CYBERNETICS AND PHYSICS, VOL. 12, NO. 4, 2023, 289–295

ENHANCING FUNCTIONALITY OF TWO-ROTOR VIBRATION MACHINE BY AUTOMATIC CONTROL

Iuliia Zaitceva
Institute for Problems
in Mechanical Engineering of RAS,
61 Bolshoy prospect V.O.,
St. Petersburg, 199178, Russia
St. Petersburg State University,
7-9 Universitetskaya nab.,
St. Petersburg, 199034, Russia
St. Petersburg Electrotechnical
University “LETI”, 5 Prof. Popova st.,
St. Petersburg, 197022, Russia
julia.zaytsev@gmail.com

Boris Andrievsky
Institute for Problems
in Mechanical Engineering of RAS,
61 Bolshoy prospect V.O.,
St. Petersburg, 199178, Russia
St. Petersburg State University,
7-9 Universitetskaya nab.,
St. Petersburg, 199034, Russia
boris.andrievsky@gmail.com

Leonid A. Sivachenko
Transport and Technological
Machines Deptartment
Belarusian-Russian University
43, Mira Ave.
212000, Mogilev, Belarus
228011@mail.ru

Article history:
Received 24.10.2023, Accepted 26.12.2023

Abstract

The demand for the development of cyber-physical systems remains high across various production sectors. While some industries have made significant strides, others still require ongoing research and development efforts. This article delves into the application of feedback control for equipment in the processing industry, using a two-rotor vibration machine equipped with induction motors as a case study. Conventionally, such equipment is manually operated with the help of affordable constructive facilities, which does not align with the principles of Industry 4.0. In response, this paper explores an architecture for an automatic control system capable of handling various technological tasks, including mixing and transporting processed media. This architecture encompasses several components, such as real-time regulator tuning, control of the rotor speed loop, and/or adjustment of the phase shift between the rotors based on machine sensor measurements. A notable advantage of this control system lies in its complete software-based implementation. The article also presents the findings from full-scale experiments, demonstrating the capabilities and effectiveness of the proposed approach.

Key words

Mechatronics, vibration machine, phase shift, vibration field, control, multiple synchronization

This study arose from a multitude of factors spanning various scientific domains, all of which are inherently interconnected. Currently, the consequences of the ongoing pandemic have profoundly affected global economic growth, consequently impacting the well-being and living standards of individuals across the world. These repercussions have also disrupted supply chains, which are pivotal to the production process [Queiroz et al., 2022]. The uncertainties stemming from the pandemic, along with unforeseen events, underscore the urgency of a swift transition to sustainable development principles. Sustainable development is anchored in the tenets of economic growth, social responsibility, and environmental equilibrium.

One of the instrumental drivers of sustainable development is cutting-edge technology. This is particularly evident in the integration of software with machinery and the evolution toward smart factories through the interconnection of equipment [Zheng et al., 2021]. Companies that have successfully revamped their production processes have achieved remarkable levels of productivity. Prominent examples include major players in the automotive, electronics, and drive technology sectors. Conversely, the engineering industry has exhibited relatively low levels of digitalization, especially in sectors like building materials, mining, metallurgy, mining chemistry, and energy, all of which are linked to intricate materials handling. Notoriously, these industries are characterized by machinery with high energy consumption, accounting for up to 30% of total energy production and efficiency levels plummeting below 1%, as evidenced in [Sivachenko et al., 2018]. Furthermore, substantial material losses occur during processing. To tackle these challenges, a fundamental shift is required a reorganization of technological processes that focuses on the development of new technological complexes, rather than the mere modernization of machinery. This shift has the potential to stimulate research across a spectrum of domains, including process automation, manufacturing logistics, digital twins, virtual testing, simulation, and other areas associated with Industry 4.0.

Production equipment represents a complex robotic system, demanding control strategies that account for a myriad of factors such as constraints, nonlinearities, disturbances, and uncertainties. Frequently, operational conditions change, necessitating controller reconfigurations. This underlines the need for modern, integrated control approaches. Intelligent control systems have emerged, ushering specific equipment into the domain of cyber-physical systems. Furthermore, these intelligent control methods have found utility at every stage of smart factory operations, extending from local equipment to overarching control of the production process [Ivanov et al., 2018]. While theoretical research in this field is ample, practical implementations remain limited. Evaluating the real-world performance of control systems on existing technology is paramount. A vital attribute is the adaptability of equipment to a multitude of tasks, manifesting in its multifunctionality and wide applicability to different materials [Sivachenko et al., 2005; Sivachenko et al., 2003]. Programmed control has the potential to partially replace the mechanical reconfiguration of machines, thus saving additional time in the production cycle. Significant advancements have been made in equipment control across industries such as transportation, agriculture, heavy engineering, and power engineering, with summarized findings available in comprehensive reviews, as seen in [Zaitceva and Andrievsky, 2022b; Kuznetsov et al., 2023b]. Furthermore, as technology continues to evolve, intelligent algorithms are continually substituting conventional control systems with modern artificial intelligence technologies, as evidenced in [Kamalov et al., 2023; Pakshin et al., 2023].

Among these approaches, model-free reinforcement learning stands out as a particularly promising method. It enables online control of systems with unknown dynamics, eliminating the need for a detailed model. This makes it highly applicable for tasks such as tracking, stabilization, tuning, and parameter identification [Li et al., 2022]. Model-free reinforcement learning has been effectively utilized in controlling industrial drive mechanisms, as exemplified by the stable operation of an injection molding machine despite external disturbances and actuator failures. Metaheuristic methods, which belong to the class of gradient-free optimization techniques, are commonly employed for parameter tuning. These methods facilitate the optimization of cost functions [Pelz et al., 2022]. Instances of their application include using evolutionary algorithms in Linear Quadratic Regulator (LQR) design for power electronics filters and applying harmony search algorithms to tune Proportional-Integral (PI) controllers in wind turbine generator systems [Keshta et al., 2016].

Reinforcement learning, as demonstrated in offline actor-critic neural network training for Proportional-Integral (PI) control of tank systems, provides an alternative method for controller tuning [Dogru et al., 2022]. In some cases, pre-training models may be necessary to safeguard against unsafe equipment operating conditions, albeit this can be resource-intensive. It is important to be mindful of potential challenges such as the overuse of recurrent neural networks [McClement et al., 2022]. However, employing specific heuristic strategies can help manually limit undesirable system parameter regions within the algorithm [Zaitceva and Andrievsky, 2022c]. Notably, [Gunther et al., 2016] proposes an advanced welding laser control framework that leverages machine learning to identify system patterns and adjust welding power accordingly.

These advancements highlight the transformative potential of intelligent control approaches and their capacity to revolutionize equipment control across diverse industries. Several studies focused on the control of the two-rotor vibration machine have tackled issues like operation during resonant modes, speed, and phase shift synchronization. For instance, [Gorlatov et al., 2015] and [Tomchin et al., 2021] present the results of the speed gradient algorithm for reaching the Sommerfeld frequency. This algorithm has also been tested for multiple-speed synchronization [Shagniev et al., 2022; Tomchina, 2023]. For the two-rotor vibration machine, [Zaitceva and Andrievsky, 2022a] proposed the adaptive multiple synchronization algorithm, simultaneously ensuring rotors phase shift tracking, demonstrating its efficacy by simulation and experiments for the twin-rotor vibratory setup SV-2M. For the same vibration machine, [Long and Dudarenko, 2022] proposed a bidirectional control law combined with Neural Network-based Proportional-Integral-Derivative (PID) controller is proposed. [Tomchina, 2022] suggested and studied by simulations the algorithms for control of the vibration fields utilizing the phase shift control. In [Andrievsky et al., 2023], the solution to the problem of robust control of the phase shift employing two Proportional-Integral (PI) rotor speed controllers with a cross-coupling and a relay-type signal controller with an integral component is proposed. For various types of reference phase-shift signals (constant, harmonic, chaotic), the results of extensive experimental studies performed on the mechatronic vibration setup SV-2M are presented. The analytical study of this controller structure with the pure relay phase-shift controller is given in [Kuznetsov et al., 2023a], where the appearance of the sliding motion for the simplified setup model is proved. The literature overview reveals that research on cyber-physical systems control is geared toward equipping technology with multitasking algorithms that offer maximum autonomy. This paper aims to introduce an intelligent control architecture that transforms a two-rotor vibrating machine into a cyber-physical system.

The remainder of the paper is structured as follows. Section 1 provides a brief overview of the laboratory setup, the SV-2M. Section 2 details the control algorithm for regulating the rotational velocities, and phase shift between the rotors of the vibration machine. Section 3 presents the experimental results, and the paper is concluded with final remarks in Section 4.

1 Laboratory Setup

1.1 Utilizing Vibrations for Technology

Vibrations are characterized as mechanical oscillations of small amplitude with high frequency [Blekhman, 2000; Blekhman, 2012]. Typically, these oscillations have amplitudes not exceeding 10 mm and angular frequencies of 300 rad/s. The theory of vibration oscillations draws from fundamental research on nonlinear oscillations and motion stability theory. The advantageous properties of vibrations find applications in various industrial processes, utilizing the vibration technology.

One notable application involves the vibratory maintenance of rotor rotation, resulting in increased torque, even in the absence of voltage. This leads to equivalent engine efficiency surpassing unity. Another widely used vibrational effect is directional movement resulting from non-directional oscillatory influences. This effect arises from system asymmetry and is the basis for tasks, among others, such as material transportation for bulk materials, the operation of vibration motors and motion transducers, pile driving, and material segregation based on density and size.

When experimenting with a vibration machine equipped with multiple motors, researchers discovered the self-synchronization phenomenon among unbalanced rotors [Blekhman, 1988]. A variant of such a machine is schematically depicted in Fig. 1. This machine consists of rotors, both kinematically and electrically unconnected, mounted on a movable base, each driven by independent asynchronous motors. Remarkably, these initially independent rotors, under some conditions, can exhibit synchronous rotation [Blekhman, 1988; Proskurnikov and Smirnova, 2020; Tomchina, 2023; Fradkov et al., 2021]. This synchronization allows for the establishment of equal or multiple speeds and precise phase shifts between the rotors. What is intriguing is that, as was observed, the tendency for self-synchronization can remain robust even when one or more motors are disconnected from the power supply. The energy required to keep the disconnected motors stationary is seamlessly transferred from the remaining motors that are still connected to the network. This transfer is facilitated by the base's vibrations on which the rotors are mounted.

1.2 Double-rotor vibrating machine

The processing of materials and technogenic raw materials is a complex operation in which various equipment and approaches are used and may consist of several stages. These include rock failure, grinding, mixing, screening, transportation, granulation, compaction, and other processes.

In this study, a two-rotor vibratory machine is considered, which can be used for mixing and transporting materials. Details of the design, complete mathematical model, and machine characteristics can also be found in [Gorlatov et al., 2015; Andrievskii et al., 2016; Fradkov et al., 2021; Shagniev et al., 2022; Andrievsky and Boikov, 2021; Tomchina, 2023], see Fig. 1.

The machine is equipped with two asynchronous motors *1* connected through a shaft with two unbalanced rotors *2*. The motors are fixed on a rigid base *3*. The design is damped by springs *4*. The vibration from the unbalanced rotors is transmitted to work table *5*. On this table, the material being processed is placed *6*. The machine design allows the installation of various sensors for data exchange with a computer.

An important component of cyber-physical systems is electronics and various sensors. The design of the machine allows you to place on it various sensors for measuring current, shaft rotation speed, angular velocity, and acceleration of the desktop in space, as well as sensors for its linear movement. Oscillatory movements of the working platform in the horizontal and vertical planes are measured by optical sensors. The laboratory setup control system consists of an upper control level using Matlab programs and a real-time control level that works with information input-output modules and data input modules from sensors.

2 Control system of vibration machine

This study proposes an integrated approach to the control of a vibration machine, consisting of setting the controller parameters stage in real time and application of the results for various tasks. A controller can have a different structure and be used to control both the rotation speed of the rotors and the phase shift between them. Note that the controller must simultaneously ensure stable operation of the system with a sufficient amount of platform movement. The standard PI controller used in this study is suitable for this. The control law is designed in [Andrievsky and Boikov, 2021] based on the so-called "averaging property", when fast oscillatory components are averaged, and for rotating rotors, only "slow" movements can be taken into account, see [Blekhman, 2000; Aleksandrov, 2023; Blekhman, 2023].

In this paper, a standard PI controller [Astrom and Hagglund, 2001] that generates a speed and phase con-

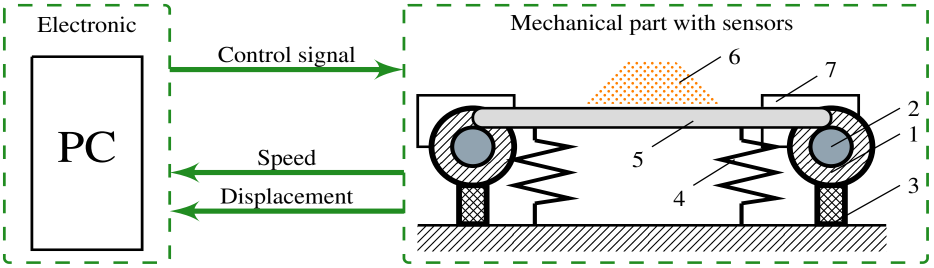

Figure 1. The structure of the laboratory installation.

trol signal is described as follows:

$$u_s(t) = K_{p_s}\Delta\omega(t) + K_{d_s}\int_0^{\tau}\Delta\omega d\tau, \quad (1)$$

$$\Delta\omega(t) = \omega(t) - \omega_{ref}(t), \quad (2)$$

$$u_\psi(t) = K_{p_\psi}\Delta\psi(t) + K_{d_\psi}\int_0^{\tau}\Delta\psi d\tau, \quad (3)$$

$$\Delta\psi(t) = \psi(t) - \psi_{\text{ref}}(t), \quad (4)$$

where $u_s(t)$ is the speed control signal applied to each motor, K_{P_s} and K_{D_s} are gains, $\omega(t)$ and $\omega_{ref}(t)$ are the actual and reference speed, respectively, $u_\psi(t)$ is the phase shift control signal, K_{P_ψ} and K_{D_ψ} are gains, $\psi(t)$ and $\psi_{\text{ref}}(t)$ are the actual and reference phase, respectively.

The resulting speed control law for each motor is written as:

$$u_l(t) = \text{sat}\big(u_s(t) + u_\psi(t)\big), \quad (5)$$

$$u_r(t) = \text{sat}\big(u_s(t) - u_\psi(t)\big), \quad (6)$$

where $u_l(t)$ and $u_r(t)$ are the control signal applied to left and right motors, respectively, and $\text{sat}(\cdot)$ denotes the saturation function.

The control signal is generated by MATLAB/Simulink software, which is convenient for making changes to the control law leaving the hardware unchangeable.

To work offline without direct operator intervention, the control system of the vibration machine must adapt to the task variables. For example, equalization of the controller parameters in the speed loop is required when changing the reference speed. Also, speed control can solve the problem of multiple stabilizations. The tasks of tuning the controller parameters, the speed, and phase loop control are discussed below.

3 Experimental Results

3.1 Controller tuning

Some results of the PI speed controller parameters tuning for vibration machines using metaheuristics are presented, cf. [Zaitceva and Andrievsky, 2022c]. The controller tuning is carried out using an iterative model-free algorithm in real-time based on encoder measurements. Following the goal of the problem being solved, an optimality criterion is introduced under given constraints. For example, the highest processing speed for a given signal or finding the minimum energy expended is a common requirement for the system and can act as a function. Also, the system's response can be restricted for its safety and limiting the overshoot for smooth drive operation. There are various possibilities for software implementation of the controller settings, but, in general, the algorithm can be described as follows:

Algorithm 1 Tuning controller parameters in real time

```
Input: initial controller parameters.
while Termination condition not reached do
    for each output measurement do
        Calculate the cost function
        Update the controller parameters
        if restrictions are not met then
            Return
        end if
    end for
end while
Output: controller parameters.
```

3.2 Rotor speed control

Let us illustrate the operation of *Algorithm 1* for the problem of stabilization of the rotation speed of the rotors by control law (1), (2) and $u_\psi = 0$ if the input is the measured rotation speed of the rotors. The terminal state is the minimum time of the transient process in terms of speed. Input data: motor reference speeds $\omega_l = 60$ rad/s and $\omega_r = 30$ rad/s, speed overshoot limit equal to 0.85, control saturation level equals 40 rad/s, initial controller parameters $K_{p0} = 1000$ s and $K_{i0} = 100$. For ease of illustration of *Algorithm 1* implementation, the standard MATLAB toolbox search algorithm of Nelder-Mead is used [Nelder and Mead, 1965].

As a result, the following controller coefficients were obtained: $K_p = 1680$ s, $K_i = 240$. The speed transients and control are shown in Fig. 2 and Fig. 3, respectively. Note that at $\psi_{\text{ref}} = 0$, the magnitude of platform oscillations is tiny, as is seen in Fig. 4. Thus, the program can change the controller parameters depending on the given

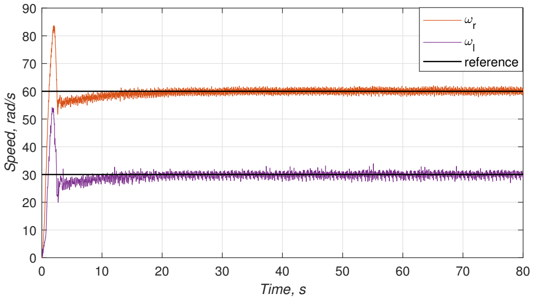

Figure 2. Rotors speed time histories without phase shift control

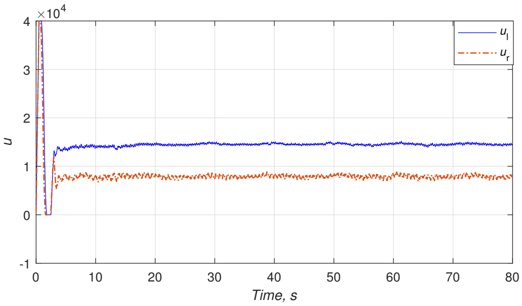

Figure 3. Control signals time histories without phase shift control

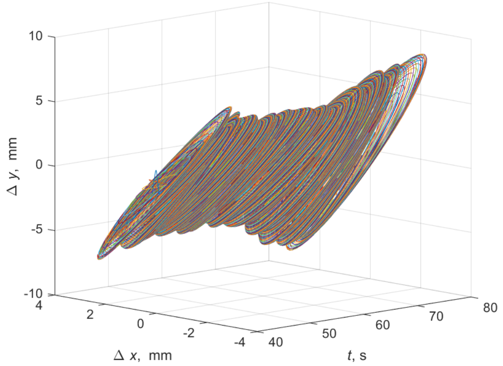

Figure 4. Trajectories of the point at the platform without phase shift control

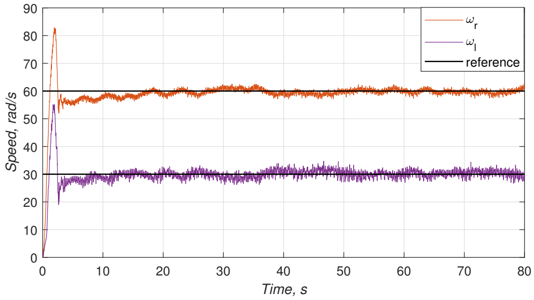

Figure 5. Rotors speed time histories with phase shift control $\psi_{\text{ref}}(t) = \pi\sin(0.7t)$.

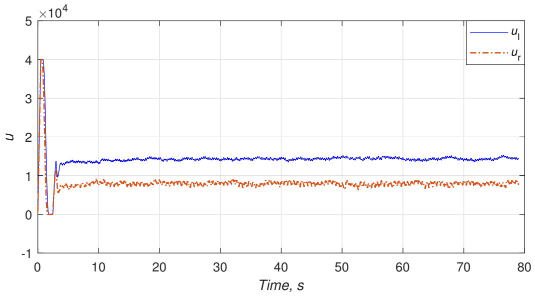

Figure 6. Control signals time histories for the case of the harmonic reference signal $\psi_{\text{ref}}(t) = \pi\sin(0.7t)$.

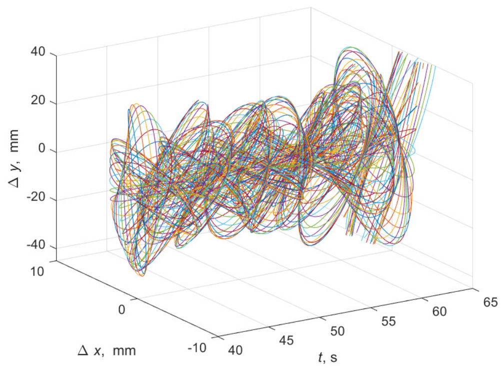

Figure 7. Trajectories of the point at the platform with harmonic reference signal $\psi_{\text{ref}}(t) = \pi\sin(0.7t)$.

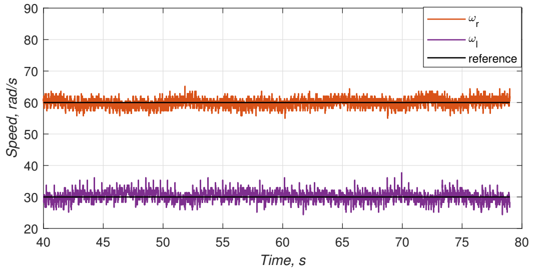

Figure 8. Rotor speed time histories for the case of the Lorenz system output reference signal

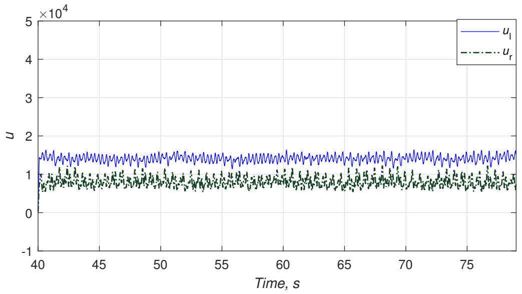

Figure 9. Control signals time histories for the case of the Lorenz system output reference signal

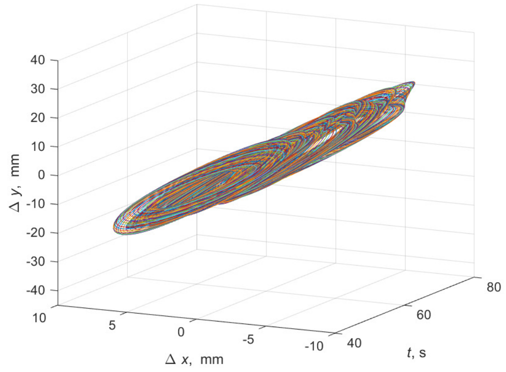

Figure 10. Trajectories of the point at the platform with reference Lorenz generator

conditions without preliminary simulations and human intervention. If the reference motor speeds change, *Algorithm 1* would be executed again.

3.3 Phase shift control

The controller in the phase loop is used to shape a vibration field, which is aimed at moving the material along the working table in a certain way. According to *Algorithm 1*, one can adjust the controller parameters in the rotor phase control loop to ensure the desirable phase shift. The control law (1)–(6) is used to control the phase with the following parameters: $K_{p_\psi} = 200$ and $K_{d_\psi} = 2000$ s. Experiments have shown that the trajectory of the vibration platform depends on the reference phase generator.

The first experiment was performed when a harmonic signal was applied as the reference phase shift. Figures 5, 6 show the time histories of rotation speed and control action, respectively. This harmonic reference signal produces the platform point trajectory shown in Fig. 7.

In the second experiment, based on [Andrievsky and Zaitceva, 2022], the Lorentz system described by the following equations was used as the reference phase shift generator:

$$\begin{aligned} x(t) &= m_t\sigma(y(t) - x(t)), \\ y(t) &= m_t(rx(t) - x(t)z(t) - y(t)), \\ z(t) &= m_t(x(t)y(t) - bz(t)), \end{aligned} \tag{7}$$

where $m_t = 10$, $r = 28$, $b = 2.66$, and $\sigma = 10$.

Figures 8– 10 show the time histories of rotor speed, control signals, and trajectories of the point on the platform with the Lorenz system (7), used as the phase shift reference signal $\psi_{\text{ref}}(t)$ generator.

These two experiments show that the amplitude of the platform oscillations has increased significantly compared to the control at $\psi_{\text{ref}}(t) \equiv 0$ and has a slope, from which the directed movement of the material along the platform can be expected.

4 Conclusion

This paper shows how the introduction of feedback into the system control leads to the synthesis of an intelligent structure that allows you to convert an electromechanical unit into a full-fledged cyber-physical system using the example of a two-motor vibration machine. The proposed framework involves all the control loops, including the control of the phase shift between the rotors, opening up new opportunities for its technological application. Also, the high level of automation saves the human operator from manually setting the controller parameters when changing the operation regimes, reducing downtime.

References

Aleksandrov, A. (2023). Stability analysis of nonstationary mechanical systems with time delay via averaging method. *Cybernetics and Physics*, **12** (1), pp. 5 – 10.

Andrievskii, B., Blekhman, I., Blekhman, L., Boikov, V., Vasil'kov, V., and Fradkov, A. (2016). Education and research mechatronic complex for studying vibration devices and processes. *J. Machinery Manufacture and Reliability*, **45** (4), pp. 369–374.

Andrievsky, B. and Boikov, V. (2021). Bidirectional controlled multiple synchronization of unbalanced rotors and its experimental evaluation. *Cybernetics and Physics*, **2** (10), pp. 63–74.

Andrievsky, B. and Zaitceva, I. (2022). Symmetrical control law for chaotization of platform vibrations. *Symmetry*, **14** (11).

Andrievsky, B., Zaitceva, I., and Barkana, I. (2023). Passification-based robust phase-shift control for two-rotor vibration machine. *Electronics*, **12** (4).

Astrom, K. and Hagglund, T. (2001). The future of PID control. *Control Engineering Practice*, **9**, pp. 1163–1175.

Blekhman, I. (1988). *Synchronization in Science and Technology*. ASME Press, N.Y.

Blekhman, I. (2000). *Vibrational Mechanics (Nonlinear Dynamic Effects, General Approach, Applications)*. World Scientific, Singapore.

Blekhman, I. (2012). Oscillatory strobodynamics – a new area in nonlinear oscillations theory, nonlinear dynamics and cybernetical physics. *Cybernetics and Physics*, **1**, pp. 5–10.

Blekhman, L. (2023). On average values of nonlinear functions of oscillating quantities and their applications. *Cybernetics and Physics*, **12** (2).

Dogru, O., Velswamy, K., Ibrahim, F., Wu, Y., Sundaramoorthy, A., Huang, B., Xu, S., Nixon, M., and Bell, N. (2022). Reinforcement learning approach to autonomous PID tuning. *Computers & Chemical Engineering*, **161**, pp. 107760.

Fradkov, A. L., Tomchina, O. P., Andrievsky, B., and Boikov, V. I. (2021). Control of phase shift in two-rotor vibration units. *IEEE Transctions on Control Systems Technology*, **29** (3), pp. 1316–1323.

Gorlatov, D., Tomchin, D., and Tomchina, O. (2015). Controlled passage through resonance for two-rotor vibration unit: Influence of drive dynamics. *IFAC-PapersOnLine*, **48** (11), pp. 313–318.

Gunther, J., Pilarski, P., Helfrich, G., Shen, H., and Diepold, K. (2016). Intelligent laser welding through representation, prediction, and control learning: An architecture with deep neural networks and reinforcement learning. *Mechatronics*, **34**, pp. 1–11.

Ivanov, D., Sethi, S., Dolgui, A., and Sokolov, B. (2018). A survey on control theory applications to operational systems, supply chain management, and industry 4.0. *Annual Reviews in Control*, **46**, pp. 134–147.

Kamalov, F., Sayari, Z., Gheisari, M., Lee, C.-C., and Jen, F. (2023). Routing algorithms in internet of things complex network with the role of machine learning. *Cybernetics and Physics*, **12** (3), pp. 182–193.

Keshta, H., Ali, A., Saied, E., and Bendary, F. (2016). Application of static var compensator (SVC) with PI controller for grid integration of wind farm using harmony search. *International J. Emerging Electric Power Systems*, **17** (5), pp. 555–566.

Kuznetsov, N., Andrievsky, B., Zaitceva, I., and Akimova, E. (2023a). Sliding-mode control of phase shift for two-rotor vibration setup. *Lecture Notes in Computer Science*, **14214 LNAI**, pp. 221–232.

Kuznetsov, N. V., Zaitceva, I., and Andrievsky, B. (2023b). Intelligent technologies in manufacturing cyber-physical systems: Evolution and future development. In Ansari, I. A. and Bajaj, V., editors, *Advanced Signal Processing for Industry 4.0*, vol. 2, pp. 4.1–4.24. IOP Publishing Ltd.

Li, X., Luo, Q., Wang, L., Zhang, R., and Gao, F. (2022). Off-policy reinforcement learning-based novel model-free minmax fault-tolerant tracking control for industrial processes. *J. Process Control*, **115**, pp. 145–156.

Long, H. D. and Dudarenko, N. (2022). Synchronization of two-rotor vibration units using neural network-based PID controller. *Cybernetics and Physics*, **11** (3), pp. 136 – 144.

McClement, D., Lawrence, N., Backstrom, J., Loewen, P., Forbes, M., and Gopaluni, R. (2022). Meta-reinforcement learning for the tuning of PI controllers: An offline approach. *J. Process Control*, **118**, pp. 139–152.

Nelder, J. and Mead, R. (1965). A simplex method for function minimization. *Computer Journal*, **7** (4), pp. 308–313.

Pakshin, P., Emelianova, J., and Emelianov, M. (2023). Iterative learning control design for a discrete-time system under delay along the sample trajectory and input backlash. *Cybernetics and Physics*, **12** (2), pp. 136–144.

Pelz, G., Costa, B., and Oliveira, S. d. (2022). Tuning of state-feedback multi-resonant controllers based on LQR using differential evolution metaheuristic. *Int. J. Electrical Power Energy Systems*, **139**, pp. 107965.

Proskurnikov, A. V. and Smirnova, V. B. (2020). Constructive estimates of the pull-in range for synchronization circuit described by integro-differential equations. In *2020 IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 1–5.

Queiroz, M., Ivanov, D., Dolgui, A., and Wamba, S. (2022). Impacts of epidemic outbreaks on supply chains: Mapping a research agenda amid the covid-19 pandemic through a structured literature review. *Annnals of Operations Research*, **319**, pp. 1159–1196.

Shagniev, O., Tomchina, O., and Fradkov, A. (2022). Learning speed-gradient synchronization control of the two-rotor vibration setup. *IFAC-PapersOnLine*, **55** (12), pp. 144–148. 14th IFAC Workshop on Adaptive and Learning Control Systems ALCOS 2022.

Sivachenko, L., Golushkova, O., Khononov, D., and Russiyan, A. (2005). Equipment for ore preparation with adaptive operation. *Gornyi Zhurnal*, (6), pp. 55–58.

Sivachenko, L., Mikhalkov, V., and Mikhalkov, D. (2003). Impact crushers with an adaptive working attachment. *Stroitel'nye i Dorozhnye Mashiny*, (12), pp. 27–32.

Sivachenko, L., Sevostyanov, V., and Ilina, T. (2018). Problem tasks in the field of resource and energy saving technologie. *J. Physics: Conf. Series*, **1066** (1).

Tomchin, D., Tomchina, O., Gorlatov, D., and Epishkin, A. (2021). Control of passage through resonance zone for 1-rotor vibration unit with time-varying load. *Cybernetics and Physics*, **2**, pp. 097–105.

Tomchina, O. (2023). Digital control of the synchronous modes of the two-rotor vibration set-up. *Cybernetics and Physics*, **12** (4), pp. 282–288. .

Tomchina, O. P. (2022). Vibration field control of a two-rotor vibratory unit in the double synchronization mode. *Cybernetics and Physics*, **11** (4), pp. 246 – 252.

Zaitceva, I. and Andrievsky, B. (2022a). Adaptive multiple synchronization and rotors phase shift tracking for two-rotor vibration machine. *Materials Physics and Mechanics*, **50** (2), pp. 216–225.

Zaitceva, I. and Andrievsky, B. (2022b). Methods of intelligent control in mechatronics and robotic engineering: A survey. *Electronics*, **11** (15).

Zaitceva, I. and Andrievsky, B. (2022c). Real-time reinforcement learning of vibration machine PI-controller. In *2022 6th Scientific School Dynamics of Complex Networks and Applications (DCNA)*, pp. 307–311.

Zheng, T., Ardolino, M., Bacchetti, A., and Perona, M. (2021). The applications of industry 4.0 technologies in manufacturing context: A systematic literature review. *Intern. J. Production Research*, **59** (6), pp. 1922–1954.