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CONTROL REGULARITIES OF THE USEFUL MINERAL EXTRACTION FROM ORE FEED STREAM WITH BALL GRINDING. SPECTRAL ANALYSIS

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ЗАКОНОМІРНОСТІ КЕРУВАННЯ ВИЛУЧЕННЯМ КОРИСНОГО МІНЕРАЛУ З РУДОПОТОКІВ ІЗ КУЛЬОВИМ ПОДРІБНЕННЯМ. СПЕКТРАЛЬНИЙ АНАЛІЗ

Purpose. Using spectral and frequency analysis methods, to determine the indicative events characterizing a process condition on a control channel “content of useful mineral in ore – content of useful mineral in a concentrate” of ore concentrating plant with ball grinding to exclude the operator from control contour.

Methodology. Spectral and frequency analysis of control object.

Findings. The analysis of the logarithmic amplitude-frequency characteristic of an enrichment section showed that the control strategy of a section and an ore concentrating plant in general through the “content of useful mineral in ore – content of useful mineral in a concentrate” channel should be based on reaction to a parameter value deviation of saleable concentrate from the set values. The spectral analysis of useful mineral content in ore and saleable concentrate and the frequency characteristics obtained on the basis of commercial operation data allowed allocating some indicative events which characterize an enrichment process condition through the specified control channel.

Originality. It has been shown for the first time that automatic control systems for the enrichment section and concentrating factory in general through the channel described above should be constructed according to the reaction to the deviation of saleable concentrate characteristics from the set ones. The analysis of dispersion spectrum parameters of general iron content in initial ore and a concentrate and amplitude-frequency characteristics through the control channel obtained during commercial operation at an ore concentrating factory has been carried out for the first time.

Practical value. The obtained results can be used for creation of automatic system of situational management of an ore dressing process of ferrous and non-ferrous metals both at separate sections with ball crushing and at factories consisting of these sections.

Keywords: *automation, indicative events, system of situational control, spectral analysis, frequency analysis, iron ore dressing, ore concentrating factory with ball crushing*

Introduction. The estimation of ore dressing stages preceding ore feeding on entering an ore concentrating factory (OCF) shows their recurrence: ore is delivered to an entrance of a crushing factory in dump trucks with a certain frequency; the beginning and the end of ore drift in a career, which has various properties influencing concentrate production also has a certain frequency. As a result, there is a problem of the previous ore dressing stage influence on controllability of OCF through the "useful mineral content in ore – useful mineral content in the concentrate" channel.

Analysis of the recent research and publications. Modern Ukrainian and foreign researchers conduct researches in the direction of use of the indicator spectral analysis of various ore properties of ferrous and nonferrous metals at an entrance of the first enrichment stage with ball crushing to set tasks for local systems of regulation and management [1, 2]. Niceties of controlling separate devices, processes and enrichment stages are considered: the crushed ore classifications at the first crushing stage [3], magnetite declamation [4], the ore-water ratio at the exit of the first enrichment stage ball mill [5], the first enrichment stage on the basis of FUZZY system [6] and intellectual identification approaches, neuromanagement, classification management and evolutionary optimization [7], the OCF power consumption during the periods of a capacity limitation of power supply systems [8].

The correlation analysis of indicators by extraction of useful mineral from ore feed stream showed that the top management level of OCF-1 and a separate enrichment section through the "useful mineral content in ore – useful mineral content in the concentrate" channel makes the management by deviation of useful mineral content in a concentrate from a preset value possible [9].

Unsolved aspects of the problem. Earlier, conceptual and semantic models of the first stage of iron ore enrichment were developed [10] (Fig. 1).

Within the models each parameter group describes the appropriate knowledge domain participating in enrichment: "A" – ore; "B" – a ore dressing; "C" – a mill; "D" – the classifier; "E" – magnetic separation; "F" – a magnetic separator; "G" – the enriched product; "H" – the impoverished product; "I" – technological variables which can be controlled on a real-time basis. Its analysis allowed unifying an approach to production situation identification which corresponds to the set operation mode of i-stage of grinding, in the following parameters: the ore expenditure in a mill (I.1), a circulation coefficient (I.3), the ratio of solid to liquid in mill discharge (I.4), density of the qualifier discharge (I.6), the active power of the mill drive engine (I.7), the useful mineral content in the enriched product (I.10).

In our case the standard control section has three stages. Simple calculation shows that for identification of a production situation which corresponds to the set section operation mode it is necessary to use eighteen parameters at least. It leads to unacceptable increase in search space of production situations which correspond to an optimum section operation mode in the existing operating conditions.

Thus, from the point of view of situation-dependent control, the set operation mode identification according to a spectrum of the useful mineral content in a concentrate is of interest. Such information makes it possible to reduce search space for setting determination of separate enrichment sections and OCF with ball grinding which will allow minimizing specific power consumption and materials on obtaining the maximum volume of a concentrate with the given useful mineral content.

Presentation of the main research and explanation of scientific results. The frequency response defines filtra-

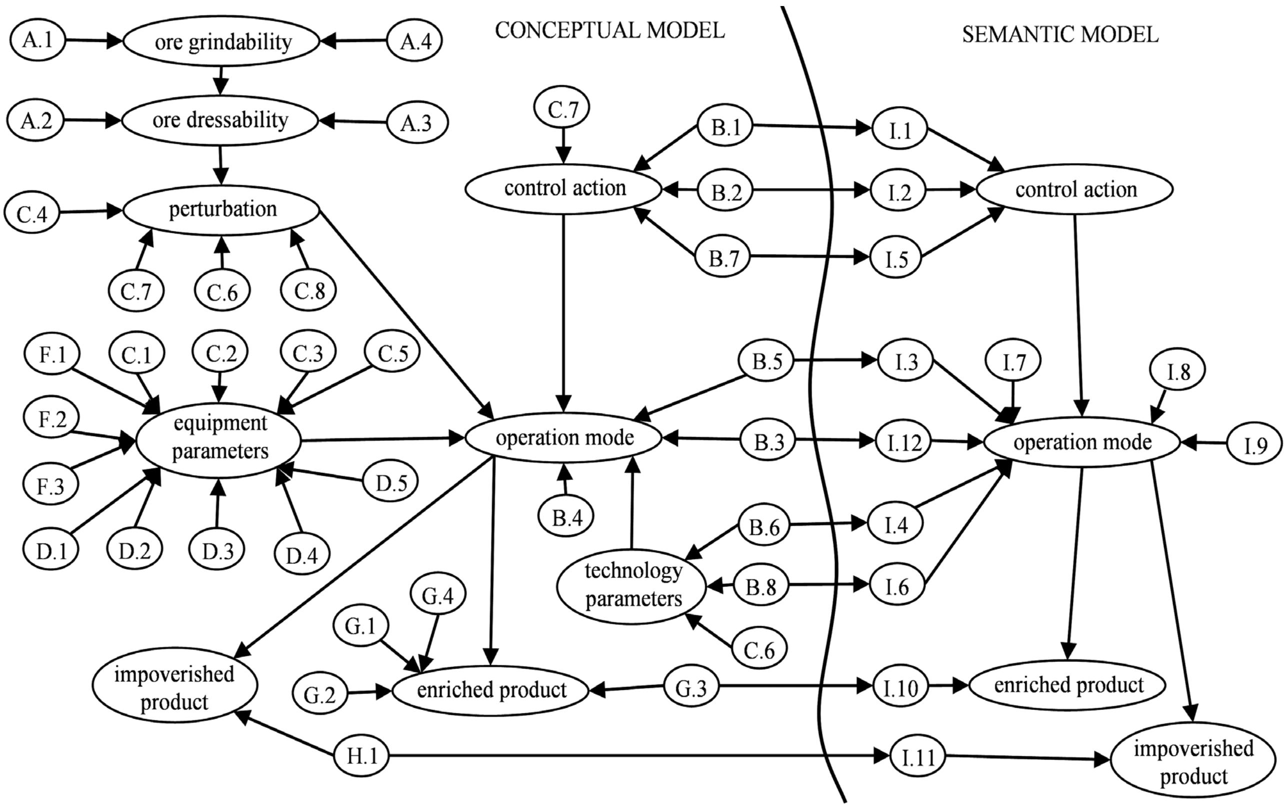


Fig. 1. Conceptual and semantic models of the first stage of iron ore enrichment

tion properties of the control object, i.e. it defines in how many times disturbance spectrums of the known frequency are extinguished while the polyharmonic process is passing through a process line. For the “the useful mineral content in ore – the useful mineral content in a concentrate” control channel the perturbing influence is the general iron content determined by natural field conditions. Remaining initial ore properties influence section productivity with the given useful mineral content in a concentrate.

To obtain an amplitude-frequency characteristic of the enrichment section, the transfer function (4) [9] transformed to the relation of two polynomials by means of the MathCAD software is given

$$W(p)=\frac{a_0+a_1\cdot p+a_2\cdot p^2+\cdots+a_{22}\cdot p^{22}}{b_0+b_1\cdot p+b_2\cdot p^2+\cdots+b_{23}\cdot p^{23}}. \quad (1)$$

Further *a* and *b* polynomial coefficients (Table) were found.

Coefficients were used for creation of the logarithmic amplitude-frequency characteristic of the OCF-1 enrichment section of Inhulets Mining and Processing Plant (InMPP) in an application program package of Matlab. Only a part of this characteristic is of interest to us on which ω_c – the frequency of a cutoff is visible (Fig. 2). The characteristic shows that $\omega_c = 0.22$ rad/hour, which corresponds to initial ore property oscillations at an enrichment section input with the period over four and a half hours ($T = 1/\omega_c = 4.54$ hours).

Table

The polynomial a and b coefficients of transfer function of enrichment section

Index	Indication	
	a	*b*
0	7.6028	12.75
1	37.079	163.53
2	59.39	900.44
3	42.356	2807.9
4	15.125	5524.8
5	2.826	7253.9
6	$2.8713\cdot10^{-1}$	6563.5
7	$1.5729\cdot10^{-2}$	4171.3
8	$4.2996\cdot10^{-4}$	1882.3
9	$4.8968\cdot10^{-6}$	606.43
10	$1.908\cdot10^{-8}$	139.83
11	$-2.1853\cdot10^{-12}$	23.114
12	$-1.8169\cdot10^{-13}$	2.7443
13	$-1.0925\cdot10^{-14}$	$2.3432\cdot10^{-1}$
14	$-4.7292\cdot10^{-16}$	$1.4378\cdot10^{-2}$
15	$-1.465\cdot10^{-17}$	$6.3199\cdot10^{-4}$
16	$-3.2277\cdot10^{-19}$	$1.9802\cdot10^{-5}$
17	$-5.0237\cdot10^{-21}$	$4.3991\cdot10^{-7}$
18	$-5.4604\cdot10^{-23}$	$6.8891\cdot10^{-9}$
19	$-4.0464\cdot10^{-25}$	$7.522\cdot10^{-11}$
20	$-1.9468\cdot10^{-27}$	$5.5933\cdot10^{-13}$
21	$-5.481\cdot10^{-30}$	$2.6981\cdot10^{-15}$
22	$-6.8552\cdot10^{-33}$	$7.6122\cdot10^{-18}$
23	0	$9.5367\cdot10^{-21}$

Regarding the control through the “the useful mineral content in ore – the useful mineral content in a concentrate” channel the logarithmic amplitude-frequency characteristic of OCF-1 enrichment section of InMPP showed that it is necessary to react to input ore property change no sooner than in four and a half hours after their fixing by monitoring means. Thus, theoretically, the control strategy of the enrichment section should be built on fixing of an essential deviation of the given saleable concentrate properties.

For more complete estimation of filtration OCF-1 properties through the “the useful mineral content in ore – the useful mineral content in a concentrate” control channel, amplitude-frequency characteristic was determined proceeding from a ratio of dispersion spectrums of an output signal – $S_Y(\omega)$ to a dispersion spectrum of an input signal – $S_X(\omega)$

$$\left|\Phi_1(j\omega)\right|=\sqrt{\frac{S_Y(\omega)}{S_X(\omega)}}, \quad (2)$$

where SX(ω) is a dispersion spectrum of general iron content in the initial ore (Fig. 3); SY(ω) is a dispersion spectrum of general iron content in the concentrate (Fig. 4).

The average value of general iron content in the concentrate and its dispersion are constant for each observation series. Therefore, spectrum analysis was carried out by means of autocorrelation functions. Since this function is the even one, before spectrum analysis it was amplified with the appropriate values which settle down to the left of ordinate axis. Thus, for the first observation series the length of implementation made 128 hours for spectrum analysis, and for the second one – 86. For both observation series sampling rate makes one hour^{-1}.

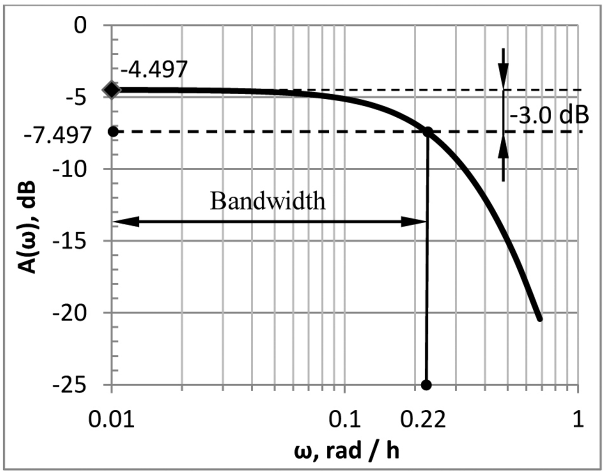
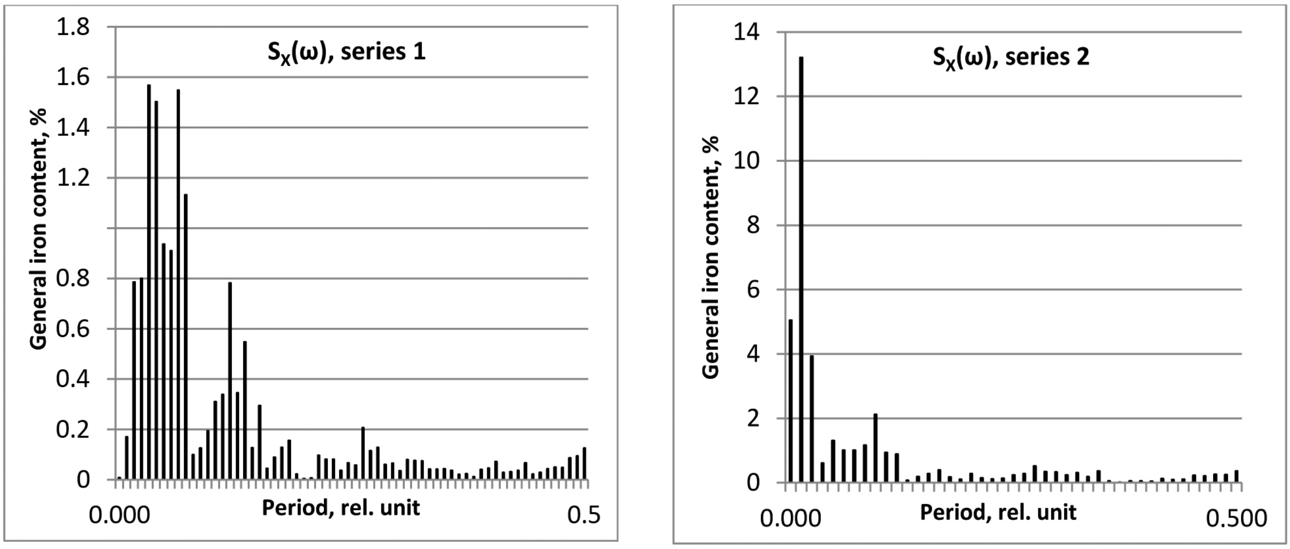
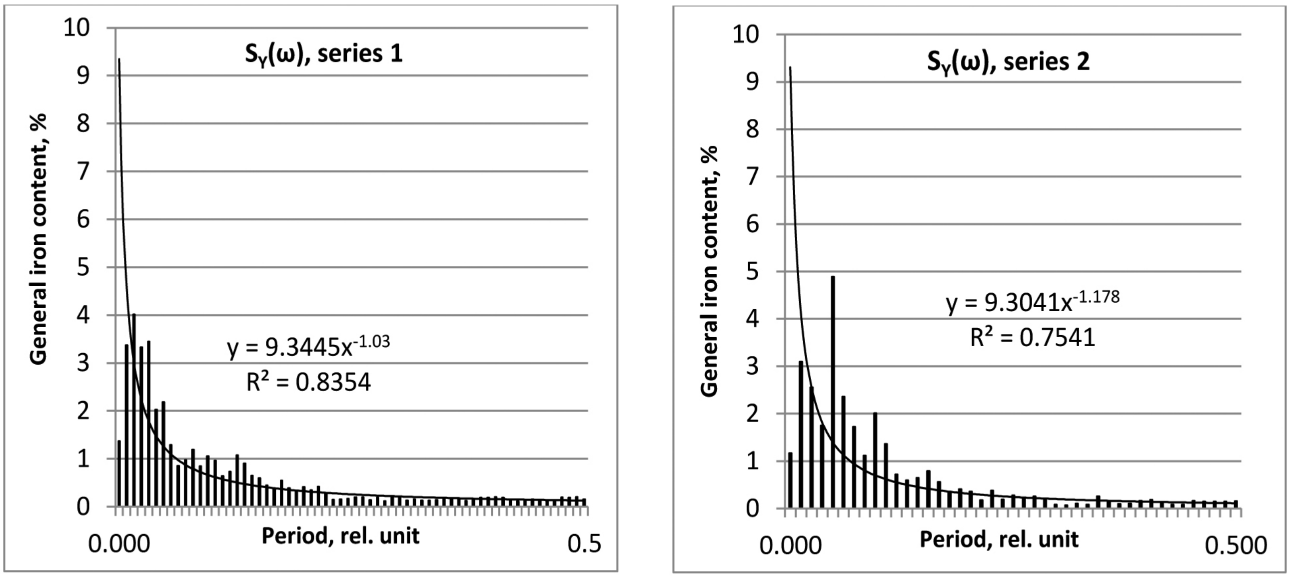


Fig. 2. The logarithmic amplitude-frequency characteristic of OCF-1 enrichment section of InMPP



a *b*

Fig. 3. The dispersion spectrum of the general iron content in the initial ore for OCF-1:
a – SX(ω), series 1; b – SX(ω), series 2



a *b*

Fig. 4. The dispersion spectrum of the general iron content in the concentrate for OCF-1:
a – SY(ω), series 1; b – SY(ω), series 2

The dispersion spectrum types (Figs. 3, 4) of the general iron content in the initial ore and a concentrate for OCF-1 show that low frequencies for all observation series have the largest amplitude. In dispersion spectrums of the general iron content in the initial ore amplitude is significantly less; however, amplitude of frequencies closed to the average spectrum is considerable. The first observation series is especially demonstrative in this sense. For dispersion spectrums of the general iron content in the concentrate, the tendency of amplitude recession from low to average frequencies under the exponential law is observed. Amplitude of a high-frequency component is present at all dispersion spectrums; however, it is close to zero.

The dispersion spectrum of the general iron content in the initial ore shows frequencies of the ore dressing operations before enrichment process after ore supply from accumulative OCF-1 bunker to the enrichment section input. Processes of the initial raw material formation in a career correspond to lower frequencies, whereas frequencies which are closer to the average ones, correspond with high probability to processes of accumulation and segregation of the initial ore while filling the OCF-1 bunker.

Comparison of dispersion spectrums of the general iron content in the initial ore and in the concentrate for both observation series shows that enrichment sections let through at the output only low frequencies corresponding to ore dressing processes at a stage of extraction and ore transportation to aggregate inputs of its crushing. At the same time amplitudes of frequencies corresponding according to our hypothesis to the processes in the OCF-1 bunker are smoothed and trended to accept values close to zero, without reaching a middle part of the spectrum.

To obtain the general spectrum of an OCF-1 output signal for each observation series on each separate frequency, the average amplitude values of output signal spectrums for each section were received. Then for each observation series using expression (2), the OCF-1 amplitude-frequency characteristic through the "the useful mineral content in ore – the useful mineral content in a concentrate" control channel proceeding from basic data features (Figs. 5, *a, b*) was obtained. The basic data features were described [9] earlier.

The amplitude-frequency characteristic of the second observation series is not similar to the amplitude-frequency characteristic of the first observation series at all and has the following features:

- the maximum amplitude of the general iron content is four times lower than the maximum amplitude value in the first observation series;
- a constant component amplitude is almost zero that means absence of influence of the initial raw material parameter;
- the maximum amplitude values belong to high frequencies.

From these observations it is possible to make a conclusion that spectrum formation of the second observation series is influenced by change of concentrating process parameters, i.e. perturbation that could arise when putting the factory into operation rather than by raw materials properties. Most likely, they are connected with the staff's actions for deduction of enrichment in a necessary status.

Conclusions and recommendations for further research.

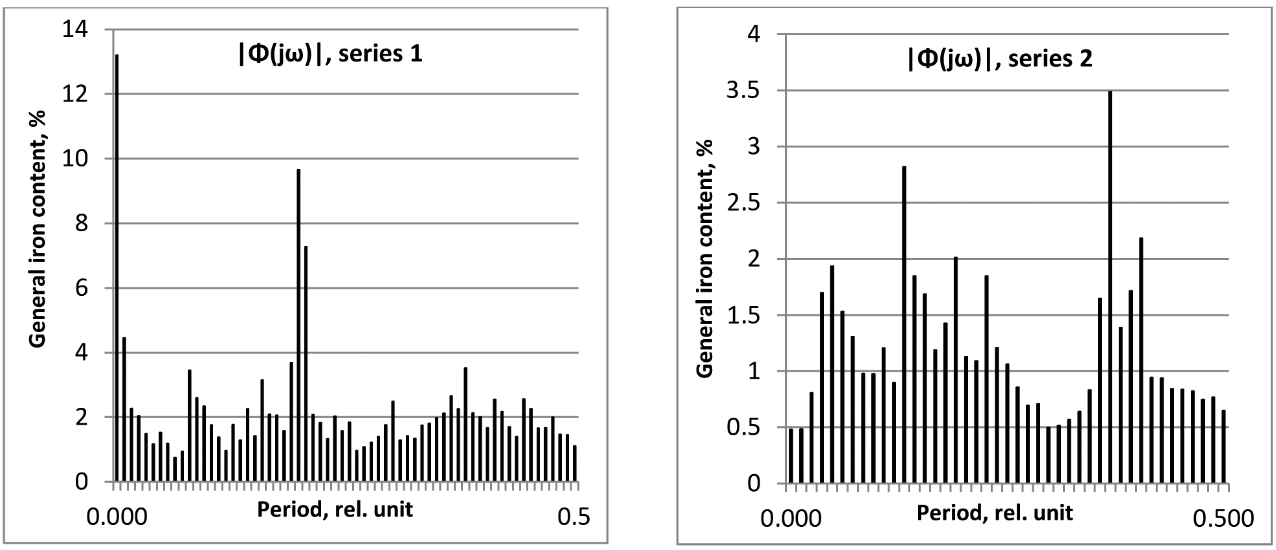
1. The analysis of decibel-log frequency characteristic of OCF-1 enrichment section of InMPP allows drawing a conclusion that, theoretically, the control strategy of the enrichment section through the "the useful mineral content in ore – the useful mineral content in a concentrate" channel should be built on fixing of an essential deviation from the given properties of a saleable concentrate.

2. Given the fact that ball grinding OCF represents the same parallel operating sections (at least 10), then the automatic factory management system in general through the "the useful mineral content in ore – the useful mineral content in a concentrate" channel should be built on fixing of the advent moments of an essential deviation of prescribed properties of the saleable concentrate.

3. The analysis of dispersion spectrums of the general iron content in the initial ore and the concentrate and OCF-1 amplitude-frequency characteristics showed that OCF-1 control opportunities through the "the useful mineral content in ore – the useful mineral content in a concentrate" channel for the purpose of maintaining the given useful mineral content in the concentrate are restricted to its content in the initial ore and weakly depend on the processes proceeding at other stages of ore dressing.

4. The amplitude-frequency characteristic of OCF-1 can be OCF-1 operation mode indicator through the "the useful mineral content in ore – the useful mineral content in a concentrate" control channel:

- a constant component exceeding more than by 2.5 times the amplitude values of all the other frequencies, except for noises, is a sign of the set factory operation mode;
- an indication of transient factory operation mode is an offset of the maximum amplitude values in a high-frequency spectrum part and insignificant amplitude difference of a high-frequency spectrum part from amplitudes of its other parts.



a *b*

Fig. 5. OCF-1 amplitude-frequency characteristics:
a – the first observation series; b – the second observation series

References.

1. Driga, V.V., 2011. A research and classification of the magnetite ore accuracy reducing factors of the continuous quality control. In: *Quality of mineral raw materials*: Col. Sc. Pap. Acad. of Mining Sciences of Ukraine, Kryvyi Rih: SAC Ukrrud-prom. – Kryvyi Rih. pp. 168–179.

2. Morozov, V.V., Shek, V.M. and Morozov, Yu.P., 2016. Enhancement of intellectual methods of management of enrichment processes on the basis of the viziometrik analysis of ore. *Mountain sciences and technologies*, 2, pp. 31–42.

3. Kondratets, V.O. and Matsui, A.M., 2016. Researches of pulp stream formation condition at sand chute an one spiral classifier. *Visnik of National Technical University "KhPI"*, 6(1178), pp. 24–30.

4. Mishchenko, V.O., Olevskyi, V.I. and Olevska, Yu.B., 2015. Mathematical models of enrichment for automated control systems for quality of magnetite declamation. *Bulletin of National Technical University "HPI": Mechanic-technology systems and complexes*, 52(1161), pp. 36–40.

5. Kondratets, V.O. and Serbul, O.M., 2010. The precision decrease of stochastic SAR pulp rarefaction in the mill with circular loading by signal filtering. *Technics in agricultural production, mechanical engineering, automation: Col. Sci. Pap. Kirovohradskyi National Technical University*, 23, pp. 78–84.

6. Azarian, A.V., 2012. The guaranteed production control of ore enrichment on the basis of Fuzzy-system. *Radio-electronic and computer system*, 6, pp. 109–113.

7. Kupin, A.I., 2009. Program-technical realization of intellectual automatic control system of technology complex. *Naukovy Visnyk Chernivetskogo Universitetu: Zbirnyk Naukovyh Prats. Computer systems and components*, 446, pp. 84–93.

8. Horolskyi, V.P., Horolskyi, D.V. and Titorenko, K.G., 2015. Multilevel intellectual optimization system of mining and processing plan power consumption. *Herald of Khmelnytskyi national university. Engineering*, 2, pp. 192–198.

9. Mladetskyi, I.K., Kuvaiev, Ya.H. and Priadko, N.S., 2017. Control regularities of the useful mineral extraction from ore feed stream with ball grinding. Correlation analysis. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 4, pp. 91–98.

10. Kuvaiev, I.A., Mladetskyi, I. and Oriol, M., 2016. Promising approach to the identification and classification of steady-state operation of an iron-ore dressing section. In: *Power Engineering and Information Technologies in Technical Objects Control*, Annual publication. Leiden: CRC Press/Balkema. pp. 67–73.

Мета. Для виключення оператора з контуру керування методами спектрального й частотного аналізу визначити індикативні події, що характеризують стан процесу по каналу „вміст корисного мінералу в руді – вміст корисного мінералу в концентраті“ рудо-збагачувальною фабрикою з кульовим подрібненням.

Методика. Спектральний і частотний аналіз об'єкта управління.

Результати. Аналіз логарифмічної амплітудно-частотної характеристики секції збагачення показав, що стратегія керування секцією й рудозбагачувальною фабрикою в цілому по каналу „вміст корисного мінералу в руді – вміст корисного мінералу в концентраті“ повинна будуватися по реакції на відхилення значень параметрів товарного концентрату від заданих. Спектральний аналіз вмісту корисного мінералу в руді й товарному концентраті та частотні характеристики, що отримані на основі даних промислової експлуатації, дозволили визначити ряд індикативних подій, які характеризують стан процесу збагачення по вказаному каналу керування.

Наукова новизна. Уперше показано, що системи автоматичного керування секцією збагачення та збагачувальною фабрикою в цілому по вищевказаному каналу повинні будуватися по реакції на відхилення характеристик товарного концентрату від заданих. Уперше виконано аналіз параметрів спектрів дисперсій вмісту загального заліза у вихідній руді й концентраті та амплітудно-частотних характеристик по каналу керування, отриманих у процесі промислової експлуатації рудо-збагачувальної фабрики.

Практична значимість. Отримані результати можуть бути використані для побудови автоматичної системи ситуаційного керування процесом збагачення руд чорних і кольорових металів як на окремих секціях з кульовим подрібненням, так і на фабриках, до складу яких ці секції входять.

Ключові слова: *автоматизація, індикативні події, система ситуаційного управління, спектральний аналіз, частотний аналіз, збагачення залізної руди, рудо-збагачувальна фабрика з кульовим подрібненням*

Цель. Для исключения оператора из контура управления методом спектрального и частотного анализа определить индикативные события, характеризующие состояние процесса по каналу „содержание полезного минерала в руде – содержание полезного минерала в концентрате“ рудо-обогатительной фабрикой с шаровым измельчением.

Методика. Спектральный и частотный анализ объекта управления.

Результаты. Анализ логарифмической амплитудно-частотной характеристики секции обогащения показал, что стратегия управления секцией и рудообогатительной фабрикой в целом по каналу „содержание полезного минерала в руде – содержание полезного минерала в концентрате“ должна строиться по реакции на отклонение значений параметров товарного концентрата от заданных. Спектральный анализ содержания полезного минерала в руде и товарном концентрате и частотные характеристики, полученные на основе данных промышленной эксплуатации, позволили выделить ряд индикативных событий, которые характеризуют состояние процесса обогащения по указанному каналу управления.

Научная новизна. Впервые показано, что системы автоматического управления секцией обогащения и обогатительной фабрикой в целом по вышеуказанному каналу должны строиться по реакции на отклонение характеристик товарного концентрата от заданных. Впервые выполнен анализ параметров спектров дисперсий содержания общего железа в исходной руде и концентрате и амплитудно-частотных характеристик по каналу управления, полученных в процессе промышленной эксплуатации рудо-обогатительной фабрики.

Практическая значимость. Полученные результаты могут быть использованы для построения автоматической системы ситуационного управления процессом обогащения руд чёрных и цветных металлов как на отдельных секциях с шаровым измельчением, так и на фабриках, в состав которых эти секции входят.

Ключевые слова: *автоматизация, индикативные события, система ситуационного управления, спектральный анализ, частотный анализ, обогащение железной руды, рудо-обогатительная фабрика с шаровым измельчением*

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ANALYTICAL SOLUTION OF THE DIRICHLET GENERALIZED BOUNDARY PROBLEM OF HEAT-EXCHANGE IN THE FINITE CYLINDER WITH HOMOGENEOUS LAYERS

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АНАЛІТИЧНИЙ РОЗВ’ЯЗОК УЗАГАЛЬНЕНОЇ КРАЙОВОЇ ЗАДАЧІ ДІРІХЛЕ ТЕПЛООБМІНУ ДВОСКЛАДОВОГО СКІНЧЕННОГО ЦИЛІНДРА

Purpose. To develop a new generalized 3D mathematic model for calculating temperature fields in the solid finite cylinder with homogeneous layers in the form of the mathematical physics boundary problem for hyperbolic equations by the Dirichlet conditions (temperature on the cylinder surface is a continuous function of the coordinate axis), and to solve the obtained boundary problem.

Methodology. Use of the known Laplace and Fourier integral transformations and application of the new integral transformation to the space with homogeneous layers.

Findings. A nonstationary temperature field in the rotating double-layer solid finite cylinder in the cylindrical coordinate system with taking into account finite velocity of the heat conduction was defined. Heat-transfer properties of the cylinder in either layer are constant at an ideal heat contact between the layers while no internal sources of the heat are available. At the initial moment of time, the cylinder temperature is constant, and temperature on the outside surface of the cylinder is known.

Originality. It is the first a mathematical 3D model for calculating temperature fields in the rotating double-layer solid finite cylinder has been created in the form of the physicomathematical boundary problem for the heat conduction hyperbolic equations by the Dirichlet conditions and with taking into account finite velocity of the heat conduction. A new integral transformation was created for the space with homogeneous layers, with the help of which it became possible to present a temperature field in the finite cylinder with homogeneous layers in the form of convergence orthogonal series by Bessel and Fourier functions.

Practical value. The obtained analytical solution of the generalized boundary problem of heat exchange in the rotating double-layer cylinder, which takes into account the known time period of the heat-conduction relaxation, can be used for detecting temperature fields, which occur in different technical systems (forming rolls, satellites, turbines, etc.).

Keywords: *Dirichlet boundary value problem, integral transformation, relaxation time, double-layer finite cylinder*

Introduction. Analysis of the recent research and publications. In the world, an essential part of the melt metal is subject to further processing in the rolling-mill shops [1]. Engineering-and-economic performance of the mill greatly depends on the roller life. Interdependence between the static and dynamic profiling methods cannot ensure proper control of the section without proper regulation of the roller heat state. The key task of