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I. V. Novytskyi,
orcid.org/0000-0002-8780-6589,
Y. O. Shevchenko[*]**,**
orcid.org/0000-0002-3895-3937

Dnipro University of Technology, Dnipro, Ukraine
[*] Corresponding author e-mail: shevchenko.yu.o@nmu.one

JUSTIFICATION OF THE CRITERION FOR OPTIMAL CONTROL OF THE SELF-GRINDING PROCESS OF ORES IN DRUM MILLS

Purpose. Justification of the criterion for automatic optimization of the ore grinding process in self-grinding drum mills by compiling and researching mathematical models of material movement inside the drum of a rotating mill.

Methodology. Methods of mathematical modeling of the internal mechanics of drum mills in combination with experimental studies of the spectral density of the variable component of the active power consumed by the drive motor of the mills are used.

Findings. As a result of the simulation, it was established that the loose material placed on the inner surface of the rotating drum undergoes periodic oscillations under certain conditions. The parameters of these oscillations depend on the radius of the drum, the amount of material and the coefficient of friction. It is theoretically justified that in the case of load fluctuations, the work of friction forces and, therefore, the process of material destruction intensifies. The theoretically obtained conclusions are confirmed by the results of experimental studies of the active power signal spectrum of the drive motor of the mills in the characteristic low-frequency range. It is found that the most intense fluctuations occur at a certain degree of filling of the drum of the mill in the working range of fillings and their intensity correlates with the productivity of the mill according to the newly created finished class.

Originality. The mechanism of occurrence of fluctuations in the ore load of drum mills is revealed and the connection of this phenomenon with indicators of the technological efficiency of the grinding process is substantiated.

Practical value. It is advisable to use the intensity of fluctuations of the ore load as a criterion for automatic control of mill loading, since this parameter characterizes the technological efficiency of the mill and can be measured quickly. Using the intensity of ore loading fluctuations as a control criterion allows implementing a search system for extreme control of mill loading.

Keywords: *performance, drum mill, oscillations, ore load, self-crushing, optimization, mathematical model*

Introduction. Optimization of the technological process is always carried out in the sense of a certain criterion. The effect obtained as a result of management optimization mainly depends on how well the criterion is chosen [1]. To assess the efficiency of production, it is most appropriate to use economic criteria, such as the cost of production, the amount of profit per unit of time, the profitability of production. The values of economic criteria are determined by the listed technological indicators of this production and external factors, such as the prices of raw materials, energy, and finished products. In order to carry out automatic control directly according to economic criteria, it is necessary to establish a connection between them and controlling influences.

In addition to the economic criteria, there are technological criteria: productivity of the finished product, its quality, operational and capital costs [2]. For production (technological process) management, a set of influences is also needed, with the help of which operational influence (direct or indirect) is realized on the value of criteria of all three types: automatic control, technological and economic.

Automatic optimization criteria are used for operational management tasks, which, in addition to an objective connection with technological or economic indicators, must satisfy the conditions of promptness of obtaining information about their value in automatic mode [3, 4]. This task turns out to be very difficult for certain industries. These include preparatory processes before beneficiation of ores.

Such features of ore preparation as multi-stage, the presence of technological feedbacks, the effect of obstacles make it difficult to solve the problem of process optimization by classical methods and lead to the need to introduce a new approach [5, 6], which is based on an in-depth study of the internal mechanics of the mill.

The results of such studies are needed in practice, because the control influences applied specifically to the crushing unit have the greatest impact on the final indicators of production functioning and, therefore, determine the relevance of optimizing management of ore crushing before beneficiation [7, 8].

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 unit, both by improving the structural elements of the mill and classifying devices, and by optimizing the management process.

In most works, a traditional approach is proposed, which is based on the use of the characteristics of the finished product [9] and control of the degree of filling of the drum using control means [10]. However, a mill with a classifier, as a control object, has significant inertia and is subject to non-stationary behavior, and is also subject to the action of uncontrolled disturbances in the form of transient properties of the output power.

In such conditions, there is a problem of reducing the inertia of management goals and additional control elements of the grinding load. The solution of this problem is considered in the works [11, 12].

The emergence of modern means of information processing and management contributed to the development of the direction based on the use of adaptive systems [13, 14]. Such systems are able to ensure the necessary quality of stabilization of regulatory parameters. Thus, in works [15, 16], the degree of filling of the mill drum is used as a parameter. But qualitative stabilization of the degree of filling does not solve the problem of determining the optimal operating mode of the mill, because it is not known at which stage this parameter should be stabilized [17]. In works [18, 19] the movement of the ore load of the mill was studied. But in these works, the research results are not aimed at solving the problem of optimal management of the ore grinding process.

Thus, we have a *very urgent question* of determining just such an inertial parameter of the mill which would directly characterize the process of material grinding in the mill drum [20, 21], and was also subject to operational automatic control and could be used to optimize the ore grinding process.

The purpose of research. It is assumed that, under certain conditions, the ore loading in the drums of the rotating mills carries out periodic low-frequency oscillations, which intensify the abrasion of the material [22]. To confirm this hypothesis, during the research, mathematical modeling methods were combined with methods of spectral analysis of random oscillatory processes in the drive system of industrial mills.

The research purpose is the substantiation of the criterion for automatic optimization of the ore grinding process in self-grinding drum mills for the intensification of material destruction inside the drum.

The object of the research is the processes occurring inside the drum of a working ore self-grinding mill.

The subject of the research is a loose material placed on the inner surface of a rotating drum which, under certain conditions, performs periodic oscillations. The parameters of these oscillations depend on the radius of the drum, the amount of material and the coefficient of friction.

To achieve the goal, the following ***tasks*** must be solved:

- to compile and investigate mathematical models of material movement processes in the drum of a rotating mill;
- to conduct experimental studies to confirm theoretical conclusions;
- on the basis of mathematical models, to determine effective operating modes of internal mill loading from the point of view of the intensity of destruction of the material;
- to determine the structural diagram of the control system of the self-grinding mill.

Research materials and methods. If we consider the task of automatic optimization of the operation of a separate unit, in our study it is a drum mill for self-crushing ore, it is necessary to establish the following connections: a criterion for automatic optimization of the drum mill → technological indicators of mill operation → characteristics of final products → economic indicators of production functioning.

In order to determine the criterion of automatic optimization of the drum mill, which would directly characterize the material grinding process, we will combine the methods of mathematical modeling and the methods of spectral analysis of random oscillatory processes in the drive system of industrial drum mills.

Mathematical model of the problem. Let a flat body of small mass m be placed on the inner surface of the drum radius R, rotating with angular velocity Ω, Fig. 1. θ is the angle of deviation of the center of gravity of the body from the vertical axis.

This problem is analogous to the classic problem of the movement of Froude's pendulum, discussed in the classical literature.

Since the dimensions of the body can be neglected under the condition of the task, the equation of moments will be replaced by the equation of forces

$$f(F_N + F_{CN}) - F_\tau = m\ddot{\theta}R, \qquad (1)$$

where $F_N = mg\cos\theta$ is a normal component of gravity; $F_\tau = mg\sin\theta$ – a tangential component; $F_{CN} = m\theta^2 R$ – centrifugal force; f – the coefficient of friction between the body and the inner surface of the drum.

Transforming (1), we get

$$\ddot{\theta} - f\dot{\theta}^2 + \frac{g}{R}\sqrt{1+f^2}\sin(\theta - \mathrm{arctg} f) = 0. \qquad (2)$$

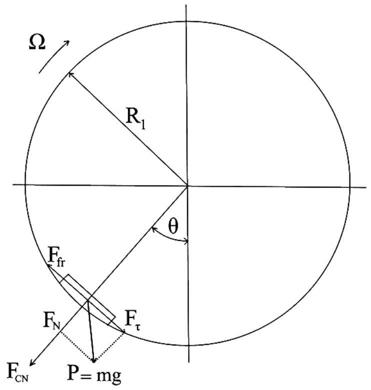


Fig. 1. The problem of the movement of a flat body on the inner surface of a rotating drum

As follows from (2), the nature of the movement of the body does not depend on its mass, but is determined by the radius of the drum, the coefficient of friction and the initial conditions.

A characteristic difference of equation (2) compared to the known linear equations of the second order is the constancy of the sign of the function of the first derivative $f\dot{\theta}^2$ (more precisely, its independence on the sign of the first derivative $\dot{\theta}$). In the general case, the sign of the function $f\dot{\theta}^2$ changes at $\Omega < \theta$, which will be discussed below.

Analysis of equation (2) shows that at f – const the system described by expression (2) is conservative and its phase trajectories have the form of closed curves (Fig. 2, *a*).

Amplitude of angle oscillations θ and its derivative $\dot{\theta}$ is determined by the initial conditions. Point 0 is a special point of the center type and has coordinates (arctg$f$; 0). If the body is at point 0, then it means that it is at rest and sliding relative to the drum with a speed Ω, deviating from the vertical by an angle θ = arctg$f$. (The analysis of the movement of the body in the "small", that is, for small deviations of the working point on the phase plane from a special point is given here and further).

When the body moves along one of the closed phase trajectories, the sign of the function $f\dot{\theta}^2$ half the period is opposite in sign $\ddot{\theta}$, and the other half coincides with it.

This fact has a deep physical meaning and reveals the mechanics of energy transfer from a rotating drum to a body oscillating on its surface [23]. The frequency of body oscillations can be roughly estimated by the formula

$$w = \sqrt{gR^{-1}\sqrt{1+f^2}}.$$

In real conditions, the coefficient of friction f depends on the relative speed of the touching surfaces, and this dependence has a rather complex form.

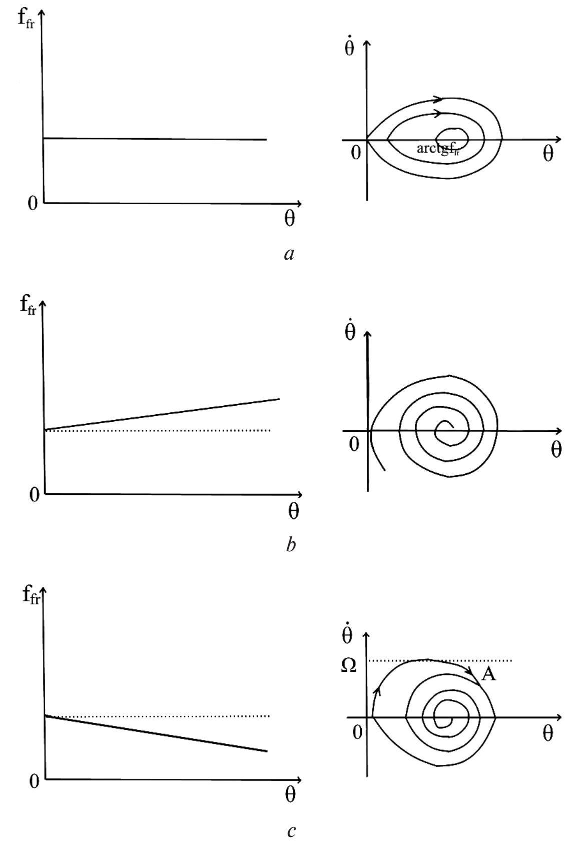


Fig. 2. Dependence of the phase trajectory on the type of function $f_{fr}(\dot{\theta})$:

a – fluctuations converge to a stable focus; b – oscillation turns into an unstable focus; c – oscillations settled on the square phase plane

On the other hand, at body velocities $\dot\theta$ greater than the speed of rotation of the drum Ω friction force $f(F_N + F_{CN})$ changes sign. In view of this, equation (2) can be written more strictly as follows

$$\ddot\theta - f\dot\theta^2 sign(\Omega-\dot\theta) + \frac{g}{R}\sin\theta - \frac{fg}{R}\cos\theta\cdot \mathrm{sign}(\Omega-\dot\theta) = 0. \quad (3)$$

Depending on the type of function $f = f(\Omega-\dot\theta)$ angle fluctuations can be either decreasing or increasing (divergent). If the characteristic $f = f(\Omega-\dot\theta)$ increases, which is possible with small differences $\Omega-\dot\theta$ and small specific loads, the oscillations converge to a stable focus (Fig. 2, *a*).

At high specific pressures that occur in mills, the characteristic $f = f(\Omega-\dot\theta)$ decreases over almost the entire range of the argument change and the phase trajectories diverge from the vicinity of the point o, which turns into an unstable focus (Fig. 2, *b*).

Increasing fluctuations of the angle θ and its derivative $\dot\theta$ limited from above by the speed of rotation of the drum Ω due to the function $\mathrm{sign}(\Omega-\dot\theta)$ in equation (3).

Thus, in this case, steady-state oscillations will be observed on the phase plane (trajectory A in Fig. 2, *c*) with an amplitude of Ω.

Now suppose that there is a certain amount of bulk material in the rotating drum (Fig. 3).

The equation of motion for this case can be written by analogy (1)

$$M_N + M_{CN} - M_\tau = J\ddot\theta, \quad (4)$$

where M_N, M_{CN}, M_τ are moments from the action of normal, centrifugal and tangential forces; J – the moment of inertia. After double integration over the radius R_1 and at the corner β (Fig. 4), we get

$$M_\tau = \gamma \int_{R_1\cos\frac{a}{2}}^{R_1} R^2 dR \int_{\theta-\arccos\left(\frac{R_1}{R}\cos\frac{\alpha}{2}\right)}^{\theta+\arccos\left(\frac{R_1}{R}\cos\frac{\alpha}{2}\right)} \sin\beta d\beta = \frac{2}{3}\gamma R_1^3 \sin^3\frac{\alpha}{2}\sin\theta; \quad (5)$$

$$M_N = f\gamma R_1 \int_{R_1\cos\frac{\alpha}{2}}^{R} RdR \int_{\theta-\arccos\left(\frac{R_1}{R}\cos\frac{\alpha}{2}\right)}^{\theta+\arccos\left(\frac{R_1}{R}\cos\frac{\alpha}{2}\right)} \cos\beta d\beta =$$
$$= f\gamma R_1^3\left(\sin\frac{\alpha}{2} - \cos^3\frac{\alpha}{2}\ln\frac{1+\sin\frac{\alpha}{2}}{\cos\frac{\alpha}{2}}\right)\sin\theta; \quad (6)$$

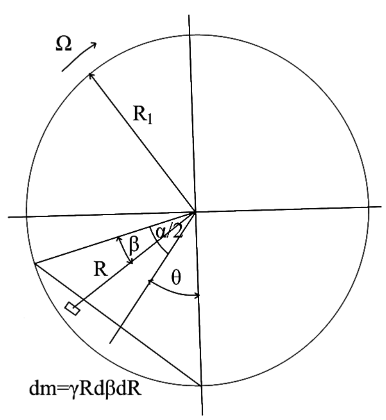


Fig. 3. The problem of the movement of a segment of bulk material along the inner surface of a rotating drum:

α – the central angle corresponding to the segment of the material, 0 – the center of gravity, Ω – the angular speed of rotation of the drum, f – the coefficient of friction between the material and the drum, θ – the angular coordinate of the center of gravity of the segment, γ – the weight of the material per unit area of the segment

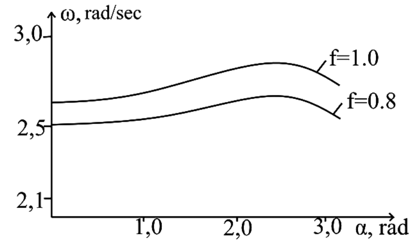


Fig. 4. Dependence of the frequency of oscillations ω on the size of the segment

$$M_{CN} = f\gamma\dot\theta^2 R_1 g^{-1}\int_{-\frac{\alpha}{2}}^{\frac{\alpha}{2}}\int_{R_1\frac{\cos\frac{\alpha}{2}}{\cos\beta}}^{R_1} R^2 d\beta dR =$$
$$= \frac{1}{3} f\dot\theta^2\gamma R_1 g^{-1}\left(\alpha - \frac{\sin\alpha}{2} - \frac{\cos^3\frac{\alpha}{2}}{2}\ln\frac{\sin\frac{\alpha}{2}+1}{1-\sin\frac{\alpha}{2}}\right); \quad (7)$$

$$J = \int_{-\frac{\alpha}{2}}^{\frac{\alpha}{2}}\int_{R_1\frac{\cos\frac{\alpha}{2}}{\cos\beta}}^{R_1} \gamma g^{-1}R^3 d\beta dR =$$
$$= \frac{1}{2}\gamma g^{-1}R^4\left(\alpha - \frac{1}{3}\sin\alpha\sin^2\frac{\alpha}{2} - \sin\alpha\cos^2\frac{\alpha}{2}\right). \quad (8)$$

Taking into account (5–8), after transformations, equation (4) will be written as follows

$$\ddot\theta - (A\dot\theta^2 + B\cos\theta)\cdot sign(\Omega-\dot\theta) + C\cdot\sin\theta = 0, \quad (9)$$

where

$$A = f\cdot\frac{4}{3}\left(\frac{\alpha - \frac{1}{2}\sin\alpha - \frac{1}{2}\cos^3\frac{\alpha}{2}\cdot\ln\frac{1+\sin\frac{\alpha}{2}}{\cos\frac{\alpha}{2}}}{\alpha - \frac{1}{3}\sin\alpha\sin^2\frac{\alpha}{2} - \sin\alpha\cos^2\frac{\alpha}{2}}\right);$$

$$B = 4fgR_1^{-1}\left(\frac{\sin\frac{\alpha}{2} - \frac{1}{2}\cos^2\frac{\alpha}{2}\cdot\ln\frac{1+\sin\frac{\alpha}{2}}{\cos\frac{\alpha}{2}}}{\alpha - \frac{1}{3}\sin\alpha\sin^2\frac{\alpha}{2} - \sin\alpha\cos^2\frac{\alpha}{2}}\right);$$

$$C = \frac{8}{3}gR_1^{-1}\left(\frac{\sin^3\frac{\alpha}{2}}{\alpha - \frac{1}{3}\sin\alpha\sin^2\frac{\alpha}{2} - \sin\alpha\cos^2\frac{\alpha}{2}}\right).$$

In principle, the equation of the movement of the center of gravity of the material segment (9) is no different from the previously considered equation (3), although it has the peculiarity that its coefficients depend on the angular dimensions of the segment α.

This means that the frequency of natural oscillations will also depend on α and in the first approximation will be determined by the formula

$$\omega = \sqrt[4]{B^2+C^2} = \sqrt{\frac{\sqrt[2]{16f^2g^2\left(\sin\frac{\alpha}{2} - \cos^2\frac{\alpha}{2}\ln\frac{1+\sin\frac{\alpha}{2}}{\cos\frac{\alpha}{2}}\right)^2 + \frac{64}{9}\sin^6\frac{\alpha}{2}}}{R_1\left(\alpha - \frac{1}{3}\sin\alpha\cdot\sin^2\frac{\alpha}{2} - \sin\alpha\cdot\cos^2\frac{\alpha}{2}\right)}}. \quad (10)$$

Fig. 4 shows the dependence of the oscillation frequency ω on the magnitude α according to expression (10) with the given R_1 and f.

Analyzing it, it can be concluded that in the working range of fillings, the frequency of oscillations is weakly dependent on the level of filling and can vary by up to 10 %.

Conducting an experimental study to confirm theoretical conclusions. Oscillations of the ore load that occur during the rotation of the mill drum, whose mechanism is described above, cause oscillations in the electromechanical drive system of the mill at the corresponding frequency.

Fig. 5 presents characteristic graphs of the normalized spectral density of the active power signal consumed by the drive motor of the SGM 40 × 75 type drum mill.

In the studied low-frequency range of the spectrum, three components stand out: at the frequency of drum rotation f_{rot} and its second harmonic, as well as the harmonic component caused by fluctuations of the ore load with frequency f_{fr}.

Thus, measuring after filtering the dispersion of the component on the frequency f_{fr}, it is possible to quickly assess the intensity of ore load fluctuations (Fig. 6, *a*) with a measuring device A (mA).

As a result of experimental research in the conditions of Lebedynskyi, Pivnichnyi, Inhuletskyi mining and concentration plants, it was established that:

- the intensity of ore load fluctuations A significantly depends on the degree of drum filling φ_{ore}, %;
- with a certain degree of filling, the intensity of oscillations increases;
- at the same degree of filling, the productivity of the mill increases according to the newly created finished class.

These conclusions illustrate the experimentally obtained dependencies presented in Fig. 6.

Determination of the effective mode of operation of internal mill loading from the point of view of the intensity of destruction of the material. The experimentally obtained results are explained by the intensification of the work of frictional forces during the increase of fluctuations of the internal mill load.

To confirm this fact theoretically, it is necessary to establish a relationship between the work of friction forces during the oscillation period and its amplitude. For this, we will use the model of single-body oscillations (1) and assume that the oscillations are harmonic. Elementary work of dissipative forces on the way is equal to

$$dA = F_{FR} dS, \tag{11}$$

where, respectively (1)

$$F_{FR} = f(F_N + F_{CN}) = f(mg\cos\theta + m\dot{\theta}^2 R);$$
$$dS = Rd[\omega t - \theta(t)]. \tag{12}$$

Here Ω is the angular speed of rotation of the drum; R – the turning radius; θ – the angle of deviation of the body from the vertical axis.

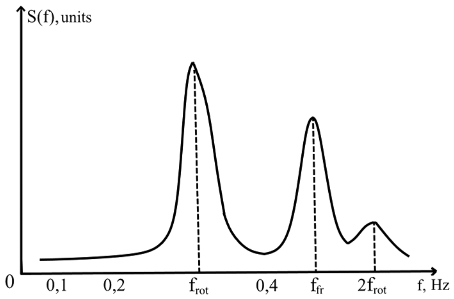
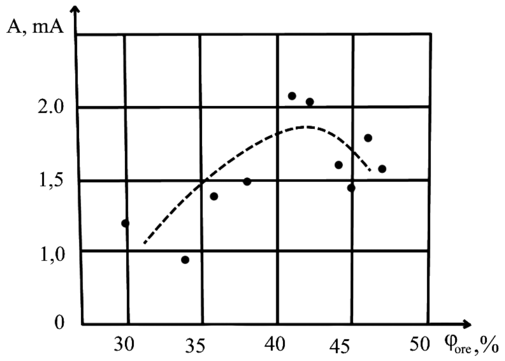
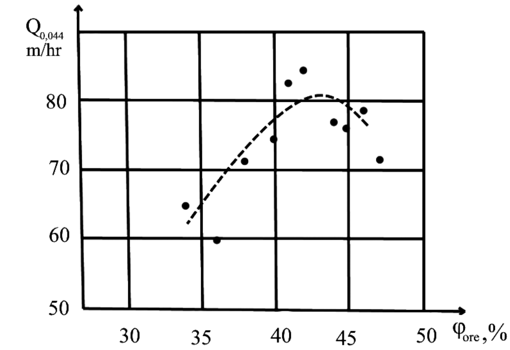


Fig. 5. Characteristic graphs normalized spectral density of the active power signal consumed by the drive motor of SGM 40 × 75 type drum mill



a



b

Fig. 6. Dependencies of fluctuation intensity of ore load (a) and productivity according to the newly created finished class (b) on the filling of the WSGM 70 × 23 drum mill

For equation (1) as a special point on the phase plane $(\theta;\dot{\theta})$ there is a point with coordinates (arctg f; 0). Therefore, we will assume that there is a change in angle in the system θ by law

$$\theta(t) = \operatorname{arctg} f + a\sin wt, \tag{13}$$

where a is the amplitude of oscillations relative to the equilibrium position; w – frequency of oscillations.

Then

$$\dot{\theta}(t) = aw\cos wt. \tag{14}$$

Now it is necessary to substitute (12) in (11) and calculate the work of friction forces during the oscillation period $T = 2\pi/w$

$$A = \int_0^{T=2\pi/w} fm(g\cos\theta + \dot{\theta}^2 R)Rd(\Omega t - \theta).$$

In the last expression, respectively (13), (14) we present θ and $\dot{\theta}$ as a function of time and perform the calculation

$$A_{fr} = \int_0^{2\pi/w} fmR[g\cos(\operatorname{arctg} f + a\sin wt) + Ra^2w^2Cos^2wt]\times$$
$$\times(\Omega - aw\cos wt)dt =$$
$$= fmR\left[\int_0^{2\pi/w} g\Omega(\operatorname{arctg} f + a\sin wt)dt + \int_0^{2\pi/w} \Omega Ra^2w^2\cos^2 wtdt -\right.$$
$$\left. - \int_0^{2\pi/w} gaw\cos wt\cdot\cos(\operatorname{arctg} f + a\sin wt)dt - \int_0^{2\pi/w} Ra^3w^3\cos^3 wtdt\right].$$

In the assumption that a – is not enough, let us perform the decomposition of the function cos leaving two members, i. e.

$$\cos(\operatorname{arctg} f + a\sin wt) \approx 1 - 0.5\cdot(\operatorname{arctg} f + a\sin wt)^2.$$

Then, calculating the integrals, we get

$$A_{fr} = fmR\Bigg[g\Omega t\Big|_0^{2\pi/w} - \frac{1}{2}g\Omega \operatorname{arctg}^2(f)t + g\Omega a w^{-1}\cdot \operatorname{arctg} f \times$$
$$\times \cos wt\Big|_0^{2\pi/w} - \frac{1}{2}g\Omega a^2 w^{-1}\left(\frac{wt}{2} - \frac{\sin 2wt}{4}\right)\Big|_0^{2\pi/w} + \Omega R a^2 \times$$
$$\times w\left(\frac{wt}{2} + \frac{\sin 2wt}{4}\right)\Big|_0^{2\pi/w} - ga\sin wt\Big|_0^{2\pi/w} + \frac{1}{2}ga\sin wt \times$$
$$\times \operatorname{arctg}^2(f)\Big|_0^{2\pi/w} + ga^2 \operatorname{arctg}^2(f)\frac{\sin^2 wt}{2}\Big|_0^{2\pi/w} +$$
$$+ ga^3\frac{\sin^3 wt}{3}\Big|_0^{2\pi/w} - Ra^3 w^2\left(\sin wt - \frac{\sin^3 wt}{3}\right)\Big|_0^{2\pi/w}\Bigg] =$$
$$= fRm\Omega\pi w^{-1}\left(2g - g\cdot \operatorname{arctg} f - \frac{1}{2}ga^2 + Ra^2 w^2\right).$$

If there are no fluctuations, that is $\alpha = 0$, then the work of friction forces will be equal to

$$\grave{A}_{fr}(a=0) = fRm\Omega\pi w^{-1}(2g - g\operatorname{arctg} f),$$

and an increase in the work of frictional forces due to oscillations is

$$\Delta A_{fr} = A_{fr} - \grave{A}_{fr}(a=0) = fRm\Omega\pi a^2 w^{-1}\left(Rw^2 - \frac{g}{2}\right).$$

Since, $w = \sqrt{\frac{g}{R}}$, finally we get

$$\Delta A_{fr} = \frac{1}{2}fRm\Omega\pi a^2\sqrt{Rg}. \qquad (15)$$

The last expression shows that the increase in the work of friction forces due to the vibrations of the internal layers of the mill load is proportional to the square of the amplitude of these vibrations.

The resulting expression (15) explains the experimentally established phenomenon of increasing the productivity of the mill according to the newly formed finished class when the fluctuations of the internal mill load are intensified.

Development of the structural diagram of the control system. An important point is that the intensity of load fluctuations depends not only on the degree of filling of the drum, but also on other factors (properties of the crushed material, wear of the lining), the influence of which causes the drift of the extremum of the characteristic $A(\varphi_{ore})$.

Therefore, to maintain an effective mode of operation with the maximum intensity of load fluctuations, it is advisable to use a step system of extreme regulation, the structural diagram of which is shown in Fig. 7.

That is, the goal of managing the process of grinding ores in drum mills is formulated as follows – it is necessary to maintain the maximum fluctuations of the internal mill load A_{fr} by adjusting the flow of raw material to the drum mill Q.

Discussion. In this work, the main task was solved – the substantiation of the criterion for optimal control of the loading of drum mills for self-crushing of ores based on the simulation of the material movement processes inside the drum. In order to solve this problem, it was necessary to formulate the equation of movement of bulk material inside the drum (9), find the conditions for the occurrence of oscillations (Fig. 2) and their parameters (10), establish theoretically (15) and experimentally (Fig. 6) the relationship between the intensity fluctuations and the technological efficiency of the grinding process, and make a structural diagram of the search system of the control of the drum mill (Fig. 7). The mathematical model of material movement in the mill drum is essentially a differential equation (9).

The presence of a non-linear term in it $A(\dot{\theta})^2$ is a distinctive feature of this suit from the known linear equations and is the main cause of the load fluctuations that occur when the drum rotates.

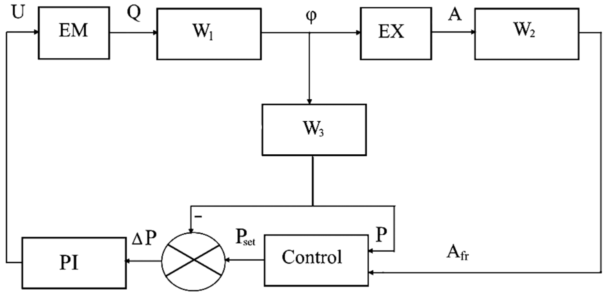


Fig. 7. Structural diagram extreme regulation systems:

W_1, W_2, W_3 – linear operators (transmission functions) of the control object (mill along the "material flow" channel Q – degree of filling φ), load fluctuation intensity meter – A, filling degree meter, respectively; EM – executive mechanism regulating the flow of material into the mill; EX – extreme static characteristic $A(\varphi)$; Control – the controlling part that forms the filling task P_{set} based on an analysis of its current measured value P and a signal characterizing the intensity of load fluctuations A_{fr}; PI – regulator that stabilizes the set value in the main circuit P_{set} through the influence of U on the executive mechanism

The experimentally obtained dependences (Fig. 6) show that the fluctuations of the ore load A increase with a certain degree of filling of the drum φ_{ore}, %(Fig. 6, *a*) and with the same fillings, the maximum productivity of the mill for the finished product $Q_{0.044}$(Fig. 6, *b*). This effect is explained by the intensification of the work of frictional forces during the oscillations that occur. This conclusion is confirmed by relation (15), which establishes a direct relationship between the work of friction forces and the parameters (in particular, the amplitude) of loading fluctuations.

Thus, it is advisable to use the intensity of oscillations as a criterion for controlling the loading of drum mills, as this parameter is informative from the point of view of the technological efficiency of the grinding process; it can be relatively simply measured and allows the implementation of an appropriate automatic control system (Fig. 7). A similar approach to controlling the modes of operation of drum mills is fundamentally different from known methods [1], which offer the use of information about the characteristics of flows at the entrance and exit of the control object. The fundamental difference of the proposed solution is that it is based on studying directly the processes that take place in the working zone of grinding, inside the drum of the mill. This makes it possible to use as an optimization criterion a parameter that is directly responsible for the intensity of material grinding and to reduce the inertia of information channels in the control loop.

It is important to note that the fluctuation of the ore load intensifies in a narrow range of drum filling. Therefore, the implementation of the proposed method is possible with the mandatory presence of an effective system of control, evaluation and stabilization of the degree of filling of the drum of the mill, which will be a limiting factor.

Conclusions and prospects for further development. So, the following is done in this research paper:

- a mathematical model of the movement of material in a rotating drum was developed, revealing the mechanism of periodic fluctuations of ore loading of self-crushing mills;
- as a result of experimental studies in industrial conditions, it was established that at a certain degree of filling of the drum, fluctuations of ore loading intensify. This effect is accompanied by an increase in the productivity of the mill based on the newly formed finished product, and this result is explained by the intensification of the work of friction forces, which is directly proportional to the amplitude of the load fluctuations;
- using the intensity of loading fluctuations as a criterion for controlling the filling of grinding mills allows implementing an extreme search system that ensures the optimal mode of operation of the mills in the sense of productivity for the newly created finished product.

The following points should be attributed to the shortcomings of the conducted research:

- mathematical modelling of the internal mechanics of mills was considered as a "flat" problem and not a spatial one;

- the influence of other (except drum filling) technological factors on the process of ore load fluctuations was not used.

In the future, it is proposed to carry out a study of the influence of such parameters as the coarseness of the source material, the characteristics of the circulating flows on the intensity of fluctuations in the loading of the drum mill.

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Обґрунтування критерія оптимального керування процесом самоподрібнення руд у барабанних млинах

*І.В. Новицький, Ю.О. Шевченко**

Національний технічний університет «Дніпровська політехніка», м. Дніпро, Україна

* Автор-кореспондент e-mail: shevchenko.yu.o@nmu.one

Мета. Обґрунтування критерія автоматичної оптимізації процесу подрібнення руди в барабанних млинах самоподрібнення шляхом складання й дослідження математичних моделей руху матеріалу всередині барабана млина, що обертається.

Методика. Використані методи математичного моделювання внутрішньої механіки барабанних млинів у поєднанні з експериментальними дослідженнями спектральної щільності змінної складової активної потужності споживаної приводним двигуном млина.

Результати. У результаті моделювання встановлено, що сипучий матеріал, поміщений на внутрішню поверхню барабана, що обертається, за певних умов здійснює періодичні коливання. Параметри цих коливань залежать від радіусу барабана, кількості матеріалу й коефіцієнта тертя. Теоретично обґрунтовано, що у разі коливань навантаження інтенсифікується робота сил тертя і, отже, процес руйнування матеріалу. Теоретично одержані висновки підтверджуються результатами експериментальних досліджень спектра сигналу активної потужності приводного двигуна млинів у характерному низькочастотному діапазоні. Встановлено, що найінтенсивніші коливання виникають при певному ступені заповнення барабана млина в робочому діапазоні заповнень і їх інтенсивність корелює із продуктивністю млина по новоствореному готовому класу.

Наукова новизна. Розкрито механізм виникнення коливань рудного навантаження барабанних млинів і обґрунтовано зв'язок цього явища з показниками технологічної ефективності процесу подрібнення.

Практична значимість. Інтенсивність коливань рудного навантаження доцільно використовувати як критерій автоматичного управління завантаженням млина, оскільки цей параметр характеризує технологічну ефективність роботи млина і може бути оперативно виміряний. Використання інтенсивності коливань рудного навантаження, як критерія управління, дозволяє реалізувати пошукову систему екстремального управління завантаженням млинів.

Ключові слова: *продуктивність, барабанний млин, коливання, рудне навантаження, самоподрібнення, оптимізація, математична модель*

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