VYTAUTAS MAGNUS UNIVERSITY MCMXXII
ISSN 1392-1134/ eISSN 2345-0371
AGRICULTURAL ENGINEERING
2024, Vol. 56, 32-37 p.
https://doi.org/10.15544/ageng.2024.56.5

INVESTIGATION OF DYNAMICS OF THE PIPE ROBOT WITH VIBRATION DRIVE BASED ON CENTRIFUGAL FORCES

Kazimieras Ragulskis[1], Arvydas Pauliukas[2], Petras Paškevičius[3], Bronislovas Spruogis[4], Arvydas Matuliauskas[4], Vygantas Mištinas[4], Igor Murovanyi[5], Liutauras Ragulskis[2]
[1]Kaunas University of Technology, Kaunas, Lithuania
[2]Vytautas Magnus University, Akademija, Kaunas District, Lithuania
[3]Company "Vaivora", Kaunas, Lithuania
[4]Vilnius Gediminas Technical University, Vilnius, Lithuania
[5]Lutsk National Technical University, Lutsk, Ukraine

Abstract

Vibration drive based on centrifugal forces can be used as an exciter of vibrations in the structure of a pipe robot. In this paper, a pipe robot with vibration drive based on centrifugal forces is proposed and investigated. A dynamic model of the pipe robot is presented, and differential equations of motion are obtained. Model in which excitation is assumed to be of unlimited power is described and investigated as well. Typical graphical relationships for the investigated pipe robot with vibration drive based on centrifugal forces are obtained and presented. It is determined that the obtained results reproduce the main dynamic effects taking place during the motion of a pipe robot with vibration drive based on centrifugal forces.
Keywords: *pipe robot, centrifugal forces, nonlinear viscous friction, vibration drive.*

Received 2024-02-12, accepted 2024-11-11

1. Introduction

Vibration drive based on centrifugal forces can be used as an exciter of vibrations in the structure of a pipe robot. In this paper, a pipe robot with vibration drive based on centrifugal forces is proposed and investigated.

A dynamic model of the pipe robot is presented, and differential equations of motion are obtained. Nonlinear viscous friction enables vibrational transportation of the pipe robot.

Model in which excitation is assumed to be of unlimited power is described and investigated as well.

Typical graphical relationships for the investigated pipe robot with vibration drive based on centrifugal forces are obtained and presented. It is determined that the obtained results reproduce the main dynamic effects taking place during the motion of a pipe robot with vibration drive based on centrifugal forces.

Nonlinear problems of vibration engineering are investigated in [1]. A capsule-type vibration-driven robot with an electromagnetic actuator and an opposing spring is analyzed in [2]. Contemporary mechanisms in robot engineering are investigated in [3]. Vision-based motion analysis and deflection measurement of a robot's crawler unit is presented in [4]. Underwater robotic system for reservoir maintenance is investigated in [5]. Simulation and experimental investigation of kinematic characteristics of the wheeled in-pipe robot actuated by the unbalanced rotor is presented in [6]. Motion simulation and impact gap verification of a wheeled vibration-driven robot for pipelines inspection is described in [7]. Mathematical modeling and computer simulation of the wheeled vibration-driven in-pipe robot motion is performed in [8]. Dynamics of a wheeled robot driven by an unbalanced rotor is investigated in [9]. Development and investigation of the vibration-driven in-pipe robot is performed in [10]. Transmissions and their dynamics are described in [11]. Nonlinear vibrating systems are presented in [12]. Design of periodic orbits for mechanical systems is investigated in [13]. Essentially nonlinear mechanical systems are analyzed in [14]. Development of spherical ultrasonic motor for pipe inspection robot is presented in [15].

Model of the pipe robot with vibration drive based on centrifugal forces is presented. First, the full system is investigated, then excitation of unlimited power is assumed and a simplified model for this case is also investigated. Graphical representations are obtained and presented.

2. Model of the pipe robot with vibration drive based on centrifugal forces

A pipe robot with vibration drive based on centrifugal forces is presented in Fig. 1. The mass of the case of the pipe robot is denoted as m_0. The displacement of the case of the pipe robot is denoted as x_0. Mass of the exciter of vibrations is denoted as m. Angle of rotation of the exciter of vibrations is denoted as φ. Further the upper dot denotes differentiation with respect to the time variable. The moment of the exciter of vibrations is denoted as $M(\dot{\varphi})$. The coordinate determining the position of the exciting mass of the exciter of vibrations is denoted as x. The force of resistance according to the coordinate x_0 is assumed as $-A - B\dot{x}_0$ where A and B are assumed to be constant values. The moment of the driving force of the unbalanced rotor is assumed to be $C - D\dot{\varphi}$ where C and D are assumed to be constant values.

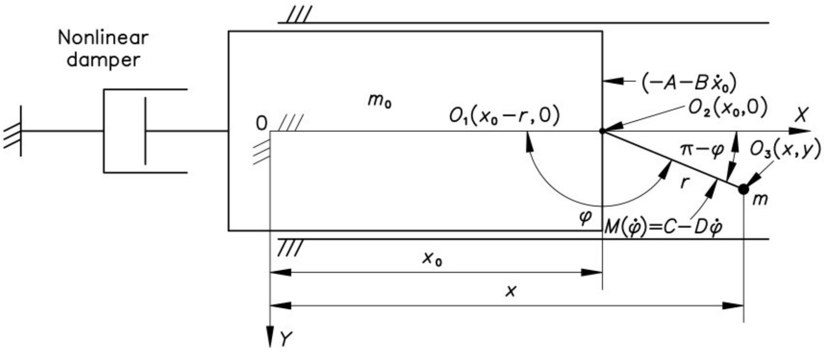

Fig. 1. Pipe robot with vibration drive based on centrifugal forces

Here $O_2(x_0, 0)$ denotes the point of attachment of the exciter of vibrations to the pipe robot. Also, $O_3(x, y)$ denotes the location of the exciting mass of the exciter of vibrations. The distance r is defined as:

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

Dynamics of the pipe robot is described by the following equations:

$$(m + m_0)\ddot{x}_0 + mr(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi) + \begin{Bmatrix} H_1\dot{x}_0 \text{ when } \dot{x}_0 > 0 \\ H_2\dot{x}_0 \text{ when } \dot{x}_0 < 0 \end{Bmatrix} = -A - B\dot{x}_0, \tag{2}$$

$$m(r^2\ddot{\varphi} + r\ddot{x}_0\sin\varphi) = C - D\dot{\varphi}. \tag{3}$$

The equations are simplified by introducing the notations:

$$\mu = \frac{m}{m_0}, h_1 = \frac{H_1}{m_0}, h_2 = \frac{H_2}{m_0}, a = \frac{A}{m_0}, b = \frac{B}{m_0}, c = \frac{C}{rm}, d = \frac{D}{rm}. \tag{4}$$

Finally, dynamics of the pipe robot with vibration drive based on centrifugal forces is described by the equations:

$$(1 + \mu)\ddot{x}_0 + \mu r(\ddot{\varphi}\sin\varphi + \dot{\varphi}^2\cos\varphi) + \begin{Bmatrix} h_1\dot{x}_0 \text{ when } \dot{x}_0 > 0 \\ h_2\dot{x}_0 \text{ when } \dot{x}_0 < 0 \end{Bmatrix} = -a - b\dot{x}_0, \tag{5}$$

$$r\ddot{\varphi} + \ddot{x}_0\sin\varphi = c - d\dot{\varphi}. \tag{6}$$

3. Investigation of dynamics of the pipe robot with vibration drive based on centrifugal forces

Typical parameters of the pipe robot were assumed:

$$\mu = 0.2, r = 1, b = 0.2, h_1 = 0, h_2 = 1000, d = 0.2, c = 0.1. \tag{7}$$

Results for three values of a representing the constant force are shown in Fig. 2, Fig. 3, and Fig. 4.

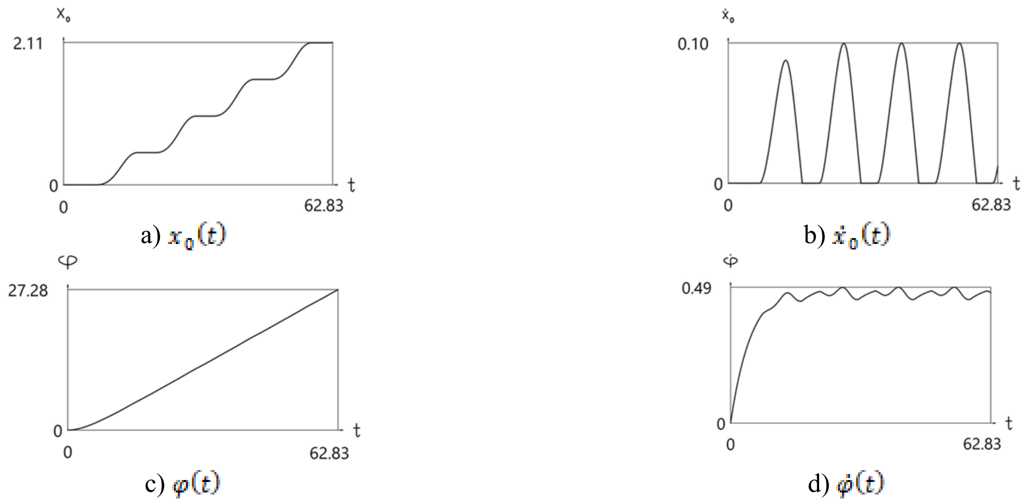

Fig. 2. Dynamics of the pipe robot with vibration drive based on centrifugal forces when $a = 0$

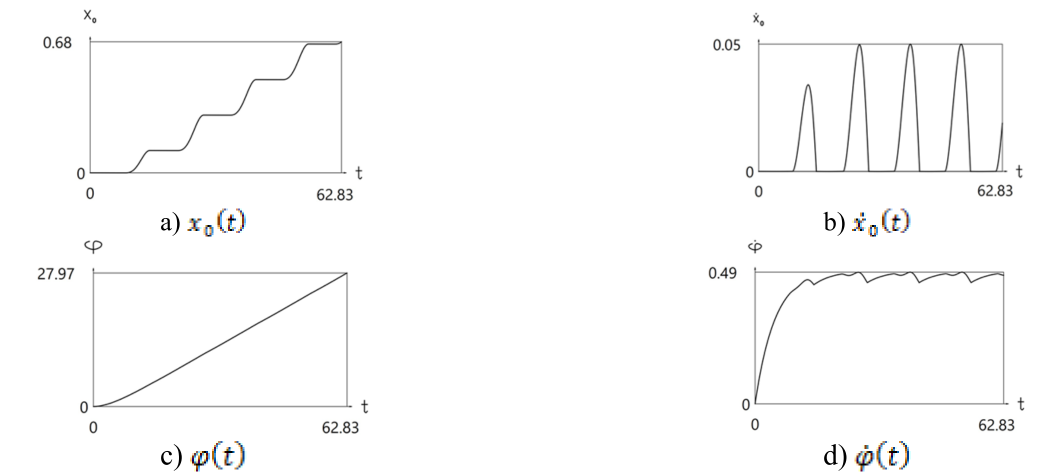

Fig. 3. Dynamics of the pipe robot with vibration drive based on centrifugal forces when $a = 0.02$

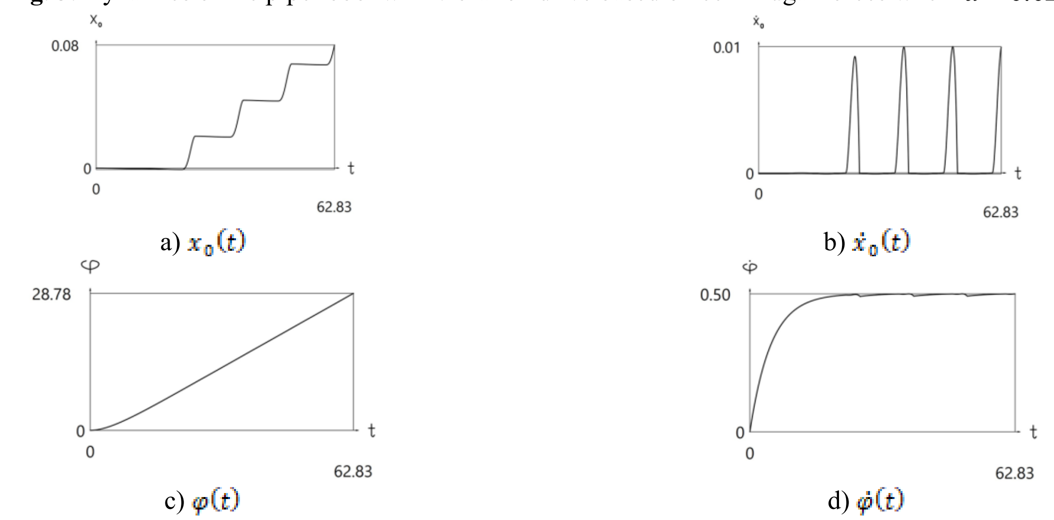

Fig. 4. Dynamics of the pipe robot with vibration drive based on centrifugal forces when $a = 0.04$

The obtained results show the influence of the values of *a* denoting the constant force to the dynamics of the pipe robot with vibration drive based on centrifugal forces. From the obtained results it is determined that the distance travelled by the pipe robot with vibration drive based on centrifugal forces for larger values of *a* decreases, time interval when the velocity is approximately equal to zero increases and maximum velocity decreases. The value of *a* has an effect influencing the values of angular velocity.

4. Pipe robot with vibration drive of unlimited power

For the case of vibration drive of unlimited power:

$$\varphi = \omega t, \tag{8}$$

where ω is the constant denoting the angular velocity of the exciter of vibrations. Dynamics of the pipe robot is described by the coordinate x_0. The equation of motion has the form:

$$(1+\mu)\ddot{x}_0 + \mu r \omega^2 \cos \omega t + \begin{Bmatrix} h_1 \dot{x}_0 \text{ when } \dot{x}_0 > 0 \\ h_2 \dot{x}_0 \text{ when } \dot{x}_0 < 0 \end{Bmatrix} = -a - b\dot{x}_0. \tag{9}$$

Typical parameters of the pipe robot were assumed:

$$\omega = 1, \mu = 0.2, b = 0.2, h_1 = 0, h_2 = 1000, r = 1. \tag{10}$$

Results for three values of *a* representing the constant force are shown in Fig. 5, Fig. 6, and Fig. 7.

a) $x_0(t)$ b)

Fig. 5. Dynamics of the pipe robot with vibration drive based on centrifugal forces when $a = 0$

a) $x_0(t)$ b)

Fig. 6. Dynamics of the pipe robot with vibration drive based on centrifugal forces when $a = 0.075$

a) $x_0(t)$ b)

Fig. 7. Dynamics of the pipe robot with vibration drive based on centrifugal forces when $a = 0.15$

The obtained results show the influence of the values of *a* denoting the constant force to the dynamics of the pipe robot with vibration drive based on centrifugal forces. From the obtained results it is determined that the distance travelled by the pipe robot with vibration drive based on centrifugal forces for larger values of a decreases, time interval when the velocity is approximately equal to zero increases and maximum velocity decreases.

This corresponds to the results obtained earlier for the pipe robot with vibration drive based on centrifugal forces when the power of the exciter of vibrations is limited.

5. Conclusions

The obtained results show the influence of the values of the constant force to the dynamics of the pipe robot with vibration drive based on centrifugal forces. From the obtained results it is determined that the distance travelled by the pipe robot with vibration drive based on centrifugal forces for larger values of the constant force decreases, time interval when the velocity is approximately equal to zero increases and maximum velocity decreases. The value of the constant force has an effect influencing the values of angular velocity.

Pipe robot with vibration drive of unlimited power is investigated. The obtained results show the influence of the values of the constant force to the dynamics of the pipe robot with vibration drive based on centrifugal forces. From the obtained results it is determined that the distance travelled by the pipe robot with vibration drive based on centrifugal forces for larger values of the constant force decreases, time interval when the velocity is approximately equal to zero increases and maximum velocity decreases.

This corresponds to the results obtained earlier for the pipe robot with vibration drive based on centrifugal forces when the power of the exciter of vibrations is limited.

References

[1] I. I. Blekhman, 2018. *Вибрационная механика и вибрационная реология (теория и приложения). (Vibration Mechanics and Vibration Reology (Theory and Applications)).* Moscow: Physmathlit. P. 752.

[2] N. N. Bolotnik, A. M. Nunuparov, V. G. Chashchukhin. Capsule-type vibration-driven robot with an electromagnetic actuator and an opposing spring: dynamics and control of motion. *Journal of Computer and Systems Sciences International,* 2016, 55(6), 986-1000 p. **DOI:** https://doi.org/10.1134/S106423071605004X.

[3] V. Glazunov, 2018. *Новые механизмы в современной робототехнике. (New Mechanisms in Contemporary Robot Engineering).* Moscow: Tehnosphere. P. 316.

[4] P. Kohut, K. Kurc, D. Szybicki, W. Cioch, R. Burdzik. Vision-based motion analysis and deflection measurement of a robot's crawler unit. *Journal of Vibroengineering,* 2015, 17(8), 4112-4121 p.

[5] P. Kohut, M. Giergiel, P. Cieslak, M. Ciszewski, T. Buratowski. Underwater robotic system for reservoir maintenance. *Journal of Vibroengineering,* 2016, 18(6), 3757-3767 p. **DOI:** https://doi.org/10.21595/jve.2016.17364.

[6] V. Korendiy, O. Kachur, V. Gurey, R. Predko, R. Palash, O. Havrylchenko. Simulation and experimental investigation of kinematic characteristics of the wheeled in-pipe robot actuated by the unbalanced rotor. *Vibroengineering Procedia,* 2022, 45, 8-14 p. **DOI:** https://doi.org/10.21595/vp.2022.22971.

[7] V. Korendiy, O. Kachur, V. Gursky, O. Kotsiumbas, P. Dmyterko, S. Nikipchuk, Y. Danylo. Motion simulation and impact gap verification of a wheeled vibration-driven robot for pipelines inspection. *Vibroengineering Procedia,* 2022, 41, 1-6 p. **DOI:** https://doi.org/10.21595/vp.2022.22521.

[8] V. Korendiy, O. Kotsiumbas, V. Borovets, V. Gurey, R. Predko. Mathematical modeling and computer simulation of the wheeled vibration-driven in-pipe robot motion. *Vibroengineering Procedia,* 2022, 44, 1-7 p. **DOI:** https://doi.org/10.21595/vp.2022.22832.

[9] V. Korendiy, O. Kachur, V. Gurey, I. Kuzio, T. Hurey, O. Havrylchenko. Dynamics of a wheeled robot driven by an unbalanced rotor and equipped with the overrunning clutches. *Vibroengineering Procedia,* 2023, 48, 1-7 p. **DOI:** https://doi.org/10.21595/vp.2022.23103.

[10] V. Korendiy, O. Kachur, R. Predko, O. Kotsiumbas, V. Brytkovskyi, M. Ostashuk. Development and investigation of the vibration-driven in-pipe robot. *Vibroengineering Procedia,* 2023, 50, 1-7 p. **DOI:** https://doi.org/10.21595/vp.2023.23513.

[11] R. Kurila; V. Ragulskienė, 1986. *Двумерные вибрационные приводы. (Two – Dimensional Vibro – Transmissions).* Vilnius: Mokslas. P. 137.

[12] V. Ragulskienė, 1974. *Виброударные системы. (Vibro-Shock Systems).* Vilnius: Mintis. P. 320.

[13] S. Spedicato, G. Notarstefano. An optimal control approach to the design of periodic orbits for mechanical systems with impacts. *Nonlinear Analysis: Hybrid Systems,* 2017, 23, 111-121 p. **DOI:** https://doi.org/10.1016/j.nahs.2016.08.009.
[14] A. S. Sumbatov; Ye. K. Yunin, 2013. *Избранные задачи механики систем с сухим трением. (Selected Problems of Mechanics of Systems with Dry Friction).* Moscow: Physmathlit. P. 200.
[15] S. Toyama, M. Hoshina. Development of spherical ultrasonic motor for pipe inspection robot. *Journal of Vibroengineering,* 2011, 13(4), 799-802 p.

Author for contacts:
Arvydas Pauliukas
Vytautas Magnus University
Studentų Str. 11, LT-53361, Akademija, Kaunas District, Lithuania
E-mail: arvydas.pauliukas@vdu.lt