ТЕХНИЧЕСКИЕ НАУКИ

ENGINEERING

> *Если бы я захотел читать, еще не зная букв, это было бы бессмыслицей.*
> *Точно так же, если бы я захотел судить о явлениях природы,*
> *не имея никакого представления о началах вещей, это было бы такой же бессмыслицей.*
> *Михаил ЛОМОНОСОВ*

ADAPTIVE CONTROL SYSTEM FOR THE MAGNETIC SEPARATION PROCESS

[1]Morkun V.S.,*
[1]Morkun N.V.,
[1]Tron V.V.,
[2]Dotsenko I.A.

УДК: 622.778
DOI: 10.21177/1998-4502-2018-10-4-545-557

The developed adaptive system controlling magnetic separation of iron ores allows reducing the period of searching for the objective control function, maintaining the optimal ratio of the concentrate yield and the grade contained under conditions of changing quality of initial ores and the equipment state. There are determined conditions and the best parameters of searching for the extremum in the system of adaptive control over iron ore magnetic separation under disturbances and noises in controlled signals. They can be achieved when deviations of static and dynamic characteristics from rated ones do not exceed ±25%.

KEYWORDS:
adaptive control system, magnetic separation, iron ore, slurry, search for extremum

Article received 30.07.2018.

Introduction

An important component of Global Goals for Sustainable Development is a goal associated with industry and innovation. Minerals are raw materials essential for modern society. The mining and quarrying industry is very important to industrial, social, and technological progress.

One of the basic characteristics determining significance of raw materials for metallurgical enterprises is their permanent high recovered grade in the fed ore concentrate. It can be provided only when all processes of ore processing from mining to concentration and sintering are subject to continuous efficient control [1–4].

Automated control systems (ACS) of processes are widely used in mining and metallurgy. At magnetic and concentrating plants, their efficiency depends greatly on the choice of controlling algorithms and the capacity of systems to provide IT support them [5–7].

Thus, increasing efficiency of automated control over iron ore magnetic concentration is a research problem which is essential for Ukraine's economy. Its solution allows improving the end product quality and reducing energy consumption at current mining enterprises' operating capacity [8–11].

Problem statement

The research is aimed at developing a system of adaptive control of magnetic separation of iron ores to reduce the period of searching for the extremum of objects dynamic characteristics under disturbances and noises in controlled signals.

Review of the literature

In [12; 13] and others, iron ore concentration controlled through improving operation of magnetic separators of iron ores of primary concentration is substantiated. The choice of the control structure, application of some criteria in creating systems of automated optimization are determined by their software and algorithmic support, i.e. the possibility to receive online data on current parameters of concentration and their efficient application to controlling impacts.

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[1]Kryvyi Rih National University, Kryvyi Rih, Ukraine, morkunv@gmail.com
[2]Academy of Mining Sciences of Ukraine, Kryvyi Rih, Ukraine

Magnetic separators of iron ores are basic concentrating machines in a technological line of iron ore magnetic and concentrating plants. In [12–16], a magnetic separator is regarded as a controlled object with a single input (feed) and two outputs (tailings and concentrate). Fig. 1 shows basic parameters determining magnetic separation. It includes controlled variables: (the magnetic iron content in the middling product ($\beta_{пп}$), the middling product yield ($\gamma_{пп}$); disturbing impacts (the magnetic iron content in the fed product (the magnetic separator feed) (α) and the recovered grade (ψ); controlling impacts (the classifier drain density ($\rho_{сл}$), the auxiliary water consumption in the separator bath (Q_B), the magnetic field strength of the separator (H_0), the rotation rate of the separator drum ($n_б$).

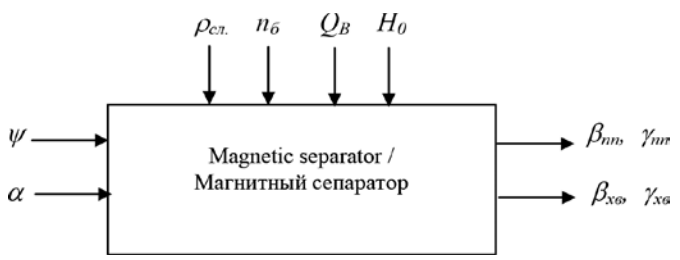

***Fig. 1.** Basic parameters of magnetic separation*
***Рис. 1.** Основные параметры процесса магнитной сепарации*

As shown in [12; 17–18], the magnetic iron content α and the degree of mineral release in the classifier drain ψ are basic disturbing impacts in magnetic separation. The slurry density changed in case of classifier drain causes changes in the granularmetric composition of the solid phase slurry, thus altering ratios between its strongly-, feebly- and non-magnetic fractions. The $\rho_{сл}$ increased reduces the yield of released ore grains while that of strongly-magnetic fraction $\gamma_{пп}$ increases because of the increased yield of strongly-magnetic aggregates. The strongly-magnetic fraction yield is proportional to the magnetic iron content α in the fed ore. The reduced density of the classifier drain makes the strongly-magnetic fraction yield be close to the output equal to α (the magnetic iron content).

In [18], there are suggested simple expressions determining the yield of strongly-magnetic fraction $\gamma_{пп}$, the yield of released ore grains $\gamma_{рз}$ and strongly-magnetic ore aggregates $\gamma_{рс}$:

$$\gamma_{т} = \alpha + K_1 \cdot \bar{d} \cdot (0{,}7 - \alpha); \tag{1}$$

$$\gamma_{рз} = \alpha - K_3 \cdot \bar{d} \cdot (0{,}7 - \alpha); \tag{2}$$

$$\gamma_{рс} = (K_1 + K_3) \cdot \bar{d} \cdot (0{,}7 - \alpha), \tag{3}$$

where $\bar{d} = K_2(\rho_{сл} - \rho_{в})$ is the average size of solid particles in the slurry; K_1 and K_2 are coefficients depending on the size of ore impregnations; K_3 is the coefficient depending on physical and mechanical properties of the fed ore and grinding modes.

The changed textural and structural characteristics of the fed ore change coefficients K_1, K_2 and K_3 causing changes in the quality of separation products. Thus, coefficients K_1, K_2 and K_3, determine the value of basic disturbing impacts in relation to magnetic separation. A. N. Mariuta received the ratio equation of the solid slurry density of the classifier drain $\rho_{б}$ and the iron content α:

$$\rho_{T} = \frac{\rho_{M}\rho_{K}}{\rho'_{M} - \alpha(\rho'_{M} - \rho_{K})} = \frac{14}{5 - 2{,}2\alpha}, \tag{4}$$

where $\rho'_{м}$ is pure magnetite density; ρ_k is quarts density.

A detailed analysis and systematized criteria of improving mineral concentration including technological, thermodynamic, kinetic, static, technical-economic, economic ones, etc were proposed in [19]. It is indicated that technological criteria mathematically expressed as a combination of basic concentration parameters are notable for their efficiency, simplicity and visualization.

Analysis of technological criteria results in the Hancock criterion substantiated by Luiken, Birbauer, Din, Chechott, Verkhovskyi [19] and others.

This criterion can be expressed as follows

$$J = \frac{\gamma(\beta - \alpha)}{\alpha\left(1 - \frac{\alpha}{\beta_T}\right)}, \tag{5}$$

where γ is the concentrate yield; α is the recovered grade in the feed product; β is the recovered grade in the concentrate; β_T is theoretically maximum recovered grade.

The popularity of this criterion is explained not only by its physical and geometrical interpretation, but also by the fact that it is simple, universal, contains all basic parameters (γ, β, α) and is statistically efficient [19].

A.N. Mariuta indicates that it is reasonable to apply this criterion to evaluation of the magnetic separator efficiency [18]. Formula (5) reveals that maximum values of E for various values of α can be achieved only when there is a certain ratio between γ and (β-α). The classifier drain increased makes the concentrate yield γ greater and reduces the difference β-α. The reduced drain density produces the reverse effect.

In [18], Mariuta suggests a complex criterion of efficiency E_1, which partially reflects the course of the process from both the technological and the economic viewpoints

$$J_1 = \beta + k_E\gamma \rightarrow max, \tag{6}$$

where k_E is the coefficient characterizing weight ratios between variables β and γ

The coefficient k_E indicates how the Fe content can be reduced in the concentrate to increase its yield and vice versa. The values of k_E depend on α and other properties of the fed ore. Formulae (5) and (6) allow controlling magnetic separation in the most efficient way.

Materials and methods

The mentioned above allows us to conclude that the classifier drain density is the basic controlling impact in the "classifier-magnetic separator" system. Operation of the magnetic separator can be assessed on the basis of the data on the recovered grade (Fe) in its products or the solid slurry density considering (4). The model of magnetic separation should consider changed textual and structural characteristics of processed ores, grinding modes and equipment conditions. Overall quality indices of concentration are determined by the ore quantity fed to the mill.

The material-balance equation for the magnetic separator looks like [19; 20]

$$\frac{dm}{dt} = M - (M_k - M_{хв}), \qquad (7)$$

or considering that $M_k = \beta Q_k$, $M_{хв} = \vartheta Q_{хв}$, $M = \alpha Q$,

$$V\frac{dm}{dt} = \alpha Q - \beta Q - \vartheta Q_{хв}, \qquad (8)$$

where M, M_k, $M_{хв}$, Q, Q_k, $Q_{хв}$ indicate weight and volume consumption of the fed material, concentrator and tailings; V is the volume of the working area of the magnetic separator; m is the iron quantity in the slurry in the working area of the separator.

Considering the fact that under the current mode, the Fe content in the working area of the separator is equal to that in the concentrator we obtain

$$W(p) = \frac{\beta}{\alpha} = \frac{K_e^{-\tau p}}{Tp+1}, \qquad (9)$$

where $T = \frac{V}{Q}$, $K = \frac{\beta_{уст}}{\alpha}$, $\beta_{уст} = \beta$ with $t \to \infty$, $\beta_{уст}$ is the established Fe content in the concentrator at the separator output.

Synthesize and study models of technological aggregates and a concentration line as a whole were presented in [14; 15; 18; 20]. For instance, [20] provides a system of equations combining characteristics of the output product of the classifier with parameters of the middling product and tailings of the magnetic separator.

$$5\frac{d\vartheta}{dt} + \zeta = 0{,}53\zeta_{щ}(t-2); \qquad (10)$$

$$\beta' = -0{,}695\zeta_{щ}^2 + 0{,}893\zeta_{щ} + 0{,}712; \qquad (11)$$

$$9\% < \zeta_{щ} < 32\%; \qquad (12)$$

$$5\frac{d\beta}{dt} + \beta = \beta(t-2),$$

where $\zeta_{й}$ is the slurry density at the classifier drain; β and ζ indicate the Fe content in the middling product and tailings.

As is shown, the magnetic separator represents a sequence of two links – non-linear static and output linear ones. To consider dynamic properties of the input part of the magnetic separator, the given model should be supplemented with input dynamic links along each control channel.

Taking into account the the fed material Q balance equation, the concentrate C and tailings T for the magnetic separator it can be written as follows [19; 21]

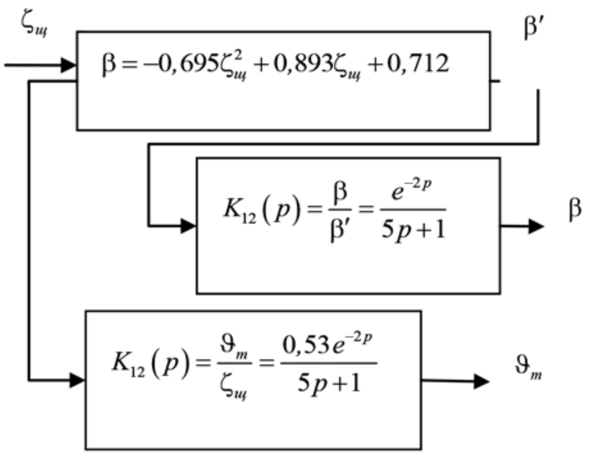

Fig. 2. *The structural scheme of the magnetic separator model*
Рис. 2. *Структурная схема модели магнитного сепаратора*

$$Q\alpha = C\beta + (Q-C)\vartheta; \qquad (13)$$

$$Q\alpha = (Q-T)\beta + T\vartheta, \qquad (14)$$

where Q, C, T indicate the mass of the feed material, concentrate and tailings; α, β, ϑ are the Fe content in the feed material, concentrate and tailings.

Then the concentrate yield is determined by the expression

$$\gamma_k = \frac{C}{Q}\cdot 100 = \frac{\alpha-\vartheta}{\beta-\vartheta}\cdot 100\%. \qquad (15)$$

Thus, (5) results in

$$E = \frac{\gamma(\beta-\alpha)}{\alpha(1-\frac{\alpha}{\beta_T})} = \frac{(\alpha-\vartheta)(\beta-\alpha)}{\alpha\left(1-\frac{\alpha}{\beta_m}\right)(\beta-\vartheta)}. \qquad (16)$$

It follows from (16) that the Hancock criterion can be calculated either on the basis of measurements of the Fe content in the feed material, concentrate and tailings or measurements of the feed material and concentrate mass and the Fe content in these products. In the latter case, the values of Q and C can be measured by one of the known methods, e.g. the ultrasonic one.

In this case, the object equation looks like

$$x = J(\beta + f, \alpha); \qquad y = x + \kappa, \qquad (17)$$

where $f(t)$ is the external disturbance applied to the object input with the controlling parameter; $k(t)$ is the disturbance accompanying the measurement of the object x output; $y(t)$ is the measured variable (the result of the x measurement).

Functions $f(t)$ and $x(t)$ are random processes with unknown laws of distribution. Yet, it is known that they have zero mathematical expectation and limited dispersion. One should find the algorithm of searching for the extremum under which the mathematical expectation of the output $M\{J(\beta+f), \alpha)+k\}$ reaches the minimum value [22–27].

To simplify the solution of the problem, let us consider $f=0$ and then the equation (17) will look like

$$x = J(\beta, \alpha);\ y = x + \kappa. \qquad (18)$$

According to the stochastic approximation method, every measured condition of an object should be used to measure the controlling impact so that the condition is observed at the limit [32]

$$M\{J(\beta, \alpha)+\text{k}\} = \min. \qquad (19)$$

Let us measure the controlling impact according to the algorithm

$$\beta\left[(k+1)T\right] = \beta(kT) - \frac{a_k}{2\Delta\beta_k}\begin{bmatrix} J'\left(\beta(kT)+\Delta\beta_k,\,\alpha\right) - \\ -J'\left(\beta(kT)-\Delta\beta_k,\,\alpha\right)\end{bmatrix}, \qquad (20)$$

$k = 0, 1, 2, \ldots$.

Here, the measurement results are used

$$J'\left(\beta(kT)+\Delta\beta_k,\,\alpha\right) = J\left(\beta(kT)+\Delta\beta_k,\,\alpha\right) + \kappa_k^{(1)}; \qquad (21)$$

$$J'\left(\beta(kT)-\Delta\beta_k,\,\alpha\right) = J\left(\beta(kT)-\Delta\beta_k,\,\alpha\right) + \kappa_k^{(2)}, \qquad (22)$$

where $\kappa_k^{(1)}$, $\kappa_k^{(2)}$ are random values realizing measurement disturbances in the interval [(*k*-1)*T*, *kT*], while $\kappa_k^{(1)} \neq \kappa_k^{(2)}$ as they are measured at different time periods within the given interval. It should be noted that unlike (20), the value $\Delta\beta_\text{k}$ of testing steps is not constant and measured with $k = 0, 1, 2, \ldots$.

The stochastic approximation method allows finding parameters of the working and testing steps b_h, $\Delta\beta_\text{k}$ ($k = 0, 1, 2, \ldots$), under which the algorithm (20) provides the extremum J' (fulfillment of condition (19) under disturbances. They are known to have zero mathematical expectation and limited dispersion.

Let us determine parameters of the working and testing steps. To achieve the search algorithm convergence (20) the parameters of the working and testing steps should satisfy the condition

$$\lim_{k\to\infty} a_k = 0,\ k = 0, 1, 2, \ldots;\ \sum_{k=1}^{\infty} a_k = \infty; \qquad (23)$$

$$\sum_{k=1}^{\infty}\left[\frac{a_k}{\Delta\beta_k}\right]^2 < \infty. \qquad (24)$$

The given conditions are observed if

$$a_k = 1/k^{\rho};\qquad \Delta\beta_k = 1/k^{\mu};$$
$$2(\rho - \mu) > 1,$$
$$\text{where } 0 \le \rho \le 1;\ \mu > 0.$$

Considering (21) and (22), let us write down the algorithm (20) as follows

$$\beta\left[(k+1)T\right] = \beta(kT) - \frac{a_k}{2\Delta\beta_k}\begin{bmatrix} J\left(\beta(kT)+\Delta\beta_k,\,\alpha\right) - \\ -J\left(\beta(kT)-\Delta\beta_k,\,\alpha\right)\end{bmatrix} +$$
$$+\frac{a_k}{2\Delta\beta_k}\left(\kappa_k^{(1)} - \kappa_k^{(2)}\right) =$$
$$= \beta(kT) - a_k\hat{r}_k + \frac{a_k}{2\Delta\beta_k}\left(\kappa_k^{(1)} - \kappa_k^{(2)}\right),\quad k = 0, 1, 2, \ldots . \qquad (25)$$

As the testing steps are quite small ($f_k = r_k$) and considering $M\{\kappa_k^{(i)}\} = 0,\ i=1,$ 2, we calculate the mathematical expectation of the *k-th* step efficiency:

$$M\{\nu_k\} = M\left\{\frac{\beta[(k+1)T] - \beta^*}{\beta(kT) - \beta^*}\right\} =$$
$$= 1 - a_k\frac{r_k}{\beta(kT) - \beta^*}. \qquad (26)$$

Proceeding to the condition (24), we calculate the mathematical expectation and dispersion of the working step $\Delta_p\beta(kT)$. It is evident that

$$M\{\Delta_p\beta(kT)\} = -\frac{a_k}{2\Delta\beta_k}\begin{bmatrix} J\left(\beta(kT)+\Delta\beta_k,\,\alpha\right) - \\ -J\left(\beta(kT)-\Delta\beta_k,\,\alpha\right)\end{bmatrix};$$

$$M\left\{\Delta_p\beta(kT) - M\{\Delta_p\beta(kT)\}\right\}^2 = M\left\{\frac{a_k}{2\Delta\beta_k}\left(\kappa_k^{(1)} - \kappa_k^{(2)}\right)\right\}^2 =$$
$$= \frac{a_k^2}{4\Delta\beta_k^2}\left[\sigma_k^2 + \sigma_{2k}^2\right],\quad k = 0, 1, 2, \ldots .$$

where σ_{ik}^2 (*i*=1, 2) – are dispersions of random values $\kappa_k^{(1)}$, $\kappa_k^{(2)}$.

It is evident that the sum of dispersions of the arbitrary large number of working steps taken during the search should be limited

$$\sum_{k=1}^{\infty}\frac{a_k^2}{2\Delta\beta_k^2}\left[\sigma_k^2 + \sigma_{2k}^2\right] < \sigma^2\sum_{k=1}^{\infty}\frac{a_k^2}{\Delta\beta_k^2} < \infty, \qquad (27)$$
$$\text{where } \sigma^2 = \max\left[\sigma_k^2 + \sigma_{2k}^2\right]/4 < \infty.$$

Hence follows a condition (24) indicating that the value of the testing step $\Delta\beta_\text{k}$ should go to zero more slowly than a_k, as otherwise dispersion values of the working steps will become intolerably large according to (27).

Let us consider the search for the extremum of multiparameter objects under disturbances

$$x = J(\beta_1,\ \beta_2,\ \alpha_1,\ \alpha_2);\qquad y = x + \kappa. \qquad (28)$$

In this case, adaptation algorithms will be written as:

$$\beta_1\left[(k+1)T\right] = \beta_1(kT) -$$
$$-\frac{a_k}{2\Delta\beta_k}\begin{bmatrix} J'\left(\beta_1(kT)+\Delta\beta_k,\ \beta_2(kT),\ \alpha_1,\ \alpha_2\right) - \\ -J'\left(\beta_1(kT)-\Delta\beta_k,\ \beta_2(kT),\ \alpha_1,\ \alpha_2\right)\end{bmatrix}, \qquad (29)$$

$k = 0, 1, 2, \ldots;$

$$\beta_2\left[(k+1)T\right] = \beta_2(kT) -$$
$$-\frac{a_k}{2\Delta\beta_k}\begin{bmatrix} J'\left(\beta_1(kT),\ \beta_2(kT)+\Delta\beta_k,\ \alpha_1,\ \alpha_2\right) - \\ -J'\left(\beta_1(kT),\ \beta_2(kT)-\Delta\beta_k,\ \alpha_1,\ \alpha_2\right)\end{bmatrix}, \qquad (30)$$

$k = 0, 1, 2, \ldots;$

where the measurement results are

$$J'\left(\beta_1(kT)+\Delta\beta_k,\ \beta_2(kT),\ \alpha_1,\ \alpha_2\right)=$$
$$=J\left(\beta_1(kT)+\Delta\beta_k,\ \beta_2(kT),\ \alpha_1,\ \alpha_2\right)+\kappa_k^{(1)};$$
$$J'\left(\beta_1(kT)-\Delta\beta_k,\ \beta_2(kT),\ \alpha_1,\ \alpha_2\right)=$$
$$=J\left(\beta_1(kT)-\Delta\beta_k,\ \beta_2(kT),\ \alpha_1,\ \alpha_2\right)+\kappa_k^{(2)};$$
$$J'\left(\beta_1(kT),\ \beta_2(kT)+\Delta\beta_k,\ \alpha_1,\ \alpha_2\right)=$$
$$=J\left(\beta_1(kT),\ \beta_2(kT)+\Delta\beta_k,\ \alpha_1,\ \alpha_2\right)+\kappa_k^{(3)};$$
$$J'\left(\beta_1(kT),\ \beta_2(kT)-\Delta\beta_k,\ \alpha_1,\ \alpha_2\right)=$$
$$=J\left(\beta_1(kT),\ \beta_2(kT)-\Delta\beta_k,\ \alpha_1,\ \alpha_2\right)+\kappa_k^{(4)},$$

where $\Delta\beta_k$ is a testing step taken as the same for both controlling impacts; κ_k^i, $i=1, 2, 3, 4$, indicate realization of the random process $x(t)$ with four measurements of the object output at the interval $[(k–1)T, kT]$.

For determining the search convergence, parameters of the working and testing steps should satisfy conditions (23) and (24) for a single-parameter object as well. The condition (24) looks like

$$\sum_{k=1}^{N\to\infty}\frac{a_k^2}{\Delta\beta_k^2}<\infty, \tag{31}$$

and indicates that the increased k should make the testing step greater and exceed the working step parameter. It should be noted that the stochastic approximation method suggests that

$$\lim_{k\to\infty}\Delta\beta_k=0\,. \tag{32}$$

Besides, the method imposes an auxiliary condition on the function J as in the area of its extremum an inequality should be observed

$$\left(\beta_1-\beta_1^*\right)\frac{\partial J}{\partial\beta_1}+\left(\beta_2-\beta_2^*\right)\frac{\partial J}{\partial\beta_2}>0\,, \tag{33}$$

and the rate of increase of J should not exceed that of the square parabola when leaving the target.

To optimize the system dynamic characteristics determined by the initial linear part of the controlled object, a method determining the constant value of $z(\infty)$ of the initial signal z of the object, i.e. the object's initial signal on the basis of the initial part of the transfer process caused by the changed input signal at the step $\Delta\chi$ is applied. The value $z(\infty)$ can be calculated for a small time period and the time lag Δt between steps can be insignificant, which reduces the search time of the extremum greatly.

With complete compensation of dynamics and time delays in the object, the search for the extremum would be based on the object's static characteristics. In this case, the actuator's reversion is determined by the following inequality

$$f\left(x_n\right)-f\left(x_{n-1}\right)+\delta\le 0\,, \tag{34}$$

where δ is the optimizer's insensibility area.

The change of the object's output signal as a result of the n-th step of the actuator is determined by

$$\Delta z_n=f\left(x_n\right)A-f\left(x_{n-1}\right)C-z_{n-1}B\,;$$
$$z_{n-1}=z_0+\sum_{i=1}^{n-1}\Delta z_i\,;$$
$$A=1-q_1\,;\ B=1-q_2\,;\ C=q_1-q_2\,;$$
$$q_1=e^{-\frac{\Delta t-\tau}{T_1}}\,;\ q_2=e^{-\frac{\Delta t}{T_1}}\,.$$

For $f(x_n)$ and $f(x_{n-1})$ recurrent formulae look like

$$\left.\begin{aligned}f\left(x_n\right)&=\left[\Delta z_n-f\left(x_{n-1}\right)C+\left(z_0+\sum_{i=1}^{n-1}\Delta z_i\right)B\right]A^{-1};\\ f\left(x_{n-1}\right)&=\left[\Delta z_{n-1}-f\left(x_{n-2}\right)C+\left(z_0+\sum_{i=1}^{n-2}\Delta z_i\right)B\right]A^{-1}\end{aligned}\right\}. \tag{35}$$

According to the mentioned results, the control is formed in compliance with this expression

$$U=\left(\Delta z_n-\Delta z_{n-1}q_1\right)A^{-1}-\left[\Delta z_n\left(\tau\right)-\Delta z_{n-1}\left(\tau\right)\right]q_1A^{-1}\,. \tag{36}$$

Thus, to calculate the operator U, two recent changes of the object's output coordinate are measured in the time period Δt between the actuator's steps Δz_n and Δz_{n-1}, as well as two recent changes of the output z during the pure time delay τ read from the actuator's step moment.

Experiments

Fig. 3 presents an experimental dependency between the Fe content increment in the concentrate of the primary magnetic separators and the classifier drain density, while Fig. 4 depicts dependency of the concentrate yield on this parameter.

The given dependencies were obtained at the concentration plant of the PJSC "ArcelorMittal Kryvyi Rih". The research suggested that with formed constant levels of the section capacity and the identical initial raw materials, the classifier drain density and the size of the material fed for the primary separation changed. Changes in the Fe content of the middling product and tailings were traced as well as the yield of these products. Besides, the influence of the changed capacity of the feed ore section on the magnetic separator operation characteristics was determined when the classifier drain density was maintained at a given level by changing the auxiliary water fed to its bath. Fluctuations of the magnetic iron content in the feed ore were insignificant and as a result of obtained data, while calculating the weight-average content for each density, they were in the limits of an admissible error. During the whole set of experiments, feed density, strength and working parameters of the separators remained constant.

Fig. 5 shows experimental dependencies of the Fe content in the middling product of primary concentration. Fig. 6 depicts dependencies of the middling product yield of primary concentration on the initial feed at the following formed levels of the classifier drain slurry density: 1 – 1700 g/l; 2 – 1800 g/l; 3 – 1900 g/l; 4 – 2000 g/l; 5 – 2100 g/l; 6 – 2200 g/l.

The dependencies in Fig. 3 and 4 reveal that the in-

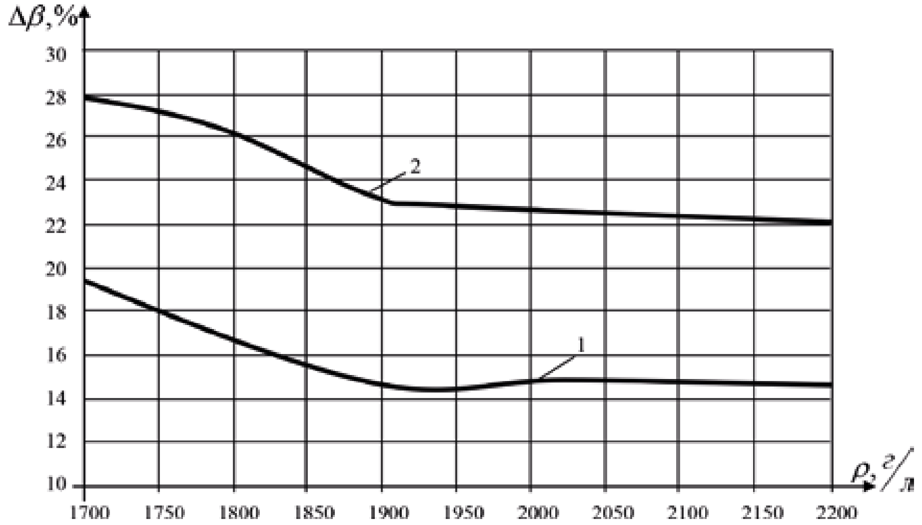

Fig. 3. *Experimental dependencies between the Fe content increment in the concentrate of the primary magnetic separators and the classifier drain density, the capacity of the initial feed section of 230 t/h: 1 – $\beta-\alpha$; 2 – $\beta-\alpha_M$*

Рис. 3. *Экспериментальная зависимость между приращением содержания железа в обогащенном продукте магнитных сепараторов I стадии и плотностью слива классификатора, производительность секции по исходному питанию 230 т/час: 1 – $\beta-\alpha$; 2 – $\beta-\alpha_M$*

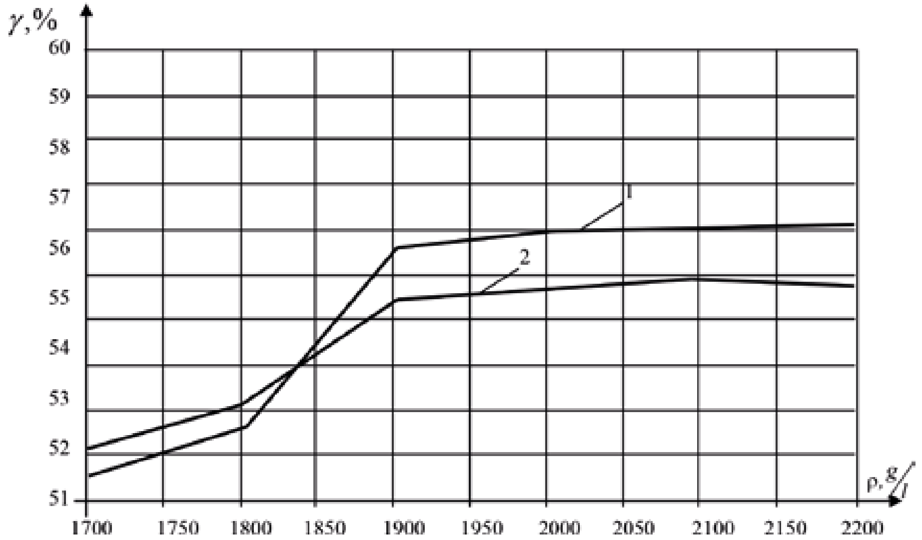

Fig. 4. *Dependencies between the classifier drain density and the concentrate yield The capacity of the initial feed section: 1 – 230 t/h; 2 – 205 t/h*

Рис. 4. *Зависимость между плотностью слива классификатора и выходом обогащенного продукта, производительность секции по исходному питанию: 1 – 230 т/ч; 2 – 205 т/ч*

creased classifier drain density increases the middling product yield, while the Fe increment in the middling product reduces. Thus, controlling the classifier drain density, one can achieve an optimal ratio between quantity and quality of the primary middling product.

Analysis of dependencies in Fig. 3 and 4 shows that although their overall view remains the same for different levels of the classifier drain density, the impact of the feed ore section capacity on operation of the magnetic separator is notable for significant ambiguity and depends on particular maintained density.

The increased classifier drain density and the ore section capacity increase this ambiguity caused by the classifier's unstable mode under conditions changing the granulometric composition of the magnetic separator feed.

Results

With the improved search, testing and working disturbances within controls u_1 and u_2 are formed so that corresponding transients should attenuate in a minimum of time in the object's input linear parts. All necessary limitations as to controls u_1, u_2 and phase coordinates x_1, x_2 are observed. At the same time formed disturbances are used to change increments of the value z to indentify static characteristics of the object's non-linear part for each control channel.

Fig. 7 provides a model of the developed system of adaptive control of iron ore magnetic separation, which is synthesized in the subsystem Simulink 4 of Matlab 6.01 [28–31].

The static characteristics of the non-linear controlled object is set in block Fcn4 as function $f(u)$.

Inertial properties of the non-linear controlled object are simulated by means of transfer function blocks (aperiodic links) Transfer Fcn2 and Transfer Fcn3. To form transport delay for the object's input and output, blocks of fixed signal delay (Transport Delay) are used. Input dynamic links are united into the block Subsystem, the output ones – into the block Subsystem 1. As in real control systems there are some disturbances, the model includes blocks imitating them: Dead Zone, Backlash и Band-Limited White Noise.

Functions of the extreme regulator are simulated by means of signum-reley Sign1. The object's static characteristics are pre-computed in the block Subsystem 5 (Fig. 7). The control adaptation algorithm is realized in the block Subsystem 2. Parameters of separate elements of the ACS are optimized by means of the block Nonlinear Control Design (NCD).

Fig. 8 provides the flowchart of the system of adaptive control over magnetic separation on the basis of ultrasonic control in the Hancock criterion variant.

The system of adaptive control over magnetic separation functions according to the above mentioned algorithm.

The behavior of the ASAC (Automated System of

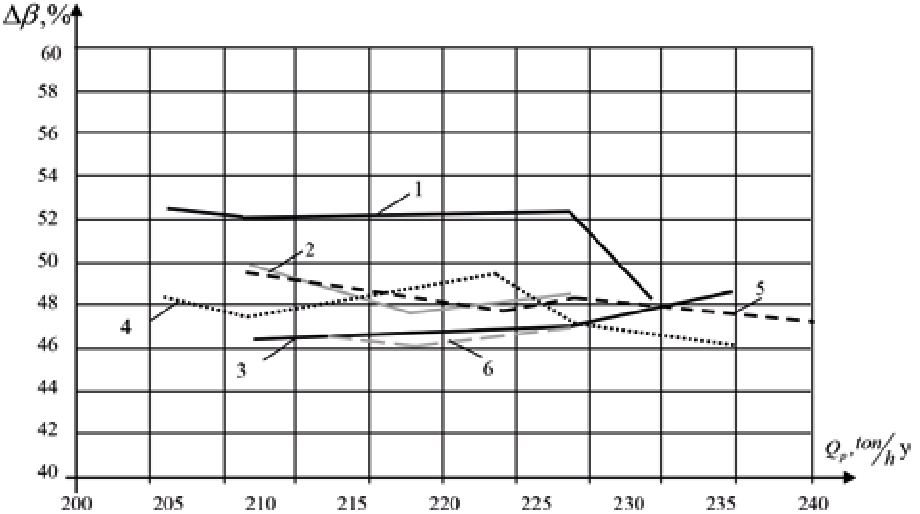

Fig. 5. *Experimental dependencies of the Fe content in the middling product of primary concentration on the capacity of the initial feed section, the classifier drain density: 1 – 1700 g/l; 2 – 1800 g/l; 3 – 1900 g/l; 4 – 2000 g/l; 5 – 2100 g/l; 6 – 2200 g/l*

Рис. 5. *Экспериментальные зависимости содержания железа в промпродукте I стадии обогащения от производительности секции по исходному питанию. Плотность пульпы на сливе классификатора: 1 – 1700 г/л; 2 – 1800 г/л; 3 – 1900 г/л; 4 – 2000 г/л; 5 – 2100 г/л; 6 – 2200 г/л*

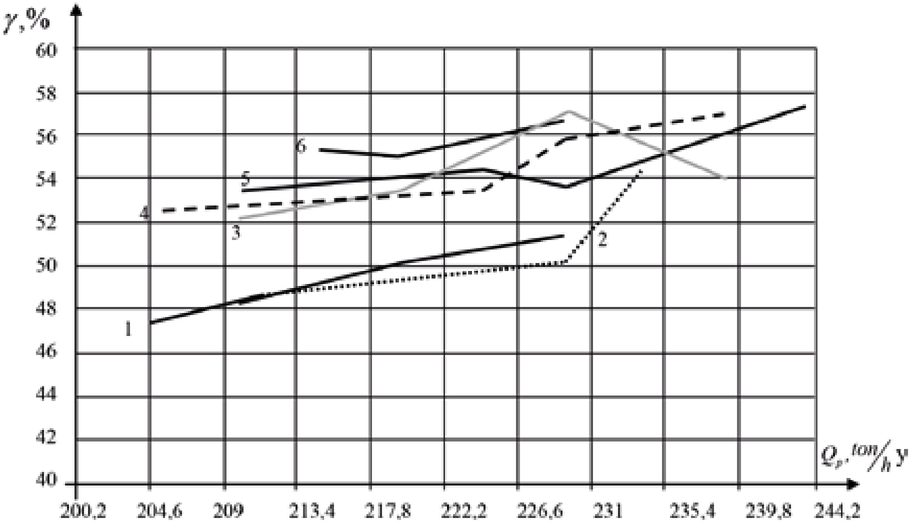

Fig. 6. *Dependencies of the middling product yield of primary concentration on the initial feed section capacity, the classifier drain density: 1 – 1700 g/l; 2 – 1800 g/l; 3 – 1900 g/l; 4 – 2000 g/l; 5 – 2100 g/l; 6 – 2200 g/l*

Рис. 6. *Зависимости выхода промпродукта I стадии обогащения от производительности секции по исходному питанию, плотность пульпы на сливе классификатора: 1 –1700 г/л; 2 – 1800 г/л; 3 – 1900 г/л; 4 – 2000 г/л; 5 – 2100 г/л; 6 – 2200 г/л*

Adaptive Control) with changed static and dynamic characteristics of the object, parameters of disturbing impacts and noises are studied. Fig. 9 shows results of the search for the objective function extremum in the adaptive system of extreme control with noises in the controlled signal.

Discussion

Conducted investigations indicate that the period of searching for the extremum in the ASAC is stable if the static characteristic drifts within ±50% of the rated value, the dynamic link parameters change within ±70% and noise power from 0 to 0.12. In case of arbitrary and short changes of the object's static and dynamic characteristics, the best parameters of the search, the trajectory of which does not change, are achieved if these characteristics change within ± 25% thus fully meeting the technological requirements.

There are formulated conditions and specified regularities of the search for the objective function extremum in the discrete system of automated optimization of iron ore magnetic separation. It is determined that with changing physical-mechanical and chemical-mineralogical characteristics of processed ores, the minimum search period can be provided if the controlling impact is formed on the basis of differences of not less than two simultaneously changed values of the controlled object's input coordinate between the actuator's steps during the pure time delay. The latter is determined considering the current position of the controlled coordinate regarding the extremum point in the form of piecewise constant functions with limited values of acceptable controls, the parameters of which are conditioned by the object's input dynamic characteristics.

There are determined regularities of forming the extreme control over inertial objects with time delays and changing static and dynamic characteristics ensuring the minimum time of transients in the system of control over magnetic separation based on measured values of the controlled coordinate at intervals between the actuator's steps formed according to the object's current static and dynamic characteristics, which are determined under intensive disturbances in the form of unclear sets, the membership of which is set by ratio predicates.

There are determined conditions and parameters of the stable search for the extremum in the system of automated control over iron ore magnetic separation, which realizes suggested search principles under intensive disturbing impacts on the object in controlled signals.

Conclusions

The developed adaptive system controlling magnetic separation allows reducing time of searching for the ob-

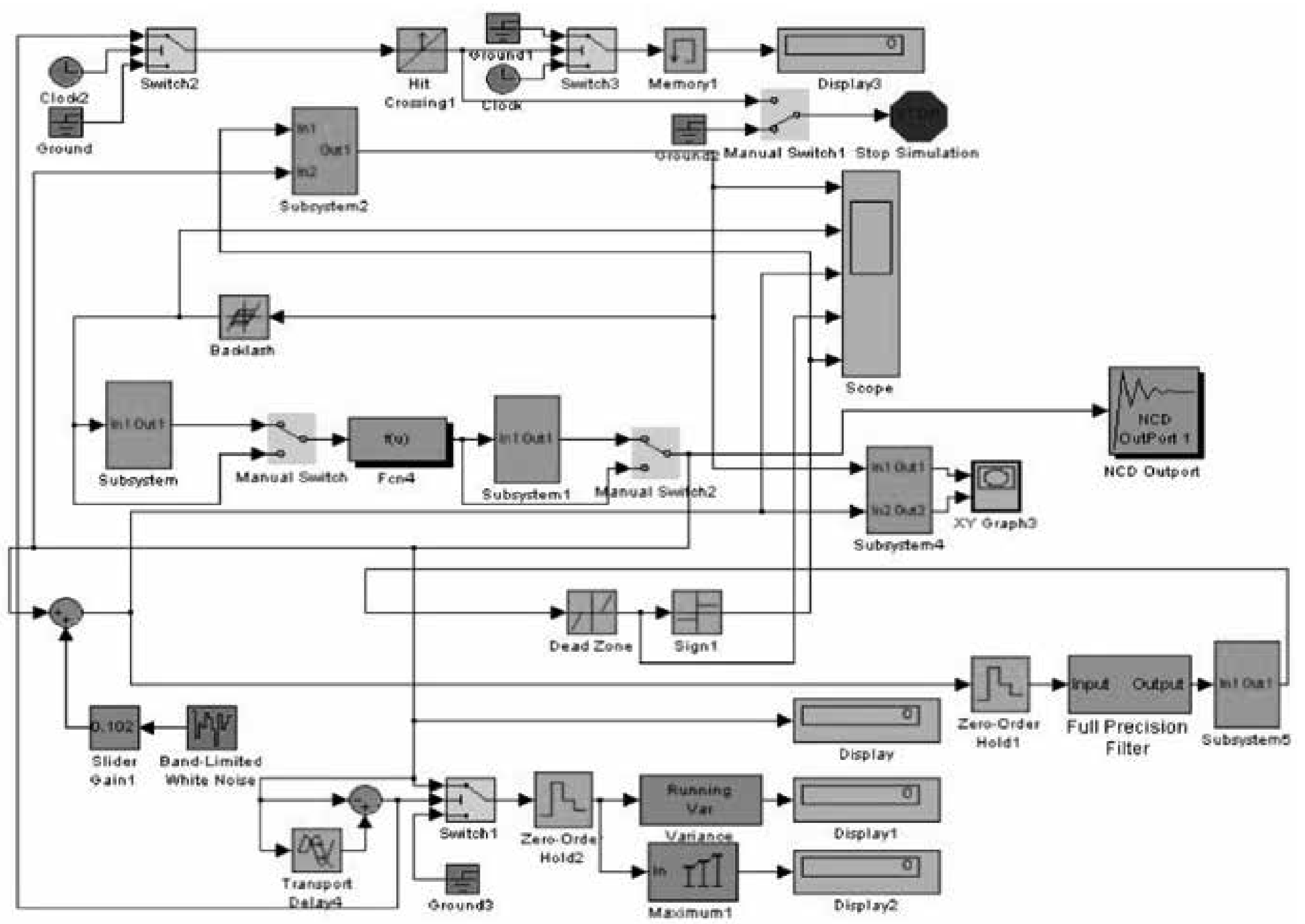

***Fig. 7.** The flowchart of the model of the system of the adaptive control over iron ore magnetic separation*

***Рис. 7.** Блок-схема модели адаптивной системы управления процессом магнитной сепарации железных руд*

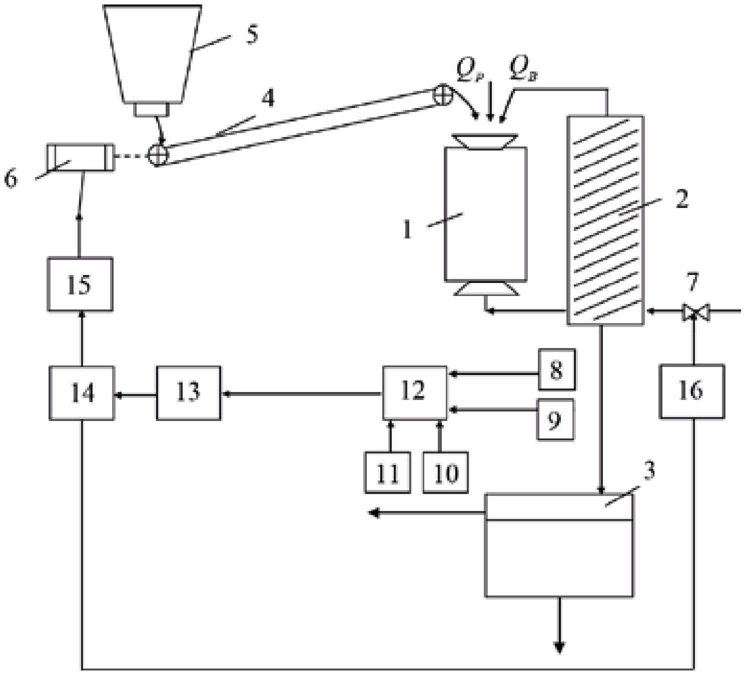

***Fig. 8.** The flowchart of the system of adaptive control over magnetic separation: 1 – mill; 2 – classifier; 3 – magnetic separator; 4 – feeder-conveyor; 5 – bin; 6 – actuating motor; 7 – controlled valve of water consumption; 8, 10 – Fe-content sensors; 9, 11 – flowmeters; 12 – input signal former; 13 – optimizer; 14 – controlling impact former; 15 – system controlling water feed into the mill; 16 – system controlling water consumption in the classifier*

***Рис. 8.** Блок-схема адаптивной системы управления процессом магнитной сепарации: 1 – мельница; 2 – классификатор; 3 – магнитный сепаратор; 4 – конвейер-питатель; 5 – бункер; 6 – приводной двигатель; 7 – регулируемый клапан расхода воды в классификатор; 8, 10 – датчики содержания железа; 9, 11 – расходомеры; 12 – формирователь входного сигнала; 13 – оптимизатор; 14 – формирователь управляющих воздействий; 15 – система управления подачей руды в мельницу; 16 – система управления расходом воды в классификатор*

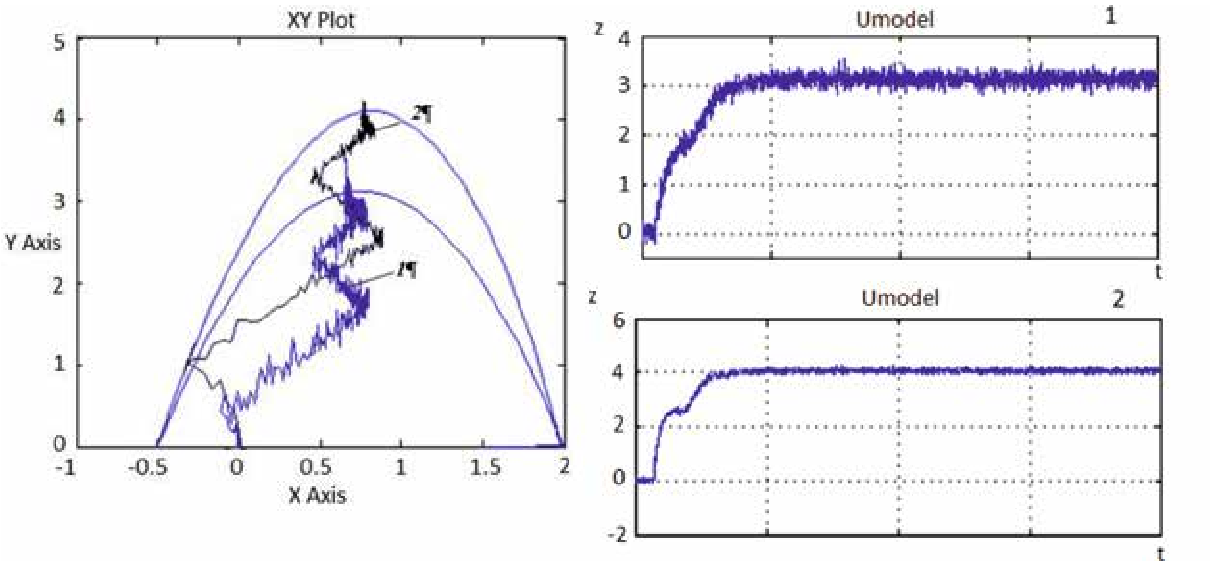

Fig. 9. *Results of the search for the objective function extremum in the control system: 1 – y=f(x),* $\delta = 0,1$*; 2 – y=1,33f(x),* $T_1^*=1,3T_1$, $\tau_1^*=1,2\tau_1$, $T_3^*=1,4T_3$, $\tau_3^* =0,7\tau_3$, $\delta = 0,05$

Рис. 9. *Результаты поиска экстремума целевой функции в системе управления: 1 – y=f(x),* $\delta = 0,1$*; 2 – y=1,33f(x),* $T_1^*=1,3T_1$, $\tau_1^*=1,2\tau_1$, $T_3^*=1,4T_3$, $\tau_3^* =0,7\tau_3$, $\delta = 0,05$

jective control function, maintaining the optimal ratio of the concentrate yield and the grade contained under conditions of changing quality of initial ores and equipment. There are determined conditions and the best parameters of searching for the extremum in the system of adaptive control over iron ore magnetic separation under disturbances and noises in controlled signals. They can be achieved when deviations of the object's static and dynamic characteristics from rated ones do not exceed ±25%.

CONTRIBUTION / *Долевое участие авторов*

Morkun V.S. – carried out research and analysis of regularities of formation of extreme control of inertial objects with delay with varying static and dynamic characteristics; **Morkun N. V. –** developed the theoretical basis for the formation of control actions in the system of extreme control of dynamic objects; **Tron V. V.** –conducted the development of the structure of the adaptive control system of the magnetic separation process in the process of ore material enrichment and the study of its operation under various conditions; **Dotsenko I. A.** – conducted a study of the control system in conditions of disturbances and noises in controlled signals.

Моркун В. С. *– проводил исследование и анализ закономерностей формирования экстремального управления инерционными объектами с запаздыванием с изменяющимися статическими и динамическими характеристиками;* ***Моркун Н. В.*** *– разработала теоретическую базу формирования управляющих воздействий в системе экстремального управления динамическими объектами;* ***Тронь В. В.*** *– проводил разработку структуры системы адаптивного управления процессом магнитной сепарации в процессе обогащения рудного материала и исследование ее работы в различных условиях;* ***Доценко И. А.*** *– проводила исследование системы управления при наличии возмущений и шумов в контролируемых сигналах.*

CONFLICT OF INTEREST / *Конфликт интересов*

The authors declare no conflict of interest / *Авторы заявляют об отсутствии конфликта интересов.*

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СВЕДЕНИЯ ОБ АВТОРАХ / *Information about authors:*

Vladimir St. MORKUN – Doctor of Technical Sciences, Professor, Vice-Rector in Research.

Kryvoi Rogh National University, Kryvoi Rogh, Ukraine, 50027.

E-mail: morkunv@gmail.com

Ph.: +38 067 976 29 25.

Number ORCID: http://orcid.org/0000-0003-1506-9759

МОРКУН Владимир Станиславович *– доктор технических наук, профессор, проректор по научной работе. Криворожский национальный университет, 50027, г. Кривой Рог, Украина.*

e-mail: morkunv@gmail.com

Тел.: +38 067 976 29 25

Номер ORCID: http://orcid.org/0000-0003-1506-9759

Irina Al. DOTSENKO – Researcher, Scientific and production complex of iron, manganese and polymetallic ores, Academy of Mining Sciences of Ukraine, Kryvoi Rogh, Ukraine, 50002

E-mail: i.a.dotsenko@i.ua

Ph.: +380564262407

Number ORCID: https://orcid.org/0000-0001-7912-2497

ДОЦЕНКО Ирина Алексеевна *– научный сотрудник.*

Научно-производственный комплекс железных, марганцевых и полиметаллических руд Академии горных наук Украины, 50002, г. Кривой Рог, Украина.

E-mail: i.a.dotsenko@i.ua

Тел.: +380564262407

Номер ORCID: https://orcid.org/0000-0001-7912-2497

Vitaliy V. TRON – PhD, Associated Professor.

Department of automation, computer science and technology Kryvoi Rogh National University, Kryvoi Rogh, Ukraine, 50027.

E-mail: vtron@ukr.net

Ph.: +380961149797.

Number ORCID: https://orcid.org/0000-0002-6149-5794

ТРОНЬ Виталий Валериевич *– кандидат технических наук, доцент.*

Кафедра автоматизации, компьютерных наук и технологий, Криворожский национальный университет, 50027, г. Кривой Рог, Украина.

E-mail: vtron@ukr.net

Тел.: +380961149797

Номер ORCID: https://orcid.org/0000-0002-6149-5794

Natalia Vl. MORKUN – Doctor of Technical Sciences, Associated Professor, Department of automation, computer science and technology.

Kryvoi Rogh National University, Kryvoi Rogh, Ukraine, 50027.

E-mail: nmorkun@gmail.com

Ph.: +380936770659

Number ORCID: http://orcid.org/0000-0002-1261-1170

МОРКУН Наталья Владимировна *– доктор технических наук, доцент. Кафедра автоматизации, компьютерных наук и технологий, Криворожский национальный университет, 50027, г. Кривой Рог, Украина.*

e-mail: nmorkun@gmail.com

Тел.: +380936770659

Номер ORCID: http://orcid.org/0000-0002-1261-1170

АДАПТИВНАЯ СИСТЕМА УПРАВЛЕНИЯ ПРОЦЕССОМ МАГНИТНОЙ СЕПАРАЦИИ

[1] В. С.Моркун*
[1] Н. В.Моркун
[1] В. В.Трон
[2] А. И.Доценко
[1] Криворожский Национальный университет, Кривой Рог, Украина, morkunv@gmail.com
[2] Академия горных наук Украины, Кривой Рог, Украина

DOI: 10.21177/1998-4502-2018-10-4-545-557

Цель. В рамках устойчивой индустриализации целью работы является создание теоретической базы и разработка адаптивной системы управления процессом магнитной сепарации железных руд, минимизирующей время поиска экстремума характеристик динамических объектов в условиях воздействия возмущений и помех в контролируемых сигналах.

Методы. В статье использованы методы оптимального управления, метод стохастической аппроксимации для повышения эффективности оптимального управления, методы численного моделирования для синтеза и анализа математической модели системы экстремального управления, компьютерные информационные и программные технологии для реализации разработанного

алгоритма поиска экстремума в виде программного обеспечения.

Результаты. В статье приведена теоретическая база формирования управляющих воздействий в системе экстремального управления динамическими объектами, позволяющих при наличии возмущений и помех в контролируемом сигнале достигнуть экстремума характеристики объекта управления за минимальное время. Установлены закономерности формирования экстремального управления инерционными объектами с задержкой и изменяющимися статическими и динамическими характеристиками, обеспечивающие минимальное время переходных процессов в системе управления процессом магнитной сепарации железных руд на базе измеренных значений регулируемой координаты через промежутки времени между шагами исполнительного механизма, формируемые в соответствии с текущими значениями статических и динамических характеристик объекта, которые определяются в условиях действия интенсивных возмущений. Разработана адаптивная система управления процессом магнитной сепарации железных руд, минимизирующей время поиска экстремума характеристик динамических объектов в условиях воздействия возмущений и помех в контролируемых сигналах.

Выводы. Разработанная адаптивная система управления процессом магнитной сепарации железных руд позволяет минимизировать время поиска целевой функции управления, поддерживать оптимальное соотношение между выходом концентрата и содержанием полезного компонента в нем в условиях изменяющегося качества исходной руды и состояния технологического оборудования. Установлены условия и впервые определено, что наилучшие параметры поиска экстремума в системе автоматического управления процессом магнитной сепарации железных руд, которая реализует предложенные принципы поиска, при наличии возмущений и шумов в контролируемых сигналах достигаются в том случае, когда отклонение статических и динамических характеристик объекта управления от номинального значения не превышает ±25%.

Ключевые слова: адаптивная система управления, магнитная сепарация, железная руда, пульпа, поиск экстремума.

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Статья поступила в редакцию 30.07.2018