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DEVISING A PROCEDURE FOR CALCULATING THE BELT TENSION OF A CONVEYOR WITH A STOPPED DRIVE WHEN CHANGING THE TRANSPORTATION LENGTH

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The object of this study is the working process of a belt conveyor. The task considered relates to designing belt conveyors taking into account the belt tension during a change in the transportation length.

It was established that when the length of a non-working conveyor changes, the static and dynamic load of the belt increases. The change in the static load of the belt on the drum of the mobile station depends on the speed of the mobile station and the parameters of the conveyor. The dynamic load of the belt depends on the acceleration of the belt, which is associated with the acceleration of the mobile station during a change in the transportation length of the conveyor.

The change in the load of the belt on the drum of the mobile station occurs in two phases: the first phase is the shift; the second phase is the acceleration and the change in the transportation length. The first phase lasts for several seconds, and the belt tension is equal to the resistance force of the empty conveyor line. The second phase lasts while the transportation length changes, and the belt tension depends on the parameters of the conveyor and the acceleration of the mobile station at this time.

For a non-operating conveyor that changes the conveyor length, the static tension of the belt on the drum of the mobile station can increase by 2 times from the initial one. The dynamic loading of the belt can have a significant increase if the acceleration of the mobile station is not stretched in time and has large values.

When operating the conveyor, it is necessary to change the transportation length when the conveyor is running.

Using the Mathcad software, a stopped conveyor with a change in the transportation length was tested. Calculations showed that the belt tension was 10 % higher than for a conveyor with a running drive.

The results make it possible to properly operate competitive machines equipped with a belt conveyor with a variable transportation length

Keywords: belt conveyor, software, operation, belt tension, theoretical research

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1. Introduction

The current trend in the development of world mechanical engineering is characterized by a constant increase in the technical level of newly designed machines and equipment, which ensures their competitiveness in the face of growing market demands. To a large extent, this applies to lifting and conveying equipment, which is widely used in various sectors of the national economy.

Within the large class of lifting and conveying equipment, there are belt conveyors whose design is aimed at increasing productivity and reducing the energy intensity of cargo transportation.

One of such structural solutions is the use of a belt conveyor with a variable transportation length. It is a semi-stationary installation that can be extended during operation.

On this conveyor, the end or remote drum is installed on a mobile station. Due to the movement of the mobile station, the transportation length changes. The presence of a telescopic device with an automatic belt tension control system allows the conveyor to be extended when the drive is not working.

Its use makes it possible to increase labor productivity and reduce energy consumption of transportation, with a flow technology of work execution:

– due to the elimination of unproductive work operations associated with the transfer of the end station of the conveyor;

– due to the possibility of lengthening or shortening the length of the conveyor during its operation;

– due to the exclusion from the traditional technological scheme, namely from the transport chain of overloading devices.

Therefore, studies on belt conveyors with variable transportation length are relevant.

2. Literature review and problem statement

The use of belt conveyors with variable transport length is discussed in work [1], which reports the results of using such a belt conveyor at the Prosper Haniel mine in Germany. Noting the great economic effect of using this equipment in production, the work indicated the need for research related to obtaining a calculation method for such a conveyor. According to the authors, in order to reliably control all operating states of the conveyor, it is advisable to develop a program that would also control transient processes. The program would make it possible to model calculations of engine control at drive stations equipped with static frequency converters. The development of a belt tension procedure could make it possible to solve this issue.

Work [2] reports the results of research into the development of algorithms and software for automated calculation of the main traction characteristics of a belt conveyor. The research is based on a well-known method for calculating a conveyor. Various conveyor variants are considered – single- and double-drum, with the presence of a pressure roller or belt, with a rigid kinematic clutch or connection between independent drums. A visual form of the user interface is developed using the example of the main parameters of a mine conveyor, which are set in the Delphi 7 programming language. Visual forms of implementation of the calculation algorithm for the traction power of the conveyor drive are given. However, this software algorithm does not provide for its possible application for calculating a belt conveyor with a variable transportation length.

In works [3, 4], a methodology is considered that makes it possible to study the dynamic behavior of the belt in DEM simulation during the transportation processes of bulk materials. The modeling was implemented in the DEM software. However, the change in the transportation length was not considered in the work.

The basic approach to conveyor belt modeling was to build a belt model by systematically placing individual particles connected into a mesh using so-called connections. An additional method of preprocessing the model was developed to create a conveyor belt in a DEM environment. However, the study did not consider the dynamics of belt tension changes during the extension of the conveyor transport length. The use of the devised methodology for modeling conveyor belts is especially suitable for modeling belt conveyor systems where there is a sufficiently strong deformation of the belt. This methodology can also be applied to systems in which the deformation of the belt or the behavior of the belt as a whole has a significant impact on the functionality of the systems. These are, for example, curved belt conveyors, tubular or sandwich conveyors and similar unconventional belt conveyor systems.

In [5], a dynamic model of a belt conveyor was considered, and a conveyor modeling algorithm was proposed on its basis. The study reports the results of mathematical modeling, which were obtained using the developed intelligent software. According to the author, modeling of the conveyor belt makes it possible to improve the design scheme of the belt conveyor. However, the study did not consider the mathematical model of the belt conveyor, which can change the length of transportation.

In [6], the method of modeling wave phenomena in the belt, the change of masses and resistance to movement, as well as the elements of the drive system, i.e., engines, torque converters, couplings, gears, and the interaction of the drive drum with the belt, is described. With the help of a computer program, dependences were obtained that made it possible to simulate the start of the conveyor drive. The results obtained by measuring instruments were compared with the results obtained computationally during the start of the conveyor drive. It was established that the resulting model could be used to study various phenomena and operating states of the conveyor. However, the transient processes that occur in the belt during the change in the length of transportation were not studied.

In work [7], the structure of a belt conveyor using 3D design software was considered. After performing the calculation according to generally accepted standards, the parameters of the belt conveyor were obtained. Then, using the Solid Works software, a 3D model of the conveyor was built, to the elements of which design loads were applied. The finite element method was used to obtain the diagram of stresses in the elements of the belt conveyor. The authors indicate the possibility of changing the conveyor model in a computer environment and using the finite element method to obtain the results of a new design without wasting time on calculations. The study indicates that the program does not provide for individual calculations of stresses in the conveyor belt. Calculations of stresses in the conveyor are considered only in a generalized form, which is based on the strength approach to materials. For a belt conveyor that can change the length of transportation, it is necessary to have special analytical dependences and software for design.

In [8], the results of research on the dynamic behavior of a conveyor belt taking into account the uneven distribution of bulk material for speed control are reported. The paper describes the results of developing a high-precision dynamic model that can take into account control over the conveyor belt speed during uneven transportation of bulk material. In this dynamic model, a model of uneven distribution of bulk material based on laser scanning technology is proposed. A high-precision longitudinal dynamic model is proposed to study the dynamic behavior of a belt conveyor. Considering the microunits of the actual load on the conveyor belt, this can well describe the transient state of the conveyor belt. These models could be used to determine the optimal speed for safety and energy saving during operation. However, the paper did not consider a mathematical model of a belt conveyor that can change the transportation length. In addition to the missing necessary mathematical support, no software is provided that simplifies the design of the transport installation.

In work [9], an improved method for designing automatic control systems for electric motors was considered in order to obtain mechanical characteristics that would ensure reliable operation of belt conveyors. An automatic control system based on the Siemens S7-1200 controller was designed, then a mathematical model of an automated electric drive was built. Based on the mathematical model, a simulation model of an automatic electric drive was constructed, and its operating modes were simulated. However, the work concerns a belt conveyor with a constant transport length. In [10], a three-stage method is presented that could be used to determine the correct way to accelerate a belt conveyor with a regulated speed during transient processes. This method takes into account potential risks under transient modes and the dynamic characteristics of the conveyor during start-up. In the example, the maximum permissible acceleration is calculated. Simulation with a predicted acceleration time is performed to determine the acceleration operation and analyze the dynamics of the conveyor. The modeling is based on the existing finite element model of a belt conveyor. However, the work concerns a belt conveyor with a constant length of transportation.

In a simplified form, the results of theoretical studies of the process of propagation of elastic deformations in a conveyor belt, which changes the length of transportation, are reported in [11]. The main assumption is as follows: the mobile station at the initial moment of the conveyor extension is uniformly accelerated. The work proves that when the length of transportation changes, the belt tension on the drum of the mobile station increases, which exists as long as the conveyor is extended. During the acceleration of the mobile station, there is a dynamic and static increase in the belt tension. With a constant movement of the mobile station (a constant increase in the length of transportation), there is only a static increase in the belt tension. It is established that the belt load when the working conveyor is extended is less than when the conveyor is extended with the drive stopped. Therefore, the conveyor must be extended during the operation of the conveyor drive. The work does not solve the problem of building a mathematical model that would take into account the acceleration time of the mobile station (the acceleration time of the electric motor of the station movement drive to constant speed) to steady motion.

Our review of the literature [1–11] showed that to solve the problem of designing belt conveyors with a transportation length, it is necessary to have a calculation procedure that takes into account the belt tension during a change in the transportation length.

3. The aim and objectives of the study

The purpose of our work is to devise a procedure for calculating the belt tension of a conveyor with a variable length of transportation with the drive stopped, which would take into account the acceleration time of the mobile station. This will make it possible to find out how to change the length of transportation with the drive running or not.

To achieve the goal, the following tasks were defined:

– to determine the speed and acceleration of the mobile station and the belt speed;

– to determine the speeds and acceleration of the loaded and empty belt lines when changing the conveyor transportation length;

– to determine the changes in the static increase in belt tension when changing the transportation length;

– to determine the dynamic increase in belt tension when changing the transportation length;

– to test the calculation of belt conveyors with a variable length based on numerical modeling.

4. The study materials and methods

The object of our study is the working process of a belt conveyor.

Working hypotheses of the study:

– changing the length of transportation of a belt conveyor under a given mode and ensuring the corresponding parameters are implemented by the operation of a mechanism or device of a technological machine, which together with the conveyor performs one or another process;

– creating energy-saving belt conveyors with a variable length of transportation is based on the use of developed methods, mathematical support and software of justified rational parameters and operating modes.

The following assumptions are adopted. A rubber-cable belt can be considered an isotropic-elastic body. Quite often, when calculating with a rubber-fabric belt, it is assumed that the traction-bearing body is an isotropic-elastic body.

The following simplifications are accepted. When determining the kinetic energy of the mechanical conveyor system, associated with determining the speed and acceleration of the mobile station and the speed of the belt during conveyor extensions, the power of internal forces takes on the level of zero. The specific static resistance to the movement of the empty line belt is constant along the entire length of the conveyor.

Based on previously performed theoretical studies [11], the results of experimental [12] and industrial [13] studies involving Mathcad software (USA), the calculation of the tension of the belt of a non-working conveyor during a change in the length of transportation was performed.

Experimental studies were performed on experimental benches at the Donbass National Academy of Civil Engineering and Architecture [12].

Industrial studies were performed at the Zasyadko mine (Donetsk city, Ukraine) in the period from 1992 to 2000.

5. Results of investigating a conveyor with a variable length of transportation with a stopped drive

5. 1. Determining the speed and acceleration of a mobile station

When determining the speed and acceleration of a mobile station during a change in the length of transportation of a conveyor with a stopped drive, the differential form of the theorem on the change in the kinetic energy of the system is used.

The total derivative of kinetic energy with respect to time is equal to the sum of the powers of all external N^e and internal N^i forces applied to the system:

$$dT/dt = N^e + N^i, \text{ N·m/s.} \tag{1}$$

The derivative of work with respect to time is equal to the power of the applied force. The sum of the work of internal forces, and therefore the powers of internal forces, is taken to be zero N^i.

The change in kinetic energy of a mechanical system, the extension of a conveyor belt, can be determined from the dependence:

$$T = T_{roadheader.} + T_{reduction\ gear.} + T_{engine.} + T_{conveyor.}, \text{ N·m.} \tag{2}$$

where $T_{roadheader}$ – change in kinetic energy of the tunneling combine, N·m; $T_{reductiongear}$ – change in kinetic energy of the gearbox of the running mechanism of the tunneling combine, N·m; T_{engine} – change in kinetic energy of the electric motor of the running mechanism of the tunneling combine, N·m; $T_{conveyor}$ – change in kinetic energy of the moving conveyor elements, N·m.

From the condition of the equilibrium state of the emerging tensions in the belt, it is obvious that the kinetic energy of the moving conveyor elements associated with the mobile station can be determined from the condition at which the belt speed of the loaded line $V_{cargo.stop.}$ (Fig. 1).

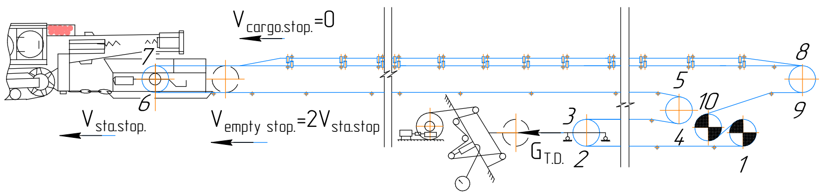

Fig. 1. Diagram of a conveyor that changes length with a stopped drive, taking into account the accepted condition

Taking into account the accepted condition, when $V'_{nempty.stop.} = 2V_{sta.}$:

$$T_{conveyor.stop.} = T'_{empty.stop.} + T'_{movable\,drum.stop.} + \\ + T'_{fixed\,drum\,.stop.} + T'_{drum.sta.stop.} + T^{stop.}_{movable\,carriage} + T^{stop.}_{sta.} \text{ N·m}, \quad (3)$$

where $T'_{empty.stop.}$, $T'_{movable\,drum.stop.}$, $T'_{fixed\,drum\,.stop.}$, $T'_{drum.sta.stop.}$, $T^{stop.}_{movable\,carriage}$, $T^{stop.}_{sta.}$ – changes in kinetic energy taking into account the accepted condition: empty line, mobile and stationary drums of the telescopic device, drum of the mobile station, mobile carriage of the telescopic device, mobile station of the conveyor with the drive stopped, respectively, N m.

Change in kinetic energy of the empty line taking into account the accepted condition:

$$T'_{empty\,stop.} = \frac{V^2_{empty\,stop.} m_{3\text{-}6}}{2g}, \text{ N·m.}$$

Taking into account the angle of the conveyor installation, the direction, and the coefficient of resistance of the belt movement on the rollers, the mass of the belt in the calculations is equal to:

$$m_{(3-6)} = \Omega_{empty} l_{(3-6)} / g, \text{ kg},$$

where Ω_{empty} – specific static resistance to the movement of the empty line, N/m; $l_{(3-6)}$ – distance from the drum of the mobile station to the tensioner drum, m:

$$\Omega_{empty} = g\left[\left(q_{belt} + q''_{rollers}\right)\omega' \cdot \cos\beta \pm q_{belt} \sin\beta\right], \text{ N/m},$$

where q_{belt} – running weight of the belt, kg; $q''_{rollers}$ – running weight of the lower roller supports, kg; ω´ – coefficient of specific resistance of the tubular belt; β – angle of installation of the conveyor, degrees:

$$T'_{empty\,stop.} = \frac{V^2_{sta.stop.} \Omega_{empty} l_{(3-6)} / g}{2g}, \text{ N·m}, \quad (4)$$

where $V_{sta.stop.}$ – speed of the mobile conveyor station with the drive stopped, m/s.

Change in kinetic energy of the drum of the mobile carriage of the telescopic device taking into account the accepted condition:

$$T'_{movable\,drum.stop.} = V^2_{sta.stop.} m_{drum.}, \text{ N·m}, \quad (5)$$

where m_{drum} – drum mass, kg; R_{drum} – drum radius, m; J_{drum} – drum moment of inertia, kg·m^2.

Change in kinetic energy of the stationary drum of the telescopic drum device taking into account the accepted condition:

$$T'_{fixed\,drum.stop.} = V^2_{sta.stop.} m_{drum.}, \text{ N·m.} \quad (6)$$

Change in kinetic energy of the drum of the mobile station taking into account the accepted condition:

$$T'_{drum.sta.stop.} = V^2_{sta.stop.} m_{drum.}, \text{ N·m.} \quad (7)$$

Change in kinetic energy of the movable carriage of the telescopic device taking into account the accepted condition:

$$T^{stop.}_{movable\,carriage.} = \frac{G_{T.D.} V^2_{sta.stop.}}{2g}, \text{ N·m}, \quad (8)$$

where $m_{T.D.}=G_{T.D.}/g$ – mass of the movable carriage of the telescopic device, which is identified with the tensioner force, kg.

The speed of the movable carriage of the telescopic device is always equal to the speed of the mobile station.

Change in kinetic energy of the mobile station of the conveyor taking into account the accepted condition:

$$T^{stop.}_{sta.} = \frac{m_{sta.} V^2_{sta.stop.}}{2}, \text{ N·m}, \quad (9)$$

where m_{sta} – mass of the mobile station, kg. Substituting the values of the parameters into equation (3) we obtain:

$$T_{conveyor.stop.} = V^2_{sta.stop.} \times \\ \times\left[2W_{empty} l_{(3-6)}\left(m_{T.D.} + m_{sta.}\right)/2 + 3m_{drum.}\right], \text{ N·m.} \quad (10)$$

Change in kinetic energy of the tunneling combine:

$$T^{stop.}_{roadheader.} = \frac{m_{roadheader.} V^2_{sta.stop.}}{2}, \text{ N·m}, \quad (11)$$

where $m_{roadheader}=m_{harvester}(f_{ruhu}\cos\beta \pm \sin\beta)$ – mass of the tunneling combine moving through the tunnel, kg; $m_{harvester}$ – mass of the tunneling combine, kg; f_{ruhu} – coefficient of resistance to movement (for tracked engines f_{ruhu}=0.1–0.2).

Change in kinetic energy of the gearbox of the running gear of the tunneling combine. For simplicity of calculation, we assume that the gearbox is two-stage:

$$T_{reduction\,gear.} = \frac{\omega^2_{engine} R^2_{1gear\,wheel}}{4} \times \\ \times\left(m_{1gear\,wheel.} + \frac{m_{2gear\,wheel.}}{i_{reduction\,gear.}}\right), \quad \text{N·m}, \quad (12)$$

where $\omega_{reduction\,gear}$ – rotation frequency of the travel electric motor, 1/rev; $J_{1gear\,wheel}$, $J_{2gear\,wheel}$ – moment of inertia, respectively, of the first and second gear wheels of the reducer, kg·m^2; $m_{1gear\,wheel.}$, $m_{2gear\,wheel}$ – mass, respectively, of the first and second gear wheels of the reducer, kg; $R_{1gear\,wheel.}$, $R_{2gear\,wheel}$ – radius, respectively, of the first and second gear wheels of the reducer, m; $i_{reduction\,gear}$ – gear ratio of the travel reducer.

Change in kinetic energy of the electric motor of the travel mechanism of the tunneling combine:

$$T_{engine.} = \frac{1}{4} m_{motor\,rotor.} R^2_{motor\,rotor.} \omega^2_{engine.}, \text{ N·m}, \quad (13)$$

where $J_{motor\ rotor}$ – moment of inertia of the rotor of the travel electric motor of the tunneling combine, kg·m^2; $m_{motor\ rotor}$ – mass of the rotor of the travel electric motor of the tunneling combine, kg; $R_{motor\ rotor}$ – radius of the rotor of the travel electric motor of the tunneling combine, m.

By substituting equations (11) to (15) into (2), the change in kinetic energy of the mechanical system of the tunneling combine – belt conveyor with the drive stopped is obtained:

$$\begin{aligned}T_{stop.} &= \frac{m_{roadheader.} V^2_{sta.stop.}}{2} + \\ &+ \frac{1}{4} m_{motor\ rotor.} R^2_{motor\ rotor.} \omega^2_{engine.} + \\ &+ \frac{\omega^2_{engine.} R^2_{1.gear\ wheel.}}{4}\left(m_{1gear\ wheel.} + \frac{m_{2gear\ wheel.}}{i_{reduction\ gear.}}\right) + \\ &+ V^2_{sta.stop.}\left[\begin{array}{l} 2\Omega_{empty} l_{(3-6)} / g + \\ + \left(m_{T.D.} + m_{sta.}\right)/2 + 3m_{drum.} \end{array}\right], \text{N}\cdot\text{m}, \end{aligned} \quad (14)$$

$$\begin{aligned}V_{sta.stop.} &= V_{caterpillar.}/2 = \\ &= R_{stars.} i_{reduction\ gear.} \omega_{reduction\ gear.}/2, \text{ m/s}, \end{aligned} \quad (15)$$

where R_{stars} is the radius of the track drive sprocket of the travel reducer of the tunneling combine, m (Fig. 2).

Substituting (15) into (16) we obtain:

$$T_{stop.} = \frac{V^2_{sta.stop.}}{2} \times \left[\begin{array}{l} \dfrac{4\left(J_{motor\ rotor.} + J_{1.gear\ wheel.} + J_{1.gear\ wheel.} i_{reduction\ gear.}\right)}{R^2_{stars.} i^2_{reduction\ gear.}} + \\ + m_{roadheader.} + m_{T.D.} + \\ + m_{sta.} + 6m_{drum.} + \dfrac{4\Omega_{empty} l_{(3-6)}}{g} \end{array}\right], \text{N·m}. \quad (16)$$

If we assume that the weight of the running gear is included in the weight of the tunneling combine, then the sum of the powers of all external forces of the conveyor with the drive stopped $N^e_{stop.}$ is equal to:

$$N^e_{stop.} = N_{engine.} + N^{stop.}_{resistance}, \text{ N·m/s}, \quad (17)$$

$$N^{stop.}_{resistance.} = \left(N^{stop.}_{roadheader.} + N^{stop.}_{conveyor.}\right)\cos 180°, \text{ N·m/s}. \quad (18)$$

The power of the resistance forces during the movement of the tunneling combine:

$$N^{stop.}_{roadheader.} = m_{roadheader.} g V_{sta.stop.}, \text{ N·m/s}. \quad (19)$$

From equation (10), we determine the resistance force of the moving elements of the conveyor $F_{elements.conveyor.}$:

$$T_{conveyor.stop.} = V^2_{sta.stop.} \frac{F_{elements.conveyor.}}{2g}, \text{ N·m}, \quad (20)$$

$$F_{elements.conveyor.} = m_{reduced.elements.conveyor.} g, \text{ N}, \quad (21)$$

where $m_{reduced.elements.conveyor.}$ – reduced mass of moving elements of the conveyor, kg.

Substituting equations (20) and (21) into (10), we obtain:

$$\begin{aligned}F_{elements.conveyor.} &= 4\Omega_{empty} l_{3-6}/g + \\ &+ m_{T.D.} + m_{sta.} + 6m_{drum.}, \text{ kg}. \end{aligned} \quad (22)$$

Taking into account equation (22), the power of the resistance forces during the movement of the elements of a stopped conveyor:

$$N^{stop.}_{conveyor.} = V_{sta.stop.} \times \left[\begin{array}{l} 4\Omega_{empty} l_{3-6} + \\ + g\left(m_{T.D.} + m_{sta.} + 6m_{drum.}\right) \end{array}\right], \text{ N·m/s}. \quad (23)$$

Substituting equations (23) and (19) into (18), we obtain:

$$N_{resistance.} = -V_{sta.stop.} \times \left[4\Omega_{empty} l_{3-6} + g\left(\begin{array}{l} m_{roadheader.} + m_{T.D.} + \\ + m_{sta.} + 6m_{drum.} \end{array}\right)\right], \text{ N·m/s}. \quad (24)$$

The power of the traction asynchronous electric motor of the tunneling combine $N_{engine.}$ for the conveyor with the drive stopped is obtained from the formula:

$$\begin{aligned}N_{engine.} &= M_{engine.} \omega_{engine} = \\ &= \left(M_p - \beta_{engine.} \omega_{engine.}\right) \omega_{engine.}, \text{ N·m/s}, \end{aligned} \quad (25)$$

where M_p is the starting torque of the running electric motor, N·m; $\beta = (M_1 - M_2)/(\omega_1 - \omega_2)$ is the coefficient characterizing the slope of the mechanical characteristic of the engine of the running mechanism of the tunneling combine, N·m·s (Fig. 3).

Taking into account equation (15):

$$N^{stop.}_{engine.} = \frac{2V_{sta.stop.}}{R_{stars.} i_{reduction\ gear.}} \times \left(M_p - \frac{2V_{sta.stop.} \beta_{engine}}{R_{stars.} i_{reduction\ gear.}}\right), \text{ N·m/s}. \quad (26)$$

Substituting equations (24) and (25) in (17), the following is obtained:

$$N^e = V_{sta.stop.} \times \left[\begin{array}{l} \dfrac{2}{R_{stars.} i_{reduction\ gear.}} \left(M_p - \dfrac{2V_{sta.stop.} \beta_{engine.}}{R_{stars.} i_{reduction\ gear.}}\right) - \\ -4\Omega_{empty} l_{3-6} - g\left(\begin{array}{l} m_{roadheader.} + m_{T.D.} + \\ + m_{sta.} + 6m_{drum.} \end{array}\right) \end{array}\right], \text{ N·m/s}. \quad (27)$$

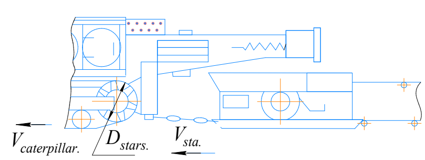

Fig. 2. Scheme for calculating the speed of a mobile station

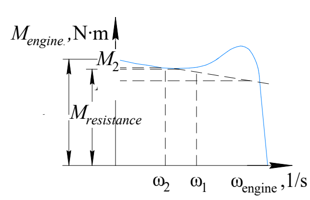

Fig. 3. Torque-frequency characteristic of an electric motor

By substituting equation (27) and differentiating by t equation (16) in (1), we obtained:

$$\frac{dV_{sta.stop.}}{dt}\times \left[\begin{array}{l}\frac{2\left(J_{motor\,rotor.}+J_{1.gear\,wheel.}+J_{2gear\,wheel.\;reduction\,gear.}\right)}{R_{stars.}i_{reduction\,gear.}}+\\ +\frac{R_{stars.}i_{reduction\,gear.}}{2}\left(\begin{array}{l}\frac{4\Omega_{empty}l_{3-6}}{g}+m_{roadheader.}+\\ +m_{T.D.}+m_{sta.}+6m_{drum.}\end{array}\right)\end{array}\right]=$$

$$=M_p-\frac{2\beta_{engine.}}{R_{stars.}i_{reduction\,gear\,.}}V_{sta.stop.}-R_{stars.}i_{reduction\,gear\,.}\times$$

$$\times\left[2\Omega_{empty.}l_{3\text{-}6}+\frac{g}{2}\left(\begin{array}{l}m_{roadheader.}+m_{T.D.}+\\ +m_{sta.}+6m_{drum.}\end{array}\right)\right],\mathrm{N\cdot m}, \quad (28)$$

$$\Im_{stop.}\frac{dV_{sta.stop.}}{dt}=M_p-\aleph_{stop.}-\Re V_{sta.stop.},\ \mathrm{N{\cdot}m}; \quad (29)$$

$$\Re=\frac{2\beta_{engine.}}{R_{stars.}i_{reduction\,gear.}},\ \mathrm{N{\cdot}s}; \quad (30)$$

$$\Im_{stop.}=$$

$$=\frac{2\left(J_{motor\,rotor.}+J_{1.gear\,wheel}+J_{2gear\,wheel.}i_{reduction\,gear.}\right)}{R_{stars.}i_{reduction\,gear.}}+$$

$$+\frac{R_{stars.}i_{reduction\,gear.}}{2}\left(\begin{array}{l}4\Omega_{empty.}l_{3-6}/g+m_{roadheader.}+\\ +m_{T.D.}+m_{sta.}+6m_{drum.}\end{array}\right),\ \mathrm{kg{\cdot}m}; \quad (31)$$

$$\aleph_{stop.}=R_{stars.}i_{reduction\,gear.}\times$$

$$\times\left[2\Omega_{empty.}l_{3-6}+\frac{g}{2}\left(\begin{array}{l}m_{roadheader.}+m_{T.D.}+\\ +m_{sta.}+6m_{drum.}\end{array}\right)\right],\ \mathrm{N{\cdot}m}. \quad (32)$$

The law of change of speed of a mobile conveyor station with a stopped drive is solved by equation (30). For this purpose, the variables are separated:

$$\frac{\Im_{stop.}dV_{sta.stop.}}{M_p-\aleph_{stop.}-\Re V_{sta.stop.}}=dt,\ \mathrm{s}. \quad (33)$$

By integrating both parts of equality, the equation is obtained:

$$-\frac{\Im_{stop.}}{\Re}\ln\left|M_p-\aleph_{stop.}-\Re V_{sta.stop.}\right|=t+C,\ \mathrm{s}. \quad (34)$$

At the beginning of the engine displacement at t=0, $V^{stop.}_{sta.shift}=0$, therefore:

$$C=-\frac{\Im_{stop.}}{\Re}\ln\left(M_p-\aleph_{stop.}\right),\ \mathrm{s}. \quad (35)$$

Substitution of equation (35) in (34) leads to the formula:

$$-\frac{\Im_{stop.}}{\Re}\ln\left|M_p-\aleph_{stop.}-\Re V^{stop.}_{sta.shift.}\right|=$$

$$=t-\frac{\Im_{stop.}}{\Re}\ln\left|M_p-\aleph_{stop.}\right|,\ \mathrm{s}. \quad (36)$$

By grouping the terms with logarithms, the following is obtained:

$$\ln\frac{M_p-\aleph_{stop.}-\Re V_{sta.stop.}}{M_p-\aleph_{stop.}}=-\frac{\Re}{\Im_{stop.}}t,\ \mathrm{s}. \quad (37)$$

After potentiating equation (37) and transformations:

$$1-\frac{\Re}{M_p-\aleph_{stop.}}V_{sta.stop.}=\exp\left(-\frac{\Re}{\Im_{stop.}}t\right),\ \mathrm{kg/m{\cdot}s^2}; \quad (38)$$

$$1-\frac{\Re}{M_p-\aleph_{stop.}}V_{sta.stop.}=\exp\left(-\frac{\Re}{\Im_{stop.}}t\right),\mathrm{m/s}. \quad (39)$$

Differentiating by t equation (40), the acceleration of the mobile station of the stopped conveyor is obtained:

$$1-\frac{\Re}{M_p-\aleph_{stop.}}V_{sta.stop.}=\exp\left(-\frac{\Re}{\Im_{stop.}}t\right),\ \mathrm{m/s^2}. \quad (40)$$

The acceleration of the mobile station is influenced by the parameters of the running electric motor of the combine and the parameters of the conveyor.

5. 2. Determining the speed and acceleration of the belt of the loaded and empty lines

If the resistance forces to the movement of the belt on the upper line are greater than the resistance forces to the movement of the belt on the lower line, it is obvious that the speed of the belt on the lower line is greater than the speed of the belt on the upper line.

When changing the length of the conveyor with the drive stopped, the speed of the empty line is greater for horizontal, Brensberg, and slightly inclined conveyors. The resistance forces to the movement of the belt on the load line and in the drive area are greater than on the empty one.

When changing the length of the conveyor with the drive stopped, the speed of the empty line may be less for an inclined conveyor, when the resistance forces to the movement of the belt on the load line and in the drive area are less than on the empty one.

For a conveyor with the drive stopped, the speed of the change in the length of transportation is equal to twice the sum of the speeds on the loaded and empty lines:

$$2V_{sta.stop.}=V_{cargo.stop.}+V_{empty.stop.},\ \mathrm{m/s}. \quad (41)$$

Hence:

$$V_{cargo.stop.}=2V_{sta.stop.}-V_{empty.stop.},\ \mathrm{m/s}. \quad (42)$$

The change in kinetic energy of the conveyor with the stopped drive is compared to the change in kinetic energy of the conveyor with the stopped drive under the adopted condition (Fig. 4, equation (10)).

The change in kinetic energy of a conveyor with a stopped drive without an accepted condition is equal to:

$$T_{conveyor.stop.}=T_{cargo.stop.}+T_{empty.stop.}+T_{wine\,drum.stop.}+$$

$$+T_{reduced.conveyor.stop.}+T_{movable\,drum.stop.}+T_{fixed\,drum.stop.}+$$

$$+T_{drum.sta.stop.}+T_{movable\,carriage.stop.}+T_{sta.stop.},\mathrm{N\cdot m}. \quad (43)$$

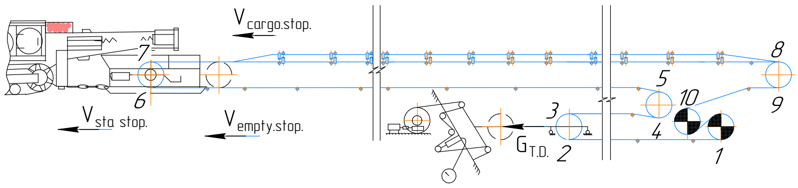

Fig. 4. Diagram of a conveyor that changes the transportation length with the drive stopped

Change in the kinetic energy of a loaded line without an accepted condition:

$$T_{cargo.stop.}=\frac{V^2_{cargo.stop.}\Omega_{cargo.}l_{(7-8)}}{2g},\ \text{N·m},\qquad(44)$$

where Ω_{cargo} is the specific static resistance to movement of the loaded line N/m:

$$\Omega_{cargo}=g\begin{bmatrix}\left(q_{cargo}+q_{belt}\ +q'_{rollers}\right)\omega'\cdot\cos\beta\pm\\ \pm\left(q_{cargo}+q_{belt}\right)\sin\beta\end{bmatrix},\text{N·m},\qquad(45)$$

where q_{cargo} – linear mass of the cargo, kg/m; q'_{rollers} – linear mass of the upper roller supports, kg/m.

Change in kinetic energy of the empty line without the accepted condition:

$$T_{empty.stop.}=\frac{\Omega'_{empty.}l_{(9-10)}V^2_{cargo.stop.}}{2g}+\frac{\Omega_{empty.}l_{(1-2)}V^2_{cargo.stop.}}{2g}+$$
$$+\frac{\Omega''_{empty}l_{(3-4)}V^2_{empty.stop.}}{2g}+\frac{\Omega_{empty}l_{(5-6)}V^2_{empty.stop.}}{2g},\text{N·m}.$$

Assuming $\Omega_{empty}=\Omega'_{empty}=\Omega''_{empty}$, we obtained:

$$T_{empty.stop.}=\frac{\Omega_{empty.}\left(V^2_{cargo.stop.}l_{(9-2)}+V^2_{empty.stop.}l_{(3-6)}\right)}{2g},\ \text{N·m}.\qquad(46)$$

Change in the kinetic energy of the remote drum without an accepted condition:

$$T_{wine\,drum.stop.}=\frac{V^2_{cargo.stop.}m_{drum.}}{4}\ ,\ \text{N·m}.\qquad(47)$$

The change in kinetic energy of the conveyor drive, which includes drive drums, a gearbox, and an electric motor, which are designated as the reduced mass of the conveyor drive, without the accepted condition takes the form:

$$T_{reduced.conveyor.drive.stop.}=\frac{m_{reduced.conveyor.drive.}V^2_{cargo.stop.}}{2},\ \text{N·m},\qquad(48)$$

where $m_{reduced.conveyor.drive.}=k\left(GD\right)^2_p i^2_p/\left(gD^2_{drum.}\right)$ – the reduced mass of the conveyor drive, kg; k – coefficient taking into account the inertia of the conveyor drive reducer, equal to 1.2–1.3; GD – torque of the motor rotor,N^2·m^2; i_p – gear ratio of the conveyor drive reducer; D_{drum} – diameter of the drive drum, m; V_{cargo} – speed of the attached line of the stopped conveyor/s.

The change in the kinetic energy of the drum of the movable carriage of the telescopic device without the assumed condition is expressed by the equation:

$$T_{movable\,drum.stop.}=$$
$$=\frac{\left(V_{empty.stop.}-V_{cargo.stop.}\right)^2 m_{drum.}}{4},\ \text{N·m}.\qquad(49)$$

The change in kinetic energy of the movable carriage of a telescopic device without the accepted condition is expressed by the equation:

$$T^{stop.}_{movable\,carriage.}=\frac{G_{T.D.}V^2_{sta.stop.}}{2g},\ \text{N·m}.\qquad(50)$$

The change in kinetic energy of the stationary drum of a telescopic device without the assumed condition is expressed by the equation:

$$T_{fixed\,drum.stop.}=\frac{V^2_{empty.stop.}m_{drum.}}{4},\ \text{N·m}.\qquad(51)$$

The change in kinetic energy of the drum of a mobile station without the assumed condition is expressed by the equation:

$$T_{drum.sta.stop.}=\frac{\left(V_{empty.stop.}-V_{cargo.stop.}\right)^2 m_{drum.}}{4},\ \text{N·m}.\qquad(52)$$

The change in kinetic energy of a mobile conveyor station without the assumed condition is expressed by the equation:

$$T_{sta.stop.}=\frac{m_{sta.}V^2_{sta.stop.}}{2},\ \text{N·m}.\qquad(53)$$

Taking into account equation (42), substitution of equations (44) to (53) in (43), the following is obtained:

$$T_{conveyor.stop.}=\frac{V^2_{empty.stop.}}{2}\times$$
$$\times\begin{bmatrix}\left(\Omega_{cargo.}l_{(7-8)}+\Omega_{empty.}l_{(9-6)}\right)/g+\\ +5m_{drum.}+m_{reduced.conveyor\,drive.}\end{bmatrix}-$$
$$-2V_{sta.stop.}V_{empty.stop.}\times$$
$$\times\begin{bmatrix}\left(\Omega_{cargo.}l_{(7-8)}+\Omega_{empty.}l_{(9-6)}\right)/g+\\ +2.5m_{drum.}+m_{reduced.conveyor\,drive.}\end{bmatrix}+$$
$$+V^2_{sta.stop.}\begin{bmatrix}2\left(\Omega_{cargo.}l_{(7-8)}+\Omega_{empty.}l_{(9-2)}\right)/g+\\ +\left(m_{T.D.}+m_{sta.}\right)/2+3m_{drum.}+\\ +2m_{reduced.conveyor\,drive.}\end{bmatrix},\text{N·m}.\qquad(54)$$

By equating equation (10) to (54), we obtain the transformation and determine the speed of the belt on the empty line when changing the length of the conveyor with the drive stopped:

$$\frac{1}{2}V^2_{empty.stop.}\begin{bmatrix}\left(\Omega_{empty.}l_{(9-6)}+\Omega_{cargo.}l_{(7-8)}\right)/g+\\ +5\,ò_{drum.}+m_{reduced.conveyor\,drive.}\end{bmatrix}-$$
$$-2V_{sta.stop.}V_{empty.stop.}\times$$
$$\times\begin{bmatrix}\left(\Omega_{cargo.}l_{(7-8)}+\Omega_{empty.}l_{(9-2)}\right)/g+\\ +2.5ò_{drum.}+m_{reduced.conveyor\,drive.}\end{bmatrix}+2V^2_{sta.stop.}\times$$
$$\times\begin{bmatrix}\begin{pmatrix}\Omega_{cargo.}l_{(7-8)}+\\ +\Omega_{empty.}l_{(9-2)}-\\ -\Omega_{empty.}l_{(3-6)}\end{pmatrix}/g+m_{reduced.conveyor\,drive.}\end{bmatrix}=0,\ \text{N·m},\qquad(55)$$

$$V_{empty.stop.} = 2V_{sta.stop.}\frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}, \text{ m/s}, \tag{56}$$

$$\Lambda = \left(\Omega_{cargo.} l_{(7-8)} + \Omega_{empty.} l_{(9-2)}\right)/g + \\ +2.5m_{drum.} + m_{reduced.conveyor\,drive.}, \text{kg}, \tag{57}$$

$$\Phi = \left(\begin{array}{l}\dfrac{\Omega_{empty.} l_{(9-2)} + l_{(3-6)}\Omega_{empty.} + \Omega_{cargo.} l_{(7-8)}}{g} + \\ +5m_{drum.} + m_{reduced.conveyor\,drive.}\end{array}\right) \times \\ \times \left(\begin{array}{l}\dfrac{\Omega_{cargo.} l_{(7-8)} + \Omega_{empty.} l_{(9-2)} - \Omega_{empty.} l_{(3-6)}}{g} + \\ +m_{reduced.conveyor\,drive.}\end{array}\right), \text{kg}^2, \tag{58}$$

$$\mathrm{P} = \left[\begin{array}{l}\left(\Omega_{empty.} l_{(9-6)} + \Omega_{cargo.} l_{(7-8)}\right)/g + \\ +5m_{drum.} + m_{reduced.conveyor\,drive.}\end{array}\right], \text{ kg}. \tag{59}$$

Under the action of this force, the belt is stretched from point 6 to point 3. As soon as the tension force at point 6 is sufficient to overcome the resistance to movement of the section $l_{(3-6)}$, this section is stretched and starts moving.

It is obvious that the static tension of the belt at the section $l_{(3-6)}$ in the displacement phase will correspond to the diagram shown in Fig. 5.

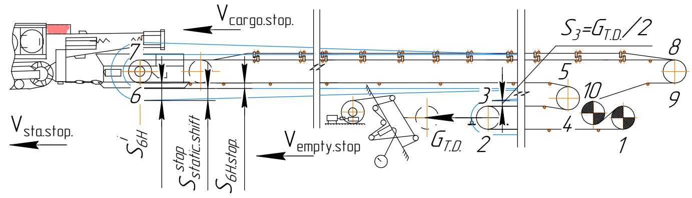

Fig. 5. Scheme of changes in static tensions in the belt during changes in the conveyor transport length with the drive stopped in the shift phase

By substituting equation (56) into (42), we obtain the rate of change of the loaded line during the change in the length of the conveyor with the drive stopped:

$$V_{cargo.stop.} = 2V_{sta.stop.}\left(1 - \frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}\right), \text{ m/s}. \tag{60}$$

Since the change in the speed of the empty line varies proportionally to the speed of the mobile station, the acceleration of the empty line is determined from the dependence:

$$j_{empty.stop.} = 2j_{sta.stop.}\frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}, \text{ m/s}^2. \tag{61}$$

Accordingly, the acceleration of the loaded line is equal to:

$$j_{cargo.stop.} = 2j_{sta.stop.}\left(1 - \frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}\right), \text{ m/s}^2. \tag{62}$$

The acceleration of the loaded conveyor line is affected by the acceleration of the mobile station and the conveyor parameters.

5. 3. Determining the static increase in belt tension during a change in the conveyor transportation length with a stopped drive

5. 3. 1. Determining the change in the static increase in belt tension during a change in the conveyor transportation length

Based on field observations, as well as experimental studies [12], it was established that during the extension of the conveyor on the drum of the mobile station, an increase in the static belt tension occurs.

In work [14] it is indicated that when starting or changing the length of a stopped conveyor, the belt displacement and acceleration phases occur.

At the initial moment of time of the conveyor changing the transportation length with a stopped drive, a belt displacement phase occurs. The belt displacement phase is associated with the propagation of a quasi-static wave of elastic deformation from point 6 to point 3 (Fig. 5).

The movement of the elastic deformation wave occurs under the action of the traction force applied to the mobile station, which moves the tape from right to left.

In [13] it was established that the speed of stretching the belt from point 6 to point 3 is inversely proportional to the change in tension on a given section of the conveyor.

Regarding the calculation scheme (Fig. 5), it can be written that the speed of stretching the belt under the action of a static load from point 6 to point 3 in the shift phase is equal to:

$$a_{static.empty.stop.} = \frac{dx}{dt} = \frac{V_{empty.stop.}E_{0.dyn.}}{\Omega_{empty.}x + S_{6H}}, \text{ m/s}, \tag{63}$$

where E_{0dyn} – aggregate dynamic stiffness of the belt, N.

When considering static deformations, it is correct to substitute the dynamic modulus of the belt stiffness since this process occurs during the movement of the traction element.

Taking into account dependence (56), the transformation of equation (63) is obtained by separating the variables:

$$\left(\Omega_{empty.}x + G_{T.D}/2\right)dx = 2E_{0.dyn.}\frac{M_p - \aleph_{stop.}}{\Re} \times \\ \times \left(1 - e^{-\frac{\Re}{\Im_{stop.}}t}\right)\frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}dt, \text{N} \cdot \text{m}. \tag{64}$$

Integrating the right and left sides of the equation with initial parameters $x=0$ and $t=0$yields the following expression:

$$\int_0^x \left(\Omega_{empty.}x + G_{T.D}/2\right)\mathrm{d}x = \\ = \int_0^t 2E_{0.dyn.}\frac{M_p - \aleph_{stop.}}{\Re}\left(1 - e^{-\frac{\Re}{\Im_{stop.}}t}\right)\frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}dt, \text{ N·m},$$

$$\frac{\Omega_{empty.}x^2}{2} + \frac{G_{T.D.}x}{2} = 2E_{0.dyn.}\frac{M_p - \aleph_{stop.}}{\Re} \times \\ \times \frac{\Lambda \pm \sqrt{\Lambda^2 - \Phi}}{\mathrm{P}}\left(t + \frac{\Im_{stop.}}{\Re}e^{-\frac{\Re}{\Im_{stop.}}t}\right), \text{N} \cdot \text{m}. \tag{65}$$

After transformations of equation (65), the dependence of change in the length of the belt stretching under the action of static load during the belt displacement phase was obtained:

$$\frac{\Omega_{empty.}x^2}{2}+\frac{G_{T.D.}x}{2}-2E_{0.dyn}\frac{M_p-\aleph_{stop.}}{\Re}\times$$
$$\times\frac{\Lambda\pm\sqrt{\Lambda^2-\Phi}}{\mathrm{P}}\left(t+\frac{\Im_{stop.}}{\Re}e^{-\frac{\Re}{\Im_{stop.}}t}\right),\mathrm{N\cdot m}.$$

Hence:

$$x=\frac{-\frac{G_{T.D}}{2}+\sqrt{\frac{G_{T.D.}{}^2}{4}+4\Omega_{empty.}E_{0dyn.}\frac{M_p-\aleph_{stop.}}{\Re}\frac{\Lambda\pm\sqrt{\Lambda^2-\Phi}}{\mathrm{P}}\left(t+\frac{\Im_{stop.}}{\Re}e^{-\frac{\Re}{\Im_{stop.}}t}\right)}}{\Omega_{empty.}},\ \mathrm{m}. \quad (66)$$

It is known that the change in static tension in the belt during its movement is equal to the product of the specific resistance of the belt to movement by the length of propagation of the static deformation:

$$S^{stop.}_{static.shift.}=\Omega_{empty.}x,\ \mathrm{N}. \quad (67)$$

By substituting equation (66) into (67), we obtain the change in the static increase in belt tension on the drum of the mobile station during a change in the conveyor length from $t=0$ to $t=t_{shift}$:

$$S^{stop.}_{static.shift.}=-\frac{G_{T.D.}}{2}+$$
$$+\sqrt{\frac{G_{T.D.}{}^2}{4}+4\Omega_{empty.}E_{0dyn.}\frac{M_p-\aleph_{stop.}}{\Re}\frac{\Lambda\pm\sqrt{\Lambda^2-\Phi}}{\mathrm{P}}\left(t+\frac{\Im_{stop.}}{\Re}e^{-\frac{\Re}{\Im_{stop.}}t}\right)},\ \mathrm{N}. \quad (68)$$

At the end of the shift phase, the increase in static belt tension is equal to:

$$S^{stop.}_{static.shift.}=\Omega_{empty.}l_{(3-6)},\ \mathrm{N}. \quad (69)$$

By substituting equation (69) into (68), we obtain the dependence from which the shift time can be determined in the Mathcad software:

$$\left(t_{shift.}+\frac{\Im_{stop.}}{\Re}e^{-\frac{\Re}{\Im_{stop.}}t_{shift.}}\right)=$$
$$=\frac{\mathrm{P}\cdot\Re\cdot l_{(3-6)}\left(\Omega_{empty.}l_{(3-6)}+G_{T.D.}\right)}{4E_{0.dyn.}\left(M_p-\aleph_{stop.}\right)\left(\Lambda\pm\sqrt{\Lambda^2-\Phi}\right)},\ \mathrm{s}. \quad (70)$$

The amount of belt displacement is influenced by the parameters of the combine's electric motor and the parameters of the conveyor.

5. 3. 2. Determining the change in the static increase in belt tension in the acceleration and length change phases

After the displacement phase, the belt acceleration phase takes place.

The belt tension at point 6 at the end of the displacement phase is always equal to:

$$S^{stop.}_{static.}=\Omega_{empty.}l_{(3-6)}+G_{T.D.}/2,\ \mathrm{N}.$$

The resistance force to the movement of the belt between point 7 and point 6 is approximately zero. Hence, the tension at point 7 in the acceleration phase is:

$$S^{stop.}_{7.static.}\approx S^{stop.}_{6.static.}=S^{stop.}_{6H}+S^{stop.}_{static.shift.}+S^{stop.}_{static.dispersal.},\ \mathrm{N}. \quad (71)$$

The tension of the belt at point 6 is:

$$S^{stop.}_{static.dispersal.}+G_{T.D.}/2=M,\ \mathrm{N}. \quad (72)$$

When determining the speed of propagation of the length of the belt under the action of static loading, the starting point of the wave front coordinate on the empty line is taken as point 3, and on the loaded line–point 7′ (Fig. 6).

The coordinate of the wave front is denoted by the value x (Fig. 7).

Let the time $t=t_{shift}$ correspond to the beginning of the belt acceleration and the change in the length of the conveyor (Fig. 8, *a*); from this moment, from the point *a* along the traction element the length of the stretched belt begins to change under the action of a static load.

By the time $t=t_1$(Fig. 8, *b*) the point *a* has traveled the path a′a, and the wave front has reached the point *b*.

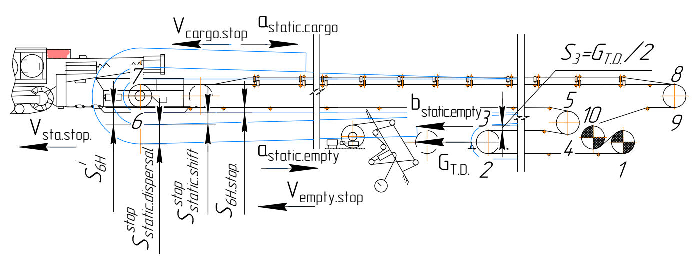

Fig. 6. Diagram of changes in static tension in the belt during changes in the conveyor transport length with the drive stopped during the acceleration phase and length changes

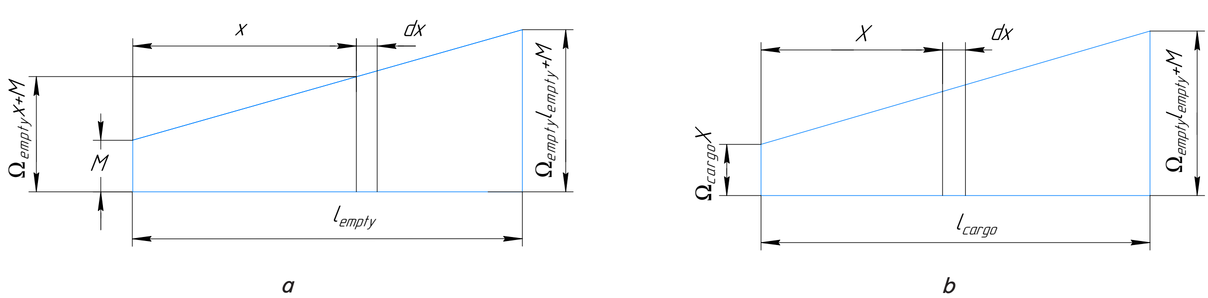

Fig. 7. Plots of change in the tension of conveyor lines with the drive stopped during the acceleration phase and changes in length: *a* – empty; *b* – loaded

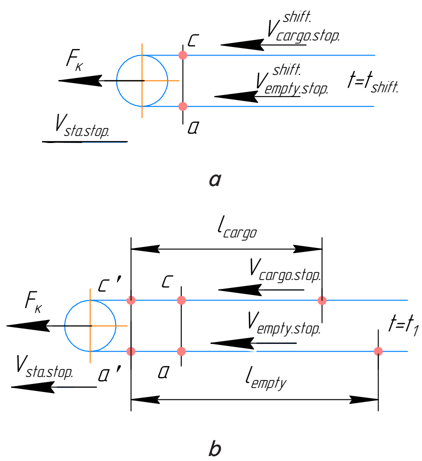

Fig. 8. Diagram of the length of the spread of belt tension under the action of static load along the traction element of the conveyor with the drive stopped during the acceleration phase and length change: *a* – $t=t_{shift}$; *b*–$t=t_1$

Tension at any point in this area:

$$S=\Omega_{empty.}x+G_{T.D.}/2+S^{stop.}_{static.dispersal.},\ \text{N}. \tag{73}$$

Since the tension acting on a given element dx on an empty line is equal to $\Omega_{empty}+M$ (Fig. 7, *a*), the deformation of the element is equal to:

$$d\Delta l_{empty.}=\left(\Omega_{empty.}+M\right)dx/E_{0.dyn.},\ \text{m}. \tag{74}$$

Elongation of the entire section:

$$\Delta l=\int_0^l\left(\Omega_{empty.}x+M\right)\cdot \mathrm{d}x/E_{0.dyn.}=$$
$$=\left(\Omega_{empty.}l^2+2Ml\right)/2E_{0.dyn.},\text{m}. \tag{75}$$

Differentiating with respect to t and noting that $d\Delta l_{empty}/dt$ is the speed of the traction element of the empty line at point a, dl_{empty}/dt is the desired speed of propagation of the belt stretching length under the action of static load on the empty line of the conveyor at a distance $x=l_{empty}$ is equal to:

$$a_{static.empty.}=\frac{V_{empty.stop.}E_{0.dyn.}}{\Omega_{empty.}l_{empty.}+M},\ \text{m/s}. \tag{76}$$

The rate of propagation of belt compression under the action of static load on an empty conveyor line at a distance $x=l_{empty}$ will be:

$$b_{static.empty.}=\frac{V_{empty.stop.}E_{0.dyn.}}{\Omega_{empty.}l_{empty.}+G_{T.D.}/2},\ \text{m/s}. \tag{77}$$

The distribution of the belt stretching length under the action of static loading along the traction element of the cargo line has the following solution.

Let the time $t=t_{shift}$ correspond to the beginning of the belt acceleration and the change in the length of the conveyor (Fig. 8, *a*). Starting from this moment, the belt begins to stretch from point c along the traction element.

At the time $t=t_1$, point c traveled the path cc', and the stretching front reached point g (Fig. 8, *b*).

The tension of the traction element in this section:

$$S=\left(\Upsilon-\Omega_{cargo.}x\right),\ \text{N}; \tag{78}$$

$$\Upsilon=S^{stop.}_{static.dispersal.}+\Omega_{empty.}l_{(3-6)}+G_{T.D.}/2,\ \text{N}. \tag{79}$$

If the magnitude of the deformation of the section cg is denoted by Δl, then an element dx can be selected at a distance x from the point g (Fig. 7, *b*). Since the tension acting on this element dx is equal to $(\Upsilon-\Omega_{cargo}x)$ (Fig. 7, *b*), the deformation of the element of the load line can be represented in the form:

$$\Delta l_{cargo.}=(\Upsilon-\Omega_{cargo.}x)\ dx/E_{0.dyn.},\ \text{m}. \tag{80}$$

Elongation of the entire section cg:

$$\Delta l=\int_0^l\left(\Upsilon-\Omega_{cargo.}x\right)\cdot \mathrm{d}x/E_{0.dyn.}=$$
$$=\left(2\Upsilon l_{cargo.}-\Omega_{cargo.}l^2_{cargo.}\right)/2E_{0.dyn.},\ \text{m}. \tag{81}$$

Differentiating this expression by t, the following is obtained:

$$\frac{d\Delta l_{cargo.}}{dt}=\frac{\Upsilon}{E_{0.dyn.}}\cdot\frac{dl_{cargo.}}{dt}-\frac{\Omega_{cargo.}l_{cargo.}}{E_{0.dyn.}}\cdot\frac{dl_{cargo.}}{dt},\ \text{m/s}. \tag{82}$$

Here $d\Delta l_{cargo.}/dt=V_{cargo.stop.}$ is the speed of movement of the traction element of the cargo line, and $dl_{cargo.}/dt$ is the desired speed of propagation of the length of the belt stretching under the action of static load on the cargo line at a distance $x=l_{cargo.}$.

Hence:

$$a_{static.cargo.}=\frac{V_{cargo.stop.}E_{0.dyn.}}{\Upsilon-\Omega_{cargo.}l_{cargo.}},\ \text{m/s}. \tag{83}$$

Compression on the load line $t_{squeeze.cargo.}$ occurs after the end of the stretching $t_{stretch.empty.}$ and compression $t_{squeeze.empty.}$ of the belt under the action of a static load on the empty line:

$$t_{squeeze.cargo}=t_{stretch.empty}+t_{squeeze.empty.}+t_{T.D.},\text{s}. \tag{84}$$

The time of stretching the belt under the action of a static load on an empty line from point 6 to point 3:

$$dt=\frac{dx}{a_{static.empty.}}=\frac{\left(\Omega_{cargo.}x+M\right)dx}{V_{empty.stop.}E_{0.dyn.}},\ \text{s}. \tag{85}$$

$$t_{stretch.empty.}=\int_0^{l_{(3-6)}}\frac{\Omega_{empty.}x+M}{V_{empty.stop.}E_{0.dyn.}}\mathrm{d}x=$$
$$=\frac{\Omega_{empty.}l^2_{(3-6)}+2Ml_{(3-6)}}{2V_{empty.stop.}E_{0.dyn.}},\ \text{s}. \tag{86}$$

Time of compression of the belt under the action of static load on an empty line from point 3 to point 6:

$$t_{squeeze.empty.}=\int_0^{l_{(3-6)}}\frac{\Omega_{empty.}\tilde{o}+G_{T.D.}/2}{V_{empty.stop.}E_{0.dyn.}}\mathrm{d}x=$$
$$=\frac{\Omega_{empty.}l^2_{(3-6)}+G_{T.D.}l_{(3-6)}}{2V_{empty.stop.}E_{0.dyn.}},\ \text{s}. \tag{87}$$

Similar to the previous considerations, you can write:

$$t_{squeeze.cargo.}=\frac{2\Upsilon l_{cargo.}-\Omega_{cargo.}l^2_{cargo.}}{2V_{cargo.stop.}E_{0.dyn.}},\ \text{s.} \tag{88}$$

Substituting the obtained expressions into formula (84) and performing the transformation, the following is obtained:

$$\Omega_{cargo.}l^2_{cargo.}-2\Upsilon l_{cargo.}+2\frac{V_{cargo.stop.}}{V_{empty.stop.}}\times$$
$$\times\left[\begin{array}{l}\Omega_{empty.}l^2_{(3-6)}+l_{(3-6)}\left(M+\dfrac{G_{T.D.}}{2}\right)+\\ +t_{T.D.}E_{0.dyn.}V_{empty.stop.}\end{array}\right]=0,\ \text{N·m.}$$

At $t_{T.D.}$=0:

$$\Omega_{cargo.}l^2_{cargo.}-2\Upsilon l_{cargo.}+2\frac{V_{cargo.stop.}}{V_{empty.stop.}}\times$$
$$\times\left[\Omega_{empty.}l^2_{(3-6)}+l_{(3-6)}\left(M+\frac{G_{T.D.}}{2}\right)\right]=0,\ \text{N·m.} \tag{89}$$

From equation (89), the magnitude of length of the propagation of a stretch of the belt on the cargo load is determined:

$$l_{cargo.}=\frac{\sqrt{\Upsilon^2-K\Omega_{cargo.}}+\Upsilon}{\Omega_{cargo.}},\ \text{m.} \tag{90}$$

where:

$$K=2\frac{V_{cargo.stop.}}{V_{empty.stop.}}\left[\Omega_{empty.}l^2_{(3-6)}+l_{(3-6)}\left(M+\frac{G_{T.D.}}{2}\right)\right],\ \text{N·m.} \tag{91}$$

Assuming that the belt is an isotropic elastic body, the resulting increase in belt tension when the conveyor is lengthened is equal to:

$$S^{stop.}_{static.dispersal.}=\varepsilon_{cargo.}E_{0.dyn.},\ \text{N.} \tag{92}$$

Relative elongation of the load lime of the traction body:

$$\varepsilon_{cargo.}=\Delta x_{cargo.}/l_{cargo.}. \tag{93}$$

Absolute extension of the load line of the conveyor during the movement of the mobile station:

$$\Delta x_{cargo.}=V_{cargo.stop.}\cdot t_{squeeze.cargo.},\ \text{m.} \tag{94}$$

Substituting equations (86) and (87) into (84) and simplifying it through K(91) at $t_{T.D.}$=0, we obtain:

$$t_{squeeze.cargo.}=\frac{K}{2V_{cargo.stop.}E_{0.dyn.}},\ \text{s.} \tag{95}$$

Substitution of equation (93) to (95) in (92) yielded:

$$\left(S^{stop.}_{static.dispersal.}\right)^2-S^{stop.}_{static.dispersal.}\Upsilon+\frac{\Omega_{cargo.}K}{4}=0,\ \text{N.} \tag{96}$$

Having isolated the value $S^{stop.}_{static.dispersal.}$ from the values K and M and having performed the transformation, we obtain:

$$S^{stop.}_{static.dispersal.}=$$
$$=\frac{V_{cargo.stop.}\Omega_{cargo.}l_{(3-6)}\left(\Omega_{empty.}l_{(3-6)}+G_{T.D.}\right)}{V_{empty.stop.}\left(2\Omega_{empty.}l_{(3-6)}+G_{T.D.}\right)-V_{cargo.stop.}\Omega_{cargo.}l_{(3-6)}},\ \text{N.} \tag{97}$$

Substituting equations (61) and (57) in (97) yielded:

$$S^{stop.}_{static.dispersal.}=\frac{\Omega_{cargo.}l_{(3-6)}\left(\mathrm{P}-\Lambda+\sqrt{\Lambda^2-\Phi}\right)\left(\Omega_{empty.}l_{(3-6)}+G_{T.D.}\right)}{\left(\Lambda+\sqrt{\Lambda^2-\Phi}\right)\left(2\Omega_{empty.}l_{(3-6)}+\Omega_{cargo.}l_{(3-6)}+G_{T.D..}\right)-\mathrm{P}\Omega_{cargo.}l_{(3-6)}},\ \text{N.} \tag{98}$$

The jump in static increase in belt tension during acceleration is influenced by belt parameters, speed of the mobile station, distance from the mobile drum to the drum of the mobile carriage, and tension on the telescopic device.

5. 4. Determining the dynamic increase in belt tension when changing the conveyor transport length with a stopped drive

A distinctive feature of our calculation of the dynamic belt load on the drum of a mobile conveyor station with a stopped drive is the presence of belt shift and acceleration phases (Fig. 9).

The dynamic belt load on the drum of the mobile station of a stopped conveyor is determined as the sum of the dynamic belt load in the belt displacement and acceleration phases:

$$S_{dyn.stop.}=S^{shift.}_{dyn.stop.}+S^{dispersal.}_{dyn.stop.},\ \text{N.} \tag{99}$$

When determining the dynamic belt load on the drum of a mobile station of a stopped conveyor during the shifting phase:

$$S^{shift.}_{dyn.stop.}=a^{shift.}_{dyn.stop.}\cdot q_{belt.}\cdot V_{empty.stop.},\ \text{N.} \tag{100}$$

Similar to the previous considerations given in [15], the propagation velocity of an elastic deformation wave on an empty conveyor line with a stopped drive in the displacement phase will be written as:

$$a^{shif.}_{dyn.stop.}=\sqrt{\frac{E_{0.dyn.}}{q_c+\dfrac{\left(z^{shif.}_{stop.}-c^{shif.}_{stop.}\right)}{j^{shif.}_{empty.stop.}}}},\ \text{m/s.} \tag{101}$$

Having determined the change in the gradient of the static tension of the belt in the displacement phase before the start of the movement of the mobile station $c^{shif.}_{stop.}$ and during the displacement phase $z^{shif.}_{stop.}$ of the conveyor with the stopped drive, we obtained:

$$c^{shif.}_{stop.}=\frac{S^{stop.}_{6H}-S_3}{l_{(3-6)}},\ \text{N/m,} \tag{102}$$

where $S^{stop.}_{6H}=G_{T.D.}/2$ is the belt tension at point 6 before the start of movement of the mobile conveyor station with the drive stopped, N:

$$z^{shift.}_{stop.}=\frac{S'_{6stop.}-S_3}{l_{(3-6)}},\ \text{N/m,} \tag{103}$$

where $S'_{6stop.}=S^{stop.}_{static.shift.}+G_{T.D.}/2$ is the belt tension at point 6 during the conveyor belt movement phase with the drive stopped, N.

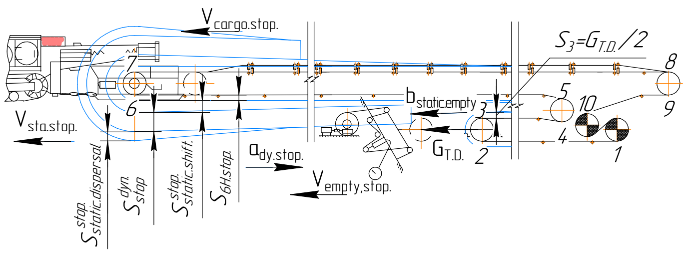

Fig. 9. Calculation diagram of tensions arising in the belt when changing the length of the conveyor transport with the drive stopped

Substituting equations (102) and (103) into (101), we obtain:

$$a^{shift.}_{dyn.stop.}=\sqrt{\frac{E_{0.dyn.}}{q_{belt.}+\dfrac{S^{stop.}_{static.shift.}/l_{(3\text{-}6)}}{j^{shift.}_{empty.stop.}}}},\text{ m/s.}\qquad(104)$$

When determining the dynamic belt load on the drum of a mobile conveyor station with the drive stopped during the acceleration phase:

$$S^{dispersal.}_{dyn.stop.}=a^{dispersal.}_{dyn.stop.}\cdot q_{belt.}\cdot V^{dispersal.}_{empty.stop.},\text{ N.}\qquad(105)$$

Similarly to the previous considerations, the propagation velocity of the elastic deformation wave on an empty line of the conveyor with the drive stopped in the acceleration phase will be written as follows:

$$a^{dispersal.}_{dyn.stop.}=\sqrt{\frac{E_{0.dyn}}{q_{belt.}+\dfrac{\left(z^{dispersal.}_{stop.}-c^{dispersal.}_{stop.}\right)}{j^{dispersal.}_{empty.stop.}}}},\text{ m/s.}\qquad(106)$$

Having determined the change in the gradient static tension of the belt in the acceleration phase after the shift phase $c^{dispersal.}_{stop.}$ and during the change in the length $z^{dispersal.}_{stop.}$ of the conveyor with the drive stopped, we obtained:

$$c^{dispersal.}_{stop.}=\left(S^{dispersal.}_{6H}-S_3\right)/l_{(3-6)},\text{ N/m,}\qquad(107)$$

where $S^{dispersal.}_{6H}=\Omega_{empty}l_{(3-6)}+G_{T.D.}/2$ is the belt tension at point 6 before the start of the conveyor belt acceleration phase with the drive stopped, N:

$$z^{dispersal.}_{stop.}=\left(S''_{6stop.}-S_3\right)/l_{(3-6)},\text{ N/m,}\qquad(108)$$

where $S''_{6stop.}=S^{stop.}_{static.dispersal.}+\Omega_{empty.}l_{(3-6)}+G_{T.D.}/2$ is the belt tension at point 6 during the acceleration phase of the conveyor belt with the drive stopped, N.

Substituting equations (107) and (108) into (106), we obtain:

$$a^{dispersal.}_{dyn.stop.}=\sqrt{\frac{E_{0.dyn.}}{q_{belt.}+\dfrac{S^{stop.}_{static.dispersal.}/l_{(3-6)}}{j^{dispersal.}_{empty.stop.}}}},\text{ m/s.}\qquad(109)$$

The dynamic increase in belt tension is influenced by a jump in static tension and belt parameters, the speed and acceleration of the mobile station, the distance from the mobile drum to the drum of the moving carriage of the telescopic device.

5. 5. Verifying the calculation of belt conveyors with variable length with a stopped drive

To compare the conveyor with a running drive with a conveyor with a stopped drive, a calculation of the jumps in tension on the drum of the mobile station was performed.

The calculation of the increase in belt tension on the drum of the mobile station consists of 5 stages:

First stage. Determining the speed $V_{sta.stop.}$ (dependence (39)) and acceleration $j_{sta.stop.}$ (dependence (40)) of the mobile station.

Second stage. Determining the speed $V_{empty.stop.}$ (dependence (56)) and acceleration $j_{empty.stop.}$ (dependence (61)) of the empty conveyor line during the change in the length of transportation with the drive stopped.

Third stage. Determining the magnitude of the jump of the static increase $S^{stop.}_{static.shift.}$ (dependence (68)) and the shift time $t_{shift.}$ (dependence (70)) during the shift period and the magnitude of the jump of the static increase $S^{dispersal.}_{static.stop.}$ (dependence (98)) during the acceleration period of the belt during the change in the length of transportation of the conveyor with the drive stopped.

Fourth stage. Determining the magnitude of the jump in dynamic loading $S^{shift.}_{dyn.stop.}$ (dependence (100)) during the shift period and dynamic loading $S^{dispersal.}_{dyn.stop.}$ (dependence (105)) during the belt acceleration period when changing the conveyor transportation length with the drive stopped.

Fifth stage. Determining the magnitude of change in belt tension on the drum of the mobile station when changing the conveyor transportation length with the drive stopped:

$$S_{6stop.}=S^{stop.}_{6H}+S^{shift.}_{static.stop.}+S^{dispersal.}_{static.stop.}+S^{shift.}_{dyn.stop.}+S^{dispersal.}_{dyn.stop.},\text{ N.}\qquad(110)$$

Below is an example of calculating the resulting jumps in belt tension in an extension conveyor, spreading from the drum of a mobile station with the drive stopped. The following initial data were accepted for the calculation in the Mathcad software:

- $l_{(3-6)}$=835 m;
- $m_{drum.}$=100 kg;
- $J_{motor.rotor.}$=3 kg·m^2;
- $J_{1motor.rotor.}$=0.01 kg·m^2;
- $J_{2motor.rotor.}$=25 kg·m^2;
- $R_{belt.}$=0.5 m;
- $m_{sta.}$=1,000 kg;
- f=0.8;
- $m_{T.D.}$=150 kg;
- $m_{roadheader.}$=3,500 kg;
- $\Omega_{empty.}$=5.33 N/m;
- $l_{(7-8)}$=800 m;
- M_p=700 Nm;
- β_{engine}=2 N·m·s;
- i_p=0.0064;
- $\Omega_{cargo=12.5}$ N/m;
- $l_{(9-6)}$=915 m;
- $E_{0.dyn..}$=2,600,000 N;
- $m_{reduced.conveyor.drive.}$=1,250 kg;
- $l_{(9-2)}$=65 m; q_{belt}=10 kg/m.

Fig. 10 shows the velocity and acceleration of the mobile station.

Fig. 11 shows the velocity and acceleration of an empty conveyor line.

In Fig. 12, the static jump in tension on the drum of the mobile station during the period of belt displacement and acceleration.

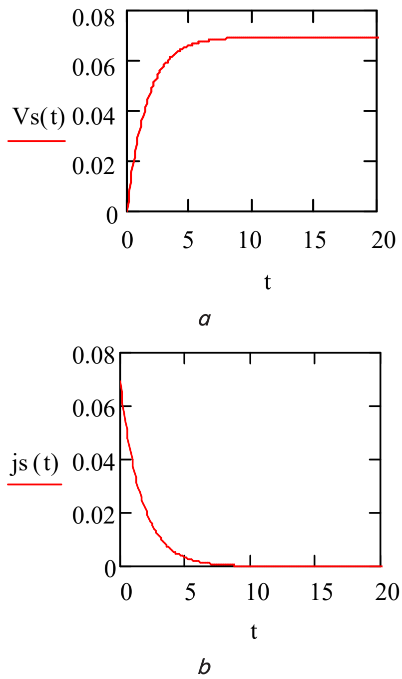

Fig. 10. Plot of changes over time, when the conveyor is extended with the drive stopped: *a* – speed of the mobile station; *b* – acceleration of the mobile station

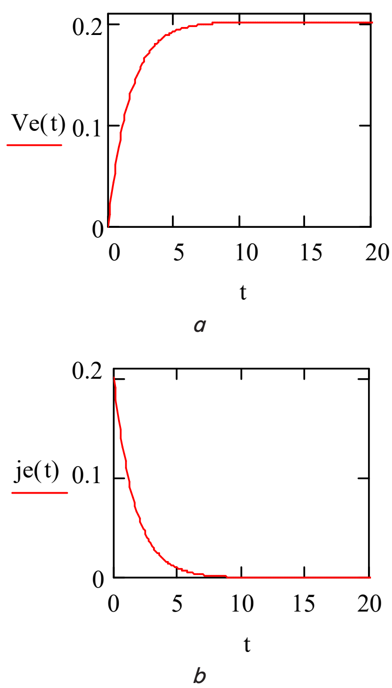

Fig. 11. Plot of changes over time, when the conveyor is extended with the drive stopped: *a* – speed of the lower line; *b* – acceleration of the lower line

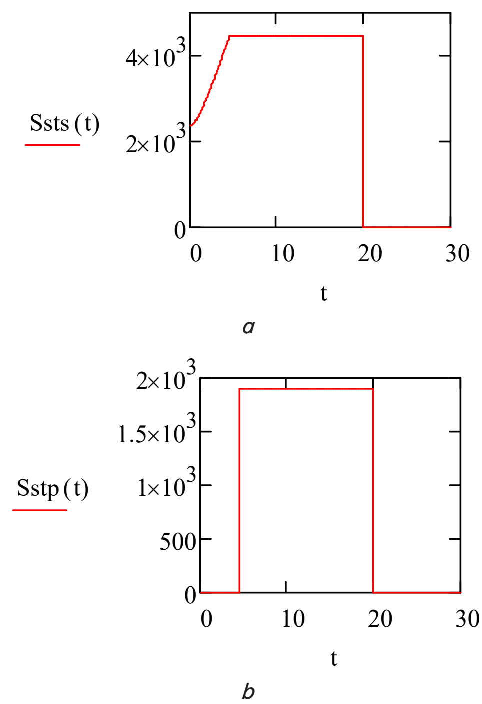

Fig. 12. Plot of change in the static jump in the belt load over time on the drum of a mobile station with the extension conveyor drive stopped: *a* – during the shift period; *b* – during the acceleration period

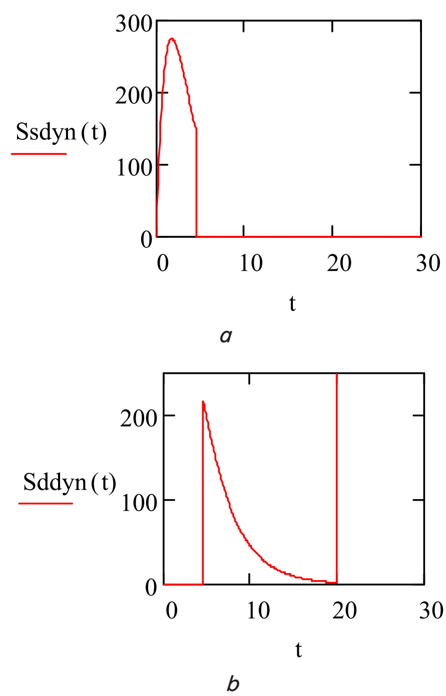

Fig. 13. Plot of change in the dynamic jump in the belt load over time on the drum of a mobile station with the extension conveyor drive stopped: *a* – during the shift period; *b* – during the acceleration period

Plots of changes in static and dynamic jump in tension during the period of belt displacement and acceleration are calculated separately.

Fig. 13 shows the dynamic jump in tension on the drum of the mobile station during the period of belt displacement and acceleration.

Fig. 14 shows the belt load on the drum of the mobile station during the extension of the conveyor with the drive stopped.

Analysis of our calculations revealed that when changing the conveyor transportation length with the drive stopped on the drum of the mobile station, there is a jump in the belt tension, which is equal to 2. In the initial period of time, the jump is maximum and changes depending on the acceleration of the mobile conveyor station. At a constant speed of the mobile station, the jump in the belt tension is constant and exists as long as the station moves.

During experimental studies for different operating modes of a belt conveyor operating at a variable transportation length, the following results were obtained: Fig. 15.

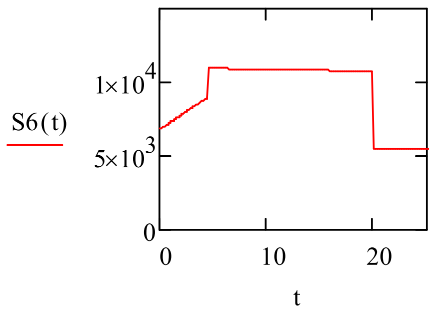

Fig. 14. Plot of belt load change over time on the drum of a mobile station with the extension conveyor drive stopped

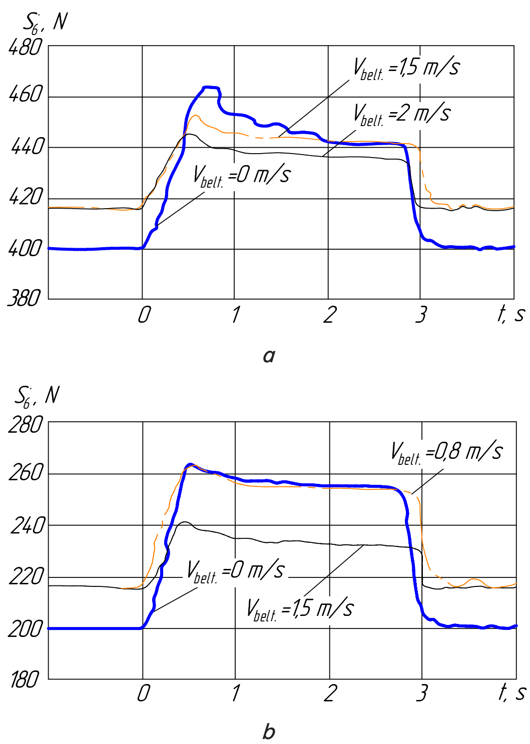

Fig. 15. Plots of belt tension changes at the mobile station of the experimental conveyor for different initial speeds of the traction-bearing body during unequally accelerated changes in the length of transportation: *a* – when the belt tension on the tensioning device is 400 N; *b* – the belt tension on the tensioning device

6. Discussion of results based on the study of parameters of belt conveyors with a stopped drive during the change in the transportation length

Our research result is the methodology devised for calculating belt conveyors with a variable transportation length. The study examined how the change and acceleration of the transportation length with a stopped conveyor drive affects the belt tension.

The results indicate that the transportation length should be changed when the conveyor is running.

The following was found out for a conveyor with a stopped drive.

It was established that during the uniformly accelerated elongation of the conveyor on the drum of the mobile station, the belt tension increases due to the increase in static and dynamic belt loading. The increase in belt tension occurs first in the phase of displacement, then in the phase of belt acceleration and change of the transportation length.

It has been determined that the change in static belt tension on the drum of the mobile conveyor station at the end of the shift phase is equal to the resistance force to the belt movement in the section from the drum of the mobile station to the moving drum of the tensioning mechanism.

In contrast to the results given in [11], the time of the shift phase, the magnitude of the static and dynamic loading of the belt on the drum of the mobile station in time were established, which is a fundamentally new result.

Our result is very important because it provides an understanding of the reasons for the occurrence of changes in belt tension during an unevenly accelerated change in the length of transportation with a stopped conveyor drive. The result is also important because it allows us to give recommendations for the correct operation of such conveyors.

It became possible to correctly design the mechanism for moving the end station of the conveyor, taking into account the characteristics of its electric motor.

It was investigated how the speed and acceleration of the mobile station and the belt of the stopped conveyor change during a change in the length of transportation. Dependences were obtained that allow us to calculate the resulting dynamic jump in belt tension that occurs at the beginning of the movement of the mobile station when the conveyor is extended.

When determining the speed (dependence (39)) and acceleration (dependence (40)) of the mobile station of the stopped conveyor, the characteristics of the electric motor of the end station movement mechanism were taken into account.

When determining the speed (dependence (56)) and acceleration (dependence (61)) of the empty line belt, the characteristics of the conveyor and the speed and acceleration of the mobile station were taken into account.

When determining the static increase in belt tension (dependences (68), (98)), the shift time (dependence (70)) and the characteristics of the conveyor were taken into account.

When determining the dynamic increase in belt tension (dependences (100), (105)), the propagation speed of the elastic deformation wave on the empty conveyor line in the displacement phase (dependence (104)) and acceleration phase (dependence (106)) of the belt was taken into account.

It was established that the static jump in belt tension on the drum of the mobile station significantly depends on the type of distance to the tensioning device. The magnitude of the dynamic increase in belt tension jump during conveyor elongation is primarily influenced by the acceleration and speed of the mobile station.

The results of the studies allow us to determine the operational parameters of a belt conveyor with a variable transportation length.

The studies reported here are a continuation of previously performed theoretical investigation of the loads arising in the belt during a change in the transportation length on the drum of the mobile conveyor station [11].

By reducing unproductive technological operations and reducing the number of overload devices, the use of a belt conveyor with a variable length of transportation makes it possible to increase productivity and reduce energy consumption in continuous flow technologies. It is recommended to perform calculations for predetermined maximum output data, such as productivity, transported load, length, and angle of installation of the conveyor.

The practical application of our results is significantly affected by the distance from the mobile station to the tensioning device.

The next stage of research may be the development of a transient process of lateral descent of the belt from a drum with insignificant curvature.

When the mobile station of the conveyor is moved, the drum turns relative to the longitudinal axis of the belt movement.

Construction of a mathematical model of the transient process of lateral descent of the belt on a drum with insignificant curvature could make it possible to design a system for automatic centering of the belt on a drum with a curvilinear generator with optimal parameters. This is very important when operating a conveyor with a variable transportation length.

7. Conclusions

1. Before the length of transportation is extended, the speed of the conveyor belt is zero. The speed and acceleration of the mobile station depend on the design parameters of the extension mechanism, the design parameters of the belt conveyor, and the acceleration time of the electric motor during start-up.

2. The speed and acceleration of the loaded and empty conveyor belt lines with the drive stopped are affected by the speed and acceleration of the mobile station, as well as the conveyor parameters. The speed and acceleration of the empty line are 3 or more times higher than the loaded one.

3. Static increase in belt tension occurs during the phase of displacement and acceleration of the belt. The maximum value of the phase of displacement is equal to the force of static resistance to movement in the area from the mobile station to the tensioning device and lasts several seconds.

4. The dynamic increase in the jump in the belt tension occurs during the phase of the belt displacement and acceleration and depends on the acceleration and speed of the mobile station. It also depends on the technical characteristics of the belt, the gradient of the increase in the belt tension during the extension of the conveyor to the sections from the drum of the mobile station to the drum of the mobile carriage of the telescopic device.

5. Analysis of our calculation of the above example revealed that when changing the length of the conveyor transportation with the drive stopped on the drum of the mobile station, a jump in the belt tension occurs 2 times larger. The maximum jump value is recorded at the maximum acceleration of the mobile station. At a constant speed of the mobile station, the jump in the belt tension is constant and exists as long as the station moves.

According to the results of our calculation, the belt tension at a constant speed of the mobile station increased by 2 times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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