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Development of a mathematical model of a frequency-controlled electromagnetic vibration motor taking into account the nonlinear dependences of the characteristics of the elements

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Abstract. The wider application of vibration machines (VM) with electromagnetic motors (EMVM) in various industries, including in vibration test benches for telecommunication devices and equipment has been studied in the paper. Difficulties associated with maintaining their productivity and efficiency at a given level are largely hindered. These factors mainly depend on the determination of the degree of influence of the nonlinearities of the input-output characteristics on the output values of the VM, the possibilities of tuning into the resonance mode, and the control of the output values while ensuring the energy-saving mode of operation of the EMVM. The mathematical model has been developed for a frequency-controlled EMVM taking into account the nonlinear dependencies of the characteristics of the elements, which makes it possible to determine the most accurate amplitude of oscillations of the EMVM working body when passing through resonance, observed with changes in the voltage frequency. The analysis of the physical processes of the influence of nonlinear elements of the electric circuit of the EMVM on the electromagnetic quantities and the derived analytical expressions of these nonlinearities, which make it possible to determine the harmonic composition of the current of the EMVM winding, are made. The system of vector control of the EMVM and the inclusion of a mathematical model of the engine into the control system have been developed, which will allow calculating the frequencies of free oscillations of the working body for tuning into the resonance mode.

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1 Introduction

In the world, by improving the dynamic modes of operation of technological machines and mechanisms, elements of the electromechanical system with modern control devices, improving the elements of the electromechanical system, using control methods, energy efficient technologies are created, renewable energy in industry [1-10]. The use of such energy-saving technologies saves not only electricity and material resources, but also provides resource-saving [11, 12].

The intensive development of the economy of the independent Republic of Uzbekistan provides for the modernization of production processes, the widespread introduction of modern technologies into production, ensuring the production of high-quality and competitive products with minimal consumption of energy resources. In this direction, the legislative bodies have adopted a number of laws [13], regulating the efficient use of electrical energy.

VM, belong to the group of resonant machines, in the resonant zone: the amplitude of vibration - displacement, speed and acceleration, useful mechanical power and productivity; specific power losses are significantly reduced. In technological processes with frequent changes in the mass of the vibrated product that change the frequency of free oscillations, there is an urgent need to adjust to the resonance mode by changing the frequency of forced oscillations using a single-phase frequency converter (FC). Providing a harmonic form of currents and voltages in the elements of the system makes it possible to obtain an energy-saving mode of operation of the EMVM with a frequency converter, the reactive elements of which form a set of interconnected oscillatory circuits with nonlinear elements. The issues of studying the mutual influence of nonlinear characteristics of elements and ways to eliminate or reduce their negative influences on the operating modes of the EMVM with a frequency converter are relevant.

2 Research methods

One of the main and most effective methods in scientific research and engineering activities for the operation of electrical equipment, including the development of electromagnetic vibration motors, is their mathematical modeling. Mathematical modeling makes it possible to carry out model experiments in order to study the behavior of equipment in characteristic modes and situations, to determine the degree of influence of individual small and weighty components of equations that were not previously taken into account in order to simplify tasks for solving nonlinear differential equations of motion of the working body on operating modes and output equipment indicators [14-16].

The development and widespread use of computer technology and the latest achievements of semiconductor technology in the control of electrical equipment have led to the disclosure of even greater possibilities of mathematical modeling of equipment.

In particular, the use of computer numerical control systems for EMVM makes it possible not only to improve the accuracy of automatic tuning into the resonance mode and control the output parameters of the vibrator, but also to significantly increase the speed of the control process. It is assumed that the values characterizing the dynamic amplitude-frequency characteristics are known, and they have sufficiently accurate values. Hence it follows that the values characterizing the speed of the process of controlling the EMVM should be taken taking into account the duration of the transient processes of the EMVM, which should be in a certain ratio. This imposes on the researcher new requirements for a thorough study of the dynamic modes of the EMVM.

However, theoretical studies carried out to date with regard to the automation of frequency-controlled VM with EMVM often do not allow determining with sufficient accuracy the amplitude A(t) of vibrations of the EMVM working body when passing through resonance, since they either assumed that a linearized model of the object or the voltage frequency changes uniformly or instead of the dynamic amplitude-frequency characteristics, static ones are used, i.e. the dynamic operating mode of the electric drive is not taken into account [8].

In matters of introducing controlled EMVM, until recently, the tasks of controlling the amplitude of oscillations of the working body of the VM by changing the voltage, the degree of magnetization and other quantities were singled out. The proposal for the frequency control of the EMVM with the imposition of the need to achieve a certain accuracy of the output values presented to the electric drive by the technical and technological requirements, entrusts the researcher to develop a control method with a simultaneous change in frequency to maintain the resonant mode of the VM and the voltage value to maintain the required vibration amplitude of the working body.

In the control of EMVM voltage the scalar control method is used. It ensures the constancy of the oscillation amplitude of the working body, regardless of the differences in the frequencies of forced and natural oscillations, however, there is a decrease in the efficiency and utilization factor.

Despite its simplicity of implementation of the scalar control method in a frequency-controlled EMVM, it has a significant drawback associated with the difficulties in the development and operation of a resonance sensor that measures the mismatch of the frequencies of forced and natural vibrations of the working body.

The purpose of this work is to develop a mathematical model of a frequency-controlled EMVM taking into account the nonlinear dependencies of the characteristics of the elements, which makes it possible to determine the most accurate amplitude A(ω) of oscillations of the EMVM working body when passing through resonance, observed with changes in the voltage frequency; development of a vector control system for EMVM and inclusion in the control system of a mathematical model of the engine, which will allow calculating the frequencies of free oscillations of the working body for tuning into the resonance mode.

3 Results and discussion

We write the nonlinear differential equation of motion of the working body of the frequency-controlled EMVM in the following form;
For an analytical expression of the tractive effort, taking into account the influence of the armature vibrations on it, it is advisable to use the Maxwell equations:

$$F(t,x) = \frac{{\Phi_\delta}^2}{2\mu_0\sigma} \tag{1}$$

This equation is valid only in the case when the magnetic field of the air gap is uniform and determines the force acting on the surface of the armature.

$$\ddot{x} + \frac{\rho}{m}\dot{x} + \omega_0^2 = F(x,t) \tag{2}$$

Where, $\rho = \rho(A,\omega)$; $\omega_0 = \Omega(A,\omega)$

$$F(x,t) = [\Phi_0 / \sigma]^2 / (2\mu_0 S_\delta) \qquad (3)$$

$$\Phi_0 = 1/w\int(u - i \cdot r)dt \qquad (4)$$

$x, \dot{x}, \ddot{x} -$ oscillation of the working body, speed (first derivative) and acceleration (second derivative) of oscillations of the working body; $\rho = \rho(A, \omega)$ and $\omega_0 = \Omega(A, \omega)$ - damping variables of the oscillating system and the frequency of free oscillations of the working body, nonlinearly dependent on the amplitude A and frequency ω; $F(x,t) -$ force with which the armature is attracted to the core; $\mu_0 -$ magnetic constant; S_δ and $\sigma -$ core end area and variable parameter of magnetic flux leakage; w, r, δ_0 and $a -$ number of turns, active resistance of the winding, static air gap and constant, depending on the geometric dimensions of the electromagnet.

It is assumed that the nature of the field in the plane of the magnetic circuit does not change depending on the ratio of the instantaneous values of the current in the winding. With a strong magnetic coupling of the windings and the armature, this assumption is quite justified.

In the Figure 1, the nature of the magnetic field of an electromagnet of an electromagnetic vibration exciter (EMVE) is shown schematically. It is divided into an armature field, the tubes of which are closed along the armature and form a flow of the working air gap Φ_δ, stray fields $\Phi_{\sigma 1}$, interlocking with each winding separately and $\Phi_{\sigma 2}$, interlocking between the two rods of the electromagnet.

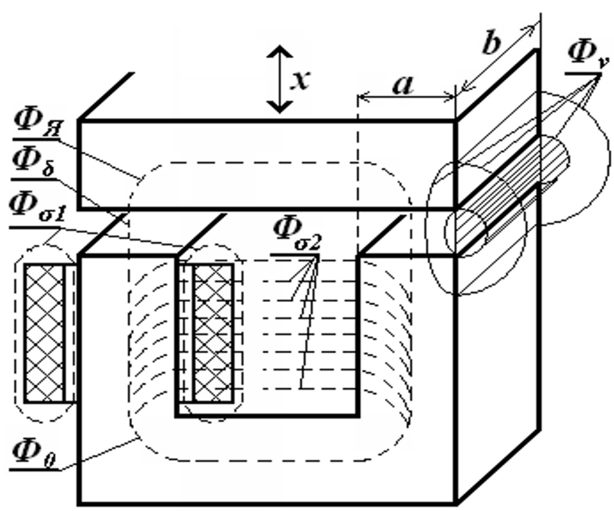


Fig. 1. Distribution of the components of the magnetic flux in parts of the magnetic circuit

It is believed that the stray fields $\Phi_{\sigma 1}$ of the main and auxiliary (magnetizing) windings have the same form in any plane aligned with the axis of the core of the magnetic circuit. With such a representation of the magnetic fields of EMVE, it is necessary to determine the nature of the stray fields.

Let us determine the analytical dependence for the magnetic flux in the air gap,

$$\Phi_\delta \approx \Phi_0 - \Phi_\sigma = \Phi_0 / \sigma \quad (5)$$

Where Φ_σ - instantaneous values of the magnetic leakage flux

$$\Phi_\sigma \approx \Phi_{\sigma 1} + \Phi_{\sigma 2} \quad (6)$$

Φ_0 - total magnetic flux in the yoke of the electromagnet created by the EMVE windings.

In the equation, the sign of approximate equality indicates that the work does not take into account those magnetic fluxes of leakage and buckling, for which there are no simplified analytical expressions, which are small values in comparison with the magnetic fluxes in the working air gap and the scattering between adjacent rods.

The magnetic flux in the working air gap will be expressed through the variable dissipation coefficient, which depends only on the geometric dimensions of the electromagnet, the static air gap and the oscillations of the armature with the working body of the vibrating machine

$$\sigma = 1 + N(\delta_0 - x) \quad (7)$$

where N - constant depending on the geometric dimensions of the inoperative air gaps between the rods of the electromagnet and the rods themselves and through the total magnetic flux in the yoke of the electromagnet, determined by the applied voltage, currents in the windings of the EMVM and armature oscillations.

To determine the value, it is necessary to solve the nonlinear differential equation (1), in the right side of which the value of the voltage frequency is involved, which changes with speed $\varepsilon = \Delta\omega / \Delta t$ in the range $0 < \omega_0 < 2\omega$. The rate ε of frequency change in the general case can be arbitrary and not constant. At the beginning of the study of the mathematical model, we will assume that it is constant $\varepsilon = const.$. To compare the results of theoretical studies on solving equation (1), we use two computational methods: an approximate method for solving a nonlinear differential equation, proposed in [12-20]; solving the equation by developing an algorithm (1) - (4) and a program for solving it using a personal computer (PC).

Then, as a solution to the nonlinear differential equation for the first point, you can write down how the amplitude of oscillations of the working body of the VM changes when passing through resonance [14-15]:

$$A(t) = \frac{(\beta+1)F(t)}{4\Omega\sqrt{\varepsilon}} * \\ * [v(y) + v(u) - v(u_0)e^{u_0^2 - u^2} - v(y_0)e^{y_0^2 - y^2}] \quad (6)$$

Where $v = \frac{(\beta-1)}{2\sqrt{\varepsilon}}[\varepsilon\tau + \Omega + \frac{\dot{\beta}\rho}{2m}]$; $u = \frac{1-\beta}{2\sqrt{\varepsilon}}[\varepsilon\tau - \Omega + \frac{\rho}{m}]$; v_0; $u_0 -$ values v and u at $t = 0$; $v(u)$ and $u(v) -$ tabulated functions.

The solution of equation (1) using a PC was carried out using the software package MATLAB. The solution to this differential equation is shown.

This algorithm was developed in 4 stages and combined into one whole.

1. Solution of the mathematical model of EMVM without taking into account nonlinear connections in the equations (Figure 2);

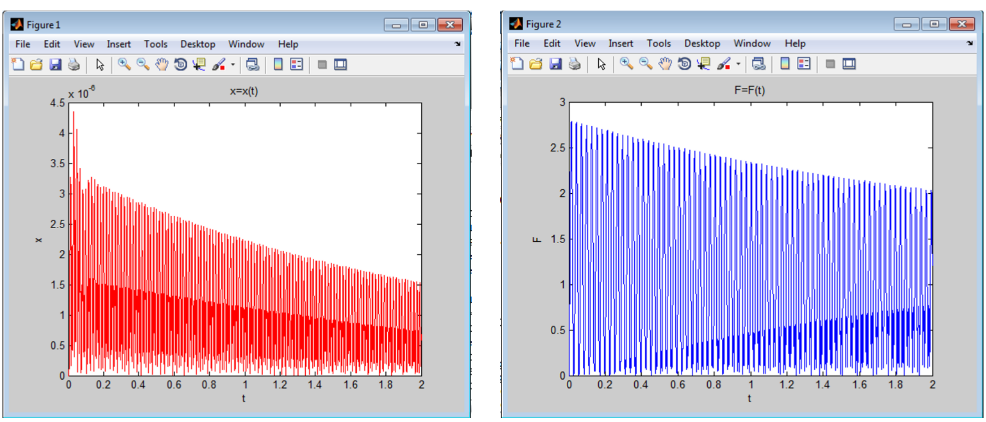
2. Solution of the mathematical model of EMVM taking into account nonlinear connections in the equations (variable air gap $L(x) = \text{var}$), which is shown in Figure 3;

3. The solution of the mathematical model of the EMVM taking into account nonlinear connections in the equations (variable air gap $L(x) = \text{var}$ and saturation of the magnetic circuit $\mu_0 = \text{var}$) belt air gap $L(x) = \text{var}$);

4. The solution of the mathematical model of the EMVM taking into account nonlinear connections in the equations (variable air gap $L(x) = \text{var}$ and saturation of the magnetic circuit $\mu_0 = \text{var}$, variable damping factor $n(x) = \text{var}$).

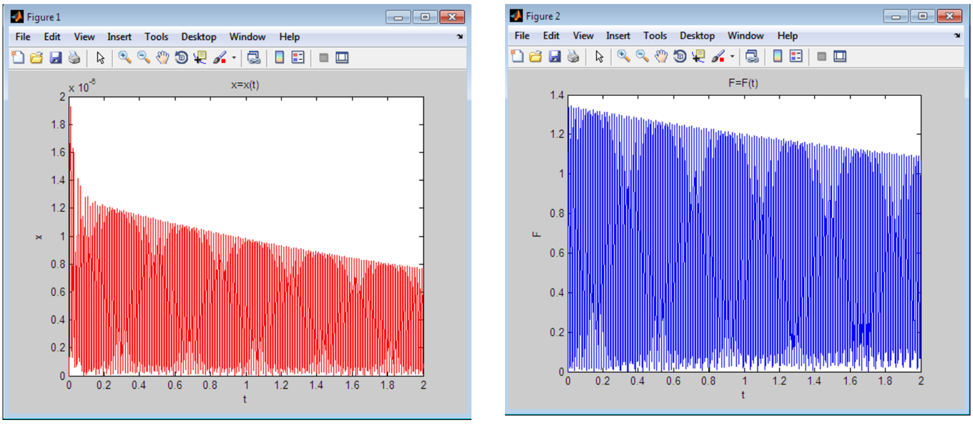
The solution to this differential equation is shown in Fig. 2-3.

The use of the proposed solution of the EMVM equations shows that the mutual influence of these quantities is significant and necessary in the calculations. Analyzing this solution, it is clearly seen that the magnetic fluxes and currents in the EMVM windings depend, in addition to electromagnetic quantities, also on the armature oscillations, and the influence of the constant component of the armature oscillations on the flows and currents is more significant than the influence of other components of the EMVM armature oscillations.



a) *b)*

Fig. 2. Solution of the mathematical model of EMVM without taking into account nonlinear connections in the equations



a) *b)*

Fig. 3. Solution of the mathematical model of EMVM taking into account nonlinear connections (variable air gap)

With certain assumptions, they showed that the influence of the saturation of the magnetic circuit, the variable nature of the inductance *L(x)* of the EMVM winding, the components of the magnetic flux of leakage, buckling and armature oscillations on the main magnetic flux, the currents in the windings, the operating modes of the frequency-controlled EMVM have not been considered until now. It has been established that in order to ensure a reliable and energy-saving mode of operation of the EMVM, it is necessary to carry out theoretical and experimental studies of the nonlinear characteristics of the elements of oscillatory mechanical, electrical and magnetic circuits of the EMVM, powered by a single-phase parallel inverter.

4 Conclusions

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