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PARAMETRIC SYNTHESIS OF COMBINED AUTOMATIC REGULATING SYSTEMS WITH DIGITAL PID-CONTROLLERS

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Проведено аналіз особливостей реалізації комбінованих систем в залежності від способу вмикання компенсатора. Запропоновано спосіб параметричного синтезу цифрових комбінованих автоматичних систем регулювання на основі принципу інваріантності з розрахунком замкненого контуру за методом багатокритеріальної параметричної оптимізації. За розробленим підходом наведено приклад синтезу комбінованої системи з цифровим ПІД-регулятором та реальним об'єктом

Ключові слова: цифрові системи регулювання, комбіновані системи, багатокритеріальний параметричний синтез, ПІД-регулятор

Проведен анализ особенностей реализации комбинированных систем в зависимости от способа включения компенсатора. Предложен способ параметрического синтеза цифровых комбинированных автоматических систем регулирования на основе принципа инвариантности с расчетом замкнутого контура методом многокритериальной параметрической оптимизации. По разработанному подходу приведен пример синтеза комбинированной системы с цифровым ПИД-регулятором и реальным объектом

Ключевые слова: цифровые системы регулирования, комбинированные системы, многокритериальный параметрический синтез, ПИД-регулятор

1. Introduction

The overwhelming majority of the industrial facility regulation systems operate on the fundamental principle of deviation. In the practice of automation, such systems account for approximately 85 % [1]. This is explained by the fact that the regulatory action in them is formed regardless of the number, type and place of application of disturbances. In this case, with the help of one regulating action, it is often possible to achieve satisfactory compensation for several disturbances. However, the regulator in such systems begins to form regulating effect to compensate for the disturbance just after emergence of deviation of the regulated value from the specified one. Therefore, it is impossible to completely eliminate discrepancy between the regulated quantity and the task given to the regulator and only minimization of these deviations can be achieved in the systems operating on the basis of deviation.

With this approach, it is far from always possible to provide required quality of regulation if there are delays in the object's regulation channel and significant disturbances. In such cases, systems with a complicated information structure (e.g. cascade systems and systems with dynamic correction) are often found to be effective. However, not all objects have the technical ability to allocate auxiliary regulated values characterized by their delay and inertiality in relation to the principal disturbances of the object and the regulatory action less than the main regulated value. In addition, appearance of additional loops can be a source of a potentially unstable system. At the same time, presence of inertiality and delay in the advance part of the object can result in a loss of any effect from introduction of an additional status variable.

If there are controlled disturbances especially dangerous to the object, their effect on the object can be significantly reduced by using feedforward control. According to this principle, about 6 % of systems work [1]. With this approach, influence of external actions (task or disturbance) is compensated by an open circuit, that is, the principle of disturbance regulation is implemented which enables to improve quality of compensation for above actions.

In this case, parameters of regulator adjustment are not limited by the system stability. Therefore, it is possible to select a transfer function of the regulator so that the regulated quantity does not deviate from the specified value when disturbance has an effect on the object.

However, practical application of just disturbance regulation is associated with great difficulties since in order to implement such an automatic regulation system (ARS), it is necessary to ensure measurement of all disturbances affecting the object. This is usually technically impossible or economically inexpedient.

As a result, the systems working based only on the principle of compensation of disturbances can be realized in relatively rare cases. Therefore, the principle of compensation of disturbances is applied in the automation practice in conjunction with the principle of deviation regulation, so the systems in which both these fundamental principles are used simultaneously are called combined systems.

Due to this approach, combined systems ensure a quick response to disturbance and accuracy of regulation regardless of the nature of disturbances. The combined systems are characterized by a significantly higher quality of regulation compared with the classical systems with just feedback and are used in various industries. It is worth noting that the issues of synthesis of continuous combined systems are elucidated more widely for today. At the same time, it is interesting for automation experts to develop a method for a parametric synthesis of combined digital automatic control systems.

2. Literature review and problem statement

Application of disturbance regulation in combined systems makes it possible to drastically reduce forced and transient components of errors. These errors are caused by perturbing or imposing influence. Under certain conditions, they can be completely counteracted. The theory of invariance is the mathematical basis for construction of high-quality combined ARS.

The method of logarithmic frequency response (LFR) is commonly used in analysis and synthesis of ARS based on the deviation control principle. However, this method can also be extended to calculation of combined automatic control systems [2]. As is well known, logarithmic amplitude-frequency response (LAFR) of an open-loop system is used in calculation of the ARS by the LFR deviation method. For application of the LFR method in calculation of a combined tracking system, its transfer function can be taken as a transfer function of the system equivalent by its properties. Next, it is necessary to find the transfer function of the equivalent (by its deviation) system in an open state. Further study of the system (analysis and synthesis) can be carried out using an equivalent LAFR constructed on the basis of this transfer function [3]. It should be noted that this method of synthesis of combined systems can be applied only to continuous ARS. It is most rational to use it in calculation of the ASR with astatism of the 1st and 2nd orders because application of this method for calculation of static ARS is connected with some difficulties.

The method of multicriterial synthesis of a combined robust stochastic system of a joint control of process parameters of the hot strip rolling mill is proposed in [4]. The mutual influence of process parameters and disturbances caused by changes in thickness and hardness of the semi-finished metal product resulting from the changes in its temperature and chemical composition are taken into account. In a robust regulation, synthesis of open and closed control loops is performed simultaneously to minimize the anisotropic norm of the vector of the robust control objective. It was shown that the developed combined system provides higher accuracy of regulating thickness, tension and size of the strip loop compared with the existing systems.

The paper [5] presents a combined control system for production of tablets with PID-controllers. A comparative study of a system with combined disturbance and deviation regulation and a system functioning only on the basis of the deviation principle was carried out. Significantly higher quality of regulation of the combined system was shown. The authors used the Simulink software package only to determine parameters of adjusting the PID-controllers. Besides, the developed system ensures operation with only continuous regulators.

A procedure for synthesis of disturbance regulators for linear systems with variable parameters is proposed in [6]. Parametrically dependent Lyapunov function is used for synthesis. It ensures robustness of all parameters altering during regulation. A problem of infinite dimensionality of difficult to solve linear matrix inequalities appears in the synthesis process. The difficulties are caused by obtaining of finite matrix inequalities in the space of parameters.

The features of synthesis of compensators for combined control systems on the basis of the invariance principle are discussed in [7]. The author proposes a procedure for choosing the structure and calculating the compensator parameters when the condition of physical realization is not fulfilled because of an approximate invariance in the frequency range most significant for the system. The presented method of synthesizing compensators is suitable only for use in the continuous combined ARS. A promising line of development of combined systems is the use of neural net technologies in the regulating process. Authors of [8] have developed a system with combined control which consists of two parts. The part dealing with disturbance regulation is implemented on the basis of an artificial neural network (ANN) which is trained to behave as a reverse dynamic model of the milling process. This solution allows one to generate a control command of the controller based on the knowledge of the system dynamics. In the second part of the system with deviation regulation, a traditional PID-controller is used in series with a static ANN. Parameters of the PID controller settings are determined by the Ziegler-Nichols method. After calculating parameters of the regulator, it is usually necessary to manually adjust it to improve regulation quality. A similar approach is used in the medical field in development of a nonlinear dynamic combined system for controlling human musculoskeletal system [9]. The disturbance compensation regulator generates muscle activation for the desired movements and the regulator in the feedback loop corrects the errors caused by muscle fatigue and external disturbances.

The disturbance regulator is an artificial neural network approximating the reverse dynamics of human hands. The feedback loop includes a PID-controller connected in series with the other ANN representing nonlinear properties and biomechanical interactions between muscles and joints. The PID-controller parameters are determined by the Ziegler-Nichols method.

The analysis has shown that the considered methods of synthesis of combined ARS are oriented to their use in continuous systems, have limited functional capabilities and do not always provide acceptable quality of regulation. Therefore, it becomes apparent that there is a necessity of development of a method of parametric synthesis of combined digital automatic regulation systems.

3. The aim and objectives of the study

The study objective was to develop a method for parametric synthesis of combined digital automatic control systems based on the principle of invariance with calculation of a closed loop using the method of multicriterial parametric optimization.

To achieve this objective, the following had to be solved:

– develop an algorithm of synthesis of a combined system with a discrete PID-controller in a closed loop;

– study application of the proposed method for synthesis of a combined system with a digital PID-controller and a high-order object with self-alignment.

4. Analysis of combined systems with disturbance compensation

An example of a combined ARS may be a system for controlling temperature of superheated steam shown in Fig. 1 where an additional action is introduced at the temperature t_n before the steam cooler (SC) and not after it, like in a cascade system.

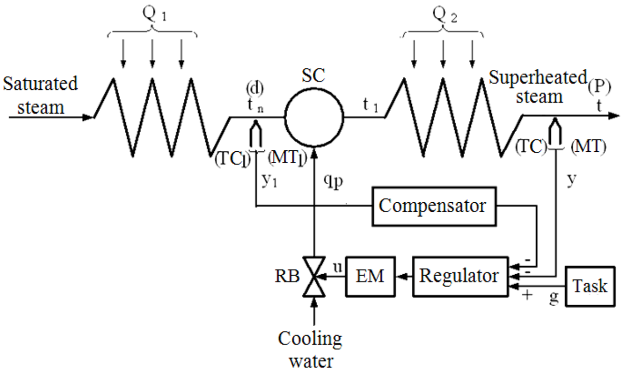


Fig. 1. Functional scheme of the combined system of superheated steam temperature regulation

Since the temperature t_n does not depend on the changes in supply of cooling water to the SC, this action does not affect stability of the system. However, compared with the cascade system, this system has a drawback: it does not take into account the disturbances caused by the spontaneous change in water supply for cooling. For example, disturbances may be caused by pressure changes in the cooling water supply line.

Efficiency of introducing an additional disturbance compensation action depends on the relationship between the delay τ_μ in the regulatory action channel and the delay τ_d in the disturbance action channel (the additional signal input which is introduced into the system) by the main regulated value. When $\tau_d=0$, introduction of the compensating action does not improve efficiency. With increase in τ_d, the degree of deviation compensation increases and when $\tau_d=\tau_\mu$, the influence of the chosen disturbance on the regulated quantity can be completely eliminated, i.e. the system becomes invariant with respect to this disturbance.

If the disturbances acting on an object are known or can be measured, then one can adjust control before disturbances start affecting the output parameter of the object. This approach is called feedforward control from process disturbances and can significantly improve control quality. If disturbance cannot be measured directly, its value must be found or measured by some indirect method.

When implementing this principle, the strongest and most dangerous disturbance is usually taken into account. This allows one to significantly reduce the dynamic error of regulation provided that the correct choice and calculation of the dynamic device (*compensator*) is made that forms the law of change of this action. In practice, depending on the method of switching the compensator, two types of combined systems are used:

1) Systems with the disturbance signal sent to the object input.

The block diagram of such a system is presented in Fig. 2.

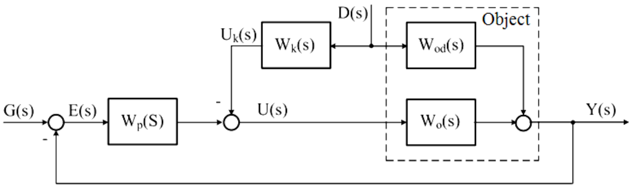


Fig. 2. Block diagram of the combined system with the compensator signal sent to the object input

In Fig. 2, $G(s)$, $E(s)$, $Y(s)$ stand for the task, the control error and the controlled value, respectively; $W_p(s)$ is transfer function of the regulator; $W_o(s)$, $W_{od}(s)$ are the object functions of transfer by the regulating channel u and the external disturbance channel d, respectively; $W_k(s)$ is the transfer function of the compensator with its task to compensate for the influence of disturbance on a controlled coordinate. Note that two or more compensators can be used if there are several strong sources of disturbance in the system.

It is seen from Fig. 2 that the controlled object in this case has two inputs and is described by a function with two arguments: $U(s)$ and $D(s)$

$$Y(s)=W_o(s)\,U(s)+W_{od}(s)D(s). \tag{1}$$

Equation of the system with substitution of the expression for $U(s)$ has the form:

$$Y(s)=W_{od}(s)D(s)+ \\ +W_o(s)\left(-W_k(s)D(s)+W_p(s)\left[G(s)-Y(s)\right]\right) \tag{2}$$

or

$$Y(s)=\frac{W_{od}(s)-W_k(s)W_o(s)}{1+W_p(s)W_o(s)}D(s)+$$
$$+\frac{W_p(s)W_o(s)}{1+W_p(s)W_o(s)}G(s). \qquad (3)$$

From equation (3), it is seen that the influence of external disturbances can be reduced in two ways: by increasing the feedback loop gain $W_p(s)W_o(s)$ or by choice of $W_{od}(s)-W_k(s)W_o(s)=0$. The following is obtained from the last expression:

$$W_k(s)=\frac{W_{od}(s)}{W_o(s)}. \qquad (4)$$

Expression (4) describes the ideal compensator for this system with the help of which invariance with respect to disturbance d can be provided. However, physical implementation of such a compensator, as a rule, is associated with significant difficulties which necessitates forced use of real compensators that meet the conditions of physical implementation. In this case, just an approximate invariance is achieved in some frequency range.

A system with an advanced compensation of disturbance makes it possible to compensate for its effect predominantly before the disturbance passes through the object. This significantly increases the overall performance of the system and eliminates its potential instability.

By the task channel, the transfer function of the closed system is described by expression

$$W_{yg}(s)=W_p(s)W_o(s)/[1+W_p(s)W_o(s)],$$

which corresponds to the transfer function of the closed loop which operates according to the deviation.

In the scheme shown in Fig. 2, the signal from the compensator output is actually sent to the output of the regulator which immediately results in a transfer by the executive mechanism of the regulatory device. If disturbance d is unfavorable in this case, then a negative impact on the object is created at the first moment. This is a disadvantage of this scheme although it can generally reduce the effect of disturbance on the regulated variable up to 10 times.

2) Combined systems with the disturbance signal sent to the regulator input.

Consider a combined system with the compensator signal sent to the regulator input (Fig. 3).

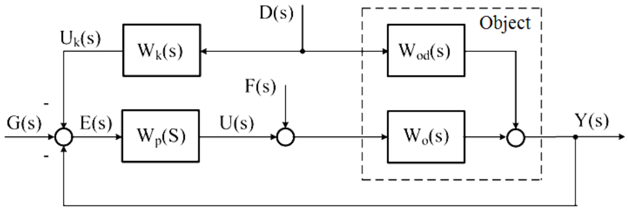


Fig. 3. Block diagram of the combined system with the compensator signal sent to the regulator input

In the Laplace images, the regulated value $Y(s)$ under the disturbance action $D(s)$ is described by the expression:

$$Y(s)=\frac{W_{od}(s)-W_k(s)W_p(s)W_o(s)}{1+W_p(s)W_o(s)}D(s), \qquad (5)$$

from which it follows that the condition for ideal compensation of the disturbance action is fulfillment of the requirement:

$$W_k(s)=W_{od}(s)-W_k(s)W_p(s)W_o(s)=0. \qquad (6)$$

Thus, the transfer function of the compensator must be determined by the formula:

$$W_k(s)=\frac{W_{od}(s)}{W_p(s)W_o(s)}. \qquad (7)$$

Such a compensator can be called ideal since it completely neutralizes the effect of disturbance on the regulated value, i. e. it ensures invariance of the system relative to disturbance. However, in many practical cases, especially in presence of delays in the channels of regulation and disturbance, such a compensator cannot be implemented physically. In particular, this situation arises when delay τ_o in the regulation channel is greater than the delay τ_d in the disturbance channel, i. e. when $\Delta\tau=\tau_o-\tau_d>0$. Thus, we have to demand compensation only for the time $t>\Delta\tau$. Then the transfer function of the ideal compensator (7) which can be implemented physically is obtained on the basis of (6). One of the ways out of such a situation [10] in order to equalize the degrees of polynomials in the denominator and the numerator of expression (7) is multiplication of its denominator by polynomial $P(s)$ required for this degree. As a result, the transfer function of the compensator is as follows:

$$W_k(s)=\frac{W_{od}(s)}{W_p(s)\,W_o(s)P(s)}. \qquad (8)$$

Optimization of parameters of this transfer function is carried out on the basis of the best approximation of the complex frequency responses (CFRs) of the real compensator (8) to the ideal one (7) at zero and resonant frequencies of the closed system loop.

The scheme of supplying the compensator signal to the regulator input is somewhat simpler for technical implementation compared with the scheme in which this signal is sent to the input of the object, i.e. the regulator output. This leads to a complication of technical implementation of the scheme of the executive device control. It should also be noted that real compensators have, as a rule, differentiating properties. As a result, in the case of abrupt changes in external disturbance, the output signal of the compensator, although for a short term, can reach large values that is undesirable for the executive device. Therefore, it is expedient to use combined systems with the supply of a compensating signal to the regulator input. That is why this system is more widespread in its use.

5. Parametric synthesis of combined systems

The principle of invariance is the basis of calculation of combined systems.

The principle of *invariance* can be formulated as follows: deviation of the initial coordinate $y(t)$ under the action of disturbance $d(t)$ must be identically equal to zero. Mathematically, this principle is described in the time domain, in Laplace images and in the frequency domain by respective expressions:

$$y(t) \equiv 0, \;\; Y(s) \equiv 0, \;\; Y(j\omega) \equiv 0. \tag{9}$$

An automated regulating system is invariant with respect to disturbances if after completion of the transition process that is determined by initial conditions, the regulated magnitude and error of the system do not depend on this disturbance.

Also, it is necessary to take into account the possibility of physical implementation of the combined system, i. e. the possibility of implementation of a compensator that meets requirements (4) or (7). We can formulate two basic conditions at which compensator can be implemented physically:

1. The compensator must not contain units with a negative net delay, i. e. the time τ_o of the object delay in the control channel must be less than that in the disturbance channel [11]. The compensator delay time must meet the condition $\tau_k=\tau_d-\tau_o\geq 0$.
2. The compensator must contain no ideal differentiating links, i. e. the degree of polynomial in the numerator m_k of the compensator transfer function should not exceed the degree of polynomial in the denominator n_k.

As a rule, the structure of the transfer function of real compensators is chosen so that its CFR coincides with CFR of the ideal compensator at a zero frequency. The choice of parameters of the transfer function of a real compensator should ensure coincidence of its CFR with the CFR of an ideal compensator at the operating frequency of the closed system. Most often, compensators are selected from a number of simple linear links (Table 1).

Table 1

Dynamic characteristics of real compensators

Compensator type	Transfer functions and frequency responses	Discrete analogs of continuous compensators
Aperiodic link of the first order	$W_k(s)=\frac{K}{Ts+1}$; $A(\omega)=\frac{K}{T^2\omega^2+1}$; $\phi\,(\omega)=-\mathrm{arctg}\,T\omega$	$W_k(z)=K\frac{T_0(z+1)}{(T_0+2T)z-2T+T_0}$
Real differentiating link	$W_k(s)=\frac{T_1 s}{T_2 s+1}$; $A(\omega)=\frac{T_1\omega}{T_2^2\omega^2+1}$; $\phi\,(\omega)=\frac{\pi}{2}-\mathrm{arctg}\,T_2\omega$	$W_k(z)=\frac{2T_1(z-1)}{(T_0+2T_2)z-2T_2+T_0}$
Integral-differentiating link	$W_k(s)=K\frac{T_1 s+1}{T_2 s+1}$; $A(\omega)=\frac{T_1^2\omega^2+1}{T_2^2\omega^2+1}$; $\phi(\omega)=\mathrm{arctg}\,T_1\omega-\mathrm{arctg}T_2\omega$	$W_k(z)=K\frac{(T_0+2T_1)z+T_0-2T_1}{(T_0+2T_2)z-2T_2+T_0}$
Nonminimal-phase link	$W_k(s)=K\frac{1-Ts}{1+Ts}$; $A(\omega)=K$; $\phi(\omega)=-2\mathrm{arctg}\,T\omega$	$W_k(z)=K\frac{(2T-T_0)z-2T+T_0}{(T_0+2T)z-2T+T_0}$

The discrete analogs of continuous compensators shown in Table 1 were obtained from the condition of maximal approximation of their CFRs to the CFRs of continuous prototypes by trapezoidal method. Non-minimal phase link can be used for a rough approximation of the ideal compensator in a form of a delay link.

In practical implementation of the combined ARS, they usually seek for an approximate system invariance in a certain frequency range. In this case, compensator is selected from a number of the dynamic links that can be easily implemented. Parameters of these links are calculated from the condition of proximity of the frequency characteristics of the ideal and real compensators in the next frequency range, that is

$$W_{kd}(j\omega)=W_{kp}(j\omega), \;\; \omega_* \leq \omega \leq \omega^*. \tag{10}$$

The range [ω_*, ω^*] depends on the frequency spectrum of the disturbance signal and the system frequency response. As a rule, disturbances in industrial ARS are low-frequency.

The combined ARS can be considered as a two-stage filter consisting of an open system and a closed loop. A characteristic feature of a closed regulation system is the presence of a peak in LFR at a working (resonant) frequency ω_p in the vicinity of which the system has the worst filtering properties. Therefore, the condition of approximate invariance is usually provided for two frequencies: $\omega=0$ and $\omega=\omega_p$. When compensating the disturbance at a zero frequency, invariance of the system under steady-state conditions is ensured if $|W_{zc}(j\omega)|\neq 0$ at $\omega=0$ (e. g., with the application of a P regulator), or the quality of regulation increases in the case of abrupt disturbances when $|d(j\omega)|\to\infty$ at $\omega\to 0$.

Thus, calculation of a partially invariant combined digital system consists of the following stages:

1. Calculation of the closed loop of the combined system taking into account the requirements to its stability and quality of regulation is performed by the method of multicriterial parametric optimization [12–14]. The method consists in satisfaction of certain requirements to the placement of the closed system poles at the expense of an appropriate choice of the regulator adjustment parameters (and the period of discretion T_a for digital systems). The calculation is carried out in the same way as for a single-loop system with a corresponding regulator and results in determination of the regulator adjustment parameters and the operating frequency of the system.
2. Derivation of a transfer function for the ideal compensator and analysis of possibility of its physical implementation.
3. Selection of the real compensator structure. First, CFR of the ideal compensator is calculated to determine quadrants of the complex plane in which zero and operating frequencies of the ideal compensator are located. On this basis, the corresponding transmitting function is selected and requirements to the CFR of the real compensator are formulated in a form of a system of equations. This system describes the conditions under which the CFR of the ideal and real compensators coincide at zero and operating frequencies.
4. Determination of parameters of the real compensator adjustment by means of solution of the system of equations obtained in the third stage.

One of the most important advantages of digital composite systems is reduction of requirements to the period of discreteness due to the reduced requirements to the closed loop. In this case, frequency of cut-off of the desired logarithmic frequency response of the system can be reduced, so the period of the system discreteness can be increased while maintaining the required stability reserve.

6. An example of calculation of a combined system with PID-controllers

As a basis, an object of regulation, i. e. a steam superheater of the PK-41 steam boiler operating at a 300 MW power generating unit was taken. The main disturbance was the change in steam load of the boiler. Transfer functions of this object for the regulatory channel and the external disturbance are accordingly described by the expressions:

$$W_o(s)=\frac{3.32}{(55s+1)(22s+1)^3},$$

$$W_{od}(s)=\frac{3.62}{(40s+1)(30s+1)}. \qquad (11)$$

The preliminary analysis has shown that the transfer functions of the ideal compensator cannot be realized physically for the specified dynamic characteristics of the object. Since the order of the transfer function in the numerator exceeds the order of the denominator, it does not meet the conditions of invariance (4), (7). As a result of calculations of the ideal compensator CFR and their analysis, it has been established that the real compensator in both systems should be selected as a real differentiating link (Table 1) with transfer functions:

$$W_k(s)=\frac{K_k T_{dk} s}{T_{dk}s+1},$$

$$W_k(z)=\frac{2K_k T_{dk}(z-1)}{(2T_{dk}+T_0)z-2T_{dk}+T_0}, \qquad (12)$$

where K_k, T_{dk} are the gain and the time constant of the differentiator, T_0, is the period of discreteness.

Parameters of adjustment of this link K_k, T_{dk} must be chosen such that its CFR coincides with the CFR of the ideal compensator for zero and resonant frequencies.

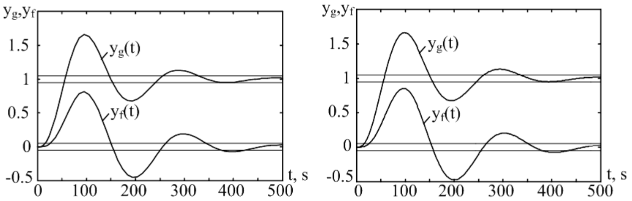
In the closed loop of the combined system (Fig. 3), instead of the continuous PID-controller, its discrete analog with the corresponding transfer functions is used:

$$W_{pid}(s)=K_p\left(1+\frac{1}{T_i s}+\frac{T_d s}{(T_d/N)s+1}\right), \quad N=10, \qquad (13)$$

$$W_{pid}(z)=K_p\left(1+\frac{T_0}{T_i}\frac{z}{z-1}+\frac{2T_d N(z-1)}{(2T_d+T_0 N)z-(2T_d-T_0 N)}\right), \qquad (14)$$

where K_p, T_i, T_d are the parameters of the PID-controller adjustment, N is normalizing factor.

In calculation of the digital system, an equivalent continuous model of digital PID-controller (14) was used, and the transfer functions of compensators corresponded to the expressions (12). The transition processes in the systems with specified object characteristics and determined parameters of regulators are presented in Fig. 4



a *b*

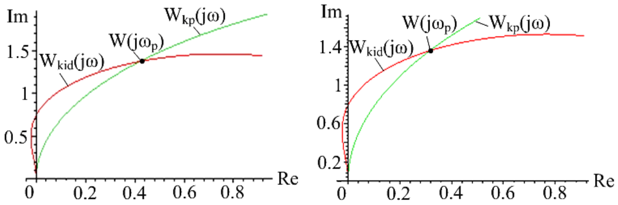
Fig. 4. The processes of working out the task y_g and compensation of disturbance y_f in the closed loop of the combined systems with: a continuous PID-controller (*a*); digital PID-controller; period of discreteness T_0=2 s (*b*)

For calculation of the systems with disturbance compensation in the digital compensator implementation, the equivalent continuous compensator was determined by the expression:

$$W_{ke}(s)=\frac{1}{T_0}W_k(z)W_e(z,s)\big|_{z=e^{T_0 s}}, \qquad (15)$$

where $W_e(z, s)=(1-z^{-1})/s$ is the transfer function of the extrapolator of zero order.

The corresponding characteristics of compensators for continuous and digital systems are shown in Fig. 5. In combined systems with continuous and digital PID-controllers, the CFR of the ideal $W_{kid}(j\omega)$ and real $W_{kp}(j\omega)$ compensators coincide at zero and operating ω_p frequencies.



a *b*

Fig. 5. Characteristics of ideal $W_{kid}(j\omega)$ and real $W_{kp}(j\omega)$ compensators for combined systems with: continuous PID-controller (*a*); digital PID-controller (*b*)

The processes of external disturbance compensation using these compensators are shown in Fig. 6

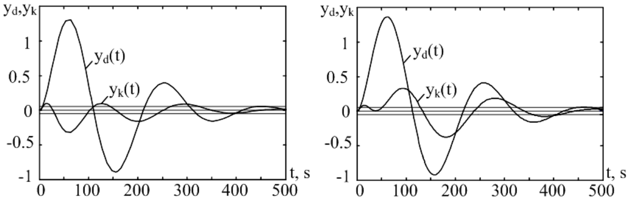
Numerical results of synthesis are given in Table. 2

Table 2

Characteristics of continuous and digital combined systems with a PID-controller

System type	K_p	T_i, s	T_d, s	K_k	T_{dk}, s	A_m	φ_m°	IAE	IAE_k
Continuous	1.00	41.00	28.09	4.92	12.15	2.14	37.8	177.4	37.95
Digital	0.938	40.91	28.96	7.14	6.43	2.06	36.7	187.5	62.25

Designations used in Table 2: K_k, T_{dk} are gain and time constant of the differentiator, A_m, φ_m are the reserves of modulus and phase stability margins, respectively, IAE, IAE_k are integral absolute quality estimates of the combined system without a compensator and with an external disturbance compensator, respectively.



a *b*

Fig. 6. The processes of compensation of external disturbance *d* in the combined system without the $y_d(t)$ compensator and with the $y_k(t)$ compensator with: continuous PID-controller (*a*); digital PID-controller (*b*); period of discreteness T_0=2 s

7. Discussion of the results of parametric synthesis of a combined digital system with PID-controllers and a real object

Applying the method of multicriterial parametric optimization, calculation of the closed loop of the combined digital system with consideration of requirements to its stability and quality of regulation was performed and parameters of the PID-controller adjustment at a specified T_0 value were determined. Application of the developed method of parametric synthesis of combined digital automatic regulation systems has a number of advantages. Namely, it makes it possible to simultaneously provide maximum stability reserve, maximum system speed, maximum filtering properties, minimum speed of variation and power of control actions, minimal system sensitivity to small variations of parameters. Since the parameters of the controller adjustment in this case are obtained on the basis of the characteristic equation of the closed ARS, they are optimal for both the process of working out the task and the processes of disturbance compensation.

It was shown that the dynamic properties of the ideal and real compensators in the region of operating frequencies coincide with a sufficient degree of accuracy (Fig. 5).

The obtained study results have shown a high degree of approximation of quality of the combined digital system with a PID-controller to that of a continuous one. This is confirmed by the transient processes of the task working out and disturbance compensation in the closed loop (Fig. 4) and compensation of the external disturbance in the combined systems (Fig. 6).

The use of compensators ensures a significant reduction of the maximum dynamic deviation of the regulated $y_k(t)$ value (Fig. 6).

In the future, there is a prospect of improvement of the proposed approach at the stage of calculating the closed loop of the composite digital system by the method of multicriterial parametric optimization in order to simultaneously determine the value of the period of discreteness and the parameters of the regulator adjustment in the system synthesis process. Determination of the value of the period of discreteness during the synthesis process will bring about some complication of the algorithm for calculating systems with digital PID-controllers, namely, to increase in the number of equations in the system from four to five. However, this is not critical when the Maple package is used for solving a system of equations.

The developed method of synthesis of combined systems can be applied in the automation practice for calculation of automatic systems with digital PID-controllers.

8. Conclusions

1. Discrete analogs of continuous compensators obtained from the condition of maximal approximation of their CFR to the CFR of continuous prototypes by the trapezoid method were proposed.

2. A method for parametric synthesis of combined digital automatic control systems with calculation of a closed loop with a discrete PID-controller using the method of multicriterial parametric optimization was developed. Analysis of the results of calculation of the combined control system of the steam superheater of the power unit steam boiler with the PID-controllers has shown that:

– under accepted conditions, the combined digital system is practically equivalent to a continuous system;

– the use of the compensator makes it possible to reduce the maximum dynamic deviation of the regulated value by approximately five times and improve the system's dynamic accuracy by about three times according to IAE.

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ASSESSMENT OF PERFORMANCE OF A DISTRIBUTED INFORMATION SYSTEM BASED ON TIME PROFILE

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Досліджується проблема визначення параметрів продуктивності для розподілених інформаційних систем, які утворені різнорідними апаратними засобами. Визначено структуру та розроблено опис процесу функціонування інформаційної системи, призначеної для розподіленого виконання завдань. Запропоновано методику оцінки продуктивності елементів розподіленої інформаційної системи на основі побудови часового профілю. Здійснено моделювання та показано зв’язок між основними показниками продуктивності системи

Ключові слова: розподілена інформаційна система, часовий профіль,послідовний виконавець, пропускна спроможність,час відгуку системи

Исследуется проблема определения параметров производительности для распределенных информационных систем, которые простроены на базе разнородных аппаратных средств. Определена структура и разработано описание процесса функционирования информационной системы, предназначенной для распределенного выполнения задач. Предложена методика оценивания производительности элементов распределенной информационной системы на основе построения временного профиля. Осуществлено моделирование и показана связь между основными показателями производительности системы

Ключевые слова: распределенная информационная система, последовательный исполнитель, временной профиль, пропускная способность, время отклика системы

1. Introduction

Most modern information systems of enterprise resource planning (ERP-systems) are based on software/hardware complexes, distributed in space, intended for the coordinated solution of various tasks [1]. When creating such information systems (IS), similar to any project, there is always the risk of unsubstantiated resource consumption. *A priori*