

## **THE PRINCIPLES OF SYNTHESIZING THE COORDINATING AUTOMATIC CONTROL SYSTEMS**

**A.A. GURSKIY, A.V. DENISENKO, S.M. DUBNA**

**Abstract.** The problem linked to the model development of the coordinating automatic control system has been solved in this scientific work. Such a task is relevant, as it is linked to increase the operational efficiency of the technological object due to the quality improvement of ratio control. As an object the steam boiler has been considered, in which it is necessary to maintain the appropriate air-fuel ratio. The article describes the stages of the model development for the coordinating automatic control system ensuring the maintenance of a given ratio between controlled variables in transient modes. The support of the set ratio is ensured by the implementation of temporal subordination for control processes. Based on the analysis of modeling results, we have made the conclusion about the expediency of using the coordinating system of automatic control. Thus, the method of stepwise synthesis for coordinating control systems was further developed.

**Keywords:** coordinating automatic control system, ratio control, steam boiler, stepwise synthesis for the multi-level systems.

### **INTRODUCTION**

Temporal subordination of control processes and coordination of transient is an important factor in order to increase the operational efficiency of some technological objects. In this case, increasing the operating efficiency of some objects is possible by using automatic coordinating control systems [1].

This class of automatic coordinating control systems has a certain feature of synthesis regarding the motions separation mode. At the same time in the systems, it must be provided the subordination of control processes according to temporal priority conditions.

The software development for automated synthesis of coordinating control systems linked with modern means of automation allows to realize the practical application of multi-level control systems in order to improve the operating efficiency of certain objects [2]. In a particular case, we have considered in this work a steam boiler (the DKVR series) for which it is advisable to synthesize the coordinating automatic control system. Such a coordinating system has been developed to improve the quality in control of the air-fuel ratio for efficient combustion of fuel.

## PROBLEM STATEMENT

The automation of tuning up process for the multi-level automatic control systems on the temporal subordination of regulation processes is the important task due to the lack of sufficiently simple methods for development systems of the appropriate class [1, 3].

Analyzing the well-known works [1, 4], we can conclude that the calculations are made not based on the appropriate control qualities, but on the transformation of the original standard control algorithm while synthesizing automatic coordinating control systems. Thus, the automated implementation for the tuning up process of coordinating automatic control systems for given control qualities is a relevant task. Accordingly, in order to solve this problem, it has been considered the synthesis of a model for the steam boiler control system for which it is important to improve the quality of regulation for the gas-air ratio in comparison with a typical traditional control system. In this case, the value of the integral indicator for the quality of work (the integral performance indicator)  $J$  for the coordinating system ought to be significantly less than the value of the

integral indicator  $J$  of the typical system. Where  $J = \int_0^{\infty} (\alpha \cdot [|e(t) / e_{\max}|] + |\phi(t) / \phi_{\max}|) dt$ ,  $\alpha$  is coefficient indicating the temporal coordination of the control processes;  $\phi(t)$  is deviations from the ratio of the values of regulated variables;  $\phi_{\max}$  is maximum deviations from the ratio of the values of regulated variables;  $e(t)$  is the deviation of some variable in time from the given value.

**Purpose of work** is to increase the operational efficiency of the technological objects due to automating the synthesis process of multi-level systems which ensure the temporal subordination of control processes.

To achieve this purpose, it was necessary to conduct a series of experiments linked to the synthesis of multi-level automatic control systems. Such systems ensure coordinated change in the values of controlled variables in transient modes, in the particular case coordinated change of gas consumption and air consumption to the combustion chamber of the steam boiler.

## REVIEW OF THE LITERATURE

Automation of the tuning processes for the systems of automatic control and coordination was presented in the work [2]. The refrigeration turbocompressor unit was considered as the control object. For the refrigeration turbocompressor unit it was necessary to change in a coordinated manner the diffuser blades pitch angle and the rotation speed of the turbocompressor shaft depending on cooling water consumption in the condenser.

This paper is considered a steam boiler in which it is necessary to coordinate the change in air consumption relative to the change in gas consumption in front of the combustion chamber during the transients.

There are various typical ratio control systems between fuel consumption and air consumption having both advantages and disadvantages.

The disadvantages of such methods for the regulating of gas-air ratio are that in order to set a given ratio between the gas and air consumption we have only

impact on the position of air consumption control element [5, 6]. The frequency controller can also be used to change the air supply fan performance into the burner.

The relevant systems use the most common air-fuel ratio control scheme in boiler units [6–8]. According to this scheme the fuel consumption is determined depending on the thermal load (steam consumption requirement) and the air consumption is regulated to provide the appropriate air-fuel ratio.

To improve the quality of regulation and liquidate the deviation from the set ratio we need to use not only one control action, as implemented in the standard control schemes. In this case it is necessary to implement an automatic system of coordinating control.

For example, a well-known scheme of the coordinating control system is presented in the scientific work by L.M. Boychuk [9]. This work shows the need to transform typical control schemes during the regulation of ratios and the need to decompose systems at the level when tuning up on the subordination of control processes. The disadvantage is that the coordinating system was not considered for the regulation of ratio between gas consumption and air consumption in the boiler unit. Also, in scientific work by L.M. Boychuk [9] it has not been considered in order to improve the ratio control quality due to simultaneous additional coordinating links between control actions with automatic optimization of the operating modes of objects.

Thus, we have developed in this work a model of the control system for the steam boiler, which has the appropriate coordinating links between the control loops, taking into account the correction of the ratio and optimization of the operating mode of the boiler unit.

## **MAIN PART**

It is known that in fairly frequent cases we strive for autonomy of control loops through dynamic decoupling of control channels. However, independence (i.e., the dynamic decoupling) of control channels from each other may be unnecessary, in particular when ensuring coordination of controlled variables during transients. The term “coordination” is found not only in the field of automatic control and in the field of control the term “coordination” is ambiguous in turn. But in this case coordination is a type of control, along with stabilization and tracking which is associated with the coordination of transients. We are talking exclusively about the coordinating automatic control systems.

The example of various transients is shown in Fig. 1 [1]. Such processes presented in Fig. 1, *b* are difficult to receive in the class of tracking automatic control systems or program system. It is obvious that the transient processes presented in Fig. 1, *b* can occur with a coordinating automatic control system. Such transients in the system can occur if there is a subordination of control processes or a motions separation mode. The different motion trajectory of systems in the space of controlled variables  $X_1$  and  $X_2$  is shown in Fig. 1, *c*. In the motions separation mode at first from the initial point  $X_0$  there is a mode of fast motions to the manifold  $m_1$  and then in a mode of slow motions to the end point  $X_r$ . In this case the manifold  $m_1$  is determined by the ratio between the variables  $X_1$  and  $X_2$ .

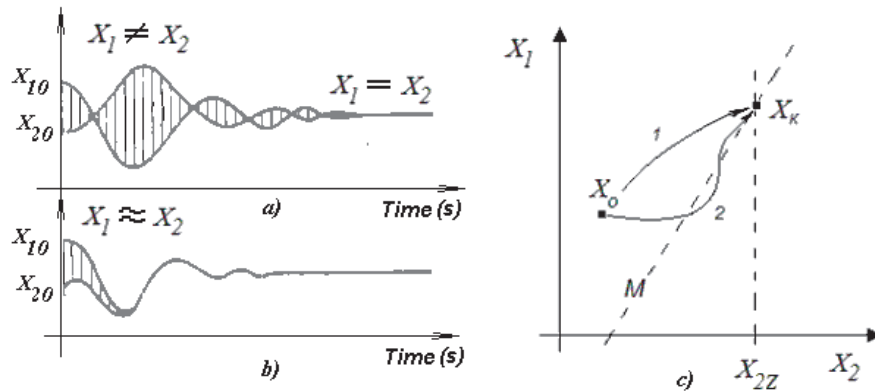


Fig. 1. Examples of transients in a typical automatic control system and in the coordinating automatic control system

It is shown in Fig. 2 the classic (typical) diagram of an automatic control system in which is implemented maintenance the ratio between the controlled variables  $X_1$  and  $X_2$ . But the coordinated change of controlled variables  $X_1$  and  $X_2$  is impossible to carry out in the dynamically unconnected system. In order to implement the subordination of control processes and ensure the motions separation mode we need availability cross-links between the control loops shown by the dotted lines in Fig. 2.

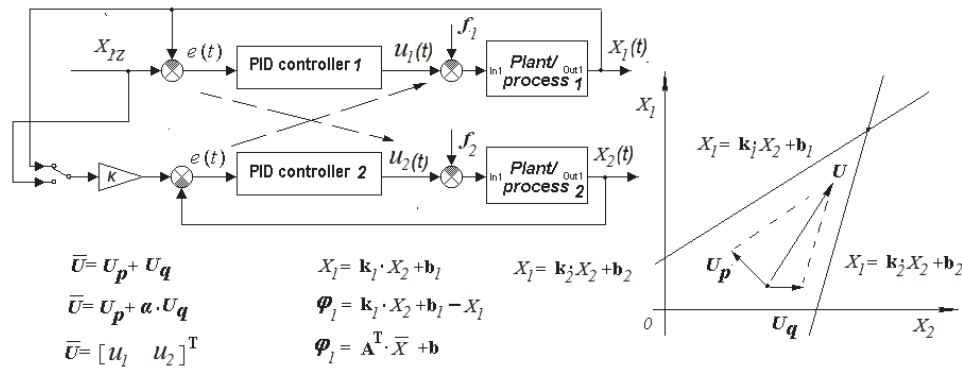


Fig. 2. Structural diagram of the typical control system and geometric formalization of the control task

In such a system we can possess two or more given ratios represented by equations of the form:  $X_1 = k \cdot X_2 + b$ , where  $b$  is a constant. Accordingly, deviations from the ratio is  $\phi = k \cdot X_2 - X_1 + b$  or in vector form is  $\phi = A^T \cdot \bar{X} + b$ , where  $A^T$  is the matrix of ratio coefficients. As shown in Fig. 2, in the space of variables  $X_1$  and  $X_2$  the ratios are presented in the form of straight lines possessing one common intersection point  $M$ . In such a system (in a system with cross-links) we can distinguish two subsystems. One system is named varying and the other system is stabilizing. One system is linked to elimination of deviations  $\phi_1$  from the ratio, the other is connected to deviation  $\phi_2$ . Herewith the control vector  $U_p$  of the varying system is directed towards Manifold One  $m_1$  and the vector  $U_q$  of the stabilizing subsystem is directed towards Manifold Two  $m_2$  of regulated ratios. Then the composition of these two subsystems and the addition of these two

vectors lead to the emergence vector  $U$  directed to the point for intersection  $M$  of the lines. When adding two vectors  $U_p + U_q$  we cannot to obtain the subordination of control processes, therefore we need to add coefficient  $a$  with this operation. So, in a system configured for the motions separation mode we can show  $U = U_p + \alpha \cdot U_q$ , where  $\alpha$  is the coefficient which the temporal subordination of control processes and respectively the motions separation mode.

As an example, we have considered the classic scheme of the automatic air-fuel ratio control system in the steam boiler while stabilizing the pressure of steam in the boiler drum (shown in Fig. 3).

The parameters of the steam boiler control channel are known. The control channel “control action  $u_{1g}$  by gas consumption – steam pressure  $Pn$ ” is described

by the 2nd order transfer function in this form  $W_{up}(s) = \frac{k_1 \cdot e^{-\tau \cdot s}}{(T_1 \cdot s + 1) \cdot (T_2 \cdot s + 1)}$ ,

where  $\tau$  is time delay;  $T_1, T_2$  are the time constants for the boiler. The dynamic properties of the boiler we can also describe by transfer function of the 1st order

aperiodic link with a delay  $W_{up}(s) = \frac{k_1 \cdot e^{-\tau \cdot s}}{T \cdot s + 1}$ , where,  $T = 200-300$  sec.,

$\tau/T = 0.025$  [10–12]. Accordingly, the inertia of the air consumption control channel is significantly less than the inertia of the steam pressure control channel. The air consumption control channel is “the control action  $u_{2v}$  on the air consumption linked with a change in the angle of the guide blades for the blower fan – the air consumption  $G_v$  before the economizer and the boiler furnace”. This channel is described by the nonlinear static characteristic of a blowing centrifugal fan.

The tuning parameters for the boiler PID controller we can determine based on the parameters of the control channels and optimize by the appropriate criterion for the quality of system operation.

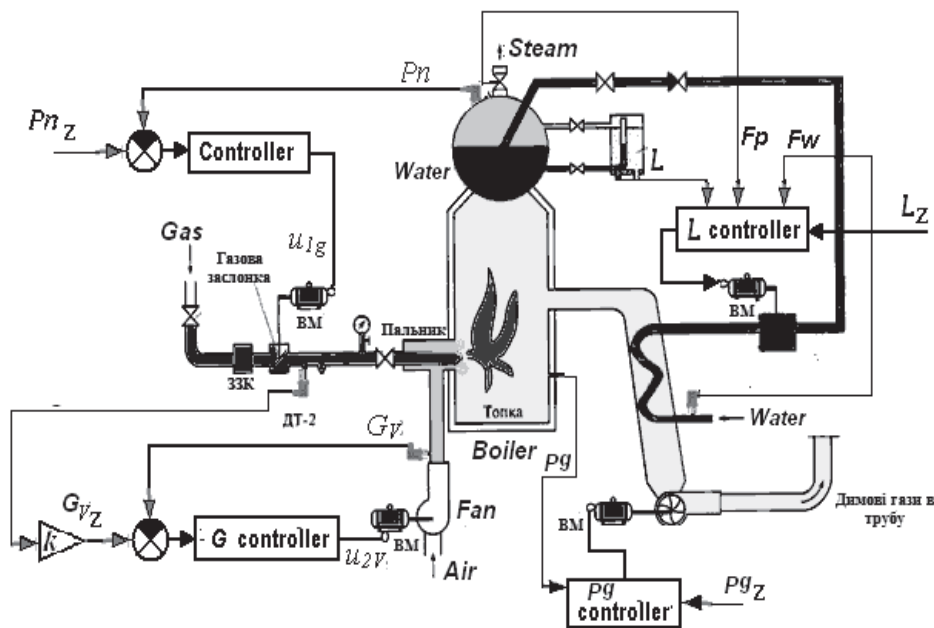


Fig. 3. Structural and technological diagram of the steam boiler

Thus, in the MATLAB\Simulink 5.2 software environment we have optimized the steam pressure PID controller parameters, then we have carried out optimization of the parameters for the ratio controller according to such integral criterion of system quality:  $J_{02} = \int_0^{\infty} |e(t)|dt$ , where  $e(t)$  is the difference between the actual and set values of the controlled variable (Fig. 4).

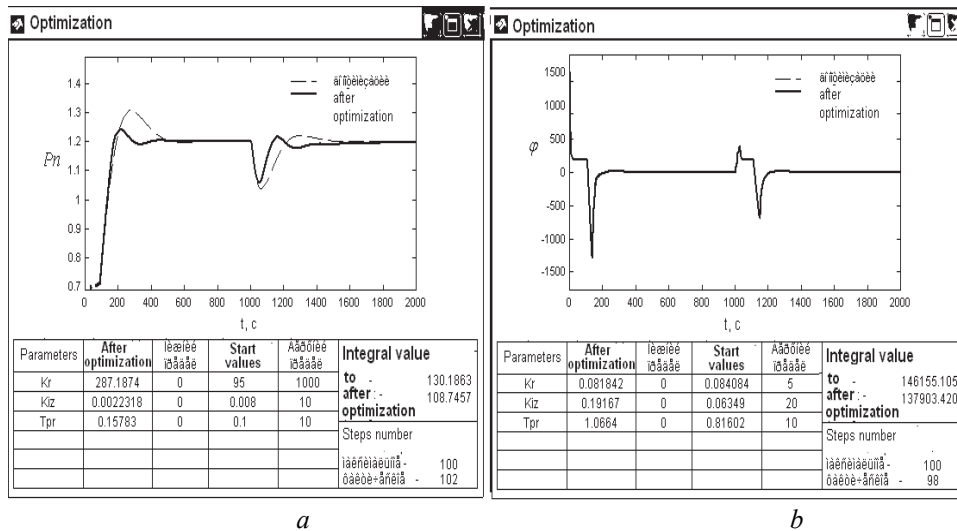


Fig. 4. The optimization results of parameters for the PID steam pressure controller in the boiler drum (a) and the ratio controller (b)

In order to synthesize such coordinating automatic control system, we can decompose the coordinating system into two systems. System one is the single-level coordinating automatic control system presented in Fig. 5. System Two is the stabilizing system and also the 2nd level of the coordinating system.

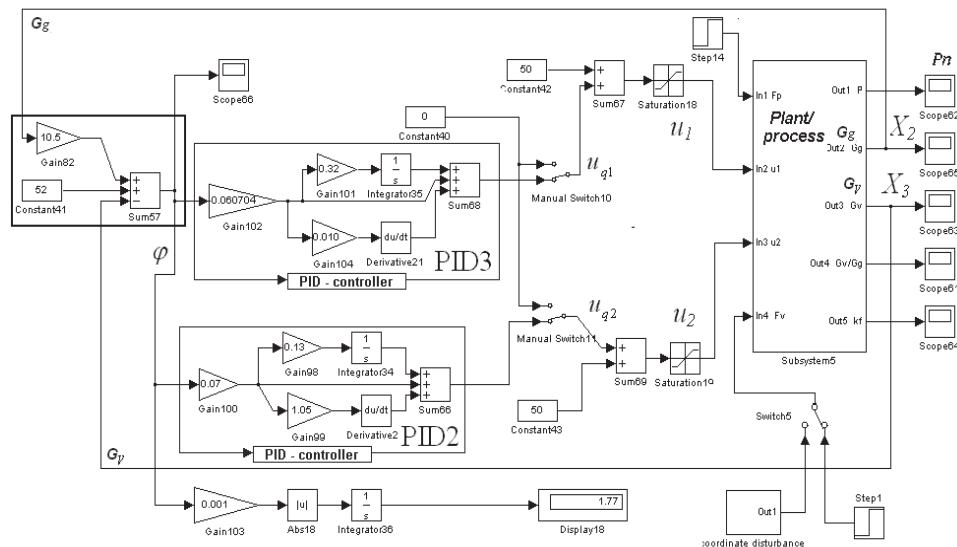


Fig. 5. Block diagram of the model for a single-level coordinating automatic control system presented by using MATLAB\Simulink

As shown in Fig. 5, two PID controllers are used simultaneously to process the deviation from the ratio of controlled variables. This is a distinctive feature of systems for this class. It is obvious that if one of the controllers (*PID2* or *PID3*) is excluded from the system and one of the control actions is fixed at a certain value, then the quality of the ratio control will noticeably deteriorate. In this case such system will convert from a coordinating system into a tracking one or into a regular stabilization one. But when two PID-controllers operate simultaneously and the values of two controlled variables change towards decreasing of deviation from the given ratio, then the quality of control ratio is noticeably higher.

The control law of a single-level coordinating system is as follows:

$$\bar{u}_q = \begin{bmatrix} u_{q1} \\ u_{q2} \end{bmatrix} = \begin{bmatrix} k_1 \cdot (1 + (k_{11}/p) + k_{12} \cdot p) \\ k_2 \cdot (1 + (k_{21}/p) + k_{22} \cdot p) \end{bmatrix} \cdot \phi, \quad (1)$$

where  $\phi = A^T \cdot \bar{X} + b$ ,  $A^T = [-1 \quad k]$ ,  $\bar{X} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$  is a vector of controlled variables,  $k_1, k_2, k_{12}, k_{11}, k_{21}, k_{22}$  are the tuning parameters of PID controllers.

The tuning parameters for the *PID2* controller are determined as in the previous case based on the parameters of the control channel  $u_2 - X_3$ , and the tuning parameters for the *PID3* are determined based on the parameters of the channel  $u_1 - X_2$ .

As a result of modeling for a single-level coordinating system we have determined that depending on the initial conditions or under the various actions  $\langle u_1 \rangle, \langle u_2 \rangle$ , deviations from the ratio are eliminated for 12–15 seconds and whilst various steady-state values of the controlled variables are implemented. We can see it in Fig. 6 showing the graphs of various transients by the deviation  $\phi$  from the ratio and by air consumption  $X_3$ .

In order to ensure stabilization of the controlled variables at the specified value, it is necessary to add to the system an extra stabilizing level, in which the deviations from another specified ratio can be processed.

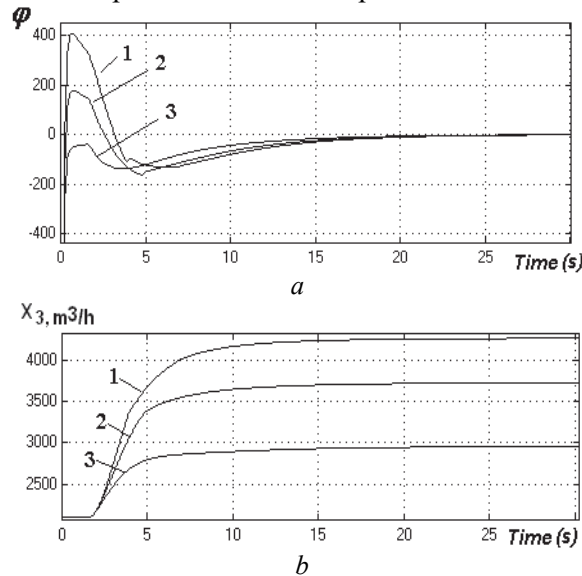


Fig. 6. Curves of transients by deviation from the specified ratio between the controlled variables (a) and step responses curves of the controlled variable  $X_3$  (b)

The structural diagram of the stabilization system model is presented in Fig. 7. In the stabilizing system of this model we can see some additional connection in addition to the PID controller. This connection sets the required value of the controlled variable  $X_3$  (air consumption), relative to the control action  $u_1$  on the controlled variable  $X_2$  (gas consumption). Such additional cross-link with the transmission coefficient ( $k_u$ ) improves the quality of control by steam pressure in the boiler drum (according to the variable  $X_1$ ).

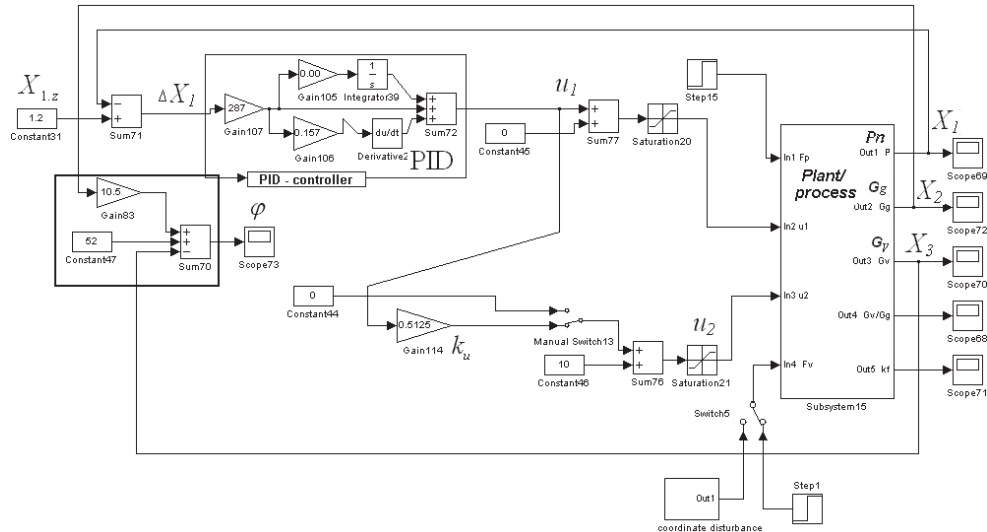


Fig. 7. Block diagram of the model for a single-level stabilizing control system presented by using MATLAB/Simulink

The systems shown in Figs. 5 and 7 have the same control object (plant or process) therefore we can combine them into one system. The structural diagram for the model of such a combined system is presented in Fig. 8.

To synthesize such a system and to move from the coordinating level of the system to the stabilizing level we need to select the leading control variable and, respectively the slave control one. In this case,  $X_2$  is as the leading control variable and, respectively  $X_3$  is the slave control one. Thus, another control loop appears in order to stabilize the variables at a set value. By Fig. 8, such a control loop appears when the switch KL1 is closed. But with such a system the control loop of steam pressure with the *PID* controller is the stabilizing subsystem, and when the KL1 contact is closed, we can see an additional internal control loop to stabilize the variable  $X_2$ .

The control law of this coordinating system is two-level and it can be represented as follows:

$$\bar{u} = \bar{u}_q + \bar{u}_p = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \bar{u}_q + \begin{bmatrix} k_3(1 + (k_{31}/p) + k_{32} \cdot p) \\ k_{u1-u2} \cdot k_3(1 + (k_{31}/p) + k_{32} \cdot p) \end{bmatrix} \cdot (X_{1,z} - X_1),$$

where  $\bar{u}_q$  is the control vector of the 1st level, according to expression (1),  $k_3, k_{31}, k_{32}$  are the tuning parameters of the 2nd level, where  $k_3, k_1, k_2$  are the parameters of the 1st control level, according to expression (1). They determine the time subordination of the control processes and, respectively, the mode separation of motions in the system.

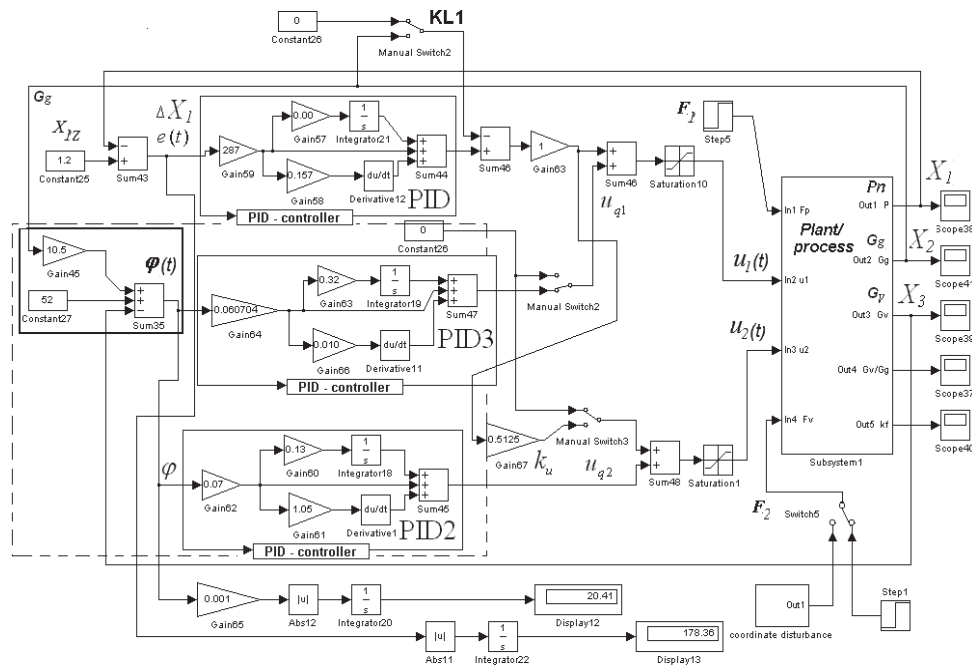


Fig. 8. Block diagram of the model for a two-level coordinated automatic control system presented by using the MATLAB\Simulink environment

In such a system the tuning parameters of the *PID* and *PID2* controllers have already optimized at the previous stage during the synthesis of the classical (typical) system. At the next stage the tuning parameters of the *PID 3* controller have optimized by the following integral criterion of quality for system operation:

$$J_{02} = \int_0^{\infty} (|\phi(t)| + \alpha \cdot |e(t)|) dt, \text{ where } \alpha \text{ is the weighting factor.}$$

The results of the optimization for the *PID 3* controller parameters are presented in Fig. 9. The presented transient process (Fig. 9) demonstrates how significant the quality of the air-gas ratio control has improved when comparing with the results presented in Fig. 4.

At the last stage the value of the coefficient  $k_{u1-u2}$  of the cross-link between the control actions  $u_1$  and  $u_2$  has optimized by the previous integral criterion, which has provided an extra improvement in the quality of control.

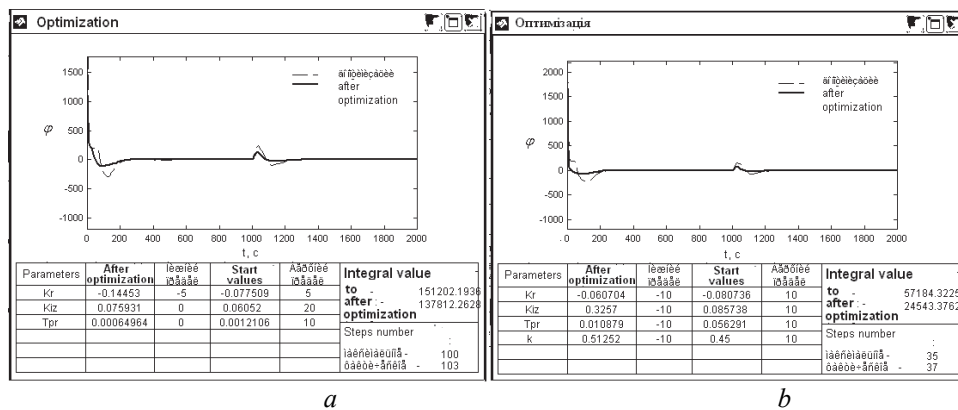


Fig. 9. The parameter optimizing results for the coordinating level of the system

## RESEARCH RESULTS

In this scientific article it has been carried out the modeling of various automatic control systems in the MATLAB\Simulink 5.2 software environment. The simulation results are presented in Fig. 10. It is evident from Fig. 10, *b* that in terms of the quality of ratio  $\varphi$  regulation the typical automatic control system (graph 1) functions significantly worse than the coordinating system (curves 2, 3), which contains additional cross-links between the control loops. However, the quality of steam pressure control is insignificantly worse while coordinating the controlled variables, unlike the typical control system. It is noticeable by comparing curves 1 and 3 in Fig. 10, *a*.

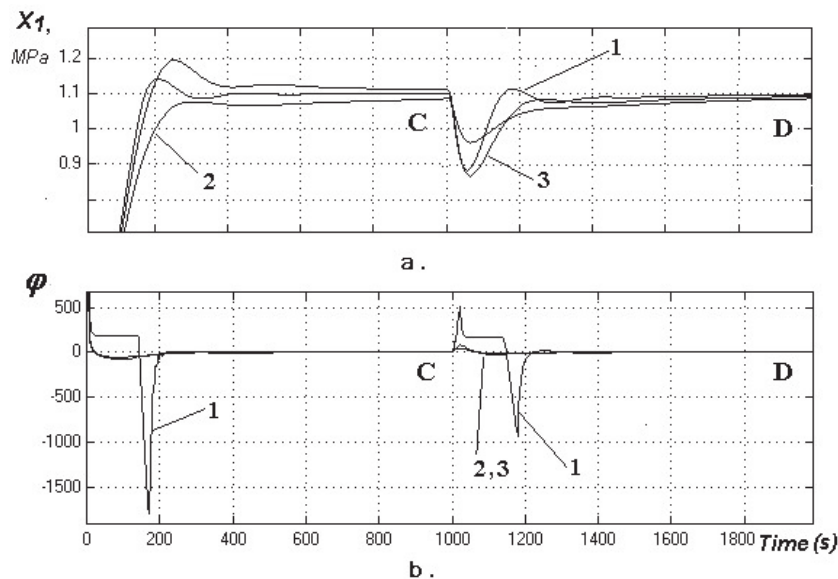


Fig. 10. The transients in various control systems, 1 is dynamic characteristic in the traditional control system; 2, 3 are dynamic characteristics in coordinating automatic control systems

The motions separation mode is clearly seen when considering motion of the system in space of the controlled variables  $X_2$ ,  $X_3$  (gas-air) shown in Fig. 11, *a*, *b*. The motion trajectory of the coordinating system is shown in Fig. 11, *a*. As shown in Fig. 11, *a* as per the motions separation mode at first the mode of fast motions comes from point A to point B located on the manifold  $m$  submitted by the dashed line. Then in the  $m$  mode of slow motions along the manifold  $m$  of the controlled ratio we can see the movement from point B to point C representing the final steady state. Due to the disturbing effect in such system the movement occurs from point C to point D along the manifold  $m$ . In Fig. 10 we have indicated points C and D in the graphs of the transients appropriating to steady conditions.

The motions separation mode is absent in a typical system of the steam boiler control. This is noticeable when considering the movement of the system in the space of controlled variables  $X_2$ ,  $X_3$ . It is presented in Fig. 11, *b*. As shown in Fig. 11, *b*, any transients and, hence, any movement of the system is associated with away from the manifold  $m$  (submitted by the dashed line) which represents the set of optimal states for gas combustion in the boiler furnace.

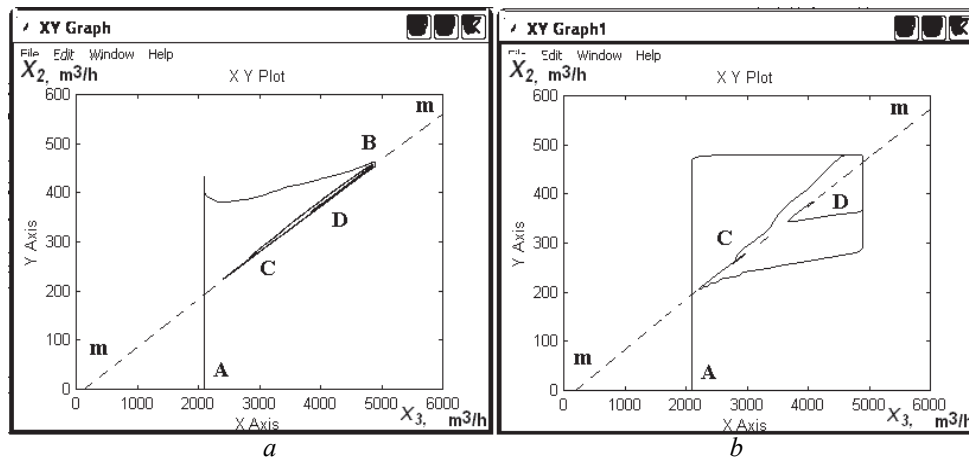


Fig. 11. Movement of the coordinating (a) and typical systems (b) in the space of controlled variables

## DISCUSSION

As a result of studies and based on simulation results, we have determined that during the coordinating automatic control system the quality of regulation for the gas-air ratio is significantly higher. But at the same time the coordinated change of gas consumption relative to air consumption and vice versa has not worsened significantly the regulation quality of steam pressure in the boiler drum with appropriate cross-link. This cross-link exists with the transfer coefficient  $k_u$  between the control actions for gas and air consumption control. Thus, as per the optimization results presented in Fig. 9, *a*, *b* we have the cross-link with the coefficient  $k_{u_1-u_2}$  allowing reducing significantly the value of the appropriate integral indicator for quality of system operation.

Ultimately, we have got the structural diagram of automatic control system shown in Fig. 12 as per the diagram of a model for the coordinating system presented by means of MATLAB\Simulink 5.2 (Fig. 8). In Fig. 12 we can see such a system differing mainly from the typical control system of the steam boiler by the presence of cross-links with links 3 and 4 and the peculiarity of tuning on the temporal subordination of control processes appropriate the motions separation mode. The diagram is also shown the automatic optimizer (AO) correcting the gas-air ratio.

Hence, the coefficient of the gas-air ratio (determining the required air flow depending on the  $G_g$  gas consumption) can be correcting through the signal  $u_o$  which has come from the output of the automatic optimizer 8. The automatic optimizer 8 forms the  $u_o$  correction signal depending on the oxygen content  $v_o$  in the flue gases and in the indicator of gas (fuel) combustion efficiency. So automatic optimizer 8 is contained in the optimization level of the system, PID controller 2 and unit 3 are contained in the stabilization level, and PID 4 and 5 controllers are contained in the coordination level of the system.

Notably, as per the structural diagram presented in Fig. 12, the complete composition of the control system must contain the underpressure  $P_y$  control loops in the boiler furnace and the control loops of water level in the boiler drum.



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#### INFORMATION ON THE ARTICLE

**Alexander A. Gurskiy**, ORCID: 0000-0001-5158-2125, Odesa National University of Technology, Ukraine, e-mail: [gurskiya2017@gmail.com](mailto:gurskiya2017@gmail.com)

**Andrey V. Denisenko**, ORCID: 0000-0002-8610-0082, National University "Odessa Polytechnics", Ukraine, e-mail: [denisenko.a.v@op.edu.ua](mailto:denisenko.a.v@op.edu.ua)

**Sergey M. Dubna**, ORCID: 0009-0002-1181-9110, Odesa National University of Technology, Ukraine, e-mail: [dubna\\_s@ukr.net](mailto:dubna_s@ukr.net)

#### ПРИНЦИПИ СИНТЕЗУ КООРДИНОВАЛЬНИХ СИСТЕМ АВТОМАТИЧНОГО УПРАВЛІННЯ / О.О. Гурський, А.В. Денисенко, С.М. Дубна

**Анотація.** Вирішено завдання, що пов'язане з розробленням моделей координувальних систем автоматичного управління. Це завдання актуальне, оскільки спрямоване на підвищення ефективності функціонування технологічних об'єктів завдяки покращенню якості регулювання співвідношення між регульованими змінними. Як приклад розглянуто паровий котел, у якому необхідно підтримувати відповідне співвідношення газ–повітря. Представлено етапи розроблення моделі координувальної системи автоматичного управління, яка забезпечує підтримання заданого співвідношення між регульованими змінними у перехідних режимах. Підтримання заданого співвідношення забезпечується через реалізацію підпорядкованості процесів регулювання. Проведені експерименти показали принципову придатність визначеного поетапного алгоритму синтезу, який можна покласти в основу автоматизації процесу налаштування систем на підпорядкованість процесів регулювання.

**Ключові слова:** координувальна система автоматичного управління, регулювання співвідношення, паровий котел, поетапне налаштування багаторівневих систем управління.