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Mechanical Systems of Precise Robots with Vibrodrives, in which the Direction of the Exciting Force Coincides with the Line of Relative Motion of the System

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1. Introduction

New mechanical systems of robots are created as well as known systems are developed which have various constitutive parts and drives. It is necessary to note the investigations performed by research associates of V. A. Glazunov and systems of structures of robots created by them as well as their theoretical basis [1]. Investigations in the field of precise manipulators and robots with vibromotors as autonomous and non autonomous systems are developed with high intensity in [2 – 7] and elsewhere. Vibromotors of new type for the performance of stationary and cyclic dynamic regimes based on piezoeffect, pulse type motions of pneumatic systems and fluids, variable and constant magnets, electrostatics and other principles have been created. In the middle of the 20 century new principles and means of mechanical systems with pneumatic and other types of vibroexciters as well as principles and means of dynamic synchronization and stabilization of systems have been created.

In the field of precise manipulators and robots the use of vibration drives operating on the basis of various principles found wide application. Thus robots created on the basis of pneumatic autovibrating vibratory drives have been applied in pipelines [2], where the asynchronous operation of those vibrators showed its effects. For investigation and creation of manipulators and on their basis vibrators with discontinuous elements were developed in order to increase their effective operation [3 – 7]. It is shown that vibrators of vibro impact type in separate case of the nonlinearity work in the zone of resonance with linear frequency spectrums [3] in this way ensureing stable operation of the system in the resonance zones. Asymptotic stabilisation of periodic regimes ensures stable operation of the system. Stabilisation of periodic nonlinear systems is investigated in [4]. Mechanical systems with impacts are investigated in [5]. Periodic orbits of mechanical systems with impacts are investigated in [6]. Vibro impact nonlinear energy sink is investigated in [7].

Because of the results of those investigations manipulator with vibro drive having advanced characteristics was created.

At the beginning of the paper schematic representation of the investigated dynamical system is described. The model of the proposed system is presented. Numerical results for different parameters of the investigated system are presented. Analysis of amplitude frequency characteristics is performed.

The aim of the research is to determine most suitable regimes of operation of the robot, which are applicable in practice.

2. Model of the system

The investigated system is shown in Fig. 1, where m_1, C_1 and H_1 are the mass of the first vibrating part, the coefficients of stiffness and of viscous friction respectively; m_2 is the mass of the second vibrating part; while C_0 and H_0 are the coefficients of stiffness and viscous friction of the limiter. The position O_sO_s is the position of static equilibrium of the mass m_1. H_2 is the coefficient of viscous friction between the mass m_2 and the immovable foundation.

Differential equations of motion of the system (Fig. 1) are obtained. Priciple of operation of this system is based on soft impacts to a deformable support of the output member m_2.

Notations according to the variables x_0, x_1, x_2 are introduced:

$$\begin{aligned} Q_0 &= C_0\left(x_0 - x_2\right) + H_0\left(\dot{x}_0 - \dot{x}_2\right), \\ Q_1 &= C_1\left(x_1 - x_2\right) + H_1\left(\dot{x}_1 - \dot{x}_2\right) - F, \\ Q_2 &= -Q_0 - Q_1. \end{aligned} \tag{1}$$

Thus the differential equations of motion have the form presented further.

Case 1, when $x_0 > x_1,\ \dot{x}_2 > 0$:

$$Q_0 = 0, \qquad (2)$$

$$m_1\ddot{x}_1 + Q_1 = 0, \qquad (3)$$

$$m_2\ddot{x}_2 + H_2\dot{x}_2 - Q_1 = 0. \qquad (4)$$

Case 2, when $x_0 > x_1,\ \dot{x}_2 = 0$:

$$Q_0\big|_{\dot{x}_2=0} = 0, \qquad (5)$$

$$m_1\ddot{x}_1 + Q_1\big|_{\dot{x}_2=0} = 0, \qquad (6)$$

$$R_1 = -Q_1\big|_{\dot{x}_2=0}. \qquad (7)$$

Case 3, when $x_0 = x_1,\ \dot{x}_2 > 0$:

$$m_1\ddot{x}_1 + Q_1\big|_{x_0=x_1} + Q_0\big|_{x_0=x_1} = 0, \qquad (8)$$

$$m_2\ddot{x}_2 + H_2\dot{x}_2 - Q_0\big|_{x_0=x_1} - Q_1\big|_{x_0=x_1} = 0. \qquad (9)$$

Case 4, when $x_0 = x_1,\ \dot{x}_2 = 0$:

$$m_1\ddot{x}_1 + Q_0\big|_{\dot{x}_2=0,\ x_0=x_1} + Q_1\big|_{\dot{x}_2=0,\ x_0=x_1} = 0, \qquad (10)$$

$$R_2 = -Q_0\big|_{\dot{x}_2=0,\ x_0=x_1} - Q_1\big|_{\dot{x}_2=0,\ x_0=x_1}. \qquad (11)$$

In the previous equations R_1 and R_2 in the cases 3 and 4 represent forces acting into the body 2.

In the Eqs. (1 – 11) the following changes are performed:

$$\mu = \frac{m_2}{m_1},\ p_0^2 = \frac{C_0}{m_2},\ p_1^2 = \frac{C_1}{m_1},$$

$$\tau = p_1 t,\quad ' = \frac{d}{d\tau},$$

$$h_0 = \frac{H_0}{\sqrt{m_1 C_1}},\ h_1 = \frac{H_1}{\sqrt{m_1 C_1}},\ h_2 = \frac{H_2}{\sqrt{m_1 C_1}},$$

$$q_0 = \left(\frac{p_0}{p_1}\right)^2 (x_0 - x_2) + h_0 (x_0' - x_2'),$$

$$q_1 = x_1 - x_2 + h_1 (x_1' - x_2') - \frac{F}{C_1}. \qquad (12)$$

If:

$$F = F_0 sin\omega t, \qquad (13)$$

then it is obtained:

$$\frac{F}{C_1} = f_0 sin\nu\tau,\ f_0 = \frac{F_0}{C_1},\ \nu = \frac{\omega}{p_1}. \qquad (14)$$

By taking into account the equations (12) – (14), after changes the Eqs. (2) – (11) take the forms presented further.

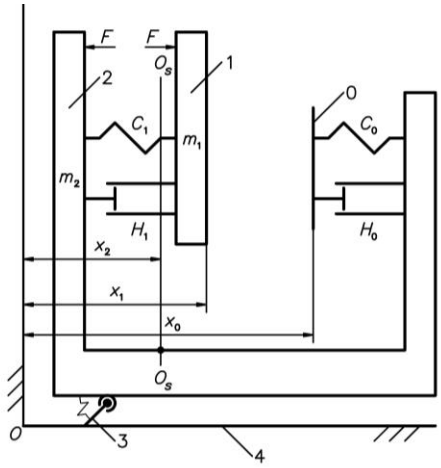


Fig. 1 Schematic representation of the system: O is the impact surface of the deformable support, m_1 is the exciting mass of the vibrator, m_2 is the moving mass of the basic element, 3 is the self stopping mechanism; x_0, x_1 and x_2 are the displacements

Case 1a, when $x_0 > x_1,\ \dot{x}_2 > 0$:

$$q_0 = 0, \qquad (15)$$

$$x_1'' + q_1 = 0, \qquad (16)$$

$$\mu x_2'' + h_2 x' - q_1 = 0. \qquad (17)$$

Case 2a, when $x_0 > x_1,\ x_2' = 0$:

$$q_0\big|_{x_2'=0} = 0, \qquad (18)$$

$$x_1'' + q_1\big|_{x_2'=0} = 0, \qquad (19)$$

$$\bar{R}_1 = -q_1\big|_{x_2'=0}. \qquad (20)$$

Case 3a, when $x_0 = x_1,\ x_2' > 0$:

$$x_1'' + q_0\big|_{x_0=x_1} + q_1\big|_{x_0=x_1} = 0, \qquad (21)$$

$$\mu x_2'' + h_2 x_2' - q_0\big|_{x_0=x_1} - q_1\big|_{x_0=x_1} = 0. \qquad (22)$$

Case 4a, when $x_0 = x_1,\ x_2' = 0$:

$$x_1'' + q_0\big|_{x_2'=0,\ x_0=x_1} + q_1\big|_{x_2'=0,\ x_0=x_1} = 0, \qquad (23)$$

$$\bar{R}_2 = -q_0\big|_{x_2'=0,\ x_0=x_1} - q_1\big|_{x_2'=0,\ x_0=x_1}. \qquad (24)$$

3. Investigation of dynamics of the system

It is assumed that:

$$\mu = 4,\ h_0 = 0.2,\ h_1 = 0.2,\ h_2 = 0.2,\ f_0 = 4. \qquad (25)$$

Investigations are performed for two values of nondimensional frequency of excitation:

$$\nu = 1, \ \nu = 4. \tag{26}$$

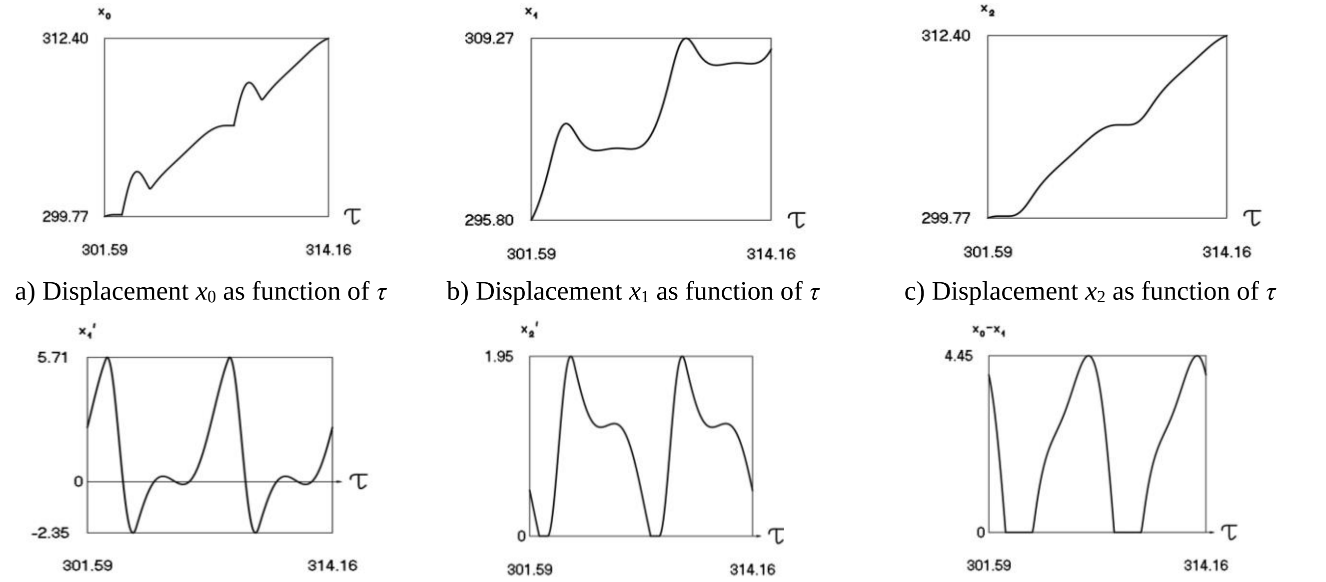
Investigations are performed for three values of $\left(\frac{p_0}{p_1}\right)^2$:

$$\left(\frac{p_0}{p_1}\right)^2 = 4, \ \left(\frac{p_0}{p_1}\right)^2 = 9, \ \left(\frac{p_0}{p_1}\right)^2 = 16. \tag{27}$$

Results for two periods of steady state motion are presented.

3.1. Value of nondimensional frequency of excitation $\nu = 1$

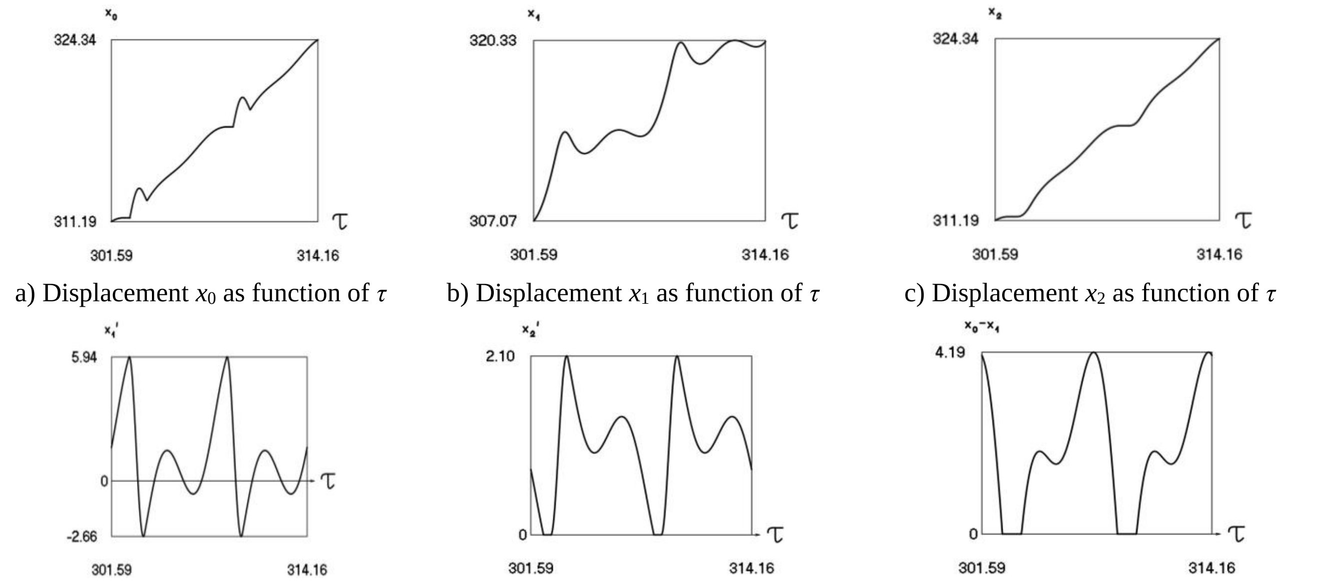
Results for the value of $\left(\frac{p_0}{p_1}\right)^2 = 4$ are presented in Fig. 2. Results for the value of $\left(\frac{p_0}{p_1}\right)^2 = 9$ are presented in Fig. 3. Results for the value of $\left(\frac{p_0}{p_1}\right)^2 = 16$ are presented in Fig. 4.



a) Displacement x_0 as function of τ b) Displacement x_1 as function of τ c) Displacement x_2 as function of τ

d) Velocity x_1' as function of τ e) Velocity x_2' as function of τ f) Difference of displacements $x_0 - x_1$ as function of τ

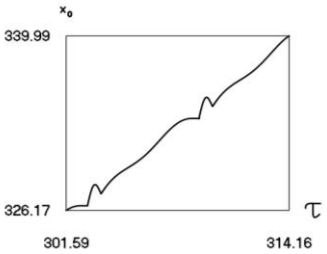
Fig. 2 Results for $\left(\frac{p_0}{p_1}\right)^2 = 4$



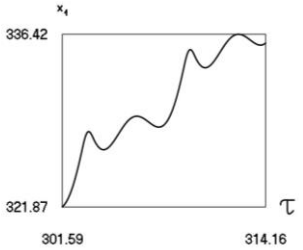
a) Displacement x_0 as function of τ b) Displacement x_1 as function of τ c) Displacement x_2 as function of τ

d) Velocity x_1' as function of τ e) Velocity x_2' as function of τ f) Difference of displacements $x_0 - x_1$ as function of τ

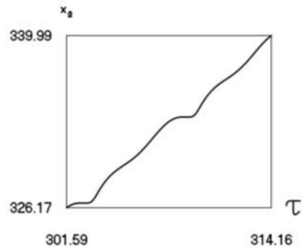
Fig. 3 Results for $\left(\frac{p_0}{p_1}\right)^2 = 9$



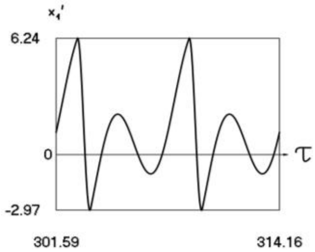
a) Displacement x_0 as function of τ



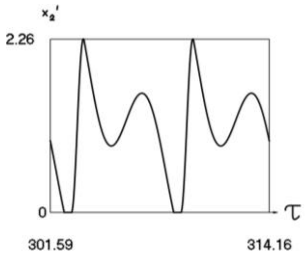
b) Displacement x_1 as function of τ



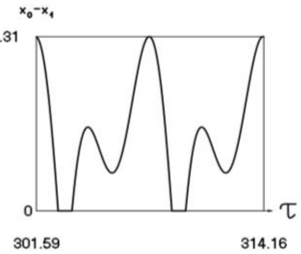
c) Displacement x_2 as function of τ



d) Velocity x_1' as function of τ



e) Velocity x_2' as function of τ



f) Difference of displacements $x_0 - x_1$ as function of τ

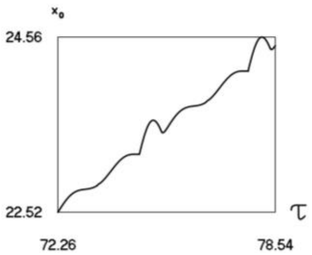
Fig. 4 Results for $\left(\frac{p_0}{p_1}\right)^2 = 16$

3.2. Value of nondimensional frequency of excitation $\nu = 4$

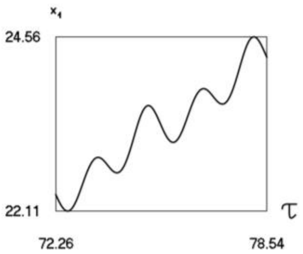
Results for the value of $\left(\frac{p_0}{p_1}\right)^2 = 4$ are presented in Fig. 5. Results for the value of $\left(\frac{p_0}{p_1}\right)^2 = 9$ are presented in Fig. 6. Results for the value of $\left(\frac{p_0}{p_1}\right)^2 = 16$ are presented in Fig. 7.

4. Amplitude frequency characteristics

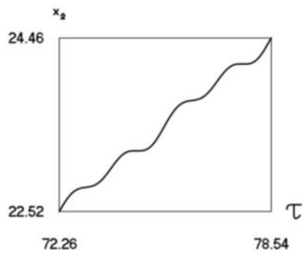
Amplitude frequency characteristics (constant part and first three harmonics) of steady state regime for the value of nondimensional frequency of excitation $\nu = 1$ and three values of $\left(\frac{p_0}{p_1}\right)^2$ are presented in Fig. 8. Amplitude frequency characteristics (constant part and first three harmonics) of steady state regime for the value of nondimensional frequency of excitation $\nu = 4$ and three values of $\left(\frac{p_0}{p_1}\right)^2$ are presented in Fig. 9.



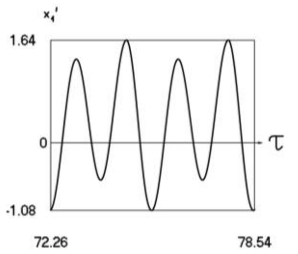
a) Displacement x_0 as function of τ



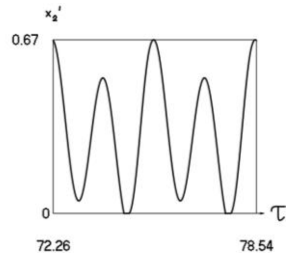
b) Displacement x_1 as function of τ



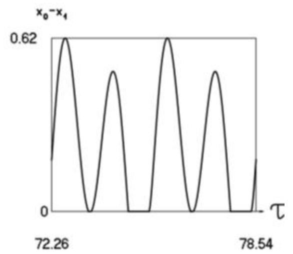
c) Displacement x_2 as function of τ



d) Velocity x_1' as function of τ

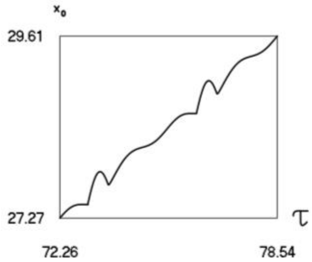


e) Velocity x_2' as function of τ

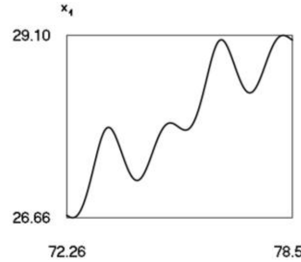


f) Difference of displacements $x_0 - x_1$ as function of τ

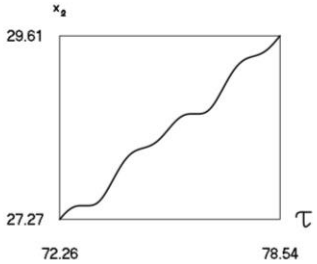
Fig. 5 Results for $\left(\frac{p_0}{p_1}\right)^2 = 4$



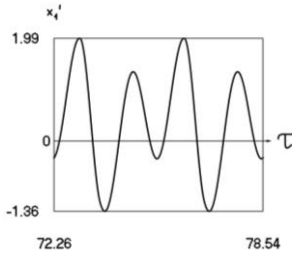
a) Displacement x_0 as function of τ



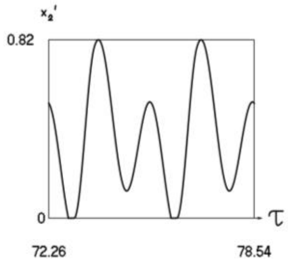
b) Displacement x_1 as function of τ



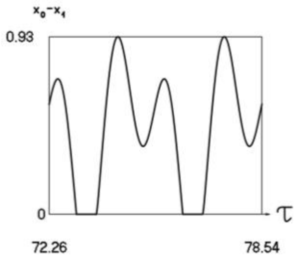
c) Displacement x_2 as function of τ



d) Velocity x_1' as function of τ

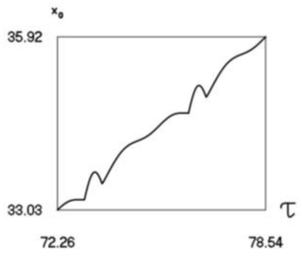


e) Velocity x_2' as function of τ

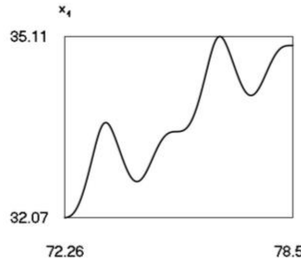


f) Difference of displacements $x_0 - x_1$ as function of τ

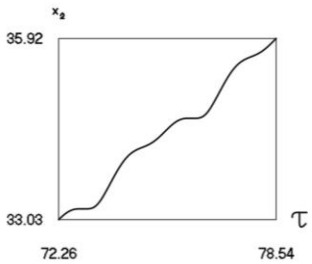
Fig. 6 Results for $\left(\frac{p_0}{p_1}\right)^2 = 9$



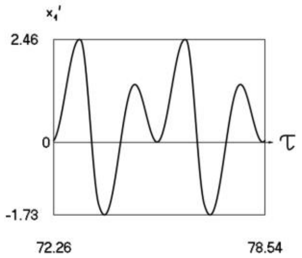
a) Displacement x_0 as function of τ



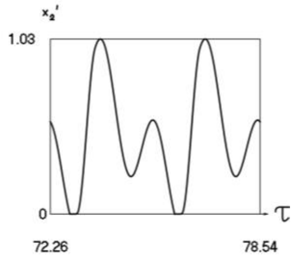
b) Displacement x_1 as function of τ



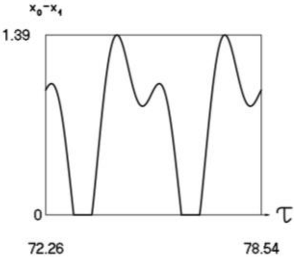
c) Displacement x_2 as function of τ



d) Velocity x_1' as function of τ

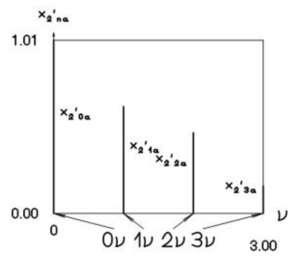


e) Velocity x_2' as function of τ

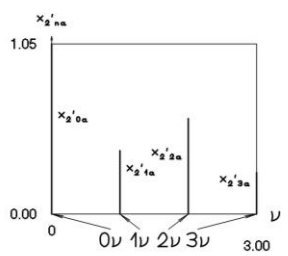


f) Difference of displacements $x_0 - x_1$ as function of τ

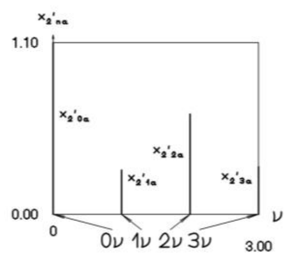
Fig. 7 Results for $\left(\frac{p_0}{p_1}\right)^2 = 16$



a) $\left(\frac{p_0}{p_1}\right)^2 = 4$

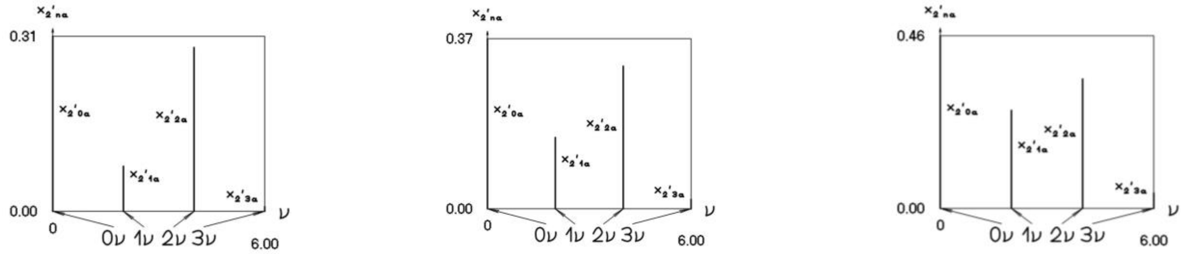


b) $\left(\frac{p_0}{p_1}\right)^2 = 9$



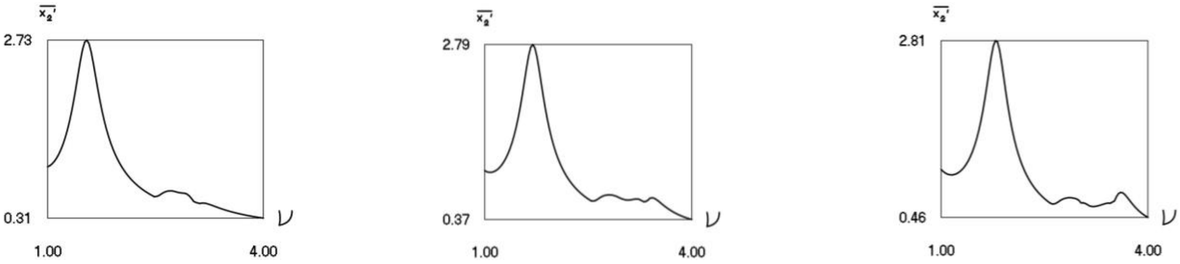
c) $\left(\frac{p_0}{p_1}\right)^2 = 16$

Fig. 8 Amplitude frequency characteristics for the value of nondimensional frequency of excitation $\nu = 1$



a) $\left(\frac{p_0}{p_1}\right)^2 = 4$ b) $\left(\frac{p_0}{p_1}\right)^2 = 9$ c) $\left(\frac{p_0}{p_1}\right)^2 = 16$

Fig. 9 Amplitude frequency characteristics for the value of nondimensional frequency of excitation $\nu = 4$



a) $\left(\frac{p_0}{p_1}\right)^2 = 4$ b) $\left(\frac{p_0}{p_1}\right)^2 = 9$ c) $\left(\frac{p_0}{p_1}\right)^2 = 16$

Fig. 10 Average velocity of the system in steady state regime as function of nondimensional frequency of excitation

On the basis of the presented results design of a pipe robot is performed.

5. Average velocity of the system in steady state regime as function of nondimensional frequency of excitation

Average velocity of the system in steady state regime as function of nondimensional frequency of excitation is investigated. Results for the three values of $\left(\frac{p_0}{p_1}\right)^2$ are presented in Fig. 10. From the presented results optimal nondimensional frequency of excitation corresponding to maximum value of average velocity of the system in steady state regime is determined.

6. Conclusions

Principles of operation of vibromotors having different typical structures are based on vibrations and waves as well as nonlinear dynamical effects and phenomena. Those motors are used in manipulators and robots. They enable to achieve high precision and good dynamic qualities.

A specific vibromotor is investigated. It moves with the displaced body. Motion in the direction of the one dimensional coordinate is assumed. Operation of the motor is based on specific interactions between rigid bodies. Direction of interactions coincides with the direction of motion of the displaced body.

It is important to choose the parameters of the investigated system in order to avoid stationary multivalued motions in the vicinities of resonances. Self stopping device is essential in the structure of the system. It limits the motion of the displaced body according to one direction.

The obtained results reveal the qualities of the investigated model. Also the influence of various parameters of the model to the obtained results describing the operation of the investigated system is presented. Analysis of amplitude frequency characteristics is performed.

Average velocity of the system in steady state regime as function of nondimensional frequency of excitation is investigated. Results for the three values of non dimensional frequency are presented. From the presented results optimal nondimensional frequency of excitation corresponding to maximum value of average velocity of the system in steady state regime is determined.

Results of the performed investigation are used in the creation of pipe robots of advanced type.

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MECHANICAL SYSTEMS OF PRECISE ROBOTS WITH VIBRODRIVES, IN WHICH THE DIRECTION OF THE EXCITING FORCE COINCIDES WITH THE LINE OF RELATIVE MOTION OF THE SYSTEM

S u m m a r y

Manipulator consisting from one sided self stopping mechanism and two masses which interact through an elastic – dissipative member is investigated. The drive of the manipulator is the generator of mechanical vibrations. With such elements the system is nonlinear. A separate case is investigated when static positions of equilibrium of both masses are located in one point. Because of this spectrum of eigenfrequencies are linear and infinite. All those facts mean that the operation of the manipulator is optimal.

Fast development of robots gives rise to the investigations of increasing intensity creating various types of robots especially in the area of high precision. Mechanical systems of robot must perform laws and trajectories of motion, positioning in space with highest possible precision as well as ensure dynamicity of highest possible stability. Those aims are achieved in the presented paper by creating a structure of the best design, based on vibroimpacts as well as by choosing corresponding nonlinear parameters of the system. The investigation is performed by analytical – numerical method. The obtained results enable to create mechanical systems for precise robots.

Keywords: manipulator, generator of mechanical vibrations, self stopping mechanism, frequency spectrums, characteristics of harmonic vibrations, mechanical systems of robots, vibrodrive with soft impacts, parameters of nonlinear elements, stability.

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