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ENERGY OPTIMIZATION OF A HOISTING ENGINE ACCELERATION

Purpose. To improve the energy characteristics of mine winder acceleration in the process of lifting the final load by optimizing and investigating the results which have been obtained with energy and dynamic indicators.

Methodology. In order to optimize the acceleration of a mine winder, a class of continuously differentiated basis functions was used. They included the free parameters, which are used for energy criterion minimization. Several approximate solutions of the variational problem were obtained. By using the numerical integration of differential equations, an analysis of the results with energy and dynamic indicators has been performed.

Findings. It has been established that the mine winder motion laws, which have been obtained in the research, allow eliminating the oscillations of its elements (load and coupling halves) at the end of acceleration mode. In addition, during the acceleration, undesirable maximal dynamic loads in the rope, coupling, and drive are significantly reduced, as well as an insignificant decrease in undesirable root-mean-square values of energy and dynamic indicators of the lifting machine can be observed. It has been proved that the numerical values of the energy and dynamic indicators of the machine movement significantly depend on the characteristics of its motion during acceleration.

Originality. The formulation of the optimization problem was performed, where the nonlinear integral functional was chosen as a criterion. It was established that the variational approach does not allow obtaining the exact solution of the problem. In order to find approximate solutions of the problem, we obtained five basis functions that contained free parameters. Besides that, for the synthesis of basis functions, the specified boundary conditions were used. They allowed reducing the undesirable dynamic indicators of the mine winder significantly. The obtained approximate (quasi-optimal) solutions to the variational problem were investigated according to a complex of energy and dynamic indicators. A rational basis function was established. It is simple and satisfies the requirement of sufficient accuracy of solving the optimization problem.

Practical value. The optimal mode of mine winder acceleration, which has been obtained in the work, might be implemented with the help of controlled electric drive of direct or alternating current, which allows increasing the efficiency of a mine winder in terms of energy and dynamic indicators.

Keywords: *hoisting, energy optimization, acceleration mode, nonlinear problem, basis function*

Introduction. An important problem of mine winder exploitation is to provide the high energy efficiency [1]. This problem is becoming increasingly urgent because of the constant increase of the cost of electricity tariffs. The variable energy losses of the electric engines of the hoisting machines make one of the main factors, which can be minimized and provides improving of the cycle efficiency of the machine [2]. Intensive and long-lasting exploitation of the mine winder with high cycle efficiency allows increasing the mining profitability.

One of the important aspects connected with the energy efficiency of mine winder exploitation is the long-term work of its elements. Electrical losses in the mine winder drive cause the electrical motor winding heating and deterioration of the drive electrical insulation. In its turn, it reduces the durability of the machine's electric drive.

The requirement of the mechanical elements (coupling, wire rope) durability is related to its level of the dynamical forces. The minimization of this level is an important issue to investigate.

Literature review. One of the ways to increase the energy efficiency of the mine winder is to optimize its parameters and operating modes. Investigations, which have been conducted in the work [3], are connected with the optimization of the mine winder drum weight with its strength remained on the same level. In the article [4] with the use of the finite-element method an approach concerning the optimal configuration of machine drive has been developed. The similar research, which is presented in the work [5], allows reducing the concentrations of the local stresses of the mine winder drum. It provides the ability to reduce the weight of the drum and probability of cracks in it. In the work, for optimization purposes, the special software OptiStruct has been used.

The problem of optimal reliability of a main-shaft device of a mine hoist was investigated in the work [6]. The authors identified the most significant factors that affect the reliability of the mechanism. In addition, a universal method, which allows obtaining an optimal construction of the main-shaft device of a mine hoist, has been developed.

In the article [7] the solution of the mine winder optimization problem has been found. The search domain was a conjunction of the mine winder motion modes and its parameters. The criterion of optimization was integral-terminal functional, which reflected undesired dynamic indicators of machine exploitation. Such an approach allowed improving the dynamic and energy indicators of the machine during its design and exploitation.

In the research paper [8], the problem of a few mine hoisting machines scheduling is formalized. The consumed energy is used as a criterion. Using the wide range of mathematical methods the authors have obtained an approximate solution of the problem. However, the problem of optimization of each mine winder remained unsolved.

Unsolved issues. Currently, the unsolved problem in the field of the high energy efficiency of the mine winder is the synthesis of such laws of its motion that would enable to minimize the energy consumption while providing the minimum dynamic loads in its elements.

Results, which have been obtained in the previous studies, allow improving construction of hoisting machines or their particular dynamics or energy efficiency indicators.

Mine winders are characterized by oscillatory features [9]. That is why energy optimal control of the mine winder motion should be found with the imposed conditions of the elimination of its elements oscillation. Such a problem must be solved by using effective mathematical methods that ensure the requirements.

Thus, the complex increasing of energy and dynamic indicators of the mine winder is an unsolved scientific problem. The solution of the mentioned problem provides high reliability and energy efficiency of the mine winder.

Unsolved aspects of the problem. In order to perform optimization of the mine winder motion, its characteristics should be taken into account. It is rational to consider the machine's movement at three stages: acceleration – steady motion – deceleration. In the statement of the optimal control problems of the machine's motion, characteristics of the transient mode (acceleration or deceleration) and direction of the final load movement are related to the boundary conditions of the machine elements.

This article explores the acceleration of the mine winder during hoisting of the final load. However, the approach developed in the research can be used for optimization of other modes of machine's motion.

Purpose. The goal of the investigation is to increase energy features of the mine winder acceleration during the final load hoisting due to its optimization and analysis of the obtained results in terms of energy and dynamic indicators.

Results. In order to synthesize the optimal acceleration mode of the mine winder, we use a dynamical model, which is described in previous research studies (Fig. 1 in the work [7]). The mathematical model, which is related to the dynamical model of the machine, is presented in the form of a system of three differential equations [7, 10]

$$\begin{cases} MM = J_1\ddot{\varphi}_1 + c_\varphi(\varphi_1 - \varphi_2) \\ c_\varphi(\varphi_1 - \varphi_2) = J_2\ddot{\varphi}_2 + c_x(\varphi_2 R - x)R, \\ c_x(\varphi_2 R - x) = m\ddot{x} + F \end{cases} \quad (1)$$

where J_1 is the reduced moment of inertia of the motor rotor and the first half-coupling; J_2 is the reduced moment of inertia of the second half-coupling, the gearbox, and rope drum; m is mass reduced to the vertical motion of final load; R is the rope drum radius; c_φ is the reduced coefficient of coupling stiffness; c_x is the reduced coefficient of rope stiffness; M is the reduced torque of mine winder drive; F is the reduced resistance force during skip motion. Note that it is very common to use ordinary differential equations [11] and partial differential equations [12] in the modelling of technical systems. This statement may be applied to the hoisting machines as well [13].

All numerical parameters which are in the equation system (1) are reduced to rope drum. The point above the symbol means differentiation by time.

Note that the mathematical model of the mine hoisting machine (1) reflects the oscillations of the drive elements and the final load. That is why the synthesis of energy optimal laws of the hoisting machine with the differential equations (1) allows eliminating the oscillations of these elements, decreases the level of the dynamical loads, and provides high reliability of its exploitation.

In order to carry out the optimization of the energetic characteristics of the mine winder, a criterion should be chosen. Within the framework of the current study we chose an integral criterion

$$Int = \left(T^{-1} \int_0^T P_{dr}^2 dt \right)^{\frac{1}{2}} \to \min, \quad (2)$$

where T is duration of the machine acceleration to the steady velocity; P_{dr} is the machine's drive power.

The criterion (2) reflects the root-mean-square value of the consumed power of the mine winder drive during its acceleration. Minimization of its criterion allows obtaining a mode of acceleration with a low level of the energy losses. The criterion (2) is a non-linear integral functional. With the consideration of the system of differential equations (1) it may be presented as follows

$$Int = \left(T^{-1} \int_0^T \left(\left(A_0 + \sum_{i=1}^{3} A_i \overset{2i}{x} \right) \sum_{j=0}^{2} B_j \overset{2j+1}{x} \right)^2 dt \right)^{\frac{1}{2}}, \quad (3)$$

where $A_0 ... A_3$ and $B_0 ... B_2$ are coefficients, which may be defined as follows

$$\begin{cases} A_0 = FR \\ A_1 = (J_1 + J_2)R^{-1} + mR \\ A_2 = mRJ_1c_\varphi^{-1} + J_1J_2(c_\varphi R)^{-1} + m\left(J_1 + J_2\right)(c_x R)^{-1} \\ A_3 = J_1J_2m(c_x c_\varphi R)^{-1} \\ B_0 = R^{-1} \\ B_1 = (c_x J_2 + c_\varphi m + c_x mR^2)(c_x c_\varphi R)^{-1} \\ B_2 = mJ_2(c_x c_\varphi R)^{-1} \end{cases}. \quad (4)$$

For an optimal problem setting, the boundary conditions of the machine elements movement should be set. They may be presented in the following form

$$\begin{cases} \varphi_1(0) = 0;\ \varphi_2(0) = -FRc_\varphi^{-1};\ x(0) = \varphi_2(0)R - Fc_x^{-1} \\ \dot{\varphi}_1(0) = \dot{\varphi}_2(0) = \dot{x}(0) = 0 \\ \varphi_1(T) = sR^{-1};\ \varphi_2(T) = \varphi_2(0) + sR^{-1};\ x(T) = x(0) + s \\ \dot{\varphi}_1(T) = \dot{\varphi}_2(T) = vR^{-1};\ \dot{x}(T) = v \end{cases}, \quad (5)$$

where s is the distance, which the load covers during acceleration mode. Initial conditions (5) mean that the dynamical system begins to move from a quiescent state. Final conditions (5) relate to the steady state movement of the machine (its steady velocity is v), and oscillations of the elements are absent. The last factor provides reducing of the dynamical loads in the elements of the mine winder after its acceleration.

The boundary conditions (5) are expressed in terms of function x(t) higher order derivatives

$$\begin{cases} x(0) = FR^2c_\varphi^{-1} + Fc_x^{-1};\ \overset{r}{x}(0) = 0,\ r \in \overline{(1,\ 5)} \\ x(T) = FR^2c_\varphi^{-1} + Fc_x^{-1} + s;\ \dot{x}(T) = v;\ \overset{y}{x}(T) = 0,\ y \in \overline{(2,\ 5)} \end{cases}. \quad (6)$$

Thus, the problem of optimal acceleration mode of a mine winder (3, 4, 6) is a variational one. In order to find its solution, a necessary condition of criterion (3) minimum has been stated. It is the Euler-Poisson [14] equation, which is a nonlinear differential equation of the twelfth order (it is very large and that is why we did not present it here). It is impossible to find the analytical solution of this equation. The numerical solution of the boundary problem (3, 6) will not bring the desired result: the change of a parameter of the system causes the need of a new solution of the problem.

In order to find an approximate solution of the variational problem (3, 4, 6) we used a class of the continuously differentiable functions. In the class, we set basis function, which meets the boundary conditions (6) and includes an unknown parameter. Such function may be found as a solution of the following boundary problem

$$\begin{cases} \overset{XII}{x}_{b.1}=0 \\ \begin{cases} x_{b.1}(0)=FR^2c_{\varphi}^{-1}+Fc_x^{-1};\ \overset{r}{x}_{b.1}(0)=0,\ r\in\overline{(1,\ 5)} \\ x_{b.1}(T)=FR^2c_{\varphi}^{-1}+Fc_x^{-1}+s;\ \dot{x}_{b.1}(T)=v; \\ \overset{y}{x}_{b.1}(T)=0,\ y\in\overline{(2,\ 5)} \end{cases} \end{cases}, \qquad (7)$$

where $x_{a.1}$ is the first basis function, which is used as an approximate variational problem (3, 4, 6) solution. Let us set more boundary problems. We will use their solutions for the same purpose – approximation of the exact solution of the variational problem (3, 4, 6). They are

$$\begin{cases} \overset{XIV}{x}_{b.2}=0 \\ \begin{cases} x_{b.2}(0)=FR^2c_{\varphi}^{-1}+Fc_x^{-1};\ \overset{r}{x}_{b.2}(0)=0,\ r\in\overline{(1,\ 5)} \\ \overset{VI}{x}_{b.2}(0)=q_1 \\ x_{b.2}(T)=FR^2c_{\varphi}^{-1}+Fc_x^{-1}+s;\ \dot{x}_{b.2}(T)=v; \\ \overset{y}{x}_{b.2}(T)=0,\ y\in\overline{(2,\ 5)} \\ \overset{VI}{x}_{b.1}(T)=q_2 \end{cases} \end{cases}; \qquad (8)$$

$$\begin{cases} \overset{XV}{x}_{b.3}=0 \\ \begin{cases} x_{b.3}(0)=FR^2c_{\varphi}^{-1}+Fc_x^{-1};\ \overset{r}{x}_{b.3}(0)=0,\ r\in\overline{(1,\ 5)} \\ \overset{u}{x}_{b.3}\left(\dfrac{T}{2}\right)=0,\ u\in\overline{(4,\ 6)} \\ x_{b.3}(T)=FR^2c_{\varphi}^{-1}+Fc_x^{-1}+s;\ \dot{x}_{b.3}(T)=v;\ \overset{y}{x}_{b.3}(Y)=0, \\ y\in\overline{(2,\ 5)} \end{cases} \end{cases}; \qquad (9)$$

$$\begin{cases} \overset{XVII}{x}_{b.4}=0 \\ \begin{cases} x_{b.4}(0)=FR^2c_{\varphi}^{-1}+Fc_x^{-1};\ \overset{r}{x}_{b.4}(0)=0,\ r\in\overline{(1,\ 5)} \\ \overset{u}{x}_{b.4}\left(\dfrac{T}{2}\right)=0,\ u\in\overline{(4,\ 8)} \\ x_{b.4}(T)=FR^2c_{\varphi}^{-1}+Fc_x^{-1}+s;\ \dot{x}_{b.4}(T)=v;\ \overset{y}{x}_{b.4}(T)=0, \\ y\in\overline{(2,\ 5)} \end{cases} \end{cases}; \qquad (10)$$

$$\begin{cases} \overset{XX}{x}_{b.5}=0 \\ \begin{cases} x_{b.5}(0)=FR^2c_{\varphi}^{-1}+Fc_x^{-1};\ \overset{r}{x}_{b.5}(0)=0,\ r\in\overline{(1,\ 5)} \\ \overset{u}{x}_{a.5}\left(\dfrac{T}{2}\right)=0,\ u\in\overline{(4,\ 10)} \\ x_{b.5}(T)=FR^2c_{\varphi}^{-1}+Fc_x^{-1}+s;\ \dot{x}_{b.5}(T)=v;\ \overset{y}{x}_{b.5}(T)=0, \\ y\in\overline{(2,\ 5)} \end{cases} \end{cases}, \qquad (11)$$

where $x_{b.2}$, $x_{b.3}$, $x_{b.4}$, $x_{b.5}$ are the second, third, fourth, and fifth basis functions; q_1 and q_2 are unknown values of the function's $x(t)$ sixth order derivative which should be found.

Let us explain the selection of such specific boundary conditions in the boundary problems (8–11). The higher orders of the function $x(t)$ derivatives in the moment of time $T/2$ are equal to zero. For that, using the system of differential equations (1), we have written the angular acceleration of the first system's reduced element (the element with the moment of inertia $J1$)

$$\ddot{\varphi}_1=B_1\overset{IV}{x}+B_2\overset{VI}{x}. \qquad (12)$$

The analysis of the boundary conditions, which are presented in the boundary problems (8–11) allows setting the following expressions

$$\begin{cases} \ddot{\varphi}_{1.b.3}\left(\dfrac{T}{2}\right)=0 \\ \ddot{\varphi}_{1.b.4}\left(\dfrac{T}{2}\right)=\dddot{\varphi}_{1.b.4}\left(\dfrac{T}{2}\right)=0 \\ \ddot{\varphi}_{1.b.5}\left(\dfrac{T}{2}\right)=\dddot{\varphi}_{1.b.5}\left(\dfrac{T}{2}\right)=\overset{IV}{\varphi}_{1.b.5}\left(\dfrac{T}{2}\right)=0 \end{cases}, \qquad (13)$$

where $\varphi_{1.b.3}$, $\varphi_{1.b.4}$, $\varphi_{1.b.5}$ is the angular coordinate of the first reduced element of the dynamic system, which corresponds to the third, fourth, and fifth basis function respectively.

Kinematic characteristics (13) of the reduced element motion laws provide the desirable feature: at the moment of time $T/2$ the torque of the inertial forces, which influence the element $J1$, equals to zero. This causes less severe conditions of the mine winder drive work (in terms of energetic and dynamics). The third and the fourth derivatives of the function φ_1 (the second and the third expression in the system (13)) provide some "continuation" of this feature in time.

Solutions of the boundary problems (7–11) (basis functions) include free parameters that can be used to find the minimum of the criterion (3). In order to do that, we need to find the higher derivatives of the basis functions and substitute them into the integrand of the criterion (3). By performing such mathematical transformations we obtain the following dependence

$$Int=f(p), \qquad (14)$$

where p is a vector of free parameters of basis functions $x_{b.1}$, $x_{b.2}$, $x_{b.3}$, $x_{b.4}$, $x_{b.5}$. For the cases, which correspond to the boundary problems (7, 9–11), the vector reduces to a scalar $p=s$. For the basis function $x_{a.2}$ the vector can be presented as follows $p=[s,\ q_1,\ q_2]^{\mathrm{T}}$.

Taking the derivative of criterion (3) by the components of the vector p and equating the obtained result to zero, we will find the necessary conditions for the criterion (3) minimum. For the basis functions, which are solutions of boundary problems (7, 9–11), such an equation has the form of a cubic equation

$$\frac{\partial Int}{\partial s}=\sum_{w=0}^{3}\alpha_w s^w=0, \qquad (15)$$

where $\alpha_0, \ldots, \alpha_3$ are coefficients of the equation defined in terms of coefficients $A_0 \ldots A_3$ and $B_0 \ldots B_2$, parameters T, v and coefficients of the basis functions $x_{b.1}$, $x_{b.3}$, $x_{b.4}$, $x_{b.5}$. Analysis of the roots of the equation (15) shows that for any (real) values of parameters T, v and coefficients $A_0 \ldots A_3$ and $B_0 \ldots B_2$ only one root is real. Two other are complex numbers. Taking into account physical concerns, we will choose the real root of the equation (15)

$$s=\frac{vT}{2}. \qquad (16)$$

For the basis function, which is a solution of the boundary problem (8), calculation of derivatives with respect to the vector p components leads to the system of nonlinear algebraic equations. It is impossible to find analytical solutions of the system. In order to find the numerical solution, the modified particle swarm optimization (ME-PSO) method was used [15], which allowed finding the minimum of the expression, (14), as the function of s, q_1, q_2. That method corresponds to the soft calculation techniques, which were used for calculation of mine winder modes [16]. All the calculations were carried out for the following values of the mine winder: $m = 4400$ kg; $J_1 = 2400$ kgm^2; $J_2 = 2000$ kgm^2; $R = 2$ m; $c_x = 1.06 \cdot 10^5$ N/m. In the calculations, the following parameters were used: $T = 4$ s; $v = 12$ m/s. The obtained optimal values of the mode parameters are $s = 24$ m, $q_1 = q_2 = 711$ m/s^6.

Substitution of the obtained results in the expressions of the basis functions $x_{b.1}$, $x_{b.2}$, $x_{b.3}$, $x_{b.4}$, $x_{b.5}$ leads to the laws of the final load movement that approximate the minimization of the criterion (3). We denote these as quasi-optimal laws. Using the system of equations (1) and quasi-optimal laws of load motion, the expressions of the kinematic, dynamic, and energy characteristics have been found.

In order to illustrate the obtained characteristic of mine winder motion, the diagrams were built. They are shown in Figure. The black plots in Figure correspond to the function $x_{b.1}$, gray plots – to the function $x_{b.4}$. In Figure all the graphical dependencies are continuous. It provides the reducing of the dynamical loads in the elements of the mine winder. Residual oscillation of the elements does not exist. It is a desirable feature as the dynamical loads during steady-state movement do not exist as well. Such characteristics increase the coupling and wire rope reliability.

Analysis of the graphical dependencies shown in Figure, reveals that the important factor affecting the maximum loads in the mine winder elements, are the features of the basis functions that were used for finding quasi-optimal solutions of the variational problem. It is obvious that selection of the specific features (in the frame of the current investigation such features were reached by adding the special boundary conditions in the boundary problems (9–11)) allows obtaining desirable characteristics of the mine winder motion. These characteristics are manifested in a significant reduction of the maximum values of the forces and torques in the machine's elements.

In order to estimate the obtained approximate solutions of the initial variational problem, we used energy and dynamic indicators. We will conduct the evaluation with root-mean-square values and the ratios of the maximal values. All these indicators reflect the undesirable features of the mine winder movement.

The calculated data are given in Table. The smallest values are highlighted in bold. Note that the last column of Table is related to the value of the optimization criterion (3).

Analysis of the data in Table shows that the worst energy and dynamic features occur for the quasi-optimal motion law, which corresponds to the basis function $x_{b.1}$. The law of motion, which was founded with the help of basis functions $x_{b.4}$ and $x_{b.5}$ have the best features. In that sense, functions $x_{b.4}$ and $x_{b.5}$ are similar. Thus, further complication of the basis function (i.e. adding extra boundary conditions in the middle of the acceleration interval) to obtain a more precise solution to the optimal problem is not expedient. Thus, in order to control the mine winder movement, we may recommend using the quasi-optimal law, which corresponds to the basis function $x_{b.4}$.

The analysis of the data in Table shows that the drive power maximum ratio varies in a narrow range. The same applies to the root-mean-square values of wire rope force, coupling and drive torques.

The root-mean-square value of the drive power for different quasi-optimal modes differs only by 4.0 %

As for the dynamic response factors of the rope, the coupling, and the drive depend on features of quasi-optimal laws of the hoisting machine. For example, the coefficient of the

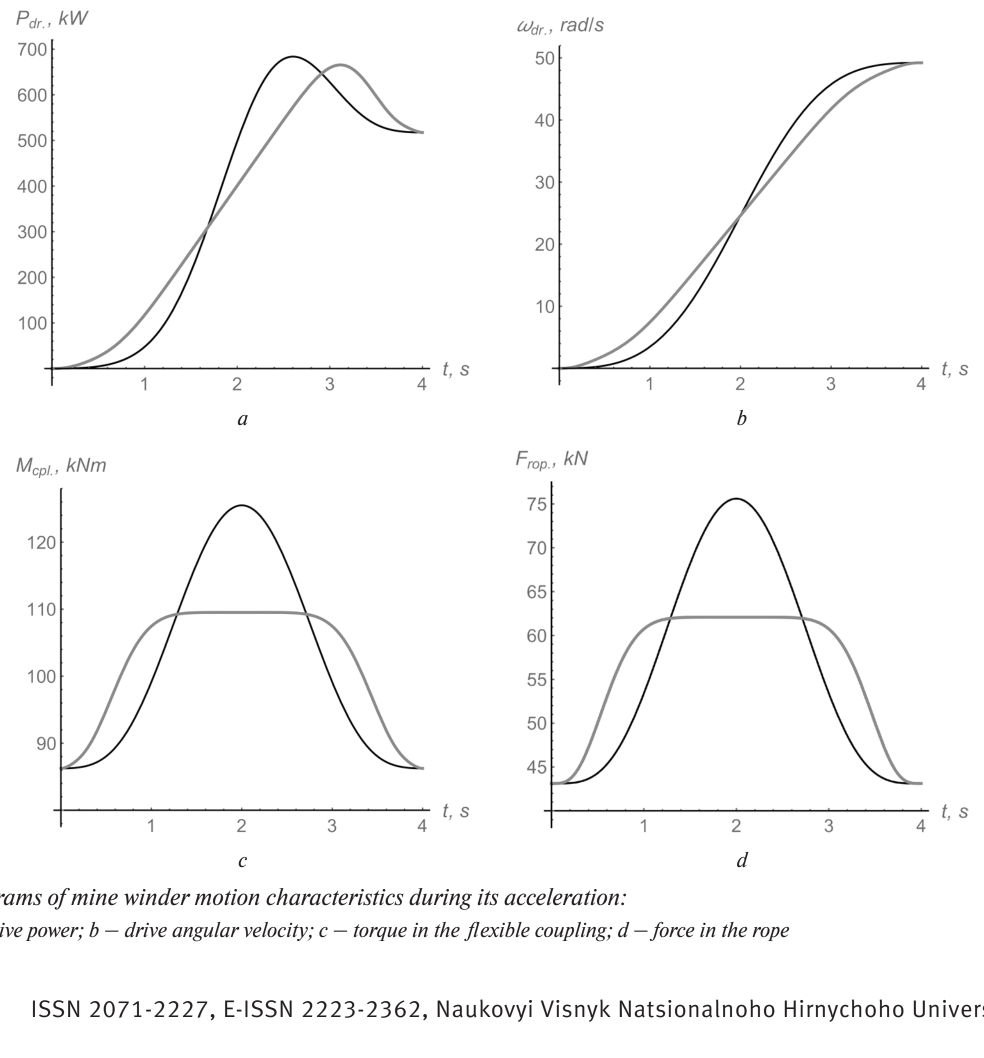

Fig. Diagrams of mine winder motion characteristics during its acceleration:
a – drive power; b – drive angular velocity; c – torque in the flexible coupling; d – force in the rope

Table

The energy and dynamic indicators which correspond to quasi-optimal control laws of mine winder motion

Basis function used in quasi-optimal motion law calculation	Dynamic response factor			Drive power maximum ratio	RMS*			
	rope	coupling	engine		rope, kN	coupling, kNm	engine torque, kNm	engine power, kW
$x_{b.1}$	1.75	1.46	1.93	1.37	57.6	103.4	122.7	442.9
$x_{b.2}$	1.53	1.33	1.66	1.34	57.1	103.0	121.3	434.6
$x_{b.3}$	1.48	1.29	1.60	**1.33**	56.9	102.9	120.8	430.9
$x_{b.4}$	**1.42**	**1.25**	**1.52**	**1.33**	**56.7**	**102.7**	**120.3**	**425.6**
$x_{b.5}$	**1.42**	**1.25**	**1.52**	**1.33**	**56.7**	**102.7**	**120.3**	**425.6**

* RMS – root-mean-square value

rope, which is related to the basis function $x_{b.4}$, is by 23.2 % less than the similar indicator for the basis function $x_{b.1}$. The dynamic response factors of the coupling for these laws vary by 16.8 %, and for the drive – by 27.0 %. These data support the previously made conclusion regarding the rationality of using the quasi-optimal law of the mine winder motion, which is based on the basis function $x_{b.4}$.

Conclusions. The article develops an approach to increasing the energy efficiency of the mine winder. It is applied to the acceleration mode of the mine winder. It can be generalized to other transient modes of the machine movement: deceleration during hoisting or lowering of the final load, and acceleration during lowering of the final load. In the work, in order to find the approximate solution of the optimal control problem (based on energetic criterion), the continuous-differentiable class of functions was used. They have a priori set of specific characteristics, which allowed eliminating the residual oscillation of the machine elements at the end of the acceleration and providing decrease in undesirable maximal values of forces and torques in the elements of the mine winder, as well as improving the energetics indicators of the machine exploitation. Calculation of the quasi-optimal laws of the mine winder motion (except one basis function) was carried out in an analytical form.

The prospect of further investigation in the scientific direction is to improve the methods of basis functions selection, which are used to find the approximate solution of the nonlinear problems of the mine winder movement control. The ultimate goal is to synthesize an effective method of basis functions selection, which allows considering an optimal problem specifics: the optimization criterion, the boundary conditions of system motion, constraints of the phase coordinates and control function.

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Енергетична оптимізація розгону приводу підйомної машини

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Мета. Підвищення енергетичних характеристик режиму розгону шахтної підйомної машини під час підйому кінцевого вантажу за рахунок проведення оптимізації та дослідження отриманих результатів за енергетичними й динамічними показниками.

Методика. Для виконання оптимізації розгону шахтної підйомної машини використано клас неперервно-диференційованих базисних функцій. Вони включали вільні параметри, за якими була проведена мінімізація енергетичного критерію. Отримано декілька наближених розв'язків варіаційної задачі. Із використанням чисельного інтегрування диференціальних рівнянь проведено аналіз результатів за енергетичними й динамічними показниками.

Результати. Встановлено, що отримані у роботі закономірності руху шахтної підйомної машини дозволяють усунути коливання її елементів (вантажу та півмуфт) у кінці її розгону. Крім того, протягом розгону значно зменшуються небажані максимальні динамічні навантаження в канаті, муфті та приводі, а також спостерігається незначне зменшення небажаних середньоквадратичних значень енергетичних і динамічних показників роботи підйомної машини. Доведено, що чисельні значення енергетичних і динамічних показників руху машини значно залежать від характеристик її руху протягом розгону.

Наукова новизна. Виконана постановка оптимізаційної задачі, де в якості критерію обрано нелінійний інтегральний функціонал. Встановлено, що варіаційний підхід не дозволяє отримати точний розв'язок задачі. Для знаходження наближених розв'язків задачі отримано п'ять базисних функцій, що містили вільні параметри. Крім того, для синтезу базисних функцій були використані задані крайові умови, що дозволили значно знизити небажані динамічні показники роботи шахтної підйомної машини. Отримані наближені (квазіоптимальні) розв'язки варіаційної задачі досліджені за комплексом енергетичних і динамічних показників. Встановлена раціональна базисна функція, що є нескладною та задовольняє вимогу достатньої точності розв'язку оптимізаційної задачі.

Практична значимість. Отриманий у роботі оптимальний режим розгону шахтної підйомної машини може бути реалізований за допомогою керованого електроприводу постійного або змінного струму, що дає змогу підвищити ефективність роботи шахтної підйомної машини за енергетичними й динамічними показниками.

Ключові слова: *шахтний підйом, енергетична оптимізація, режим розгону, нелінійна задача, базисна функція*

Энергетическая оптимизация разгона привода подъемной машины

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Цель. Повышение энергетических характеристик режима разгона шахтной подъемной машины при подъеме конечного груза за счет проведения оптимизации и исследования полученных результатов по энергетическим и динамическим показателям.

Методика. Для выполнения оптимизации разгона шахтной подъемной машины использован класс непрерывно-дифференцированных базисных функций. Они включали свободные параметры, по которым была проведена минимизация энергетического критерия. Получено несколько приближенных решений вариационной задачи. С использованием численного интегрирования дифференциальных уравнений проведен анализ результатов по энергетическим и динамическим показателям.

Результаты. Установлено, что полученные в работе закономерности движения шахтной подъемной машины позволяют устранить колебания ее элементов (груза и полумуфт) в конце ее разгона. Кроме того, в течение разгона значительно уменьшаются нежелательные максимальные динамические нагрузки в канате, муфте и приводе, а также наблюдается незначительное уменьшение нежелательных среднеквадратических значений энергетических и динамических показателей работы подъемной машины. Доказано, что численные значения энергетических и динамических показателей движения машины значительно зависят от характеристик ее движения при разгоне.

Научная новизна. Выполнена постановка оптимизационной задачи, где в качестве критерия выбран нелинейный интегральный функционал. Установлено, что вариационный подход не позволяет получить точное решение задачи. Для нахождения приближенных решений задачи получено пять базисных функций, содержащих свободные параметры. Кроме того, для синтеза базисных функций были использованы заданные краевые условия, которые позволили значительно снизить нежелательные динамические показатели работы шахтной подъемной машины. Полученные приближенные (квазиоптимальные) решения вариационной задачи исследованы с помощью комплекса энергетических и динамических показателей. Установлена рациональная базисная функция, которая является несложной и удовлетворяет требование достаточной точности решения оптимизационной задачи.

Практическая значимость. Полученный в работе оптимальный режим разгона шахтной подъемной машины может быть реализован с помощью управляемого электропривода постоянного или переменного тока, что позволяет повысить эффективность работы шахтной подъемной машины по энергетическим и динамическим показателям.

Ключевые слова: *шахтный подъем, энергетическая оптимизация, режим разгона, нелинейная задача, базисная функция*

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