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DETERMINING THE MECHANISM FOR CALCULATING THE TENSION OF A WORKING CONVEYOR BELT DURING A CHANGE IN THE TRANSPORTATION LENGTHFROM MEDICAL MASK WASTE

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This paper examines the working process of a belt conveyor with a working drive that can change the length of transportation. The conveyor can be used for tunneling, development of minerals in mines and quarries, transportation of materials in warehouses. The use of such a conveyor makes it possible to reduce the time for operations to increase or decrease the length of transportation, to exclude reloaders between the working equipment and conveyor itself from the transport chain.

It was established that when changing the length of transportation of a working conveyor, the static and dynamic load on 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 speed of the beltgenerated by the conveyor drive. The dynamic loading on the belt depends on the acceleration of the belt, which is related to the acceleration of the mobile station during the change in the length of the conveyor.

For a working conveyor that changes the length of transportation, the static tension of the belt on the drum of the mobile station can increase by 1.1–1.4 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 over time and acquires large values.

Based on the dependencesderived in the current work, a calculation procedure is proposed for the design of a belt conveyor with a working drive that can change the length of transportation.

The Mathcad software was applied to verify the designcalculation procedure.

The results make it possible to employ new design methods in the construction of competitive machines equipped with a belt conveyor with a variable length of transportation

Keywords: belt conveyor, software, design, belt tension, theoretical studies

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1. Introduction

The modern trend in the evolution of global mechanical engineering is characterized by the constant improvement of the technical level of newly designed machines and equipment, which ensures their competitiveness under the conditions of growing market requirements. To a large extent, this applies to lifting and transport machinery, which is widely used in various sectors of the national economy.

Belt conveyors occupy a prominent place in the large class of lifting and transport equipment; the development of structures is a way of increasing productivity and reducing the energy consumption of cargo transportation.

One of such structural solutions is the use of a belt conveyor with a variable length of transportation. It is a semi-stationary installation capable of extending during operation.

On this conveyor, the final or remote drum is installed at a mobile station. Owing to the movement of the mobile station, the length of transportation changes. The presence of a telescopic device with a system of automatic belt tension control makes it possible to extend the conveyor while the drive is working.

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

– due to the exclusion of unproductive work operations related to 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;

– owing to the exclusion from the traditional technological scheme, namely from the transport chain of reloading devices.

However, the use of belt conveyors with a variable length of transportation and their wide practical application is restrained by the lack of a generally accepted calculation procedure, which should be devised.

2. Literature review and problem statement

Work [1] considers the use of belt conveyors with a variable length of transportation, in which the results of the use of such a belt conveyor at the "Prosper Haniel" mine in Germany were given. Noting the great economic effect of the application of this technique in production, the work indicated the need to carry out research related to devising a methodology for calculating 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 will allow simulating calculations of motor regulation at drive stations equipped with static frequency converters.

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

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 processes of transportation of bulk materials. The simulation was implemented in DEM software.

The principal approach to the modeling of the conveyor belt was to build a model of the belt by systematically placing individual particles connected in a grid with the help of so-called connections. An additional model preprocessing method was developed to build a conveyor belt in a DEM environment. However, this study did not consider the dynamics of the belt tension change 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, in which there is a sufficiently strong deformation of the belt. Also, this methodology could be applied to systems in which belt deformation or belt behavior in general has a significant impact on system functionality. These are, for example, curved belt conveyors, tubular or sandwich conveyors, and similar non-traditional belt conveyor systems.

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

Paper [6] describes the method of modeling wave phenomena in the belt, the change of mass and movement resistance, as well as the elements of the drive system, i.e., motors, torque converters, couplings, gears, and the interaction of the drive drum with the belt. With the help of a computer program, dependences were derived that made it possible to simulate the start of the conveyor drive. The results obtained by the measuring devices were compared with the results obtained by calculation during the start-up 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 of the transportation length were not investigated.

Work [7] considers the design of a belt conveyor with the involvement of 3D design software.

After performing the calculation according to generally accepted norms, the parameters of the belt conveyor were obtained. Next, with the involvement of SolidWorks software, a 3D model of the conveyor was built to the elements of which calculated loads were applied. The design of stresses in the elements of the belt conveyor was obtained using the finite element method. The authors indicate the possibility of changing the conveyor model in the computer environment and obtaining the results of a new design using the finite element method without spending 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 the generalized form, which comes from the strength approach to materials.

For a belt conveyor that can change the length of transportation, onemust have special analytical dependences and software for design.

Work [8] reports the results of research into the dynamic behavior of a conveyor belt taking into account the uneven distribution of bulk material for speed control. The work describes the results of the development of a high-precision dynamic model that can take into account the speed control of the conveyor belt 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 for studying the dynamic behavior of a belt conveyor. Given the micro-units 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 conservation during operation.

However, the work did not consider the mathematical model of the belt conveyor, which can change the length of transportation. In addition to the missing necessary mathematical software, software that simplifies the design of the transport installation is not provided.

Paper [9] discusses the improved methods for designing systems of automatic control of electric motors in order to obtain mechanical characteristics that would enable the reliable operation of belt conveyors. An automatic control system based on the Siemens S7-1200 controller was designed, then a mathematical model of the automated electric drive was built. Based on the mathematical model, a simulation model of the automatic electric drive was constructed, and its modes of operation were simulated. However, the work concerns a belt conveyor with a constant length of transportation.

Work [10] reports a three-stage method that can be used to determine the correct way to accelerate a belt conveyor with adjustable speed during transient processes. This method takes into account potential risks in transient modes and dynamic characteristics of the conveyor during start-up. In the example, the maximum allowable acceleration is calculated. Simulation with predicted acceleration time is performed to determine the acceleration operation and analyze the dynamics of the conveyor. The simulation is based on the existing finite element model of the belt conveyor. However, the work concerns a belt conveyor with a constant length of transportation.

In a simplified form, paper [11] reports the results of theoretical studies into the process of propagation of elastic deformations in a conveyor belt that changes the length of transportation. The main assumption is the following: the mobile station at the initial moment of the conveyor extension accelerates uniformly. The work proved that during the change in the length of transportation on the drum of the mobile station, the tension of the belt increases, which exists until the conveyor is lengthened. During the acceleration of the mobile station, there is a dynamic and static increase in the belt tension. With constant movement of the mobile station (constant increase in the length of transportation), there is only a static increase in belt tension. It was established that the belt load when the working conveyor is extended is less than when the conveyor is extended with the drive stopped. Therefore, it is necessary to extend the conveyor 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 driving the station's movement to constant rotations) to constant motion.

Our review of the literature [1–11] showed that to solve the problem of designing belt conveyors with a variable length of transportation, it is necessary to have a mathematical model that will make it possible to devise a methodology for its calculation.

3. The aim and objectives of the study

The purpose of our work is to devise a methodology for designing belt conveyors with a variable length of transportation, which would take into account the time of acceleration of the mobile unit during the extension of the conveyor. This will make it possible to design new competitive machines equipped with belt conveyors with a variable length of transportation, for example, a rotary excavator with a telescopic boom.

To achieve the goal, the following tasks were defined:

– to determine the speed and acceleration of the mobile station and the speed of the working conveyor belt, which would take into account the acceleration time of the mobile station to steady motion;

– to determine the dynamic increase in belt tension during the change in the length of conveyor transportation with a working drive, which takes into account the time of acceleration of the mobile station to steady motion;

– to verify the procedure for designing belt conveyors with variable length of transportation based on numerical simulation.

4. The study materials and methods

The object of research is the work process of a tubular belt conveyor.

Our research working hypotheses:

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

– the construction of energy-saving belt conveyors with a variable length of transportation is based on the use of devised methods, mathematical support and software based on rational parameters and modes of operation.

As part of the study, the following assumptions were accepted. A rubber-cable belt can be considered an isotropically elastic body. Quite often, when calculating with a rubber fabric belt, it is assumed that the traction-carrying body is an isotropic-elastic body. The following simplifications were also adopted. When determining the kinetic energy of the mechanical conveyor system, related to the determination of the speed and acceleration of the mobile station and the speed of the belt during the extension of the conveyor, the power of internal forces is assumed to be zero. Specific static resistance to movement of the belt of the empty branch is constant along the entire length of the conveyor.

On the basis of previously performed theoretical studies [11], the results of experimental [12] and industrial [13] research with the involvement of Mathcad software, the procedurefor calculating the tension of the conveyor belt working during the change of the transportation length was verified.

Experimental studies were performed on experimental benchesat the Donbass National Academy of Construction and Architecture [12].

The bench consists of two hinged joints 1 and 2, a remote mobile station 3, a main drive station 4, a tensioning station 5, a winch for changing the length 6, loads 7 for belt tension 8, a belt tension measuring system 9, a rope 10 for moving the end station (Fig. 1).

The change in the length of transportation took place as follows. When winch 6 is turned on with the help of cable traction 10, the position of mobile station 3 changes (extension, reduction of the transportation length). The reserve of belt necessary for this is in cargo tensioning device 7.

Measurements of the belt tension and the speed of the mobile station during the change of the transportation length were performed at the station by measuring sensors (Fig. 2).

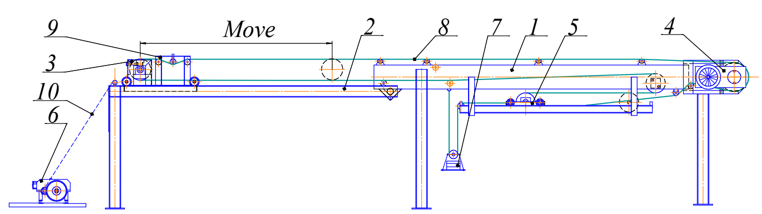

Fig. 1. Scheme of the experimental bench for determining the resulting increase in belt tension during the change in the length of transportation

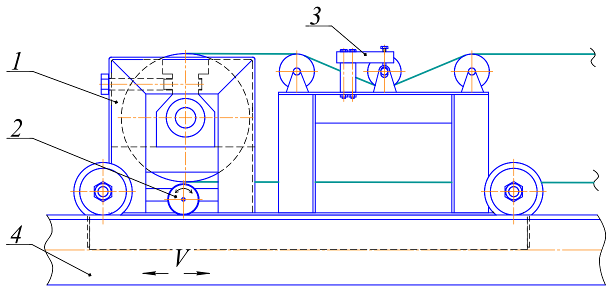

Fig. 2. Scheme of a mobile station equipped with sensors: 1 — terminal station; 2 — encoder-incremental Hohner AWI — 40; 3 — force sensor CAS BSA-500L; 4 — bench bed

The aforementioned NI USB-6009 data acquisition device and PowerGraph3.3Pro software were used to collect data from the force sensors and encoders, and a Texas Instruments four-channel instrumentation amplifier was used to power and preamplify the signal of the force sensors.

A special unit consisting of two frequency converters and a starter was mounted to control the bench drives (belt drive, winch for changing the length of transportation).

Experimental studies were performed for different modes of operation of the belt conveyor.

Fig. 3 shows the results of experimental studies.

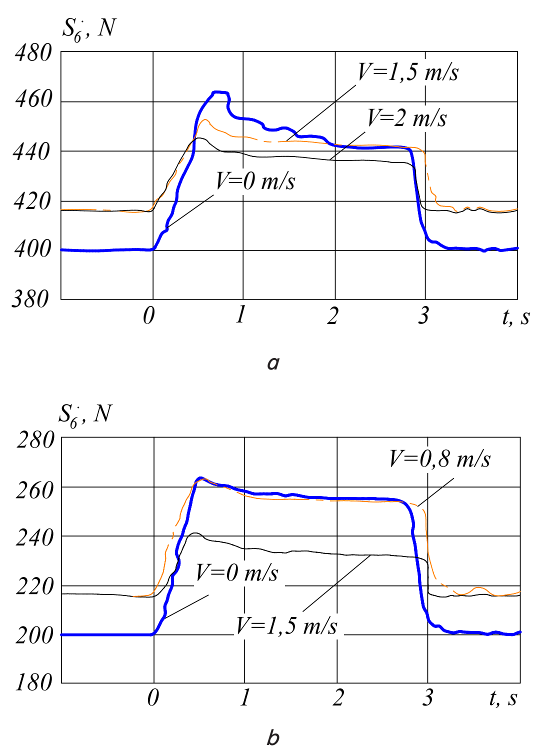

Fig. 3. Plots of changes in belt tension at the mobile station of the experimental conveyor for different initial speeds of the traction-carrying body during unevenly accelerated changes in the length of transportation: *a* — belt tension on the tensioning device of 400 N; *b* — belt tension on the tensioning device of 200 N

Industrial research was carried out at the mine named after O. Zasyadko, the city of Donetsk, in the period from 1992 to 2000.

5. Results of the study on determining the software for the calculation of a conveyor with a variable length of transportation

5. 1. Determination of the speed and acceleration of the mobile station and the speed of the conveyor belt during the change in the length of transportation

The speed of movement of the belt of the working conveyor (Fig. 4) is much higher than the speed of movement of the tunnel combiner.

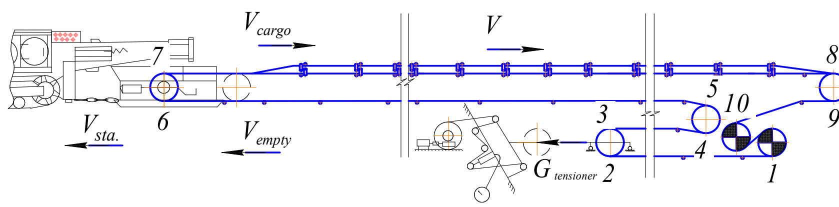

Fig. 4. Schematic of a length-changing conveyor with a working drive

Analysis of the calculation scheme (Fig. 4) revealed that the speed vector of the mobile station and the speed vector of the belt generated by the drive of the working conveyor are collinear.

Hence the speed of movement of the working conveyor belt:

– on the loading branch of the conveyor:

$$V_{cargo} = V - V_{sta.},\ \text{m/s}; \qquad (1)$$

– on an empty conveyor branch:

$$V_{empty} = V + V_{sta.},\ \text{m/s}, \qquad (2)$$

where V is the speed of the belt movement generated by the conveyor drive, m/s;

$V_{sta.}$ is the speed of movement of the mobile station of the working conveyor during the change of the length of transportation, m/s.

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

$$\frac{dT}{dt} = N^e + N^i,\ \text{N·m/s}. \qquad (3)$$

The power of internal forces was assumed equal to zero $N^i=0$.

The change in the kinetic energy of the mechanical system of the extension of the belt conveyor was determined using the following dependence:

$$T = T_{roadheader} + T_{reduction} + T_{motor} + T_{conveyor},\ \text{N·m}, \qquad (4)$$

where $T_{roadheader} = \frac{m_{roadheader} V_{sta.}^2}{2}$ is the change in the kinetic energy of the tunnel combiner, N·m;

$m_{roadheader} = m_{harvester}\left(f \cdot \cos\beta \pm \sin\beta\right)$ – mass of the tunnel combiner moving through the tunnel, kg;

$m_{harvester}$ – weight of the tunnel combiner, kg;

f – movement resistance coefficient (for crawler motors f=(0.1–0.2);

β is the angle of inclination of the tunnel, degree;

$T_{reduction}=\frac{\omega^2_{motor}R^2_{1gear\,wheel}}{4}\left(m_{1.gear\,wheel.}+\frac{m_{2gear\,wheel}}{i_{reduction}}\right)$ – change in the kinetic energy of the reducer of the running mechanism of the tunnel combiner, N·m;

ω_{motor} – frequency of rotation of the running electric motor of tunnel combiner, 1/rev;

$R_{1gear\,wheel..}$ – radius of the first gear wheel of the reducer, m;

$i_{reduction}$ – gear ratio of the running gear;

$m_{1gear\,wheel}$, $m_{2\,ear\,wheel}$ – mass, respectively, of the first and second gears of the gearbox, kg;

$T_{motor}=\frac{1}{4}m_{motor\,rotor}\cdot R^2_{motor\,rotor}\cdot\omega^2_{motor}$ – change in the kinetic energy of the electric motor of the running mechanism of the tunnel combiner, N·m;

$m_{motor\,rotor.}$ – mass of the rotor of the running electric motor of the tunnel combiner, kg;

$R_{motor\,rotor}$ – radius of the rotor of the running electric motor of the tunnel combiner, m;

$$T_{conveyor}=T_{cargo}+T_{empty}+T_{wine.drum}+T_{conveyor\,drive}+T_{movable\,drum}+T_{fixed\,drum}+T_{drum.sta.}+T_{movable\,carriage}+T_{sta.}=\frac{V^2_{sta.}}{2}\left[\left(\Omega_{cargo}l_{(7-8)}+\Omega_{empty}l_{(9-6)}+G_{tensioner}\right)/g+m_{conveyor\,drive}+m_{drum.}+m_{sta.}\right]$$

– change in the kinetic energy of moving conveyor elements, N·m;

T_{cargo}, T_{empty}, $T_{wine.drum}$, $T_{conveyor\,drive}$, $T_{movable\,drum}$, $T_{fixed\,drum}$, $T_{drum.csta.}$, $T_{movable\,carriage}$, $T_{sta.}$ – changes in the kinetic energy of the empty branch, mobile and stationary drums of the telescopic device, the drum of the mobile station, the mobile carriage of the telescopic device, the mobile station of the conveyor with a working drive, respectively, N·m;

Ω_{cargo} – specific static resistance to movement of the belt of the loaded branch, N/m;

Ω_{empty} – specific static resistance to movement of the belt of the empty branch, N/m;

β – angle of installation of the conveyor, degree;

$l_{(7\text{-}8)}$ – the length of the cargo branch of the conveyor, m;

$l_{(9\text{-}6)}$ – the length of the empty branch of the conveyor, m;

$m_{conveyor\,drive}=k(GD)^2_{motor}i^2_{conveyor}/\left(gD^2_{drum}\right)$ – reduced weight of the conveyor drive, kg;

k – is a coefficient that takes into account the inertia of the conveyor drive reducer, equal to 1.2–1.3;

GD – engine rotor torque, $H^2\cdot m^2$;

$i_{conveyor}$ – transmission ratio of the conveyor drive reducer;

D_{drum} – diameter of the drive drum;

m_{sta} – mass of the mobile station, kg;

m_{drum} – mass of the conveyor drum (drums are all the same), kg.

After performing the corresponding transformations, the change in the kinetic energy of the mechanical system of the mechanism for changing the length of the belt conveyor with a working drive during the length change was equal to:

$$T=\frac{V^2_{sta.}}{2}\times\left[\begin{array}{l}\frac{4\left(J_{motor\,rotor}+J_{1gear\,wheel}+J_{2gear\,wheel}i_{reduction}\right)}{R^2_{stars}i^2_{reduction}}+\\+m_{roadheader}+m_{tensioner}+m_{sta.}+m_{conveyor\,drive}+\\+m_{drum}+\frac{\Omega_{cargo}l_{(7-8)}+\Omega_{empty}l_{(9-6)}}{g}\end{array}\right],\ \text{N·m},\quad(5)$$

where R_{stars} – the radius of the track drive sprocket of the running reducer of the tunnel combiner, m;

$J_{1gear\,wheel}$, $J_{2gear\,wheel}$ – the moment of inertia of the first and second gear wheels of the running reducer, respectively, kg·m²;

$m_{tensioner}=G_{tensioner}/g$ – the mass of the movable carriage of the telescopic device, identified with the force of the tensioning device, kg;

$G_{tensioner}$ – the force of the tensioning device, N;

g – acceleration of free fall, m/s².

The sum of the powers of all external forces N^e is equal to:

$$N^e=N^e+N_{resist},\ \text{N·m/s};\quad(6)$$

$$N_{resist.}=(N_{roadheader}+N_{conveyor})\cdot\cos180°,\ \text{N·m/s}.\quad(7)$$

After the transformations, the power of the resistance forces during the movement of the conveyor elements with a working drive:

$$N_{conveyor}=V_{sta.}\left[\begin{array}{l}\Omega_{cargo}l_{(7-8)}+\Omega_{empty}l_{(9-6)}+\\+G_{tensioner}+\\+g\left(m_{conveyor\,drive}+m_{drum}+m_{sta.}\right)\end{array}\right],\ \text{N·m/s}.\quad(8)$$

The power of the resistance forces during the movement of the tunnel combiner connected to the mobile station of the working conveyor, which changes the length of transportation:

$$N_{roadheader}=m_{roadheader}g\cdot V_{sta.},\ \text{N·m/s}.\quad(9)$$

Substituting equations (8) and (9) into (7), we get:

$$N_{resist}=-V_{sta.}\left[\begin{array}{l}\Omega_{cargo}l_{(7-8)}+\Omega_{empty}l_{(9-6)}+G_{tensioner}+\\+g\left(\begin{array}{l}m_{roadheader}+\\+m_{conveyor\,drive}+m_{drum.}+m_{sta.}\end{array}\right)\end{array}\right],\ \text{N·m/s}.\quad(10)$$

The power of the running asynchronous electric motor of the tunnel combiner N_{motor} **is** determined by the formula:

$$N_{motor}=M_{engine}\omega_{engine}=\left(M_{start}-\beta_{motor}\cdot\omega_{engine}\right)\omega_{engine},\ \text{N·m/s},\quad(11)$$

where M_{start} is the starting torque of the running electric motor, N·m;

$\beta_{motor}=\left(M_1-M_2\right)/\left(\omega_1-\omega_2\right)$ – the coefficient characterizing the slope of the mechanical characteristics of the engine of the running gear of the tunnel combiner, N·m·s (Fig. 5).

The speed of the mobile station, expressed in terms of the frequency of rotation of the running mechanism of the tunnel combiner, was written down by the equation:

$$V_{sta.}=V_{caterpillar}/2=\omega_{2\,gear\,wheel}D_{stars}/4=$$
$$=R_{stars}i_{reduction}\omega_{motor}/2,\ \text{m/s}, \qquad (12)$$

where $V_{caterpillar}$ is the speed of the combine track (Fig. 6).

By substituting equation (12) into equation (11), we obtained:

$$N_{motor}=\frac{2V_{sta.}}{R_{stars}i_{reduction}}\left(M_{start}-\frac{2V_{sta.}\beta_{motor}}{R_{stars}i_{reduction}}\right),\ \text{N·m/s}. \qquad (13)$$

Hence:

$$N^{e}=\frac{2V_{sta.}}{R_{stars}i_{reduction}}\left(M_{start}-\frac{2V_{sta.}\beta_{motor}}{R_{stars}i_{reduction}}\right)-$$
$$-V_{sta.}\left[\begin{array}{l}\Omega_{cargo}l_{(7-8)}+\Omega_{empty}l_{(9-6)}+G\ +\\ +g\left(\begin{array}{l}m_{roadheader}+m_{conveyor\,drive}+\\ +m_{drum.}+m_{sta.}\end{array}\right)\end{array}\right],\ \text{N·m/s}. \qquad (14)$$

After differentiating equation (5) with respect to t and substituting equation (14) into equation (3), we obtained:

$$\Im\frac{dV_{sta.}}{dt}=M_{start}-\aleph-\Re V_{sta.},\ \text{N·m}, \qquad (15)$$

where:

$$\Re=2\beta_{motor}/\left(R_{stars}i_{reduction}\right),\ \text{N/s};$$

$$\aleph=R_{stars}i_{reduction}\times$$
$$\times\left[\begin{array}{l}\Omega_{cargo}l_{(7-8)}+\Omega_{empty}l_{(9-6)}+\\ +g\left(\begin{array}{l}m_{H}+m_{roadheader}+\\ +m_{conveyor\,drive}+m_{drum}+m_{sta.}\end{array}\right)\end{array}\right]/2,\ \text{N·m};$$

$$\Im=2\left(\begin{array}{l}J_{motor\,rotor}+J_{1gear\,wheel}+\\ +J_{2gear\,wheel}i_{reduction}\end{array}\right)/\left(R_{stars}i_{reduction}\right)+$$
$$+R_{stars}i_{reduction}\left(\begin{array}{l}m_{roadheader}+m_{tensioner}+m_{sta.}+\\ +m_{conveyor\,drive}+m_{drum.}+\\ +\Omega_{cargo}l_{(7-8)}/g+\Omega_{empty}l_{(9-6)}/g\end{array}\right)/2,\ \text{kg·m}.$$

The speed of the mobile station during the change of the transportation length is determined by solving the transformation of equation (15)

$$V_{sta.}=\frac{M_{start}-\aleph}{\Re}\left(1-e^{-\frac{\Re}{\Im}t}\right),\ \text{m/s}. \qquad (16)$$

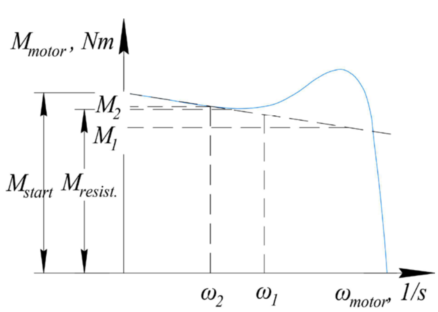

Fig. 5. Torque-frequency characteristic of the electric motor

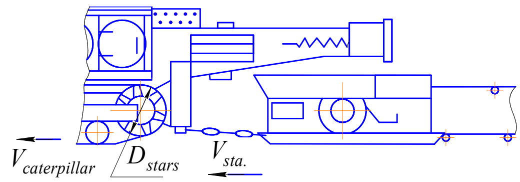

Fig. 6. Scheme for calculating the speed of a mobile station

By differentiating equation (16) with respect to t, the acceleration of the mobile station when the conveyor is operating is determined:

$$j_{sta.}=\frac{dV_{sta.}}{dt}=\frac{M_{start}-\aleph}{\Re}\exp\left(-\frac{\Re}{\Im}t\right),\ \text{m/s}^2. \qquad (17)$$

As can be seen from the resulting dependence, the change in speed and acceleration depends on the parameters of the belt conveyor and the extension mechanism (running mechanism of the tunnel combiner).

5. 2. Determination of the dynamic increase in belt tension of the extending conveyor with a working drive

The dynamic force for acceleration of a segment of the belt of length ∂x is equal to:

$$\partial S_{dyn}=\partial m_{belt}\cdot j_{belt}=\rho\cdot\partial x\frac{\partial^2 u}{\partial t^2},\ \text{N}, \qquad (18)$$

where $u(x,t)$ is the displacement at the moment t of the section of the belt to which effort is applied, which is actually the absolute elongation, m;

ρ – total linear mass of the moving branch of the belt, kg/m (for an empty branch $\rho=q_{belt}$);

q_{belt} – linear weight of the belt, kg/m.

A similar equation for determining the dynamic tension in the belt during its non-stationary motion is given in [14, 15].

In equation (18), the component $\partial x/\partial t$ is the dynamic rate of propagation of elastic deformations in the belt $a_{dyn.}$, and the component $\partial u/\partial t$ is the speed of displacement of the belt cross-section during the change of the transportation length without taking into account the speed of the belt generated by the conveyor drive $V_{belt\,offset}$.

When changing the length of transportation for a working conveyor, this speed is equal to the speed of change in length V_{sta}.

Since the tension at point 6 is practically equal to the tension at point 7, it is advisable to consider the change in the dynamic load of the belt on the drum of the mobile station for an empty branch.

Hence:

$$S_{dyn.}S=a_{dyn.}\cdot q_{belt}\cdot V_{sta.},\ \text{N}. \qquad (19)$$

The dynamic speed of propagation of the wave of elastic deformation in the belt during the change in the length of transportation of the conveyor with a working drive was considered taking into account the following calculation scheme (Fig. 7).

The front of the dynamic wave of elastic deformation during the change in the length of transportation passes the following path over time:

$$x=a_{dyn.}\cdot t,\ \text{m}. \qquad (20)$$

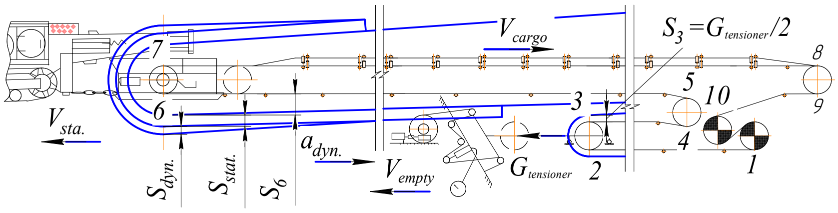

Fig. 7. Calculation diagram of emerging tensions in the belt when changing the length of conveyor transportation with a working drive

At the front of the stretching wave, the static tension in the belt before the movement of the mobile station:

$$S_a=\left(S_6-c\cdot x\right),\text{N;} \qquad (21)$$

$$c=\frac{S_{6H}-S_3}{l_{(3-6)}},\ \text{N/m;} \qquad (22)$$

$$S_6=\Omega_{empty}l_{(3-6)}+G_{tensioner},\ \text{N,} \qquad (23)$$

where S_6 – initial static tension of the belt at point 6 of the working conveyor, N;

c – gradient of the static tension of the belt before the start of movement of the mobile station of the working conveyor, N/m;

$S_3=G_{tensioner}/2$ – static tension of the belt at point 3, N;

$l_{(3\text{-}6)}$ – distance between the mobile station and the tensioner, m.

After applying the force that moves the mobile station, the belt tension at point 6 of the working conveyor will be equal to:

$$S_{6.\,move}=S_a+S_{stat.}+S_{dyn.},\ \text{N,} \qquad (24)$$

where S_{stat} – increase in static tension in the belt when changing the length of transportation of the working conveyor, *N*;

$S_{dyn.}$ – dynamic tension of the belt during the change of the transportation length of the working conveyor, *N*.

The gradient of the static tension of the belt when changing the length of the working conveyor:

$$z=\frac{S_6'-S_3}{l_{(3-6)}},\text{N/m,} \qquad (25)$$

where S_6=S_6+$S_{stas.}$ – the static tension of the belt at point 6 during the change in the length of the working conveyor, *N*.

By substituting the values of quantities in (24), we obtained:

$$S_{6.move}=\left[S_6+x\left(z-c\right)\right]+V_{sta.}\cdot q_{belt}\cdot a_{\partial dyn.},\ \text{N.} \qquad (25)$$

Lengthening of the belt ∂u on the segment ∂x after the start of movement of the mobile station:

$$\partial u=j_{belt}\cdot\left(\partial t\right)^2,\ \text{m} \qquad (26)$$

where $j_{belt}=j_{sta.}=\partial^2u/\partial t^2$ is the acceleration of the belt movement during the movement of the mobile station, m/s^2.

Relative elongation of the belt at point 6:

$$\varepsilon_6=\partial u/\partial x. \qquad (27)$$

Substituting (27) into (26) and integrating over t, we get:

$$\varepsilon_6=j_{sta.}t/a_{dyn.}; \qquad (28)$$

$$S_{6.move}=S_6+\Delta S,\ \text{N,} \qquad (29)$$

where $\Delta S=\sigma_6B_{belt}i_{pad}$ is the increase in belt tension at point 6, which occurs when the end station is moved, N;

B_{belt} – belt width, m;

i_{pad} – the number of spacers.

A rubber-cable belt can be considered an isotropically elastic body. Quite often, when calculating with a rubber fabric belt, it is assumed that the traction-carrying body is an isotropic-elastic body. Taking into account the above, the resulting increase in belt tension at point 6:

$$\Delta S=\sigma_6B_{belt}i_{pad}=E_{0gyn.}\varepsilon_6,\ \text{N,} \qquad (30)$$

where $\Delta S=\sigma_6B_{belt}i_{pad}=E_{0gyn.}\varepsilon_6$ is the dynamic modulus of elasticity of the belt, N; σ_6 is the stress per meter of belt width at point 6, N/m.

Substituting equations (25), (30), and (28) into (29) and assuming that at the moment t the dynamic wave of elastic deformation has traveled the distance $x=\sigma_{dyn.}t$, and the displacement speed of the belt section at point 6 $V_6=j_{sta.}t$, after the transformations, the dependence of the dynamic speed of propagation of the wave of elastic deformation on the empty branch of the working conveyor was derived:

$$a_{dyn.}=\sqrt{\frac{E_{0.dyn.}}{q_{belt}+\dfrac{\left(z-c\right)}{j_{sta.}}}},\ \text{m/s.} \qquad (31)$$

Substituting equations (22) and (25) into (31), we get:

$$a_{dyn.}=\sqrt{\frac{E_{0.dyn.}}{q_{belt}+\dfrac{S_{stat.}/l_{(3-6)}}{j_{sta.}}}},\ \text{m/s.} \qquad (32)$$

By substituting equation (32) into (19), a dynamic increase in belt tension during the change in the length of conveyor transportation with a working drive is obtained:

$$S_{dyn.}=q_{belt}\cdot V_{sta.}\times$$
$$\times\sqrt{E_{0.dyn.}\cdot j_{sta.}/\left(q_{belt}\cdot j_{sta.}+S_{stat.}/l_{(3-6)}\right)},\ \text{N.} \qquad (33)$$

The jump in the dynamic increase in belt tension is influenced by the 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 mobile carriage of the telescopic device.

5. 3. Verification of the procedure for designing belt conveyors with variable length of transportation based on numerical modeling

As noted in work [11], the conveyor must be extended during operation of the conveyor drive. Therefore, in order to design such a conveyor, in addition to the traction calculation, it is necessary to have the software for the calculation of the emerging tension jumps (dynamic and static) in the elongating working conveyor, which are spread from the site of the disturbance-drum of the mobile station.

The procedure for calculating the increase in belt tension on the drum of the mobile station consists of 5 stages.

The first stage. Determine speed $V_{sta.}$ (dependence (16)) and acceleration $j_{sta.}$. (dependence (17)) of the mobile station.

The second stage. Determine the speed of the loaded V_{cargo} (dependence (1)) and empty V_{empty} (dependence (2)) of the conveyor branch during the change in the transportation length.

The third stage. Determine the jump value of the static load of the belt S_{stat} (dependence (100) [11]) when changing the length of transportation:

$$S_{stat.} = \left(R + \sqrt{R^2 + \Pi}\right) / \left[4V_{empty}\left(V_{cargo} - V_{sta.}\right)\right], \text{ N}, \tag{34}$$

where:

$$R = V_{sta.}\begin{bmatrix} 2V_{empty}\begin{pmatrix}\Omega_{empty} l_{(3-6)} + \\ +G_{tensioner}/2\end{pmatrix} + \\ +V_{sta.}\,\Omega_{cargo} l_{(3-6)}\end{bmatrix}, \text{ N·m}^2/\text{s}^2;$$

$$\Pi = 8V_{sta.}^2 V_{empty} \cdot \Omega_{cargo}\left(V_{cargo} - V_{sta.}\right) \times$$
$$\times\left(\Omega_{empty} \cdot l_{(3-6)}^2 + G_{tensioner} \cdot l_{(3-6)}\right), \qquad \text{N}^2\text{m}^4/\text{s}^4.$$

The fourth stage. Determine the jump in the dynamic load of the belt (dependence (33)) during the change in the length of transportation.

The fifth stage. Determine the amount of change in the tension of the belt on the drum of the mobile station during the change in the length of transportation (sum S_6 – dependence (23), $S_{stat.}$ – dependence (34), S_{dyn} –dependence (33)):

$$S_{6.move} = S_6 + S_{stat.} + S_{dyn.}, \text{ N}. \tag{35}$$

Below is an example of the calculation of emerging belt tension jumps in an extending, working conveyor, spreading from the drum of a mobile station. For calculation using the Mathcad software, the following initial data are accepted:

$J_{motor\ rotor.}$=3 kg·m^2; R_{stars}=0.5 m; $l_{(3\text{-}6)}$=835 m;

$m_{tensioner.}$=150 kg; $J_{1gear\ wheel}$=0.01 kg·m^2; f=0.8;

$J_{2gear\ wheel.}$=25 kg·m^2; g=10m/s^2; $m_{sta.}$=1,000 kg;

$l_{(9\text{-}6)}$=915 m; $l_{(9\text{-}2)}$=65 m; m_{drum}=100 kg;

Ω_{empty}=5.33 N/m; M_{start}=700 N/m; $m_{harvester}$=35000 kg;

$\beta_{motor.}$=2 N·m/s; $l_{(7\text{-}8)}$=800 m; Ω_{cargo}=12.5 N/m;

$E_{0.dyn}$=2,600,000 N; $i_{reduction.}$=0.0064; q_{belt}=10 kg/m;

$m_{conveyor\ drive}$ =1250 kg; V_c=1.6 m/s.

Fig. 8 shows the result of calculating the speed and acceleration over time of the mobile station of the lengthening, working conveyor.

Fig. 9 shows the result of the calculation of the speed change over time of the upper and lower branches of the extending, working conveyor.

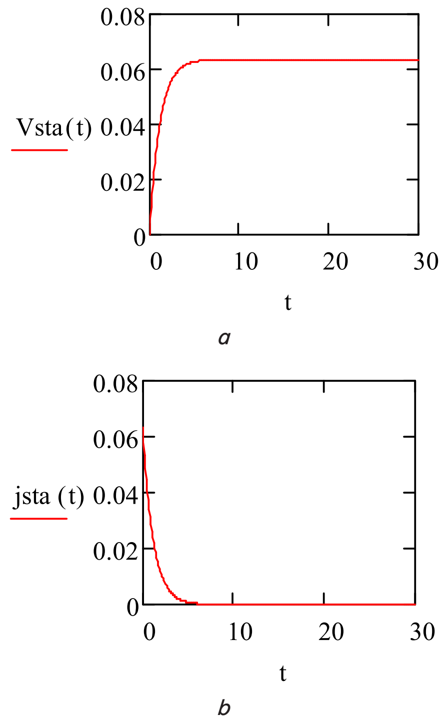

Fig. 8. Plot of time-dependent changewhen the working conveyor is extended: *a* – speed of the mobile station; *b* – acceleration of the mobile station

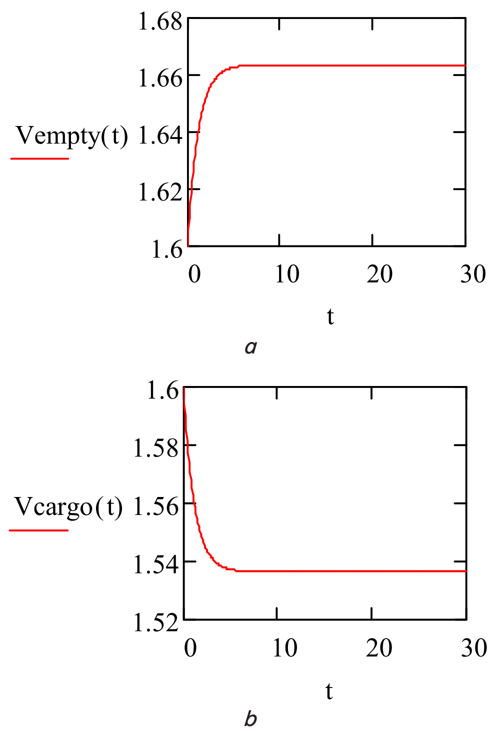

Fig. 9. Plot of time-dependent change when the working conveyor is extended: *a* – speed of the upper branch; *b* – speed of the lower branch

Fig. 10 shows the result of calculating the change in the static jump of the belt load on the drum of the mobile station of the extending, working conveyor.

Fig. 11 shows the result of calculating the change in the dynamic jump of the belt load on the drum of the mobile station of the extending, working conveyor.

Fig. 12 shows the result of calculating the belt load on the drum of the mobile station of the extending, working conveyor.

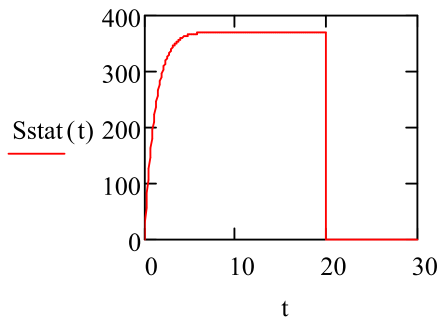

Fig. 10. The plot of change in the static jump of the belt load over time on the drum of the mobile station of the extending, working conveyor

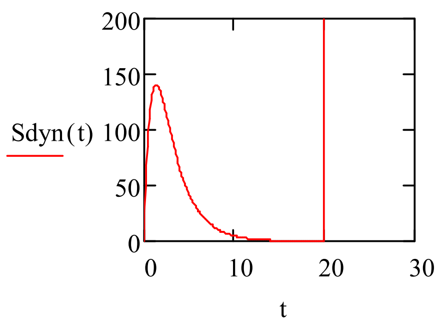

Fig. 11. The plot of change in the dynamic jump of the belt load over time on the drum of the mobile station of the extending, working conveyor

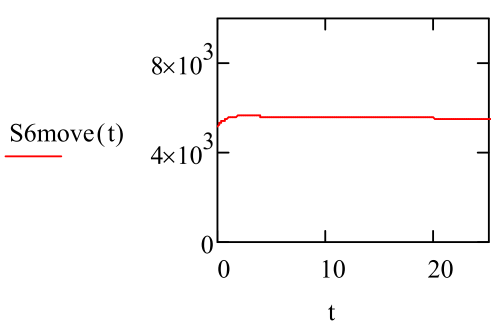

Fig. 12. The plot of change in the belt load over time on the drum of the mobile station of the extending, working conveyor

6. Discussion of results of investigatingthe parameters of belt conveyors operating during the change in the length of transportation

The result of the current research is the development of a methodology for the design of belt conveyors with a variable length of transportation. In the study, it was considered how the change and acceleration of the transportation length of the working conveyor affects the tension of the belt. The result is very important because it provides an understanding of the causes of changes in belt tension during unevenly accelerated changes in the length of transportation of a working conveyor. The result is also important because it makes it possible not only to perform calculations during design but also gives recommendations for the correct operation of such conveyors.

In contrast to the mathematical model built in [11], our result allows for the design of a conveyor that changes the transportation length unevenly at an accelerated rate. 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 studied how the speed and acceleration of the mobile station and the belt of the working conveyor changes during the change in the length of transportation. Dependences were derived that make it possible to calculate the emerging dynamic jump tension of the belt, which occurs at the beginning of the movement of the mobile station during the extension of the conveyor.

With we determined the speed, according to formula (16), and the acceleration, according to formula (17), of the mobile station of the working conveyor, the characteristics of the electric motor of the movement mechanism of the final station were taken into account.

When determining the jump in the dynamic increase in belt tension according to formula (33), the speed and acceleration of the mobile station were taken into account

On the basis of the mathematical model built,by using Mathcad software, the procedure for designing belt conveyors with variable length of transportation was verified based on numerical simulation. This made it possible to establish that the static jump of the belt tension on the drum of the mobile station is greater, the greater the difference between the absolute speed of the belt of the upper and lower branches of the conveyor. Also, the distance from the drum of the mobile station to the drum of the mobile carriage of the telescopic device and the specific static resistance to the movement of the lower branch of the conveyor significantly affect the amount of static increase in the tension jump of the belt. The magnitude of the dynamic increase in the belt tension jump with an elongated conveyor is primarily influenced by the acceleration and speed of the mobile station. When extending the conveyor with a stopped drive, all these values will be larger.

Our results make it possible to determine the parameters for the design of a belt conveyor with a variable length of transportation, which is advisable to use in the construction of tunnels [16, 17], the construction of a rotary excavator with a telescopic boom [18, 19].

The current study is a continuation of previously performed theoretical research [11] of loads in the belt that occur during the change in the length of transportation on the drum of the mobile station of the conveyor.

Due to the reduction of unproductive technological operations and the reduction inreloading devices, the use of a belt conveyor with a variable length of transportation makes it possible to improve productivity and reduce energy consumption in continuous flow technologies.

In the general case, the limitations inherent in this study are the stability of solutions to changes in factors affecting belt tension. It is recommended to perform calculations for predetermined, maximum output data such as productivity, transported cargo, length and angle of installation of the conveyor.

The next stage of research may involve the development, based on numerical modeling, of a procedure for calculating the tension of a stopped conveyor belt during an unevenly accelerated change in the length of transportation. The implementation of such a study is associated with constructing a more complex mathematical model since there is a mode of acceleration and steady movement of the belt during a change in length transportation. Devising such a calculation procedure based on numerical modeling couldmake it possible todemonstrate visually what increase in belt tension would occur when the stopped conveyor is lengthened. This is very important when writing recommendations for the operation of a conveyor with a variable length of transportation.

7. Conclusions

1. Before extending the length of transportation, the speed of the working conveyor belt is equal to thespeed in specifications. When the length of transportation is extended, the absolute speed of the cargo branch of the conveyor is reduced by the speed of the mobile station. The absolute speed of an empty branch of the conveyor increases by the speed of the mobile station.

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 magnitude of the dynamic increase in the belt tension jump when the conveyor is extended is affected by the acceleration and speed of the mobile station, the technical characteristics of the belt, the gradient of the increase in belt tension during the extension of the conveyor in the sections from the drum of the mobile station to the drum of the mobile carriage of the telescopic device.

3. Verification of the design methodology of a belt conveyor with a variable length of transportation involves numerical modeling, the result of which is the traction calculation of the conveyor and the determination of the change in belt tension on the drum of the mobile station during the extension of the conveyor.

Determining the change in belt tension on the drum of the mobile station during the extension of the conveyor involves the calculation of the following:

– speed and acceleration of the mobile station;

– speeds of the cargo and empty branches of the conveyor;

– values of jump of the static load of the belt;

– values of the jump in the dynamic load of the belt;

– belt tension on the drum of the mobile station.

Analysis of the results of these calculations revealed that during the change in the length of transportation of the conveyor with a working drive on the drum of the mobile station, there was a slight jump in the tension of the belt. The maximum value of the jump is registered at the maximum acceleration of the mobile station. At zero acceleration, it is absent. At a constant speed of the mobile station, the belt tension jump is constant and persists as long as the station is moving. The tension of the belt at the maximum acceleration of the mobile station increased by 1.1 times, and at constant speed of the mobile station – by 1.07 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 and the results reported in this paper.

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Data availability

All data are available 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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