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

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.
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, 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
3 Results and discussion

\[ F(t) = \frac{\Phi}{\mu \sigma} \]

\[ \ddot{x} + \frac{\rho}{m} \dot{x} + \omega^2 = F(t) \dot{x} \]

\[ \rho = \rho A \omega^2 \cdot \omega = \Omega A \omega^2 \]
\[ F \times t = \Phi_{\delta} \sigma \mu S_{\delta} \]

\[ \Phi_{\delta} = w \int u - i \cdot r' \, dt \]

\[ x \hat{\Phi} - \Phi_{\sigma} S_{\delta} \]

\[ \omega = \Omega A \omega \]

\[ \omega = \Omega A \omega \]

\[ w \delta \alpha - \Phi_{\sigma} \Phi_{\delta} \Phi_{\sigma} \Phi_{\delta} \]

\[ \Phi_{\sigma} \Phi_{\delta} \Phi_{\sigma} \Phi_{\delta} \]

\[ \Phi_{\sigma} \Phi_{\delta} \Phi_{\sigma} \Phi_{\delta} \]
Let us determine the analytical dependence for the magnetic flux in the air gap,

\[ \Phi_0 \approx \Phi_0 - \Phi_\sigma = \Phi_\sigma \]

\[ \Phi_\sigma \approx \Phi_{\sigma_1} + \Phi_{\sigma_2} \]

\[ \Phi_{\sigma_1} \approx \Phi_{\sigma_1}, \Phi_{\sigma_2} \]

Where \( \Phi_0 \) - instantaneous values of the magnetic leakage flux and \( \Phi_\sigma \) - 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

\[ \sigma = \sigma + N(\delta - x) \]

\[ \varepsilon = \omega \Delta t \]

\[ \varepsilon = \omega \Delta t < \omega_1 < \omega_2 \]

\[ \varepsilon = \text{const} \]

\[ A(t) = - \beta + \frac{F(t)}{\Omega \sqrt{\varepsilon}} \]

\[ \vec{v} \cdot \vec{y} + \nu \vec{u} = v \vec{u} \cdot \vec{e}^{y-u} - v \vec{y} \cdot \vec{e}^{y-v} \]

\[ \vec{v} = \frac{\beta - \frac{\varepsilon \tau + \Omega + \frac{\beta}{\sqrt{\varepsilon}}}{m} u = \frac{\beta}{\sqrt{\varepsilon}} \varepsilon \tau - \Omega + \frac{\beta}{\sqrt{\varepsilon}} v \cdot u \cdot v - \vec{v} \]

\[ \vec{u} \]
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 EMV 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 \( \mu = \text{var} \));
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 \( \mu = \text{var} \), variable damping factor \( n_x = \text{var} \)).

The solution to this differential equation is shown in Figure 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.
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**

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.

![Fig. 3.](image1.png) ![Fig. 2.](image2.png)

Fig. 3. a) $\sigma(x)$, b) $L(x)$.
References


