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Obtaining the Analytic Dependence for Estimating the Ore Mill Operation Modes

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Abstract**—**The particular significance of comprehensive estimation of the increase in the operation efficiency of the mill motor electromechanical system, providing the main technological process for obtaining a metallic concentrate, as well as the technical state of the system are substantiated. The works carried out in the sphere of investigating, creating, and improving the operation modes of electric drive motors and ore-grinding mills have been studied. Analytic dependences for estimating the operation modes of the ore-grinding mills aimed at improving the ore-crashing process maintenance and technical service efficiencies have been obtained. The obtained analytic dependencies establish a link between the technological and power parameters of the electromechanical system, and allow to estimate the state of the system and reveal the controlled parameters required for the efficient management in case of changing the technological parameters. It has been substantiated that the changes in the technological factors affecting the consumption power of the drive motor do not cause an instability in the electromechanical system.

Keywords**—**Electromechanical system, estimation, operation mode, productivity, technological process, the mill filling degree.

I. Introduction

THE ore mill-motor electromechanical system has a complicated structure, the estimation of whose operation modes is of particular interest for its regulation and management. The necessity of estimating the operation modes of the mentioned electromechanical system is also explained by the fact that the improvement of the technical and economic indices of the grinding process is conditioned by its efficient management, which is possible to implement only by the comprehensive estimation and control of the system [1]-[4].

The analysis of the well-known works devoted to the estimation of the operating modes of the ore-mill motor system shows that theoretical and experimental investigations on estimating and controlling different units have been carried out, as well as considerable estimation methods and means have been developed by different authors. A significant experience has been gained in the sphere of drive motors, the study and creation of the ore mill operation modes and their improvement. By the investigations of the operation modes, the known works can conventionally be classified into three groups [5]-[9]:

- Works, in which the system is investigated by estimating the technological factors;
- Works, in which the system is investigated by controlling and estimating the mechanical factors;
- Works, in which the system is investigated by controlling and estimating the corresponding characteristics of the drive motors.

Considering that the technical and economic requirements set to the grinding process change, the traditional methods for investigating the electromechanical systems cannot be applied for them.

Taking into account the peculiarities of maintaining the system mill-motor, as well as the random nature of changing the technological factors, a necessity arises to investigate the dynamics of changing the mill operation modes conditioned by the ore grinding technological factors.

II. Substantiating the Method for Estimating the Ore Mill Operation Modes

The ore mill operating modes are conditioned by numerous technological factors. It complicates the solution of problems on the mill state estimation and management. Considering the factors having a significant impact on the mill operation, in order to study the physical phenomena going on in the mill, a necessity has arisen to obtain analytic dependences for the process estimation and control. In particular, analytic dependences have been obtained, characterizing the dynamics of the change in the consumption power of the drive motor at changing the grinding productivity, the mill filling degree, the lining thickness, and the dimensions of the ground material [9]. Only the factors, changing at maintaining the mill have been given much attention, while the factors such as the mill diameter, length, rotation velocity, etc., having no significant impact on the mill operation modes are considered.

Below are introduced the course of obtaining the dependences, characterizing the dynamics of the change in the drive motor consumption power at changing different technological factors.

A. The Dynamics of the Change in the Drive Motor Consumption Power at Changing the Grinding Productivity

$$L_Q(\omega) = 20\lg A(\omega) = 20\lg(T_a\omega) - 20\lg\sqrt{1+\omega^2}.$$

Let us introduce an equation, establishing the link between the useful power consumed in the grinding process and the technological parameters of grinding [10].

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$$\frac{6}{\delta}\left(\frac{1}{d}-\frac{1}{D}\right)Q = k_0 P_o\,, \qquad (1)$$

where δ is the specific density of the ground materail, D and d - the average diameters of the material pieces before and after grinding; Q - the grinding productivity; k_o - proportionality coefficient; P_0 - the useful power consumed in the grinding process.

If we assume that the grinding productivity in the stable state is equal to Q, and its change – to ΔQ, in the case when the grinding process falls out of the stability state, (1) will have the following form:

$$\left(\frac{1}{d}-\frac{1}{D}\right)Q \pm \left(\frac{1}{d}-\frac{1}{D}\right)\Delta Q = \frac{1}{6}k_0\delta\Delta P_o\,. \qquad (2)$$

The drive motor consumption power is determined:

$$P = \frac{P_0}{\eta_1\eta_2} = \frac{98{,}6KR^{1{,}5}L\psi(\gamma+\delta)x\sin\alpha\cdot 10^{-3}}{\eta_1\eta_2}\,, \qquad (3)$$

where P_0 is the useful power consumed for grinding; η_1 -the transfer efficiency from the motor shaft to the mill drum; η_2 - the motor efficiency; K - the mill filling degree; L – the mill drum length; R - the inner radius of the drum; α - by-path angle of the active load; γ - the volumetric density of the grinding steel balls; δ - the density of the ground material; x – the distance of the O point of the mill drum axis from the center of gravity of the sector correstponding to the filling degree; ψ - the relative rotation velocity of the mill drum; g - the acceleration of the free fall.

Taking (2) and (3) into account, the dynamics of the change in the consumption power of the mill drive motor at changing the grinding productivity will have the following form:

$$\left(\frac{1}{d}-\frac{1}{D}\right)Q \pm \left(\frac{1}{d}-\frac{1}{D}\right)\frac{d(Q)}{dt} = \frac{1}{6}k_0\delta\eta_1\eta_2\frac{d(P)}{dt}\,. \qquad (4)$$

Considering (4), we obtain:

$$Q \pm \frac{d(Q)}{dt} = T_a\frac{dP}{dt}\,, \qquad (5)$$

where

$$T_a = \frac{k_0\delta\eta_1\eta_2}{6\left(\frac{1}{d}-\frac{1}{D}\right)}\,,$$

Based on the analytical dependence (5) obtained for the dynamics of the change in the consumption power of the ore mill electric drive motors at changing the grinding productivity, the transfer function has been determined

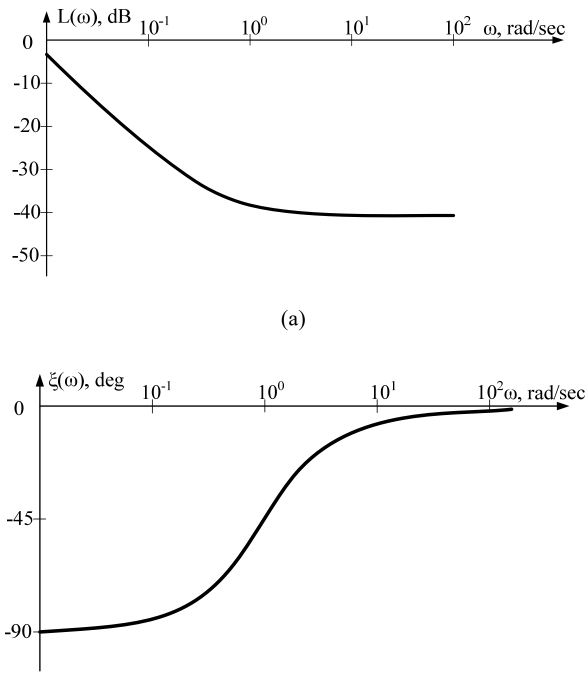
$$W_Q(j\omega) = \frac{Q(j\omega)}{P(j\omega)} = \frac{T_a\left(j\omega+\omega^2\right)}{1+\omega^2}. \qquad (6)$$

From (6), the logarithmic amplitude-frequency and phase-frequency characteristics, describing the link of the mill drive motor power and the grinding productivity have been obtained:

$$L_Q(\omega) = 20\lg A(\omega) = 20\lg(T_a\omega) - 20\lg\sqrt{1+\omega^2}\,, \qquad (7)$$

$$\xi_Q(\omega) = arctg\,\frac{a}{b} = arctg\left(\frac{1}{\omega}\right). \qquad (8)$$

Considering dependences (7) and (8), the amplitude-frequency and phase-frequency characteristics, describing the link of the mill drive motor power and the grinding productivity have been plotted in Fig. 1. *While plotting the* characteristics, $\delta = 2{,}8\,T/m^3$; $\eta_1 = 0{,}9$; $\eta_1 = 0{,}87$; $D = 0{,}4\,mm$; $d = 0{,}051\,mm$; $k_o = 0{,}233\,m/\sec.kWt$ are taken as initial parameters.



(b)

Fig. 1 Characteristics of the link of the mill drive motor power and the grinding productivity: (a) amplitude-frequency; (b) phase-frequency

From the dependences introduced in Fig. 1, it follows that, in case of a change in the grinding productivity, the system operates in the stable mode.

B. The Dynamics of the Change in the Drive Motor Consumption Power at Changing the Mill Filling Degree

The change in the grinding productivity leads to the change in the intra-mill load and to the change in the mill filling degree respectively:

$$\Delta Q = \frac{dG}{dt} = \delta L \pi R^2 \frac{dK}{dt}. \quad (9)$$

Based on (4) and (9), the following dependence will be obtained:

$$Q \pm \delta L \pi R^2 \frac{dK}{dt} = T_{2a} \frac{d\text{P}}{dt}. \quad (10)$$

Considering that the grinding productivity can be presented as [10]:

$$Q = \frac{98{,}6 k_0 K R^{1{,}5} L \psi \delta (\gamma + \delta) x \sin\alpha . 10^{-3}}{6\left(\frac{1}{d} - \frac{1}{D}\right)},$$

Equation (10) will have the following form:

$$\frac{98{,}6 k_0 K R^{1{,}5} L \psi \delta (\gamma + \delta) x \sin\alpha . 10^{-3}}{6\left(\frac{1}{d} - \frac{1}{D}\right)} \pm \delta L \pi R^2 \frac{dK}{dt} = \quad (11)$$

$$= \frac{k_0 \delta \eta_1 \eta_2}{6\left(\frac{1}{d} - \frac{1}{D}\right)} \frac{d\text{P}}{dt}.$$

By modifying (11), we obtain:

$$K \pm T_2 \frac{dK}{dt} = T_{2a} \frac{d\text{P}}{dt}, \quad (12)$$

where

$$T_2 = \frac{66{,}96 \pi \sqrt{R}\left(\frac{1}{d} - \frac{1}{D}\right)}{k_0 \psi (\gamma + \delta) x \sin\alpha}, \qquad T_{2a} = \frac{66{,}96 \eta_1 \eta_2}{R^{1{,}5} L \psi (\delta + \gamma) x \sin\alpha}.$$

According to (12), the transfer function expressed by the link of the mill filling degree and the drive motor consumption power will be

$$W_K(j\omega) = \frac{j\omega T_{2a} + \omega^2 T_2 T_{2a}}{1 + T_2^2 \omega^2}.$$

The logarithmic amplitude-frequency and phase-frequency characteristics expressed by the link of the filling degree and the motor consumption power will respectively be:

$$L_K(\omega) = 20\lg\left(\frac{\omega^2 T_{2a}}{\sqrt{1 + T_2^2 \omega^2}}\right), \ \xi_K = arctg\left(\frac{1}{\omega T_2}\right).$$

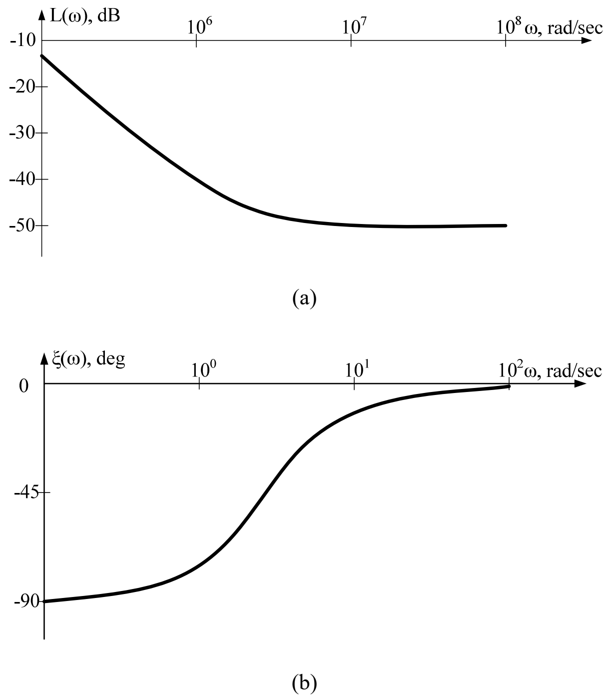


Fig. 2 Characteristics of the link of the drive motor power and the mill filling degree for an asynchronous electric drive: (a) amplitude-frequency; (b) phase-frequency

In Fig. 2, the amplitude-frequency and phase-frequency characteristics describing the link of the mill drive motor power and the mill filling degree for the mill electric drive are introduced. From the presented dependences, it can be seen that at changing the filling degree, the system operates in a stable mode. At the same time, it should be noted that taking into account the fact that the change in the filling degree has a significant impact on the output parameter of the electromechanical system, it becomes necessary to control its value for efficient management of the system.

C. The Dynamics of the Change in the Drive Motor Consumption Power at Changing the Lining Thickness

Because of the lining wear, the diameter of the mill drum becomes larger, and the characteristic of the mill consumption power changes. Let us assume that as a result of the wear, the drum radius changes by Δ R. In that case, the drum radius will become R+Δ R. As a result, the following equation is obtained for the mill electric drive:

$$\frac{K L n_3 (\gamma + \delta) x \sin\alpha \cdot 10^{-3}}{\eta_1 \eta_2} (R + \Delta R)^2 = \Delta\text{P}, \quad (13)$$

from which

$$R^2 + 2R\frac{dR}{dt} + \frac{d^2R}{dt^2} = T_{3a}\frac{dP}{dt}, \qquad (14)$$

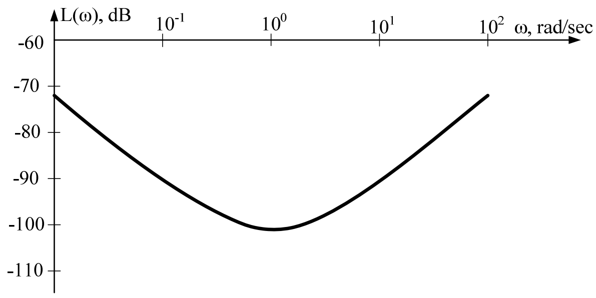
where

$$T_{3a} = \frac{\eta_1\eta_2}{KLn_3(\delta+\gamma)x\sin\alpha}10^3 .$$

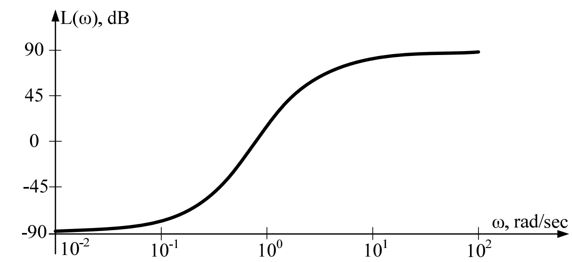
According to (14), the frequency function expressed by the link of the mill drum lining thickness and the drive motor consumption power will be:

$$W_R(j\omega) = \frac{j\omega T_{3a}}{(j\omega)^2 + 2j\omega R(j\omega) + R(j\omega)}, \qquad (15)$$

Based on (15), the characteristics of the link of the mill drive motor power and the lining thickness have been plotted (Fig. 3).



(a)



(b)

Fig. 3 The characteristics of the link of the drive motor power and the lining thickness: (a) amplitude-frequency; (b) phase-frequency

While plotting the characteristics, as initial parameters $R - 1{,}44m$; $n_3 = 181\, rot/\min$; $\delta = 2{,}8T/m^3$; $\eta_1 = 0{,}9$; $\eta_2 = 0{,}873$; $U = 3500\,V$; $D = 0{,}4mm$; $d = 0{,}051mm$; $k_o = 0{,}233m/\sec .kWt$; $x_d = 1{,}016$ have been taken.

From the amplitude-frequency and phase-frequency characteristics introduced in Fig. 3, it can be seen that the decrease in the lining thickness conditioned by its wear does not lead to the unstable state of the system.

D. The Dynamics of the Change in the Drive Motor Consumption Power at Changing the Dimensions of the Ground Material Particles at the Mill Inlet

By designating $\left(\frac{1}{d} - \frac{1}{D}\right) = d_1$, and assuming that the change in the dimensions of the ground material is Δd_1, we will have:

$$(d_1 \pm \Delta d_1)Q = \frac{1}{6}k_0\delta\eta_1\eta_2(\Delta P): \qquad (16)$$

Considering (16), we will have:

$$d_1 \pm \frac{dd_1}{dt} = T_{4a}\left(\frac{dP}{dt}\right), \qquad (17)$$

where

$$T_{4a} = \frac{k_0\delta\eta_1\eta_2}{6Q}$$

According to (16), the frequency function expressed by the relation between the ground ore particle dimensions and the drive motor consumption power will be:

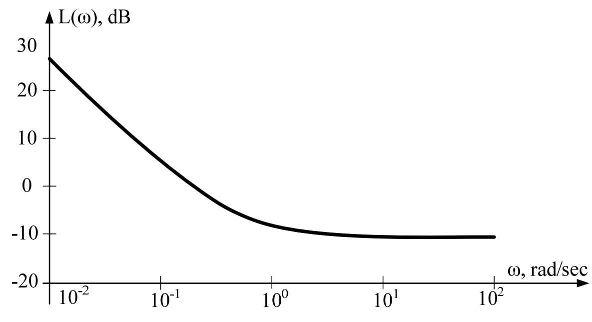
$$W_d(j\omega) = \frac{j\omega T_{4a}}{1 \pm j\omega},$$

Below are introduced the logarithmic amplitude-frequency and phase-frequency characteristics, describing the link of the drive motor power and the grain dimensions of the ground ore:

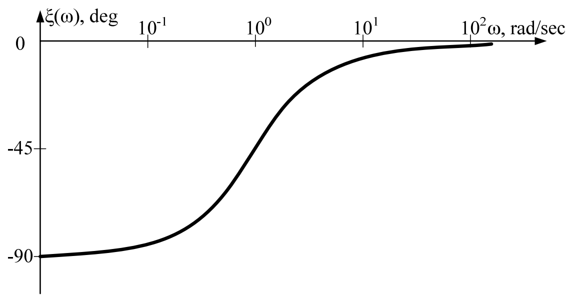
$$L_d(\omega) = 20\lg(T_{4a}\omega) - 20\lg\sqrt{1+\omega^2}$$

$$\xi_d(\omega) = arctg\left(\frac{1}{\omega}\right)$$

In Fig. 4, the amplitude-frequency and phase-frequency characteristics, describing the link of the drive motor power and the grain dimensions of the ground ore are introduced. From the presented dependences, it follows that at the change in the dimensions of the ground material, the system remains in the stable state.



(a)



(b)

Fig. 4 Characteristics of the link of the drive motor power and the grain dimensions of the ground material at the mill inlet 111(a) amplitude-frequency; (b) phase-frequency

It should be mentioned that although the impact of the above-mentioned technological parameters on the operation of the system is evident, they do not lead to the unstable state of the system. It means that the system mill - motor should be managed under the conditions of controlling the values of the technological parameters.

The obtained analytic dependences and the results of their analysis allow to reveal the controlled technological parameters and the electric parameters, responding to their change based on the requirements set to the developed control system.

III. Conclusion

1. Analytic characteristics establishing a link between the technological and power parameters of the electromechanical system have been obtained.
2. Amplitude-frequency and phase-frequency characteristics have been obtained, allowing to estimate the state of the system and reveal the necessary controlled parameters for efficient management at changing the technological parameters.
3. It has been revealed that despite the mill filling degree, the lining thickness, the dimensions of the ground material, and the grinding productivity, the changes affect the value of the drive motor consumption power, but the effects of the mentioned technological parameters do not lead to the unstable state of the system. Thus, it follows that the system should be managed at controlling the values of the considered technological parameters.

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