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OPTIMIZATION THE START-UP MODE OF BUCKET ELEVATOR BY CRITERION OF MEAN RATE OF CHANGE EFFORTS IN TRACTION BODY DURING CLASH ON DRIVE DRUM

Loveykin V. S.[1], Loveykin J. V.[2], Tkachuk L. B.[1]

[1]National University of Life and Environmental Sciences of Ukraine, Ukraine.
[2]Taras Shevchenko National University of Kyiv, Ukraine.

Corresponding authors: lovvs@ukr.net, yuriyl@ua.fm.

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Abstract. The oscillations of the structural elements, the drive mechanism and the traction body are minimized by optimizing the movement modes of the grain elevator during transient processes, which made it possible to increase its efficiency. Based on the chosen dynamic model, a mathematical model was created using the d'Alamber's principle. The optimization process of the start-up mode of the bucket elevator was considered by the criterion of mean rate of change efforts in the traction body during clash on the drive drum. Found laws of motion for working branch, the tensioning drum and the drive drum which correspond to the optimal mode of movement of the bucket elevator. Based on the discovered laws of motion were built kinematical characteristics of the main parts of the elevator which are presented in the form of graphical dependencies for the optimal motion mode. The graphical dependencies of the effort changes in the traction body during clash on the drive drum and shrinkage from the tensioning drum also received. Based on the graphical dependencies established that during start-up bucket elevator at the optimal mode of motion there are small oscillating processes that are the smallest just in the optimization by the criterion of mean rate of change efforts in the traction body during clash on the drive drum.

Key words: bucket elevator, dynamic model, mathematical model, motion mode, dynamic load, effort, oscillation.

Introduction

To improve the technological of processing and transportation of grain is advisable to increase the efficiency of work the bucket elevator. During the motion oscillations occur in the elements of the drive mechanism, traction body and supporting structures, which lead to increasing dynamic loads [1]. These loads are most significant during transition processes (start, braking or locking, switch from one speed to another), which leads to the accumulation of fatigue stresses in the construction of the elevator. This in turn leads to premature destruction of it, and complicates the technological process of transportation of grain material (rashes and damage the grain), which negatively affects the safe operation of the elevator as a whole.

Formulation of problem

The minimize oscillations of structural elements, drive mechanism and traction body can be through optimization of movement grain elevator during transition processes that will improve its efficiency.

Analysis of recent research results

Works Khorolsky I. M., Kondrahin V. P., Spivakovsky A. O. and others [2-6] were devoted to simulation of working process elevator as multimass system with closed loop. In work [7] the optimization of mode start-up is reduced to finding the minimum time start conveyor under different conditions (strength ribbon, no slip ribbon on the drum, and the maximum moment of the motor). But at the calculation are used statistical indicators of conveyor, which do not fully reflect dynamic processes of vertical belt bucket elevators.

In [8] the mathematical model of the motion of the bucket elevator where accepted statistical mechanical characteristic of the drive motor is not fully reflects the movement of the elevator. Therefore there is a need to use the dynamic characteristics of the drive motor, which is enough to reflect the dynamic processes at the time of launch.

For optimization the modes of motion of the lifting machines used the methods of dynamic programming [9], the maximum principle [10] and the calculus of variations [11-14].

The most appropriate method to eliminate of oscillations in the elements of the bucket elevator is the calculus of variations, because at the decision of problems in the final result will getting smooth functions of changes kinematics characteristics.

The traction body (ribbon) is the main element of grain elevator, that's why the modes of motion for optimization appropriate to use criteria that reflect the dynamic load in the traction body.

Purpose of research

Improve the efficiency of the bucket elevator by optimizing the mode of motion of drive mechanism.

Results of research

For optimization the modes of motion of the bucket elevator selected the dynamic model. We will consider that all elements of the bucket elevator are absolutely rigid bodies besides ribbon and drive mechanism. All inertial masses are reduced to axis of rotation of the drive drum. The rigidity of drive mechanism reduces to this axis too. We consider that slip between the ribbon and the drive and tension drums are absent. Such assumption is provided the necessary preloading ribbon and enough clutches between drive and tension drums with ribbon. Mass of buckets and areas between ribbons is replaced one weight, which is concentrated in their center of mass at the working and non-working branches of the conveyor. Rigidity of the ribbon on the working and non-working branches of the conveyor consider the same.

Ignored the transverse vibrations of the buckets and ribbon, because they are minor compared to the main movement and they are more dependent on design features of the elevator but not from the mode of movement.

The chain contour of ribbon with buckets and drums are represented as chain open-circuited contour in the dynamic model of the bucket elevator (Fig.1). Conditional cut of ribbon made at the point of clash the ribbon on the tension drum. This is accepted that the tension of the ribbon at this point is equal to pre-loading ribbon with device tensioning with a force F_0. Such assumption is accepted and used by many authors for the study of ribbon and chain conveyors [2].

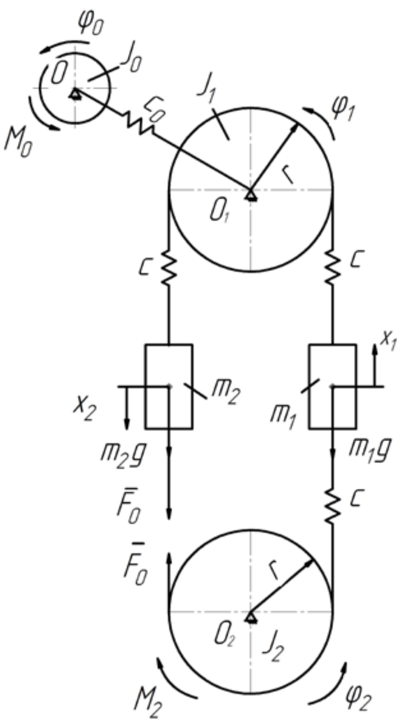


Fig. 1. Dynamic model of the bucket elevator.

As a result of the accepted assumptions the bucket elevator consider as mechanical system with five degrees of freedom, which is presented as a dynamic model, shown in Fig. 1. For generalized coordinates was taken the angular coordinates of rotor of the electric motor, which are reduced to the axis of the drive drum φ_0 , drive drum $\varphi 1$ and tension drum φ_2 and also longitudinal the linear coordinates of the center of mass of the working and non-working branches of the bucket elevator.

For the purpose of differential equations of motion bucket elevator, dynamic model is presented in Fig. 1, we use the principle of dynamic equilibrium of d'Alembert. According to this principle the equations of motion have the form:

$$\begin{cases} J_0\ddot{\varphi}_0 = M_0 - c_0(\varphi_0 - \varphi_1), \\ J_1\ddot{\varphi}_1 = c_0(\varphi_0 - \varphi_1) - cr(\varphi_1 r - x_1) + cr\left(x_2 - \varphi_1 r\right), \\ m_1\ddot{x}_1 = c(\varphi_1 r - x_1) - c(x_1 - \varphi_2 r) - m_1 g, \\ m_2\ddot{x}_2 = F_0 + m_2 g - c(x_2 - \varphi_1 r), \\ J_2\ddot{\varphi}_2 = cr(x_1 - \varphi_2 r) - M_2 - F_0 r, \end{cases} \quad (1)$$

where: J_0 , J_1 , J_2 – moments of inertia relative to their axes of rotation of the drive mechanism, which was erected to the axis of rotation of the drive drum, drive and tension drum to accordance,

m_1, m_2, – the total masses of the working and non-working branches of the elevator to accordance,

c_0 – stiffness of elastic elements of the drive mechanism that reduced to the axis of rotation of the drive drum,

c – stiffness of half the length of ribbon on the working (non-working) branch of the conveyor,

M_0 – the driving moment on shaft of the motor that reduced to the axis of rotation of the drive drum,

M_2 – the moment of resistance from loading buckets that reduced to the axis of rotation of the tension drum,

r – the radius of the drive drum and tension drum, which were adopted equal,

g – acceleration of free fall.

Consider the optimization process the start-up mode of the bucket elevator by the criterion of mean rate of change efforts in the traction body during clash on the drive drum. We will define the efforts in the traction body during clash on the drive drum from the third equation of the system (1):

$$R_{11} = c\left(\varphi_1 r - x_1\right) = m_1\ddot{x}_1 + c\left(x_1 - \varphi_2 r\right) + m_1 g. \quad (2)$$

From the last equation of the system (1) will find the coordinate x_1 through φ_2 and it second derivative for time:

$$x_1 = \varphi_2 r + \frac{J_2}{cr}\ddot{\varphi}_2 + \frac{M_2/r + F_0}{c}. \quad (3)$$

We will differentiate expression (3) for time, as a result we receive:

$$\begin{aligned} &\dot{x}_1 = \dot{\varphi}_2 r + \frac{J_2}{cr}\dddot{\varphi}_2, \ \ddot{x}_1 = \ddot{\varphi}_2 r + \frac{J_2}{cr}\overset{IV}{\varphi}_2, \\ &\dddot{x}_1 = \dddot{\varphi}_2 r + \frac{J_2}{cr}\overset{V}{\varphi}_2, \ \overset{IV}{x}_1 = \overset{IV}{\varphi}_2 r + \frac{J_2}{cr}\overset{VI}{\varphi}_2, \\ &\overset{V}{x}_1 = \overset{V}{\varphi}_2 r + \frac{J_2}{cr}\overset{VII}{\varphi}_2, \ \overset{VI}{x}_1 = \overset{VI}{\varphi}_2 r + \frac{J_2}{cr}\overset{VII}{\varphi}_2. \end{aligned} \quad (4)$$

Substituting the expressions (3) and (4) in depending (2), then we have:

$$R_{11} = \frac{m_1 J_2}{cr}\overset{IV}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\ddot{\varphi}_2 + \frac{M_2}{r} + F_0 + m_1 g. \quad (5)$$

We will differentiate expression (5) for time, as a result we receive the depending of speed changes efforts in the traction body during clash on the drive drum:

$$\dot{R}_{11} = \frac{m_1 J_2}{cr}\overset{V}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\dddot{\varphi}_2. \quad (6)$$

The mean rate of change efforts in the traction body during clash on the drive drum defined as an integrated functional:

$$\dot{R}_{11ск} = \left[\frac{1}{t_1}\int_0^{t_1} \dot{R}_{11}^2 dt\right]^{\frac{1}{2}}, \quad (7)$$

where: t – time, t_1 – the duration of the transition process (start, braking, speed change, reverse).

The integrand expression of functional (7) is:

$$f = \dot{R}_{11}^2 = \left[\frac{m_1 J_2}{cr}\overset{V}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\dddot{\varphi}_2\right]^2. \quad (8)$$

Differentiating the expression (8) in compliance with the equation (9), we have:

$$\frac{\partial f}{\partial \varphi} = \frac{\partial f}{\partial \dot{\varphi}_2} = \frac{\partial f}{\partial \ddot{\varphi}_2} = \frac{\partial f}{\partial \overset{IV}{\varphi_2}} = 0,$$

$$\frac{\partial f}{\partial \dddot{\varphi}_2} = 2\left(m_1 + \frac{J_2}{r^2}\right) r \left[\frac{m_1 J_2}{cr}\overset{V}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\dddot{\varphi}_2\right],$$

$$\frac{\partial f}{\partial \overset{V}{\varphi_2}} = 2\frac{m_1 J_2}{cr}\left[\frac{m_1 J_2}{cr}\overset{V}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\dddot{\varphi}_2\right],$$

$$\frac{d^3}{dt^3}\frac{\partial f}{\partial \dddot{\varphi}_2} = 2\left(m_1 + \frac{J_2}{r^2}\right) r \left[\frac{m_1 J_2}{cr}\overset{VIII}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\overset{IV}{\varphi_2}\right],$$

$$\frac{d^5}{dt^5}\frac{\partial f}{\partial \overset{V}{\varphi_2}} = 2\frac{m_1 J_2}{cr}\left[\frac{m_1 J_2}{cr}\overset{X}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right) r\overset{VIII}{\varphi_2}\right]. \quad (10)$$

After substituting expression (10) in equation (9) we obtain the differential equation tenth order:

$$\left(\frac{m_1 J_2}{cr}\right)^2 \overset{X}{\varphi_2} + 2\frac{m_1 J_2}{cr}\left(m_1 + \frac{J_2}{r^2}\right) \cdot r \cdot \overset{VIII}{\varphi_2} + \left(m_1 + \frac{J_2}{r^2}\right)^2 r^2 \overset{VI}{\varphi_2} = 0. \quad (11)$$

Divide all the members of (11) on the coefficient near oldest derivative and will made a substitution:

$$k = \sqrt{\frac{m_1 + J_2/r^2}{m_1 J_2} cr^2} = \sqrt{\frac{m_1 r^2 + J_2}{m_1 J_2} c}, \quad (12)$$

we got

$$\overset{X}{\varphi_2} + 2k^2 \overset{VIII}{\varphi_2} + k^4 \overset{VI}{\varphi_2} = 0. \quad (13)$$

Equation (13) is a homogeneous differential equation tenth order with constant coefficients. For it solution will make the characteristic equation $r^{10} + 2k^2 r^8 + k^4 r^6 = 0$, which can be written in this form:

$$r^6\left(r^4 + 2k^2 r^2 + k^4\right) = 0. \quad (14)$$

Solution of equation (14) gives:

$$r^6 = 0, \quad (15)$$

$$r^4 + 2k^2 r^2 + k^4 = 0. \quad (16)$$

From equation (15) we'll have six roots:

$$r_1 = r_2 = r_3 = r_4 = r_5 = r_6 = 0, \quad (17)$$

and the equation (16) is biquadrate equation which after the replacement $p = r^2$, have a form $p^2 + 2k^2 p + k^4 = 0.$

Solution of this equation gives:

$$p_{1,2} = -k^2 \pm \sqrt{k^4 - k^4} = -k^2,$$

$$p_1 = p_2 = -k^2.$$

Then

$$r_{7,8} = \sqrt{p_1} = \sqrt{-k^2} = \pm k_i, \qquad r_{9,10} = \sqrt{p_2} = \sqrt{-k^2} = \pm k_i. \quad (18)$$

As a result, the general solution of equation (13), based on the roots (17) and (18) of the characteristic equation (14), has the form:

$$\varphi_2 = C_1 + C_2 t + C_3 t^2 + C_4 t^3 + C_5 t^4 + C_6 t^5 + \left(C_7 + C_8 t\right)\sin kt + \left(C_9 + C_{10} t\right)\cos kt,$$

$$\dot{\varphi}_2 = C_2 + 2C_3 t + 3C_4 t^2 + 4C_5 t^3 + 5C_6 t^4 + \left(C_8 - C_9 k - C_{10} kt\right)\sin kt + \left(C_{10} + C_7 k + C_8 kt\right)\cos kt,$$

$$\ddot{\varphi}_2 = 2C_3 + 6C_4 t + 12C_5 t^2 + 20C_6 t^3 - \left(2C_{10} + C_7 k + C_8 kt\right)k\sin kt + \left(2C_8 - C_9 k - C_{10} kt\right)k\cos kt,$$

$$\dddot{\varphi}_2 = 6C_4 + 24C_5 t + 60C_6 t^2 - \left(3C_8 - C_9 k - C_{10} kt\right)k^2\sin kt - \left(3C_{10} + C_7 k + C_8 kt\right)k^2\cos kt,$$

$$\overset{IV}{\varphi_2} = 24C_5 + 120C_6 t + \left(4C_{10} + C_7 k + C_8 kt\right)k^3\sin kt - \left(4C_8 - C_9 k - C_{10} kt\right)k^3\cos kt,$$

$$\overset{V}{\varphi_2} = 120C_6 + \left(5C_8 - C_9 k - C_{10} kt\right)k^4\sin kt - \left(5C_{10} + C_7 k + C_8 kt\right)k^4\cos kt, \quad (19)$$

where: $C_1, C_2, \ldots, C_{10}$ – constant of integration which found from the boundary conditions of motion:

$$\begin{cases} t = 0: \varphi_2 = 0, \dot{\varphi}_2 = 0, \ddot{\varphi}_2 = 0, \dddot{\varphi}_2 = 0, \overset{IV}{\varphi_2} = 0, \\ t = t_1: \dot{\varphi}_2 = \omega_y, \ddot{\varphi}_2 = 0, \dddot{\varphi}_2 = 0, \overset{IV}{\varphi_2} = 0, \overset{V}{\varphi_2} = 0. \end{cases} \quad (20)$$

where: ω_y – the established angular velocity of the tensioning drum, t_1 – the duration of the transition process (start-up).

Substituting the boundary conditions (20) in the system of dependencies of kinematic characteristics of the tensioning drum (19), we obtain a system of linear equations to determine the constants C_i *(i=1, 2, …, 10)*:

$$\begin{cases} C_1 + C_9 = 0, \\ C_2 + C_{10} + C_7 k = 0, \\ 2C_3 + 2C_8 k - C_9 k^2 = 0, \\ 6C_4 - 3C_{10}k^2 - C_7 k^3 = 0, \\ 24C_5 - 4C_8 k^3 + C_9 k^4 = 0, \\ C_2 + 2C_3 t_1 + 3C_4 t_1^2 + 4C_5 t_1^3 + \\ + 5C_6 t_1^4 + (C_8 - C_9 k - C_{10} k t_1)\sin kt_1 + \\ + (C_{10} + C_7 k + C_8 k t_1)\cos kt_1 = \omega_y, \\ 2C_3 + 6C_4 t_1 + 12C_5 t_1^2 + 20C_6 t_1^3 - \\ - (2C_{10} + C_7 k + C_8 k t_1)k \sin kt_1 + \\ + (2C_8 - C_9 k - C_{10} k t_1)k \cos kt_1 = 0, \\ 6C_4 + 24C_5 t_1 + 60C_6 t_1^2 - \\ - (3C_8 - C_9 k - C_{10} k t_1)k^2 \sin kt_1 - \\ - (3C_{10} + C_7 k + C_8 k t_1)k^2 \cos kt_1 = 0, \\ 24C_5 + 120C_6 t_1 + \\ + (4C_{10} + C_7 k + C_8 k t_1)k^3 \sin kt_1 - \\ - (4C_8 - C_9 k - C_{10} k t_1)k^3 \cos kt_1 = 0, \\ 120C_6 + (5C_8 - C_9 k - C_{10} k t_1)k^4 \sin kt_1 + \\ + (5C_{10} + C_7 k + C_8 k t_1)k^4 \cos kt_1 = 0. \end{cases} \tag{21}$$

As a result of solving the system of equations (21) we find the constants of integration C_i *(i=1,2,…,10)* and substitute the depending (19).

The (19) is the optimization the mode of motion of the bucket elevator by criterion of mean rate of change efforts in the traction body during clash on the drive drum during start-up.

For the bucket elevator with parameters that were calculated [15]: $J_o=65\ kg\cdot m^2$, $J_1=78{,}4\ kg\cdot m^2$, $J_2=78{,}4\ kg\cdot m^2$, $\omega_y=5{,}7\ rad/s$, $R=0{,}315\ m$, $c_0=2000\ N\cdot m/rad$, $c=330000\ N/m$, $n_1=32$, $n_2=32$, $m_в=9\ kg$, $m_к=9\ kg$ in the program of the *Mathematica 9.0* [16] were calculated kinematic characteristics that are represented as graphs which are shown in the Fig. 2.

These graphs show characteristics for optimal mode of motion by the criterion of mean efforts in the traction body – the dotted line, and by the criterion of mean rate of change efforts – a solid line. Knowing the law of motion of the tensioning drum, which corresponds to the optimal mode of motion of the bucket elevator by a system of differential equations (1) we find the laws of motion of other parts. Law of motion of the working branch is defined from dependencies (3) and (4) and represented as graphs on the Fig. 3.

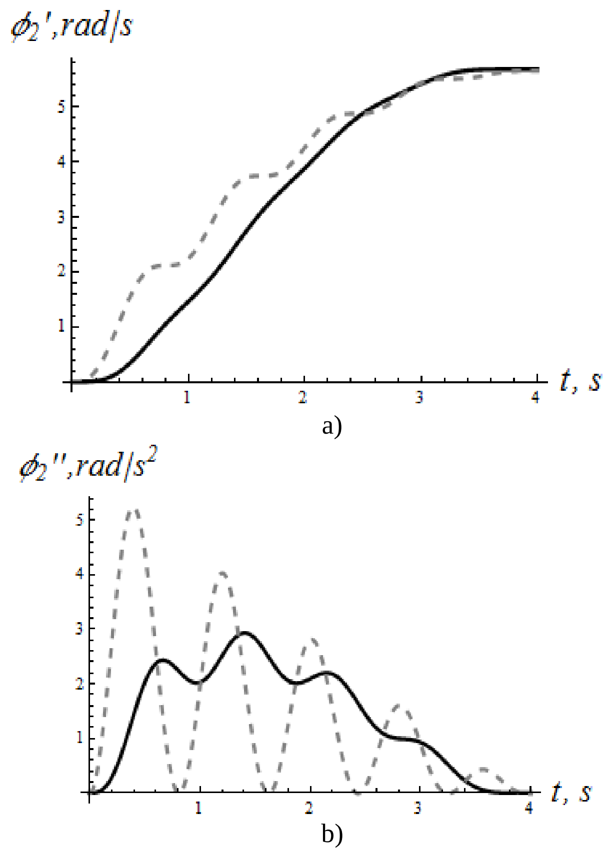


Fig. 2. Graphs of changes kinematic characteristics of the tensioning drum: a) speed, b) acceleration.

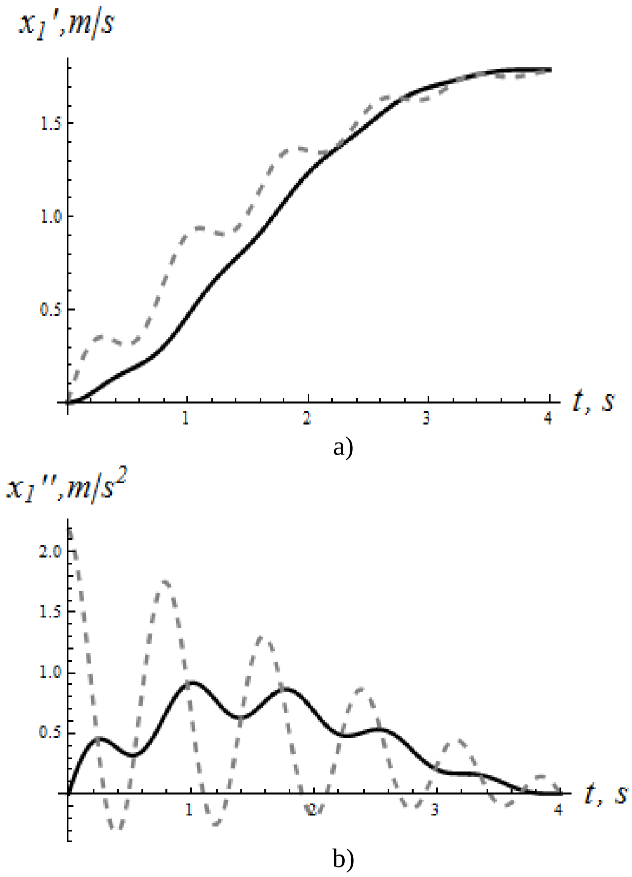
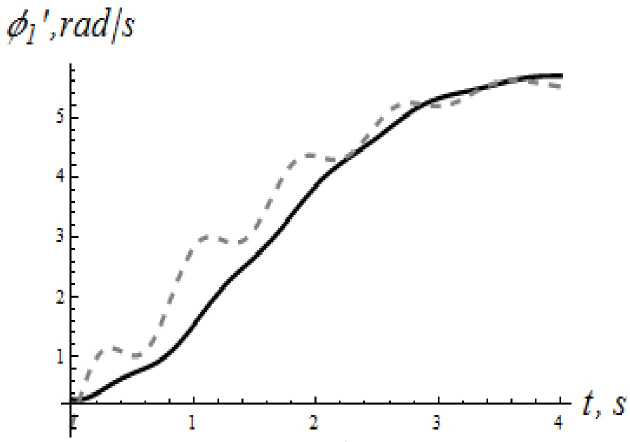


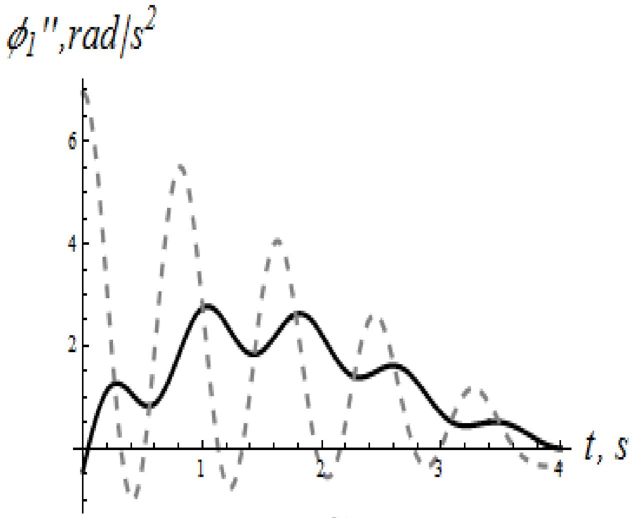
Fig. 3. Graphs of changes kinematic characteristics of the working branch: a) speed, b) acceleration.

And the law of motion of the drive drum will defined from the third equation (1) and represented as graphs on the Fig. 4:

$$\varphi_1 = -\varphi_2 + 2\frac{x_1}{r} + \frac{m_1}{cr}(\ddot{x}_1 + g),$$
$$\dot{\varphi}_1 = -\dot{\varphi}_2 + 2\frac{\dot{x}_1}{r} + \frac{m_1}{cr}\dddot{x}_1,\ \ddot{\varphi}_1 = -\ddot{\varphi}_2 + 2\frac{\ddot{x}_1}{r} + \frac{m_1}{cr}\overset{IV}{x_1}, \quad (22)$$
$$\dddot{\varphi}_1 = -\dddot{\varphi}_2 + 2\frac{\dddot{x}_1}{r} + \frac{m_1}{cr}\overset{V}{x_1},\ \overset{IV}{\varphi_1} = -\overset{IV}{\varphi_2} + 2\frac{\overset{IV}{x_1}}{r} + \frac{m_1}{cr}\overset{VI}{x_1}.$$



a)



b)

Fig. 4. Graphs of changes kinematic characteristics of the drive drum: a) speed, b) acceleration.

Solving the penultimate equation of system (1), we found the law of motion non-working branch of elevator:

$$m_2\ddot{x}_2 + cx_2 = cr\varphi_1 + m_2 g + F_0. \quad (23)$$

Substitute into the equation (26) the expression φ_1 from the system (22) considering of expressions x_1 and $\ddot{x}_1$ at (3) and (4), resulting we have:

$$m_2\ddot{x}_2 + cx_2 = cr\varphi_2 + \left(2\frac{J_2}{r^2} + m_1\right)r\ddot{\varphi}_2 + \frac{m_1 J_2}{cr}\overset{IV}{\varphi_2} + m_2 g + 2\frac{M_2}{r} + 3F_0. \quad (24)$$

Then substitute into the equation (24) expressions φ_2, $\ddot{\varphi}_2$ and $\overset{IV}{\varphi_2}$ from the system (19), so we have:

$$m_2\ddot{x}_2 + cx_2 = cr\begin{bmatrix} C_1 + C_2 t + C_3 t^2 + C_4 t^3 + \\ (C_5 + C_6 t)\sin kt + \\ +(C_7 + C_8 t)\cos kt \end{bmatrix} + \left(m_1 + 2\frac{J_2}{r^2}\right)r\begin{bmatrix} 2C_3 + 6C_4 t - \\ -(2C_8 + C_5 k + C_6 kt)k\sin kt + \\ +(2C_6 - C_7 k - C_8 kt)k\cos kt \end{bmatrix} +$$
$$+\frac{m_1 J_2}{cr}\begin{bmatrix} (4C_8 + C_5 k + C_6 kt)k^3\sin kt - \\ -(4C_6 - C_7 k - C_8 kt)k^3\cos kt \end{bmatrix} + m_2 g + 2\frac{M_2}{r} + 3F_0$$

$$m_2\ddot{x}_2 + cx_2 = \begin{bmatrix} crC_1 + \\ +2C_3\left(m_1 + 2\frac{J_2}{r^2}\right)r + \\ +m_2 g + 2\frac{M_2}{r} + 3F_0 \end{bmatrix} + \left[crC_2 + 6C_4 r\left(m_1 + 2\frac{J_2}{r^2}\right)\right]t + crC_3 t^2 + crC_4 t^3 +$$
$$+\left\{\begin{bmatrix} crC_5 - (2C_8 + C_5 k)kr\left(m_1 + 2\frac{J_2}{r^2}\right) + \\ +(4C_8 + C_5 k)k^3\frac{m_1 J_2}{cr} \end{bmatrix} + \begin{bmatrix} crC_6 - C_6 k^2 r\left(m_1 + 2\frac{J_2}{r^2}\right) + \\ +C_6 k^4\frac{m_1 J_2}{cr} \end{bmatrix}t\right\}\sin kt +$$
$$+\left\{\begin{bmatrix} crC_7 + (2C_6 - C_7 k)kr\left(m_1 + 2\frac{J_2}{r^2}\right) - \\ -(4C_6 - C_7 k)k^3\frac{m_1 J_2}{cr} \end{bmatrix} + \begin{bmatrix} crC_8 - C_8 k^2 r\left(m_1 + 2\frac{J_2}{r^2}\right) + \\ +C_8 k^4\frac{m_1 J_2}{cr} \end{bmatrix}t\right\}\cos kt$$

$$m_2\ddot{x}_2 + cx_2 = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + (a_4 + a_5 t)\sin kt + (a_6 + a_7 t)\cos kt \quad (25)$$

We write the equation (25) in this form:

$$\ddot{x}_2 + k_1^2 x_2 = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + (a_4 + a_5 t)\sin kt + (a_6 + a_7 t)\cos kt \quad (26)$$

Here

$$k_1 = \sqrt{m_2/c}\,. \qquad (27)$$

The general solution of (29) we looking as the sum of a full solution of the homogeneous equation and a partial solution of the full equation, so:

$$x_2 = x_2^* + x_2^{**} \qquad (28)$$

The homogeneous equation $\ddot{x}_2^* + k_1^2 x_2^* = 0$. We write to him the characteristic equation $r^2 + k^2 = 0$, whence $r_{1,2} = \pm k_i$. Then the general solution of the homogeneous equation is:

$$x_2^* = A_1 \sin k_1 t + A_2 \cos k_1 t, \qquad (29)$$

where: A_1 i A_2 – constants which determined from initial conditions of movements.

Based on the type of the right side of the equation (29), his partial solution has the form:

$$\begin{aligned} x_2^{**} &= B_0 + B_1 t + B_2 t^2 + B_3 t^3 + \\ &+ (B_4 + B_5 t)\sin kt + (B_6 + B_7 t)\cos kt \end{aligned} \qquad (30)$$

We will differentiate expression (5) for time twice, as a result we receive:

$$\begin{aligned} \ddot{x}_2^{**} &= 2B_2 + 6B_3 t - \left(2B_7 k + B_4 k^2 + B_5 k^2 t\right)\sin kt + \\ &+ \left(2B_5 k - B_6 k^2 - B_7 k^2 t\right)\cos kt \end{aligned} \qquad (31)$$

Substituting expressions (33) and (34) in equation (29), then we have:

$$\begin{aligned} &2B_2 + 6B_3 t - \begin{pmatrix} 2B_7 k + \\ + B_4 k^2 + B_5 k^2 t \end{pmatrix}\sin kt + \\ &+ \left(2B_5 k - B_6 k^2 - B_7 k^2 t\right)\cos kt + \\ &+ k_1^2 \begin{bmatrix} B_0 + B_1 t + B_2 t^2 + B_3 t^3 + \\ + (B_4 + B_5 t)\sin kt + \\ + (B_6 + B_7 t)\cos kt \end{bmatrix} = \\ &= a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \\ &+ (a_4 + a_5 t)\sin kt + \\ &+ (a_6 + a_7 t)\cos kt. \end{aligned} \qquad (32)$$

We group the components of the left side of the equation (32) according to the components of the right side of the equation and then obtain:

$$\begin{cases} 2B_2 + B_0 k_1^2 = a_0, \\ 6B_3 + B_1 k_1^2 = a_1, \\ B_2 k_1^2 = a_2,\ B_3 k_1^2 = a_3, \\ -\left(2B_7 k + B_4 k^2\right) + B_4 k_1^2 = a_4, \\ -B_5 k^2 + B_5 k_1^2 = a_5, \\ \left(2B_5 k - B_6 k^2\right) + B_6 k_1^2 = a_6, \\ -B_7 k^2 + B_7 k_1^2 = a_7. \end{cases} \qquad (33)$$

Having solved a system of linear equations, we find:

$$\begin{aligned} B_0 &= \frac{a_0 - 2a_2/k_1^2}{k_1^2}, \\ B_1 &= \frac{a_1 - 6a_3/k_1^2}{k_1^2}, \\ B_2 &= \frac{a_2}{k_1^2},\ B_3 = \frac{a_3}{k_1^2}, \\ B_4 &= \frac{2ka_7/\left(k_1^2 - k^2\right) + a_4}{k_1^2 - k^2}, \\ B_5 &= \frac{a_5}{k_1^2 - k^2}, \\ B_6 &= \frac{a_6 - 2ka_7/\left(k_1^2 - k^2\right)}{k_1^2 - k^2}, \\ B_7 &= \frac{a_7}{k_1^2 - k^2}. \end{aligned} \qquad (34)$$

Then the general solution of equation (26) has the form:

$$\begin{aligned} x_2 &= A_1 \sin k_1 t + A_2 \cos k_1 t + B_0 + B_1 t + B_2 t^2 + \\ &+ B_3 t^3 + (B_4 + B_5 t)\sin kt + (B_6 + B_7 t)\cos kt \end{aligned} . \qquad (35)$$

Take the time derivative of the expression (35):

$$\begin{aligned} \dot{x}_2 &= A_1 k_1 \cos k_1 t - A_2 k_1 \sin k_1 t + B_1 + 2B_2 t + 3B_3 t^2 + \\ &+ (B_5 - B_6 k - B_7 kt)\sin kt + (B_7 + B_4 k + B_5 kt)\cos kt; \\ \ddot{x}_2 &= -A_1 k_1^2 \sin k_1 t - A_2 k_1^2 \cos k_1 t + 2B_2 + 6B_3 t - \\ &- (2B_7 + B_4 k + B_5 kt)k \sin kt + (2B_5 - B_6 k - B_7 kt)k \cos kt. \end{aligned} \qquad (36)$$

The unknown constants A_1 and A_2 determined from initial conditions of motion:

$$t = 0 : x_2 = \dot{x}_2 = 0\,. \qquad (37)$$

Having substituted the initial conditions (40) in the depending (38) and (39) we get:

$$\begin{cases} A_2 + B_0 + B_6 = 0; \\ A_1 k_1 + B_1 + B_7 + B_4 k = 0. \end{cases} \qquad (38)$$

From the system (41) we have:

$$\begin{aligned} A_1 &= -(B_1 + B_7 + B_4 k)/k_1; \\ A_2 &= -B_0 - B_6. \end{aligned} \qquad (39)$$

After finding the law of motion the non-working branch of elevator we can define the law of motion of the rotor of the electric motor that reduced to the axis of the drive drum.

For this we use the second equation of (1):

$$\begin{aligned} \varphi_0 &= \varphi_1\left(1 + 2\frac{cr^2}{c_0}\right) + \frac{J_1}{c_0}\ddot{\varphi}_1 - \frac{cr}{c_0}(x_1 + x_2), \\ \dot{\varphi}_0 &= \dot{\varphi}_1\left(1 + 2\frac{cr^2}{c_0}\right) + \frac{J_1}{c_0}\dddot{\varphi}_1 - \frac{cr}{c_0}(\dot{x}_1 + \dot{x}_2), \\ \ddot{\varphi}_0 &= \ddot{\varphi}_1\left(1 + 2\frac{cr^2}{c_0}\right) + \frac{J_1}{c_0}\overset{IV}{\varphi}_1 - \frac{cr}{c_0}(\ddot{x}_1 + \ddot{x}_2). \end{aligned} \qquad (40)$$

Table 1. The mean and maximum values for optimal regimes.

Indexes	Criteria for evaluation			
	The mean efforts in the traction body		The mean rate of change efforts in traction body	
	The mean value	The maximum value	The mean value	The maximum value
$\dot{x}_1$, *m/s*	1.311	1.784	1.246	1.793
$\ddot{x}_1$, *m/s²*	0.733	2.184	0.525	0.918
$\dot{\varphi}_1$, *rad/s*	4.116	5.622	3.909	5.693
$\ddot{\varphi}_1$, *rad/s²*	2.365	6.941	1.575	2.777
$\dot{\varphi}_2$, *rad/s*	4.184	5.664	3.983	5.693
$\ddot{\varphi}_2$, *rad/s²*	2.029	5.246	1.712	2.935
R_{11}, *N*	14944	15586	14947	15425
R_{21}, *N*	9042	9988	9039	9413

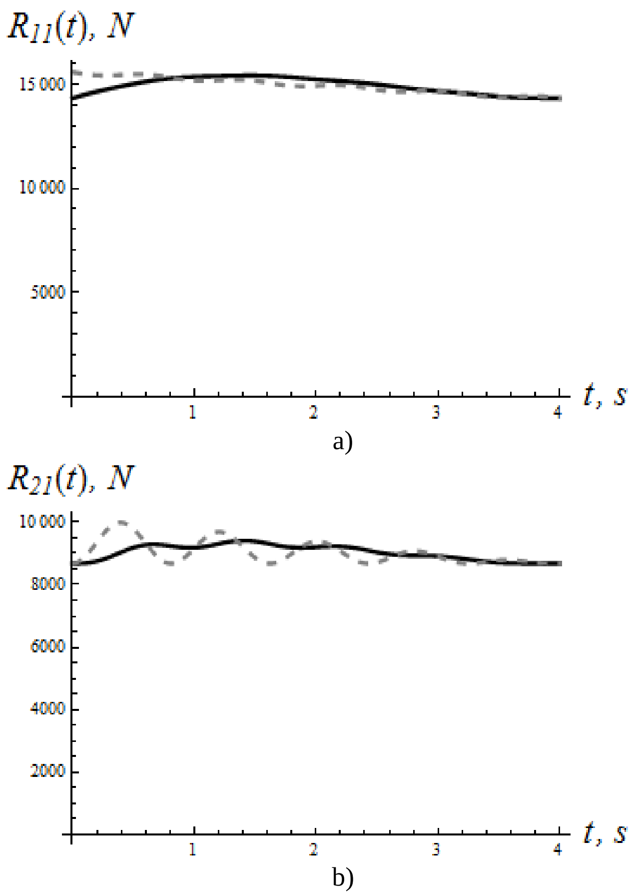


Fig. 5. Graphs of change of efforts in the traction body: a) during clash on the drive drum, b) at shrinkage of the tensioning drum.

Now can find dependences of changes of resilient and driving moments of the drive mechanism from using the first equation of the system (1):

$$M_{01} = c_0(\varphi_0 - \varphi_1), \quad (41)$$

$$M_0 = M_{01} + J_0\ddot{\varphi}_0. \quad (42)$$

Effort in the traction body during clash on the drive drum is defined by the following expression (Fig. 5. a):

$$R_{11} = c(\varphi_1 r - x_1). \quad (23)$$

Efforts in traction body at shrinkage of the tensioning drum (Fig. 5. b):

$$R_{21} = c(x_1 - \varphi_2 r). \quad (24)$$

In the program Mathematica 9.0 for optimal mode of motion was calculated the mean and the maximum values of the following indicators:

- angular velocity and acceleration of the drive and tensioning drums,
- linear velocity and acceleration consolidated mass of working branches,
- efforts in the traction body during clash on the drive drum and at shrinkage of the tensioning drum.

As a result of the calculations obtained data are presented in the Table 1.

From the graphic of dependencies can see that at start-up of the bucket elevator in its moving parts there are oscillatory processes.

The magnitude of these oscillations depends on the accuracy of modelling parts of the conveyor.

To simplify the optimization mode of motion by criterion of mean rate of change efforts in the traction body during clash on the drive drum is used a dynamic model with one mass on the working and non-working branches in accordance.

After analysing the graphs can see that oscillatory processes occurring during optimization the mode of start-up by the criterion of mean efforts in the traction body is greater than during optimization by the criterion of mean rate of change efforts.

The maximum value of acceleration on the working branch and on the drive drum during optimization effort in the traction body is 2.5 times higher than the same value at optimization of rate of change efforts.

Also, the maximum value of efforts in the traction body at shrinkage of the tensioning drum at the first criterion is 4% higher than in the second.

It should be noted that the graphs of change efforts in the traction body during clash on the drive drum have smaller fluctuations than at the shrinkage of the tensioning drum.

Conclusions

1. The dynamic model the mode of motion of the bucket elevator was constructed as mechanical system with five degrees of freedom. For optimization the mode

of motion of the bucket elevator by the criterion of mean rate of change efforts in the traction body during clash on the drive drum was created a mathematical model, which based on the chosen dynamic model. Using the developed mathematical model obtained dependences of kinematic and force characteristics of parts for this optimal mode. Analyzing the results can see that optimization for both criteria of evaluation leads to oscillations, but in the second case (rate of change), these oscillations are much smaller.

2. In order to get rid of these oscillations is recommended to optimize the mode of motion by the criterion of mean acceleration the rate of change efforts in the traction body during clash on the drive drum.

3. Also it is necessary be noted that during conducted research was obtained optimal mode of motion at a constant force of resistance downloading the grain. It would be advisable to consider the impact of variable resistance downloading the grain, as is done for scraper conveyors in [17-20].

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ОПТИМІЗАЦІЯ РЕЖИМУ ЗАПУСКУ КОВШОВОГО ЕЛЕВАТОРА ЗА КРИТЕРІЄМ СЕРЕДНЬОЇ ШВИДКОСТІ ЗМІНИ ЗУСИЛЛЯ В ТЯЗІ ТІЛА ПІД ЧАС ЗІТКНЕННЯ НА ПРИВОДНИЙ БАРАБАН

В. С. Ловейкін, Ю. В. Ловейкін, Л. Б. Ткачук

Анотація. Коливання структурних елементів, механізму привода і тягового органу зведені до мінімуму шляхом оптимізації режимів руху на елеватор під час перехідних процесів, що дозволило підвищити його ефективність. В залежності від обраної динамічна модель, математична модель була створена з допомогою принципу д ' Аламбера. Процес оптимізації пускового режиму ковшового елеватора був розглянутий критерій Середня швидкість зміни зусилля на тяговий орган під час зіткнення на приводному барабані. Знайдені закони руху робочої гілки, натяжний барабан приводний барабан, який відповідає оптимальному режиму руху в ковшовий елеватор. На основі виявлених законів руху були побудовані кінематичні характеристики основних частин ліфта, які представлені у вигляді графічних залежностей для оптимального режиму руху. Графічні залежності зміни зусиль на тяговий орган в ході зіткнення на приводному барабані і усадка з натяжної барабана також отримав. На основі графічних залежностей встановлено, що при пуску ковшового елеватора при оптимальному режимі руху є невеликі коливальні процеси, які є найменшими, всього в оптимізації за критерієм середньої швидкості зміни зусилля на тяговий орган у ході зіткнення на приводному барабані.

Ключові слова: ковшовий елеватор, динамічна модель, математична модель, режим руху, динамічних навантажень, зусиль, коливань.

ОПТИМИЗАЦИЯ РЕЖИМА ЗАПУСКА КОВШОВОГО ЭЛЕВАТОРА ПО КРИТЕРИЮ СРЕДНЕЙ СКОРОСТИ ИЗМЕНЕНИЯ УСИЛИЯ В ТЯГЕ ТЕЛА ВО ВРЕМЯ СТОЛКНОВЕНИЯ НА ПРИВОДНОЙ БАРАБАН

В. С. Ловейкин, Ю. В. Ловейкин, Л. Б. Ткачук

Аннотация. Колебания структурных элементов, механизма привода и тягового органа сведены к минимуму путем оптимизации режимов движения на элеватор во время переходных процессов, что позволило повысить его эффективность. В зависимости от выбранной динамическая модель, математическая модель была создана с помощью принципа д'Аламбера. Процесс оптимизации пускового режима ковшового элеватора был рассмотрен критерий Средняя скорость изменения усилия на тяговый орган во время столкновения на приводном барабане. Найдены законы движения рабочей ветви, натяжной барабан и приводной барабан, который соответствует оптимальному режиму движения в ковшовый элеватор. На основе обнаруженных законов движения были построены кинематические характеристики основных частей лифта, которые представлены в виде графических зависимостей для оптимального режима движения. Графические зависимости изменения усилий на тяговый орган в ходе столкновения на приводном барабане и усадка из натяжного барабана также получил. На основе графических зависимостей установлено, что при пуске ковшового элеватора при оптимальном режиме движения есть небольшие колебательные процессы, которые являются самыми маленькими, всего в оптимизации по критерию средней скорости изменения усилия на тяговый орган в ходе боестолкновения на приводном барабане.

Ключевые слова: ковшовый элеватор, динамическая модель, математическая модель, режим движения, динамических нагрузок, усилий, колебаний.