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Practical aspects of the implementation of logical control programs for technological equipment of digital agriculture using the mathematical apparatus of difference equations

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Abstract. The emergence of new types of hardware devices for digitization of agriculture and the development of the software base and new approaches to the design of logical control systems cause a problem of changing the methodology of construction. One of the main issues is the formalization of the design stages of the mathematical apparatus of difference equations. The article is devoted to the implementation of programs for logical control of technological equipment using the mathematical apparatus of difference equations. The results obtained while working on the article will allow formalizing the process of designing logical control systems, taking into account the specifics presented by the control object.

1 Introduction

The current stage of development of society is attributed to the post-industrial, which is based on information as a means and object of production. In these conditions, the means of collecting, processing and transmitting information have changed: an increasing number of people use mobile devices to work with information resources, and a global network and cloud technologies are used to access large amounts of data.

2 Methods

When controlling the electrical automation of technological objects, there is a need to control changes in the parameters of the control object and the formation of a control action based on the data obtained. It is advisable to solve the problems of parameter control with the subsequent change of the control action using regulators - specialized hardware and software devices [1]. Within the framework of solving a logical control problem based on a classical PLC (programmable logic controller), it is not possible to implement a controller without the use of specialized hardware solutions. For example, for controllers manufactured by OVEN that implement control functions, it is necessary to additionally purchase a hardware module

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PID (proportional-integral-differentiating) regulation TPM-210 [2]. The approach given below makes it possible to implement a PID controller using limited resources of the logic control system programming tools without involving specialized additional hardware modules [3].

As an example, let's consider a range of high-precision turning and milling machining centers, in which temperature control of individual components (bed, spindle, tool) is used to achieve accuracy class A [4]. The terms of reference require the development of an algorithm for thermal compensation regulation of the bed of a high-precision turning and milling machining center of an inclined layout, which will be able to maintain a constant temperature in the cooling circuit of the bed with a value of 22 ± 0.5 ° C [5].

The cooling circuit is a closed system comprising a copper alloy pipeline with a length of 20000 mm and ⌀ 15 mm, cooling is carried out by means of a working fluid with a temperature of 10 ° C supplied to the circuit from the cooling station [6].

The flow rate of the coolant (water) is regulated using a direct-acting flow regulator with electronic proportional control RPCED1 by Duplomatic Oleodinamica, which is controlled by an electronic control unit for proportional distributors without feedback EDM-M111/20E0 by Duplomatic Oleodinamica (Figure 1).

The electronic unit is a digital amplifier for controlling proportional distributors without feedback. The amplifier supplies a current directly proportional to the reference signal and independent of temperature fluctuations or load resistance [7]. The pulse width modulator stage allows to reduce the hysteresis of the valve, thereby improving the control accuracy. Temperature readings in the cooling circuit are taken and transmitted to the electronic control unit of the temperature sensor TT-103A-G1/8-L16-H114-L013 by Turck, which has the following characteristics: accuracy 0.1% f.s, operating range -50...+500 °C, user settings, output signal 4...20 mA (2-pins), initial setting 0...150 °C, PNP output switch, protection class IP67 [8].

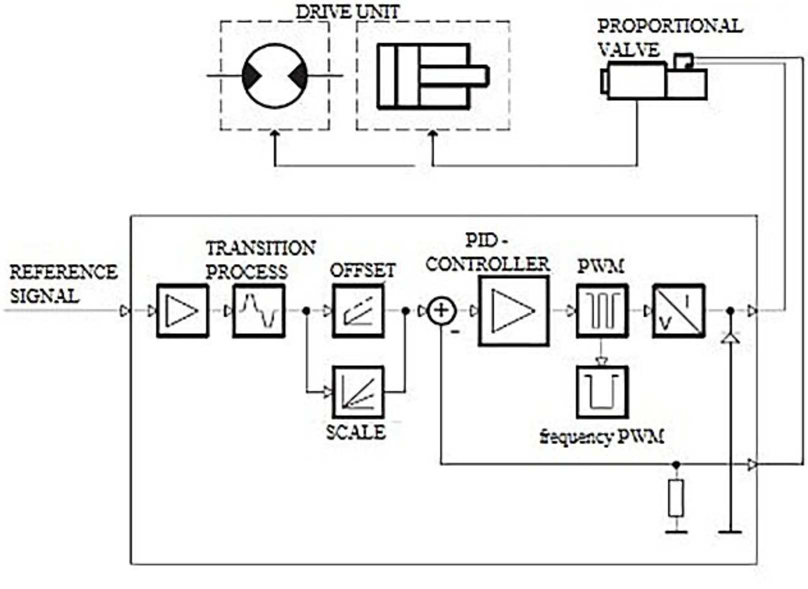

Fig 1. Scheme of operation of the electronic unit of the flow regulator.

3 Results

3.1 Obtaining the transfer function of the control object

When controlling the temperature of the bed of machining centers, the physical process of convective heat transfer (heat transfer) is used, in which heat energy is transferred between the surface of a solid body (bed) and a coolant (working fluid). In the technological system of the machine, the process of heat transfer occurs when this working fluid moves under the pump of the cooling station, as a result, forced convection occurs [9].

The basic law for convective heat transfer between the working fluid and the cooling circuit of the bed is the Newton-Rikhman law in differential form:

$$c_T \frac{dT}{dt} = \sum_{i=1}^{n} P_i - c_o \,(T - T_e) \tag{1}$$

Where c_{hc} – heat capacity of the cooled object;

$\frac{dT}{dt}$ - derivative of object temperature with respect to time;

$\sum_{i=1}^{n} P_i$ – the sum of thermal powers acting on the cooled object;

c_0 - heat transfer constant (calculated experimentally, finding the optimal value);

T – control object temperature;

T_e - ambient temperature.

We transform the resulting differential equation:

$$c_T \frac{dT}{dt} + c_o(T - T_e) = \sum_{i=1}^{n} P_i \tag{2}$$

$$\frac{c_T}{c_o}\frac{dT}{dt} + (T - T_e) = c_0^{-1} \sum_{i=1}^{n} P_i \tag{3}$$

$T_{ob} = \frac{c_T}{c_o}(c)$ - dynamic characteristic of object reaction time;

$T_{sup} = T - T_e$ – superheat temperature;

$$p = \frac{d}{dt} \tag{4}$$

$$\frac{dT_{sup}}{dt} = \frac{dT}{dt}, \quad T_e = const \tag{5}$$

$$T_{ob} \frac{dT_{sup}}{dt} + T_{sup} = \mathrm{c}_0^{-1} \sum_{i=1}^{n} P_i \tag{6}$$

$$T_{ob} p T_{sup} + T_{sup} = c_o^{-1} \sum_{i=1}^{n} P_i \tag{7}$$

$$T_{sup}(T_{ob} p + 1) = c_0^{-1} \sum_{i=1}^{n} P_i \tag{8}$$

$$\frac{T_{sup}}{\sum_{i=1}^{n} P_i} = \frac{c_0^{-1}}{T_{ob} p + 1} \tag{9}$$

where $\sum_{i=1}^{n} P_i$ – input action,

T_{sup} – output action. In the course of transformations, we obtain the transfer function of the control object:

$$W(p) = \frac{c_o^{-1}}{(1 + pT_K)} = \frac{k_{ob}}{T_{ob}p + 1} \tag{10}$$

The mathematical model of the control object is a first-order aperiodic link that responds to the input action with a delay proportional to the time constant. Due to the fact that the heating zones of the bed are not localized and are not known in advance, it is not possible to estimate the point of application, the magnitude and power of the disturbing influences. As a result, the perturbation control principle is not applicable for solving the problem. In this case, we will implement deviation control.

When the machine is in a static position (without movement of the axes), a proportional controller can be used for thermal compensation, the algorithm of which will maintain the temperature in the optimal range. With the active operation of the technological units of the machine, the static control error will be directly proportional to the heating power, which means that it is advisable to use the integral component in the controller [10,11].

According to formula (10), it can be seen that the dynamic characteristic of the reaction time of the object (the time constant of the control object as a transmission link) is large due to the high heat capacity and large mass of the frame, in this case the differential component of the controller can be excluded. Therefore, to regulate the parameters of the thermal compensation of the frame, a PI (proportional-integral) controller is used, the integral component of which will allow to avoid a static control error.

3.2 Mathematical model of the controller in a discrete form

Consider the transfer function of the PID controller***:***

$$W(p) = \text{Кр} + \frac{1}{T_i p} + T_d p \tag{11}$$

where: Кр – gain of the proportional part of the regulator,

Ti - integration time constant,

Td – differentiation time constant.

The control signal of the PID controller (3) can be written as a differential equation:

$$U(t) = \text{Кр}\text{Ɛ}(t) + \frac{1}{T_i}\int_0^t \text{Ɛ}(t)dt + T_d\frac{d\text{Ɛ}}{dt} \tag{12}$$

where: $U(t)$ – controller output value (control signal),

$\text{Ɛ}(t)$ - error signal (control error).

Let us transform the differential equation into a difference one by means of discretization of the function, provided that the quantization will be carried out with a short cycle time T. To do this, we replace the derivative with the difference of the first order, and the integral with the interpolation formula using the method of rectangles:

$$U[n] = \text{Кр}\text{Ɛ}[n] + \frac{T}{T_i}\sum_{i=1}^{n}\text{Ɛ}[i] + \frac{Td}{T}(\text{Ɛ}[n] - \text{Ɛ}[n-1]) \tag{13}$$

For software implementation in a logic controller, it is necessary to transform formula (5) using recurrent (difference) algorithms, expressing the value of the control signal U[n] through the previous value U[n-1] and the correction term ΔU[n]:

$$\Delta\text{U}[\text{n}] = \text{U}[\text{n}] - \text{U}[\text{n}-1] = \text{q0 Ɛ}[\text{n}] + \text{q1 Ɛ}[\text{n}-1] + \text{q2 Ɛ}[\text{n}-2] \tag{14}$$

where according to equation (13) we have:

$$\text{q}_0 = \text{Кр} + \frac{T}{Ti} + \frac{Td}{T} \tag{15}$$

$$\text{q}_1 = -\text{Кр} - \frac{2Td}{T} \tag{16}$$

$$q_2 = \frac{Td}{T} \tag{17}$$

Using the correction term ΔU[n] we obtain a recurrent equation for describing the control signal of the PID controller in a discrete form.

3.3 Implementation of the controller in the language of function blocks

Based on the obtained recursive expression, which describes the PID controller model in a discrete form, a custom functional block is implemented in the FBD (Function Block Diagram) programming language, using limited software and resources. The input parameters will be general parameters and controller parameters. General settings include: T_{bed} – optimal bed temperature (22 degrees Celsius), T_{cur} – current bed temperature (from the sensor installed on the bed), T – PLC cycle time (10 ms). Regulator options include: K_p – the transfer coefficient of the proportional part of the regulator, T_i - integration time constant, T_d – differentiation time constant. To solve the problem of thermal control, the differential component is excluded; in this case, the time constant of differentiation is taken equal to 0 ($T_d = 0$). The paper proposes a sequence of actions that allows you to get a PID controller block in the FBD language (Figure 2).

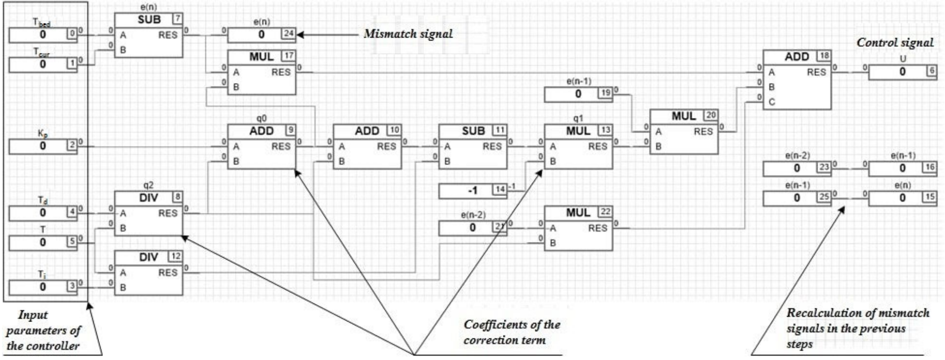

Fig. 2. Implementation of the PID controller in the language of function blocks.

Step 1. The transfer function W(p) of the PID controller is written as:

$\boldsymbol{W(p)} = \mathrm{Kp} + \frac{\boldsymbol{1}}{\boldsymbol{T_i p}} + \boldsymbol{T_d p}$, where: Kp – the transmission coefficient of the proportional part, T_i, T_d - the time constant of integration and differentiation.

Step 2. The control signal of the PID controller is represented as a differential equation: $\boldsymbol{U(t)} = \mathrm{Kp}\mathcal{E}(\boldsymbol{t}) + \frac{\boldsymbol{1}}{\boldsymbol{T_i}}\int_{\boldsymbol{0}}^{\boldsymbol{t}} \mathcal{E}(\boldsymbol{t})\boldsymbol{dt} + \boldsymbol{T_d}\frac{\boldsymbol{d}\mathcal{E}}{\boldsymbol{dt}}$, where: U(t) – output value of the controller (control signal), $\mathcal{E}(\mathbf{t})$ - mismatch signal (regulation error).

Step 3. The control signal of the PID controller is represented as a difference equation:

$$\boldsymbol{U[n]} = \mathrm{Kp}\mathcal{E}[\boldsymbol{n}] + \frac{\boldsymbol{T}}{\boldsymbol{T_i}}\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \mathcal{E}[\boldsymbol{i}] + \frac{\boldsymbol{T}\mathrm{d}}{\boldsymbol{T}}(\mathcal{E}[\boldsymbol{n}] - \mathcal{E}[\boldsymbol{n-1}])$$

Step 4. The control signal of the PID controller is written in recurrent form:

$$\Delta U[n] = U[n] - U[n-1] = q_0\,\mathcal{E}[n] + q_1\,\mathcal{E}[n-1] + q_2\,\mathcal{E}[n-2],$$

where, $q_0 = \mathrm{Kp} + \frac{\boldsymbol{T}}{\boldsymbol{T}\mathrm{i}} + \frac{\boldsymbol{T}\mathrm{d}}{\boldsymbol{T}}$, $q_1 = -\mathrm{Kp} - \frac{\boldsymbol{2T}\mathrm{d}}{\boldsymbol{T}}$, $q_2 = \frac{\boldsymbol{T}\mathrm{d}}{\boldsymbol{T}}$ - coefficients of the correction term.

4 Conclusions

The results of a set of formalized mathematical descriptions have been obtained that allow the design of logical control programs of any complexity using the developed design environment in the language of functional blocks. Comprehensive testing of the logical control system should include: load testing, failure testing and acceptance testing. These types of test tests allow us to draw unambiguous conclusions about the possibility of operating the system under development. The developed methodological aspects allow us to offer a comprehensive solution to the problem of designing and implementing logical control systems. Each phase of the development process forms a specific solution, a set of which covers the entire iterative process of designing and implementing the system.

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