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ADAPTIVE CONTROL SYSTEM OF THE SELF-GRINDING PROCESS OF ORES IN AUTOGENOUS MILLS

The main goal *is development of an adaptive self-regulating system for controlling the loading process of drum mills for autogenous ore grinding, providing specified indicators of control quality under conditions of uncontrolled disturbances.*

Methodology. *To achieve this goal, methods of system analysis and synthesis of automatic control theory systems and mathematical modeling methods were used to assess the quality of processes for regulating the parameters of the adaptive system.*

Scientific novelty. *A method is proposed for solving the problem of synthesizing an adaptive loading control system for autogenous mills, which takes into account in its formulation restrictions on the level of control action and a possible change in the structure of the mathematical model of the object.*

Conclusions. *The feasibility of using adaptive self-regulating systems for controlling the loading of autogenous fuel mills is substantiated. The problem of synthesizing the main loop of the control system is formulated and solved, taking into account real restrictions on the control action and possible changes in the structure of the mathematical model of the object. The dependence of the control time of the main loop on the restrictions on the control action has been studied. As a result of modeling the processes in the self-tuning loop of the adaptive system, it was established that the time for setting the model parameters is significantly less than the decay time of the correlation function of the processes that cause drift of the object parameters. Thus, the fulfillment of the conditions of quasi-stationarity indicates the operability of the adaptive system.*

Practical significance. *The use of the proposed adaptive system for controlling the loading of autogenous mills provides the necessary indicators of control quality under conditions of restrictions on the control action and the non-stationary nature of the facility.*

Key words: *autogenous mill, modeling, adaptive system, mathematical model, loading control, self-tuning, quality indicators, uncontrolled disturbances, uncontrolled disturbances.*

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АДАПТИВНА СИСТЕМА УПРАВЛІННЯ ПРОЦЕСОМ САМОПОДРІБНЕННЯ РУД У БАРАБАННИХ МЛИНАХ

Метою цієї роботи *є розробка адаптивної самонастроювальної системи управління процесом завантаження барабанних млинів самоподрібнення руд, що забезпечує заданих показників якості управління в умовах дії неконтрольованих збурень.*

Методологія передбачає *використання методів системного аналізу і методів синтезу з теорії автоматичного управління, а також методи математичного моделювання для оцінки якості процесів налаштування параметрів адаптивної системи.*

Наукова новизна. *Запропоновано метод вирішення задачі синтезу адаптивної системи управління завантаженням млинів самоподрібнення, які враховують у своїй умові обмеження на рівень управляючого впливу і можливість зміни структури математичної моделі цього об'єкту.*

Висновки. *Обґрунтована доцільність використання адаптивних самонастроювальних систем управління завантаженням млинів самоподрібнення. Вирішена задача синтезу основного контуру системи управління з урахуванням реальних обмежень на управляючий вплив і можливе змінення структури математичної моделі об'єкта. Досліджена залежність часу регулювання основного контуру від обмежень на управляючий вплив. У результаті моделювання процесів у контурі самоналаштування адаптивної системи встановлено, що час настройки параметрів моделі значно менше часу спадання кореляційної функції процесів, що визивають дрейф параметрів об'єкту. Виконання умови квазістаціонарності свідчить про працездатність розробленої адаптивної системи управління млином.*

Практична значимість. *Використання запропонованої адаптивної системи управління завантаженням млинів самоподрібнення забезпечує необхідні показники якості управління в умовах обмеження на управляючий вплив та не стаціонарність цього об'єкту управління.*

Ключові слова: *млин самоподрібнення, моделювання, адаптивна система, математична модель, управління завантаженням, самоналаштування, показники якості, неконтрольовані збурення.*

Introduction. The emergence and development of modern means of information processing makes it possible to implement effective multi-level systems of automatic management of technological processes of enrichment technology, in which the object of management is the entire technological line, and the economic efficiency of its work is taken as a quality criterion **(**Sokur et al., 2020)**.**

Such generalized economic criteria are the most sensitive to the modes of operation of the resource-intensive devices of the two-stage technological lines (Novytskyi et al., 2022). Therefore, the development of effective local control systems for aggregates such as drum mills, which account for more than half of all beneficiation technology costs (Sokur et al., 2016), is an urgent task.

Setting the problem of research. Fig. 1 presents a functional scheme of the control system with a classifier for the degree of filling of a self-grinding mill working.

It is known that for self-grinding mills, the degree of drum filling is a critical parameter (Novytskyi et al., 2021), the control and regulation of which ensures trouble-free (absence of jamming) and efficient operation of the mill.

Therefore, the purpose of managing the local system of Fig. 1 – to ensure, by adjusting the frequency of rotation of the feeder blade V, the stabilization of the degree of filling of the mill φ at the level of the task φ_{val}, the value of which is determined at the top level of the hierarchy.

As an object of control, a self-crushing mill with a classifier along the channel «feeder blade speed V – degree of drum filling φ» is described with sufficient accuracy by the transfer function:

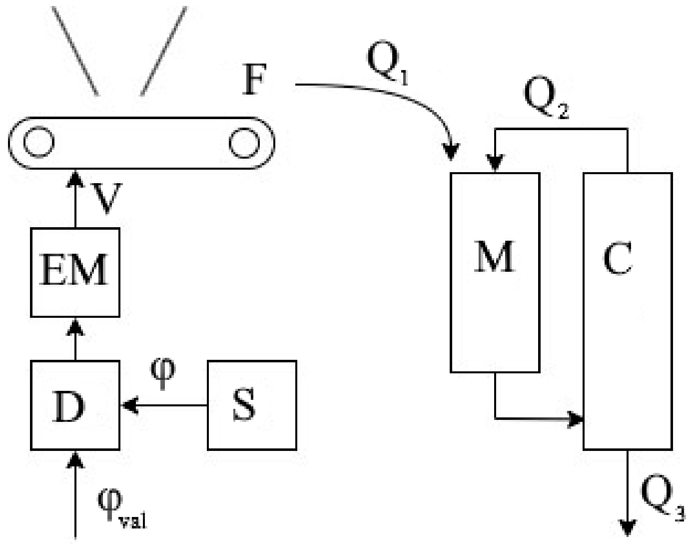


Fig. 1. Control system for the degree of filling of a self-grinding mill working: M – autogenous mill, C – classifier, S – mill filling sensor, F – feeder, D – computing device, EM – executive mechanism, Q_1, Q_2, Q_3 – respectively, flows of initial ore, reversible loading and finished product

$$W_{OC} = \frac{K}{T_2^2 p^2 + T_1 p + 1}. \tag{1}$$

The main task of managing the degree of filling φ is complicated by the fact that the self-grinding drum mill is essentially an inertial and non-stationary object – the parameters of the transfer function (1), such as K, T_1, T_2, as change in a fairly wide range (up to 15% of nominal values). The main reason for the drift of the model parameters is a change in the physical and mechanical properties of the original ore sent for grinding (Khotskina, 2014). In addition to affecting the transmission coefficient K, these disturbances can qualitatively change the structure of the object (1), which acquires the properties of value $T_1 < 2T_2$ an oscillating link.

Thus, to ensure the effective operation of the control system of such a non-stationary object, it is necessary to provide for adaptive regulation of the parameters of the main circuit.

The **main goal of the research** is development of an adaptive self-regulating system for controlling the loading process of drum mills for autogenous ore grinding, using methods of analysis and synthesis of automatic control theory systems and mathematical modeling methods and providing specified indicators of control quality under conditions of uncontrolled disturbances.

Literature review. A large number of works by domestic and foreign authors are devoted to solving the problems of increasing the efficiency of the grinding mill as due to the improvement of structural elements of mills (Arvidsson, 2006) and classifying devices (Morkun et al., 2018) and to optimization the management process.

Most of them involve a traditional approach based on the use of information about the characteristics of the input flow of material (Pistun et al., 2002) and the finished product of the grinding process (Fedoryshyn et al., 2012). The emergence of modern means of information processing and management contributed to the development of the direction based on the use of adaptive systems (Feng et al., 2019). Conventionally, they can be divided into two types: systems with adjustment of model parameters (Novytskyi & Shevchenko, 2014), which is considered in this research paper, and systems based on non-parametric identification methods. The second type working with non-parametric models (mainly neural networks) have a number of advantages.

However, they have a long adjustment time and their application in production requires a strict justification of quasi-stationarity conditions.

Solving the problem. Synthesis of the system must be performed in two important main stages:

1) determination of the structure and calculation of the nominal values of the parameters of the main control scheme;

2) determination of the structure of the self-regulation scheme.

In the process of synthesizing the main scheme of the system, two factors must be taken into account:

– the roots of the characteristic equation of the object model (1) can be complex;

– the speed of the feed web is limited by size, i.e.

$$V \le V_{max} . \quad (2)$$

Taking into account these conditions, it is advisable to use the synthesis method (Novytskyi & Us, 2017), which provides an aperiodic response of a closed control system to a typical input influence with a given adjustment time T_{adj} and re-adjustment of no more than 2%. In Fig. 2 shows the structural diagram of the main circuit where W_{d1} and W_{d2} are the transfer functions of correction devices:

$$W_{d1} = \frac{C_1 T_2^2}{p + C_2}, \quad (3)$$

$$W_{d2} = \frac{C_3 \left(p + C_2\right)}{p + C_4}.$$

Calculation of the values of the parameters C_1, C_2, C_3, C_4 that ensure the aperiodic response of the closed system Fig. 2 with a given adjustment time T_{adj} is performed as follows. The transmission function of the system on the channel «$\varphi_{val} - \varphi$» is as follows:

$$W_c(p) = \frac{W_{d1} \cdot W_{d2} \cdot W_{oc}}{1 + W_{d2} \cdot W_{oc}} =$$

$$= \frac{KC_1C_3}{p^3 + \frac{T_1 + C_4 T_2^2}{T_2^2} \cdot p^2 + \frac{KC_3 + T_1 C_4 + 1}{T_2^2} \cdot p + \frac{C_4 + C_2 C_3 K}{T_2^2}}.$$

We denote:

$$\omega^3 = KC_1C_3 = \frac{C_4 + C_2 C_3 K}{T_2^2}, \quad (4)$$

and next reduce the transfer function $W_c(p)$ to the normalised form:

$$W_c(\bar{p}) = \frac{1}{\bar{p}^3 + \frac{T_1 + C_4 T_2^2}{T_2^2 \omega} \cdot \bar{p}^2 + \frac{KC_3 + T_1 C_4 + 1}{T_2^2 \omega^2} \cdot \bar{p} + 1}, \quad (5)$$

where $\bar{p} = p / \omega$ is a normalised argument.

To ensure the aperiodicity of the response, the parameters of the transfer function (5) for the third-order system should have the following values (Dorf & Bishop, 2022):

$$\omega = \frac{4,04}{T_{adj}}.$$

$$\alpha = \frac{T_1 + C_4 T_2^2}{T_2^2 \cdot \omega} = 1,9.$$

$$\beta = \frac{KC_3 + T_1 C_4 + 1}{T_2^2 \cdot \omega^2} = 2,2.$$

Thus, the sequence of calculating the values of the parameters C_1, C_2, C_3, C_4 of the correcting devices will be as follows:

$$\omega = \frac{4,04}{T_{adj}}.$$

$$C_4 = \frac{\alpha T_2^2 \omega - T_1}{T_2^2}.$$

$$C_3 = \frac{\beta T_2^2 \omega^2 - T_1 C_4 - 1}{K}. \quad (6)$$

$$C_1 = \frac{\omega^3}{KC_3}.$$

$$C_2 = \frac{C_1 T_2^2 K C_3 - C_4}{KC_3}.$$

The output data are the parameters of the object model K, T_1, T_2 and the specified adjustment time T_{adj}.

It should be noted that the minimum possible setting time of T_{adj} is determined by restrictions on the control influence, in this case it is the maximum speed of the feeder blade V according (2).

In (Fig. 3, *a)* presents the transient process of changing the degree of filling $\varphi(t)$ in the control system for $\varphi_{val} = 40\%$, defined nominal values of the object's parameters: $K = 60\, sec \cdot m^{-1}; T_1 = 16\, sec; T_2 = 12\, sec; V_{max} = 1\frac{m}{sec}$ and the parameters of the correction devices (6) calculated according to $C_1 = 0,001$; $C_2 = 0,0852$; $C_3 = 0,0405$; $C_4 = 0,1448$. In (Fig. 3, *b*) shows the process of changing the control influence $V(t)$ – the speed of the feeder.

From (Fig. 3, *a, b*), it follows that condition (2) for limiting the speed of the feeder web in the control

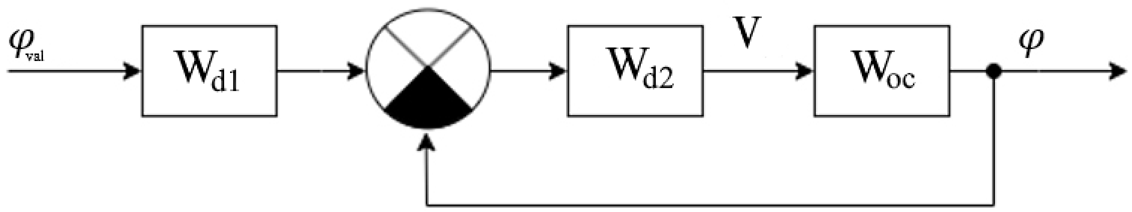
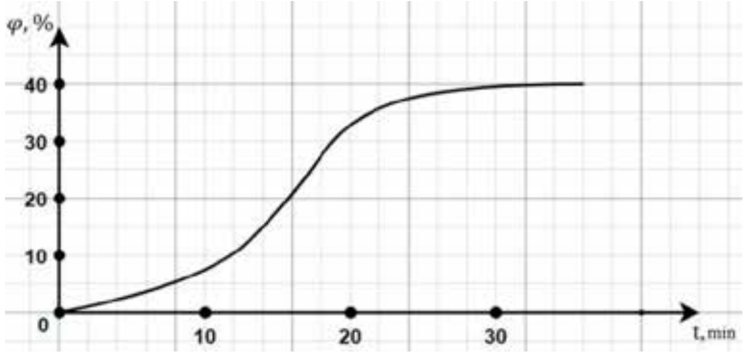
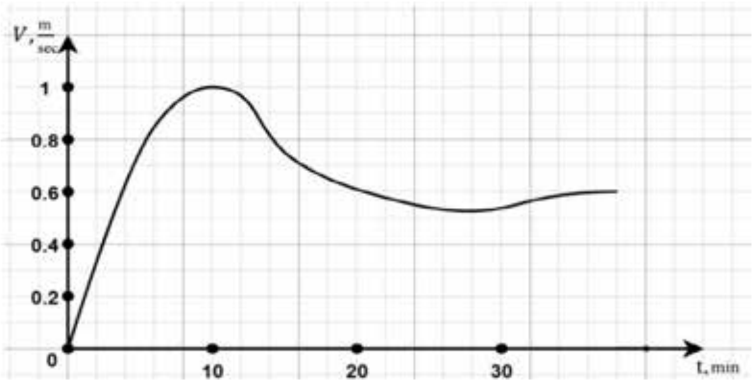


Fig. 2. Structural diagram of the main circuit of the adaptive control system



a)



b)

Fig. 3. Processes of changes in the degree of φ(t) filling (a) and the speed of the feeder blade $V(t)$ in the management system (b)

process will be fulfilled if the specified adjustment time T_{adj} is at least 30 minutes. In the opposite case, condition (2) is violated, overregulation increases and oscillations occur in the system.

To solve the problem of adapting the system to the physical and mechanical properties of the original ore, which change and cause changes in the values of the model parameters of the control object K, T_1, T_2 it is advisable to use a self-adjusting system with an adjustable model (Fig. 4).

The control influence $V(t)$ simultaneously enters the inputs of the control object and the model. The mismatch between object and model outputs ε (mismatch function) is used to adjust model parameters $P = \{K_M, T_{1M}, T_{2M}\}$ according to the gradient law:

$$\frac{dP}{dt} = -\alpha grad \varepsilon^2, \qquad (7)$$

where P – is the adjustable element, α – is the coefficient that determines the adjustment speed.

In the computing device D (Fig. 4) according to the adjusted parameters of the model K_M, T_{1M}, T_{2M} in accordance with expressions (6), the values of the parameters of the correction devices – C_1, C_2, C_3, C_4, are calculated, in which an aperiodic response is ensured in the main circuit and the processes correspond (Fig. 3).

Calculation of processes in the adaptive system (Fig. 4) was performed by the methods Δt . In picture (Fig. 5) we can see the processes of setting parameters of the control object model K_M, T_{1M}, T_{2M} with simultaneous jump-like application of them on the object by 10 %.

From the graphs (Fig. 5) obtained, it follows that the process of setting model parameters ends within 40 minutes. This is significantly less than the period of quasi-stationarity, which is determined by the rate of change in the properties of the original ore and, in the presence of storage bunkers, is several hours.

After setting the parameters of the model, the processes in the main circuit along the channel « $\varphi_{val} - \varphi$ » correspond to the curves in (Fig. 3) and have the desired quality indicators.

Conclusions and prospects for further development. In this work, an adaptive system is proposed (Fig. 2) to control the loading process of self-grinding mills, which provides the specified characteristics of transient processes in the main control circuit in conditions of non-stationarity of the object.

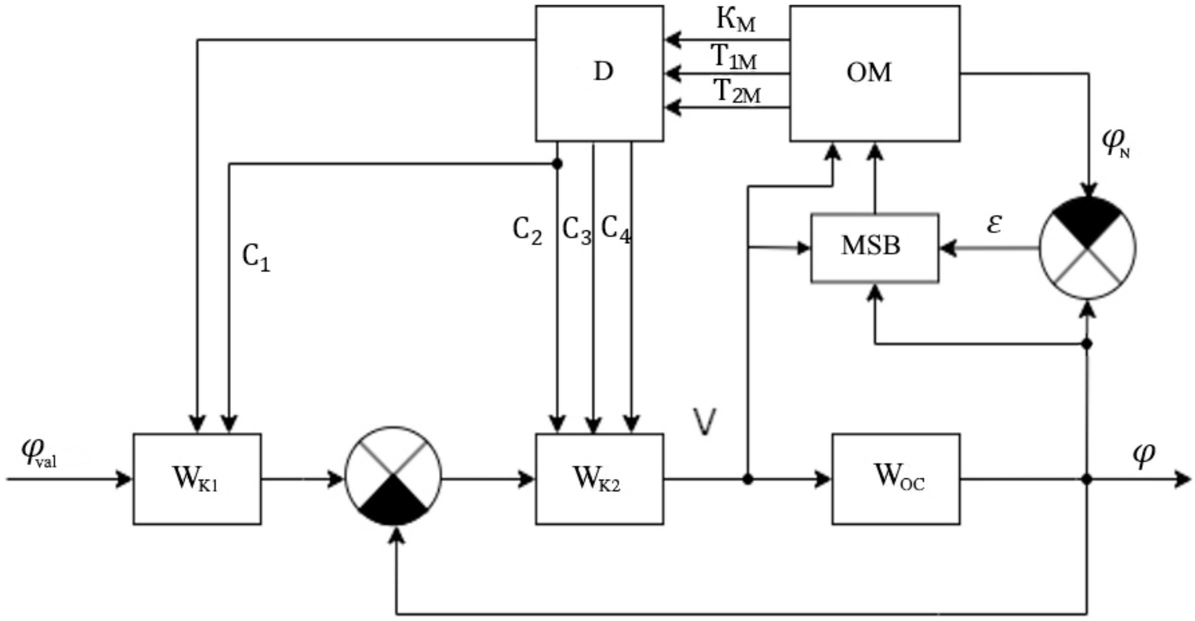


Fig. 4. Structural diagram of the adaptive control system: MSB – model setting block, OM – object model, D – computing device

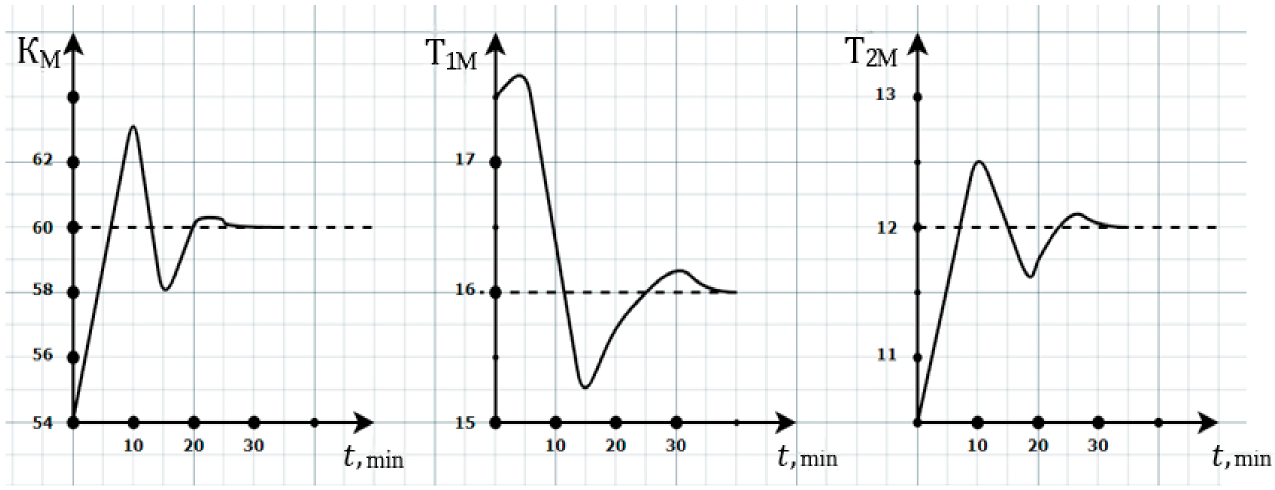


Fig. 5. Processes of setting parameters of the adaptive system object model

At the same time, the specified (minimum) adjustment time in the main circuit is determined by the limitation on the level of influence of control – speed of the feeder V (2). Using of an adaptive self-adjusting control system (Fig. 4) for the filling of self-grinding mills allows ensuring the necessary indicators of the quality of management in the conditions of variable parameters of the object of control (6). As a result of modeling the processes in the adaptive system, it is established that setting its parameters ends much faster (Fig. 5) than changing the parameters of the control object.

So, the following is done in this research paper:

1) use of an adaptive self-regulating control system for the filling of self-grinding mills allows you to ensure the necessary indicators of the quality of management in the conditions of changes in the parameters of the object;

2) the adjustment time of the main loop of the filling control system of the self-grinding mill is determined by restrictions on the level of control influence.

In the future, it is proposed to carry out research on the development of a method for determining the parameter α (7), which affects the speed of setting the parameters of our adaptive system model.

BIBLIOGRAPHY:

1. Sokur V. I. Investigation of the process of crushing solid materials in the centrifugal disintegrators / V. I. Sokur, V. S. Biletskyi, I. O. Vidmid, E.M. Robota. *Eastern-European Journal of Enterprise Technologies*. 2016. № 81. P. 34–40.

2. Novytskyi I. V. A systematic approach to solving the problems of optimal management of two-stage technological lines / I.V. Novytskyi, V.V. Sliesariev, Y.O. Shevchenko. *Collection of research papers of the National Mining University*. 2022. № 71. P. 211–216. doi: https://doi.org/10.33271/crpnmu/71.222

3. Sokur V. I. Ore preparation: crushing, grinding, classification. Kremenchuk. V.I. Sokur, V.S. Bileskiy., I.O. Vidmid., E.M. Robota. Kremenchug 2020. ISBN 978-617-639-272-9.

4. Novytskyi I. V. Основні принципи організації пошукових процедур при управлінні процесом само-здрібнювання в барабанних млинах / I.V. Novytskyi, V.V. Sliesariev, A.V. Malienko. *Collection of research papers of the National Mining University*. 2021. № 66. P. 245–253. doi: 10.33271/crpnmu/66.245

5. Khotskina V. B. Automatization of control processes at the first stage of ore enrichment using quickly acting regressive models. *Naukovyi Visnyk Natsionalnogo Hirnychoho Universytetu*. 2014. № 3. P. 145–151.

6. Novytskyi I. V. Обґрунтування критерія оптимального керування процесом самоподрібнення руд у барабанних млинах / I.V. Novytskyi, Y.O. Shevchenko. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu.* 2024. № 4. P. 211–216. doi: https://doi.org/10.33271/nvngu/2024-4/061

7. Arvidsson S. Remote control and automation in Swedish iron ore mining. Metallurgy – An integral part of Innovative Sweden: The Ministry of Industry. Employment and Communications, Sweden. 2006.

8. Morkun V., Morkun N. Estimation of the crushed ore particles density in the pulp flow based on the dynamic effects of high energy ultrasound. *Archives of Acoustics*. 2018. № 43(1). P. 61–67. doi: 10.24425/118080

9. Pistun Y. Automatic control and optimization of ball mills / Y. Pistun, V. Zagraj, A. Skobalo /// Proc. of VIII Forum of Power Engineers, Techn. Univ. of Opole, May 29–31. 2002. ISBN 83-88492-04-7. PP. 575–581, Publ. House of Tech. Univ. of Opole. Opole. Poland.

10. Fedoryshyn R. The improved system for automation and optimization of solid material grinding by means of ball mills / R. Fedoryshyn, H. Nykolyn, V. Zagraj, Y. Pistun. Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium. Austria. 2012. P. 053–056. ISBN 978-3-901509-91-9.

11. Feng L., Yang F., Zhang W., Tian H. Model Predictive Control of Duplex Inlet and Outlet Ball Mill System Based on Parameter Adaptive Particle Swarm Optimization. Mathematical Problems in Engineering. 2019.

12. Novytskyi I. V. Adaptyvna systema upravlinnya zavantazenyam barabanyh mlyniv somopodribnennya [Adaptive loading control system for autogenous drum mills] / I. V. Novytskyi, Y. O. Shevchenko. Collection of research papers of the National Mining University. 2014. № 44. P. 103–109. url: https://ir.nmu.org.ua/handle/123456789/152406

13. Bai Y., He F. Modeling on the effect of coal loads on kinetic energy of balls for ball mills. *Energies*. 2015. № 8. PP. 6859–6880.

14. Novytskyi I. V Modern theory of healing: textbook for universities / I. V. Novytskyi, S. A. US. *National Mining University*. Dnipro. 2017. ISBN 978-966-350-661-6

15. Dorf R. Modern Control Systems / R. C. Dorf, R. H. Bishop. Prentice Hall. 2008. ISBN 0132270285.

REFERENCES:

1. Sokur, V., Biletskyy, L., Sokur, D., & Bozyk, I. (2016). Investigation of the process of crushing solid materials in the centrifugal disintegrators. *Eastern-European Journal of Enterprise Technologies,* 3/7(81), 34–40.

2. Novytskyi, I., Sliesariev, V., & Shevchenko, Y. (2022). A systematic approach to solving the problems of optimal management of two-stage technological lines. Collection of research papers of the National Mining University, 71, 2011- 216. https://doi.org/10.33271/crpnmu/71.222

3. Sokur, M. I., Biletskyi, V. S., Vidmid, I. O., & Robota, E. M. (2020). Ore preparation (crushing, grinding, classification): monograph. ISBN 9786176392729.

4. Novytskyi, I., Sliesariev, V., & Maliienko, A. (2021). The basic principles of organizing prospecting procedures for managing the process of autogenous grinding of ores in drum mills. *Collection of Research Papers of the National Mining University,* 66, 245–253. https://doi.org/10.33271/crpnmu/66.245

5. Khotskina, V. (2014). Automatization of control processes at the first stage of ore enrichment using quickly acting regressive models. *Naukovyi Visnyk Natsionalnogo Hirnychoho Universytetu,* 3, 145–151.

6. Novytskyi, I., & Shevchenko, Y. (2024). Обґрунтування критерія оптимального керування процесом самоподрібнення руд у барабанних млинах. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu,* 4, 61–66. https://doi.org/10.33271/nvngu/2024-4/061

7. Arvidsson, S. (2006). Remote control and automation in Swedish iron ore mining. Metallurgy – An integral part of Innovative Sweden: The Ministry of Industry. *Employment and Communications,* Sweden.

8. Morkun, V., & Morkun, N. (2018). Estimation of the crushed ore particles density in the pulp flow based on the dynamic effects of high energy ultrasound. *Archives of Acoustics,* 43(1), 61–67. doi: 10.24425/118080

9. Pistun, Y., Zagraj, V., & Skobalo, A. (2002). Automatic control and optimization of ball mills, *Proc. of VIII Forum of Power Engineers, Techn. Univ. of Opole*, 575–581, ISBN 83-88492-04-7.

10. Fedoryshyn, R., Nykolyn, H., Zagraj, V., & Pistun, Y. (2012). The improved system for automation and optimization of solid material grinding by means of ball mills. Annals of DAAAM for 2012 & Proceedings of the 23rd International DAAAM Symposium, 053–056, ISBN 978-3-901509-91-9.

11. Feng, L., Yang, F., Zhang, W., & Tian, H. (2019). Model Predictive Control of Duplex Inlet and Outlet Ball Mill System Based on Parameter Adaptive Particle Swarm Optimization. *Mathematical Problems in Engineering*.

12. Novytskyi, I., & Shevchenko, Y. (2014). Adaptive loading control system for autogenous drum mills. *Collection of research papers of the National Mining University,* 44, 103–109. url: https://ir.nmu.org.ua/handle/123456789/152406

13. Bai, Y., He, F. (2015). Modeling on the effect of coal loads on kinetic energy of balls for ball mills. *Energies,* 8, 6859–6880.

14. Novytskyi, I., & Us, S. (2017). Modern theory of healing: textbook for universities. *National Mining University*. ISBN 978-966-350-661-6.

15. Dorf, R. & Bishop, R. (2022). Modern Control Systems. *14th Edition*. ISBN 978-0-13-730725-8.