ISSN 1392-1134/ eISSN 2345-0371
AGRICULTURAL ENGINEERING
2021, Vol. 53, 55-62 p.
https://doi.org/10.15544/ageng.2021.53.10

INVESTIGATION OF DYNAMICS OF MANIPULATORS AND ROBOTS, THE MOTION OF WHICH IS EXCITED BY AN EXTERNAL VARIABLE FORCE THROUGH MUTUAL IMPACTS OF THEIR SEPARATE ELEMENTS

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

Abstract

Manipulators and robots find a number of applications in agricultural engineering. They are used in pipe robots for transportation of materials. Also pipe robots are applied for cleaning of internal surfaces of the pipes. Impact interactions take place in the process of dynamic behavior in the elements of manipulators and robots. Their precise investigation is an important engineering problem. A model having one degree of freedom with forced excitation and impacts is investigated. The values of coefficient of restitution and coefficient of viscous damping have basic effect to the dynamic behavior of such systems. In this paper the investigations of the dependence of regions with single valued regimes of motion from the coefficient of restitution and from the coefficient of viscous damping are performed. This paper is devoted to numerical experiment: the model of the system is presented in detail as well as the parameters for which calculations were performed are indicated. The presented graphical relationships enable to choose the regimes suitable for operation of elements of manipulators and robots. They are applicable in the process of design of pipe robots.
Keywords: *elements of manipulators, elements of robots, impact interactions, forced excitation, nonlinear behaviour, coefficient of restitution, coefficient of viscous damping.*

Received 2021-10-19, accepted 2021-12-14

1. Introduction

Manipulators and robots find a number of applications in agricultural engineering. They are used in pipe robots for transportation of materials. Also pipe robots are applied for cleaning of internal surfaces of the pipes.

Impact interactions take place in the process of dynamic behavior in the elements of manipulators and robots. Their precise investigation is an important engineering problem.

Mechanical system of the manipulator – robot is presented in Fig. 1. The driving force of the case of the manipulator 1 is provided by the impacting element 2 to which the variable external force is acting, while the one-sided motion of the case 2 is ensured by the self stopping device 4 because of the interaction with the immovable foundation. The self stopping device may be a mechanism based on friction between the elements 4 and 5 or it can be based on mechanisms of various types, for example it can be a worm gear mechanism.

Pipe robot with impact interactions is described in (Spruogis *et al.*, 2002). In this paper impact interactions in the elements of a pipe robot are investigated in detail.

Pipe robots and their application in agricultural engineering are investigated in (Ragulskis, Spruogis, Bogdevičius, Pauliukas *et al.*, 2020). This paper continues the investigations about pipe robots in agricultural engineering presented in the previous paper.

Related problems of analysis of dynamics of nonlinear systems and elements of manipulators and robots are investigated in (Glazunov, 2018), (Blekhman, 2018), (Bolotnik *et al.*, 2016), (Bansevičius *et al.*, 1985), (Kibirkštis *et al.*, 2018), (Ragulskis *et al.*, 1965), (Mištinas *et al.*, 2006), (Ragulskis, Bogdevičius *et al.*, 2006), (Ragulskis, Spruogis, Matuliauskas, Mištinas, two references, 2006), (Matuliauskas *et al.*, 2007), (Ragulskis, Bogdevičius *et al.*, 2008), (Ragulskis, Ragulskis *et al.*, 2008), (Ragulskis, Spruogis, Bogdevičius, Matuliauskas, Mištinas, Ragulskis, three references, 2020), (Ragulskis, Spruogis, Bogdevičius *et al.*, 2021), (Ragulskis, Spruogis, Matuliauskas *et al.*, 2021), (Ragulskis, Spruogis, Paškevičius *et al.*, 2021), (Spedicato, Notarstefano, 2017), (Sumbatov, Yunin, 2013) and in a number of other research papers.

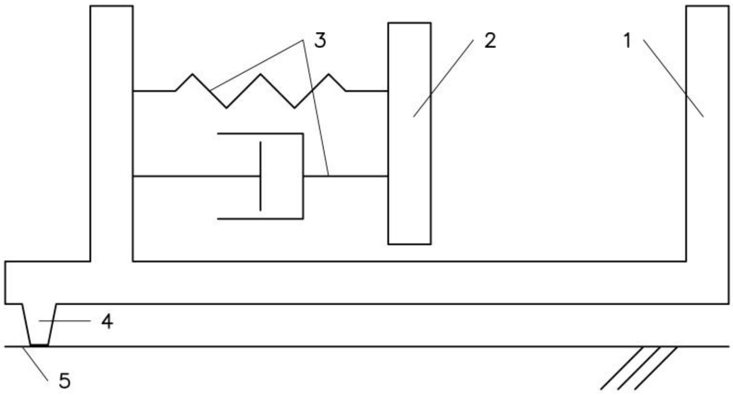


Fig. 1. Mechanical system of the manipulator – robot: 1 – case, 2 – element impacting into the case, 3 – elements connecting the impacting mass and the case, 4 – one sided self stopping device between the case and the immovable foundation, 5 – the immovable foundation

Dynamics of vibrating systems with impacts is investigated in (Ragulskienė, 1974). Transmissions and their vibrations are analysed in (Kurila, Ragulskienė, 1986). Dynamics of elements of manipulators and robots is presented in (Ragulskis *et al.*, 1987). This paper is based on some of the basic results presented in those three research monographs.

A model having one degree of freedom with forced excitation and impacts is investigated. The values of coefficient of restitution and coefficient of viscous damping have basic effect to the dynamic behavior of such systems. In this paper the investigations of the dependence of regions with single valued regimes of motion from the coefficient of restitution and from the coefficient of viscous damping are performed.

The presented graphical relationships enable to choose the regimes suitable for operation of elements of manipulators and robots. This paper is devoted to numerical experiment: the model of the system is presented in detail as well as the parameters for which calculations were performed are indicated. This paper is a continuation of investigations of the authors presented in their other papers.

The presented results of the performed investigation are used in the process of design of elements of manipulators and robots. They are applicable in the process of design of pipe robots.

2. Model of the element of the system with impact interactions

Dynamics of the investigated system in non dimensional form is described by the following differential equation:

$$x'' + 2hx' + x = f \sin \nu\tau, \tag{1}$$

where x denotes the non dimensional displacement, h denotes the non dimensional viscous damping coefficient, f denotes the non dimensional excitation amplitude, ν denotes the non dimensional frequency, τ denotes the non dimensional time variable, the prime in the superscript indicates derivative with respect to non dimensional time.

This equation is valid when:

$$x < 0. \tag{2}$$

Impact is described in the following way:

$$x'^{+} = -Rx'^{-}, \tag{3}$$

where R denotes the restitution coefficient, superscript minus denotes the quantity before impact, superscript plus denotes the quantity after impact.

Impact takes place when:

$$x = 0. \tag{4}$$

Zero initial conditions were assumed, that is:

$$x(0) = 0,\ x'(0) = 0. \tag{5}$$

Motions of the investigated element of manipulators and robots in regimes that are periodic are analysed.

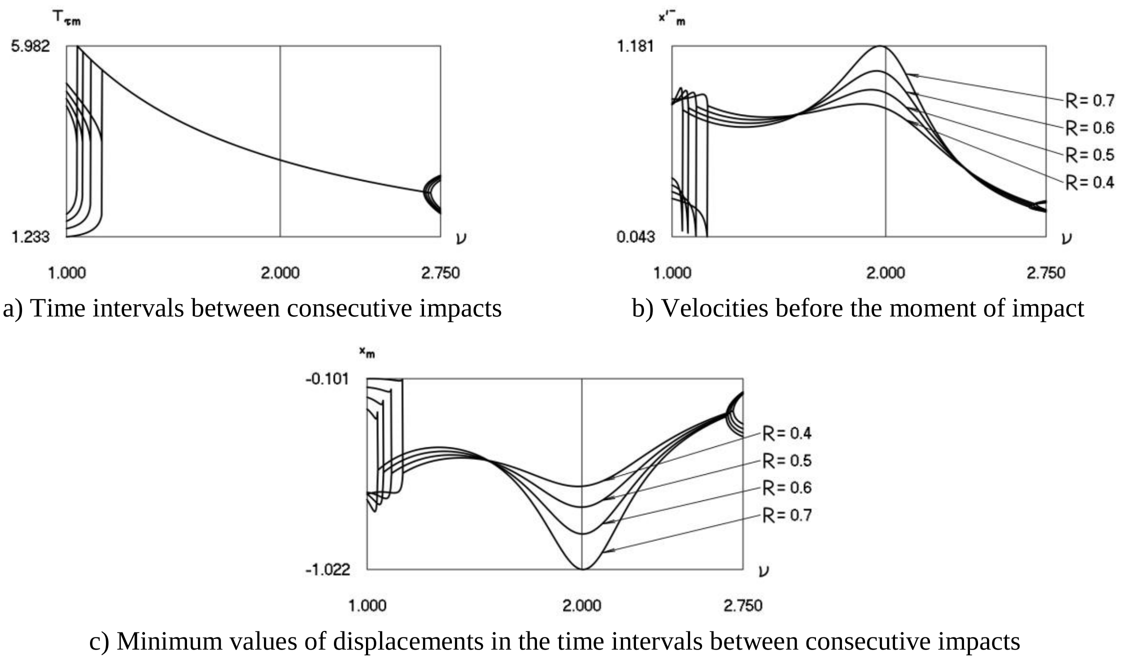
3. Dependence of regions of single valued motions of the investigated element of manipulators and robots from the coefficient of restitution

The following values of the parameters of the vibro impact system with forced excitation were assumed in the presented investigation:

$$f = -0.5,\ h = 0.1. \tag{6}$$

3.1. Regions in the vicinity of the value of non dimensional frequency equal to two

Main characteristics of dynamics of the investigated system in periodic regime of motion at $\nu = 2$ are shown in Fig. 2.



a) Time intervals between consecutive impacts

b) Velocities before the moment of impact

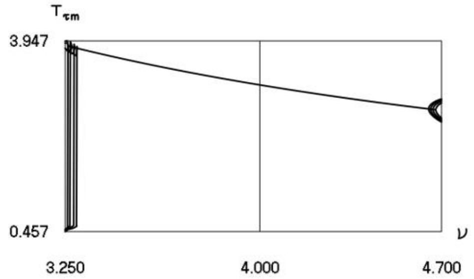
c) Minimum values of displacements in the time intervals between consecutive impacts

Fig. 2. Dependence of minimum values and of maximum values from the coefficient of restitution for $f = -0.5,\ h = 0.1$ in the vicinity of $\nu = 2$

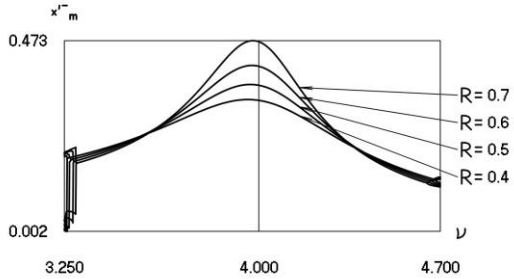
In Fig. 2 the values of time intervals between consecutive impacts, velocities before the moment of impact and minimum values of displacements in the time intervals between consecutive impacts are represented. Results for the following values of coefficient of restitution $R = 0.4,\ R = 0.5,\ R = 0.6,\ R = 0.7$ are presented. Time intervals between consecutive impacts are mutually similiar in a greater part of the represented frequency region for the four values of coefficient of restitution. Frequency regions with single valued regimes of motion and their dependence on the coefficient of restitution are seen from the presented graphical relationships.

3.2. Regions in the vicinity of the value of non dimensional frequency equal to four

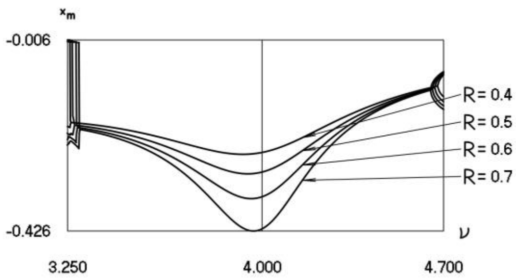
Main characteristics of dynamics of the investigated system in periodic regime of motion at $\nu = 4$ are shown in Fig. 3.



a) Time intervals between consecutive impacts



b) Velocities before the moment of impact



c) Minimum values of displacements in the time intervals between consecutive impacts

Fig. 3. Dependence of minimum values and of maximum values from the coefficient of restitution for $f = -0.5,\ h = 0.1$ in the vicinity of $\nu = 4$

3.3. Regions in the vicinity of the value of non dimensional frequency equal to six

Main characteristics of dynamics of the investigated system in periodic regime of motion at $\nu = 6$ are shown in Fig. 4.

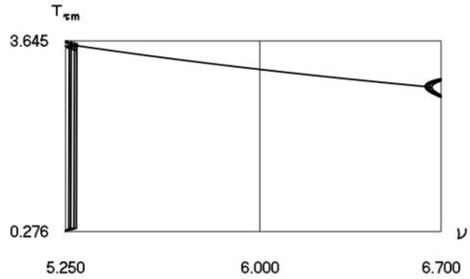
4. Dependence of regions of single valued motions of the investigated element of manipulators and robots from the coefficient of viscous damping

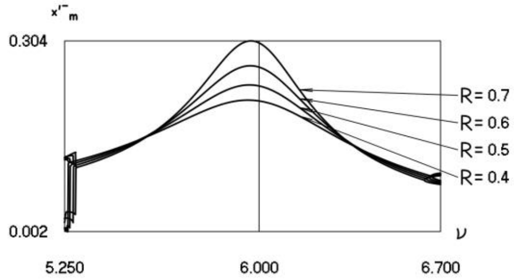
The following values of the parameters of the vibro impact system with forced excitation were assumed in the presented investigation:

$$f = -0.5,\ R = 0.7. \qquad (7)$$

4.1. Regions in the vicinity of the value of non dimensional frequency equal to two

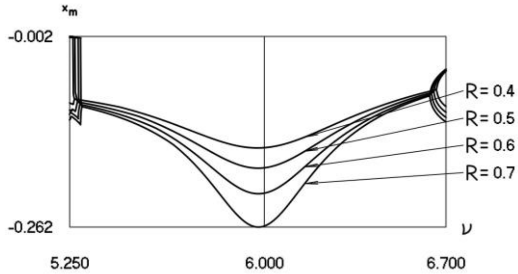
Main characteristics of dynamics of the investigated system in periodic regime of motion at $\nu = 2$ are shown in Fig. 5.





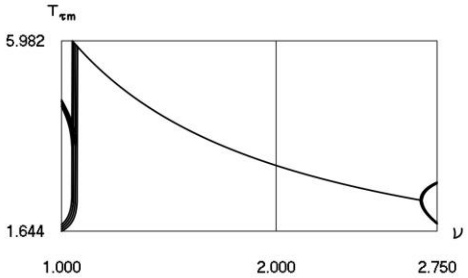
a) Time intervals between consecutive impacts

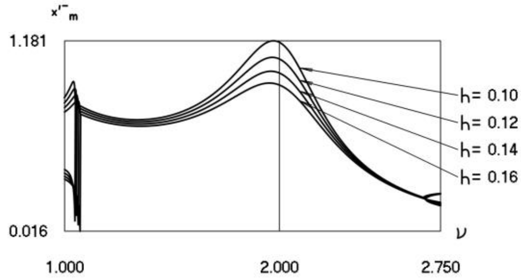
b) Velocities before the moment of impact



c) Minimum values of displacements in the time intervals between consecutive impacts

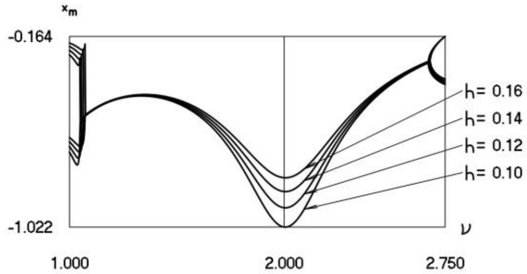
Fig. 4. Dependence of minimum values and of maximum values from the coefficient of restitution for $f = -0.5,\ h = 0.1$ in the vicinity of $\nu = 6$





a) Time intervals between consecutive impacts

b) Velocities before the moment of impact



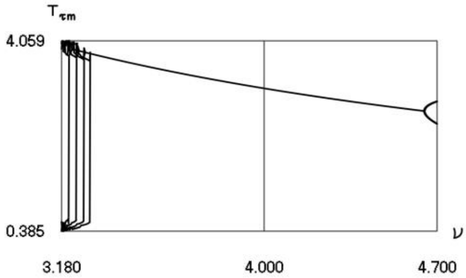
c) Minimum values of displacements in the time intervals between consecutive impacts

Fig. 5. Dependence of minimum values and of maximum values from the coefficient of viscous damping for $f = -0.5,\ R = 0.7$ in the vicinity of $\nu = 2$

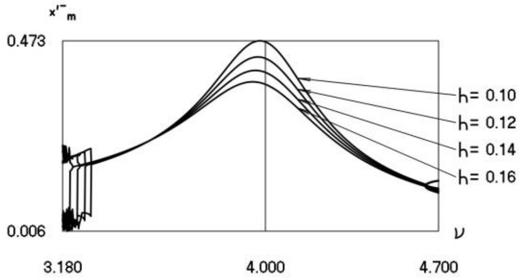
In Fig. 5 the values of time intervals between consecutive impacts, velocities before the moment of impact and minimum values of displacements in the time intervals between consecutive impacts are represented. Results for the following values of coefficient of viscous damping $h = 0.1,\ h = 0.12,\ h = 0.14,\ h = 0.16$ are presented. Time intervals between consecutive impacts are mutually similiar in a greater part of the represented frequency region for the four values of coefficient of viscous damping. Frequency regions with single valued regimes of motion and their dependence on the coefficient of viscous damping are seen from the presented graphical relationships.

4.2. Regions in the vicinity of the value of non dimensional frequency equal to four

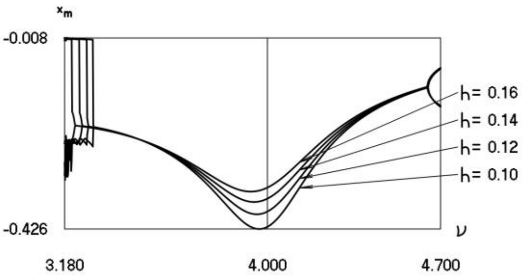
Main characteristics of dynamics of the investigated system in periodic regime of motion at $\nu = 4$ are shown in Fig. 6.



a) Time intervals between consecutive impacts



b) Velocities before the moment of impact

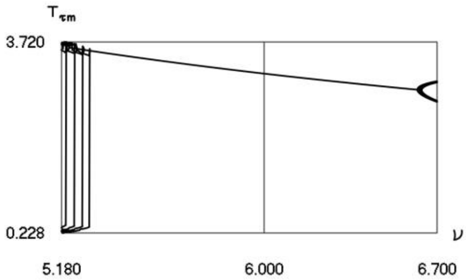


c) Minimum values of displacements in the time intervals between consecutive impacts

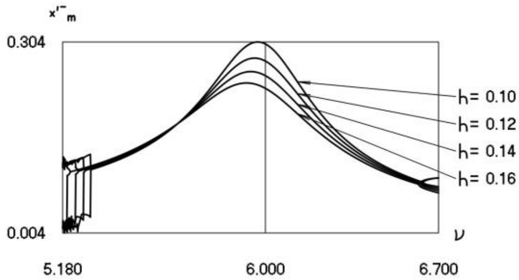
Fig. 6. Dependence of minimum values and of maximum values from the coefficient of viscous damping for $f = -0.5,\ R = 0.7$ in the vicinity of $\nu = 4$

4.3. Regions in the vicinity of the value of non dimensional frequency equal to six

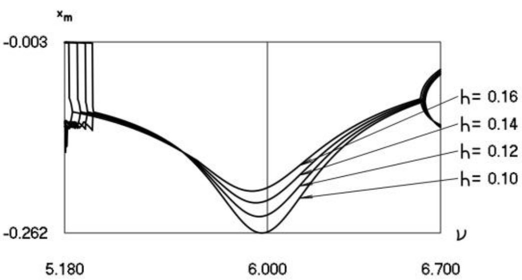
Main characteristics of dynamics of the investigated system in periodic regime of motion at $\nu = 6$ are shown in Fig. 7.



a) Time intervals between consecutive impacts



b) Velocities before the moment of impact



c) Minimum values of displacements in the time intervals between consecutive impacts

Fig. 7. Dependence of minimum values and of maximum values from the coefficient of viscous damping for $f = -0.5,\ R = 0.7$ in the vicinity of $\nu = 6$

5. Conclusions

Impact interactions take place in the elements of manipulators and robots, especially in pipe robots, which are used in agricultural engineering.

In this paper a model having one degree of freedom with forced excitation and impacts is investigated numerically. Such impact interactions take place in the elements of pipe robots. The values of coefficient of restitution and coefficient of viscous damping have basic effect to the dynamic behavior of such systems.

Various dynamic regimes of operation in essentially nonlinear systems, such as vibro impact systems, take place. They include multi valued and chaotic regimes of motion. Regions of single valued motions play an important role in the theory of vibro impact systems, as they are desirable from the engineering point of view. Thus, the investigations of the dependence of regions with single valued regimes of motion from the coefficient of restitution and from the coefficient of viscous damping are performed.

The presented graphical relationships enable to choose the regimes suitable for operation of elements of manipulators and robots, including pipe robots, which are applicable in agricultural engineering. The three obtained regions of single valued motions and their dependence on the coefficient of restitution and on the coefficient of viscous damping are described in detail: in the vicinity of the value of non dimensional frequency equal to two, in the vicinity of the value of non dimensional frequency equal to four and in the vicinity of the value of non dimensional frequency equal to six.

This paper is devoted to numerical experiment: the model of the system is presented in detail as well as the parameters for which calculations were performed are indicated.

The presented results of the performed investigation are used in the process of design of elements of pipe robots in which impact interactions take place.

References

[1] 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.

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

[3] 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.

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

[5] 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.

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

[7] A. Matuliauskas, V. Mištinas, L. Patašienė, K. Ragulskis, B. Spruogis. Interaction of vibrating and translation motions. *Journal of Vibroengineering,* 2007, 9(4), 77-81 p.

[8] V. Mištinas; A. Matuliauskas; K. Ragulskis; B. Spruogis, 2006. Behaviour of dynamic processes in self-exciting vibration of an inpipe robot. *Vibroengineering 2006: Proceedings of the 6th International Conference, October 12-14 2006, Kaunas, Lithuania, Lithuanian Academy of Sciences, IFToMM National Committee, Kaunas University of Technology, ISSN 1822-1262,* Kaunas, 91-94 p.

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

[10] K. Ragulskis; R. Bansevičius; R. Barauskas; G. Kulvietis, 1987. *Vibromotors for Precision Microrobots.* New York: Hemisphere. P. 326.

[11] K. Ragulskis; M. Bogdevičius; V. Mištinas, 2006. Analysis of dynamic processes in self-exciting vibration of an inpipe robot. *Mechanika 2006: Proceedings of the 11th International Conference, April 6-7 2006, Kaunas University of Technology, Lithuanian Academy of Sciences, IFTOMM National*

Committee of Lithuania, Baltic Association of Mechanical Engineering, ISSN 1822-2951, Kaunas, 274-277 p.
[12] K. Ragulskis, M. Bogdevičius, V. Mištinas. Behaviour of dynamic processes in self-exciting vibration of a pipe robot. *Journal of Vibroengineering,* 2008, 10(3), 397-399 p.
[13] L. Ragulskis, K. Ragulskis, A. Bubulis, B. Spruogis, V. Mištinas, A. Matuliauskas. Investigation of dynamics of fluid in the elements of a pipe robot. *Journal of Vibroengineering,* 2008, 10(2), 209-212 p.
[14] K. Ragulskis, B. Spruogis, M. Bogdevičius, A. Matuliauskas, V. Mištinas, L. Ragulskis. Qualities of a vibrator, the elastic element of which has different coefficients of stiffness in the two intervals of displacements, in a separate case. *Journal of Mechanical Engineering, Automation and Control Systems,* 2020, 1(1), 37-45 p. **DOI:** https://doi.org/10.21595/jmeacs.2020.21532.
[15] K. Ragulskis, B. Spruogis, M. Bogdevičius, A. Matuliauskas, V. Mištinas, L. Ragulskis. Dynamics of a two mass pipe robot with the self-stopping mechanism based on viscous friction. *Mathematical Models in Engineering,* 2020, 6(4), 172-178 p. **DOI:** https://doi.org/10.21595/mme.2020.21824.
[16] K. Ragulskis, B. Spruogis, M. Bogdevičius, A. Matuliauskas, V. Mištinas, L. Ragulskis. Motion of vibration manipulators with self stopping device in one direction with interactions of two non deformable elements in one direction. *Mechanika,* 2020, 26(6), 526-531 p. **DOI:**https://doi.org/10.5755/j01.mech.26.6.25527.
[17] K. Ragulskis, B. Spruogis, M. Bogdevičius, A. Matuliauskas, V. Mištinas, L. Ragulskis. 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. *Mechanika,* 2021, 27(5), 408-414 p. **DOI:** http://dx.doi.org/10.5755/j02.mech.27470.
[18] 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.
[19] K. Ragulskis, B. Spruogis, A. Matuliauskas, V. Mištinas. Investigation of dynamics of a pipe robot. *Journal of Vibroengineering,* 2006, 8(2), 40-44 p.
[20] K. Ragulskis, B. Spruogis, A. Matuliauskas, V. Mištinas. Analysis of vibrations in the element of a pipe robot. *Journal of Vibroengineering,* 2006, 8(4), 9-11 p.
[21] K. Ragulskis, B. Spruogis, A. Matuliauskas, V. Mištinas, L. Ragulskis. Investigation of impact motions in elements of manipulators and robots. *Mathematical Models in Engineering,* 2021, 7(3), 54-62 p. **DOI:** https://doi.org/10.21595/mme.2021.22240.
[22] 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.
[23] 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.
[24] 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.
[25] B. Spruogis, K. Ragulskis, M. Bogdevičius, M. Ragulskis, A. Matuliauskas, V. Mištinas. Robot Performing Stepping Motion inside the Pipe. *Patent LT 4968 B,* 2002.
[26] 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.

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