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SCREW FEEDER: OPTIMIZATION OF MOTION MODES CONSIDERING THAT THE MOMENTS OF RESISTANCE FORCES CHANGE UNDER LINEAR LAW

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Summary. The paper deals with screw feeder's mathematical model that characterizes motion of dynamics, on the base of which optimization of the motion modes is carried out. Taking into account that the moments of resistance forces change under linear law at the optimal and not optimal modes of motion, the results for theoretical investigations of dynamics of startup are demonstrated.

Key words: screw feeder, dynamic load, optimization, moment of resistance.

1. INTRODUCTION

Conveyors relate to the gears of continuous action with constant distributed load. Mode of operation of the electric motor in such gear is long. Essentially, calculating engine power, load during startup and stop is rarely examined. Namely, startup and stop relate to transients that are characterized by unstable transportation and mixing of cargo, by higher specific energy consumption and by considerable dynamic loadings. This results in the decrease of operating cycle and leads to frequent breakages. That increases, in turn, expenses for repair.

One of the requirements, which are set up to the electric drive of conveyors, is necessity to secure smoothness of transients, in particular restriction of accelerations and jerks, with the aim to eliminate blows and vibrations of the gear and decrease dynamic loads in the presence of elastic communications [11].

2. MATERIAL AND METHODS

The works [0,2,7,8,9,16,17,19] are devoted to research the dynamics of motions' modes of mechanisms of conveyers and other machines. In the paper [11] the dynamics of driving mechanism with elastic-overload clutch during transients is under investigation.

Scientific researches, which are noted in work [8], characterize the dynamics of high-speed screw conveyor, considering variable speed of the array of bulk cargo in the working space of the trough. The paper describes the models, which allow to estimate the kinematic and dynamic parameters of screw conveyors, their power consumption; to set appropriate tasks for choosing the rational schemes of loading and startup operating modes of screw conveyors, and to develop a system of smoothing percussive loadings on their working parts.

Character of change of optimizing criterion under condition that the number of boundary conditions increases; optimum motion modes of dynamic systems in the presence of dry friction, which allow to minimize the fluctuations, arising during transients; optimization of transitive modes of motions jack-lift, all these tasks are investigated accordingly in works [14,15,20].

Thus, described works are about the dynamics of motion of machines, about the criteria of optimization in general, but namely optimization of motion modes of screw conveyors and feeders are not been studied.

Therefore the objective of this paper is to define an optimum motion mode of the screw conveyor, by one of the chosen criteria of optimality, for the purpose of reduction the dynamic loads.

3. RESULTS AND DISCUSSION

Screw feeder is presented in the form of dynamic model that consists of four weights, connected by elastic elements (fig. 1) [13].

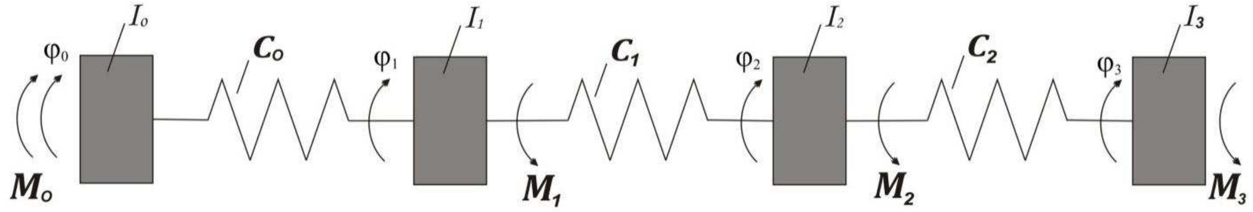


Fig 1. The dynamic model of screw feeder

On the basis of the constructed dynamic model by means of D'Alembert's principle [13], differential equations of motion of screw feeder are written (1):

$$\begin{cases} I_0\ddot{\varphi}_0 = M_o - C_0(\varphi_0 - \varphi_1); \\ I_1\ddot{\varphi}_1 = C_0(\varphi_0 - \varphi_1) - C_1(\varphi_1 - \varphi_2) - M_1; \\ I_2\ddot{\varphi}_2 = C_1(\varphi_1 - \varphi_2) - C_2(\varphi_2 - \varphi_3) - M_2; \\ I_3\ddot{\varphi}_3 = C_2(\varphi_2 - \varphi_3) - M_3, \end{cases} \quad (1)$$

where I_0, I_1, I_2, I_3 - respectively inertia moments of links of drive mechanism and elements of screw shaft with the transported cargo.

These moments erected to the turning axis of the screw;

$\varphi_0, \varphi_1, \varphi_2, \varphi_3$ - the generalized angular coordinates of turning movement of the concentrated weights respectively of drive mechanism and of screw shaft with cargo;

M_o - the start-up torque on motor shaft, which is erected to the turning axis of the screw;

M_1, M_2, M_3 - the moments of resistance forces from the moving cargo along sections of screw shaft;

C_0, C_1, C_2 - respectively rigidity of links of drive mechanism and rigidities of screw shaft sections. Sections are presented by separate elements. These rigidities are erected to the turning axis of the screw.

At the beginning of the work it is possible to note stages of gradual changes of moments of resisting forces on each section of the screw feeder in the process of movement the cargo.

In the previous researches [8,17] for simplification of calculations has been made the assumption that the moments of resistance forces are presented as constant values. In this research is considered the case, when M_1, M_2, M_3 change relative to rotation speed of screw shaft under the linear law:

$$\begin{aligned} M_1 &= M_{H1}\left(K_1 - \frac{K_1 - 1}{w_y}\dot{\varphi}_1\right); \\ M_2 &= M_{H2}\left(K_2 - \frac{K_2 - 1}{w_y}\dot{\varphi}_2\right); \\ M_3 &= M_{H3}\left(K_3 - \frac{K_3 - 1}{w_y}\dot{\varphi}_3\right), \end{aligned} \quad (2)$$

where $K_1 = K_2 = K_3 = 1{,}8$ - the factors, that consider increase of the moments of resisting forces at the beginning of motion in comparison with the established motion mode of the conveyor (it is set experimentally); M_{H1}, M_{H2}, M_{H3} – nominal values of resisting moments on each of sections; w_y – steady-state angular speed of screw shaft.

From the equations of system (1) $\varphi_2, \varphi_1, \varphi_0$, their derivatives and the start-up torque of the engine, that is erected to the turning axis of the screw, are found:

$$M_0 = C_0(\varphi_0 - \varphi_1) + I_0\ddot{\varphi}_0. \quad (3)$$

After some transformations final expression of the start-up torque, that depends on φ_3 and also on its derivatives, has been obtained.

$$M_0 = C_0\left(\begin{Bmatrix}\varphi_3-\left[al-kM_{H3}\dfrac{K_3-1}{w_y}+m\right]\dot{\varphi}_3+\left[lb-kI_3+ma+\dfrac{I_1}{C_0}\right]\ddot{\varphi}_3- \\ -\left[lc+mb+\dfrac{I_1}{C_0}a\right]\dddot{\varphi}_3+\left[ld+mc+\dfrac{I_1}{C_0}b\right]\overset{IV}{\varphi}_3-\left[md+\dfrac{I_1}{C_0}c\right]\overset{V}{\varphi}_3+\dfrac{I_1}{C_0}c\overset{VI}{\varphi}_3+ \\ +l\left[\dfrac{M_{H2}K_2}{C_1}+fM_{H3}K_3\right]-kM_{H3}K_3+\dfrac{M_{H1}}{C_0}K_1\end{Bmatrix}- \\ -\left\{\varphi_3-a\dot{\varphi}_3+b\ddot{\varphi}_3-c\dddot{\varphi}_3+d\overset{IV}{\varphi}_3+\dfrac{M_{H2}K_2}{C_1}+fM_{H3}K_3\right\}\right)+ \\ +I_0\left(\begin{matrix}\ddot{\varphi}_3-\left[al-kM_{H3}\dfrac{K_3-1}{w_y}+m\right]\dddot{\varphi}_3+\left[lb-kI_3+ma+\dfrac{I_1}{C_0}\right]\overset{IV}{\varphi}_3-\left[lc+mb+\dfrac{I_1}{C_0}a\right]\overset{V}{\varphi}_3+ \\ +\left[ld+mc+\dfrac{I_1}{C_0}b\right]\overset{VI}{\varphi}_3-\left[md+\dfrac{I_1}{C_0}c\right]\overset{VII}{\varphi}_3+\dfrac{I_1}{C_0}c\overset{VIII}{\varphi}_3\end{matrix}\right), \tag{4}$$

where the following designations are accepted:

$$a=\frac{1}{w_y}\left[\left(\frac{1}{C_1}+\frac{1}{C_2}\right)M_{H3}\left(K_3-1\right)+\frac{M_{H2}}{C_1}\left(K_2-1\right)\right];$$

$$b=\left\{\frac{I_2}{C_1}+I_3\left(\frac{1}{C_1}+\frac{1}{C_2}\right)+\frac{M_{H2}}{C_1}\frac{M_{H3}}{C_2w_y^2}\left(K_2-1\right)\left(K_3-1\right)\right\};$$

$$c=\frac{1}{C_1C_2w_y}\left(I_2M_{H3}\left(K_3-1\right)+I_3M_{H2}\left(K_2-1\right)\right);$$

$$d=\frac{I_2I_3}{C_1C_2};\quad f=\left(\frac{1}{C_1}+\frac{1}{C_2}\right);\quad k=\frac{C_1}{C_0C_2};\quad l=\left(1+\frac{C_1}{C_0}\right);\quad m=\frac{M_{H1}}{C_0}\frac{K_1-1}{w_y}.$$

In order to optimize modes of motion, it is necessary to have a quantitative estimation of feeder properties in the form of criterion or system of criteria. These criteria reflect the basic undesirable properties of machines and their mechanisms during all cycle; therefore they are represented in integral form [14]. There are many criteria of optimization. We should analyze most of them in order to obtain “the best” that, in this case, results in the decrease dynamic loads.

To estimate motion mode of the conveyor at startup we have selected, as criterion, mean-square deviation of speeds of angular coordinates of the second and third masses

$$\dot{\mathrm{I}}_{231}=\left[\frac{1}{t_1}\int_0^{t_1}f_{231}dt\right]^{1/2}, \tag{5}$$

where t - time; t_1 - finite moment of time of the finished motion cycle or influence; $f_{231}=\left(\dot{\varphi}_2-\dot{\varphi}_3\right)^2$ - a measure of motion or influence of mechanical system or its element.

From the last equation of system (1), we find φ_2 and $\dot{\varphi}_2$:

$$\varphi_2=\varphi_3+\frac{I_3}{C_2}\ddot{\varphi}_3+\frac{M_{H3}}{C_2}\left(K_3-\frac{K_3-1}{\omega_y}\dot{\varphi}_3\right);$$
$$\dot{\varphi}_2=\dot{\varphi}_3+\frac{I_3}{C_2}\dddot{\varphi}_3-\frac{M_{H3}}{C_2}\frac{K_3-1}{\omega_y}\ddot{\varphi}_3. \tag{6}$$

Then criterion for estimating the motion mode of the feeder will be as follows:

$$\left(\dot{\varphi}_2-\dot{\varphi}_3\right)=\frac{I_3}{C_2}\dddot{\varphi}_3-\frac{M_{H3}}{C_2}\frac{K_3-1}{\omega_y}\ddot{\varphi}_3;$$
$$f_{231}=\left(\dot{\varphi}_2-\dot{\varphi}_3\right)^2=\frac{1}{C_2^2}\left[I_3\dddot{\varphi}_3-\frac{M_{H3}\left(K_3-1\right)}{\omega_y}\ddot{\varphi}_3\right]^2. \tag{7}$$

Euler-Puasson’s equation [16] is minimum criterion condition (5):

$$\frac{\partial f_{231}}{\partial\varphi_3}-\frac{d}{dt}\frac{\partial f_{231}}{\partial\dot{\varphi}_3}+\frac{d^2}{dt^2}\frac{\partial f_{231}}{\partial\ddot{\varphi}_3}-\frac{d^3}{dt^3}\frac{\partial f_{231}}{\partial\dddot{\varphi}_3}=0. \tag{8}$$

As function f_{231} depends from $\ddot{\varphi}_3$ and $\dddot{\varphi}_3$, thus equation (8) becomes:

$$\frac{d^2}{dt^2}\frac{\partial f_{231}}{\partial\ddot{\varphi}_3}-\frac{d^3}{dt^3}\frac{\partial f_{231}}{\partial\dddot{\varphi}_3}=0,$$

from which we obtain

$$-\frac{2M_{H3}\left(K_3-1\right)}{C_2^2\omega_y}\left[I_3\overset{V}{\varphi}_3-\frac{M_{H3}\left(K_3-1\right)}{\omega_y}\overset{IV}{\varphi}_3\right]-\frac{2I_3}{C_2^2}\left[I_3\overset{VI}{\varphi}_3-\frac{M_{H3}\left(K_3-1\right)}{\omega_y}\overset{V}{\varphi}_3\right]=0. \tag{9}$$

Equation (9) has a combination of derivatives from φ_3, so first find the solutions of the characteristic equation. Given the fact that $\varphi_3=e^{\lambda t}$ and $\dfrac{M_{H3}\left(K_3-1\right)}{\omega_y}=p$, the characteristic equation looks like:

$$\frac{2}{C_2^2}\left[p^2\lambda^4 e^{\lambda t} - I_3^2\lambda^6 e^{\lambda t}\right] = 0;$$

$$\frac{2}{C_2^2} \neq 0, \text{ that is why } \quad e^{\lambda t}\left(\lambda^4 - \frac{I_3^2}{p^2}\lambda^6\right) = 0, \qquad (10)$$

where λ - the root of the characteristic equation.

By defining the roots of the characteristic equation $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0,\ \lambda_{5,6} = \pm\frac{p}{I_3}$, we write the general solution of equation (9):

$$\varphi_3(t) = C_1 + C_2 t + C_3 t^2 + C_4 t^3 + C_5 e^{+\lambda_5 t} + C_6 e^{-\lambda_6 t}, \qquad (11)$$

where C_1, C_2, C_3, C_4, C_5, C_6 - constants of integration, which are determined from the boundary conditions of motion of the system.

As equation (11) contains six unknowns, it requires for its solution six boundary conditions:

$$\begin{cases} \varphi_3 = 0; & \dot{\varphi}_3 = 0; & \ddot{\varphi}_3 = 0; & \Rightarrow \text{when } t = 0; \\ \dot{\varphi}_3 = \omega_y; & \ddot{\varphi}_3 = 0; & \dddot{\varphi}_3 = 0; & \Rightarrow \text{when } t = t_1. \end{cases} \qquad (12)$$

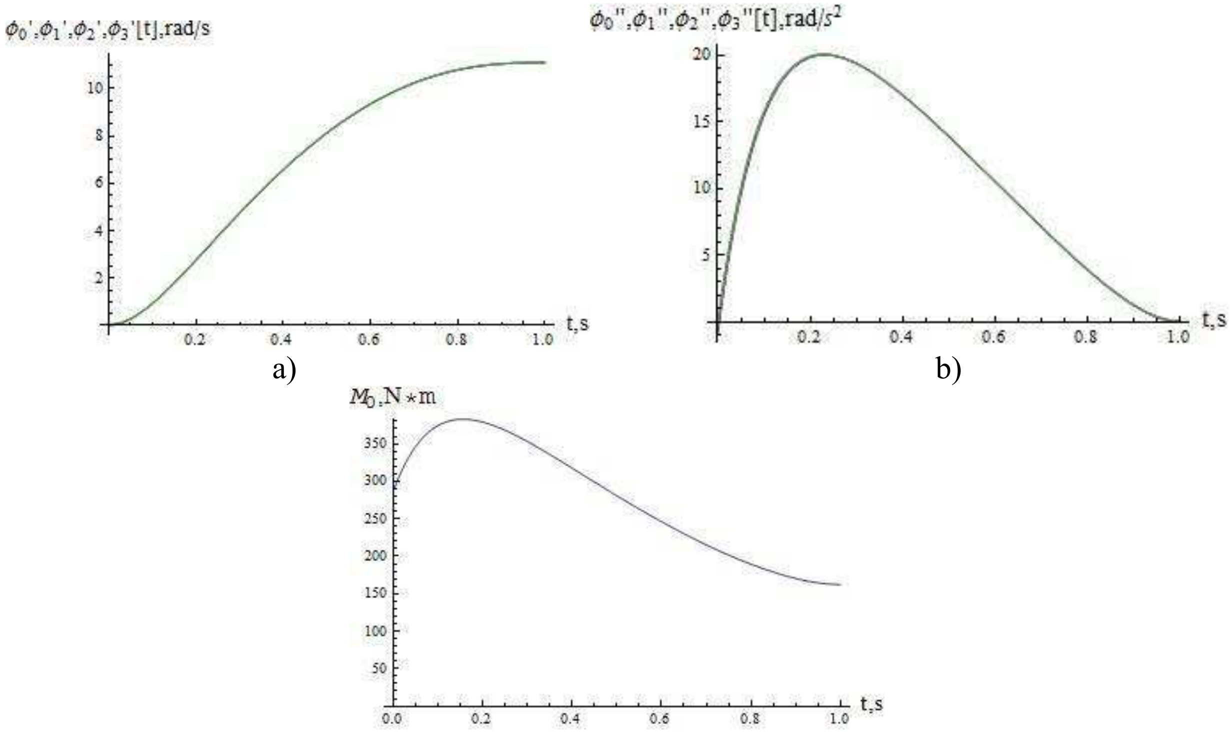
The constants of integration were defined, taking into account the dependencies (11) and conditions (12). Basing on dependencies (2) and (11), given the constants of integration, optimal motion modes of other links have been found from system (1). They are presented as graphs in Figure 2.

Input data for graphs of angular speed, angular acceleration and the motive moment at optimal start-up are as follows:

$$I_0 = 4{,}14\,кг\cdot м^2,\ I_1 = I_2 = I_3 = 0{,}632\,кг\cdot м^2;\quad K_1 = K_2 = K_3 = 1{,}8;$$

$$\omega_н = 11.1\frac{рад}{c};\quad M_1 = 27\left(1{,}8 - 0{,}072\dot{\varphi}_1[t]\right)\ Н\cdot м;\quad M_2 = 54\left(1{,}8 - 0{,}072\dot{\varphi}_2[t]\right)\ Н\cdot м;$$

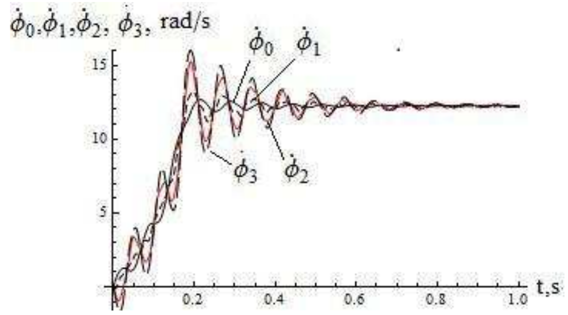
$$M_3 = 81\left(1{,}8 - 0{,}072\dot{\varphi}_3[t]\right)\ Н\cdot м;\quad t_1 = 1c;\ C = 15517{,}2\frac{Н\cdot м}{рад};\ C_0 = 29350{,}7\frac{Н\cdot м}{рад}.$$



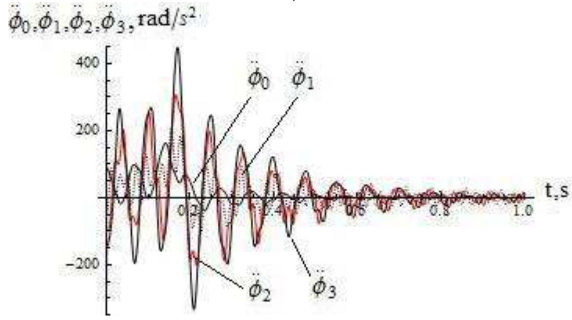
c)

Fig. 2. The graphs of angular speed (a), angular acceleration (b) $\dot{\varphi}_3$ and motive moment (c) at optimal start-up

In order to see the impact of the optimization on the mode of start-up, we demonstrate for comparison the graph of dynamics startup of screw feeder without optimization (Fig. 3) [13].



a)



b)

Fig. 3. Research results of the dynamics startup of screw feeder: the graph of angular speed (a), the graph of angular acceleration (b).

Obtained results of researches show, that, in the case shown in Fig. 3a, the maximum angular speed reaches 16 rad / s, that is 1.4 times larger than at the optimal mode (Fig. 2 a). Another difference between the graphs is that the nature of speed change is smooth during the optimal mode of motion, and during not optimal - oscillatory (amplitude of oscillation varies from -1.6 to 16 rad / s; especially sharply fluctuate the third and the fourth masses.) In both cases rated speed is reached during 1s.

The graph of acceleration (Fig. 2, b) demonstrates visually that soon after the conveyor's start the shift of cargo is accompanied by the smooth growth of the acceleration to the maximum value of 20 rad/s^2 for 0.3s. Eventually acceleration decreases gradually. At the same time in Figure 3 is visible a pronounced oscillatory character of curve. The maximum value of acceleration reaches 446 rad/s^2, and then decreases to -336 rad/s^2, and further the amplitude of oscillation gradually fades. Analysis of obtained results shows that during optimum mode of start-up maximum value of acceleration of the links in the 22.3 times less than the corresponding acceleration during not optimal mode, that leads to considerable reduction of dynamic loads in the elements of construction.

The start-up torque possesses the character, that is similar to the character of change of driving link's jerk, because initial value of the moment reaches 290 N*m (to overcome drag torque, which arises in the beginning of motion), and then the value of the moment smoothly decreases to nominal value (fig. 4).

Analyzing these results, we see that due to optimization are reduced to minimum fluctuation of systems' parts, and eventually action of dynamic loads practically disappears in the drive elements and screw conveyor shaft.

4. CONCLUSION

So, as a result of the researches the optimal mode of motion that provides smooth startup of conveyor is determined. The absence of oscillations indicates the decrease of dynamic loads on the driving mechanism that, in turn, increases the reliability of conveyor.

5. LITERATURE

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ВИТОК ВИНТА: ОПТИМИЗАЦИЯ СПОСОБОВ ДВИЖЕНИЯ, КОГДА МОМЕНТЫ СОПРОТИВЛЕНИЯ ВЫЗЫВАЮТ ИЗМЕНЕНИЕ В СООТВЕТСТВИИ С ЛИНЕЙНЫМ ЗАКОНОМ

Аннотация. Работа касается математической модели витка винта, которая характеризует движение в динамике, на основе, которой выполнена оптимизация способов движения. Принимая во внимание, что моменты сил сопротивления изменяются в соответствии с линейным законом в оптимальном и неоптимальных способах движения, результаты для теоретических исследований динамики запуска продемонстрированы.

Ключевые слова: виток винта, динамический груз, оптимизация, момент сопротивления.