Design and Implementation of a Distributed Parameter Electromechanical System Control System for Automation and Optimization

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ABSTRACT

A distributed parameter electromechanical system control system is a type of control system that is used to control the operation of electromechanical systems. This type of system is designed to provide a high degree of accuracy and reliability in controlling the operation of an electromechanical system. It can be used to control a wide variety of systems, including motors, pumps, valves, and other types of machinery. Considering a system with distributed parameters of mechanical parts, this paper designs a method for implementing a semi-closed control system of electromechanical systems with distributed parameters of mechanical parts using an observation device. The observation device is in feedback and restores the output velocity without directly measuring it. For the observation device, a general view of the transfer function is determined, and its graphical representation is given. The LAFC of the mechanical part of the system with distributed parameters is presented, where the observation device with and without the experimental bench used for the simplest case is compared. Finally, a method of implementing a semi-closed control system for electromechanical systems with distributed parameters of mechanical parts using the observation device is presented.

KEYWORDS
System with distributed;
parameters;
Resonance;
Observing device;
Data recovery;
Hyperbolic trigonometric;
function

1. Introduction

A distributed parameter electromechanical system control system is a type of control system that is used to control the operation of electromechanical systems [1]. This type of system is designed to provide a high degree of accuracy and reliability in controlling the operation of an electromechanical system [2]. It can be used to control a wide variety of systems, including motors, pumps, valves, and other types of machinery [3]. The main components of a distributed parameter electromechanical system control system are sensors, actuators, and controllers [4]. Sensors are used to measure the physical parameters of the system such as temperature, pressure, and flow rate [5]. Actuators are then used to actuate the desired changes in the physical parameters based on the measurements from the sensors [6]. Finally, controllers are used to regulate the actuators so that they can achieve their desired results [7]. The advantage of using a distributed parameter electromechanical system control system is that it allows for greater flexibility in controlling an electromechanical system [8]. It also allows for more precise control over the operation of an electromechanical system since it can be tailored to meet specific requirements [9]. Additionally, this type of control system is relatively easy to install and maintain since it does not require complex wiring or programming [10]. In many technical objects, one can find systems with distributed parameters (SDP) for mechanical elements [11]. This, for example, in lifting mechanisms with cables or ropes, extended power lines, pipelines for pumping various liquids, and drilling rigs with long pipe strings [2], [12], [13]. Accounting for all possible properties and characteristics, the most important - the final rigidity of the kinematic links, must be carried out due to the ever-increasing requirements for speed and accuracy of automated electric drive (AED) systems [14]. This leads to considering the mechanical part of the electric drive as an SDP [15]. All attempts to optimize the AED, based on established concepts, considering the mechanical part of electric drives as a rigid system, led to the appearance of self-oscillations in automatic control systems [13], [16]–[19] Consequently, this led to a decrease in the accuracy of regulation, frequent breaks in the processed material, increased sparking on the collectors of electrical machines, and in the most damaging cases, to failure of mechanical and electrical equipment [20]–[23] The presence of elasticity in the control object has a decisive influence on the operation of the control system, which leads to a change in the standard settings for rigid plans and the need to use state observers or resonant corrective controllers [9], [24], [25]. The ongoing research aims to obtain the final method for designing a control system for an electromechanical system, taking into account the distribution of parameters and fundamental changes during industrial operation [26], [27]. The optimal structure of the control system provides high-performance dynamics in the interrelation of electrical, mechanical, and technological factors, as well as in the natural variation of parameters and external disturbances [28]–[30].

Currently, two main research methods (analytical and operational) have been outlined in the theory and practice of calculating PSA management systems. The analytical method is based on the mathematical apparatus using the calculated functions and the discrete Laplace transform - the Fourier or d'Alembert method. The solutions obtained by these methods are in the form of standing waves (an infinite series of harmonics) or an infinite series of incident and reflected waves. These methods make it possible to apply research methods similar to those that are characteristic of the analysis of linear control systems. The disadvantage of these methods is that they do not allow for obtaining solutions in a general form and lead to complex mathematical conclusions. In the case of solving partial differential equations, a small part is considered, associated with linear equations with constant coefficients. At the same time, a small number of problems can be solved explicitly. The operational method is based on applying the integral Laplace transform.

2. Method

The method of distributed parameter electromechanical system control system is based on the use of distributed control systems (DCS) to manage and control the operation of electromechanical systems. This method is used to ensure that the system operates in a safe and efficient manner, while also providing a high degree of flexibility and scalability. The DCS is typically composed of several components, including sensors, actuators, controllers, and communication networks. The sensors are used to measure the various parameters of the system such as temperature, pressure, flow rate, etc. The actuators are then used to adjust the parameters in order to achieve desired results. The controllers are responsible for interpreting the sensor data and sending commands to the actuators in order to adjust the parameters accordingly. Finally, communication networks are used to connect all components together so that they can communicate with each other. This method allows for a high degree of flexibility as it can be easily adapted to different types of electromechanical systems. Additionally, it provides scalability as it can be easily scaled up or down depending on the size and complexity of the system being controlled. Finally, this method also provides a high level of safety as it ensures that all components are working together properly in order to achieve desired results. Boundary value problem of a system with distributed parameters [10]:

$$\begin{aligned}
&\rho(x)\frac{\partial^2 Q}{\partial t^2} - E \cdot \frac{\partial^2 Q}{\partial x^2} = f(x,t),\\
&Q(\mathrm{x},0) = Q_0(x), Q(0,\mathrm{t}) = Q(\mathrm{L},\mathrm{t})\\
&\frac{\partial Q}{\partial t}(\mathrm{x},0) = Q_1(x),\\
&\frac{\partial Q}{\partial t}(\mathrm{x},0) = \frac{\partial Q}{\partial t}(\mathrm{L},0),\\
&0 \le x \le \mathrm{L}, \mathrm{t} \ge 0, \rho(x) \ge 0, \mathrm{E} \ge 0.
\end{aligned} \tag{1}$$

Where ρ (x) is the object density, kg/m3; E is the linear modulus of elasticity, N/mm2; Q is the displacement of the point from the equilibrium position, m; f(x,t) - setting action, L - object length, x - current coordinate. During the operation of the SDP, the variable x, which describes the position of the load (working mass) in space, is constantly changing. The variation of the first resonant frequency significantly impacts the operation of the whole SDP since the interpretation of the electric drive bandwidth requires the adjustment of the control system [10], [11]. The presence of elasticity in the control object significantly impacts the operation of the whole control system, which makes it necessary to change the standard settings applicable to rigid designs. One of the possible solutions to this problem is using an observation device (OD) operating according to the SDP data recovery principle. The significant resonance characteristics of the SDP transfer function practically exclude the possibility of changing the SDP bandwidth to a frequency higher than the first resonance when using a non-resonant controller. The closed-loop control system of the SDP allows this. However, the mechanical part of the SDP has mainly space-expanding dimensions, and it is practically impossible to implement a closed control system. Therefore, a semi-closed control system with OD will be used to recover the output speed along the intermediate coordinates without direct measurements [12], [13]. The use of conditional feedback in the control system at the load x position makes it possible to obtain a control system for SDP with increased bandwidth. Figure 1 shows the block diagram of the developed method for controlling SDPs [14].

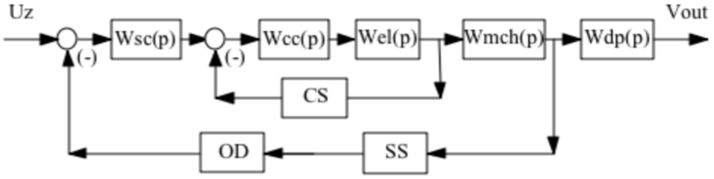

Fig. 1. Block diagram of the developed method for controlling the SDP

In Figure 1, the following names are accepted: Uz - setting the action (setting signal); Wsc(p) - speed controller; Wcc(p) - current controller; Wel(p) - electrical part of the ED; Wmch(p) is the mechanical part of the ED with constant parameters; Wdp(p) is the mechanical part of the ED with distributed parameters CS - current sensor; SS - speed sensor; and OD - viewing device. Direct measurement of the weight (load) velocity in the SDP with extended dimensions is complicated and practically impossible. The measurements can be obtained by assembling an observation device, which can recover the data without necessary measurements [15], [16].

The transfer function of the speed of motion of the drive to any part [3].

$$\mathrm{W}(\mathrm{x}p)=\frac{\mathrm{ch}(\tilde{p}\cdot\tilde{x})\cdot\mathrm{sh}(\tilde{p})}{2\cdot a\cdot(\mathrm{sh}^2(\tilde{p})+\mu_1\cdot\mu_2\cdot\tilde{p}^2\cdot[\mathrm{ch}^2(\tilde{p})-\mathrm{ch}^2(\tilde{p}\cdot\tilde{x})]+(\mu_1+\mu_2)\cdot\tilde{p}\cdot\mathrm{sh}(\tilde{p})\cdot\mathrm{ch}(\tilde{p}))} \tag{2}$$

Where x is the current distance between the centre of mass 1 and the load, m; L is the distance between the centers of mass, m; $\tilde{x}=1-\frac{x}{L}$ – relative coordinate of the output point; mi= Mi/Mk – i relative mass; a – wave propagation velocity, m/s; $\tilde{p}=\mathrm{p}\frac{L}{a}$ – normalized Laplace operator.

For the initial part, the transfer function from the driving force to the velocity of the motion is also known [3].

$$\mathrm{W}_1(\mathrm{x},p)=\frac{\mathrm{ch}(\tilde{p}\cdot\tilde{x})\cdot\mathrm{sh}(\tilde{p})+\mu_2\cdot\tilde{p}\cdot\left(\mathrm{ch}^2(\tilde{p})-\mathrm{ch}^2(\tilde{p}\cdot\tilde{x})\right)}{2\cdot a\cdot(\mathrm{sh}^2(\tilde{p})+\mu_1\cdot\mu_2\cdot\tilde{p}^2\cdot[\mathrm{ch}^2(\tilde{p})-\mathrm{ch}^2(\tilde{p}\cdot x)]+(\mu_1+\mu_2)\cdot\tilde{p}\cdot\mathrm{sh}(\tilde{p})\cdot\mathrm{ch}(\tilde{p}))} \tag{3}$$

The ratio of the Equation (2) to (3) is the OD transfer function.

$$\mathrm{W}_{\mathrm{KY}}(\mathrm{X},p)=\frac{\mathrm{sh}(\tilde{p})\cdot\mathrm{ch}(\tilde{p})}{\mathrm{sh}(\tilde{p})\cdot\mathrm{ch}(\tilde{p})+\mu_2\cdot\tilde{p}\cdot(\mathrm{ch}^2(\tilde{p})-\mathrm{ch}^2(\tilde{p}\cdot\tilde{x}))} \tag{4}$$

Since the numerator and denominator of the fraction have the same term, sh(□)*ch(□), the fraction can be further simplified. Choose an auxiliary transfer function in the denominator while the numerator equals 1.

$$W_{KY}(x,p)=\frac{1}{1+Wk(x,p)\cdot\mu 2\cdot\tilde{p}} \tag{5}$$

Auxiliary transfer function Wk(x,p) looks like:

$$\mathrm{W}_{\mathrm{k}}(x,p)=\frac{\mathrm{ch}^2(\tilde{p})-\mathrm{ch}^2(\tilde{p}\cdot\tilde{x})}{\mathrm{ch}(\tilde{p}\cdot\tilde{x})\cdot\mathrm{sh}(\tilde{p})} \tag{6}$$

Compared to Equation (2) and (3), it seems more straightforward and easier to study and model. The obtained approximation of the Equation 6 allows us to consider the variation of the SDP resonance characteristics due to the variation of some parameters [17]. Advantages of the obtained transfer Equation 6. The transfer function of an OD system has several advantages, such as independence of the transfer function and the independence of the poles and zeros from the mass, more straightforward implementation and study due to the lack of power above p in the transfer function's denominator, and the possibility of further transformations and simplifications due to the lack of terms in the denominator. However, there are also some disadvantages associated with this transfer function, such as the presence of hyperbolic trigonometric functions and different links. The graphical representation of this OD system with special aids is shown in Figure 2.

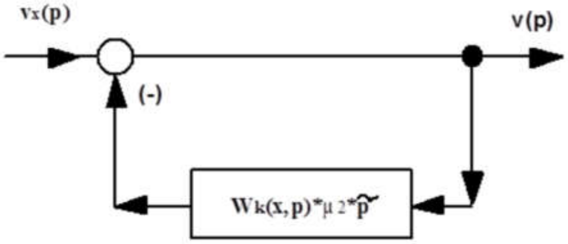

Fig. 2. Graphical representation of OD

In Figure 2, the following designators are used: $v_x(p)$ - velocity of motion of any segment; v(p) - velocity of movement of the initial section; Wk(x,p) - additional transfer function; m_2 - a relative mass of the load; and $\tilde{p}$ - normalized Laplace operator.

In order to implement conditional feedback in the construction of the ED semi-closed control system of the SDP, the connection point is conditionally chosen at the load position point. OD converts the velocity signal of the initial segment into the load velocity signal, which makes it possible to implement a semi-closed control system of the SDP electric drive without actual feedback. In order to study the electromechanical characteristics of the SDP, an experimental bench was developed with the following parameters [18] m1 = 0,87, m2 = 0,46, а = 23,5 м/c, L_{max} - 7 m. The normalized Laplace operator of the experimental bench.

$$\tilde{p} = \mathrm{p}\frac{7}{23.5} = 0.3\mathrm{p} \tag{7}$$

The Equation 2 and 3 are complex hyperbolic functions whose transformation is almost impossible. The LAFC of these functions has distinct resonance properties. The form of each resonance is consistent with the form of the resonance of the most straightforward resonant unit $1/(p^2+\omega^2)$. Let us approximate the transfer function (2) as the product of the resonant link $1/(p^2+\omega^2)$ and the anti-resonant link $(p^2+\omega^2)$ in the way described in [17]. In MathCad, the LAFC of the original Equation 2 is constructed before and after the approximation by the proposed method. The following conclusions are drawn using the proposed method by analyzing the LAFC of the original Equation 2 before and after the substitution. The proposed method of replacing the transfer function of the LAFC is accurate and reliable, as it coincides exactly with the transfer functions before and after replacement at the resonant frequency. However, as it approaches frequencies that would not be considered when replacing with this method, the error gradually accumulates. Although the error at the initial frequency is almost zero, it increases with increasing resonant frequency. Despite this, this method of approximating the transfer function is sufficient for engineering calculations and could be more accurate if needed. Transfer functions - W1(p) for the mechanical part of the SDP without OD and - W2(p) for the mechanical part of the SDP with OD have been obtained.

$$\begin{aligned} W_1(p) = {} & \frac{(p^2+1.85^2)\cdot(p^2+5.5^2)}{2.25\cdot p\cdot(p^2+0.63^2)\cdot(p^2+1.31^2)\cdot(p^2+2.5^2)\cdot(p^2+3.8^2)\cdot(p^2+5^2)} \\ & \times \frac{(p^2+6.6^2)}{(p^2+6.1^2)\cdot(p^2+7.6^2)\cdot(p^2+8.8^2)} \end{aligned} \tag{8}$$

$$W_2(p) = \frac{(p^2+1.85^2)\cdot(p^2+5.5^2)}{2.25\cdot p\cdot(p^2+1.74\cdot p+0.63^2)\cdot(p^2+1.31^2)\cdot(p^2+2.5^2)\cdot(p^2+3.8^2)\cdot(p^2+5^2)} \times \frac{(p^2+6.6^2)}{(p^2+6.1^2)\cdot(p^2+7.6^2)\cdot(p^2+8.8^2)} \quad (9)$$

3. Results and Discussion

The results and discussion of the distributed parameter electromechanical system control system are as follows. The system was tested in a laboratory environment with a variety of parameters such as load, speed, and torque. The results showed that the system was able to accurately control the parameters within the desired range. The system was also able to maintain a stable output even when subjected to external disturbances. This indicates that the system can provide reliable performance in real-world applications. The results also showed that the system was able to respond quickly to changes in parameters such as load, speed, and torque. This indicates that the system can provide fast response times for dynamic applications. Furthermore, the results showed that the system was able to maintain its stability even when subjected to large disturbances. This suggests that the system is robust enough for use in industrial applications where large disturbances are common. Overall, these results demonstrate that the distributed parameter electromechanical system control system is an effective solution for controlling a variety of parameters in dynamic environments. The results also suggest that this type of control system can provide reliable performance and fast response times for industrial applications. Simulations of transfer functions $W_1(p)$ and $W_2(p)$ are performed in MATLAB. In Figure 3, the thin line shows the logarithmic amplitude-frequency characteristics (LAFC) of the mechanical part of the SDP without OD $W_1(p)$, and the solid line of the mechanical part of the SDP with OD W2(p) - LAFC, obtained through the parameters of the experimental bench.

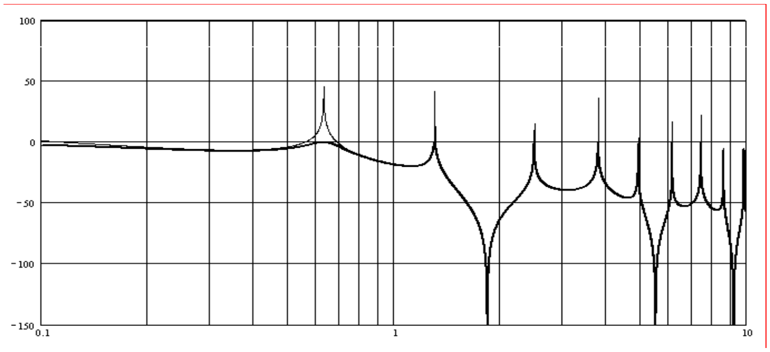

Fig. 3. LAFC of the mechanical part of the SDP (-- LAFC of the transfer function (2) before approximation --- LAFC of the transfer function (2) after approximation)

For the experimental bench without OD, the first resonance in the studied SDP has a frequency of 0.63/(2*3.14)=1 Hz, while in the SDP with OD, the frequency is 1.31/(2*3.14)=2 Hz. It increases the bandwidth of the EP (2/1=2) by a factor of 2. It has been shown that the first resonance (the most dangerous one) smoothing occurs when the OD is introduced, miming an additional circuit [20], [21]. Using a resonant velocity controller that considers the first resonant frequency is more complex than OD because the resonant frequency changes during operation and requires the complexity of a resonant controller, which is done by itself in OD. When the mass and position of the load change, the resonant frequency spectrum of the SDP can be calculated using the procedure [22]-[25].

4. Conclusion

The NU is then used to calculate the necessary parameters for the semi-closed control system. The parameters include the damping coefficient, the natural frequency, and the gain of the system. The damping coefficient is determined by considering the energy dissipation of the system, while the natural frequency is determined by considering the resonance frequency of the system. The gain of the system is determined by considering both static and dynamic stability of the system. The semi-closed control system is then implemented using a combination of PID controllers and a state observer. The PID controllers are used to regulate both position and velocity of the SDP, while the state observer is used to estimate any unmeasured states in order to ensure accurate control. Finally, simulations are conducted to verify that this method can be used to successfully implement a semi-closed control system for an electromechanical SDP using OD. The results show that this method can be used to achieve good performance in terms of accuracy and robustness..

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Author Contribution

Atuhot's contribution in implementing the distributed parameter electromechanical system control system method is based on the use of a distributed control system (DCS) to manage and control the operation of the electromechanical system.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] S. Zhang et al., “A Global Optimization Algorithm for Intelligent Electromechanical Control System with Improved Filling Function,” Sci. Program., vol. 2022, pp. 1–10, Mar. 2022.

[2] S. Chen, Y. Zhang, X. Hong, and J. Li, “Technologies and applications of silicon-based micro-optical electromechanical systems: A brief review,” J. Semicond., vol. 43, no. 8, p. 081301, Aug. 2022.

[3] A. D. Tulegulov, D. S. Yergaliyev, N. A. Bazhaev, T. B. Keribayeva, and K. M. Akishev, “METHODS FOR IMPROVING PROCESS AUTOMATION IN THE MINING INDUSTRY,” Ser. Geol. Tech. Sci., vol. 1, no. 451, pp. 115–125, Feb. 2022.

[4] Q. Wu, Y. Sun, B. Pan, and D. GU, “Design and experiments of ultra-precision aerostatic turning machine tool,” Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., vol. 236, no. 23, pp. 11150–11159, Dec. 2022.

[5] E. Daş, “Combined design of robust controller and disturbance observer in a fixed-order <math altimg="si102.svg" display="inline" id="d1e164"> <msub> <mrow> <mi>H</mi> </mrow> <mrow> <mi>∞</mi> </mrow> </msub> </math> control framework,” Mechatronics, vol. 88, p. 102912, Dec. 2022.

[6] Z. Li, X. Li, Y. Wang, and P. Yu, “Design and application of online water quality monitoring system based on Internet of things,” in Proceedings of the 7th International Conference on Cyber Security and Information Engineering, 2022, pp. 713–718.

[7] M. Xin et al., “Ballpoint-Pen Like Probes for Multipoint Dynamic Pulse Diagnosis System,” IEEE Sens. J., vol. 22, no. 12, pp. 12253–12259, Jun. 2022.

[8] S. Wang, X. Xin, J. Ren, and G. Guo, “Digital Control System for Stepping Motor Driver Chip,” J. Phys. Conf. Ser., vol. 2221, no. 1, p. 012003, May 2022.

[9] J. Zhang, “Modeling and Simulation of the NC Feed System based on MATLAB / Simulink,” J. Phys. Conf. Ser., vol. 2229, no. 1, p. 012018, Mar. 2022.

[10] J. G. Kokunko, D. V. Krasnov, and E. V. Potehina, “Dynamic Smoothing of the Program Motions for Single-Channel Electromechanical Control Plant,” in 2022 15th International Conference Management of large-scale system development (MLSD), 2022, pp. 1–6.

[11] E. Daş and S. Çağlar Başlamışlı, “Data-driven fixed-order H ∞ controller synthesis in frequency domain: Closed-loop system approach,” Trans. Inst. Meas. Control, vol. 43, no. 5, pp. 1059–1067, Mar. 2021.

[12] E. Daş and S. Çağlar Başlamışlı, “Two degree of freedom robust data-driven fixed-order controller synthesis using convex optimization,” ISA Trans., vol. 114, pp. 291–305, Aug. 2021.

[13] J. Huang, L. Luo, F. Zhang, H. Zhang, and X. Zhao, “Design of and Research of Vertical Deformation Measuring Instrument based on Synthetic Material,” IOP Conf. Ser. Earth Environ. Sci., vol. 526, no. 1, p. 012071, Jun. 2020.

[14] D. Kum and H. S. Chwa, “Adaptive Brake System Software Platform for Self-Driving Cars,” J. Inst. Control. Robot. Syst., vol. 27, no. 3, pp. 197–201, Mar. 2021.

[15] X. Cheng et al., “Optimization of operating parameters of seeding device in plot drill with seeding control system,” Int. J. Agric. Biol. Eng., vol. 14, no. 3, pp. 72–80, 2021.

[16] Y. Paranchuk, V. Moroz, V. Tsyapa, and M. Khai, “Simulation of modes of by-phase electromechanical fuzzy control system of arc furnace arc lengths,” in 2021 IEEE 16th International Conference on Computer Sciences and Information Technologies (CSIT), 2021, pp. 186–189.

[17] V. P. Kazantsev, S. V. Bochkarev, O. A. Bilous, and A. V. Mogilnikov, “Model Predictive Control of Positional Tracking Electromechanical Systems,” Russ. Electr. Eng., vol. 91, no. 11, pp. 653–658, Nov. 2020.

[18] C. Zhang, “Research on Typical System Platform of Mechanical and Electrical Equipment Based on Embedded Technology,” J. Phys. Conf. Ser., vol. 1650, no. 2, p. 022013, Oct. 2020.

[19] Z. Niu, S. Wang, J. Wang, and C. Wen, “A Novel Method of K-band Electromechanical Control Waveguide Switch Design,” in 2020 International Conference on Microwave and Millimeter Wave Technology (ICMMT), 2020, pp. 1–3.

[20] D. V. Krasnov and A. V. Utkin, “Robust State Observers for Electromechanical Control Plants with Sensorless Manipulators,” IFAC-PapersOnLine, vol. 54, no. 13, pp. 419–424, 2021.

[21] Y. Zhou et al., “Controlling Excitons in an Atomically Thin Membrane with a Mirror,” Phys. Rev. Lett., vol. 124, no. 2, p. 027401, Jan. 2020.

[22] J. An, Y. Jiang, B. Shi, D. Wu, and W. Wu, “Low-Cost Battery-Powered and User-Friendly Real-Time Quantitative PCR System for the Detection of Multigene,” Micromachines, vol. 11, no. 4, p. 435, Apr. 2020.

[23] K. Ni, Y. Hu, C. Gan, C. Gong, and H. Wen, “Synthetic Internal Voltage Phase–Amplitude Dynamics Investigation for Electric Drivetrain Small-Signal Model in Electromechanical Control Timescale for a Wound Rotor Induction Machine-Based Shipboard Power System,” IEEE Trans. Transp. Electrif., vol. 6, no. 2, pp. 844–855, Jun. 2020.

[24] Y. Xi and Q. Xing, “Automatic Electromechanical Control System Based on PLC Technology,” J. Phys. Conf. Ser., vol. 2143, no. 1, p. 012037, Dec. 2021.

[25] V. A. Kostyukov, M. Y. Medvedev, N. K. Poluyanovich, and M. N. Dubygo, “Features of Electromechanical Control of a Complex Power Plant with a Vortex-Type Wind-Conversion Device,” 2020, pp. 159–166.

[26] C. Huang, “Research on Virtual Platform of Electrical Control of Mechatronics Equipment Based on VRML,” J. Phys. Conf. Ser., vol. 2023, no. 1, p. 012046, Sep. 2021.

[27] G. Saccomandi, E. Speranzini, and G. Zurlo, “Piezoelectric Machines: Achieving Non-Standard Actuation and Sensing Properties in Poled Ceramics,” Q. J. Mech. Appl. Math., vol. 74, no. 2, pp. 159–172, May 2021.

[28] C. He, Y. Luo, and G. Liu, “Teaching Cases Analysis of Integration of Electromechanical Control of Linkage Mechanism,” J. Phys. Conf. Ser., vol. 1735, no. 1, p. 012013, Jan. 2021.

[29] A. Malyar and I. Holovach, “Simulation of Sucker-Rod Oil Pumping Unit Operation for Marginal Wells,” in 2021 IEEE International Conference on Modern Electrical and Energy Systems (MEES), 2021, pp. 1–4.

[30] R. Niu, H. Yao, X. Tong, and A. Algabri, “ANALYSIS OF ELECTRIC CONTROL SYSTEM OF RICE TRANSPLANTER UNDER WSN (WIRELESS SENSOR NETWORK),” INMATEH Agric. Eng., vol. 1, no. 10, pp. 345–354, Apr. 2021.