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# AUTOMATIC CONTROL OF JET GRINDING ON THE BASIS OF ACOUSTIC MONITORING OF MILL OPERATING ZONES

**Purpose.** Increasing the jet mill productivity by use of automatic control of the grinding chamber filling level based on the acoustic monitoring results of the jet grinding process.

**Methodology.** Simulation is performed in MATLAB. Acoustic signals of the mill operating zones are used to determine the grinding process parameters.

**Findings.** A simulation model of the automatic jet mill control system is created, which takes into account the inertia of material flows in the grinding chamber and classifier, as well as the main disturbing influences on the process of forming the mill output flow. To analyze the control process, there are three main parts – the information component (regulator and technical means of automation), a set of mathematical models that describe the physical processes in the grinding chamber and in the classifier. A study on the automatic control process of the grinding chamber filling is made under the condition of determining the controlled value indirectly through spectral analysis of the acoustic signal in the mill. The insignificant influence of perturbations on the controlled quantity due to very slow filling of the chamber with material in comparison with the period of stream fluctuations at a chamber entrance owing to perturbation action is shown.

**Originality.** For the first time the possibility has been proved of using a relay regulator in control of the grinding chamber filling, determined indirectly through spectral analysis of the acoustic signal in a jet mill. The efficiency of the mill operation at automatic control of the grinding chamber filling according to the relay law is investigated.

**Practical value.** It is shown that with the transition from automated to automatic control of the grinding chamber filling, the mill productivity increases by 10–15 %. The obtained results are used to build a system of automatic jet mill control.

**Keywords:** *modeling, automation, automatic control system, jet grinding*

**Introduction.** Dry fine and ultrafine grinding mills, in particular jet plants, have high energy consumption, which constrains their widespread use. In production conditions in the grinding process the operating technological parameters change: energy pressure, the number of revolutions of the rotor of the classifier, discharge pressure on the fan, the size of the finished product, which depend on minor deviations of technological parameters and type of raw material. Changing these parameters sometimes leads to a violation of the technological process [1]. To increase the efficiency of grinding plants, it is important to develop a system of current control and the grinding process control at all.

**Literature review.** In recent years, many fine grinding control systems have been developed. The largest problems for researchers are the high inertia of the grinding process and the delay. This negatively affects the control of deviation and regulation when changing the parameters of the feedstock in the mill that works with a separator (classifier) [1]. Systems with compensation for changes in the properties of the primary material are difficult to implement in practice due to the lack of sensors to control the properties of the material on the feed.

It should be taken into consideration that the finished product (grinding product) is a product with a given particle size distribution, which determines the value of the specific side surface of the dispersed material. If the distribution function of the dispersed material by size is known $\varphi(x)$, then the specific surface area is $s=\int_0^{\infty}\frac{k_s}{x}\varphi(x)dx$. According to the Rittinger hypothesis, the productivity of the mill on the newly obtained surface is a constant value $Qs$ = const, whence the mill productivity with a given particle size distribution is $Q=\frac{\text{const}}{s}$, because it is characterized by a distribution function $\varphi(x)$ and energy voltage, which is determined by the constant of the mill. If the mill is in a closed loop with the classifier, it is necessary to take into account its separation characteristics $E(x)$ [2].

Mill performance stabilization systems are the easiest to implement if the quality of the grinding product is constant. The productivity of the mill can be controlled and fairly accurately measured by conveyor scales, which is used to stabilize the supply of material to the mill, but without monitoring. In this case, the delay in the implementation of the control command is very significant.

The following approaches and methods are used in the development of automatic control systems for grinding processes [3]:

- use of the regression static equations in control. Control systems with regression statistical dependencies use the dependencies that are obtained during training based on the results of the experiment. The maximum value of the efficiency of the mill is achieved if the effects take statistically average values, which in practice is not always confirmed;

- search systems with direct measurement of the characteristics of ready products. In these systems with direct measurement of the ready product characteristics, the control object (mill) is a kind of "black box", and the search for the optimum is conducted in a quasi-static mode continuously;

- adaptive systems based on structural models of the control object with parametric identification in the control process [4]. The creation of such systems based on the structural model of the control object with the implementation of parametric identification of this model in the control process is possible in connection with the development of modern computers. This approach is based on the control of state variables of the control object, and is very promising for improving the control quality of the grinding process. However, the disadvantage of existing adaptive systems is the use of linear models to predict nonlinear grinding processes, as well as not optimal control;

- extreme control systems for average engine power used and mill noise. The control effect is the flow of source material into the mill. In industry, such systems are not widely used, because the maximum productivity of the ready product does not correspond to the operating extreme point [5];

- adjusting the degree of internal mill filling. In this case, the automation of grinding uses parameters that reflect the energy efficiency of the destruction process, such as the degree of filling of the chamber, average power, and so on. This simplifies the control of the mill, as the inertia of the channel "degree of filling" is much less than "productivity" [5]. However, effective control requires a close connection between the state variables taken into account and the product quality indicator. Unaccounted factors, as well as changes in the characteristics of the object in the operation process, which is difficult to predict, lead to the fact that the range of filling the mill is chosen wide.

The random nature of changes in the size of the material and its physical and mechanical properties, as well as changes in energy parameters and mill characteristics do not allow using the control system of the grinding process with rigid (calculated) optimization of the accepted quality criterion [6]. In the works by Gorobets V. I. [3] it is proposed to regulate the process of gas-jet grinding under the influence of various perturbations on it using a system with two extreme regulators that maintain maximum productivity and optimal material concentration in the flow, or with process features with one indicator of extremum. But it is necessary to take into account the relative proximity of the optimal grinding mode to the limit of stable mill operation, the transition through which can cause an emergency. Therefore, a small offset is introduced into the control law, which already causes deviations from the maximum productivity. Moreover, the control is carried out by the amount of pressure loss along the path of the mill, which increases the inertia of the control system.

In [7], a method aimed at expanding functionality, increasing efficiency and improving the optimization of the process of grinding materials is proposed. This result is obtained due to the fact that the mill provides control of the amount of material loading and the flow rate of the transport medium while optimizing at least one controlled parameter. As such a parameter the specific power consumption for grinding the material is determined, while the productivity of the mill for a given class of crushed material is determined as an additional controlled optimization parameter. In order to optimize the controlled parameters and achieve maximum productivity with minimum energy consumption, they periodically measure the crushed material during operation, control the overload of the mill unit and set the corresponding maximum load value of the mill, while at each time the transport medium is served into the unit, the amount of which is calculated quantitatively. With this approach, there is no main criterion for optimization, so this can lead to a situation in which perturbations superimposed on each other cause a malfunction of the unit.

In recent years, the control of fine grinding has often been performed using several optimization circuits [8]: the optimization circuit of the mill for clinker grinding, the control circuit of sulfur dioxide in cement, the control circuit of the specific surface of cement, the control circuit of thinness cement grinding. But in this case it is necessary to take into account different delay times in each circuit, different input and output factors and their ratios, which is quite difficult to regulate.

In ITM NASU and SSAU the method of the analysis of jet grinding characteristics on acoustic signals of mill operating zones is created [1]. On this basis, a control system for the grinding process is developed.

**The purpose** of the work is to increase the productivity of the jet mill due to the transition to automatic control of the filling level of the grinding chamber based on the results of acoustic monitoring of the jet grinding process.

**Methods.** As a tool for studying the grinding process control in a jet mill, the simulation model of the automatic control system created in [9] is used. In this model there are three main parts – the information component (regulator and technical means of automation), a set of mathematical models that describe the physical processes in the grinding chamber and a set of mathematical models that describe the physical processes in the classifier. In this case, the last two parts of the control system model are actually the object of control.

The peculiarity of the simulation model of the automatic grinding control system in the jet mill is that the analytical dependences between its parameters, which are real physical quantities, are obtained by statistical processing of experimental results on a laboratory mill for physical modeling of processes occurring in the mill. The adequacy of the model is confirmed by testing the results of research conducted on the model in relation to real jet mills [1].

Thus, the research is carried out using computer simulations of different operation modes of the jet mill in order to substantiate the control law of the grinding chamber filling and determine its parameters that ensure maximum productivity of the mill without coming to blockage.

**Results.** The regularity of the change in the time of the grinding chamber filling is determined, on the one hand, by its own dynamic properties of the jet mill, and on the other – by the nature of the perturbations. With this in mind, we substantiate the perturbations that affect the controlled value.

There are two main perturbations on the output stream of the classifier [9]. The first disturbance is due to the peculiarity of the technological process and operates in a narrow frequency range of 0.4–0.6 Hz. Its amplitude has both a random component and a deterministic one, which nonlinearly depends on the input stream of the classifier [1]. Therefore, a simulator of the corresponding signal is added to the simulation model of the jet mill control system used as a research tool [9].

The second disturbing effect on the output stream of the classifier occurs due to the periodic change in the impeller speed under the condition of automatic control of the material size. In fact, this disturbing effect is formed by the system of automatic control of the size of the material, and it is a function of both the speed of rotation of the impeller shaft and the input flow of the classifier [1]

$$\Delta Q_{cl}(t) = 0.0021 \cdot n_{imp}^2(t) - 0.0085 \cdot n_{imp}(t) - \\ - 0.00057 \cdot n_{imp}(t) \cdot (Q_2(t) - Q_c(t)),$$

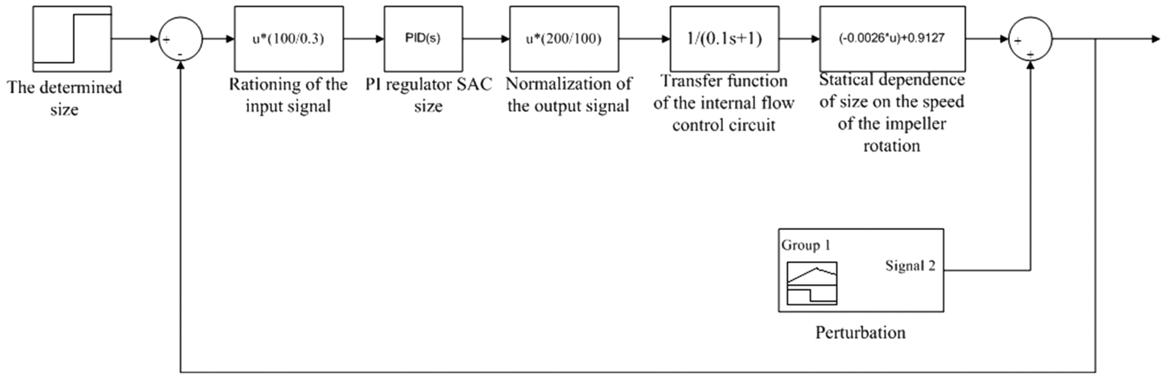


*Fig. 1. Scheme of the simulation model of the automatic material size control system*

where $n_{imp}$ is the speed of the output shaft of the impeller drive, $s^{-1}$.

To simulate this disturbing effect, a simulation model of the automatic material size control system was created (Fig. 1).

The simulation model of the automatic material size control system takes into account the dynamic properties of the motor and gear drive of the impeller. The synthesis of the internal circuit of the current control system is performed with the adjustment of the controller to the technical optimum, and the external circuit of the speed control – to the symmetrical optimum [9].

A perturbing effect ("Perturbation" block) is also added in the model of the automatic material size control system in Fig. 1. It simulates the change in material size due to changes in its properties [9], in the form of a signal that changes stepwise in time with a random period and amplitude.

Another feature of the control object that must be taken into account when synthesizing the jet mill control system is that the filling of the grinding chamber is currently impossible to measure directly.

However, the indirect method proposed in [1] can be used for determining this value through spectral analysis of the acoustic signal in the mill. This method requires the information accumulation in the form of a sliding sample from the values of the acoustic signal of a certain length. In addition, the information about the fullness of the camera is averaged over a period of time. Thus, there is inertia to obtain information about the filling of the grinding chamber.

Therefore, the law of automatic control of the grinding chamber filling must be effective for the presence in the feedback channel of this value of the time delay, which is determined by the time of information accumulation for spectral analysis of the acoustic signal in the mill. To test this condition, a simulation of a given time delay is introduced into the control system model.

In order to substantiate the control law of the grinding chamber filling of the jet mill, we analyze the dynamic properties of the mill as a control object. For this purpose we will carry out modeling of its work on condition of giving of a pulse control signal without input of feedback (Fig. 2).

Fig. 2 confirms that due to the slow filling of the grinding chamber, the dynamic properties of the control object are determined by the integrating component – the controlled quantity reacts quickly to changes in the control effect, but changes much more slowly over time than the control effect. For objects with such dynamic properties, it is sufficient to apply the relay control law to keep the controlled value in a rather narrow range of values.

Also, with the help of computational experiments based on a simulation model of the mill control system, the influence of perturbations on the controlled value was investigated (Fig. 3).

The normalized standard deviation between the graphs in Fig. 3 is 97.14 % provided that this indicator is equal to 100 % with complete coincidence of graphs. Therefore, the simulation results in Fig. 3 confirm the insignificant effect of perturbations on the controlled value due to the very slow filling of the chamber with material compared to the period of fluctuations of the flow at the inlet to the chamber due to the action of perturbations. This is another reason for the feasibility of using the relay control law of the filling chamber of the grinding mill.

On the basis of the simulation model of the filling system of the jet mill grinding chamber, a study on the efficiency of the relay controller is conducted with a dead zone of ± 2 % of the set level (Fig. 4). This takes into account the presence of a time delay in the feedback on the controlled value.

The results of modeling the control system in Fig. 4 confirm the efficiency of using a relay controller for automatic

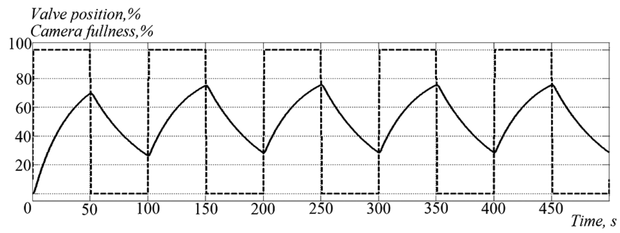


*Fig. 2. Time change in the valve position at the outlet of the mill hopper (dotted line) and the filling of the grinding chamber (solid line) with open control method*

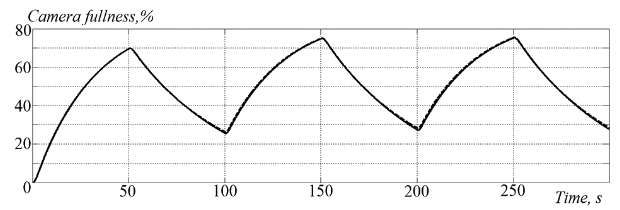


*Fig. 3. Change in time of filling of the grinding chamber in the absence (dashed line) and the presence (solid line) of the impact of perturbations on the open control system of the mill*

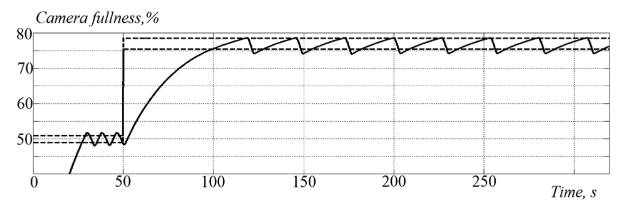


*Fig. 4. Change in time of the grinding chamber filling under the operation condition of the automatic control system using the relay regulator*

control of the grinding chamber filling in conjunction with the indirect method for determining the filling through spectral analysis of the acoustic signal in the mill. Beyond the upper limit of the control range, the relative error is only 0.1 %. Beyond the lower limit of the control range, the relative error is greater and is equal to 1.6 %, which leads to a small relative error of the control system of a given level of the grinding chamber filling 0.56 % in the direction of decrease (Fig. 4).

To substantiate the parameters of the relay control law of the grinding chamber filling, the static characteristics of the classifier of the jet mill as a control object was considered (Fig. 5).

On the static characteristic of the mill it is possible to allocate a site of desirable values of its productivity (between points *A* and *B* in Fig. 5). In this case, due to the peculiarities of the jet mill, it is impossible to ensure its operation with the maximum value of productivity (point *B*), because there is a high risk of blockage. Thus, remembering that after point *A* the productivity of the mill hardly changes and considering the requirement to provide a significant margin for the inflow to prevent blockage (significant distance from point *B*), the actual filling of the grinding chamber should be such that operation of the mill corresponds to point *A* in Fig. 5. However, if the relay control law is used, the actual filling of the grinding chamber will vary within a certain range, as the average input and output flows of the mill classifier will. Under this condition, it is advisable to take the lower limit of this range, which would correspond to point *A* in Fig. 5. Accordingly, the width of this range characterizes the degree of approach to point *B* in Fig. 5, and is determined by the dead zone of the relay regulator. In addition, at point *A* in Fig. 5, the average output flow and, accordingly, the mill productivity depend on the insensitivity zone of the relay controller because of the significant nonlinearity of the static characteristic in this area.

Therefore, we study the dependence of the input flow oscillation amplitude of the mill classifier, as well as its average output flow from the insensitivity zone width of the relay regulator, provided that the filling level of the grinding chamber corresponds to point *A* in Fig. 5.

Modeling of the control system at different settings of the relay controller showed that the oscillation amplitude of the mill classifier input flow almost directly proportionally depends on the insensitivity zone value of the controller (linear regression coefficient is 0.998, Fig. 6, *a*). Thus, under the requirement to ensure a significant distance from point *B* in Fig. 5 (the point corresponds to the mode of mill blockage) and with fluctuations in the classifier input flow, the dead zone of the relay regulator should be as small as possible.

However, it should be noted that the period of the discrete control influence change and, accordingly, the period of the grinding chamber filling oscillation and flows in the mill also depend on the insensitivity zone – the smaller the insensitivity zone is, the higher the frequency of these oscillations is. This is an important fact because of the control unit actuator service life depends on its switching frequency. From Fig. 6 it is seen that even with sufficiently large values of the insensitivity zone of the relay regulator, there are relatively small fluctuation amplitudes of the classifier input stream in terms of providing a significant margin to point *B* in Fig. 5. For example, at an insensitivity zone of 5 % we have the oscillation amplitude of the input classifier flow of 80 kg/h, i. e. this is the value that deviates from point *A* towards point *B* in Fig. 5. Thus, we have a fairly significant margin for the classifier input flow in terms of preventing mill blockage at the level of 1250 – 1080 = 170 kg/h (Fig. 5).

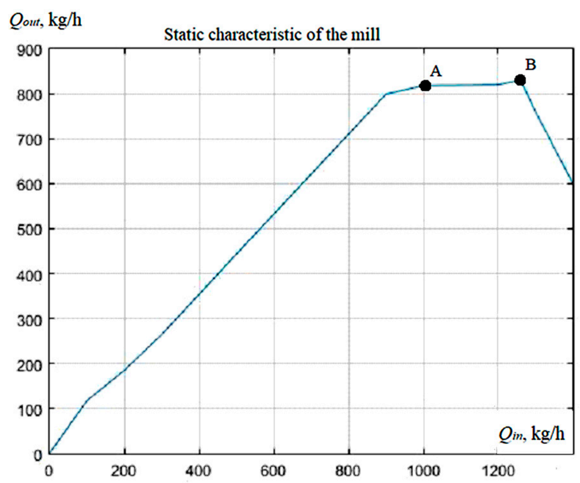


*Fig. 5. Static dependence of the output flow of the jet mill classifier on the input*

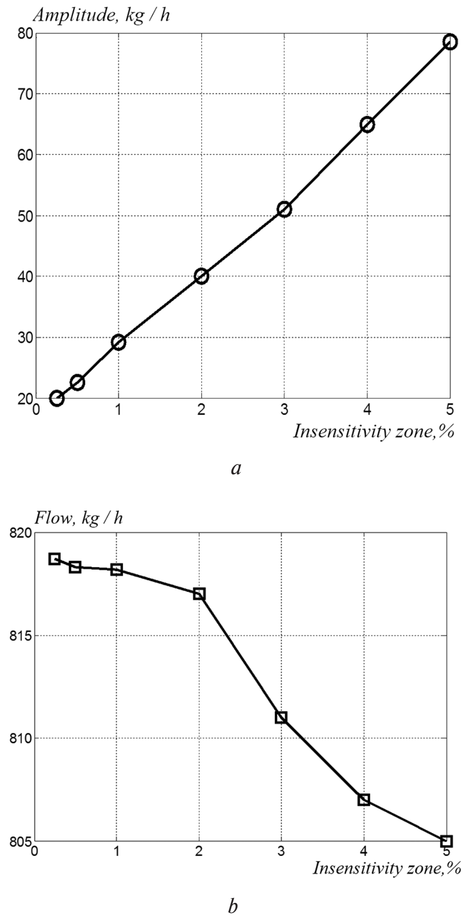


*Fig. 6. Dependence of the oscillation amplitude of the input flow (a) and the average output flow (b) of the mill classifier on the dead zone of the filling chamber relay regulator*

Therefore, it can be concluded that for providing the required margin for the input flow of the mill classifier, any value of the dead zone of the filling chamber relay regulator in the range of values from 0.5 to 5 % is acceptable. However, in terms of preventing a significant switching frequency of the control system actuator, the dead zone of the regulator should be as large as possible.

Analyzing the dependence obtained during the simulation of the control system in Fig. 6, *b*), we pay attention to its nonlinearity, as well as the inverse nature.

Thus, increasing the insensitivity relay regulator zone of the filling grinding chamber leads to a decrease in the average output classifier flow and, accordingly, the mill productivity. However, in Fig. 6, *b*, we can distinguish two areas where the dependence of the average output flow of the mill classifier on the insensitivity zone of the relay regulator is significantly different. For the values of the insensitivity regulator zone from 0.5 to 2 %, the average output flow of the classifier hardly changes

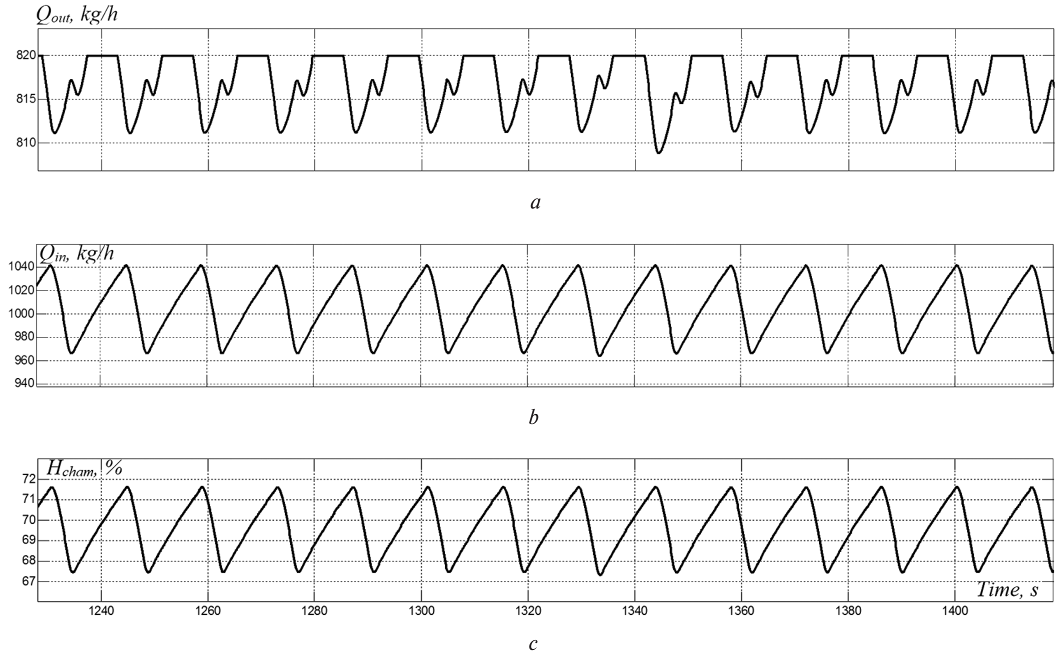


*Fig. 7. Change in time of the output (a) and input (b) flows of the classifier and the filling of the grinding chamber (c) of the jet mill with automatic control of the grinding process using a relay controller with a dead zone of 2 %*

(decreases only by 0.2 %), while after the value of 2 % it begins to decrease rapidly according to the linear law. Therefore, for preventing a decrease in the mill productivity, any dead zone value of the relay regulator of the grinding chamber filling in the range from 0.5 to 2 % is acceptable. However, as the period of actuator switching, which determines the cyclic of flow change inside the mill, changes in direct proportion to the insensitivity zone of the regulator, in the specified range of the insensitivity zone it is advisable to choose the right limit as 2 %. Then the switching actuator period will be equal to 14.5 s (Fig. 7).

Thus, the results of the research can be concluded that 2 % insensitivity zone of relay regulator satisfies all three criteria that characterize the efficiency of the automatic control system of the mill grinding chamber (average productivity, margin of the classifier input flow to prevent mill blockage and the period of actuator switching)

So, for the relay regulator with an insensitivity zone ± 2 % of the set level, the research of operation efficiency of automatic control system of the grinding chamber filling is carried out (Fig. 7).

The analysis of the results in Fig. 7 confirms the efficiency of the control system and, accordingly, the correctness of the justification and determination of the law of the filling control of the mill grinding chamber. From Figs. 7, *a, b*) it is seen that the input and output classifier streams change over time cyclically with a period of 14.5 s. The change range of the classifier output flow is from 811 to 820 kg/h, and the output – from 967 to 1040 kg/h. The average value of the output flow is 817 kg/h, which is only 0.3 % less than the maximum value, and the average value of the classifier input flow is 1007 kg/h. At the same time there is a considerable distance between the maximum value of an entrance stream of 1040 kg/h and its critical value of 1250 kg/h at the excess of which there is a mode of mill blockage.

Regarding the controlled value of the control system, it also changes cyclically over time with a period of 14.5 s in a fairly narrow range of values between 67.5 to 71.7 % (Fig. 7, *c*).

Thus, the possibility of using a relay controller for automatic control of the jet mill is proved in combination with the proposed method of indirect determination of the grinding chamber filling through spectral analysis of the acoustic signal in the mill. Automatic control of the filling of the mill grinding chamber allows, in contrast to the operator control, to get closer to the critical value of the classifier input flow at the beginning of the blockage, thus increasing the mill productivity to 10 %.

**Conclusions.** Studies on the jet mill as an object of automatic control under the control of the grinding chamber filling showed that the filling rate of the chamber is significantly less than the rate of flow in the mill, so the dynamic properties of the control object are determined by the integrating component. But it changes over time much more slowly than the control effect. In addition, for this reason, the controlled value is hardly affected by perturbations. According to this, the relay law of controlling of the grinding chamber filling is chosen.

It is established that all three criteria that characterize the efficiency of the automatic control system of the mill grinding chamber (average productivity, margin relative to the input flow of the classifier to prevent mill blockage and the period of the actuator switching) are satisfied by the insensitivity zone of the relay regulator of 2 %.

Studies have shown that the combined use of a relay controller with an insensitivity zone of ±2 % and of an indirect method of its determination through spectral analysis of the acoustic signal in the mill allows keeping the grinding chamber filling, as well as input and output classifier flows in a narrow range ±3.5 %. The cyclic change in time of these parameters is 14–15 s. This makes it possible to increase the filling level of the grinding chamber, and thus increase the output flow of the jet mill to 10 % without approaching the critical value of the classifier input flow at the mill blockage beginning

The control method proposed in the work is a theoretical basis for solving an important scientific and applied problem of the jet mill control process automation.

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## Автоматичне керування струминним подрібненням на основі акустичного моніторингу робочих зон млина

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**Мета.** Збільшення продуктивності струминного млина за рахунок переходу до автоматичного керування рівнем наповненості камери здрібнення на базі результатів акустичного моніторингу процесу подрібнення.

**Методика.** Моделювання виконано у програмі MATLAB. Для визначення параметрів процесу подрібнення використовуються акустичні сигнали робочих зон млина.

**Результати.** Створена імітаційна модель системи автоматичного керування струминним млином, в якій ураховані інерційності потоків матеріалу в камері здрібнення та класифікаторі, а також основні збурюючі впливи на процес формування вихідного потоку млина. Для аналізу процесу керування виділені три основні частини – інформаційна складова (регулятор і технічні засоби автоматизації), сукупність математичних моделей, що описують фізичні процеси в камері здрібнення та у класифікаторі. Проведено дослідження процесу автоматичного керування наповненістю камери здрібнення за умови визначення керованої величини непрямим шляхом через спектральний аналіз акустичного сигналу у млині. Показано незначний вплив збурень на керовану величину через дуже повільне наповнення камери матеріалом у порівнянні з періодом коливань потоку на вході до камери внаслідок дії збурень.

**Наукова новизна.** Уперше доведена можливість використання релейного регулятора при керуванні наповненістю камери здрібнення за умови її визначення непрямим шляхом через спектральний аналіз акустичного сигналу у струминному млині. Досліджена ефективність роботи млина при автоматичному керуванні наповненістю камери здрібнення за релейним законом.

**Практична значимість.** Показано, що за умови переходу від автоматизованого до автоматичного керування наповненістю камери здрібнення продуктивність млина збільшується на 10–15 %. Отримані результати використовуються для побудови системи автоматичного керування струминним млином.

**Ключові слова:** *моделювання, автоматизація, система автоматичного керування, струминне подрібнення*

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