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Investigation of Dynamics of the Manipulator with Self-Stopping Mechanism and Vibration Drive Based on Centrifugal Forces

Kazimieras RAGULSKIS*, Algimantas BUBULIS, Vytautas JŪRĖNAS***, Joris VĖŽYS****, Petras PAŠKEVIČIUS*****, Liutauras RAGULSKIS******

*Kaunas University of Technology, K. Donelaičio st. 73, LT-44249, Kaunas, Lithuania, E-mail: kazimieras3@hotmail.com
**Kaunas University of Technology, K. Donelaičio st. 73, LT-44249, Kaunas, Lithuania, E-mail: algimantas.bubulis@ktu.lt
***Kaunas University of Technology, K. Donelaičio st. 73, LT-44249, Kaunas, Lithuania, E-mail: vytautas.jurenas@ktu.lt
****Kaunas University of Technology, K. Donelaičio st. 73, LT-44249, Kaunas, Lithuania, E-mail: joris.vezys@ktu.lt
*****Company "Vaivora", Palemono st. 2a, LT-52191, Kaunas, Lithuania, E-mail: info@vaivorairko.lt
******Vytautas Magnus University, Vileikos st. 8, LT-44404, Kaunas, Lithuania, E-mail: l.ragulskis@if.vdu.lt
(Corresponding author)

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1. Introduction

Vibration drive based on centrifugal forces is often used in elements of manipulators and robots. In this paper manipulator with vibration drive based on centrifugal forces and with the self-stopping mechanism is investigated. Self-stopping mechanism enables the motion of the manipulator in one direction and prevents the motion in the opposite direction. It represents essential nonlinearity in the dynamic model of the investigated system.

The model of the investigated manipulator is described and equations determining the motion of the manipulator are obtained. First the results for the conservative system are described and investigated. One can note that the results of the investigation of the conservative system remind the dynamics of a simple pendulum, but the main nonlinear effects become evident when investigating the system using the full dynamic model. Then the full dynamic model is investigated in detail. Also, the model with excitation of unlimited power is described and investigated.

Various typical graphical relationships determining the dynamic behavior of the investigated manipulator with vibration drive based on centrifugal forces in steady state regimes of motion are presented. The obtained results are used in the process of design of manipulators with vibration drive based on centrifugal forces.

New mechanisms in contemporary robot engineering are presented in [1]. Essentially nonlinear systems are analyzed in [2]. Dynamics of transmissions is described in [3]. Investigation of dynamics of robots is performed in [4]. A vibration-driven robot is analyzed in [5]. Motion analysis of a robot's crawler unit is described in [6]. Underwater robotic system is investigated in [7]. Simulation and experimental investigation of the in-pipe robot excited by the unbalanced rotor is described in [8]. Motion simulation of a wheeled vibration-driven robot is performed in [9]. Mathematical modeling of the vibration-driven robot is described in [10]. Dynamics of a robot driven by an unbalanced rotor is analyzed in [11]. Development and theoretical investigation of the vibration-driven robot is described in [12]. Development and analysis of spherical ultrasonic motor for robots is performed in [13].

First the model of the manipulator with vibration drive based on centrifugal forces is described. Then investigations for three cases are performed: 1) the conservative system, 2) the full system, 3) the system with excitation of unlimited power. Graphical representations for typical parameters of the investigated manipulator with vibration drive based on centrifugal forces are presented and described.

2. General dynamic model of the manipulator with vibration drive based on centrifugal forces

The manipulator with vibration drive based on centrifugal forces is shown in Fig. 1. Further m_0 denotes the mass of the case of the manipulator, x_0 denotes the displacement of the case of the manipulator, m denotes the mass of the exciter of vibrations, φ denotes the angle of rotation of the exciter of vibrations. The moment of the exciter of vibrations is denoted as $M(\dot{\varphi})$, where the upper dot denotes differentiation with respect to the time variable. Also, x denotes the coordinate determining the position of the exciting mass of the exciter of vibrations. The force of resistance to the motion of the manipulator according to the coordinate x_0 representing the effect of external media to the motion of the manipulator is assumed as $-A-B\dot{x}_0$, where A and B are constants. The moment of the driving force of the unbalanced rotor according to the coordinate φ is assumed as $C-D\dot{\varphi}$ where C and D are constants.

The system has two degrees of freedom: the displacement of the manipulator x_0 and the angle of rotation of the exciter of vibrations φ. The point of attachment of the exciter of vibrations to the manipulator is denoted as $O_2(x_0, 0)$ and location of the exciting mass of the exciter of vibrations is denoted as $O_3(x, y)$. Also, the following notation is introduced:

$$O_2O_3 = r. \tag{1}$$

Location of the exciting mass of the exciter of vibrations is expressed as:

$$x = x_0 + r\cos(\pi-\varphi) = x_0 - r\cos\varphi, \tag{2}$$

$$y = r\sin(\pi-\varphi) = r\sin\varphi. \tag{3}$$

Velocities are determined as:

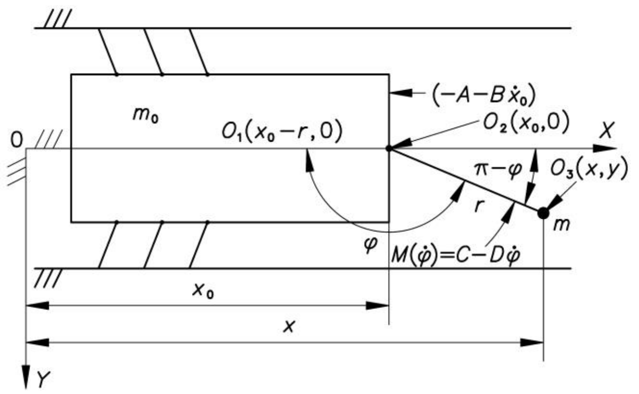


Fig. 1 Manipulator with vibration drive based on centrifugal forces: m_0 is the mass of the case of the manipulator, x_0 is the displacement of the case of the manipulator, m is the mass of the exciter of vibrations, φ is the angle of rotation of the exciter of vibrations, $M(\dot{\varphi})$ is the moment of the exciter of vibrations, x is the coordinate determining the position of the exciting mass of the exciter of vibrations

$$\dot{x} = \dot{x}_0 + r\dot{\varphi}\sin\varphi, \tag{4}$$

$$\dot{y} = r\dot{\varphi}\cos\varphi. \tag{5}$$

Based on presented results kinetic energy has the following form:

$$T = \frac{m}{2}\left(\dot{x}_0^2 + r^2\dot{\varphi}^2 + 2r\dot{x}_0\dot{\varphi}\sin\varphi\right) + \frac{m_0}{2}\dot{x}_0^2. \tag{6}$$

Differential equations of motion have the following form:

$$\left(m+m_0\right)\ddot{x}_0 + mr\left(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi\right) = -A - B\dot{x}_0\,, \tag{7}$$

$$m\left(r^2\ddot{\varphi} + r\ddot{x}_0\sin\varphi\right) = C - D\dot{\varphi}\,, \tag{8}$$

where $-A-B\dot{x}_0$ is the force of resistance to the motion of the manipulator according to the coordinate x_0 representing the effect of external media to the motion of the manipulator, $C-D\dot{\varphi}$ is the moment of the driving force of the unbalanced rotor according to the coordinate φ.

The following notations are introduced:

$$\mu = \frac{m}{m_0},\ a = \frac{A}{m},\ b = \frac{B}{m},\ c = \frac{C}{rm},\ d = \frac{D}{rm}. \tag{9}$$

Thus, dynamics of the investigated manipulator with vibration drive based on centrifugal forces is described by the following equations:

$$\left(1+\mu\right)\ddot{x}_0 + \mu r\left(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi\right) = -a - b\dot{x}_0\,, \tag{10}$$

$$r\ddot{\varphi} + \ddot{x}_0\sin\varphi = c - d\dot{\varphi}\,. \tag{11}$$

3. Investigation of dynamics of the conservative system

In the Eqs. (10) and (11) it is assumed that:

$$a = b = c = d = 0. \tag{12}$$

Dynamics of the conservative system is described by the following equations:

$$\left(1+\mu\right)\ddot{x}_0 + \mu r\left(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi\right) = 0\,, \tag{13}$$

$$r\ddot{\varphi} + \ddot{x}_0\sin\varphi = 0\,. \tag{14}$$

The following parameters of the investigated conservative system were assumed:

$$\mu = 0.2,\ r = 1. \tag{15}$$

Calculations were performed by using C++ Builder Community Edition. Numerical integration of equations of motion was performed by using the Newmark constant average acceleration procedure.

Results for various typical initial conditions are presented in Fig. 2, Fig. 3, Fig. 4, and Fig. 5.

From the presented results the influence of the values of the initial velocity as well as of the initial angular velocity on the dynamics of the conservative system is seen. From the presented results it is seen that the direction of transportation is determined by the sign of the initial velocity.

Eigen period and eigenfrequency as functions of the initial angular velocity are presented in Fig. 6.

4. Investigation of dynamics of the manipulator

When the self-stopping mechanism prevents the motion of the case of the manipulator, then it is assumed that:

$$\dot{x}_0 = 0. \tag{16}$$

Thus, in this case only the following equation is solved:

$$r\ddot{\varphi} = c - d\dot{\varphi}. \tag{17}$$

Further investigation of dynamics of the manipulator with vibration drive based on centrifugal forces is performed.

The following parameters of the investigated system were assumed:

$$\mu = 0.2,\ r = 1,\ b = 0.2,\ d = 0.2,\ c = 0.1. \tag{18}$$

Steady state motions are investigated. Results for various values of the constant force are presented in Fig. 7, Fig. 8, and Fig. 9.

From the presented results the influence of the values of the constant force to the dynamics of the manipulator with vibration drive based on centrifugal forces is seen. From the presented results it is seen that the distance travelled by the manipulator with vibration drive based on centrifugal forces with the increase of the value of the constant force decreases substantially, period when the velocity is equal to zero increases substantially as well as maximum velocity decreases substantially, also one can note that the value of the constant force influences the values of angular

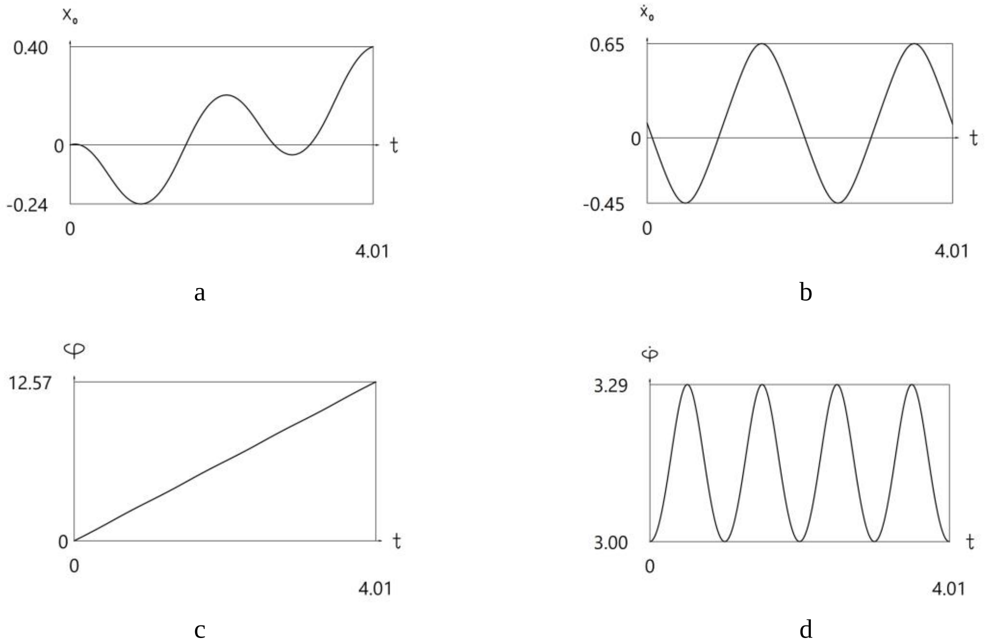


Fig. 2 Dynamics of the conservative system when $x_0(0) = 0$, $\dot{x}_0(0) = 0.1$, $\varphi(0) = 0$, $\dot{\varphi}(0) = 3$: a – $x_0(t)$, b – $\dot{x}_0(t)$, c – $\varphi(t)$ and d – $\dot{\varphi}(t)$

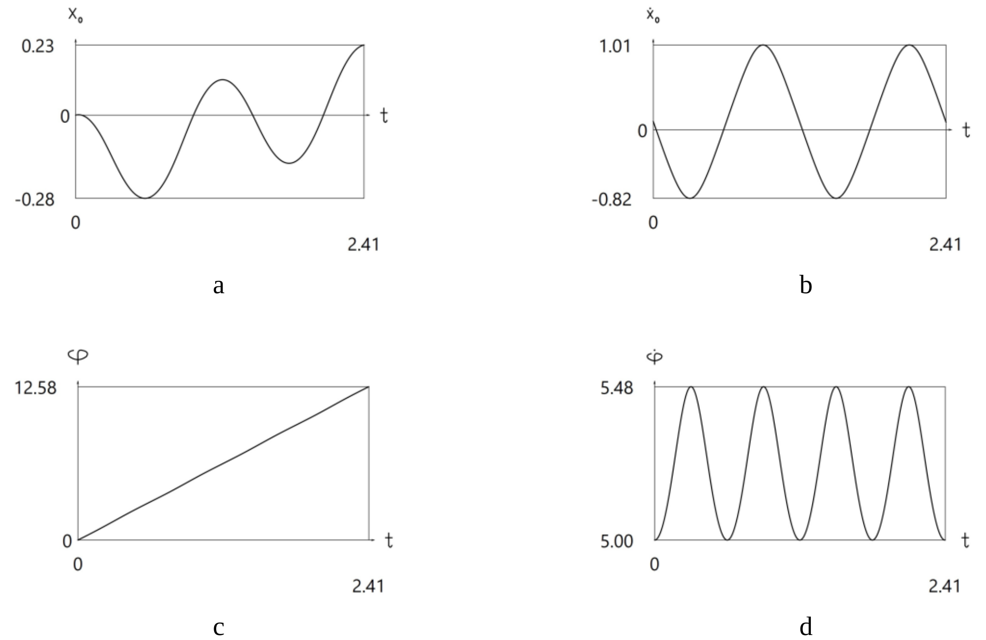


Fig. 3 Dynamics of the conservative system when $x_0(0) = 0$, $\dot{x}_0(0) = 0.1$, $\varphi(0) = 0$, $\dot{\varphi}(0) = 5$: a – $x_0(t)$, b – $\dot{x}_0(t)$, c – $\varphi(t)$ and d – $\dot{\varphi}(t)$

velocity, but the ranges of its variation are not so substantially different.

Minimum and maximum values as functions of the constant force are presented in Fig. 10. The minimum value of velocity is equal to zero for all values of the constant force.

5. System with excitation by vibration drive of unlimited power

In this case in the previous equations, it is assumed that:

$$\varphi = \omega t\,, \tag{19}$$

where ω is the constant angular velocity of rotation of the exciter of vibrations. In this case only the variable x_0 remains and the differential equation of motion becomes the following one:

$$\left(1+\mu\right)\ddot{x}_0 + \mu r\omega^2 \cos\omega t = -a - b\dot{x}_0\,. \tag{20}$$

Further investigation of dynamics of the manipulator with vibration drive based on centrifugal forces is performed.

The following parameters of the investigated system were assumed:

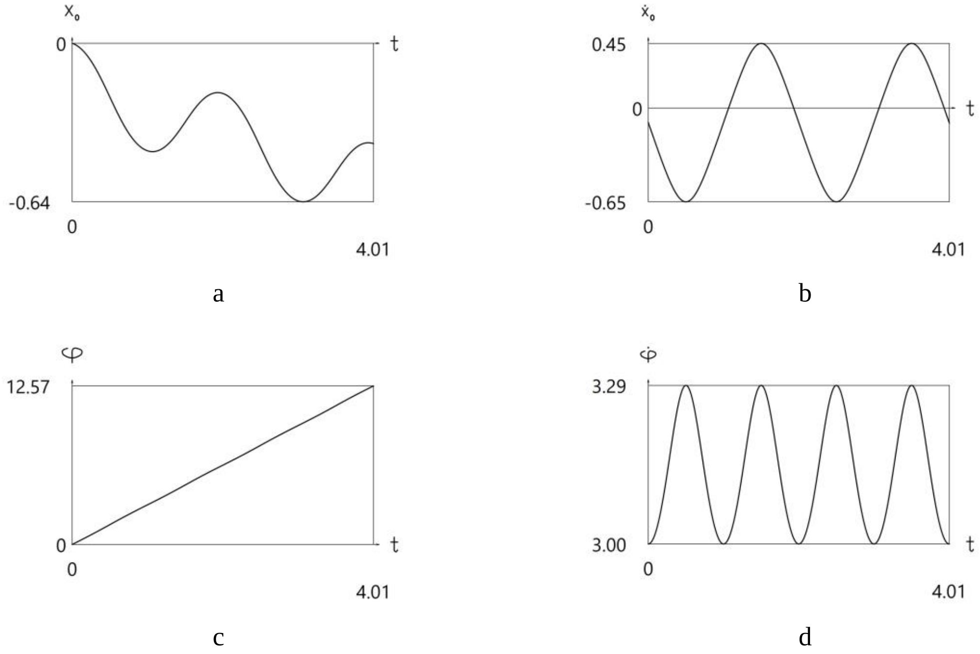


Fig. 4 Dynamics of the conservative system when $x_0(0) = 0$, $\dot{x}_0(0) = -0.1$, $\varphi(0) = 0$, $\dot{\varphi}(0) = 3$: a – $x_0(t)$, b – $\dot{x}_0(t)$, c – $\varphi(t)$ and d – $\dot{\varphi}(t)$

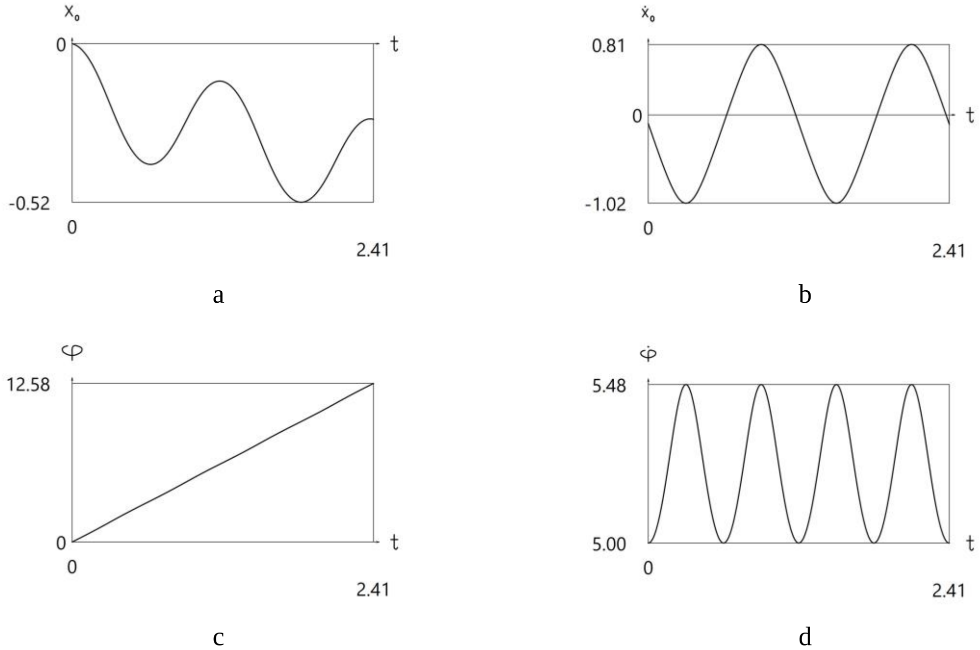


Fig. 5 Dynamics of the conservative system when $x_0(0) = 0$, $\dot{x}_0(0) = -0.1$, $\varphi(0) = 0$, $\dot{\varphi}(0) = 5$: a – $x_0(t)$, b – $\dot{x}_0(t)$, c – $\varphi(t)$ and d – $\dot{\varphi}(t)$

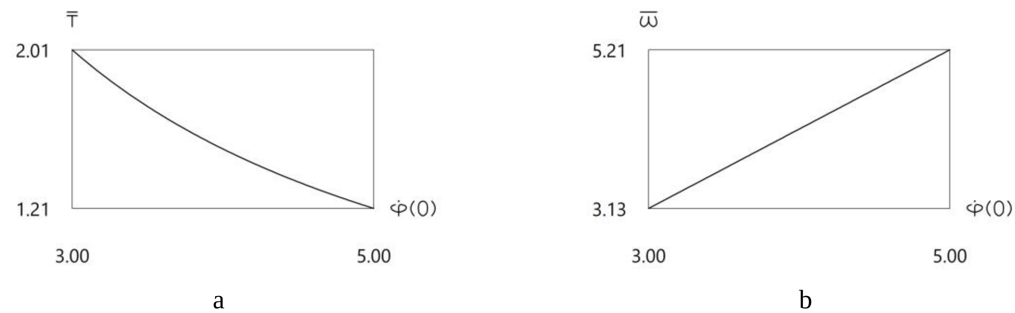
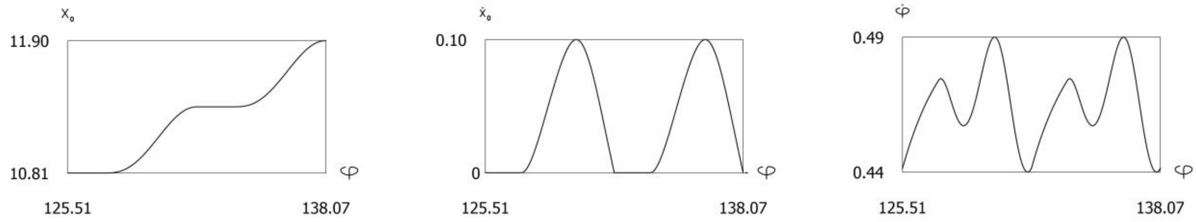
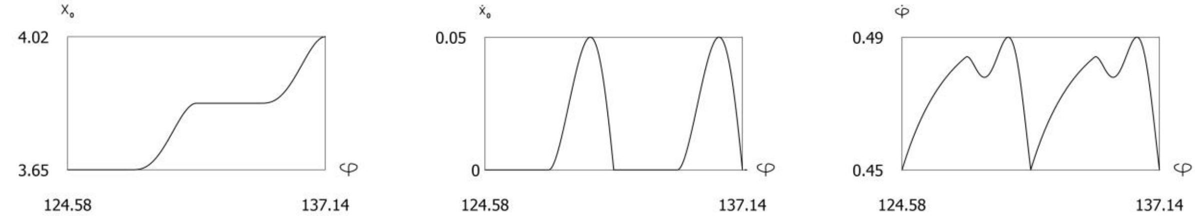


Fig. 6 Eigen period and eigenfrequency as functions of the initial angular velocity: a – $\bar{T}\left(\dot{\varphi}(0)\right)$, b – $\bar{\varpi}\left(\dot{\varphi}(0)\right)$



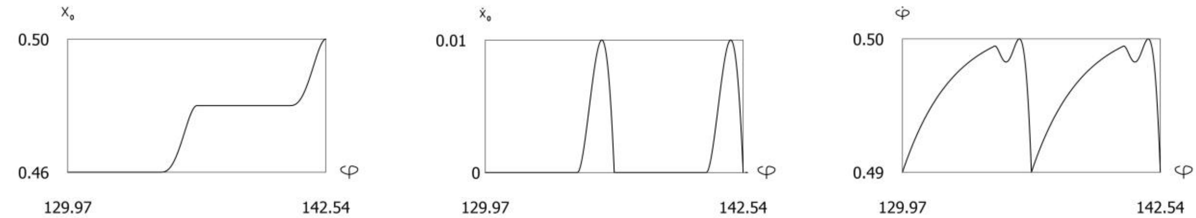
a b c

Fig. 7 Steady state dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0$: a – $x_0(\varphi)$, b – $\dot{x}_0(\varphi)$, c – $\dot{\varphi}(\varphi)$



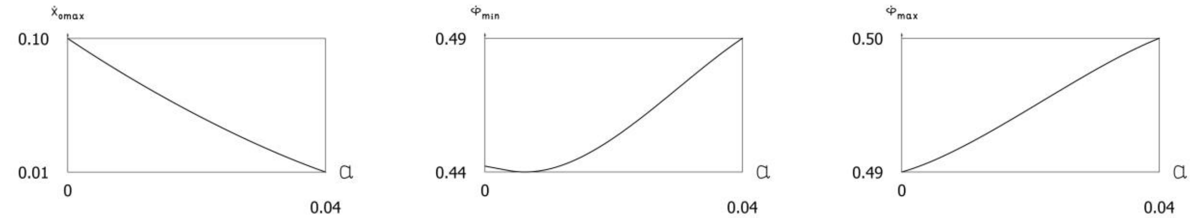
a b c

Fig. 8 Steady state dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0.02$: a – $x_0(\varphi)$, b – $\dot{x}_0(\varphi)$, c – $\dot{\varphi}(\varphi)$



a b c

Fig. 9 Steady state dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0.04$: a – $x_0(\varphi)$, b – $\dot{x}_0(\varphi)$, c – $\dot{\varphi}(\varphi)$



a b c

Fig. 10 Minimum and maximum values as functions of the constant force: a – $\dot{x}_{0max}(a)$, b – $\dot{\varphi}_{min}(a)$, c – $\dot{\varphi}_{max}(a)$

$$\omega = 1,\ \mu = 0.2,\ b = 0.2,\ r = 1. \tag{21}$$

Steady state motions are investigated. Results for various values of the constant force are presented in Fig. 11, Fig. 12, and Fig. 13.

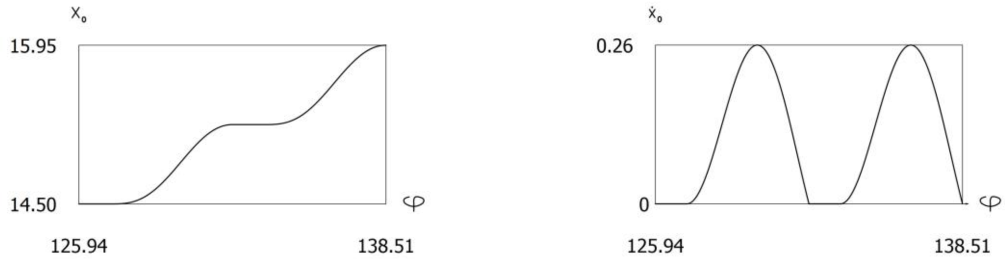
From the presented results the influence of the values of the constant force to the dynamics of the manipulator with vibration drive based on centrifugal forces is seen. From the presented results it is seen that the distance travelled by the manipulator with vibration drive based on centrifugal forces with the increase of the value of the constant force decreases substantially, period when the velocity is equal to zero increases substantially as well as maximum velocity decreases substantially. Those effects correspond to the previously determined ones for the manipulator with vibration drive based on centrifugal forces with limited power.

Maximum values of velocity as function of the constant force are presented in Fig. 14. The minimum value of velocity is equal to zero for all values of the constant force.

6. Experimental investigations of dynamics of the manipulator

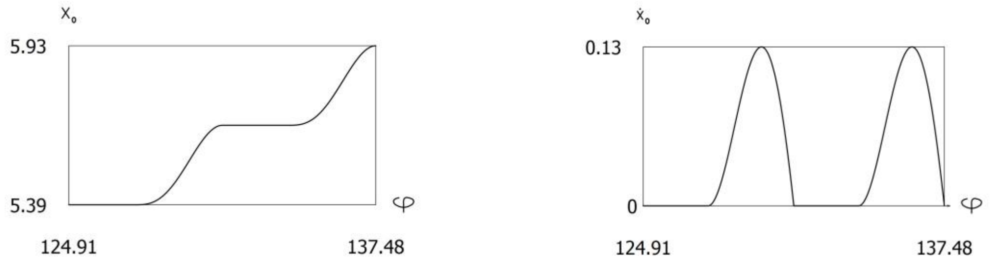
Experimental investigations of the investigated manipulator with vibration drive based on centrifugal forces were performed.

A general view of the manipulator with vibration drive based on centrifugal forces is presented in Fig. 15.



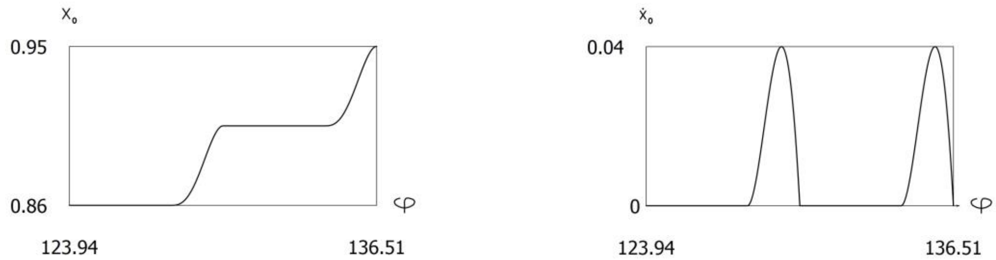
a b

Fig. 11 Steady state dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0$: a – $x_0(\varphi)$, b – $\dot{x}_0(\varphi)$



a b

Fig. 12 Steady state dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0.075$: a – $x_0(\varphi)$, b – $\dot{x}_0(\varphi)$



a b

Fig. 13 Steady state dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0.15$: a – $x_0(\varphi)$, b – $\dot{x}_0(\varphi)$

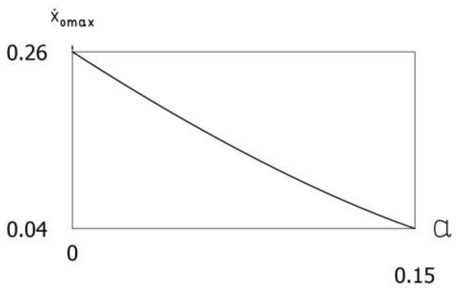


Fig. 14 Maximum values of velocity as function of the constant force $\dot{x}_{0max}(a)$

In the figure supporting elements of the self-stopping mechanism, case of the manipulator, centrifugal mass on the axis of the electric motor, electrical micro motor, connecting wires and transparent case of the manipulator are seen.

Based on the theoretical results, a prototype of the device was developed (Fig. 15). It consists of a cylindrical housing (2) with a rigidly mounted vibrator (4), driven by unbalanced DC motor, inside and thin metal rods (1) mounted on the outside of the housing, in rows of three at 120° intervals, with an angle of inclination of $45^\circ \pm 3^\circ$ degrees with respect to the longitudinal axis of the housing (Fig. 15). For the experiment, the prototype of the device is placed in a cylindrical glass tube (6) with its metal rods (1) resting on the inner side of the glass tube. When the vibrator is triggered by an electrical signal, the rods undergo a directional linear motion inside the tube by means of oscillations in mechanical contact with the inner surface of the glass tube. Experimental tests of the device show that the maximum linear velocity of the device is obtained when an oscillation at 14 Hz is excited.

Technical parameters of the device:

1. Length - 24 mm.
2. Housing diameter - 15 mm.
3. Metal rod diameter - 1,2 mm.
4. Length of metal rods - 8 mm.
5. Angle of inclination of the metal rods - 45°.
6. Frequency of vibration - 14 Hz.
7. Maximum linear speed - 18 mm/s.
8. Mass of the device - 40 g.
9. DC electrical signal up to 6 V is used.

10. MT73 vibration motor 6 - 9 V, current up to 1,5 A.

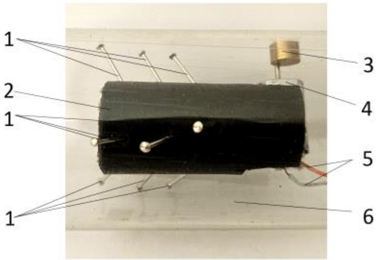


Fig. 15 Manipulator with vibration drive based on centrifugal forces: *1* – supporting elements of the self-stopping mechanism, *2* – case of the manipulator, *3* – centrifugal mass on the axis of the electric motor, *4* – electrical micro motor, *5* – connecting wires, *6* – transparent case of the manipulator

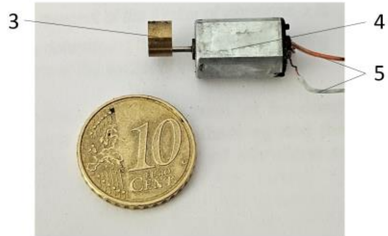
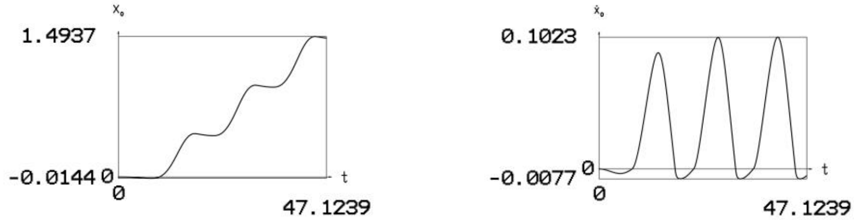


Fig. 16 Electrical micro motor with misbalanced mass: *3* – centrifugal mass on the axis of the electric motor, *4* – electrical micro motor, *5* – connecting wires

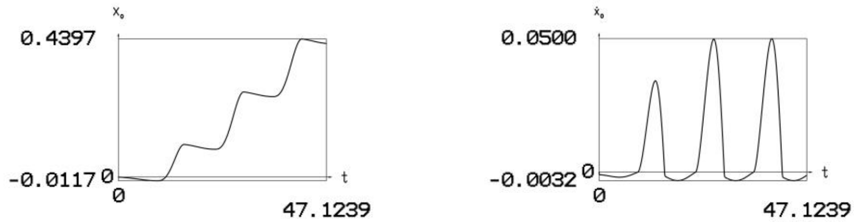
In Fig. 16 an electrical micro motor with centrifugal mass on the axis of the electric motor is shown in detail. In the figure centrifugal mass on the axis of the electric motor, electrical micro motor and connecting wires are seen.

The obtained experimental results are presented in Fig. 17 and Fig. 18.



a b

Fig. 17 Experimental investigation of dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0$: a – $x_0(t)$, b – $\dot{x}_0(t)$



a b

Fig. 18 Experimental investigation of dynamics of the manipulator with vibration drive based on centrifugal forces when $a = 0.02$: a – $x_0(t)$, b – $\dot{x}_0(t)$

From the presented results, similarity between Fig. 17 and Fig. 7 is observed as well as similarity between Fig. 18 and Fig. 8 is observed.

The main source of inadequacy of experimental results with the numerical ones is the fact that in the numerical model an ideal self-stopping mechanism is assumed, while the real self-stopping mechanism behaves in a more complicated way. More precise modelling of a real self-stopping mechanism is an important engineering problem and must be addressed in future investigations.

Experimental results show qualitative agreement with the previously obtained numerical ones.

7. Conclusions

The results for the conservative system are described and investigated. From the presented results the influence of the values of the initial velocity as well as of the initial angular velocity on the dynamics of the conservative system is seen. From the presented results it is seen that the direction of transportation is determined by the sign of the initial velocity. Eigen period and eigenfrequency as functions of the initial angular velocity are determined.

The full dynamic model is investigated in detail. From the presented results the influence of the values of the constant force to the dynamics of the manipulator with vibration drive based on centrifugal forces is seen. From the presented results it is seen that the distance travelled by the manipulator with vibration drive based on centrifugal forces with the increase of the value of the constant force decreases substantially, period when the velocity is equal to zero increases substantially as well as maximum velocity decreases substantially, also one can note that the value of the constant force influences the values of angular velocity, but the ranges of its variation are not so substantially different.

The model with excitation of unlimited power is described and investigated. From the presented results the influence of the values of the constant force to the dynamics of the manipulator with vibration drive based on centrifugal forces is seen. From the presented results it is seen that the distance travelled by the manipulator with vibration drive based on centrifugal forces with the increase of the value of the constant force decreases substantially, period when the velocity is equal to zero increases substantially as well as maximum velocity decreases substantially. Those effects correspond to the previously determined ones for the manipulator with vibration drive based on centrifugal forces with limited power.

Experimental investigations of the investigated manipulator with vibration drive based on centrifugal forces were performed. Experimental results show qualitative agreement with the previously obtained numerical ones.

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K. Ragulskis, A. Bubulis, V. Jūrėnas, J. Vėžys,
P. Paškevičius, L. Ragulskis

INVESTIGATION OF DYNAMICS OF THE MANIPULATOR WITH SELF-STOPPING MECHANISM AND VIBRATION DRIVE BASED ON CENTRIFUGAL FORCES

S u m m a r y

Manipulators of this type can be used as constituent parts of robots of several dimensions. Vibration drive based on centrifugal forces is often used in elements of manipulators and robots. In this paper manipulator with vibration drive based on centrifugal forces and with the self-stopping mechanism is investigated. The model of the investigated manipulator is described and equations determining the motion of the manipulator are obtained. The conservative system is investigated. Then the full dynamic model is investigated. Also, the model with excitation of unlimited power is investigated. Numerical solution of the obtained equations is performed. First the results for the conservative system are described and investigated. Then the full dynamic model is investigated in detail. Also, the model with excitation of unlimited power is described and investigated. Various typical graphical relationships determining the dynamic behavior of the investigated manipulator with vibration drive based on centrifugal forces in steady state regimes of motion are presented. Experimental investigations are performed. The obtained results are used in the process of design of manipulators with vibration drive based on centrifugal forces.

Keywords: centrifugal forces, manipulators, nonlinear behavior, robots, self-stopping mechanism, vibration drive.

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