ISSN 1392-1134/ eISSN 2345-0371
AGRICULTURAL ENGINEERING
2023, Vol. 55, 57-65 p.
https://doi.org/10.15544/ageng.2023.55.7

RESULTS OF INVESTIGATION OF IMPROVED CALCULATION OF VISCOUS FRICTION IN THE MODEL OF A PIPE ROBOT

***Kazimieras Ragulskis*[1], *Bronislovas Spruogis*[2], *Arvydas Pauliukas*[3], *Petras Paškevičius*[4], *Anatolii Korpach*[5], *Arvydas Matuliauskas*[6], *Vygantas Mištinas*[7], *Liutauras Ragulskis*[8]**
[1]Kaunas University of Technology, Kaunas, Lithuania
[2, 6, 7]Vilnius Gediminas Technical University, Vilnius, Lithuania
[3]Vytautas Magnus University, Akademija, Kaunas District, Lithuania
[4]Company "Vaivora", Kaunas, Lithuania
[5]National Transport University, Kyiv, Ukraine
[8]Vytautas Magnus University, Kaunas, Lithuania

Abstract

This is the full article based on a conference paper. Pipe robots are used in agricultural engineering for transportation of materials. Also, they are used for cleaning the internal surfaces of the pipes. In the process of numerical investigation of dynamics of a pipe robot, a specific model for viscous friction is used. This influences the results of numerical calculations of dynamics of a pipe robot. A numerical procedure for more precise calculation of viscous friction is proposed in the paper. Results of investigations for two values of time steps are obtained and presented: without the proposed procedure and with it. Advantages of the improved calculation of viscous friction are indicated.
Keywords: *viscous friction, pipe robot, vibrational transportation, dynamic processes.*

Received 2023-09-04, in revised form 2023-12-10

1. Introduction

This is the full article based on a conference paper (Ragulskis *et al.*, 2023). Graphical results without improved calculation of viscous friction and with it were obtained for two typical values of time steps. In the conference paper only results for the first value of time step and only with improved calculation of viscous friction are presented in detail. This paper presents the results of calculations for both values of time steps without application of the proposed procedure and with it.

Pipe robots are used in agricultural engineering for transportation of materials. Also, they are used for cleaning the internal surfaces of the pipes.

In the process of numerical investigation of dynamics of a pipe robot, a specific model for viscous friction is used. This influences the results of numerical calculations of dynamics of a pipe robot.

A numerical procedure for more precise calculation of viscous friction is proposed in the paper. Results of investigations for two values of time steps are obtained and presented: without the proposed procedure and with it.

Advantages of the improved calculation of viscous friction are indicated.

Pipe robots are investigated in [1]. Related problems of dynamics are investigated in [2 - 11] and in other research papers. Dynamics of essentially nonlinear vibrating systems is investigated in [12]. Dynamics of transmissions is investigated in [13]. Robots and their dynamics are investigated in [14].

First the model of a pipe robot having one degree of freedom with forced harmonic excitation is presented. Then the procedure for improved calculation of viscous friction is described. Graphical results without improved calculation of viscous friction and with it are obtained and mutually compared.

2. Model of the pipe robot

Model of a pipe robot was presented in a conference paper [15].

It is assumed that the pipe robot is described by the differential equation:

$$\ddot{x} + 2h\dot{x} = f \sin \omega t, \tag{1}$$

where x denotes the displacement of the pipe robot, h denotes the coefficient of viscous friction, f denotes the amplitude of harmonic excitation, ω denotes the frequency of harmonic excitation, t denotes the time variable, and the upper dot denotes differentiation with respect to the time.

The nonlinear viscous friction has the form:

$$2h = \begin{cases} 2h_2, \text{ when } \dot{x} > 0, \\ 2h_1, \text{ elsewhere}, \end{cases} \tag{2}$$

where h_1 and h_2 are assumed to be constant values.

The force of viscous friction is denoted as:

$$P = 2h\dot{x}. \tag{3}$$

3. Improved calculation of viscous friction in the model of a pipe robot

Procedure for improved calculation of viscous friction in the model of a pipe robot was presented in a conference paper [15].

It is assumed that T denotes the time step, the subscript 0 represents the beginning of a time step and the subscript T represents the end of a time step.

Viscous friction is assumed as:

$$2h = \begin{cases} 2h_2, \text{ when } (\dot{x} > 0) \vee \left((\dot{x} = 0) \& (\ddot{x} > 0)\right), \\ 2h_1, \text{ elsewhere}. \end{cases} \tag{4}$$

If:

$$\dot{x}_T > 0, \tag{5}$$

and:

$$\dot{x}_0 < 0, \tag{6}$$

or if:

$$\dot{x}_T < 0, \tag{7}$$

and:

$$\dot{x}_0 > 0, \tag{8}$$

then the concept of reduced time step is introduced:

$$T_r = -\frac{\dot{x}_0}{\dot{x}_T - \dot{x}_0} T. \tag{9}$$

Then:

$$x_{T_r} = x_0 + (x_T - x_0)\frac{T_r}{T}, \tag{10}$$
$$\dot{x}_{T_r} = 0, \tag{11}$$
$$\ddot{x}_{T_r} = \ddot{x}_0 + (\ddot{x}_T - \ddot{x}_0)\frac{T_r}{T}. \tag{12}$$

4. Results of investigation of dynamics of a pipe robot

The following parameters of the pipe robot are assumed:

$$\omega = 1, f = 1, h_1 = 1, h_2 = 0.1. \tag{13}$$

Calculations from zero initial conditions are performed:

$$x(0) = 0, \dot{x}(0) = 0. \tag{14}$$

Results for two values of the time step are investigated:

$$T = \frac{\frac{2\pi}{\omega}}{40}, \tag{15}$$

and:

$$T = \frac{\frac{2\pi}{\omega}}{80}. \tag{16}$$

Results of calculations for the first value of the time step with improved calculation of viscous friction were presented in a conference paper [15].

4.1. Results of calculations for the first value of the time step

4.1.1. Conventional calculation of viscous friction

Variation of displacement, velocity, acceleration, and velocity multiplied by acceleration is presented in Fig. 1.

The phase trajectories of the pipe robot are presented in Fig. 2.

Force of viscous friction as function of velocity is presented in Fig. 3.

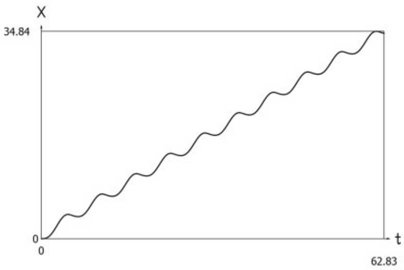
4.1.2. Improved calculation of viscous friction

Results of calculations for the first value of the time step with improved calculation of viscous friction were presented in a conference paper [15].

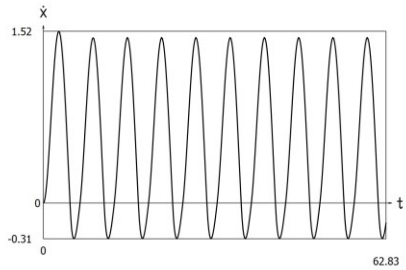
Variation of displacement, velocity, acceleration, and velocity multiplied by acceleration is presented in Fig. 4.

The phase trajectories of the pipe robot are presented in Fig. 5.

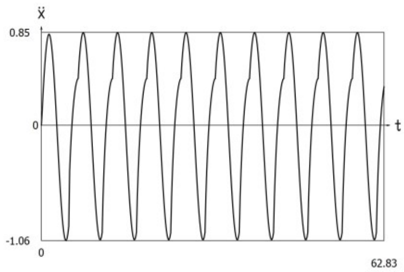
Force of viscous friction as function of velocity is presented in Fig. 6.



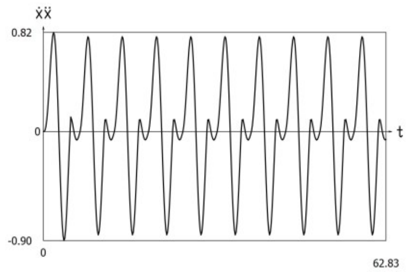
a) Displacement as function of time



b) Velocity as function of time

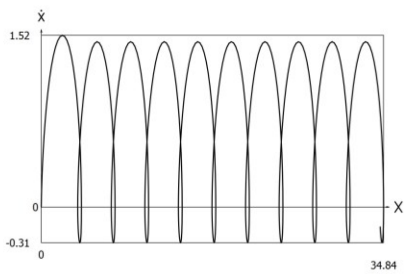


c) Acceleration as function of time

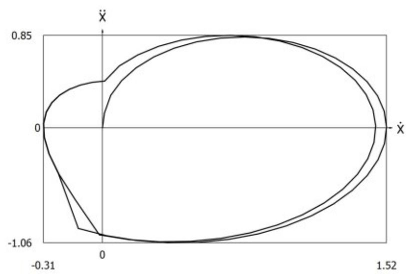


d) Velocity multiplied by acceleration as function of time

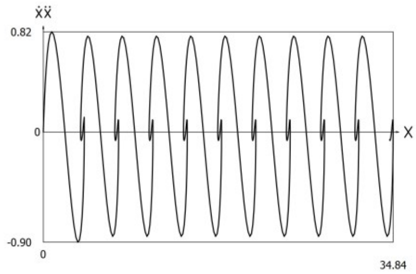
Fig. 1. Dynamics of the pipe robot



a) Velocity as function of displacement



b) Acceleration as function of velocity



c) Velocity multiplied by acceleration as function of displacement

Fig. 2. Phase trajectories of the pipe robot

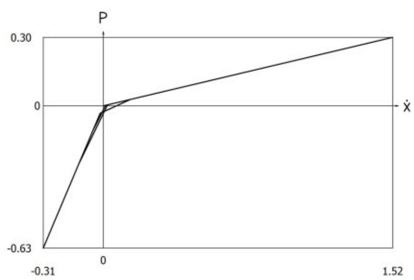
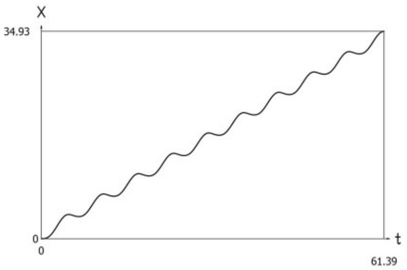
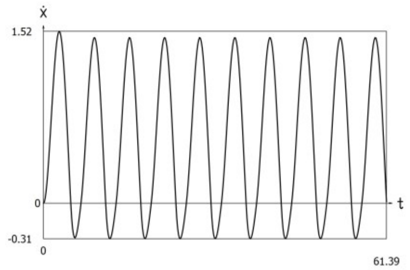


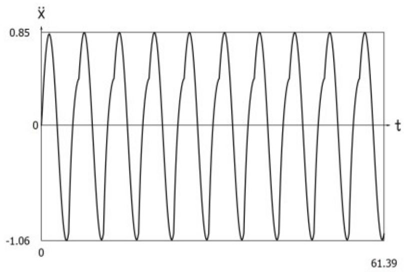
Fig. 3. Force of viscous friction as function of velocity



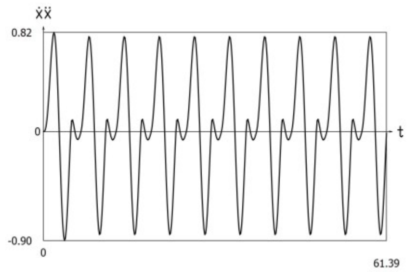
a) Displacement as function of time



b) Velocity as function of time

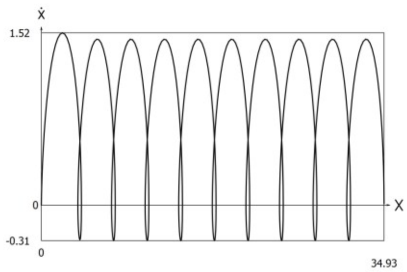


c) Acceleration as function of time

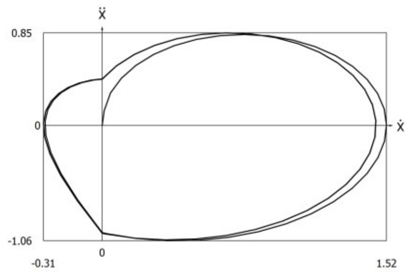


d) Velocity multiplied by acceleration as function of time

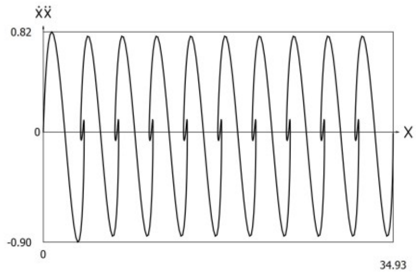
Fig. 4. Dynamics of the pipe robot [15]



a) Velocity as function of displacement



b) Acceleration as function of velocity



c) Velocity multiplied by acceleration as function of displacement

Fig. 5. Phase trajectories of the pipe robot [15]

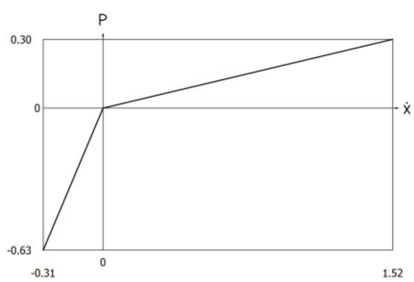


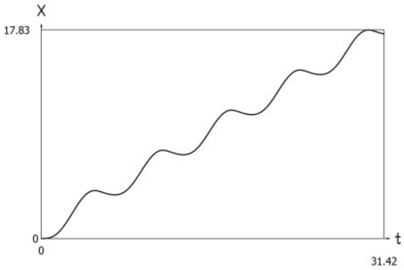
Fig. 6. Force of viscous friction as function of velocity [15]

It can be noted that the improved procedure for calculation of viscous friction has advantages, which are evident from the comparison of some of the corresponding graphical results. This is especially clear from the comparison of force of viscous friction as function of velocity at the origin of the coordinate system.

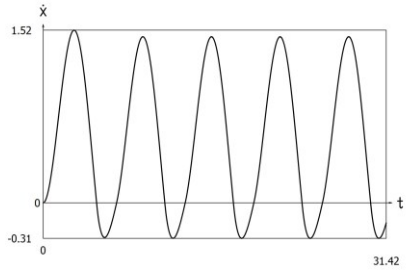
4.2. Results of calculations for the second value of the time step

4.2.1. Conventional calculation of viscous friction

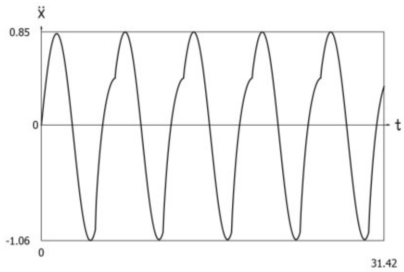
Variation of displacement, velocity, acceleration, and velocity multiplied by acceleration is presented in Fig. 7.



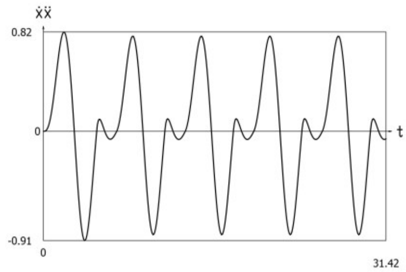
a) Displacement as function of time



b) Velocity as function of time



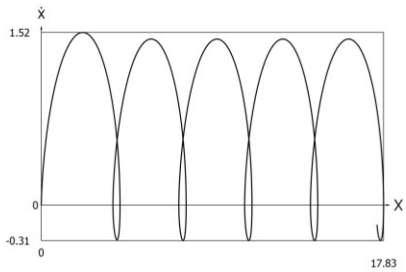
c) Acceleration as function of time



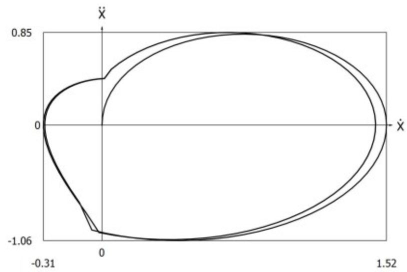
d) Velocity multiplied by acceleration as function of time

Fig. 7. Dynamics of the pipe robot

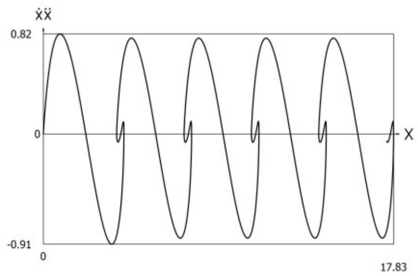
The phase trajectories of the pipe robot are presented in Fig. 8.



a) Velocity as function of displacement



b) Acceleration as function of velocity



c) Velocity multiplied by acceleration as function of displacement

Fig. 8. Phase trajectories of the pipe robot

Force of viscous friction as function of velocity is presented in Fig. 9.

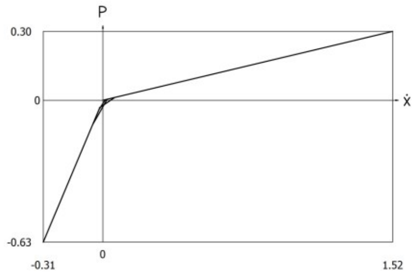
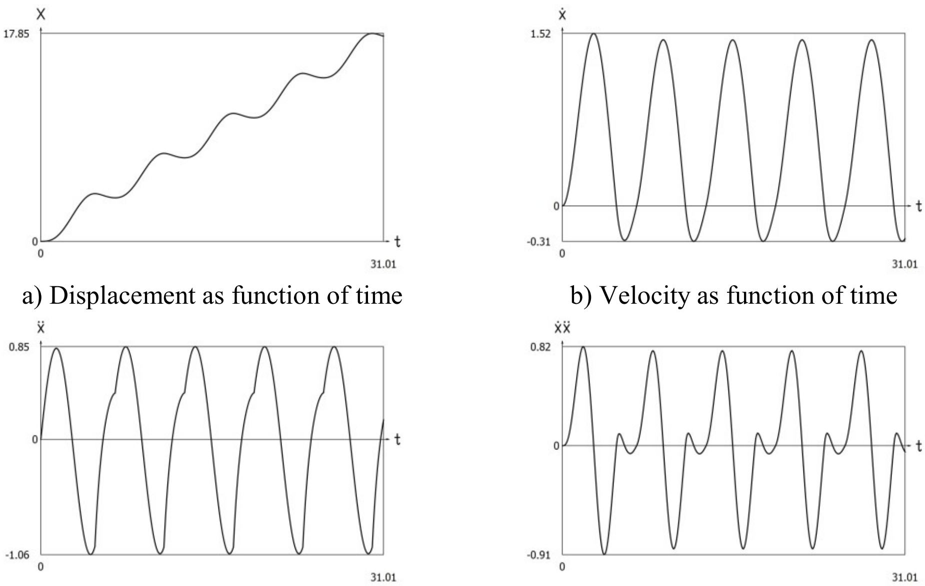


Fig. 9. Force of viscous friction as function of velocity

4.2.2. Improved calculation of viscous friction

Variation of displacement, velocity, acceleration, and velocity multiplied by acceleration is presented in Fig. 10.



a) Displacement as function of time

b) Velocity as function of time

c) Acceleration as function of time

d) Velocity multiplied by acceleration as function of time

Fig. 10. Dynamics of the pipe robot

The phase trajectories of the pipe robot are presented in Fig. 11.

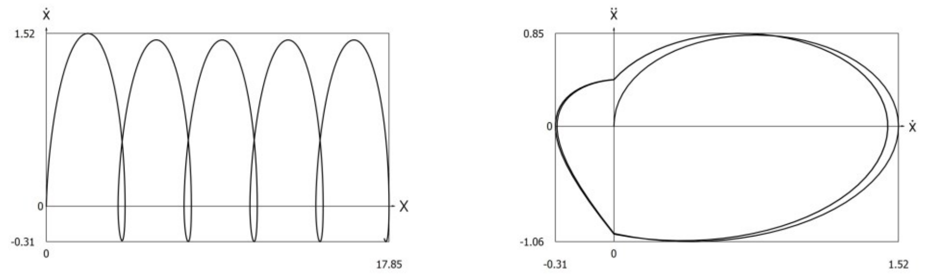
Force of viscous friction as function of velocity is presented in Fig. 12.

It can be noted that the improved procedure for calculation of viscous friction has advantages, which are evident from the comparison of some of the corresponding graphical results. This is especially clear from the comparison of force of viscous friction as function of velocity at the origin of the coordinate system.

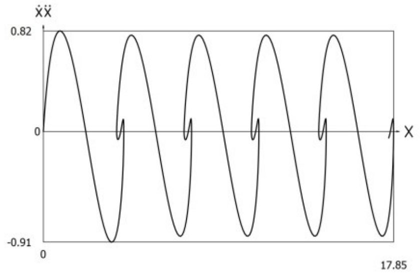
From the presented investigation advantages of the improved calculation of the force of viscous friction are observed.

5. Conclusions

In the process of numerical investigation of dynamics of a pipe robot, a specific model for viscous friction is used. This influences the results of numerical calculations of dynamics of a pipe robot. A numerical procedure for more precise calculation of viscous friction is proposed in the paper. Results of investigations for two values of time steps are obtained and presented: without the proposed procedure and with it.



a) Velocity as function of displacement b) Acceleration as function of velocity



c) Velocity multiplied by acceleration as function of displacement

Fig. 11. Phase trajectories of the pipe robot

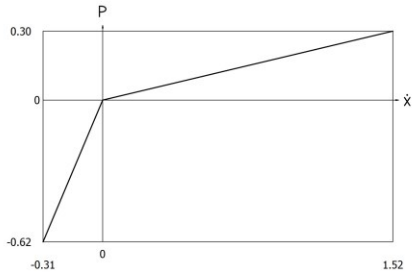


Fig. 12. Force of viscous friction as function of velocity

Variations of displacement, velocity, acceleration, and velocity multiplied by acceleration are investigated. Phase trajectories of the pipe robot are obtained. Force of viscous friction as function of velocity is represented.

It can be noted that the improved procedure for calculation of viscous friction has advantages, which are evident from the comparison of some of the corresponding graphical results. This is especially clear from the comparison of force of viscous friction as function of velocity at the origin of the coordinate system.

From the presented investigation advantages of the improved calculation of the force of viscous friction are observed.

6. Acknowledgements

The authors thank the anonymous reviewers of the conference paper (Ragulskis *et al.*, 2023) for indicating the importance of presenting detailed results of calculations.

References

[1] K. Ragulskis, B. Spruogis, M. Bogdevičius, A. Pauliukas, A. Matuliauskas, V. Mištinas, L. Ragulskis. Investigation of dynamics of a pipe robot with vibrational drive and unsymmetric with respect to the direction of velocity of motion dissipative forces. *Agricultural Engineering,* 2020, 52, 1-6 p. **DOI:** https://doi.org/10.15544/ageng.2020.52.1.

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

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

[4] 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.
[5] R. Bansevičius; A. Ivanov; N. Kamyshnyj; A. Kostin; L. Lobikov; V. Michieiev; T. Nikolskaja; K. Ragulskis; V. Shangin, 1985. *Промышленные роботы для миниатюрных изделий. (Industrial Robots for Miniature Products).* Moscow: Mashinostroyenye. P. 264.
[6] E. Kibirkštis, D. Pauliukaitis, V. Miliūnas, K. Ragulskis. Synchronization of pneumatic vibroexciters operating on air cushion with feeding pulsatile pressure under autovibration regime. *Journal of Mechanical Science and Technology,* 2018, 32(1), 81-89 p. **DOI:** https://doi.org/10.1007/s12206-017-1209-7.
[7] K. Ragulskis; J. Vitkus; V. Ragulskienė, 1965. *Самосинхронизация механических систем (1. Самосинхронные и виброударные системы). (Self-Synchronization of the Mechanical Systems (1. Self-Synchronizations and Vibro-Shock Systems)).* Vilnius: Mintis. P. 186.
[8] K. Ragulskis, B. Spruogis, P. Paškevičius, A. Matuliauskas, V. Mištinas, A. Pauliukas, L. Ragulskis. Investigation of dynamics of a pipe robot experiencing impact interactions. *Advances in Robotics & Automation Technology,* 2021, 1(2), 1-8 p. **DOI:** 10.39127/2021/ARAT:1000103.
[9] B. Spruogis, K. Ragulskis, M. Bogdevičius, M. Ragulskis, A. Matuliauskas, V. Mištinas. Robot Performing Stepping Motion inside the Pipe. *Patent LT 4968 B,* 2002.
[10] 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.
[11] 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.
[12] V. Ragulskienė, 1974. *Виброударные системы. (Vibro-Shock Systems).* Vilnius: Mintis. P. 320.
[13] R. Kurila; V. Ragulskienė, 1986. *Двумерные вибрационные приводы. (Two – Dimensional Vibro – Transmissions).* Vilnius: Mokslas. P. 137.
[14] K. Ragulskis; R. Bansevičius; R. Barauskas; G. Kulvietis, 1987. *Vibromotors for Precision Microrobots.* New York: Hemisphere. P. 326.
[15] K. Ragulskis, B. Spruogis, A. Pauliukas, P. Paškevičius, A. Korpach, A. Matuliauskas, V. Mištinas, L. Ragulskis. Improved calculation of viscous friction in the model of a pipe robot. *Proceedings of the 11th International Conference BALTTRIB'2022,* 2023, 11, 34-38 p. **DOI:** 10.15544/balttrib.2022.8.

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