Розглянуто метод настройки пропорціонально-інтегрально-диференціального регулятору з додатковою керуючою дією диференціатора. Встановлено, що запропонований регулятор забезпечує бажаний вид перехідної характеристики замкнутої системи за показниками якості: перерегулювання, час регулювання. Показана можливість створення графічного інтерфейсу користувача автонастройки в середовищі MatLab розробленого регулятору та ручною підстройкою на основі досвіду користувача

Ключові слова: пропорціонально-інтегрально-диференціальний алгоритм, передаточна функція, якість, інтерфейс, Matlab/Simulink

Рассмотрен метод настройки пропорционально-интегрально-дифференциального регулятора с дополнительным управляющим воздействием дифференциатора. Установлено, что предложенный регулятор обеспечивает желаемый вид переходной характеристики замкнутой системы по показателям качества: перерегулирование, время регулирования. Показана возможность создания графического интерфейса пользователя автонастройки в среде MatLab разработанного регулятора и ручной подстройки на основе опыта пользователя

Ключевые слова: пропорционально-интегрально-дифференциальный алгоритм, передаточная функция, качество, интерфейс, Matlab/Simulink

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DEVELOPMENT OF THE PROGRAM FOR SELF-TUNING A PROPORTAL-INTEGRAL-DIFFERENTIAL CONTROLLER WITH AN ADDITIONAL CONTROLLING ACTION

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1. Introduction

In modern information technologies an important role is given to instrumental means and environments for the development of an automated control system (ACS). Instrumental means of development are related to problem-oriented software. A developer can focus on resolving the set task in order to solve it in the most convenient form. Constituent parts are the high-level languages [1].

Development of software means for adjustment proceeds in the direction of broadening the range of supported controllers, the application of artificial intelligence techniques and methods of diagnosis, development of the user interface [2]. One of the constituent factors of the complex problem on the task of control is an automated support of parameters at the assigned level, using proportional-integral-differential (PID)-controllers.

During automated adjustment and adaptation the same methods of identification and calculation of the controller are used as during manual tuning, but they are performed in automatic mode. The most effective methods of automated tuning are those using a computer, temporarily included in the control circuit. Exploiting the power of the CPU and due to the absence of constraints on the software volume, there is the possibility to create a software tool with wide service properties and high-quality mathematical processing [3].

The use of the PID-law leads to the improvement of regulating quality, but wide acceptance of the algorithm is limited by the complexity of its tuning. This is explained by the peculiarity of work of ACS with a PID-controller, namely, high sensitivity to deviations in the optimum of its tuning. Thus, the automated tuning and adaptation are the most urgent tasks when building PID-controllers. Despite the large number of commercially available products, there are still many unresolved problems related to quality control, the influence of nonlinearities in the control object and external disturbances in the process of identification.

2. Literature review and problem statement

The process of tuning a PID-controller for the objects of chemical technology based on experimental rules is intuitive while attempts to set up a controller without preliminary approximate estimation of coefficients may prove futile. Historically, there were proposed a great number of methods for the calculation of parameters of controllers, but most of them require significant expenditures of time and do not always yield a satisfactory result, which would ensure the desired quality of control. Based on the review of existing methodologies for tuning, one can conclude that the methods by Ziegler-Nichols, Kopelovich, and CHR, are the most expedient for the application under industrial conditions.

The search for methods to improve tuning a PID-controller is still under way. Specifically, author of [4], by way of generalizing the disarranged terminology in the calculation of controllers, proposed the unified rules for tuning PI and PID- controllers taking into consideration a zone of insensitivity, though any information on other types of nonlinearities is missing. While developing the subject of non-linear controllers, authors of ref. [5] obtained a transfer function of the resonator, which predetermines the non-linear properties of control object. To conduct the study, the authors constructed a simulation model in order to determine stability of the amplitude and the frequency of auto-oscillations. The use of the z-transform when applying traditional methods for the synthesis of analog controllers was described in [6]. Practical implementation, however, turns out to be difficult and has limitations. Authors of article [7], in order to calculate parameters of tuning a PID-controller, employed the Matlab programming environment and applied optimization rules for the criterion of effectiveness (ITAE). The specified algorithm ensures prompt response of the system, reducing the impact of disturbances, but it represents only the final stage of the synthesis of a controller. Author of [8] proposed a PID-controller design methodology based on the reference model of reliable tuning (MoReRT). Achieving the robustness and stability reserve of the system is achieved by a set of rules for tuning, which are characterized by ambiguity for the objects with the same dynamic properties. In study [9], author focuses on the issue of using PID-controllers in the multi-circuit systems taking into consideration the principle of decentralization and the use of methods from the theory of phase space for interpreting the results. A search-free method for estimating the parameters of linear controllers is given in [10]. It implies building a complex frequency characteristic of suboptotic controller and bringing it closer to the appropriate characteristic of a typical controller. The main unresolved issue is determining the frequencies of approximation and the smoothing constant. In paper [11], authors devised a technique for tuning a PI-controller and a correcting device with a phase advance, which makes it possible to create an adaptive system. The model does not imply the estimation of influence of variable coefficients and examining the transient processes at the same time.

Despite the presence of a totality of sufficiently developed and inhomogeneous algorithms, there is still a big gap between theory and practice. In many ways, it is associated with the use of well-developed reliable algorithms for tuning and their modifications. The needs of the industry grow each year, caused by the increasing pace of production, technology change, flexibility. The studies conducted into the quality of work of 100 thousand control circuits at 350 enterprises have revealed that from 49 to 63 % of circuits operate with "weak" (close to breaking the circuit) settings [12]. On average, one-third of circuits run with normal settings, one third with "weakened", and one third with practically "weak" settings. This sets the task on improving the methods of control by employing sophisticated models that allow optimization of control, but it also gives rise to the problem of search for the algorithms of their tuning, to study the influence of controller's coefficients on the transient processes. This requires multiple launch of the model with modified coefficients and editing the properties of the model under condition of providing the user with a convenient interface.

3. The aim and objectives of the study

The aim of present work is to improve operation quality of proportional-integral-differential controller by introducing an additional controlling influence of the differentiator, and to implement its auto-tuning under interactive mode from the stage of identification of the control object to the construction of the curve of the transition process.

To achieve the set aim, the following tasks have to be solved:

– perform an analysis of the impact of components of a PID-controller on its cumulative effect in order to ensure stability reserve and system robustness at unsatisfactory dynamic properties of the control object;

– to assess the information base of a control system (introduction of additional signals) and to devise the models of structures of PID-controllers with an additional controlling action of the differentiator and to estimate its settings;

– to create a software application that would enable automated design of the control circuit of the proposed structures to the controller with the possibility of manual tuning based on the results of system's operation.

4. Study into properties of the control system

The initial stage in the estimation of controller's tuning is the experimental study of the control object and construction of the acceleration curve. In order to obtain it, we give a step influence to the input of the object. We determine the driver that affects the controlled magnitude. We change by a jump the incoming action by a few percent of the motion of the controlling mechanism and observe a change in the controlled magnitude followed by processing of the resulting curve [3].

A control object can be improperly designed (dependent control circuits, a large delay, high order of the object) and be nonlinear. Sensors may have bad contact with the object, the noise in the measured channel can be large, the resolution of the sensor may not be high enough, the source of the incoming influence on the object may have a large inertia. Before starting the tuning, it is required to make sure there are no such problems. Despite the diversity and complexity of actual control objects, the PID-controllers typically employ only two structures of mathematical models: the first-order model with a delay, and the second-order model with a delay. Much less frequently used are the models of higher orders, though they better correspond to an object.

Calculation of parameters of the controller based on formulae cannot enable optimal tuning because results obtained analytically are based on extremely simplified models of the object. Specifically, they do not take into consideration the nonlinearity of the type of "constraint" for the controlling influence. In addition, the models employ parameters that are identified with a certain error. That is why, after calculating parameters of the controller, it is advisable to fine-tune it, based on practice, theoretical analysis, and experiment:

– a growth of the proportional coefficient of amplification (P-controller) ensures greater accuracy and operational performance of the system, but can lead to the loss of stability. In this case, it is necessary to take into consideration that changes in the load must be small so that the static error remains in the permissible limits;

– a reduction in the integral component (I-controller) provides a more intensive decrease in the control error, but a low speed of performance. Such a controller is not applicable for use in systems without self-adjustment;

– an increase in the differential component (D-controller) increases stability reserve and operational performance. Differential control suffers worse from noise than other types of control since it amplifies this noise.

A shortcoming of all experimental techniques is the incompleteness of information about system's stability reserve and robustness, which determine operational reliability of the controller. The examined factors require analysis on a change in the dynamics of the control object; in this case, it is better to obtain a transition characteristic of the control object, to simulate it taking into consideration a range of change in the parameters and receive settings that are close to optimal.

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5. Development of structures of the PID-controller with an additional controlling action of the differentiator

Proportional control corresponds to the use of "instantaneous" information about the system, the integral control – of the "past" of the system. An element that is responsible for utilizing "predictive" information about the system is the differentiator.

We propose the structures of PID-controllers [13, 14, 15] with an additional controlling action of the differentiator (PID-CACD). The structure of the controllers includes a differentiation unit whose input receives the output signal, proportional to the sum of the output signals of one (two, three) components of a standard PID-controller. The output signal of the additional unit is added to the output signal of the PID-controller as an additional controlling action.

The block diagram of PID-PD-controller controller is shown in Fig. 1. The input of additional differentiator 7 receives the output signal of adder 5, which summarizes the output signals of proportional conversion unit 2 and differentiation unit 4 of a standard PID-controller. Additional controlling action of differentiator 7 is added to the basic signal of PID-controller in adder 6.

A transfer function of the devised structure of the controller takes the form:

$$W(s)=K_p+\frac{1}{T_i\cdot s}+\left(T_d+K_p\cdot K_d\right)\cdot s+T_d\cdot K_d\cdot s^2, \quad (1)$$

where K_p is the proportional amplification coefficient; T_i is the time constant of integration; T_d is the time constant of differentiation; K_d is the amplification coefficient of additional differentiator.

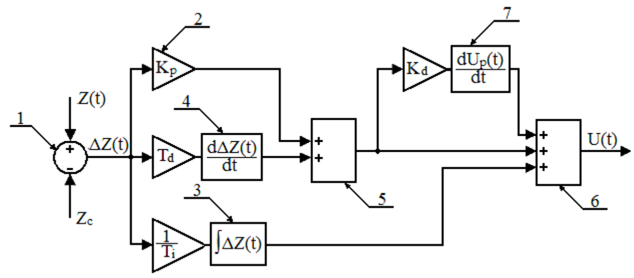

Fig. 1. PID-PD-controller: 1 (5, 6) – adder, 2 – proportional component, 3 – integral component, 4 – differential component 7 – additional differentiator, $Z_c(t)$ – controlling action (a setpoint), $Z(t)$ – measuring signal of the controlled parameter, $\Delta Z(t)$ – error signal

The circuit of a PID-ID controller is shown in Fig. 3. The structure of the controller differs in that the output of proportional conversion unit 2 is connected to the input of second adder 6, while the outputs of integration unit 3 and of the first differentiation unit 4 are, accordingly, connected to the inputs of first adder 5, the output of second one is connected to the input of second differentiation unit 7. The output of adder 6 is the controlling action of this controller.

The circuit of a PID-ID controller is shown in Fig. 2. The output of proportional conversion unit 2 is connected to the input of second adder 6. The outputs of integration unit 3 and of first differentiation unit 4 are connected to the inputs of first adder 5. The output of adder 5 is connected to the input of second differentiation unit 7. The output of adder 6 is the controlling action of this controller.

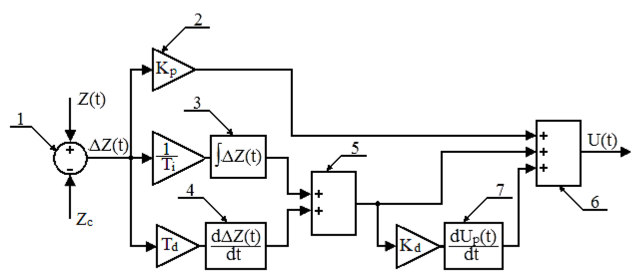

Fig. 2. PID-ID-controller

The calculation of a transfer function of the given structure of the controller showed:

$$W(s)=K_p+\frac{K_d}{T_i}+\frac{1}{T_i\cdot s}+T_d\cdot s+T_d\cdot K_d\cdot s^2. \quad (2)$$

PID-3D-controller performs additional differentiation of all three output constituents of a standard PID-controller (Fig. 3).

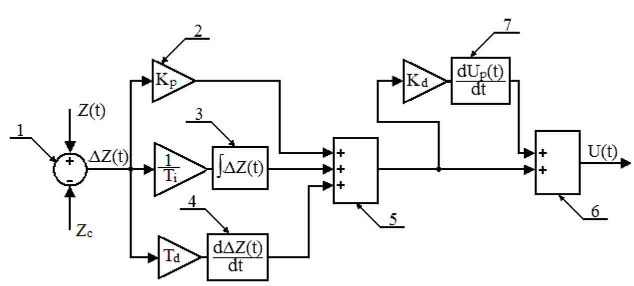

Fig. 3. PID-3D-controller

Transfer function based on structural diagram (Fig. 4):

$$W(s)=K_p+\frac{1}{T_i\cdot s}+T_d\cdot s+\left(K_p+\frac{1}{T_i\cdot s}+T_d\cdot s\right)\cdot K_d\cdot s. \quad (3)$$

To configure a PID-CACD, it is necessary to determine the settings: K_p, T_i, T_d, K_d.

6. Calculation of settings of PID-CACD

The calculation of PID-CACD settings was conducted using the express-method [16]. Dependences of settings on the dynamic characteristics of an object are estimated based on the experimental-statistical data in the form of regression equations.

A control object is represented by the sequential connection of two aperiodic links of the first order with a link of delay:

$$W_o(s)=\frac{K_o}{1+T_1\cdot s}\cdot\frac{1}{1+T_2\cdot s}\cdot e^{-\tau\cdot s}. \quad (4)$$

The object's amplification coefficient (K_O) varies from 0.4 % to 4 %, time constants ($T_{1(2)}$) from 1 to 35 units of time. Clean delay (τ) is calculated in the course of a statistical experiment using a relative delay:

$$\tau_r=\tau/T_o, \quad (5)$$

where T_o is the general time constant of the object; $\tau_r\approx(0{,}05\text{–}1{,}0)$.

We shall consider in more detail the calculation of PID-CACD settings.

To perform the task, we used a classic one-factor experiment, that is, we changed in the parameters of the model of dynamics of the examined object only one parameter leaving all the others unchanged. First, we determined the impact of change in the ratio of time of full delay (τ) to the total time constant of the object (T_o). By changing the time of clean delay, we changed ratio (τ/T_o) in the range from 0.1 to 0.8 and, through multiple solutions to the system of differential equations, we searched for optimal parameters of settings of a multi-parametric controller. During further investigation, it was found that the optimal settings of the controller are significantly affected not only by ratio (τ/T_o), but also by the very magnitude of time constant.

The second series of experiments was carried out when changing the overall time constant of objects (T_o) in a range from 4 min. to 50 min. Note that in this series of experiments we accurately maintained ratio T_1/T_2=0.4 by a change in the time constants in the range from T_1/T_2=1/2.5 to T_1/T_2=10/25. When processing the statistical data obtained, in order to achieve more exact calculations, we applied a method of piecewise-nonlinear approximation, that is, the observed objects were divided into two groups according to ratio (τ/T_o<=0.3) and (τ/T_o>0.3); we obtained specific regression equations for each group.

In the third series of experiments, we changed ration (T_1/T_2); in this case, the basic value was accepted from ratios: (T_1/T_2=0.4) and (τ/T_o=0.3). The obtained regression equations express the dependence of corrective coefficients on a change in the ratio (T_1/T_2). In this series of experiments the models of objects were also divided into two groups according to ratio (T_1/T_2<=0.4) and (T_1/T_2>0.4), while the total change in this ratio was in the range from 0.1 to 0.9.

For objects according to ratio τ/T_o<=0.3, regression equations:

$$K_{p1}=(0.298-72.0967\cdot\tau_r)/(1.0-18.088\cdot\tau_r), \quad (6)$$

$$T_{i1}=\left(0.598+1.477\cdot\tau_r+12.857\cdot\tau_r^2\right)\cdot(T_o/18.5), \quad (7)$$

$$T_{d1}=\left(26.2-72.485\cdot\tau_r+105.714\cdot\tau_r^2\right)\cdot(T_o/18.5), \quad (8)$$

$$K_{d1}=\left((1.6443-16.636\cdot\tau_r)/(1-12.6592\cdot\tau_r)\right)\cdot(T_o/15). \quad (9)$$

For ratio τ/T_o>0.3:

$$K_{p1}=\left(9.9878-21.2\cdot\tau_r+12.982\cdot\tau_r^2\right), \quad (10)$$

$$T_{i1}=\left(0.583-1.12\cdot\tau_r+20.5714\cdot\tau_r^2\right)\cdot(T_o/18.5), \quad (11)$$

$$T_{d1}=\left(15.267-1.5929\cdot\tau_r-8.2143\cdot\tau_r^2\right)\cdot(T_o/18.5), \quad (12)$$

$$K_{d1}=\left(3.4798-6.2025\cdot\tau_r+2.9296\cdot\tau_r^2\right)\cdot(T_o/18.5). \quad (13)$$

These settings were subsequently refined using the following formulae:

– for ratio T_1/T_2<=0.4:

$$K_p=K_{p1}/K_o, \quad (14)$$

$$T_i=T_{i1}(0.764+1.6298\cdot(T_1/T_2)-$$
$$-2.5973\cdot(T_1/T_2)^2)K_o, \quad (15)$$

$$T_d=T_{d1}(0.7962-0.1333\cdot(T_1/T_2)+$$
$$+0.9416\cdot(T_1/T_2)^2)/K_o, \quad (16)$$

$$K_d=K_{d1}\left(0.8304+0.4262(T_1/T_2)\right). \quad (17)$$

– for ratio T_1/T_2>0.4:

$$K_p=K_{p1}/K_o, \quad (18)$$

$$T_i=T_{i1}(1.4235-1.7065\cdot(T_1/T_2)+$$
$$+1.615\cdot(T_1/T_2)^2)K_o, \quad (19)$$

$$T_d=T_{d1}(1.2068-0.8698\cdot(T_1/T_2)+$$
$$+0.877\cdot(T_1/T_2)^2)/K_o, \quad (20)$$

$$K_d=K_{d1}\left(0.8333+0.4167\cdot(T_1/T_2)\right). \quad (21)$$

The scope of industrial application of the proposed controller is very wide. It could be used in chemical, oil-refining and metallurgical industries, in the production of building materials, as well as in many areas of food production and in other sectors where there are control objects with a significant time delay and where standard PID-controllers are used.

7. Building a software tool for tuning a PID-controller with additional information signals

A full cycle of tuning a PID-CACD controller in interactive mode is enabled by GUI developed in the MatLab programming environment [17]. The program automates the stages of development: identification of an object, calculation of the settings of the controller, construction of ACS transition process, determining quality indicators (Fig. 4).

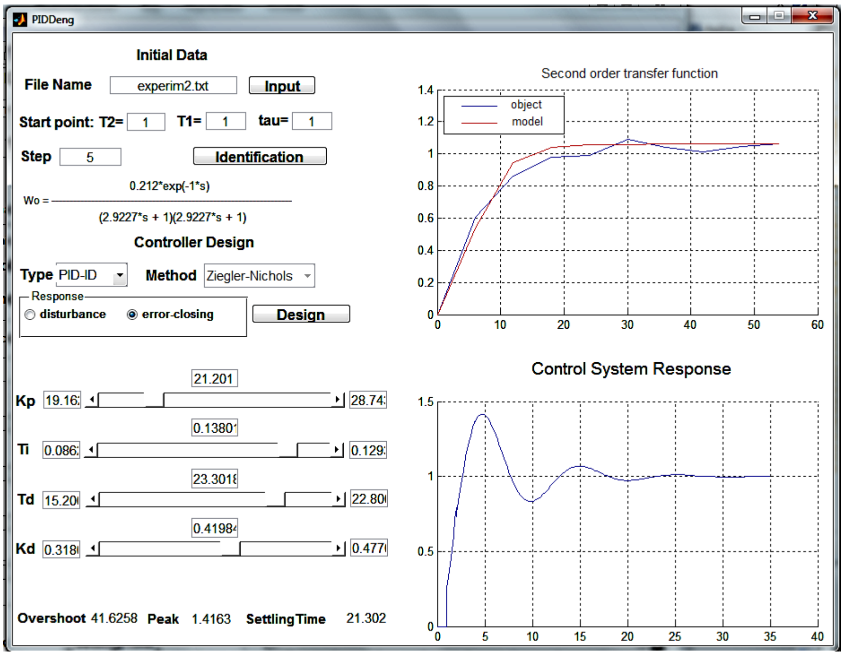

Fig. 4. Interface of PID-CACD auto-tuning software

The approximation of the object was carried out by a model in the form of (4) and implemented by the minimization of square of the difference of values of the output magnitudes of the model and the object. We use the MatLab function: fmincon optimset. The approximation is launched by pressing the button "Identification". As a result, a graph of the output magnitude of the model is constructed; the numerator and denominator of the transfer function are entered into fields "Nominator" and "Denominator". Next, one can then choose the type of controller. Pressing the button "Design" results in calculating the parameters of the controller tuning and in the construction of the ACS transition process graph.

As a result, parameters of tuning are calculated, which are displayed in the fields above the corresponding sliders, with a transition process chart being built. The bottom of the window displays quality estimated: Overshoot – over-regulation, Peak – maximum deviation, Setting Time – time of control.

8. Discussion of the research results

We examine influence of the structure and method of tuning a proportional-integral-differential controller with an additional controlling action of the differentiator on control quality. It is important because the introduction of an additional controlling action is limited by difficult tuning (non-linearity of the object, external disturbances). But there are objective difficulties associated with a large number of methods for estimating parameters of the controllers; however, most of them require significant expenditures of time and do not always produce a satisfactory result, which would ensure the desired quality of control.

In the framework of the research described in the present article, we determined the structures of PID-controllers with an additional controlling action of the differentiator, with settings calculated by the express-method. This makes it possible to substantiate the approach to determining the settings of the controller with an additional controlling action and to obtain certain effects from the implementation into production. Specifically, it is possible to ensure the desired form of ACS transitional characteristic for the indicators of over-regulation, time of control.

Typically, when tuning controllers, the experimental techniques are applied, characterized by incomplete information about stability reserve of the systems and robustness. However, the use of such methods is justified only for extremely simplified object models. When trying to overcome these constraints in order to improve the quality of control, there are objective difficulties associated with the need to fine-tune a controller, based on experience, theoretical analysis, and experiment. In the framework of the research described in the present paper, we proposed a procedure for overcoming these difficulties. It is based on the fact that the output signal of additional differentiation unit is added to the output controlling signal of a standard PID-controller and is used as an additional controlling action. This technique has allowed us to implement control that does not allow significant displacements of the controlling element. It increases stability reserve and robustness of the system. This is essential for objects with a limited reserve of the controlling load. This means that the obtained scientific result in the form of analytical dependences for calculating the settings of a controller with an additional controlling action of the differentiator to ensure robustness depending on the dynamic properties of an object is interesting from a theoretical point of view.

From a practical point of view, using the Guide environment of the system MatLab, we demonstrated the possibility of creating a graphic interface of auto-tuning a controller that does not require from the user knowledge in the field of programming and in-depth knowledge of the theory of automated control, as well as controllers with an additional control action of the differentiator, and makes it possible to automate all stages of the development from identification of an object to assessing the quality of a controller.

The study, which started with a series of papers [13 16], is planned to continue to improve the structure of PID-CACD and extend the scope of application.

9. Conclusions

1. It was established that a shortcoming of all experimental methods for tuning the controllers is the incompleteness of information on the system's stability reserve and robustness. The choice of the optimal model of the object should be based on sufficiency criteria of control quality at minimal complexity of the model. The calculation of parameters of

tuning a controller based on formulae cannot ensure optimal tuning of the controller since the results obtained analytically are based on extremely simplified object models.

2. We proposed a structure of the PID-controller with an additional controlling action of the differentiator whose input signal is the output signal of a standard PID-controller proportional to two or three of its components.

The experiment employed a classic one-factor experiment on changing one of the dynamic characteristics of the object. By multiple solutions to the system of differential equations we searched for optimal parameters of settings of a multi-parametric controller. When processing the statistical data obtained, in order to achieve more accurate calculation, we applied the method of piecewise-nonlinear approximation. Dependences of setting parameters on the dynamic characteristics of the object are calculated based on experimental-statistical data taking into consideration quality indicators: over-regulation, time of control.

3. A software application for auto-tuning PID-CACD was developed, which displays graphs of the transition process and calculates parameters of the controller, using several methods for tuning. Before starting the system, the user is given a graphic menu for entering *a priori* information about control object: the range of change in the input and output signals of the object, structure of the controller, initial approximations of the settings. Identification is performed by means of an analysis of response to the incoming jump in an open circuit.

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