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SYNTHESIS OF THE ALGORITHM FOR THE FLOW PARAMETERS OPTIMAL CONTROL OF THE REVERSIBLE CONVEYOR

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ABSTRACT

Context. The problem of optimal control of flow parameters of a conveyor-type transport system containing sections with reversible conveyors is considered. The object of the stady was an analytical model of a reversible transport conveyor for synthesizing an algorithm for optimal control of the flow parameters of a reversible transport conveyor.

Objective. The goal of the work is to develop a synthesis technique for an algorithm for optimal control of the flow parameters of a reversible transport conveyor based on an analytical model of a conveyor section containing a transport delay.

Method. An analytical model of a reversible conveyor has been developed for the case of a constant speed of a conveyor belt, which makes it possible to determine the values of the output flows from the reverse section with known values of material flows coming to the input of the conveyor section. To build a model of the reversible section of the conveyor, an analytical model of the section of the conveyor in partial derivatives, containing the transport delay, was used. When constructing the model, the assumption was made about the instantaneous switching of the direction of movement of the conveyor belt, and it is also assumed that the interval between switching the direction of the belt speed exceeds the values of the transport delay for the conveyor section. To synthesize an algorithm for optimal control of the reversible conveyor, a control quality criterion was introduced. The formulation of the problem of optimal control of the flow parameters of the reversible conveyor is given, based on the Pontryagin maximum principle. The Hamilton function for the controlled system is written, taking into account the criterion of the quality of control of the reversible conveyor. A technique for synthesizing an algorithm for optimal control of the material output flow of a section of a reversible conveyor is demonstrated. The conditions for switching the direction of the speed of the conveyor belt are determined.

Results. The developed model of the reversible conveyor section is used to synthesize an algorithm for optimal control of the material output flow of the reversible conveyor section.

Conclusions. A method for the synthesis of algorithms for optimal control of the flow parameters of a transport system with sections containing reversible conveyors has been developed. The construction of an analytical model opens up new perspectives for the design of transport conveyor control algorithms, which can be used to reduce the specific energy costs for material transportation in the mining industry.

KEYWORDS: reversible conveyor, PiKh-conveyor model, transport delay, conveyor belt speed, transport system, conveyor control.

ABBREVIATIONS

PDE-model is a model of continuous representation of the movement of material along the technological route of the production line, using equations in partial derivatives;

PiKh-model is an analytical model of a conveyor line that allows you to determine the density of the material and the material flow at an arbitrary point on the conveyor belt;

RC (reversible conveyor) is a conveyor whose belt is capable of changing the direction of speed to the opposite in order to move the material in the opposite direction.

NOMENCLATURE

S_d is a conveyor line length;

T_d is a characteristic time for the material to pass the transport route;

$[\chi]_0(t,S)$ is a linear density of the material at the moment of time t at the point of the transport route with the coordinate $S \in [0, S_d]$;

$[\chi]_1(t,S)$ is a material flow at the moment of time t at the point of the transport route with the coordinate $S \in [0, S_d]$;

$\Psi(S)$ is an initial distribution of material along the technological route;

Θ is a limit value of the linear density of the material for the conveyor section;

$\lambda_i(t)$ is a material flow from the i-th bunker incoming to the input of the conveyor section;

$\lambda_{i\max}$ is a maximum allowable value of the material flow from the i-th bunker incoming to the input of the conveyor section, $0 \le \lambda_1(t) \le \lambda_{i\max}$;

$\sigma_i(t)$ is a planned value of the output flow from the conveyor section, determined by the input flow from the i-th bunker;

$a(t)$ is a conveyor belt speed;

G^{-1} is a function inverse to the function $G(\tau)$;

$H(S)$ is a Heaviside function;

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$\delta(S)$ is a Dirac delta function;

τ_{um} is a dimensionless time of switching the direction of the belt speed, $m = 0,1,2,3...$;

τ_{u0} is a dimensionless value of the start time of the transport conveyor belt;

τ_{uk} is a dimensionless value of the transport conveyor completion time, $m = 0$;

$\Delta\tau_{u(m+1)} = \tau_{u(m+1)} - \tau_{um}$ is a dimensionless time interval between switching the direction of the belt speed;

$\Delta\tau_{\xi}$ is a dimensionless value of the transporting delay at the route point, determined by the value ξ;

$\Delta\tau_1$ is the dimensionless value of the transporting delay at the route point, determined by the value $\xi = 1$.

INTRODUCTION

The conveyor is one of the most effective ways to transport material in the mining industry [1, 2]. The length of the transportation route for modern conveyor-type transport systems has reached one hundred kilometers [3, 4] and continues to increase. With a conveyor belt fill factor of 50–70% with material [5], transportation costs reach 20% of the material mining cost [6, 7]. Reducing transport costs is achieved by increasing the load factor of the conveyor belt material [8, 9]. To do this, control systems for belt speed [10, 11, 12], the output flow of material from the accumulating bunker [3, 13, 14], and energy management methodology [15, 16, 17] are used.

The division of the transport conveyor into sections increases the efficiency of managing a section of the transport route within a separate section and the reliability of the functioning of the transport system as a whole [18, 19]. Technological trajectories of individual elements of the material within the section are similar, do not intersect, and are displaced relative to each other [20]. The displacement of technological trajectories is determined by the value of the speed of the conveyor belt.

Increasing the material load factor of the conveyor belt can also be achieved by changing the route of material transportation. Such control is carried out using reversible conveyors, which allow changing the direction of material movement within the section to the opposite direction [21, 22, 23]. The present study is devoted to the synthesis of optimal control algorithms for the flow parameters of a reversible conveyor.

The object of study is an analytical model of a transport reversible conveyor.

The subject of study is analytical methods for designing a transport reversible conveyor control system.

The purpose of the work is analytical methods for designing a transport reversible conveyor control system.

1 PROBLEM STATEMENT

The reversible conveyor (RC) is used to ensure material is transported in both forward and reverse directions (Fig. 1). This method of designing a conveyor-type transport system provides a more uniform loading of branched transport routes as a result of redirecting material flows from a more loaded transport route to a less loaded route.

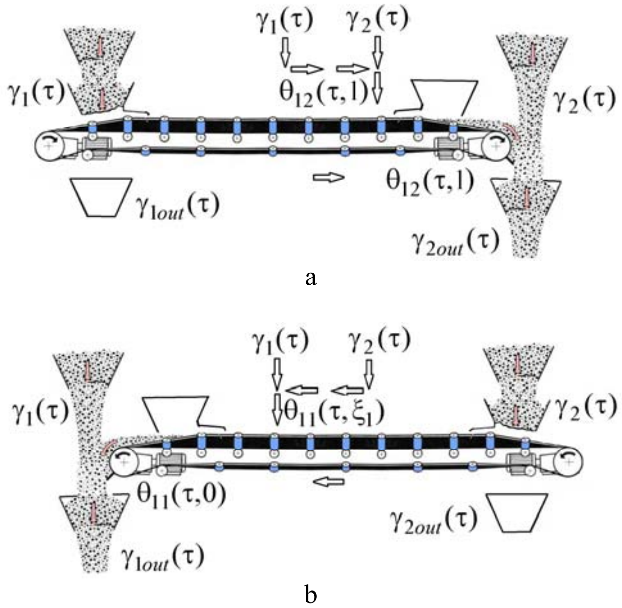

Figure 1 – Schematic diagram of the functioning of the transport reversible conveyor:
a – the direct moving belt; b – the reverse moving belt

The transport reversible conveyor is a complex dynamic distributed system with a transport delay. An analytical solution to the problem of the main conveyor, which makes it possible to calculate the value of the output flow for a given initial distribution of material along the transport route, was obtained in [1]. The problem of synthesizing the optimal control of the flow parameters of the transport main conveyor is considered in [2, 3].

For a reversible conveyor, the problem of synthesizing optimal control can be represented as successive algorithms for optimal control of the material flow between the switching points of the direction of the conveyor belt speed. The initial conditions for the equation of the transport conveyor [1] at the point of switching the direction of movement are determined by the current distribution of material along the transport route.

When synthesizing algorithms for optimal material flow control, let us assume:

a) there is no control over the flow of material incoming the reversible conveyor from the input accumulating bunker;

b) belt speed between switching intervals is constant;

c) the change of speed direction is instantaneous;

d) the time interval $\Delta\tau_{um}$ between two adjacent switching of the direction of speed exceeds the time $\Delta\tau_1$ ($\xi = 1$) of the passage of the material along the transport path of the conveyor section.

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The accepted assumption about the instantaneous switching of the speed of the belt implies the absence of restrictions on the amount of change in the speed of the conveyor belt, due to the occurrence and propagation of dynamic stresses along the conveyor belt. The assumption of the absence of material flow control at the input and the assumption of a constant belt speed makes it possible to simplify the problem of synthesizing algorithms for optimal material flow control by considering at the initial stage a model of a reversible conveyor with a constant transport delay in the presence of relay control. Separate studies will be devoted to the synthesis of algorithms for optimal control of the speed of the reversible conveyor belt and the flow of material coming from the accumulation bunker.

2 REVIEW OF THE LITERATURE

To build a model of a separate section of the transport conveyor, the finite element method is used [24, 25, 26]; finite difference method [27]; Lagrange method; method using the aggregated equation of state [11]; equations of system dynamics [14]. The methods are based on various numerical schemes for calculating the flow parameters of the transport system. Also, models based on neural networks [4, 28, 29] and regression equations [30, 31, 32] are widely used to describe the state of the transport conveyor. The synthesis of an optimal algorithm for controlling the flow parameters of a transport multi-section conveyor using a model that includes a neural network is presented in [33]. Among the existing models used to calculate the flow parameters of the transport conveyor section, it should be noted the analytical PiKh-model (PDE-model) [34], which is used to synthesize algorithms for optimal control of the flow parameters of the conveyor, taking into account the energy management methodology [6], to synthesize the optimal speed control algorithm movement of the conveyor belt [8], as well as for generating a training data set in a model based on a neural network [33] and on a linear regression equation [32]. The analytical PiKh-model also proved to be good in describing the change in the flow parameters of a multi-section main conveyor and modeling a conveyor with an input/output accumulating bunker. In this study, the scope of the analytical PiKh-model of the transport conveyor will be expanded, using it to build a model of a reversible conveyor.

The principle of operation of a multi-section transport system containing reversible conveyors is described in [21] when simulating transport flows in the “Rudna” mine (Poland). Later, the “Rudna” mine transport system was considered during research in [22, 23]. Interest in the use of reversible conveyors is associated, on the one hand, with the use of a reversible conveyor to change the route of material transportation, and on the other hand, with the use of a reversible conveyor as an accumulation bunker in the transport system. The principle of operation of the reversible conveyor section described in [21] is used to develop a reversible conveyor model based on the analytical PiKh-model.

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3 MATERIALS AND METHODS

To build a model of a transport reversible conveyor that determines the state of the flow parameters of a section along the transportation route, we will use the equation PiKh–model of the conveyor in a dimensionless form [34]

$$\frac{\partial\theta_0(\tau,\xi)}{\partial\tau}+g(\tau)\frac{\partial\theta_0(\tau,\xi)}{\partial\xi}=\delta(\xi)\gamma(\tau)\,, \tag{1}$$

$$\theta_0(0,\xi)=\mathrm{H}(\xi)\psi(\xi)\,. \tag{2}$$

The state of the flow parameters of the reversible conveyor section is described by dimensionless variables:

$$\tau=\frac{t}{T_d}\,,\ \xi=\frac{S}{S_d}\,, \tag{3}$$

$$\theta_0(\tau,\xi)=\frac{[\chi]_0(t,S)}{\Theta}\,,\ \psi(\xi)=\frac{\Psi(S)}{\Theta}\,, \tag{4}$$

$$\gamma_i(\tau)=\lambda_i(t)\frac{T_d}{S_d\Theta}\,,\ \gamma_{i\max}=\lambda_{i\max}\frac{T_d}{S_d\Theta}\,,\ i=1,2\,, \tag{5}$$

$$\Theta=\max\left\{\Psi(S),\frac{\lambda_i(t)}{a(t)}\right\},\ \vartheta_i(\tau)=\sigma_i(t)\frac{T_d}{S_d\Theta} \tag{6}$$

$$g(\tau)=a(t)\frac{T_d}{S_d}\,,\ [\chi]_1(t,S)=a(t)[\chi]_0(t,S) \tag{7}$$

$$\delta(\xi)=S_d\delta(S)\,,\ H(\xi)=H(S)\,. \tag{8}$$

The solution of equation (1) with initial conditions (2) has the form [34]

$$\theta_0(\tau,\xi)=\left(1-H(\xi-G(\tau))\right)\frac{\gamma_1(G^{-1}(G(\tau)-\xi))}{g(G^{-1}(G(\tau)-\xi))}+ \\ +\mathrm{H}(\xi-G(\tau))\psi(\xi-G(\tau))\,, \tag{9}$$

$$G(\tau)=\int_0^\tau g(\alpha)d\alpha\,, \tag{10}$$

$$\theta_1(\tau,\xi)=g(\tau)\theta_0(\tau,\xi)\,. \tag{11}$$

The presented solution makes it possible to determine the density of the material $\theta_0(\tau,\xi)$ and the flow of the material $\theta_1(\tau,\xi)$ at an arbitrary point in time τ for each point ξ of the transport route. In this study, let us focus on building a model of a transport reversible conveyor, the belt speed of which is constant and equal g_0 (with the exception of the moment of switching the direction of movement of the conveyor belt)

$$g(\tau)=g_0\,,\ G(\tau)=g_0\tau\,, \\ 0\le\tau\le\tau_{u1}\,. \tag{12}$$

For a constant belt speed, solution (9)–(11) can be written in the following form

$$\theta_0(\tau,\xi) = \left(1 - H\left(\xi - g_0\tau\right)\right)\frac{\gamma_1(\tau - \Delta\tau_\xi)}{g_0} + \tag{13}$$
$$+\mathrm{H}(\xi - g_0\tau)\psi(\xi - g_0\tau),$$
$$\theta_1(\tau,\xi) = g_0\theta_0(\tau,\xi), \tag{14}$$
$$\Delta\tau_\xi = \xi / g_0, \tag{15}$$
$$0 \le \tau \le \tau_{u1}.$$

The resulting solution (9)–(11) makes it possible to determine the output flow of material from the conveyor section

$$\theta_1(\tau,1) = \left(1 - H\left(1 - g_0\tau\right)\right)\gamma_1(\tau - \Delta\tau_1) + $$
$$+\mathrm{H}(1 - g_0\tau)\psi(1 - g_0\tau)g_0, \tag{16}$$
$$\Delta\tau_1 = 1/g_0.$$

Solution (13)–(16) of equation (1) was obtained for the case of material movement only in the forward direction (Fig. 1a) without speed switching.

If there are points of switching the direction of the flow at the instants of time τ_{um}, the values of the output flows $\gamma_{1out}(\tau)$, $\gamma_{2out}(\tau)$ of the reversible conveyor, taking into account the solution (16), take the form

$$\gamma_{n\,out}(\tau) = \sum_{m=0}^{M} F_{n,m}(\tau)\left(\gamma_{n1}(\tau) + \gamma_{n2,m}(\tau) + \gamma_{n3,m}(\tau)\right), \tag{17}$$
$$\gamma_{n1}(\tau) = \gamma_n(\tau), \quad n = (1,2), \tag{18}$$
$$\gamma_{12,m}(\tau) = \left(1 - H\left(1 - g_0\Delta\tau_{m\tau}\right)\right)\gamma_2(\tau - \Delta\tau_1), \tag{19}$$
$$\gamma_{22,m}(\tau) = \left(1 - H\left(1 - g_0\Delta\tau_{m\tau}\right)\right)\gamma_1(\tau - \Delta\tau_1), \tag{20}$$
$$\gamma_{n3,m}(\tau) = H\left(1 - g_0\Delta\tau_{m\tau}\right)\gamma_n(\tau_{um} - \Delta\tau_{m\tau}), \tag{21}$$
$$\Delta\tau_{m\tau} = \left(\tau - \tau_{um}\right), \tag{22}$$
$$F_{1,m}(\tau) = \frac{1-(-1)^m}{2}\left(H\left(\tau - \tau_{um}\right) - H\left(\tau - \tau_{u(m+1)}\right)\right), \tag{23}$$
$$F_{2,m}(\tau) = \frac{1+(-1)^m}{2}\left(H\left(\tau - \tau_{um}\right) - H\left(\tau - \tau_{u(m+1)}\right)\right), \tag{24}$$
$$\tau_m = \infty, \; m > M.$$

The flow of material into the bunker occurs with the forward direction of the conveyor belt (Fig. 1a), and the flow of material into the bunker $\gamma_{1out}(\tau)$ occurs with the reverse direction of the conveyor belt (Fig. 1b).

Functions $F_{1,m}(\tau)$, $F_{2,m}(\tau)$ determine the time interval $\Delta\tau_{u(m+1)}$ between switching the direction of movement of the material along the conveyor belt. The function $F_{2,m}(\tau)$ is equal to one for the case if the conveyor moves in the forward direction (Fig. 1a) and the inequality $\tau_{um} \le \tau < \tau_{u(m+1)}$, (m is even) is fulfilled. Similarly, the function $F_{2,m}(\tau)$ is equal to one for the case if the conveyor moves in the opposite direction (Fig. 1b) and the inequality $\tau_{um} \le \tau < \tau_{u(m+1)}$, ($m$ is odd) is satisfied. The function $\gamma_{22,m}(\tau)$ determines the flow of material from the bunker $\gamma_1(\tau)$ to the bunker $\gamma_{2\,out}(\tau)$ with a transport delay (Fig. 1a) in the time interval $\tau_{um} \le \tau < \tau_{u(m+1)}$. The function $\gamma_{12,m}(\tau)$ determines the flow of material from bunker $\gamma_2(\tau)$ to bunker $\gamma_{1\,out}(\tau)$ with the same transport delay $\Delta\tau_1$ (Fig. 1b).

The function $\gamma_{23,m}(\tau)$ determined by the flow of material from the conveyor during the time interval $\Delta\tau_1$ from the moment of switching τ_{um}. The flow of material $\gamma_{23,m}(\tau)$ is formed by the distribution of material $\psi_m(\xi)$ along the conveyor belt at a time τ_{um}

$$\gamma_{23,m}(\tau) = \gamma_{23,m}(\tau_{um} + \Delta\tau_{m\tau}) = \psi_m(1 - g_0\Delta\tau_{m\tau}). \tag{25}$$

Taking into account the assumption $\Delta\tau_{um} > \Delta\tau_1$, the distribution of material along the conveyor belt is completely determined by the material flow $\gamma_2(\tau)$. This dependence at a constant speed of the belt within the time interval $\Delta\tau_{um}$ can be represented in the following form

$$\gamma_2(\tau_{um} - \Delta\tau_{m\tau}) = \psi_m(1 - g_0\Delta\tau_{m\tau}), \tag{26}$$

whence for the time interval $\Delta\tau_1$ from the moment of the time of switching τ_{um}, the expression is obtained for the output flow from the conveyor belt in the forward direction of motion

$$\gamma_{23,m}(\tau) = \gamma_{23,m}(\tau_{um} + \Delta\tau_{m\tau}) =$$
$$= \gamma_2(\tau_{um} - \Delta\tau_{m\tau}) = \gamma_2(2\tau_{um} - \tau). \tag{27}$$

For the reverse direction of movement of the belt, the distribution of material $\psi_m(\xi)$ along the conveyor belt at the moment of time τ_{um} is given by the flow of material $\gamma_1(\tau)$

$$\gamma_1(\tau_{um} - \Delta\tau_{m\tau}) = \psi_m(g_0\Delta\tau_{m\tau}). \tag{28}$$

Taking into account the relationship between the output flow $\gamma_{13,m}(\tau)$ and the distribution of material $\psi_m(\xi)$ along the conveyor belt for the period of time $\Delta\tau_1$ from the time of switching τ_{um}

$$\gamma_{13,m}(\tau) = \gamma_{13,m}(\tau_{um} + \Delta\tau_{m\tau}) = \psi_m(g_0\Delta\tau_{m\tau}), \tag{29}$$

the value of the material flow $\gamma_{13,m}(\tau)$ is obtained when the conveyor moves in the opposite direction

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$$\gamma_{13,m}(\tau) = \gamma_{13,m}(\tau_{um} + \Delta\tau_{m\tau}) = \\ = \gamma_1(\tau_{um} - \Delta\tau_{m\tau}) = \gamma_1(2\tau_{um} - \tau) . \quad (30)$$

At given times of switching τ_{um} the direction of movement of the belt, expressions (17) determine the flow of material in the transport system in the presence of a reverse mode of operation of the conveyor.

4 EXPERIMENTS

To carry out numerical experiments, the software has been developed that makes it possible to calculate the values of the flow parameters of the transport conveyor in accordance with the RC model (17)–(26). Test values of material flows $\gamma_1(\tau)$, $\gamma_2(\tau)$, incoming the section of the reversible conveyor from the accumulation bunkers, as well as the value of the planned output flow $\vartheta_2(\tau)$ from the section of the conveyor represented by periodic functions (Fig. 2):

$$\gamma_1(\tau) = 2.0 + \sin(0.4\pi\tau), \\ \gamma_2(\tau) = 2.0 + \sin(0.2\pi\tau), \\ \vartheta_2(\tau) = 2.0 + 2.0\sin(0.2\pi\tau + \pi). \quad (31)$$

Periodic functions in the form (31) are used in the qualitative analysis of the flow parameters of transport and production systems [26, 35, 36], the production process of which is periodic. This approach makes it possible to reveal the qualitative features of the model and the relationship between flow parameters [37]. When carrying out numerical experiments, it was assumed that at the initial time the conveyor section is fully loaded with material

$$\psi(\xi) = 1 . \quad (32)$$

In the absence of reversible control, the material flows $\gamma_1(\tau)$, $\gamma_2(\tau)$, incoming the section of the reversible conveyor from the accumulation bunkers, form the output material flow $\gamma_{2out}(\tau)$ from the conveyor section (Fig. 3) in accordance with the RC model (17)–(26). The type of function $\psi(\xi)$, which specifies the initial distribution of material along the RC section, affects the value of the output material flow only in the initial period of time $\tau < 1$. For the time moments of the transport system operation $\tau \geq 1$, the initial distribution of the material does not affect the state of the output flow parameters of the conveyor section (Fig. 3). In the absence of reversible control, the output flow of material from the conveyor section is determined by the expression

$$\gamma_{2out}(\tau) = \gamma_2(\tau) + \gamma_1(\tau - 1) . \quad (33)$$

which contains the transport delay $\Delta\tau_1 = 1$. The superposition of material flows from the accumulation bunkers $\gamma_1(\tau)$, $\gamma_2(\tau)$, that form the output flow $\gamma_{2out}(\tau)$, leads to the fact that in the allocated time intervals the output flow $\gamma_{2out}(\tau)$ deviates significantly from the planned material flow $\vartheta_2(\tau)$, required to maintain a continuous production process (Fig. 3). With the reversible movement of the belt, the flow of material changes direction, and therefore, $\gamma_{2out}(\tau) = 0$. The condition (Fig. 4) was used to calculate the switching points of the belt movement direction

$$\Delta\gamma_2(\tau) = \gamma_{2out}(\tau) - 2\vartheta_2(\tau) > 0 . \quad (34)$$

The function $\Delta\gamma_2(\tau)$, on the basis of which the switching points are numerically calculated, is shown in Fig. 4. When $\Delta\tau_{m\tau} >> 1$, to improve the performance of calculations, the RC model (17)–(26) can be replaced by the approximate model (33).

The method for calculating switching points in accordance with condition (34) was used to synthesize the algorithm for controlling the output flow from the conveyor section.

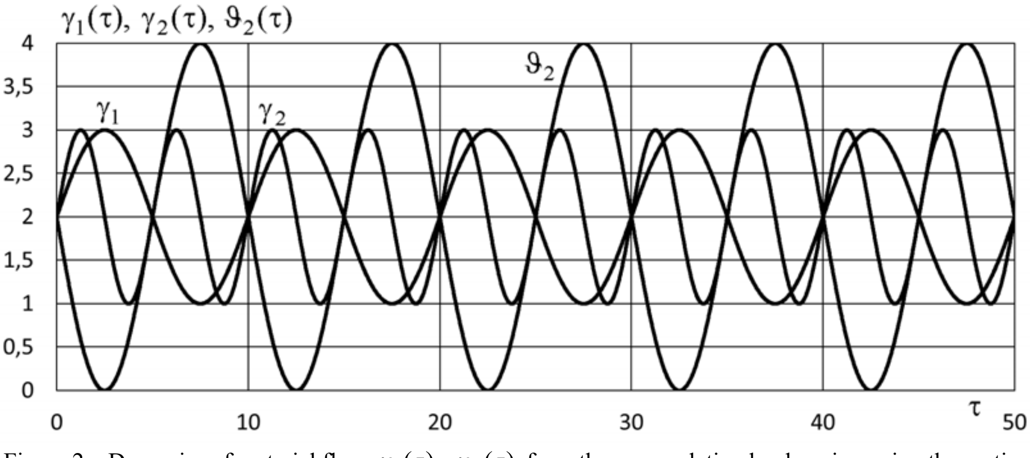

Figure 2 – Dynamics of material flows $\gamma_1(\tau)$, $\gamma_2(\tau)$ from the accumulation bunkers incoming the section of the reversible conveyor and the plan material flow $\vartheta_2(\tau)$ from RC

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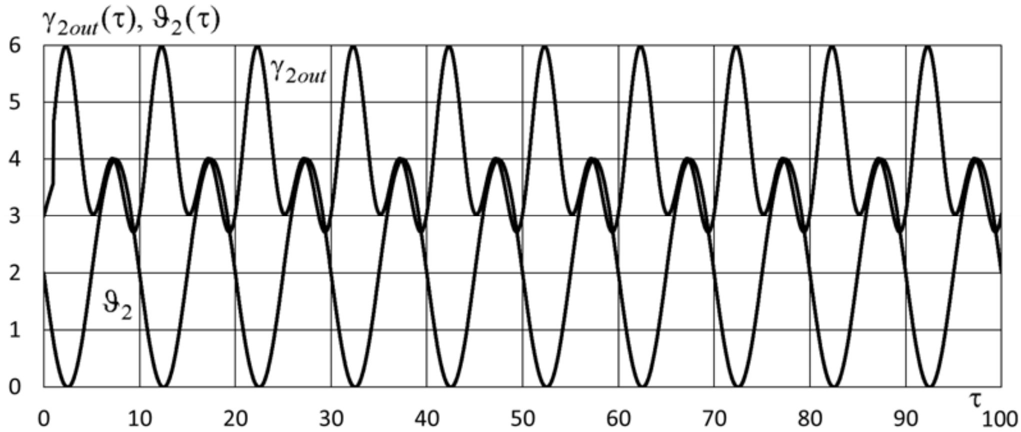

Figure 3 – Comparison of the material flow $\gamma_{2out}(\tau)$ from the conveyor in the absence of reverse control with the value of the planned material flow $\vartheta_2(\tau)$ from RC

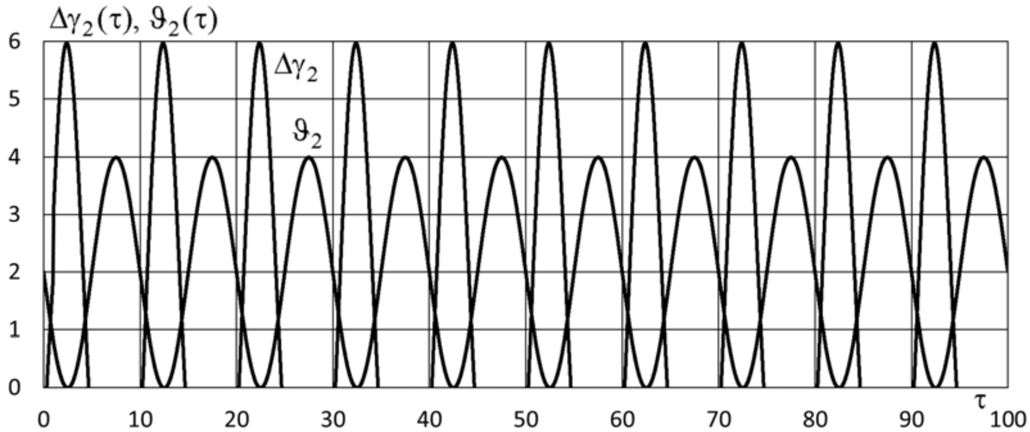

Figure 4 – A function $\Delta\gamma_2(\tau)$ for constructing points for switching the reversible mode of a conveyor section for a given planned value of the output flow $\vartheta_2(\tau)$

5 RESULTS

Let us formulate the problem of constructing an optimal program for controlling the flow of material $\gamma_{2out}(\tau)$, coming out of the reversible conveyor to meet the needs of the processing industry in the material. The transport conveyor will be controlled by switching the direction of material movement. Let us determine the value of the switching points τ_{um} of the direction of material movement during a period of time $\tau = [0, \tau_{uk}]$ with continuous control $u(\tau) = [0; \gamma_{2out}(\tau)]$ of the output flow of material from the reverse conveyor, which lead to a minimum of the functional

$$J(\tau_{uk}) = \int_0^{\tau_{uk}} \left(u(\tau) - \vartheta_2(\tau)\right)^2 d\tau \to \min , \qquad (35)$$

with a limitation on the value of material flow

$$u(\tau) = [0; \gamma_{2out}(\tau)], \qquad (36)$$
$$\infty > \gamma_{2out}(\tau) > 0 .$$

The control value $u(\tau)$ is equal to $\gamma_{2out}(\tau)$ for forward material movement the control value $u(\tau)$ is zero for reverse material movement. To build a control system, this paper uses a very simple criterion of control quality, which makes it possible to demonstrate the features of control of a reversible conveyor. It is assumed that there are no restrictions on the maximum permissible value of the linear density of the material along the conveyor belt.

The Pontryagin function for control problem (35), (36) has the form:

$$H = -\left(u(\tau) - \vartheta_2(\tau)\right)^2 \to \max . \qquad (37)$$

From the condition of the maximum of the Pontryagin function, the optimal control of the reversible conveyor is determined $u(\tau)$

$$\frac{\partial H}{\partial u(\tau)} = -2\left(u(\tau) - \vartheta_2(\tau)\right) = 0 . \qquad (38)$$

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Since the control $u(\tau)$ takes one of the values $\left[0;\gamma_{2out}(\tau)\right]$, and in the general case

$$u(\tau) \neq \gamma_{2out}(\tau),$$

then equality (38) cannot be used to construct the optimal control of the reversible conveyor. Taking this into account, the conditions for the proposed switching of the conveyor operation mode are determined by the inequalities

$$\gamma_{2out}(\tau) - \vartheta_2(\tau) > \vartheta_2(\tau),\ u(\tau) = 0,$$
$$\gamma_{2out}(\tau) - \vartheta_2(\tau) \leq \vartheta_2(\tau),\ u(\tau) = \gamma_{2out}(\tau),$$

for which the Pontryagin function has a minimum. Thus, for a finite interval $\Delta\tau_1 = 1$ the point of switching the direction of movement at the moment of time τ_{um0}, defined by the condition

$$\gamma_{2out}(\tau_{um0}) = 2\vartheta_2(\tau_{um0}), \quad (39)$$
$$\Delta\gamma_2(\tau) = \gamma_{2out}(\tau) - 2\vartheta_2(\tau),$$

For switching points when the condition is satisfied

$$I(\tau) > 0, \quad (40)$$

the conveyor line operates in reversible mode, $u(\tau) = 0$. As a rule, for existing conveyor systems, the condition $\Delta\tau_{um} >> \Delta\tau_1$ is satisfied, and the switching points are determined by equation (39).

A numerical experiment demonstrating the synthesis of an algorithm for the material output flow control for boundary and initial conditions (31), (32) is presented in Fig. 5. The presence of peak values of the output flow is explained by the fact that starting from the moment of switching the direction of movement and during the time interval $\Delta\tau = \Delta\tau_1 = 1$ the output flow of material $\gamma_{2out}(\tau)$ determined only by the input flow of material $\gamma_2(\tau)$, and during the time interval for which the condition $\Delta\tau \geq 1$ is satisfied, the output flow of material $\gamma_{2out}(\tau)$ is determined by the input flows of material $\gamma_1(\tau)$ and $\gamma_2(\tau)$, which and leads to a jump in the function $u(\tau) = \left[0;\gamma_{2out}(\tau)\right]$ at $\Delta\tau = 1$. An analysis of the results of a numerical experiment shows that the initial distribution of material (32) does not affect the value of the output flow at $\tau >> 1$.

6 DISCUSSION

One of the significant difficulties that researchers encounter when designing control systems for a transport system containing reversible conveyors is building a model of a reversible conveyor section. Let us consider one of the ways in which these difficulties can be overcome.

One such way is to use an approximate model for the section of the conveyor in which the transport delay $\Delta\tau_1 = 0$ is assumed. This case may correspond to a simplified model of the reversible conveyor section in the following form

$$\gamma_{n\,out}(\tau) = \sum_{m=0}^{M} F_{n,m}(\tau)\left(\gamma_1(\tau) + \gamma_2(\tau)\right). \quad (41)$$

For a conveyor section of small length ($S_d \approx 200$ meters [23]), at a belt speed of one meter at the second, the transport delay is several minutes. For conveyor sections of medium length ($S_d \approx 2000$ meters [23]), the transport delay can be about one hour. If there are several reversible sections through which the flow of material moves in the transport system, then the total transport delay of the

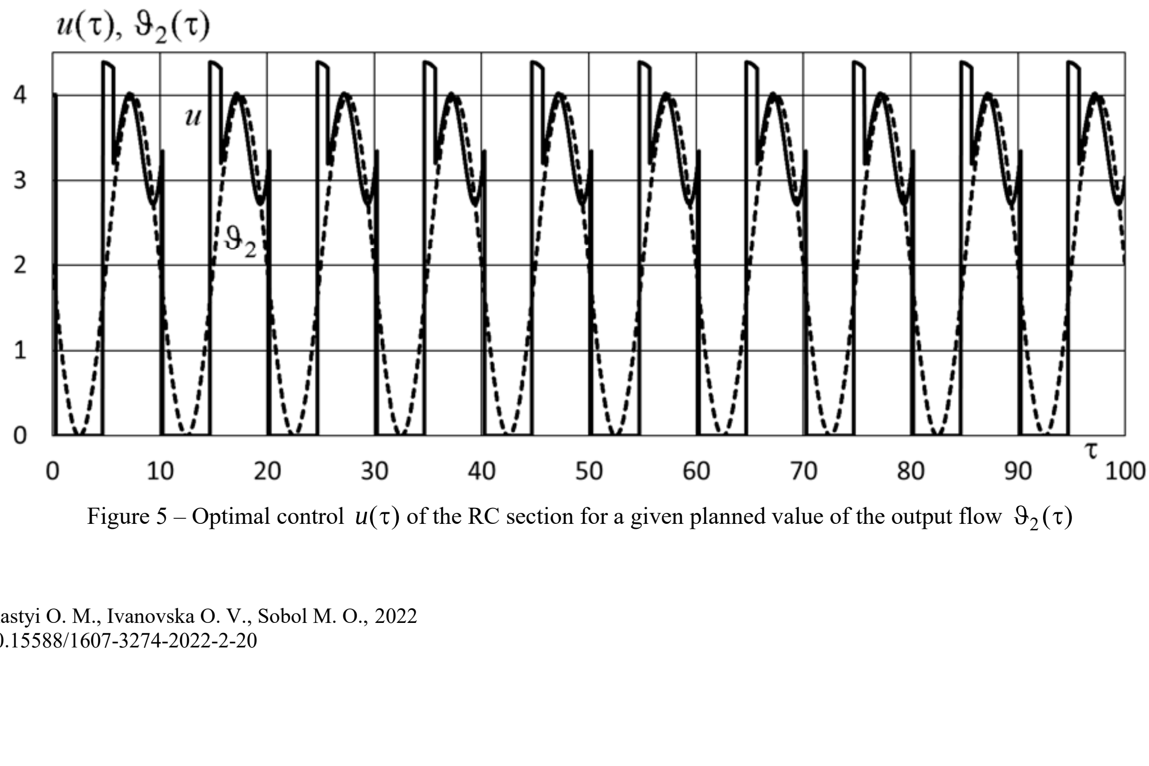

Figure 5 – Optimal control $u(\tau)$ of the RC section for a given planned value of the output flow $\vartheta_2(\tau)$

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conveyor system during the sequential movement of material can be obtained as a result of adding the transport delays of individual sections. Thus, the value of the transport delay can be significant in the value. Neglecting the transport delay in the model of the conveyor section can lead to significant errors in the calculation of the flow parameters of the transport system, and the model itself, accordingly, should not be used to build algorithms for optimal control of the flow parameters of the transport system.

The use of model (41) implies not only an approximate calculation of the values of the flow parameters of the conveyor section, but also the fact that the specific energy costs for the movement of material are not optimized for the reversible sections of the transport system. The reduction in energy costs for moving the mined material along the transport route makes the problem of building accurate analytical models of reversible sections that can be used to synthesize algorithms for optimal control of the output flow of a conveyor-type transport system relevant.

When constructing the model and synthesizing material flow control algorithms, a number of assumptions are made in this paper. The purpose of these assumptions is to simplify as much as possible the mathematical transformations necessary to build the model, demonstrating the general methodology for creating models of reversible conveyor sections and the features of synthesizing the algorithm for optimal material flow control.

CONCLUSIONS

The actual problem of synthesizing algorithms for optimal control of the flow parameters of a conveyor-type transport system containing sections with reversible conveyors is considered. An analytical model of a reversible conveyor for the design of transport conveyor control systems is proposed.

The scientific novelty of obtained results is that for the first time an analytical model of a reversible conveyor section has been proposed for conveyor-type transport systems. This model, under the assumptions of a constant speed of the conveyor belt, of instantaneous switching of the direction of movement of the conveyor belt and of the value of the time interval between two adjacent switching of the direction of speed $\Delta\tau_{um} \geq \Delta\tau_1$, makes it possible to calculate the output flows of material $\gamma_{1out}(\tau)$, $\gamma_{2out}(\tau)$ from the section of the reversible conveyor with known values of the input flows of material $\gamma_1(\tau)$, $\gamma_2(\tau)$. The construction of an analytical model of a reversible conveyor section allows, for a given control quality criterion, to synthesize simple algorithms for optimal control of the flow parameters of a transport system containing sections with reversible conveyors.

The practical significance of obtained results is that a technique has been developed for constructing algorithms for optimal control of the flow parameters of a transport system with sections containing reversible conveyors, which can be used to reduce the specific energy costs for transporting material at mining enterprises.

Prospects for further research is to develop systems for controlling the belt speed of the reversible conveyor.

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СИНТЕЗ АЛГОРИТМУ ОПТИМАЛЬНОГО УПРАВЛІННЯ ПОТОЧНИМИ ПАРАМЕТРАМИ РЕВЕРСИВНОГО КОНВЕЄРА

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АНОТАЦІЯ

Актуальність. Розглянуто проблему оптимального управління потоковими параметрами транспортної системи конвеєрного типу, що містить секції з реверсивними конвеєрами. Об'єктом дослідження була аналітична модель транспортного реверсивного конвеєра для синтезу алгоритму оптимального керування потоковими параметрами транспортного реверсивного конвеєра. Мета роботи – розробка методики синтезу алгоритму оптимального керування потоковими параметрами транспортного реверсивного конвеєра, що базується на аналітичній моделі конвеєрної секції, що містить транспортну затримку.

Метод. Розроблено аналітичну модель реверсивного конвеєра для випадку постійної швидкості конвеєрної стрічки, що дозволяє визначити значення вихідних потоків з реверсивної секції при відомих значень потоків матеріалу, що надходять на вхід секції конвеєра. Для побудови моделі реверсивної секції конвеєра використано аналітичну модель секції конвеєра у приватних похідних, що містить транспортну затримку. При побудові моделі введено припущення про миттєве перемикання напрямку руху стрічки конвеєра, а також передбачається, що інтервал між перемиканнями напрямку швидкості руху стрічки перевищує значення транспортної затримки для секції конвеєра. Для синтезу алгоритму оптимального управління реверсивним конвеєром запроваджено критерій якості управління. Дана постановка задачі оптимального управління потоковими параметрами реверсивного конвеєра, заснована на принципі максимуму Понтрягіна. Записано функцію Гамільтона для керованої системи, яка враховує критерій якості керування реверсивним конвеєром. Продемонстровано методику синтезу алгоритму оптимального управління вихідним потоком матеріалу секції реверсивного конвеєра. Визначено умови перемикання напрямку швидкості руху стрічки конвеєра.

Результати. Розроблена модель секції реверсивного конвеєра використана синтезу алгоритму оптимального управління вихідним потоком матеріалу секції реверсивного конвеєра.

Висновки. Розроблено методику синтезу алгоритмів оптимального керування потоковими параметрами транспортної системи з секціями, що містять реверсивні конвеєри. Побудова аналітичної моделі відкриває нові перспективи для проектування алгоритмів керування транспортним конвеєром, які можуть бути використані для зниження питомих енергетичних витрат на транспортування матеріалу на підприємствах гірничодобувної промисловості.

КЛЮЧОВІ СЛОВА: реверсивний конвеєр, PiKh-модель конвеєра, транспортна затримка, швидкість стрічки конвеєра, транспортна система, керування конвеєром.

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СИНТЕЗ АЛГОРИТМА ОПТИМАЛЬНОГО УПРАВЛЕНИЯ ПОТОКОВЫМИ ПАРАМЕТРАМИ РЕВЕРСИВНОГО КОНВЕЙЕРА

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АННОТАЦИЯ

Актуальность. Рассмотрена проблема оптимального управления потоковыми параметрами транспортной системы конвейерного типа, содержащей секции с реверсивными конвейерами. Объектом исследования являлась аналитическая модель транспортного реверсивного конвейера для синтеза алгоритма оптимального управления потоковыми параметрами транспортного реверсивного конвейера. Цель работы – разработка методики синтеза алгоритма оптимального управления потоковыми параметрами транспортного реверсивного конвейера, основанной на аналитической модели конвейерной секции, содержащей транспортную задержку.

Метод. Разработана аналитическая модель реверсивного конвейера для случая постоянной скорости конвейерной ленты, позволяющая определить значения выходных потоков с реверсивной секции при известных значений потоков материала, поступающих на вход секции конвейера. Для построения модели реверсивной секции конвейера использована аналитическая модель секции конвейера в частных производных, содержащая транспортную задержку. При построении модели вве-

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дены допущение о мгновенном переключении направления движения ленты конвейера, а также предполагается, что интервал между переключениями направления скорости движения ленты превышает значения транспортной задержки для секции конвейера. Для синтеза алгоритма оптимального управления реверсивным конвейером введен критерий качества управления. Дана постановка задачи оптимального управления потоковыми параметрами реверсивного конвейера, основанная на принципе максимума Понтрягина. Записана функция Гамильтона для управляемой системы, учитывающая критерий качества управления реверсивным конвейером. Продемонстрирована методика синтеза алгоритма оптимального управления выходным потоком материала секции реверсивного конвейера. Определены условия переключения направления скорости движения ленты конвейера.

Результаты. Разработанная модель секции реверсивного конвейера использована для синтеза алгоритма оптимального управления выходным потоком материала секции реверсивного конвейера.

Выводы. Разработана методика синтеза алгоритмов оптимального управления потоковыми параметрами транспортной системы с секциями, содержащими реверсивные конвейера. Построение аналитической модели открывает новые перспективы для проектирования алгоритмов управления транспортным конвейером, которые могут быть использованы для снижения удельных энергетических затрат на транспортировку материала на предприятиях горнодобывающей промышленности.

КЛЮЧЕВЫЕ СЛОВА: реверсивный конвейер, PiKh-модель конвейера, транспортная задержка, скорость ленты конвейера, транспортная система, управление конвейером.

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