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RESEARCH OF THE OF IDENTIFICATION ALGORITHM OF CONTROL OBJECT OF SECOND-ORDER LINKS WITH A DELAY TIME

Об'єктом дослідження є оптимальні настроювання регулятора та показники якості перехідних процесів. Одним з найбільш проблемних місць є те, що сучасні технологічні процеси є складними об'єктами керування, при проектуванні систем автоматизації важливим стає питання ідентифікації об'єкту керування та розрахунок настроювань регулятора і їх оптимізація. Оптимальні настроювання регулятора дозволять забезпечити максимально можливу в умовах даної технології якість продукції та мінімальну її собівартість при заданому обсязі виробництва. Визначення оптимальних настроюваних параметрів регулятора шляхом проведення експерименту на самому об'єкті може призвести до втрати якості готової продукції, псування сировини, каталізаторів. Алгоритм розрахунку було реалізовано за допомогою програмного пакету «Maple».

В ході дослідження запропоновано і досліджено алгоритм ідентифікації об'єктів управління з різним характером перехідних процесів ланками другого порядку з часом запізнювання. В ході дослідження, на підставі отриманих таким чином передавальних функцій еквівалентних об'єктів, були знайдені настройки П-, ПІ- і ПІД-регуляторів (пропорційних, пропорційно-інтегральних і пропорційно-інтегрально-диференційних регуляторів) методом трикутників, методом незагасаючих коливань (метод Ніколаса-Циглера) і з використанням запропонованого алгоритму. Ці настройки призначені для автоматичних систем регулювання. Проведений порівняльний аналіз показників якості перехідних процесів досліджуваних автоматичних систем регулювання при настройках, що отримані різними методами. За результатом порівняльного аналізу зроблено висновок, що знайдені параметри регулятора за запропонованим алгоритмом значно поліпшили динамічні властивості системи (перерегулювання, час регулювання, статична і динамічна погрішності). Запропоновано і досліджено алгоритм пошуку настройок регулятора з введенням обмеження на перерегулювання перехідного процесу, який показав також позитивний результат. Погрішність ідентифікації не перевищує 3 %, що є цілком допустимо для розрахунків такого типу.

Ключові слова: *ланка другого порядку, настройки регулятора, час регулювання, алгоритм ідентифікації, перехідний процес, час запізнення.*

1. Introduction

The rising cost of raw materials on world markets causes a rapid increase in the cost of production of Ukrainian industries. Thus, at present, the share of the cost of natural gas in chemical products reaches 75 %. So, in order for Ukrainian products to be competitive in the global market, there is an acute need for more efficient use of raw materials, energy, and the like. That is, it is necessary to carry out optimization of technological processes.

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At the majority of enterprises, technical modernization was carried out, including control systems. But, as it turns out, this may not be enough, if at the lowest level of the control system the main device in the automatic control system (automatic control system) is the controller, it is incorrectly configured. The controller generates a control signal in order to obtain the required accuracy and quality of the transition process. The proportion of incorrectly tuned controllers used in industry is more than 50 % [1].

Determining the optimal parameters of the controller by conducting an experiment at the facility itself can lead to a loss in the quality of the finished product, damage to raw materials, and catalysts. And even to the occurrence of emergencies, including fires, explosions, emissions of harmful substances into the environment. Therefore, the development of theoretical methods for calculating the optimal controller settings is a very important and urgent task [2].

2. The object of research and its technological audit

The object of research is the optimal controller infusions and transient quality indicators. The subject of research is single-loop automatic control systems (ACS).

One of the most problematic places is that modern technological processes are complex control objects, when designing automation systems, it becomes important to identify the control object and calculate the controller settings and optimize them. Optimal adjustments of the controller will ensure the highest possible product quality in the conditions of this technology and its minimum cost with a given production volume. Determining the optimal setting parameters of the controller by conducting an experiment at the facility itself can lead to a loss in the quality of the finished product, damage to raw materials, and catalysts.

The existing methods have a number of significant drawbacks, which are the reason why at the present time the most effective, from the point of view of optimal control, method of finding controller settings is an experimental search.

The quality of any control system is determined by the magnitude of the error, but the error function for any point in time is difficult to determine because it is described using a high order differential equation and depends on a large number of system parameters. Therefore, assess the quality of control systems for some of its properties, which are determined using quality criteria.

Among all known quality criteria, the most universal is the integral quality criterion, which evaluates the generalized properties of the ACS: accuracy, stability margin, speed.

3. The aim and objectives of research

The aim of research is development of an algorithm for identifying the control object; it has a delay time along the acceleration curve by a link of the second-order with a delay time.

To achieve the aim it is necessary to solve the following objectives:

1. To find the optimal controller settings based on the integral quadratic optimization function with a restriction on the overshoot of the transition process.

2. To make a comparison of the quality indicators of transient processes of the investigated automatic control systems with the settings obtained by different methods.

4. Research of existing solutions of the problem

Among the scientific works devoted to this topic, it is possible to distinguish the work [1]. In this paper, the high speed of technological processes, the presence of a large number of disturbances caused by the interaction of individual parts of the production process and changes in external conditions are considered. As well as the dependence of the operating modes of the equipment on time, necessitates the creation of high-quality automatic control systems.

The efficiency of the production process directly depends on the operation of control systems. In some cases, new units, in principle, cannot function without high-quality automatic control systems (ACS) [2].

In [3], a transient oscillating process is also approximated by an oscillating link and a delay link in a similar way as in [4]. According to the obtained model, the frequency $\omega\pi$ is found, at which the phase of the system is π, and the amplitude at this frequency, on the basis of which four parameters of the second-order model of the control object (CO) are calculated with a delay.

There are directions in which methods of identification of controlled objects are explored, which are based on:

- method of least squares [5];
- method of instrumental variables [6];
- identification by frequency characteristics [7];
- randomized identification algorithms [8];
- active identification using an additional test signal [9, 10].

The common problems of applying these methods are guaranteed the convergence of dynamic identification processes, the weak applicability of these methods in the case of large-scale problems (a large number of unknown parameters), and the significant cost of the corresponding software.

Thus, the results of the analysis allow to conclude that the development of theoretical methods for calculating the optimal controller settings is a very important and promising task.

5. Methods of research

The calculation algorithm was implemented using the «Maple» software package.

Transients of control objects can be aperiodic or oscillatory. It is known that both processes with a sufficient accuracy degree can be described by a second-order differential equation [1].

6. Research results

Let's consider the block diagram of a single-loop ACS, which is shown in Fig. 1.

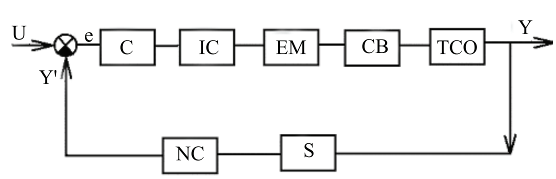

Fig. 1. The structural diagram of single-loop automatic control system: C – controller; IC – intermediate converter; EM – executive mechanism; CB – controller body; TCO – technological control object; S – sensor; NC – normalizing converter

When removing an acceleration curve on a real control object, the transient process of an equivalent control object (an open-loop system from IC – an intermediate converter to NC – normalizing converter is provided, provided that the transfer function of the secondary device is 1). That is, if identifying an equivalent second-order control object by the acceleration curve, then the functional scheme of a single-loop ACS can be given as follows (Fig. 2).

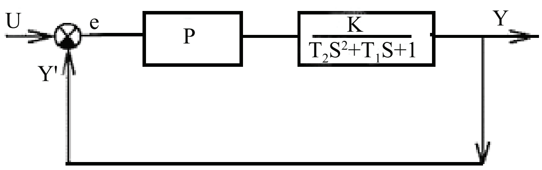

Fig. 2. Transformed block diagram of a single-loop automatic control system

The differential equation of the second-order control link is:

$$(T'')^2 \frac{d^2y}{dt^2} + T'\frac{dy}{dt} + y = K_p u_0, \qquad (1)$$

where T'', T' – time constants; K_p – coefficient.

The nature of the transition process of this link depends on the magnitude of the relationship T'/T''.

If $T'/T'' \geq 2$, then the transition process will be aperiodic, and when $T'/T'' < 2$ – oscillatory.

Let's find the roots of the differential equation (1):

$$P_{1,2} = -\frac{T'}{2(T'')^2} \pm \sqrt{\left[\frac{T'}{2(T'')^2}\right]^2 - \frac{1}{(T'')^2}}. \qquad (2)$$

If $T'/T'' > 2$, then the roots P_1 and P_2 will always be real and negative. Then the equation of the transition function will be:

$$y(t) = K_P u_0 \left[1 - \frac{\alpha_2}{\alpha_2 - \alpha_1}\exp(-\alpha_1 t) + \frac{\alpha_1}{\alpha_2 - \alpha_1}\exp(-\alpha_2 t)\right], \qquad (3)$$

where $\alpha_1 = -P_1$; $\alpha_2 = -P_2$; u_0 – step perturbation.

When $T'/T'' < 2$ the roots will be complex:

$$P_{1,2} = \alpha_0 \pm j\omega_0, \qquad (4)$$

where

$$\alpha_0 = \frac{T'}{2(T'')^2}; \; \omega_0 = \sqrt{\frac{1}{(T'')^2} - \left[\frac{T'}{2(T'')^2}\right]^2}.$$

In this case, the transition function is described by the equation:

$$y(t) = K_P u_0 \left[1 - \exp(-\alpha_0 t)\left(\cos\omega_0 t + \frac{\alpha_0}{\omega_0}\sin\omega_0 t\right)\right]. \qquad (5)$$

Let's consider the identification of control objects on the example of a link of the fifth order, has a transfer function:

$$W = \frac{1}{1.5\cdot s^5 + 4\cdot s^4 + 10\cdot s^3 + 10\cdot s^2 + 5\cdot s + 1}. \qquad (6)$$

Let's build the acceleration curve (Fig. 3).

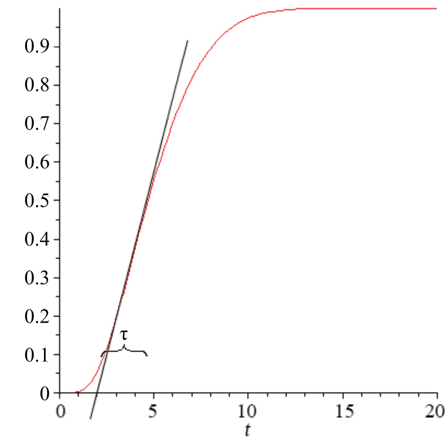

Fig. 3. The acceleration curve of the fifth-order link

To determine the delay time of the fifth-order link, let's build a tangent to the acceleration curve, as shown in Fig. 3, let's find the delay time and substitute the fifth-order link (6) into the transfer function:

$$W = \frac{e^{-2\cdot s}}{1.5\cdot s^5 + 4\cdot s^4 + 10\cdot s^3 + 10\cdot s^2 + 5\cdot s + 1}. \qquad (7)$$

Let's build again the acceleration curve of the fifth-order link only with the delay time (Fig. 4).

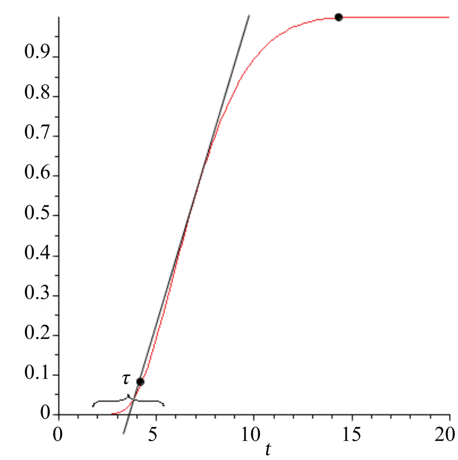

Fig. 4. The acceleration curve of the fifth-order link with a delay time

When the tangent was rebuilt (Fig. 4), the delay time for the second-order link was found.

From Fig. 4 it is shown that the acceleration curve is aperiodic, therefore, in order to find the equation for the acceleration curve, it is possible to use equation (3).

The coefficient K is found by the acceleration curve (K=1). In this equation there are two more unknown parameters α_1 and α_2. In order to find them, let's take two points on the acceleration curve, select these points approximately as shown in Fig. 4.

Let's make equations for these two points. As a result, let's obtain the system of equations:

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$$\begin{cases} 0.0368 = 1\cdot u_0 \begin{bmatrix} 1-\dfrac{\alpha_2}{\alpha_2-\alpha_1}\exp(-\alpha_1\cdot 3.71)+ \\ +\dfrac{\alpha_1}{\alpha_2-\alpha_1}\exp(-\alpha_2\cdot 3.71) \end{bmatrix}, \\ 0.997 = 1\cdot u_0 \begin{bmatrix} 1-\dfrac{\alpha_2}{\alpha_2-\alpha_1}\exp(-\alpha_1\cdot 14.35)+ \\ +\dfrac{\alpha_1}{\alpha_2-\alpha_1}\exp(-\alpha_2\cdot 14.35) \end{bmatrix}. \end{cases} \quad (8)$$

The system of two equations thus formed is solved for α_1 and α_2. The easiest way to find these variables is using the Maple math package.

Let's find the variables α_1 and α_2. Let's substitute these values into equation (3) to find the transition function equation. After the substitution, let's obtain the equation:

$$y(t) = 1 - 5.58\cdot 10^5 \exp(-0.558\cdot t) + \\ + 5.58\cdot 10^5 \exp(-0.558\cdot t). \quad (9)$$

Let's build a fifth-order link acceleration curve on a single graph and a curve that corresponds to the obtained equation (9), Fig. 5.

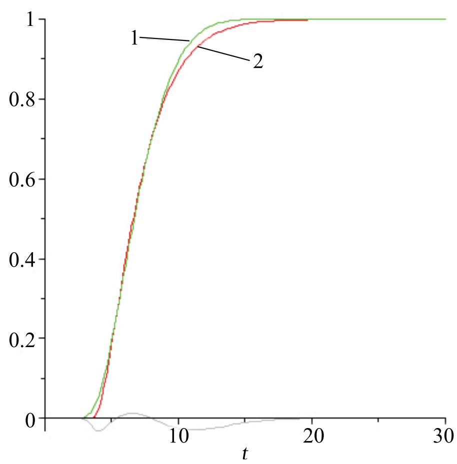

Fig. 5. The initial and the obtained acceleration curves of an equivalent object: 1 – acceleration curve of the fifth-order link with the delay time; 2 – transient link of the second-order link with a delay time

Analyzing Fig. 5, it I possible to conclude that a second-order aperiodic link with delay time almost exactly describes the aperiodic control object with a delay time. The maximum deviation between curves 1 and 2 does not exceed 3 %.

Therefore, in further calculations, let's use a second-order link with a delay time instead of an equivalent control object. Let's make the inverse Laplace transform of the equation to get its transfer function:

$$W = \frac{7.942\cdot 10^9 \cdot e^{-3.6\cdot s}}{2.5\cdot 10^{11}\cdot s^2 + 2.8\cdot 10^{11}\cdot s + 7.784\cdot 10^{10}}. \quad (10)$$

Thus, at two points of the acceleration curve of an aperiodic control object with a delay time, its second-order aperiodic link with a delay time can be identified quite accurately.

Let' consider the identification of control objects on the example of a link of the fifth order, which has a transfer function:

$$W = \frac{1}{s^5 + 4\cdot s^4 + 7\cdot s^3 + 12\cdot s^2 + 4.5\cdot s + 1}. \quad (11)$$

Let's build the acceleration curve (Fig. 6).

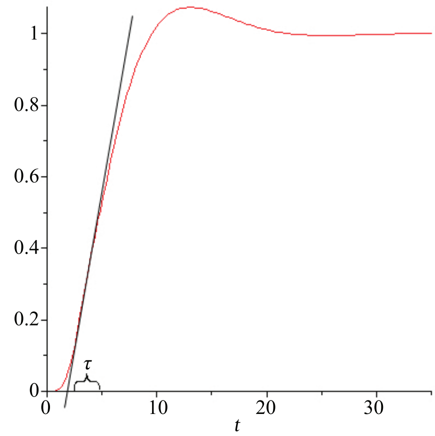

Fig. 6. The acceleration curve of the fifth-order link with the delay time from a tangent line

To determine the delay time of the fifth-order link, let's build a tangent to the acceleration curve, as shown in Fig. 6. Let's find the delay time and substitute the fifth-order link in the transfer function:

$$W = \frac{e^{-2\cdot s}}{1.5\cdot s^5 + 4\cdot s^4 + 10\cdot s^3 + 10\cdot s^2 + 5\cdot s + 1}. \quad (12)$$

Let's build again the acceleration curve of the fifth-order link only with the delay time in Fig. 7.

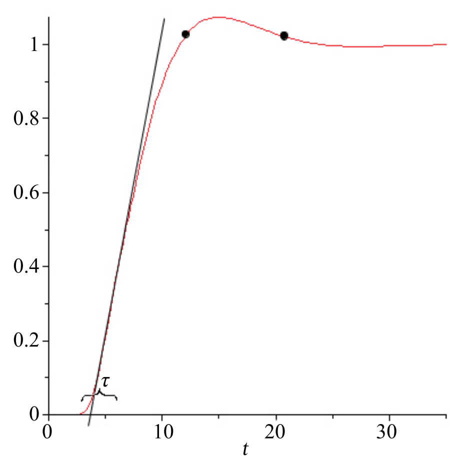

Fig. 7. The acceleration curve of the fifth-order link with a delay time (oscillatory character)

When the tangent was re-build (Fig. 7), the delay time for the second-order link was found.

From Fig. 7 it is shown that the acceleration curve is oscillatory, therefore, in order to find the equation for the acceleration curve, it is possible to use equations (5).

The coefficient K is found by the acceleration curve ($K=1$). In this equation there are two more unknown parameters α_0 and ω_0. In order to find them, let's take two points on the acceleration curve (Fig. 7), choose these points approximately, as shown in Fig. 7.

Let's make equations for these two points. As a result, let's obtain the system of equations:

$$\begin{cases} 1.025 = 1\cdot u_0 \begin{bmatrix} 1-\exp(-\alpha_0\cdot 12.06)\times \\ \times\left(\cos\omega_0\cdot 12.06+\dfrac{\alpha_0}{\omega_0}\sin\omega_0\cdot 12.06\right)\end{bmatrix}, \\ 1.026 = 1\cdot u_0 \begin{bmatrix} 1-\exp(-\alpha_0\cdot 20.21)\times \\ \times\left(\cos\omega_0\cdot 20.21+\dfrac{\alpha_0}{\omega_0}\sin\omega_0\cdot 20.21\right)\end{bmatrix}. \end{cases} \quad (13)$$

The system of two equations thus formed is solved with respect to α_0 and ω_0. The easiest way to find these variables is using the Maple math package.

Let's find the variables α_0 and ω_0. Let's substitute these values into the equation:

$$y(t)=K_r u_0\left[1-\exp(-\alpha_0 t)\left(\cos\omega_0 t+0.1\cdot\frac{\alpha_0}{\omega_0}\sin\omega_0 t\right)\right], \quad (14)$$

to find the equation of the transition function. After the substitution:

$$y(t)=1-\exp(-0.1935t)\times \times\left(\cos(0.2081t)+0.093\sin(0.2081t)\right). \quad (15)$$

Let's build on the same graph an acceleration curve of a fifth-order link and a curve that corresponds to the obtained equation (15), Fig. 8.

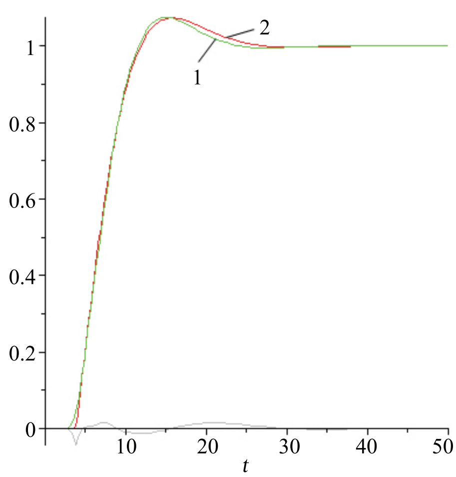

Fig. 8. Comparison of the initial and the obtained acceleration curves of an equivalent object: 1 – a fifth-order link acceleration curve with a delay time; 2 – transient second-order link with a delay time

Analyzing Fig. 8, it is possible to conclude that the second-order oscillatory link with the delay time almost exactly describes the oscillatory control object with the delay time. The maximum deviation between curves 1 and 2 does not exceed 3 %.

Therefore, in further calculations, let's use a second-order link with a delay time instead of an equivalent control object. Let's do the inverse transform of the Laplace equation to get its transfer function:

$$W=\frac{0.25\cdot(1.74\cdot 10^{9}\cdot s+8.1\cdot 10^{18})\cdot e^{-3.8s}}{2.5\cdot 10^{19}\cdot s^2+9.675\cdot 10^{18}\cdot s+2.02\cdot 10^{18}}. \quad (16)$$

Thus, in the study of automatic control systems, control objects in which complex technological processes, it is possible to conclude that the equivalent transfer function can be represented in the case of an aperiodic acceleration curve with a delay time by an aperiodic second-order link with a delay time, and in the case of an oscillatory acceleration curve, a vibrating second-order link with a delay time. This will greatly facilitate the process of analyzing and optimizing the ACS dynamic characteristics.

Having obtained the transfer function of an equivalent object from an experimental acceleration curve, it is possible to synthesize ACS. Let's consider single-loop ACS. Such an ACS, taking into account the transfer function of an equivalent object, can be given in the form of an ACS with a single feedback (Fig. 2).

The existing methods have a number of significant drawbacks, which are the reason why at the present time the most effective from the point of view of the optimal control method for finding the settings of the controller is an experimental search.

The quality of any control system is determined by the magnitude of the error:

$$\varepsilon(t)=u(t)-y(t), \quad (17)$$

where $u(t)$ – the reference signal; $y(t)$ – the output signal (Fig. 9).

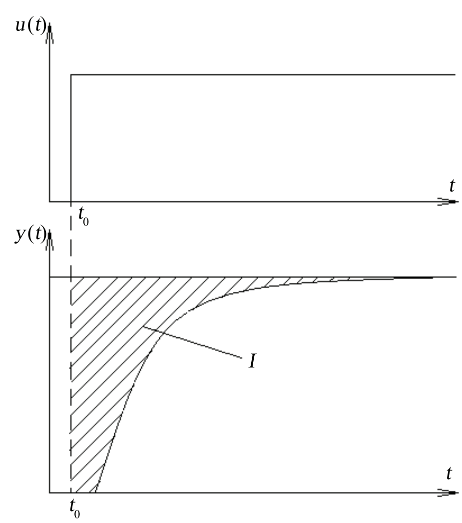

Fig. 9. Integral quality criterion

But the error function $\varepsilon(t)$ for any point in time is difficult to determine, since it is described using a high-order differential equation and depends on a large number of system parameters. Therefore, let's assess the quality of control systems for some of its properties, which are determined using quality criteria.

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Among all known quality criteria, the most universal is the integral quality criterion, which evaluates the generalized properties of the ACS: accuracy, stability margin, speed.

Therefore, the essence of this work lies in the fact that the algorithm based on the integral quadratic optimization function was developed, with which the optimal controller settings were calculated. The integral criterion proposed in [6, 7] gives a generalized estimate of the damping rate and the deviation of the controlled variable in the form of a single numerical value. It is according to the formula [5, 6]:

$$I = \int_0^T \left[y(t) - u(t) \right]^2 \mathrm{d}t = \int_0^T \varepsilon^2(t) \mathrm{d}t, \tag{18}$$

where T – the regulation time.

This integral defines the square of the plane between the problem $u(t)$ and the transition curve $y(t)$. This integral will depend on the controller settings, that is, in the case of the PID controller (proportional-integral-differential controller) on the regulation coefficient K_r, integration time T_i, differentiation time T_d, that is $I = f(K_r, T_i, T_d)$. The proposed algorithm is based on the solution of the optimization problem: finding such values of K_r, T_i, T_d for which the quadratic integral criterion would be minimal:

$$I = f(K_r, T_i, T_d) = \min. \tag{19}$$

These values of K_r, T_i, T_d will be the optimal tuning parameters of the controller. For most processes, the integral criterion is a unimodal function, which makes it possible to apply the proposed algorithm.

The P-controller (proportional controller) has one tuning parameter – the coefficient of regulation K_r, therefore the quadratic integral criterion will be a function of one variable $I = f(K_r)$. Let's determine the coefficient of regulation K_{r0}, at which this integral will be minimal, it is possible to solve the equations $dI_2/dK_r = 0$. Also, the optimal regulation coefficient can be determined by plotting the dependence $I = f(K_r)$ and determining the value of K_{r0}, at which $I = \min$, directly according to the graph (Fig. 10). This value of the control coefficient will be optimal, and accordingly, the system with this value of the controller gain will have a minimum dynamic error.

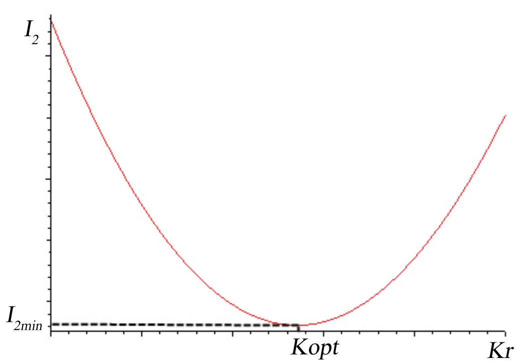

Fig. 10. Optimization of the automatic control system with a proportional controller

The PI controller (proportional-integral controller) has two tuning parameters – the regulation coefficient K_r and the integration time T_i, therefore the quadratic integral criterion will be a function of two variables $I = f(K_r, T_i)$, and the graph of this function will be some kind of surface. To find the values of K_r and T_i, at which the method of the fastest descent is applicable [7, 8].

The essence of this method is that one of the variable parameters is fixed, that is, an arbitrary numeric value is assigned to one of the tuning parameters, for example, $K_r = K_{r0}$, so I turns into a function of one variable $I = f(T_i)$. Then find the value T_{i0}, at which the quadratic integral criterion will be minimal $I = \min$. This can be done by solving the equation $dI_2/dT_i = 0$ or directly on the graph $I = f(T_i)$ (Fig. 11).

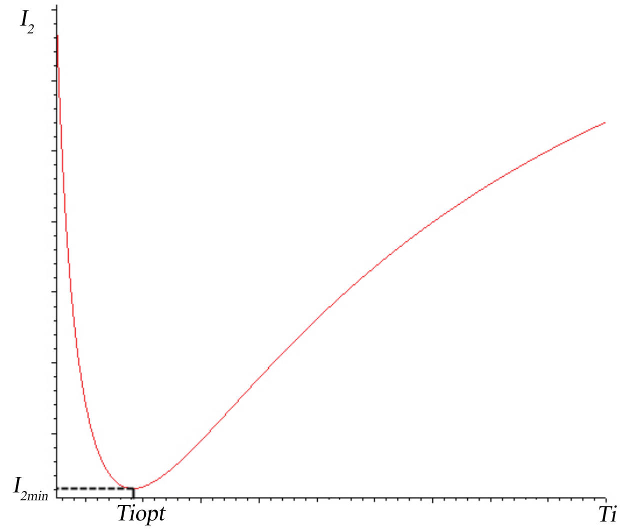

Fig. 11. Finding the optimal integration time of the proportional-integral controller according to the graph $I = f(T_i)$

At the next step, the second variable parameter is fixed – the integration time T_i, assigning to it the value found at the previous step $T_i = T_{i0}$. Then find the value of K_{r1}, at which the condition would be fulfilled $I_2 = \min$ by solving the equation $dI_2/dK_r = 0$ or directly on the graph $I = f(K_r)$ (Fig. 12). After that, the whole cycle repeats. The number of necessary iterations can be determined, for example, from the condition that the change in the quadratic optimization function during the last iteration will not exceed 5 %. As a rule, 3–5 iterations are sufficient to find such values K_r and T_i for which the quadratic integral criterion will be minimal. These values will be the optimal settings of the PI controller.

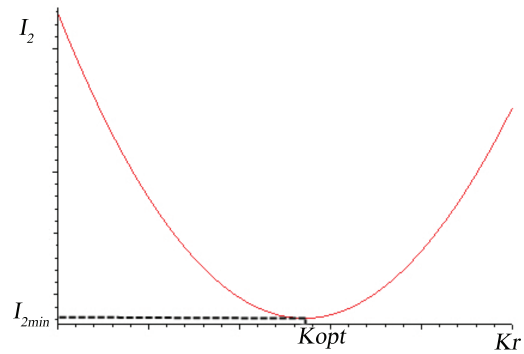

Fig. 12. Finding K_{opt} of proportional-integral controller on the graph $I = f(K_r)$

The PID controller (proportional-integral-differential controller) has three tuning parameters – the regulation coefficient K_r, the integration time T_i and the differentiation time T_d, therefore the quadratic integral criterion will be a function of three variables $I = f(K_r, T_i, T_d)$. Unlike systems with a P controller and PI controller, the graph of this function is a hypersurface, which can obviously be given. To find the values of K_r, T_i, T_d, for which $I = \min$, let's also apply the steepest descent method. The number of iterations can be determined in the same way as in the previous case. The values of K_r, T_i, T_d found in this way, for which the quadratic integral criterion will be minimal, will be the optimal settings of the PID controller. The quality indicators of ACS transient processes (overshoot, regulation time, static and dynamic errors), in which the optimal settings of the controllers were calculated using this algorithm, as well as by the method of triangles and the Ziegler-Nichols method are given in comparative Tables 1, 2.

The research results (Fig. 7, *b–d* and Tables 1, 2) show an improvement in the dynamic properties of the system when using optimal controller settings calculated by the proposed method as compared to the most common engineering methods of searching for controller settings for ACS with aperiodic and oscillatory COs. The overshoot has decreased by 10 times, the regulation time has decreased to 30 %, the static and dynamic errors have decreased by 2–3 times.

A characteristic feature of the oscillatory process is overshoot. High overshoot is considered a lack of automatic control systems, and for some systems is completely unacceptable because it causes system overload, etc. The permissible overshoot value is determined by the specific working conditions and the ACS purpose. Therefore, an important task is the synthesis of systems with given (limited) indicators of the quality of the transition process.

In this paper, let's propose an algorithm to search for controller settings with the introduction of restrictions on the transient overshoot.

Table 1

Comparative table of the quality of the automatic control system for the control object of aperiodic nature

Method for finding controller settings	Control law	Control object	Controller settings			Control quality indicators			
			K_r	T_i	T_d	σ	Δ_{st}	T_p	J
Proposed method	P controller	Purge column	2.39	∞	0.00	17.26	29.52	465.45	148.04
Triangle method			0.24	∞	0.00	0.00	80.39	816.34	665.90
Z-N method			4.12	∞	0.00	52.36	19.52	765.26	130.18
CHR method			1.24	∞	0.00	1.31	44.70	202.83	273.18
Proposed method		Gas reactor	1.14	∞	0.00	45.90	46.72	27.09	13.69
Triangle method			0.57	∞	0.00	25.77	63.79	18.33	14.60
Z-N method			1.78	∞	0.00	83.71	35.93	69.26	17.04
CHR method			0.53	∞	0.00	15.47	65.15	18.28	12.97
Proposed method	PI controller	Purge column	1.62	187.95	0.00	0.00	0.00	959.79	124.97
Triangle method			0.29	135.56	0.00	40.09	0.00	2564.73	247.94
Z-N method			3.71	60.28	0.00	53.47	0.00	895.26	122.30
CHR method			1.44	56.36	0.00	55.50	0.00	1709.88	176.51
Proposed method		Gas reactor	0.66	7.57	0.00	0.00	0.00	32.45	5.24
Triangle method			0.68	6.07	0.00	5.66	0.00	24.05	5.01
Z-N method			1.60	6.24	0.00	37.87	0.00	60.54	5.66
CHR method			0.62	5.84	0.00	8.46	0.00	24.53	5.11
Proposed method	PID controller	Purge column	3.07	85.01	95.58	0.00	0.00	219.48	73.98
Triangle method			0.20	135.56	30.12	39.12	0.00	2805.33	241.60
Z-N method			4.95	27.40	167.68	33.43	0.00	372.91	80.15
CHR method			2.47	27.40	83.84	54.81	0.00	1598.62	129.71
Proposed method		Gas reactor	0.68	5.88	0.89	0.48	0.00	15.78	4.30
Triangle method			0.47	6.07	1.35	5.64	0.00	31.55	4.61
Z-N method			2.14	2.84	3.25	60.73	0.00	30.37	4.62
CHR method			1.07	2.84	1.62	14.14	0.00	23.71	3.48

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Table 2

Comparative table of the quality of the automatic control system for the control object of oscillatory nature

Method for finding controller settings	Control law	Control object	Controller settings			Control quality indicators			
			K_r	T_i	T_d	σ	Δ_{st}	T_p	J
Proposed method	P controller	NO_x absorber	1.01	∞	0.00	66.44	49.76	119.00	55.61
Triangle method			0.60	∞	0.00	42.74	62.56	81.22	51.60
Z-N method			1.76	∞	0.00	106.29	36.21	5500.00	760.42
CHR method			0.53	∞	0.00	38.77	65.42	53.08	47.23
Proposed method		Purge column	1.01	∞	0.00	56.43	49.78	57.73	22.97
Triangle method			0.61	∞	0.00	33.14	62.08	31.33	16.06
Z-N method			1.72	∞	0.00	87.54	36.79	150.81	33.01
CHR method			0.52	∞	0.00	28.61	65.99	31.57	19.88
Proposed method	PI controller	NO_x absorber	0.30	25.35	0.00	0.00	0.00	102.45	15.46
Triangle method			0.72	12.60	0.00	24.94	0.00	116.58	11.73
Z-N method			1.59	13.11	0.00	Unstable process			
CHR method			0.62	12.26	0.00	24.98	0.00	125.07	11.82
Proposed method		Purge column	0.34	13.76	0.00	0.00	0.00	56.72	8.34
Triangle method			0.73	7.02	0.00	16.96	0.00	51.79	5.88
Z-N method			1.55	7.49	0.00	42.97	0.00	180.33	9.69
CHR method			0.60	7.01	0.00	15.95	0.00	46.83	6.07
Proposed method	PID controller	NO_x absorber	0.56	10.82	3.23	2.31	0.00	47.88	8.14
Triangle method			0.50	12.60	2.80	1.07	0.00	34.37	8.89
Z-N method			2.11	5.96	6.66	71.93	0.00	200.23	16.42
CHR method			1.06	5.96	3.33	38.71	0.00	71.03	8.71
Proposed method		Purge column	0.64	5.88	1.90	1.99	0.00	26.18	4.37
Triangle method			0.51	7.02	1.56	1.85	0.00	28.89	4.94
Z-N method			2.06	3.41	3.62	45.87	0.00	38.54	4.37
CHR method			1.03	3.41	1.81	26.97	0.00	31.62	4.20

This algorithm consists in the fact that according to the transformed formula (22) a possible overshoot area is build:

$$\sigma = \frac{y_{\max} - y_{set}}{y_{set}}, \quad (20)$$

$$y = 1 + \sigma, \quad (21)$$

$$y = \frac{y_{\max}}{y_{set}}. \quad (22)$$

After that, the area is limited to the desired overshoot value (the line for the P controller, and the plane for the PI and PID controllers) (Fig. 13).

The point of intersection of the two planes (lines) will be the optimal tuning parameters of the controller with the specified value of the overshoot of the transient process.

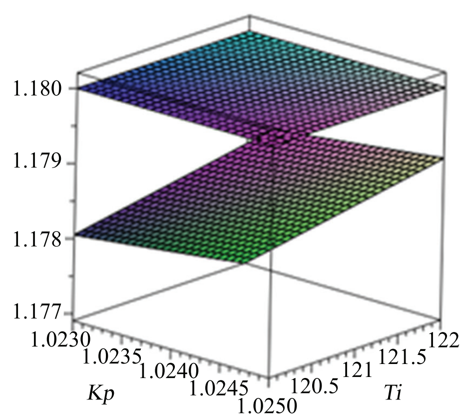

Fig. 13. Finding controller settings with overshoot limit

From the analysis of the research results, it is possible to state the improvement of the dynamic properties of the system when using the controller parameters calculated according to the proposed algorithm:

– reduction of overshoot by 10 times;
– reduction of regulation time up to 10 times.

In the study of systems using the P controller, it is necessary to note an increase in deregulation, but at the same time the static error of the system decreases by 2–3 times compared with other methods.

7. SWOT analysis of research results

Strengths. In this paper, an algorithm for identifying control objects with different types of transients by second-order links with a delay time is proposed and investigated. The identification error does not exceed 3 %, which is quite acceptable for calculations of this type. According to the results of a comparative analysis, it is concluded that the found parameters of the controller according to the proposed algorithm significantly improved the dynamic properties of the system (overshoot, regulation time, static and dynamic errors). Also in this work, an algorithm is proposed for searching the controller settings with the introduction of a restriction on the overshoot of the transition process, which also shows a positive result.

Weaknesses. The quality of any control system is determined by the magnitude of the error, but the error function for any point in time is difficult to determine because it is described using a high order differential equation and depends on a large number of system parameters. Therefore, assess the quality of control systems for some of its properties, which are determined using quality criteria.

Opportunities. The task of further research will be the development and improvement of the search algorithm for the controller settings with the specified (limited) quality indicators of transient processes.

The research results show an improvement in the dynamic properties of the system when using the optimal controller settings calculated by the proposed method as compared to the most common engineering methods for searching the controller settings for ACS with aperiodic and oscillatory COs. The overshoot has decreased by 10 times, the regulation time has decreased to 30 %, the static and dynamic errors have decreased by 2–3 times.

Threats. When implementing this algorithm for identifying control objects, significant additional equipment costs are not required. Today, there are many theoretical and experimental methods for finding PID controller settings. However, there is no universal method that would allow determining the optimal PID controller settings for systems and objects of various types.

8. Conclusions

1. An algorithm for identifying control objects with different types of transients by second-order links with a delay time is proposed and investigated. The identification error does not exceed 3 %, which is quite acceptable for calculations of this type. On the basis of the transfer functions of equivalent objects obtained in this way, the settings of the P, PI and PID controllers for the ACS are found by the triangle method, the sustained oscillation method (Ziegler-Nichols method) and using the proposed algorithm.

2. A comparative analysis of the quality indicators of transient processes of the investigated ACS with the settings obtained by different methods. The results show an improvement in the dynamic properties of the system when using the optimal controller settings calculated by the proposed method, compared to the most common engineering methods for searching the controller settings for the automatic control system with aperiodic and oscillatory COs. The overshoot has decreased by 10 times, the regulation time has decreased to 30 %, the static and dynamic errors have decreased by 2–3 times.

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