Adjustment of automatic control systems of production facilities at coal processing plants using multivariant physico-mathematical models

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Abstract. The structure of multi-variant physical and mathematical models of control system is offered as well as its application for adjustment of automatic control system (ACS) of production facilities on the example of coal processing plant.

1. Introduction

One of the most important problems in ACS development is their structural and parametric adjustment, for which, as a rule, special testing ranges, workbenches, as well as existing physical models of control objects, functioning as parts of control system of a physical model (CSPM).

In [1, 2] the features, conditions and procedure for application of such systems in the test tasks, adjustment and research of full-scale control systems are considered. The efficiency of the procedures offered here can be significantly increased by generalizing CSPM in case of control of multivariate physico-mathematical model of a full-scale control object – multivariate control system of a physical model (MvCSPM).

The controlled component in MvCSPM is a combination of (by analogy with full-scale mathematical [3]) physical model of the technological control object in the form of its information representation [4], and mathematical incremental model, functioning in the increments to data on changes of input and output effects of physical model.

Multivariance is created by connecting to a single functioning physical model any finite number of recalculation models using the above indicated combination, and, thus, form a finite set of simultaneously functioning physico-mathematical models of full-scale objects of any physical nature and, accordingly, control systems, but they and their mathematical incremental models should have a similar structure.

The main advantage of MvCSPM is the fact that its use will allow the multiple full-scale control systems (FCS) to be simultaneously explored, tested and configured, provided that each FCS and the corresponding to it control system of physico-mathematical model will be similar [5]. Another positive feature of the physico-mathematical modelling in comparison with the full-scale mathematical one is the possibility to change easily enough the technological operational modes of the physical model, which is not always feasible or is associated with high costs for full-scale objects.
In this paper we examine one of the possible procedures adapted to the solution of problems of simultaneous adjustment of the finite set of ACS output actions and states of technological units at a coal processing plant, which are an important component of automated technological complexes, largely determining efficiency of their operation.

The proposed option is based on multivariate physico-mathematical modelling using full-scale data, obtained with the help of existing monitoring systems, as well as modelling and full-scale data with the specified statistical properties formed by the multivariant generator in the form of a closed dynamic system (MV generator (CDS) [6]); similarity of control systems [7-9], control of their of similarity due to purposeful change of the dynamic properties of external influences transformation channel and the properties of these influences per se, including uncontrolled ones; search procedures.

2. Structure and description of a multivariant model control system

The integrated structure MvCSPM is shown in Figure 1, where the following notations are used:

- \( P \) \( F \): generalized vector of impact, including, respectively, control, external and output effects of the physical model;
- \( Y_{red} \): reduced to the output disturbance effects as an integral evaluation of uncontrolled disturbances, expressed on a scale of output effects;
- superscripts “R”, “F”, “C”, “P”, “PM”, and “#” mean, respectively, real, full-scale, compromise values of impact of the full-scale control object, impacts of its physical, physico-mathematical model and the given values;
- subscripts “red” and “l” – reduced impacts and number of a physical model ACS;
- the dotted line indicates the presence of other parallel contours connected to PM, the number of which equals to \( L \).

The ACS structure shown in Figure 1 corresponds to the control system by deviation, the object of which is affected by uncontrolled disturbances.

The mathematical part of the system in general is represented by the relations

\[
Y_{PM}^i = Y^P + \delta Y_{ul}^{PM} + \delta Y_{red}^{PM}, \quad i = 1, L;
\]

\[
\delta Y_{il}^{PM} = \varphi_{il}^{PM} \{ \delta U_{i}^{PM} \}, \quad l = 1, L;
\]

\[
\delta U_{i}^{PM} = U_{i}^{PM} - U^{F}, \quad l = 1, L;
\]

\[
\delta U_{i}^{PM} = f_{i}^{PM} \{ \delta Y_{i}^{PM} \}, \quad l = 1, L;
\]

\[
\delta Y_{il}^{PM} = Y_{PM}^{i} - y_{red}^{PM}, \quad l = 1, L;
\]

\[
\delta Y_{red}^{PM} = Y^P - Y_{i}^{P} - Y_{w}^{P};
\]

\[
y_{red}^{PM} = F \{ \delta Y_{red}^{PM}, \alpha_{i}; \sigma_{i} \}. 
\]
Figure 1. Multivariant model control system.

where \( \Phi_l \{ \} \) – operator of the mathematical incremental model \( l \) \( (l = 1, L, L \) – number of modeled ACS) physico-mathematical models of control object;

\( f_l \{ \} \) – control law of \( l \) ACS;

\( F \{ \} \) – operation algorithm of multivariant generator of time series data with given statistical properties;

\( Y_i^p \) – effects of regulatory impacts of the physical model.

Each \( (l \) in \( L \) ) simultaneously working in MvCSPM physico-mathematical ACS should reflect dynamic properties and operating conditions of the corresponding \( l \) of the full-scale system, \( l = 1, L \), which are generally different. To do this, \( l \) model and \( l \) full-scale ACS should be similar [1]. Their similarity is achieved in the mathematical part of the physico-mathematical model due to purposeful change of (ACS similarity control [1]) either the coefficients values of operator \( \Phi_{il}^{PM} \{ \} \), or properties of a time series reduced to the output of physico mathematical disturbance model \( \delta_{y_{red}^{PM}} \), or both.

Formation of \( \Phi_{il}^{PM} \{ \} \) is carried out by changing the mathematical model of the channel transformation of regulatory impacts of a physical model \( \Phi_i^p \{ \} \), in particular through the use of special corrective operators \( \Phi_e \{ \} \) [10]. These disturbances \( \delta_{y_{red}^{PM}} \) with the specific properties are
formed using multivariant generator of time series data with desired properties, based on algorithm [6], adapted to the multivariant case.

3. ACS adjustment

The integrated scheme of full-scale ACS adjustment with the use of multivariate physical and mathematical models of the controlled system being the part of MvCSPM is shown in Figure 2. It was used for control system adjustment of the technological complex at the processing plant “Matyushinskaya”. The description of technical realization of the complex is presented in [11].

Below, as an example we consider the application of this procedure for two ACS: the suspension density of a dense-media separator and dense-media hydrocyclone. Adjustment of the slurry density, fed to the separator and sump of hydrocyclones power supply, is performed in the ACS according to deflection by dilution of conditioned slurry with additional water. The structure of these full-scale and physico-mathematical ACS (Figure 1) is the same.

The problem is presented in the following form.

Given

1. The mathematical model of conversion channels of controlling impacts for dense-media separator and for dense-media cyclone has the form

\[ \varphi(s) = \frac{k}{Ts + 1} \cdot e^{-\tau} \],

where \( k \) – transfer coefficient, \( T \) – time constant of inertia, \( \tau \) - time of pure delay.

Figure 2. Scheme of full-scale ACS adjustment with application of MvCSPM.
2. Parameters of $k$, $T$, and $\tau$ models of control objects (dense-media separator and dense-media hydrocyclone), estimates of which are given within the ranges [11]

- for the dense-media separator

\[ -2.3 \leq k \leq -1.8 \text{ kg \cdot m}^3 \text{ stroke \%}; \]
\[ 7.0 \leq T \leq 12.0 \text{ s}; \]
\[ 5.0 \leq \tau \leq 7.0 \text{ s}; \tag{10} \]

- for the dense-media hydrocyclone

\[ -2.0 \leq k \leq -1.4 \text{ kg \cdot m}^3 \text{ stroke \%}; \]
\[ 7.0 \leq T \leq 12.0 \text{ s}; \]
\[ 5.0 \leq \tau \leq 7.0 \text{ s}. \tag{11} \]

The values of these coefficients were evaluated at the stage of design and further specified experimentally during implementation in the “local” and “remote” modes of operation.

3. The disturbances reduced to the output of full-scales objects, the estimates of which were calculated by the known pattern [12] on the basis of the initial data on the operation of full-scale ACS using average values of the coefficients $k$, $T$ and $\tau$ from ranges (10) and (11).

The autocorrelation functions (ACF) of the reduced disturbances were approximated by the expression:

\[ r_{red}(\theta) = \sigma_{red}^2 \cdot e^{-\alpha_{red} |\theta|}, \tag{12} \]

where $\sigma_{red}^2$ – dispersion of the reduced disturbance, $\alpha$ – ACF coefficient, $\theta$ – time of a shift between sections of a sequence of reduced disturbance. Average values of the reduced disturbances characteristics.

- for the dense-media separator

\[ \sigma_{red} = 11.05 \frac{kg}{m^3}; \alpha_{red} = 0.11; \tag{13} \]

- for the dense-media hydrocyclone

\[ \sigma_{red} = 10.10 \frac{kg}{m^3}; \alpha_{red} = 0.17. \tag{14} \]

4. Proportional-integral law of control with the transfer function

\[ f_{pi}(s) = k_p + \frac{k_i}{s}, \tag{15} \]

where $k_p$ and $k_i$ – coefficients of its proportional and integral part.
5. Quality criteria of ACS operation in the form control mean-square errors
   - for the dense-media separator: $q_1^F$ and $q_1^{PM}$;
   - for the dense-media hydrocyclone $q_2^F$ and $q_2^{PM}$;
   - for the physical model $q_p^F$,

where the superscripts “F”, “PM”, “P” means “full-scale”, “physico-mathematical” and “physical” and subscript “1” and “2” – dense-media separator and dense-media hydrocyclone, respectively.

6. Multivariant physico-mathematical model of the control system – MvCSPM, the structure of which corresponds to the scheme in Figure 1. The basic controlled component of MvCSPM is a physical model of the production unit [13]. The conversion channel model of regulatory impacts of an object physical model corresponds to expression (9); its coefficient values $k^p = 1.6 \, ^\circ C/min/\%$; $T^p = 3.0$ sec.; $\tau^p = 1.0$ sec. The reduced disturbances to the physical model output were calculated similarly to the full-scale object according to the scheme [12]. The normalized ACF, as well as the full-scale regulation objects, was approximated by expression (12) with the parameters values $\sigma_{red}^p = 1.4 \, (^\circ C)$; $y_{av}^p = 1.1 (^\circ C)$; $\alpha_{red}^p = 0.3$.

The control law of ACS model is described by expression (15), with the following values of its superscripts coefficients, corresponding to the minimum control mean-square error: $k_p^F = 1.875$; $k_i^F = 0.625$.

7. Multivariant generator of model and full-scale (data series) impacts with the given statistical properties, allowing the desired finite number of such data series to be simultaneously formed.

4. The scheme and solution results
The solution of the problem was carried out using MvCSPM, customized for ACS of production facilities, and the procedure of simultaneous adjustment of both physico-mathematical systems in accordance with the scheme shown in Figure 2 for $l = 1.2$.

1. Matching of the input and output effects of the full-scale control facility and physical model of disturbances was carried out in this example by their reduction to the dimensionless data by normalizing the expression

$$Z_p = \frac{Z - Z_{min}}{Z_{max} - Z_{min}}; \quad Z = \{y; y_{red}; U\}.$$  \hspace{1cm} (16)

where $Z_{max}$ and $Z_{min}$ – the maximum and minimum values of the corresponding variables.

2. The calculation of the reduced to the output of considered full-scale objects and physical model of perturbations was made by a single scheme [12] for dimensionless data.

3. Similarity of full-scale ACS density slurry of a dense-media separator and hydrocyclone with the model ACS, the controlled component of which is a physical model, was evaluated by the correlation coefficient between the characteristics of and with respect to the proximity of targeted indicators reflecting the effectiveness of these systems [8]. As the latter the mean-square control errors were used.

As a result of estimation of these ACS similarities the following average sample estimations of characteristics were obtained:
where $r_{pf1}$ and $r_{pf2}$ – accordingly, the correlation coefficient between the $q_1^F$ and $q_1^P$, $q_2^F$ and $q_2^P$.

Comparison of the correlation coefficient values and performance characteristics of ACS operation with the required for their similarity [7-9] leads to the conclusion about the absence of similarity between the model and full-scale ACS. The values of the correlation coefficient between the mean square control errors of full-scale and a model ACS is significantly less than the required $r_{FP}^* = 0.95 \pm 0.5$. This conclusion is confirmed by the values $\Delta q_1^F = |q_1^F - q_1^P| = 0.387$ and $\Delta q_2^F = |q_2^F - q_2^P| = 0.344$, which is much higher than the permitted level of their deviation (10%).

Thus, the lack of similarity between the full-scale and model systems of ACS makes it necessary to deliberately change (control similarity) dynamic properties of the model ACS for establishing their similarity.

4. Adjustment of the initial conditions of physico-mathematical ACS was implemented via the following sequence of operations: 1) opening of the negative feedback of physical-mathematical ACS; 2) evaluation of deviations of regulatory impacts of full-scale and physical ACS; 3) recalculation of these deviations with the operator $\phi^{PM}_{\{1\}}$ for calculation $\Delta Y^{PM}_{\{1\}}$; 4) further in accordance with the scheme in Figure 1 the calculation of the output impact value $Y^{PM}_{\{1\}}$ of physico-mathematical system of regulation.

The implementation of the indicated above operations allows the value of the output impact at the output of ACS physico-mathematical model to be defined, corresponding to the value of its full-scale system.

5. Similarity control for both full-scale ACSs was carried out due to changes in the reduced disturbances properties with the help of MV generator (CDS), and due to changes in the operator parameters $\phi^{PM}_{\{1\}}$. The results in the form of properties values of conversion channel models of regulating impacts and reduced disturbances of similar ACS are given in the table below. Figures (1) and (2) shown in the first row of the table in parentheses mean that all the characteristics and parameters related to the dense-media separators are marked in the text by figure 1, and dense-media hydrocyclones – by figure 2.

6. Adjustment of model ACSs was carried out in the mode of physico-mathematical simulation using search engine optimization techniques (deformable polyhedron [14]) by the minimum of mean-square control error. The following values of ACS adjustment for the dimensionless data on changes in input and output impacts of ACS physico-mathematical model were obtained.

- for the dense-media separator

$$k_{n1}^{PM} = 0.773; \quad k_{i1}^{PM} = 0.011; \quad q_1^{PM} = 0.871; \quad (17)$$

- for the dense-media hydrocyclone

$$k_{p2}^{PM} = 0.863; \quad k_{i2}^{PM} = 0.01; \quad q_2^{PM} = 0.883. \quad (18)$$
Table 1. Parameter values of ACS characteristics.

|                      | Dense-media separator (i) | Dense-media hydrocyclone (i) |
|----------------------|---------------------------|-----------------------------|
|                      | Full-scale data           | Data of physico-mathematical modelling | Full-scale data | Data of physico-mathematical modelling |
| \( \sigma_{\text{red}} \) | 1.00                      | 1.00                        | 1.00            | 1.00                                      |
| \( \alpha_{\text{red}} \) | 0.09                      | 0.54                        | 0.10            | 0.50                                      |
| \( k \)              | -2.00                     | -1.60                       | -1.80           | -1.60                                     |
| \( T \)              | 12.00                     | 2.00                        | 11.00           | 2.20                                      |
| \( \tau \)           | 6.00                      | 1.00                        | 5.00            | 1.00                                      |

7. Recalculation of the parameter values of adjustment (17) and (18) for the condition of full-scale ACSs functioning was made in accordance with the expressions [1]

\[
k_{p1} = k_{p2} \cdot \frac{k_{\tau T_2}}{k_{2 \tau T_1}} \cdot e^{\alpha (\tau_1 - \tau_2)}; \quad (19)
\]

\[
k_{I1} = K_{I2} \cdot \frac{y_{\alpha} k_{\tau T_2}}{y_{\alpha} k_{1 \tau T_1}} \cdot e^{\beta (\tau_1 - \tau_2)}; \quad (20)
\]

The values obtained for these parameters also for dimensionless data indicative of change in ACS effects are listed below under (21) and (23); in the second line under (22) and (24) the values of the same parameters in the natural scale of their change are given

- for the dense-media separator

\[
k_{p1}^F = -0.618; \quad k_{i1}^F = -0.001; \quad q_1^F = 0.870; \quad (21)
\]

\[
k_{p2}^F = -0.618 \frac{\% \ stroke \cdot m^3}{kg}; \quad k_{i2}^F = -0.001 \frac{\% \ stroke \cdot m^3}{kg \cdot s}; \quad q_2^F = 9.613 \frac{kg}{m^3}; \quad (22)
\]

- for the dense-media hydrocyclone

\[
k_{p2}^F = -0.767; \quad K_{i2}^F = -0.007; \quad q_2^F = 0.883; \quad (23)
\]

\[
k_{p2}^F = -0.767 \frac{\% \ stroke \cdot m^3}{kg}; \quad k_{i2}^F = -0.007 \frac{\% \ stroke \cdot m^3}{kg \cdot s}; \quad q_2^F = 8.918 \frac{kg}{m^3}; \quad (24)
\]

In the result of the use of ACS adjustment values (22) and (24) in the full-scale conditions and their further specification the conclusion about the high efficiency of adjustment procedure with the use of physico-mathematical modelling was made. Deviations of full-scale coefficient values from the model ones and the values of intermediate modulus error of control for these systems do not exceed 10%. In addition, the simultaneous execution of modelling experiments in the process of ACS adjustment allows the time and material-energy resources associated with the functioning of the physical model to be significantly reduced.

It is also important that the simulation modelling complex based on MvCSPM can be an effective tool in the learning process for the solution of problems connected with testing, adjustment and study of ACS.
5. Conclusions
The use of multivariate control systems of physico-mathematical models is appropriate for adjustment of the automatic control systems of production facilities, including for coal processing plants as well as in the training process of universities students and personnel of industrial enterprises and organizations. It is advisable to apply the proposed adjustment process of control systems that include more complex structures of production facilities, particularly facilities with recycling, distributed controls, etc.

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