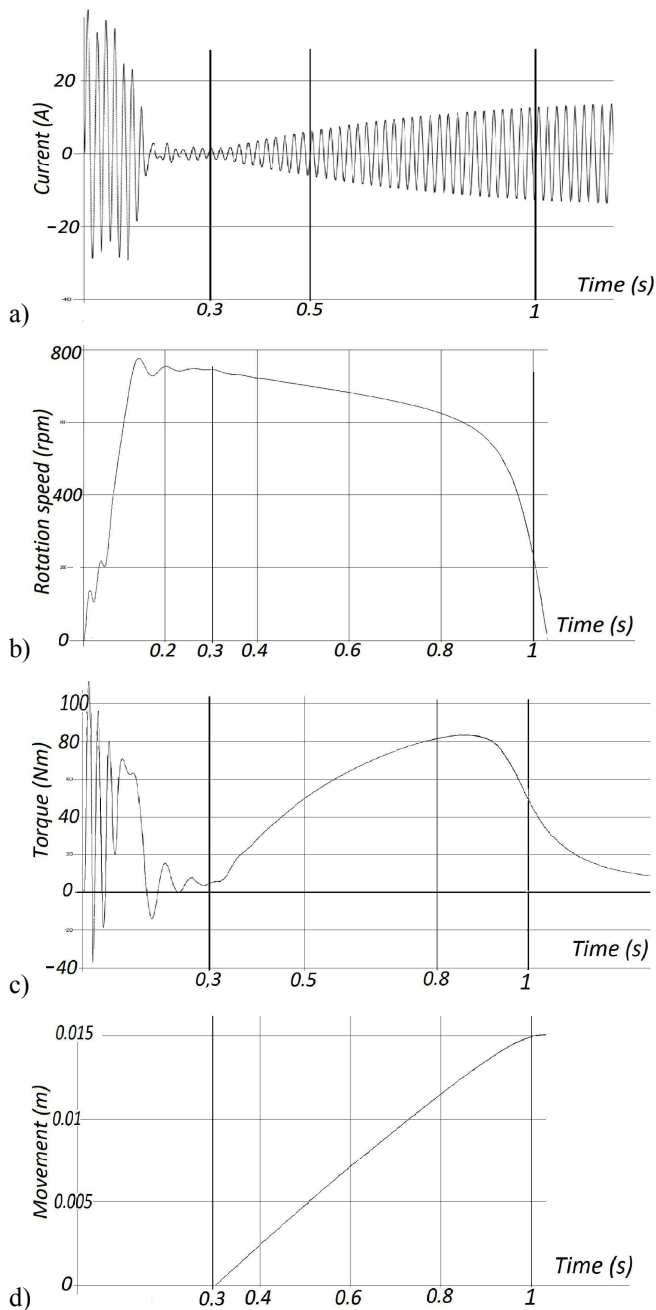


Fig. 5. The time dependencies: a) the frequency n of rotation of the rotor; b) the values of the current I of the stator winding; c) the electromagnetic torque M_a of the rotor; d) movement X_T of output link of the ACM with the workload 30 kN

the rotor (Figs. 4c, 5c) and the current of the stator windings (Figs. 4a, 5a). This period of work is related to the mechanical tension created in the system and accompanied by a systematic increase in the load on the ACM motor, which causes a decrease in speed of its rotor (Figs. 4b, 5b). At the same time, there is a systematic increase in torque on the rotor to a certain value, which depends on the characteristics of a particular engine. After reaching the certain maximum torque value, a further increase in the load on the rotor leads to a rapid loss of engine performance and its stop. It shows that the ACM motor must be adapted to work in modes which involve the possibility of stopping the rotor under the influence of external workload. Rotor stop is accompanied by an increase in the amperage of the stator windings to the certain maximum without further changes,

which takes about 0.8-1 s (Figs. 4a, 5a). This characteristic of current serves as a signal to stop the clamping process for the ACM control system and period of reaching this value, in fact, determines the nominal duration of the clamping process.

IV. CONCLUSIONS

The results of the research confirm engineering feasibility of usage of the electromechanical ACM in lathes to replace their mechanical analogues. It was ascertained that the studied characteristics of the investigated ACM were within the limits that determine its suitability for use in lathes. The displacement characteristic of the output link of the electromechanical ACM indicates the possibility of using the presented construction in combination with a traditional collet chuck. The relatively short duration of the fixation process is about 1 s, which contributes to the reduction in processing time and could affect the productivity of mass production. Controlling the ACM by changing the characteristics of current supply expands the possibilities to regulate the magnitude of the clamping force in order to counteract external perturbations. This feature also facilitates the process of integrating the mechanism into the structure of new and existing lathes since this does not require the development of additional mechanical and hydraulic subsystems of a lathe to supply power to the ACM.

The analysis of the form of the obtained graphs made it possible to expand and clarify the understanding of the peculiarities of ACM work of this type. This also helps to increase the efficiency of research and development work related to the creation of new structures of this type and to identify more optimal mechanism settings.

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