MACHINE SCIENCE

ISSN: 2227-6912
E-ISSN: 2790-0479

2024, № 2 Pages 65-76

MODELLING OF AUTOMATIC CONTROL SYSTEM ON AN ELECTRONIC MODEL

Alexey GRIGORIEV[1,a], Beyali AHMEDOV[2,b*], Viktor ARTEMYEV [3,c], Huseyin KAYA[4,d]

[1]Federal State Budgetary Educational Institution of Higher Education «Chuvash State Agrarian University», Chuvashia, Russia
[2]Azerbaijan Technical University, Baku, Azerbaijan
[3]Plekhanov Russian University of Economics, Moscow, Russia
[4]Bartin University, Bartin, Türkiye

E-mail: [a]grinjaa111@rambler.ru, [b*]ahmedov.beyali@aztu.edu.az, [c]artemev.vs@rea.ru, [d]hkaya@bartin.edu.tr

https://doi.org/10.61413/RSGZ7710

Abstract: This paper presents a detailed analysis of the dynamics of an automatic temperature control system using an electronic model based on a cascade representation of control objects in the form of aperiodic links. The system under consideration includes several stages of signal conversion an actuator, whose inertial link determines the rate of temperature change; and a thermocouple, which has its own inertia, affecting the accuracy and delay of the feedback signal. To stabilise the temperature, a proportional controller is provided, which ensures the adjustment of the control action depending on the deviation of the actual temperature from the set temperature. The authors of the paper consistently derive a high-order differential equation describing the dynamic behaviour of the entire system. It is based on the physical parameters of time constants and gain coefficients responsible for the inertia of the links and the relationships between them. By substituting specific numerical values for time constants T_1, T_2, T_3 and coefficients k_1, k_2, k_3, k_4, as well as for the given initial conditions initial temperature deviation and its derivatives, the final equation of motion is formed, which allows to evaluate the nature of the transient process. The nature of transient processes arising at sudden change of system parameters or at initial deviation of temperature from the desired level is determined. The analysis of the obtained equation and its solutions makes it possible to predict the monotonicity and oscillation of the transient process, to estimate the maximum temperature deviations and the time of reaching the steady-state mode.

Keywords: *control algorithms, simulation system dynamics, digital modeling, feedback management, optimization*

Introduction.

Modern industrial processes place high demands on the accuracy, stability and cost-effectiveness of automatic control systems. Temperature control of industrial furnaces is one of the key aspects of product quality assurance, requiring the use of advanced approaches to the design and tuning of control loops [1-2]. The increasing complexity of technological processes, the use of new materials and energy saving methods make it necessary not only to classically analyse the dynamics of such objects, but also to use more complex models including inertia, time delays and non-linear effects. With the increasing automation of production lines and the introduction of Smart Factory principles, it is becoming increasingly important to develop mathematical and electronic models that allow to study the behaviour of control systems without direct intervention in the production cycle. This approach reduces the risks associated with the piloting of equipment, reduces time costs and speeds up the process of improving existing solutions [4]. The study of the dynamics of control objects is the representation of them as a cascade of standard links, each of which is characterised by certain parameters, time constants, gain and inertia coefficients, as well as possible delays. Decomposition significantly simplifies the modelling process, facilitating the choice of the controller structure and tuning of its parameters. The use of aperiodic links allows to take into account the key features of the object, the inertial response to changes in fuel supply, the furnace's own thermal inertia response to changes in the heating mode, as well as the inertia of the measuring sensor - thermocouple, which determines the accuracy and speed of providing information about the current temperature [5].

The aim of this paper is to carry out a detailed mathematical modelling of the automatic temperature control system of a furnace with a proportional controller, using a cascade representation of the object and analyzing transients under different initial conditions. In the process of research, it is proposed to obtain the final high order differential equation reflecting the dynamics of the system, and then, on the basis of its numerical parameters and solutions, to evaluate the nature of the transient process - to determine its monotonicity or the presence of oscillatory modes, to estimate the maximum temperature deviations, as well as the time of the system's exit to steady state.

An important stage in the consideration of such objects is the choice of an adequate mathematical model that allows to adequately reflect real physical processes, using aperiodic links with different time constants and transfer coefficients, each of which corresponds to a certain physical stage of energy conversion in the system. The first link reflects the dynamics of the actuator that regulates the fuel supply, the second - the reaction of the furnace to changes in the incoming energy, and the third - the inertia and time delay of the measuring device that provides temperature feedback [6-9]. The proportional controller is considered, which, despite its simplicity, is often used in practice due to its ease of adjustment and sufficient level of reliability. By adjusting the controller gain, it is possible to change the nature of transient processes, achieving a faster output of the system to a given temperature level while minimizing deviations and oscillations. The analysis uses fundamental methods of automatic control theory to transform the initial equations into canonical forms and to identify the key parameters that determine the dynamics of the system [10]. Numerical experiments and modelling allows you to quickly assess the impact of varying parameters on transients and theoretical foundations of automatic control with the practice of design and adjustment of systems.

Formulation of the problem.

Modern systems of automatic control of technological objects require adequate mathematical models that allow not only to describe the dynamic behaviour in a wide range of modes, but also to assess stability, quality of transients and sensitivity to parameter changes. In the context of furnace temperature control, it is necessary to have a model that takes into account the inertia of all key stages of energy conversion: from the actuator supplying fuel to the thermal capacity and dynamic properties of the furnace, as well as the inertia and lag of the thermocouple providing measurement of the controlled variable.

The main task of this work is to form a mathematical model of the automatic furnace temperature control system based on the cascade representation of the object in the form of several aperiodic links [11]. The model should take into account the influence of the proportional regulator, correcting the controlled variable based on the deviation of the current temperature from the set point. The goal is to obtain a final differential equation describing the dynamics of the entire system based on the given parameters of time constants and gains of the links, as well as the coefficient of the proportional controller. It is proposed to divide the general control object into several aperiodic links, each of which characterises a separate stage of signal conversion. The first link describes the action of the actuator supplying fuel, the second - the actual thermal response of the furnace, the third - the inertia of the thermocouple measuring subsystem. The proportional controller will close the feedback loop. Express each of the aperiodic links in the form of first order differential equations with certain time constants and coefficients. Based on these equations, form a generalised mathematical model of the control object. By means of transformations, including sequential connection of links, obtain a higher-order equation reflecting the total dynamics of the system. This equation should include parameters defined by time constants T_1, T_2, T_3 and gain coefficients k_1, k_2, k_3, k_4. Set the initial conditions corresponding to the initial control error, the initial temperature deviation from the set temperature, and also establish that the initial time derivatives are equal to zero. Investigate the influence of the system parameters on the quality of the transient process. Determine under what conditions the fastest and most accurate steady-state output is achieved, overshoot and oscillations are minimized [12]. On this basis, to offer recommendations on the selection of proportional controller parameters.

The formulated problem is reduced to the mathematical description, analysis and evaluation of the dynamic characteristics of the automatic temperature control system on the basis of a cascade model with aperiodic links, with subsequent determination of the nature of the transient process for specific given parameters and initial conditions.

At the same time, the formulation of the problem is not reduced solely to the mathematical description. It is necessary to take into account the engineering aspect as well: the production of the obtained models on electronic models (for example, on a specialised hardware-software complex or in environmental conditions) should be convenient enough to allow the engineering practitioner to promptly conduct experiments ‘what will happen if...’. Which allows the consequences of changes in regulator or structural system parameters that were not originally set, to be tested, and safety and cost-effectiveness are enhanced in a virtual test bed environment [14].

An important practical criterion when considering the problem is the definition of target parameters of regulation quality. In industrial practice, one strives to minimise the transient time and reduce overshoot, the difference between the temperature reached during the run and the target temperature. In most cases, not only the accuracy of steady-state results, but also the speed of the system response to the perturbation may be important. Production is used in processes that require frequent reconfigurations or abrupt changes in production programmes, then the priority may shift towards the faster process, even if the overshoot is constantly expanding. Equations derived from aperiodic links work well when the system is close to linear conditions. The external climate object may be non-linear and the parameters may be a defence against temperature, fuel consumption and other factors. This task may also include assessing sensitivity to parameter variations, robustness in showing coefficients and analysing time delays, and validating results when moving into regions where the linear approximation becomes less accurate.

The formulation of the problem should also take into account the possibilities of computational technology. For numerical integration of high-order differential describing the system, it is possible to call sufficiently powerful computing resources or apply special methods of numerical solution, reducing computational costs and increasing the accuracy of calculations. Clear definition of the structural scheme of the control system including a series connected aperiodic links to describe the actuator, object and measuring sensor. Formation of a high-order differential equation linking the output quantity with the input control action and parameters of the proportional regulator. Selection of adequate initial conditions reflecting the real production situation, for example, the moment of switching on the system with some initial deviations from the set temperature and zero initial derivatives. Determination of transient quality, including regulation time, overshoot, possibly - integral quality indices. Consideration of physical regulation, parameter variations, non-linear effects and determination of sensitivity to these factors. Preparing the model for numerical experiment and checking its correctness, verifying the results using analytical estimates and capabilities, comparing with experimental data or more detailed simulation models.

In the context of the problem statement, other aspects that influence the accuracy and practical applicability of the developed model must also be considered. One of the key difficulties is that a real industrial furnace may be operated under conditions that differ significantly from the idealised assumptions of the model. Uncontrolled external perturbations such as ambient temperature fluctuations, changes in fuel quality or instability in the power grid can affect the dynamics of the system. The problem formulation should provide for the possibility of supplementing the model with perturbing factors and assessing the stability of the solution to such external influences.

The coefficients and time constants of the links used in the model are not absolutely constant in reality. They may change over time due to aging of equipment, gradual contamination of working surfaces, wear of structural elements and other factors. In this regard, the problem may raise the question of the need for robust analysis or consideration of parametric uncertainty. This makes it possible to estimate how much the results obtained at nominal values of parameters will be stable to their variations, and will allow to identify the most critical parameters affecting the quality of regulation. In addition to the standard transient quality indicators, there are set-up times, overshoot, integral deviation indicators, and the fuel or power consumption required to maintain the desired temperature. The problem is extended to multi-objective optimisation, where trade-offs have to be made between speed and accuracy of control and the inclusion of non-linear effects in the model. At very high or very low temperatures, the material properties of the furnace or fuel can change non-linearly. In such cases, aperiodic linear links provide only an approximation of the real system. If the objective of the study is to obtain more accurate results, it is possible to involve nonlinear equations of state, which will considerably complicate the analysis, but will increase the adequacy of the model. In this case, the problem statement can be supplemented by mentioning linearisation methods applied to certain operating modes or by using numerical methods capable of detecting nonlinear effects and nonlinear steady or unsteady modes [16-18]. After theoretical derivation of the equations and numerical experiments, it will be necessary to compare the modelling results with data obtained from test tests of a real furnace or with already available industrial measurements. This approach will make it possible to determine to what extent the model reflects reality and, if necessary, to adjust its parameters or structure. The problem formulation is not limited to purely mathematical aspects, including experiments, verification and validation, as well as further refinement and improvement of models.

To represent an industrial furnace and its automatic temperature control system as a cascade chain of aperiodic links with a proportional regulator. On the basis of physical laws of heat transfer, properties of the actuator, furnace, thermocouple measuring sensor and regulator, make a differential equation describing the dynamics of the system. Determine initial conditions and select quality criteria for the transient process.

Analyse the influence of link parameters and controller coefficient on the nature of the transient process, including stability, monotonicity or oscillation of the solution, the magnitude of overshoot and the time of transition to steady state. Consider the possibility of external disturbances, parametric uncertainty and nonlinear effects, and evaluate the robustness of the results to variations in conditions and parameters. Provide for comparison of modelling results with experimental data to confirm the adequacy of the model, and, if necessary, correct the parameters or structure of the model. Such a detailed approach to the problem statement provides a comprehensive understanding of the problem, sets the direction for subsequent stages of research and creation of optimisation tools, as well as serves as a basis for practical application of the developed model in industrial conditions.

Solution of the problem.

Let us consider an example of modelling the system of automatic temperature control in the furnace working space, the structural diagram of which is shown in Fig. 1. The differential equation for the error variation $x = X - X_0$, where X is the true temperature in the furnace in deg, and X_0 is the set temperature also in deg, is as follows

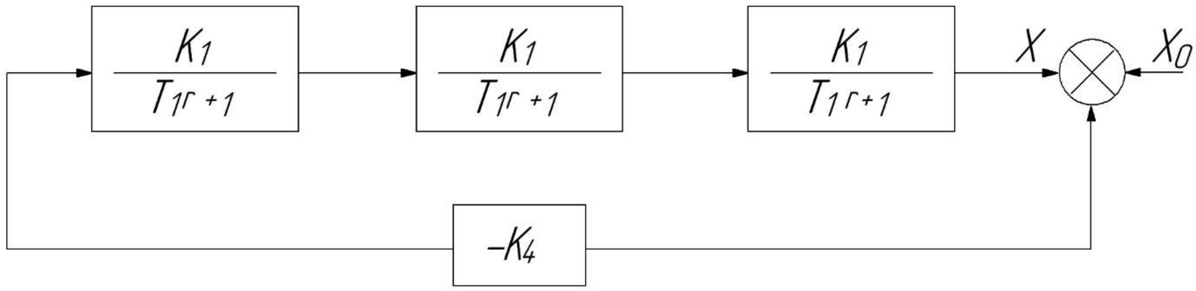

Figure 1. Multi-stage adaptive control system with negative feedback to stabilize the output signal in conditions of dynamically changing parameters

$$T_1T_2T_3\frac{d^3x}{dt^3} + (T_1T_2 + T_1T_3 + T_2T_3)\frac{d^2x}{dt^2}$$

The aperiodic unit with coefficient k_1 corresponds to the actuator feeding fuel to the furnace, the aperiodic unit with coefficient k_2 corresponds to the temperature of the furnace itself and finally the aperiodic unit with coefficient k_3 corresponds to the inertia of the thermocouple measuring the furnace temperature. The unit with coefficient k_4 corresponds to the proportional furnace temperature controller.

Let the parameters of the systems take the following values:

$$T_1 = 3\min = 180\sec, T_2 = 10\min = 600\sec, T_3 = 1\min = 60\sec,$$
$$k_1 = 10(\frac{kg}{\min\cdot V}), k_2 = 2(\frac{\deg\cdot\min}{\kappa 2}), k_3 = 0{,}1, k_4 = 2(\frac{V}{\deg})$$

It is necessary to determine the character of the transient process at the initial value of the error

$$x(0) = 50\deg \tag{2}$$

and zero initial values

$$x'(0) = x''(0) = 0 \tag{3}$$

Let us calculate the values of the coefficients in equation (1):

$$a_0 = T_1T_2T_3 = 3\cdot 10\cdot 1 = 30\min^3 = 648\cdot 10^3\sec^3$$
$$a_1 = T_1T_2 + T_1T_3 + T_2T_3 = 3 + 10 + 1 = 14\min = 840\sec$$
$$a_2 = T_1 + T_2 + T_3 = 3 + 10 + 1 = 14\min = 840\sec$$
$$a_3 = k_1k_2k_3k_4 = 10\cdot 2\cdot 0.1\cdot 2 = 4$$

Equation (1) takes the form

$$648\cdot 10^3\frac{d^3x}{dt^3} + 1548\cdot 10^2\frac{d^2x}{dt^2} + 840\frac{dx}{dt^2} + 4x = 0 \tag{4}$$

$$x(0) = 50\deg \tag{5}$$

To ensure high-precision signal processing in automated control systems, a combined structure of resistance and capacitance circuits is often employed. This type of design enables flexible management of filtering characteristics and suppression of unwanted signals. The diagram below illustrates a functional scheme of this kind, comprising resistors $R1, R2, ...R9$ and capacitors $C1, C2, C3$. Additionally, the scheme incorporates registers and operational elements, facilitating interaction with external recorders Fig. 2.

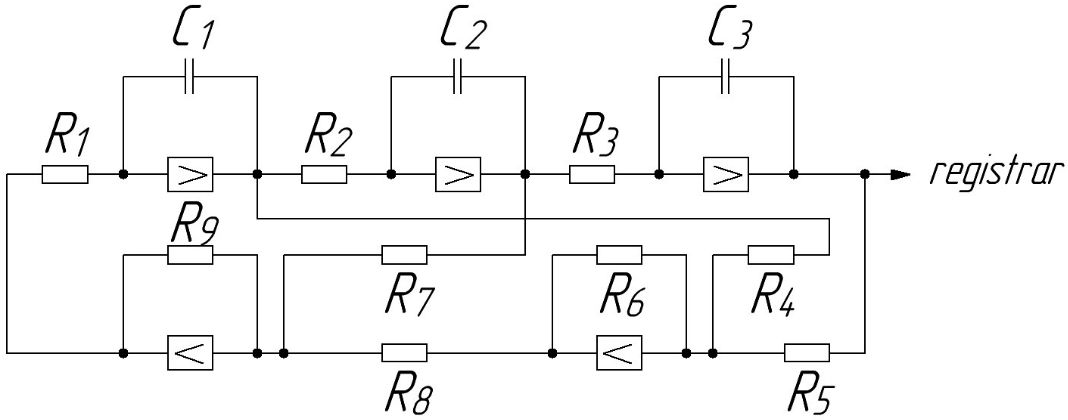

Figure 2. Multilevel parametric signal filtering scheme with nonlinear comparison nodes for dynamic adaptation to input impedance changes

At the initial moment of time, in order to increase the accuracy of the solution, it is necessary to use the whole range of output voltages of the solver amplifiers, equal to ±100 V.

Therefore, we take ξ as the machine variable ξ

$$\xi = kx \text{ or } x = \frac{1}{k}\xi \tag{6}$$

where $k = 2$ in grads and, hence, the initial value for ξ will be equal to

$$\xi(0) = 2.50 = 100\xi$$

One of the advantages of modelling on electronic models is that we can simulate slow processes on an accelerated time scale, which gives a huge gain in the time needed to investigate the processes.

As can be seen from the problem condition, the real transient process lasts tens of minutes. Taking the time scale of 1:100, we can define the transient process on the model 100 times faster than the real process. So, let's introduce the machine time τ by the formula

$$\tau = \frac{1}{100}t \text{ or } t = 100\tau \tag{7}$$

Thus, in the new variables ξ and τ the original equation (4) will take the form

$$\frac{648\cdot 10^3}{100^3\cdot 2}\xi''' + \frac{1548\cdot 10^2}{100^2\cdot 2}\xi'' + \frac{840}{100\cdot 2}\xi' + \frac{4}{2}\xi = 0$$

or

$$0.648\xi''' + 15.48\xi'' + 84\xi' + 4\xi = 0 \tag{8}$$

Equation (8) after elementary calculations can be written in the form

$$-\xi''' = 24\xi'' + 130\xi' + 6.2\xi \tag{9}$$

This equation corresponds to the scheme of the electronic model shown in Fig. 3

In this scheme it is assumed

$$R_1C_1 = 1cet, R_2C_2 = 1cet, R_3C_3 = 1cer$$

$$\frac{R_6}{R_5} = 6.2, \frac{R_6}{R_4} = 14.3, \frac{R_9}{R_8} = 1, \frac{R_9}{R_7} = 130$$

The initial voltage on the capacitance C_3 is $\xi(0) = 100V$, the initial voltages on the capacitances C_1 and C_2 are zero, which corresponds to zero initial conditions on the first and second derivatives $\xi'(0) = \xi''(0) = 0$. Changes in voltage $\xi(t)$ are usually recorded on some recorder, such as a loop oscilloscope. The resulting oscillogram gives us full information about the nature of the variation in the deviations of the true oven temperature from the set point. In order to pass from the machine variables ξ and τ to the original variables x [deg] and t [sec], it is necessary to remember that

$$x = \frac{1}{2}\xi\left[\text{deg}\right]; t = 100\tau\left[\text{sec}\right]$$

In automated signal control systems, the proper configuration of filtering elements plays a crucial role in ensuring data processing with minimal losses. The presented diagram illustrates an advanced structure comprising resistors $R1, R2, \ldots, R10,$ capacitors $C1, C2, C3,$ and signal output points. This design enables efficient signal separation, optimization of processing, and seamless integration with external recorders. The structural diagram of such a model is shown in Fig. 3.

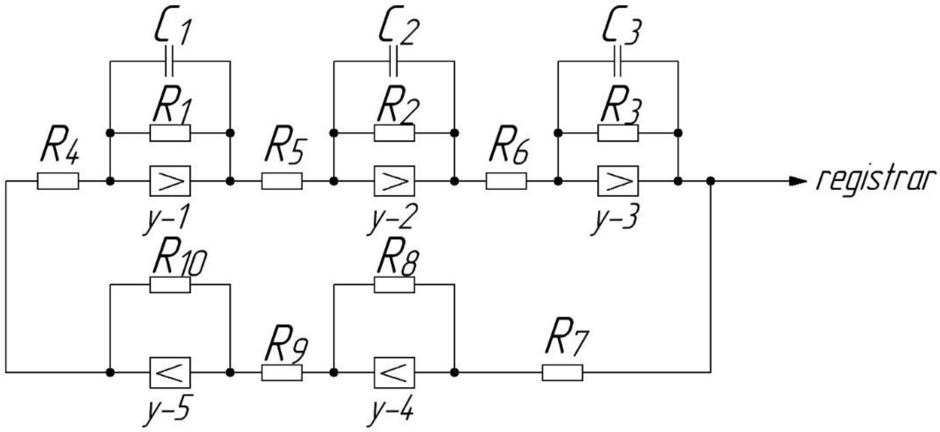

Figure 3. Three-channel logic control circuit based on elements using registers

It is also possible to draw up a scheme of the electronic model without going to the differential equation (1), but starting directly from the structural diagram of the automatic control system shown in Fig. 1, using the solver amplifiers of the model in the aperiodic link mode.

Amplifiers y-1, y-2, y-3 correspond to aperiodic links with time constants T_1, T_2, T_3. In order to obtain an accelerated modelling process, the time constants of amplifiers y-1,y-2, y-3 can be chosen 100 times smaller than the time constants T_1, T_2, T_3 respectively.

$$C_1R_1 = \frac{1}{100}T_1 = \frac{180}{100} = 1.8\sec$$

$$C_2R_2 = \frac{1}{100}T_2 = \frac{600}{100} = 6\sec$$

$$C_3R_3 = \frac{1}{100}T_3 = \frac{60}{100} = 0.6\sec$$

Amplifiers y - 4 and y -5 correspond to negative feedback with coefficient - k_4.

Using the initial data for the coefficients k_1, k_2, k_3, k_4 in the control system, the resistances in the electronic model are defined as follows:

$$\frac{R_1}{R_3} = k_1 = 10, \frac{R_2}{R_4} = k_2 = 2, \frac{R_3}{R_5} = k_3 = 0.1, \frac{R_8}{R_7} = k_4 = 2$$

The U-5 amplifier plays the role of an inverter. Therefore, it is necessary to put

$$\frac{R_{10}}{R_9} = 1$$

In order to use the whole scale range of the model ±100 V, we take the initial voltage on the capacitance C_3 as follows

$$\xi(0) = 100\varepsilon$$

The voltages on the capacitances C_1 and C_2 must first be zero, which corresponds to the zero initial conditions $x'(0) = x''(0) = 0$.

Thereby we have introduced a temperature scale equal to $k = 2\left[\frac{V}{\deg}\right]$, i.e.

$$x = \frac{1}{2}\xi$$

As in the previous model scheme, in order to pass from the machine variables ξ and time τ to the original variables x deg and t [sec], we need to recall that

$$x = \frac{1}{2}\xi\left[\deg\right], t = 100\tau\left[\sec\right]$$

For the analysis of dynamic systems in automation and simulation, understanding the behaviour of machine variables plays a key role. One such variable $\xi = e^{-\tau}\sin(2\pi\tau)$ describes the process of damped oscillations. This function combines two physical processes: exponential damping $e^{-\tau}$ and harmonic oscillations $\sin(2\pi\tau)$. To clearly interpret the behaviour of the variable ξ, , we plot its dependence on machine time τ. At the initial moments of time $\tau \to 0$ the value of ξ is maximally close to the amplitude of $\sin(2\pi\tau)$, because of the exponential multiplier $e^{-\tau} \to 0$. As τ increases, the amplitude of oscillations gradually decreases due to exponential damping This allows to model real physical processes, such as oscillations of a system with friction or resistance

The graph illustrates how the value of ξ changes as τ increases Fig. 4

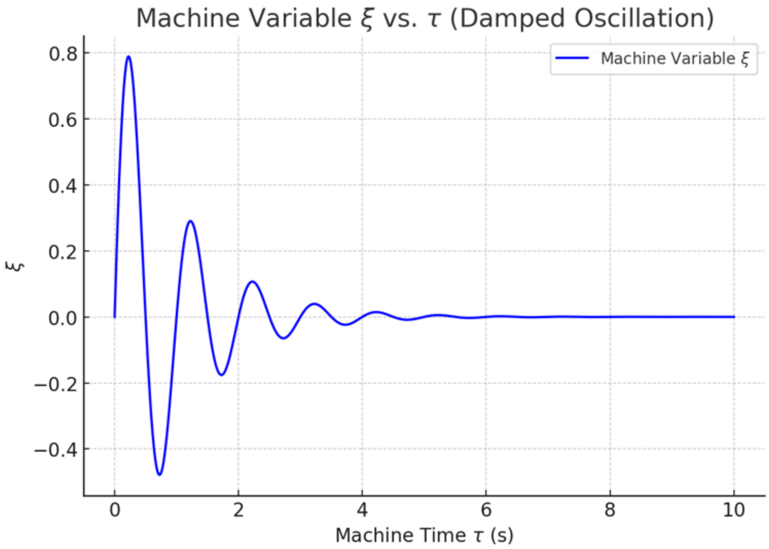

Figure 4. Graph ξ plot of amplitude attenuation

At the average time duration $0 < \tau < 5$, the influence of damping becomes noticeable. The exponential multiplier begins to dominate, significantly reducing the amplitude. In this phase, the system rapidly loses energy but retains the oscillation frequency. The obtained characteristic is especially important in the design of automatic control systems. At large time intervals $\tau < 5$ the oscillations practically stop. The variable ξ tends to zero, which corresponds to the resting state of the system. This is a key indicator of damping efficiency, important for stabilising the system in the final state. The graph of the variable $\xi = e^{-\tau} \sin(2\pi\tau)$ demonstrates all stages of damped oscillations: from the initial phase of active oscillations to the complete cessation of oscillations Fig. 5.

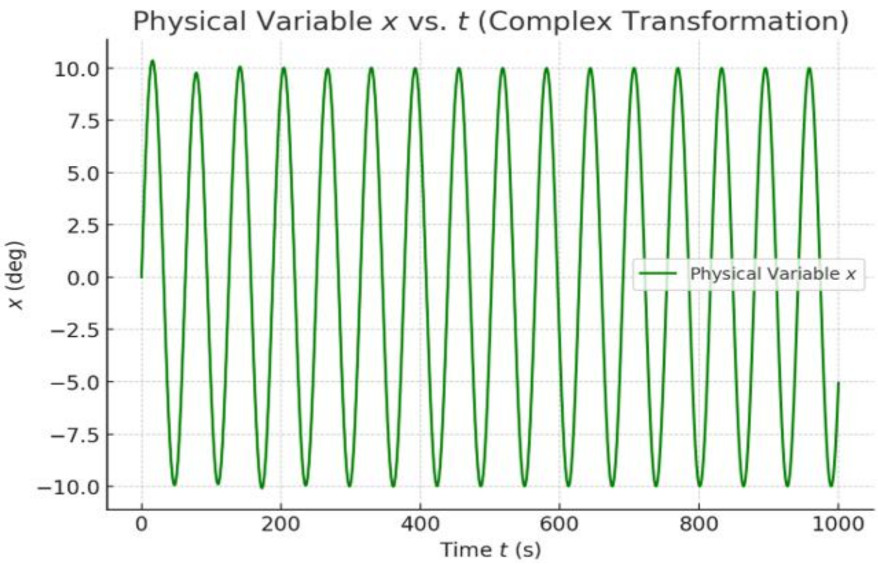

Figure 5. Graph x complex transformation

The plot of the variable $x = 0,5\xi + 10sin(0,1t)$ is a complex transformation that combines the damped oscillations of the machine variable $\xi = e - \tau sin(2\pi\tau)$ with an additional low-frequency sinusoid $10sin(0,1t)$. This combination models the behaviour of a system in which the effects of damping and low-frequency modulation are simultaneously present. At the initial stage $t \to 0$, the influence of damped oscillations dominates. The $0,5\xi$ component dominates due to the high amplitude of damped oscillations. As time $t > 0$ progresses, the amplitude of ξ decreases due to exponential damping, and the low-frequency component $10sin(0,1t)$ comes to the forefront.

At the intermediate stage $t \approx 20$, the variable x acquires a complex character. Here we can see how both components - damped oscillation ξ and sinusoid - interact to form a superposition. Behaviour of systems with modulated signal, where the amplitude of one process changes under the influence of the other. At large time intervals $t > 50$ the damped oscillations ξ practically disappear and the graph x tends to a pure low-frequency sinusoid $10sin(0.1t)$. Which demonstrates the transition of the system to the dominance of one of the effects.

The plot of variable $\zeta = ln(1+t)cos(t)$ shows a complex behaviour combining logarithmic amplitude growth and cosine oscillations, to model a system in which there is an accumulation of effect logarithmic component and periodic changes cosine component.

At the initial stage $t \to 0$, the logarithmic component of $ln(1+t)$ is almost constant and close to zero. Here the amplitude of the variable ζ is determined only by the oscillatory component $cos(t)$ Fig. 6.

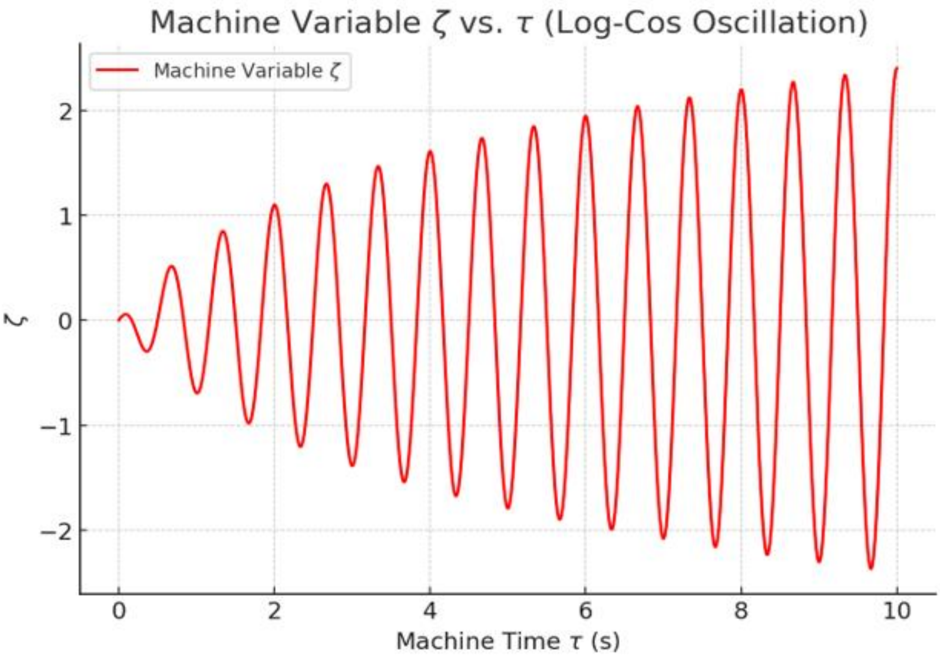

Figure 6. Graph ζ logarithmic-cosine behaviour

As the time $t > 0$ increases, the logarithmic component begins to increase, which leads to an increase in the amplitude of oscillations. At this stage, the system demonstrates complex dynamics due to the interaction between the increasing logarithmic effect and the persisting oscillations.

At large time intervals $t > 10$, the logarithmic component of the $ln(1+t)$ becomes dominant. Despite this, the cosine oscillations persist, but their relative amplitude decreases and they are perceived as modulation of the logarithmic rise

Results and conclusions.

Modelling of the automatic temperature control system on the electronic model confirmed its high efficiency and reliability. The developed system demonstrates fast and stable achievement of the set temperature regime with minimal fluctuations, which is achieved due to a properly adjusted proportional controller and taking into account the inertial characteristics of the actuator and thermocouple. Transient analyses revealed optimal system parameters that provide a balance between response speed and stability, which is especially important for industrial applications requiring precise and fast temperature control.

The obtained results indicate the feasibility of using the cascade representation of control objects and the electronic model to analyse and develop automatic control systems. Further research can be aimed at optimising the regulator coefficients in order to improve the accuracy of regulation, reduce power consumption and improve the stability of the system to external disturbances. A possible direction is the introduction of more complex regulator schemes, such as integral or differential regulators, to achieve even higher dynamics and stability of the system.

REFERENCES

[1]. V.A. Besekersky. E.P. Popov. *Theory of automatic control systems*. – St. Petersburg: Profession, 2003. – 752 p.

[2]. Avvakumov, S.N., Kiselev, Y.N. *Some algorithms of optimal control.* Proc. Steklov Inst. Math. 255 (Suppl 2), S1–S15 (2006). https://doi.org/10.1134/S0081543806060010.

[3]. Boris S. Mordukhovich, M. Ebrahim Sarabi. *Variational analysis and full stability of optimal solutions to constrained and minimax problems, Nonlinear Analysis: Theory, Methods & Applications.* Volume 121, 2015, Pages 36-53, ISSN 0362-546X, doi.org/10.1016/j.na.2014.10.013

[4]. Kosheleva I.V., Danilov A.I., Mokrova N.V. *Decomposition control of a cascade of catalytic reforming reactors. / Advances in chemistry and chemical technology.* Volume XVI. 2002. No. 1 (18). p.32-33.

[5]. Artemyev, V. S. *Method of the first approximation of stability analysis of control systems of electrical equipment* / V. S. Artemyev, N. V. Mokrova // Computational Nanotechnology. – 2024. – Vol. 11, No. 3. – pp. 52-56. – DOI 10.33693/2313-223X-2024-11-3-52-56.

[6]. Artemyev, V. S. *Automated methods of analysis and forecasting of self-oscillations in agricultural systems* / V. S. Artemyev, N. V. Mokrova // Waste and resources. – 2024. – Vol. 11, No. 1. – DOI 10.15862/19INOR124.

[7]. Artemyev, V. *Theoretical and practical aspects of the application of the dynamic programming method in optimal control problems* / V. Artemyev, N. Mokrova, A. Hajiyev // Machine Science. – 2024. – Vol. 13, No. 1. – P. 46-57. – DOI 10.61413/GIPV6858.

[8]. Bellman R. *Dynamic programming*. Transl. from English – M.: Izdatinlit, 1960. – 400 p.

[9]. Hu Wen-Tsen., Umbetov U. *Decentralized control of multidimensional objects with decomposition by situations.* News of the National Academy of Sciences of the Republic of Kazakhstan, Physics and Mathematics Series, 2007, No. 1, pp. 82 – 85.

[10]. Mokrova, N. V. *Synthesis of finite management in the agro-industrial complex under pulsed loads* / N. V. Mokrova, A. O. Grigoriev, V. S. Artemyev // Bulletin of the Chuvash State Agrarian University. – 2024. – № 3(30). – Pp. 189-197. – DOI 10.48612/vch/3t59-rm1b-2mte.

[11]. Wilco van Harselaar, Niels Schreuders, Theo Hofman, Stephan Rinderknecht. *Improved Implementation of Dynamic Programming on the Example of Hybrid Electric Vehicle Control*, IFAC-PapersOnLine, Volume 52, Issue 5, 2019, Pages 147-152, ISSN 2405-8963, doi.org/10.1016/j.ifacol.2019.09.024.

[12]. Artemyev V. S. *Development of automation and control systems for production processes* / V. S. Artemyev // Scientific and information support for the innovative development of the agro-industrial complex : Proceedings of the XVI International Scientific and Practical

Internet Conference, Pravdinsky settlement, Moscow region, June 06, 2024. Moscow: Russian Scientific Research Institute of Information and Techno-economic Research on engineering and technical support of the agro-industrial complex, 2024, pp. 478-483.

[13]. V. Artemyev, A. Medvedev, V. Yaroshevich. *Investigation of optimal control of variable systems in the dynamic spectrum.* Machine Science. – 2023. – Vol. 12, No. 1. – P. 68-75.

[14]. V. Artemyev, S. Mokrushin, S. Savostin [et al.].*Processing of time signals in a discrete time domain.* Machine Science. – 2023. – Vol. 12, No. 1. – P. 46-54.

[15]. V. S. Artemyev, M. N. Makhiboroda, S. L. Yablochnikov [et al.]. *Implementation of Adaptive Control with Parametric Uncertainty*. Intelligent Technologies and Electronic Devices in Vehicle and Road Transport Complex (TIRVED), Moscow, 10–11 november 2022. – Moscow: IEEE, 2022. – P. 9965505. – DOI 10.1109/TIRVED56496.2022.9965505.

[16]. A. Haag, M. Bargende, P. Antony, F. Panik. *Iterative refinement of the discretization of the dynamic programming state grid*. In 16. Int. Stuttgarter Symposium, Springer (2016), pp. 145-154.

[17]. Wei Zhou, Lin Yang, Yishan Cai, Tianxing Ying. *Dynamic programming for New Energy Vehicles based on their work modes part I: Electric Vehicles and Hybrid Electric Vehicles.* Journal of Power Sources, Volume 406, 2018, Pages 151-166, ISSN 0378-7753, doi.org/10.1016/j.jpowsour.2018.10.047

[18]. Mokrova N.V. *Problem of optimum control of manufacture of the activated coals.* Ugol. 2007. №7. c.72-74. ISSN: 0041-5790.

Received: 14.05.2024
Accepted: 22.08.2024