STUDY OF THE VIBRATION DYNAMICS OF A MACHINE WITH AN ELECTRODYNAMIC VIBRATION EXCITER

Mirzayev Otabek Abdukarimovich

Associate Professor, Karshi State Technical University, Republic of Uzbekistan, Karshi city.

E-mail: kiamoa@mail.ru

Abstract: This paper analyzes the dynamic characteristics of a technological machine equipped with an electrodynamic vibration exciter under nonlinear loading conditions. The amplitude–frequency relationships of the machine are investigated both in idle (no-load) mode and under load while operating from a current source, and the corresponding characteristics are obtained. The study revealed that multiple-valued (ambiguous) regions may occur in the amplitude–frequency characteristics, and some of their branches correspond to unstable operating modes. In addition, the conditions leading to the occurrence of such phenomena are substantiated.

Keywords: vibration machine, nonlinear technological load, resonance, amplitude–frequency characteristic, process velocity.

Introduction: Electrodynamic vibration exciters [1, 2] are widely used as components of test benches [3]. At the same time, they are also employed as drive mechanisms for working bodies in various vibration and vibro-impact machines and devices [4, 5]. However, existing studies insufficiently address the general characteristics of such machines, especially their operation under nonlinear technological loading conditions arising from the interaction between the working body and the processed medium or object.

Main Part: In this study, the dynamic characteristics of the machine are analyzed both in the idle (no-load) mode and during operation when the electrodynamic exciter is powered by a current source.

Figure 1 shows the schematic diagram of a vibration machine equipped with an electrodynamic vibration exciter. The excitation device consists of a permanent magnet (2) elastically connected to the корпус (1), forming a uniform magnetic field in the annular gaps between the coils (3 and 4). The coils are supplied by an alternating current source (5). When alternating current passes through the coil windings, a time-varying excitation force $f(t)$ acting on the magnet is generated [1–2].

$$f(t) = \alpha\sigma\gamma(t) \quad (1)$$

$\alpha -$ the nonlinear dynamic behavior of a vibration system with an electrodynamic vibration exciter,

$\sigma -$ the length of the coil winding wire, $\gamma -$ **electric current value**

When the magnet moves with a velocity of $\dot{x}(t)$, an electromotive force directed opposite to it is induced in the coil winding.

$$\xi(t) = \alpha\sigma x(t) \ (2)$$

The working body (6) of the vibration machine is rigidly connected to the magnet. This body (6) interacts with the processed object or medium, and the entire system is pressed against them under the action of a constant force ρ .

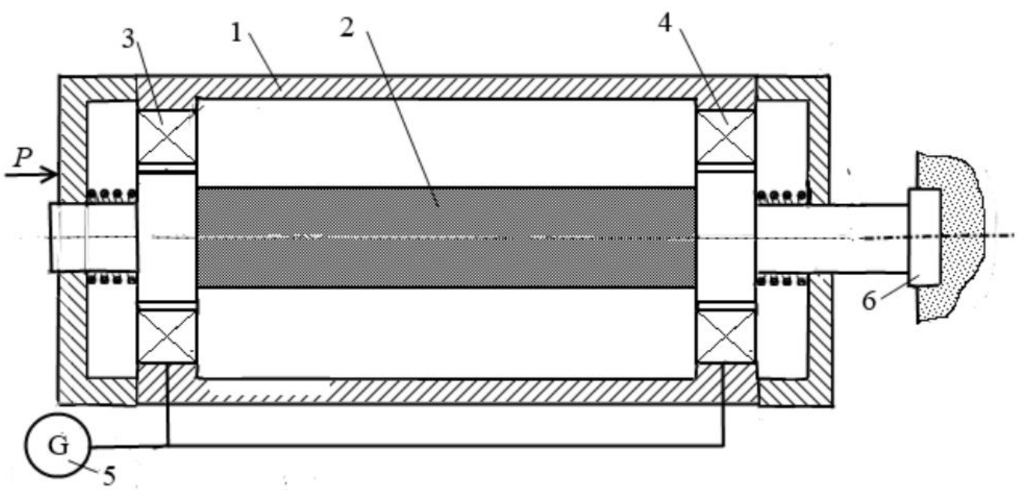

Figure 1. Schematic diagram of the vibration machine.

As a result of the interaction between the working body (6) and the processed medium, a technological load is generated in the vibration system. To describe this load, the nonlinear dynamic characteristic of the working process is used: $f_l = f_l(x, \dot{x})$[4,5]

This relationship defines how the interaction force depends on the displacement (x) of the working body and its velocity (\dot{x}). Initially, the dynamic characteristics of the system are analyzed in the absence of technological loading $(f_l = 0)$,, i.e., in the no-load operating mode.

Taking into account expressions (1) and (2), the state of the electromechanical system under steady-state harmonic oscillations can be described by the following system of equations:

$$\begin{cases}(c - m\omega^2 + j\omega b)\widetilde{\Theta} = \alpha\sigma\tilde{I} \\ (R + j\omega L)\tilde{I} = \widetilde{U} - j\omega\alpha\sigma\tilde{a}\end{cases} \quad (3)$$

Here $m, c,$ and (b) represent the mass of the moving parts, the stiffness of the elastic elements, and the coefficient of viscous damping, respectively; ($\widetilde{U}, \tilde{I}$—) denote the complex amplitudes of the supply voltage and the current in the coil windings; ($\tilde{a}$) is the complex amplitude of the device oscillation; (\omega) is the oscillation frequency; and ($j = \sqrt{-1}$) is the imaginary unit.

If the current is specified in advance, i.e., the coils are supplied from a current source and the current variation follows a harmonic law $i(t) = j\omega t$, where ($I = const$) is the constant amplitude of the current, then from equation (3) the complex amplitudes of the device vibrations and the supply voltage of the coils can be determined.

$$\tilde{a} = \frac{\alpha\sigma}{W(j\omega)} I, \widetilde{U} = \left[Z(j\omega) + \frac{j\omega(Bl)^2}{W(j\omega)}\right] I, \quad (4)$$

It should be noted here that

$$W(j\omega) = (c - m\omega^2 + j\omega b) \quad (5)$$

The expression describes the frequency-dependent dynamic stiffness of the mechanical part of the system.

$Z(j\omega) = R + j\omega l$ - whereas it is treated as the overall complex impedance of the electrical circuit. After substituting the notations introduced in equation (4), expressions describing the vibration amplitude of the device and the complex value of the coil supply voltage are obtained.

$$\tilde{a} = \frac{\alpha\sigma I}{c - m\omega^2 + j\omega b}, \tilde{U} = I\left[R + j\omega L + \frac{(Bl)^2}{c - m\omega^2 + j\omega b}\right] \quad (6)$$

Based on Euler's equation

$$\cos\phi = \frac{a(}{\sqrt{(c - m\omega^2)^2 + (\omega b)^2}} \quad (7)$$

In addition, relationships describing the initial phase of the working element's oscillation process are also determined. Here, expressions (6) and (7) are equivalent to the relationships derived from the analysis of forced vibrations of an oscillator under the action of a harmonic force, where the force amplitude is equal to zero. The second relation in (5) defines the supply voltage. The second term in it represents the influence of the mechanical parameters of the system on the impedance (total resistance) of the electrical circuit.

$$F_0 = \alpha\sigma I \quad (8)$$

In this case, both the amplitude of the instrument's oscillations and the output voltage of the power supply reach their maximum values. The resonant values of the instrument's oscillation amplitude and the supply voltage are given as follows:

$$a_r = \frac{\alpha\sigma I}{b\omega_0}, \tilde{U}_r = I\left[R + j\omega L + \frac{(Bl)^2}{c - m\omega^2 + j\omega b}\right] \quad (9)$$

From this it can be seen that, in the resonance regime, electromagnetic oscillations in the coil lead to the appearance of an additional active electrical resistance in the circuit. The magnitude of this resistance is inversely related to the viscous damping coefficient (b), which characterizes the dissipative properties of the mechanical system; the smaller (b) is, the more pronounced the additional active resistance becomes. This phenomenon is explained by the increase in oscillation amplitude as (b) decreases; the increase in amplitude, in turn, leads to a stronger back electromotive force and an increase in the output voltage of the power supply.

In addition, in the limit case $\omega \rightarrowtail \infty$ the supply voltage $U \rightarrowtail \infty$ is observed to increase without bound. This phenomenon is explained by the fact that the inductive reactance of the coil increases proportionally with frequency (5). From a physical point of view, at high frequencies the reactive impedance of the inductive element dominates, and the energy stored in the electromagnetic field increases, resulting in a sharp rise in the external voltage required to excite the system.

Nonlinear technological load. We now proceed to describe the operation of an electrodynamic vibration exciter machine during a technological process.

The interaction between the working element and the workpiece or medium being processed generates an additional technological load on the working element of the machine. As a rule, this load can be expressed in the form of a force acting on the working element $f_l = f_l(x, \dot{x})$ which is nonlinear with respect to the coordinates and velocity of the working element. When powered by a current source, the equation of motion takes a form similar to (3) and can be written as follows.

$$\ddot{m}x + b\dot{x} + cx = \alpha\sigma I e^{jwt} + f_l(x, \dot{x}) \quad (10)$$

To determine an approximate harmonic solution of equation (8), the method of harmonic linearization [4] is applied to the function $f_{il} = f_l(x, \dot{x})$.

With this in mind $f_l(x, \dot{x}) = P_l(a) + c_l(a)x + b_l(a)\dot{x}$

bu yerda $P_l(a)$ — texnologik yuklamaning doimiy tarkibiy qismi; $c_l(a)$ va —$b_l(a)$ garmonik chiziqlashtirish koeffitsiyentlari bo‘lib, ular [4] manbada keltirilgan formulalar asosida hisoblanadi.

Here, $P_l(a)$ is the constant component of the technological load; $c_l(a)$ and $b_l(a)$ are the coefficients of harmonic linearization, which are calculated using the formulas given in reference [4].

$$P_l(a) = \frac{1}{T}\int_0^T f_l(x, \dot{x})dt, \quad (11)$$

$$c_l(a) = \frac{2}{Ta}\int_0^T f_l(x, \dot{x})\cos(\omega t)\,dt, b_l = (a) = \frac{2}{Ta\omega}\int_0^T f_l(x, \dot{x})\sin(\omega t)\,dt, \qquad (12)$$

Since the entire system is pressed against the processed medium by a constant force (P) (see Fig. 1), the constant component of the nonlinear load is equal to $P_l = p$. Therefore, taking expression (9) into account, the equation of motion (8) takes the following form.

$$m\ddot{x} = (b + b_l)\dot{x} + (c + c_l)x = \alpha\sigma I e^{jwt} \quad (13)$$

Thus, a linear equation with coefficients dependent on the unknown amplitude has been obtained. Solving equation (10) yields the following expression for the complex amplitude.

$$\tilde{\hat{a}} = -\frac{\alpha\sigma I}{(c+c_l)-m\omega^2+jw(b+b_l)} \quad (14)$$

Results of the study: Numerical simulations showed that the vibration machine with an electrodynamic exciter exhibits pronounced nonlinear characteristics. A nonlinear resonance is observed in the frequency range of 20–26 Hz, accompanied by a significant increase in vibration amplitude. With a further increase in frequency, subharmonic and chaotic motion regimes emerge. The obtained results confirm the necessity of accounting for nonlinear stiffness in the design of vibrating technological systems.

In the study of the dynamics of a vibration machine with an electrodynamic exciter, the following results were obtained, which are presented in Table 1.

Main parameters of the vibratory system

Table 1

Parameter	**Symbol**	**Value**	**Unit**
Mass of the working platform	$\boldsymbol{m}$	**42**	$\boldsymbol{kg}$
Stiffness of elastic elements	$\boldsymbol{k}$	$\mathbf{1.8 \cdot 10^5}$	$\boldsymbol{N/m}$
Damping coefficient	$\boldsymbol{c}$	**950**	$\boldsymbol{N \cdot c/m}$

Nonlinear stiffness coefficient	α	$3.3 \cdot 10^7$	N/m^3
Excitation current amplitude	I	$1 \div 5$	A
Electrodynamic force coefficient	K_f	110	N/A
Excitation frequency	f	$5 \div 30$	Gs
Initial displacement	x_0	0.002	m

Conclusion: It should be noted that the form of expression (11) coincides with expression (5), which was obtained for the idle (free-run) operating regime. Therefore, the calculations performed above remain formally valid when replacing the quantities $(c + c_l)$ and $(b + b_l)$ respectively. The main difference between equations (5) and (11) is that the latter represents an equation with respect to the unknown amplitude (a), from which the coefficients
$(c + c_l)$ and $(b + b_l)$ are determined as functions of (a).

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