Method for determining the traction force of the ground cable car drive

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Abstract. The article is devoted to the problem of determining the necessary indicators of the traction force of the ground cable car drive, in the modes of start-up, steady motion and braking when operating them in curved workings with a variable path profile. Therefore, for each case of using a cable car in the mine, the required amount of traction must be calculated based on the specific values of the cable car profile parameters and the curvature of the path in the horizontal plane. The method of determining the traction force given below allows you to calculate the required traction force based on the design data of the ground cable car for specific operating conditions. To calculate the traction force, all the resistances to the movement of the composition of the trolleys and the traction rope are determined.

1. Introduction

Ground-based cable cars are widely used in coal mines. For the transport of auxiliary goods and people on site mining operations with a variable profile of rails exceeding ±5°, which excludes the use of locomotive rollback and the possibility of using a terminal cable car, ground cable cars are used. They are used mainly on ventilation horizons in workings with stable soils. When transporting goods in long curved workings with unpredictable impact of negative factors, the vehicles used practically work in conditions of uncertainty. As a result, numerous accidents and failures in the auxiliary transport system serving the preparatory faces.

Due to failures in the operation of local transport means, preparatory mine faces lose up to 0.53 m of workings per shift. In this regard, the purpose of this method is to establish the actual indicators of the traction force of the ground cable car drive, in the modes of start-up, steady motion and braking when operating them in curved workings with a variable path profile.

2. Determination of the drive thrust force

When operating a ground cable car, transport platforms can move along horizontal sections of the track, along curves, along slopes with ascent and descent. For specific mining and geological conditions, sections of the path can occur in various combinations. Therefore, for each application of the cable car in the mine, the required traction force must be calculated based on the specific values of the parameters of the profile of the cable car and the curvature of the track in the horizontal plane [1-3]. The method for determining the traction force, given below, allows you to calculate the required traction force based on the design data of the ground cable car for the specific conditions of its operation. To calculate the traction force, all resistances to the movement of the trolley train and traction rope are determined.

A simplified design diagram of the cable car is shown in Figure 1.
The main resistance to the movement of the trolley along the horizontal rectilinear section of the track can be determined from the following expression:

\[ W_\omega = G^T_\omega \cdot \omega_\Omega \]  

where:

\[ G^T_\omega = g \cdot m_T \]  

where: \( m_T \) - the mass of the cart (loaded or empty);

\( \omega_\Omega \) - the coefficient of the main resistance to the movement of the bogie, which depends on the condition of the bearings, wheels and track. The values of this coefficient are shown in Table 1.

| Carrying capacity, (t) | coefficient of the main resistance to the movement |  |
|------------------------|-------------------------------------------------|---|
|                        | for a loaded trolley                         | for empty trolley          |
| 1                      | 0.009                                          | 0.011                       |
| 2                      | 0.008                                          | 0.010                       |
| 3                      | 0.007                                          | 0.009                       |
| 5                      | 0.006                                          | 0.007                       |
| 10                     | 0.005                                          | 0.005                       |

* calculated by author for mine conditions

When rollback by intermediate drifts, to sections of horizontal horizontal and inclined workings, where are the rail lines the paths are in the worst condition, than in capital investments workings, coefficient the main one resistance when moving calculations should be made zoom in by 50-60%.

On trolley, located on an incline paths other than forces harmful resistances, still active and longitudinal component your own weights. [4-6] Scheme forces that valid for located on an incline trolley tracks, pictured in Figure 2.
In this case, when moving a loaded trolley down a slope, the main resistance is:

\[ W_o = G_o^T \cdot (\omega_o \cdot \cos \beta - \sin \beta) \]  

(3)

where: \( \beta \) is the working angle.

The resistance to the movement of the trolley along the inclined working is equal to 0 if

\[ \omega_o \cdot \cos \beta - \sin \beta = 0 \]  

(4)

or

\[ \omega_o = \tan \beta \]  

(5)

The obtained value of \( \tan \beta \) is called the trolley equilibrium slope. If the slope of the track is greater than the slope of the balance, then the tractive effort required to move the trolley downward is negative and the movement of the trolley can be carried out on its own. When the trolley moves upward at a constant speed, the resistance to the trolley movement is:

\[ W_o = G_o^T \cdot (\omega_o \cdot \cos \beta + \sin \beta) \]  

(6)

Taking into account the above formulas, it is possible to determine the resistance to the movement of the train:

- on a horizontal track:
  \[ W_o^C = (z \cdot G_o^T + G_o^B) \cdot \omega_o \]  

(7)

- on an inclined section of the path when moving down:
  \[ W_o^C = (z \cdot G_o^T + G_o^B) \cdot (\omega_o \cdot \cos \beta - \sin \beta) \]  

(8)

- on an inclined section of the path when moving up:
  \[ W_o^C = (z \cdot G_o^T + G_o^B) \cdot (\omega_o \cdot \cos \beta + \sin \beta) \]  

(9)

where \( z \) is the number of trolleys in the train. When mining rope haulage, from 1 to 10 trolleys of various carrying capacity can be used;

\( G_o^T \) - the force of gravity of the tow car.
It should be noted that an assumption is made in formulas 8 and 9. It consists in the fact that the coefficient of resistance to the movement of the tow car is taken equal to the coefficient of resistance to the movement of the transport car.

In addition to the main resistance to the movement of the train, there are additional resistances that arise as a result of the movement of the train of trolleys along the curves of the track and as a result of the action of inertial forces during periods of unsteady movement.

In practical calculations, the resistance to the movement of trolleys on curves is not taken into account, since when designing a mine cable car, large turning radii are laid down, which reduce the resistance to movement to a minimum. Therefore, the turn can significantly affect the calculations of the traction force only during the cable haulage of a single trolley, when the value of the traction force transmitted by the drive is small.

The resistance to motion arising from the action of inertial forces \((W_a)\) is calculated only for transient operating modes of the cable car, where it is necessary to check the condition for adhesion of the rope to the pulley at a given acceleration or deceleration.

\[
W_a = \pm M \cdot a
\]

where:  
- \(M\) - reduced mass of translationally moving and rotating parts of the trolley;  
- \(a\) - trolley acceleration or deceleration.

When the trolley is accelerating, the movement resistance is assumed to be positive, and when decelerating, it is negative. The main resistance to the movement of the rope is determined by the complex resistances that arise when the rope moves along the rollers. On the horizontal section of the path, the main resistance is

\[
W_k = P \cdot \omega_k
\]

where:  
- \(\omega_k\) is the coefficient of the main resistance to the movement of the rope. In the absence of friction of the rope on the soil, the excavation \(\omega_k = 0.15-0.35\);  
- \(P\) is the force of the rope pressure on the rollers.

\[
P = g \cdot p_k \cdot L
\]

where:  
- \(p_k\) is the linear mass of one meter of the rope;  
- \(L\) is the length of the cable car rope located on the horizontal section of the mine.

In an inclined development, the main resistance to the movement of the rope \((F_k)\) is determined from the condition of the balance of the rope. If \(\tan \beta > \omega_k\), then the downward movement of the rope is carried out under the action of its own weight. In this case, the tension of the rope on the winch pulley is equal in magnitude and opposite in sign to the force that moves the rope down the roadway.

\[
F_k = p_k \cdot L_k \cdot g \cdot (\omega_k \cdot \cos \beta - \sin \beta).
\]

Here \(L_k\) - the length of the rope located in the inclined mine, if \(\tan \beta < \omega_k\), then to move the rope down the inclined working downhill at a constant speed, you need to apply a force equal to the resistance to the movement of the rope.

\[
W_k = p_k \cdot L_k \cdot g \cdot (\omega_k \cdot \cos \beta - \sin \beta).
\]

The resistance to the movement of the rope up the slope is equal to

\[
W_k = p_k \cdot L_k \cdot g \cdot (\omega_k \cdot \cos \beta + \sin \beta).
\]

The resistance to the movement of the rope along the roller battery, shown in Figure 3, can be calculated "point by point" at a given value of the rope tension at the point of runaway and at a given location of the rollers.
Figure 3. Scheme of bending to the anatomical roller battery.

The resistance of each roller can be determined by the formula:

$$W_p = \xi \cdot F_{SB}$$  \hspace{1cm} (16)

where:  
- $F_{SB}$ is the rope tension at the point of running onto the roller;  
- $\xi$ - coefficient characterizing the increase in resistance to the movement of the rope on the roller. Depends on roller design and bearing lubrication. In calculations, it is taken equal to $\xi = 0.02 - 0.06$.

The tension of the rope at the point of runaway from the first roller is:

$$F_{EB} = F_{SB} + \xi \cdot F_{SB} = F_{SB} \cdot (1 + \xi).$$  \hspace{1cm} (17)

It is equal to the tension at the point of running onto the second roller. The tension at the point of escape from the second roller is:

$$F_{EB}'' = F_{SB}(1 + \xi) + \xi \cdot F_{SB} \cdot (1 + \xi) = F_{SB} \cdot (1 + \xi)^2.$$  \hspace{1cm} (18)

The tension of the rope at the point of runaway from the next $n$-th roller of the roller battery is generally written as follows:

$$F_{EB}^n = F_{SB} \cdot (1 + \xi)^n,$$  \hspace{1cm} (19)

where:  
- $F_{SB}$ is the rope tension at the point of running onto the first roller battery;  
- $n$ - number of roller in a roller battery.

The resistance to the movement of the rope along the end block is determined by the resistance of the rope stiffness at the point of running onto the block and at the point of runaway from it and by the resistances in the bearings of the block axis.

The tension of the rope at the points of runaway on the block $F'$ and at the point of runaway from it $F''$ are related by the ratio:

$$F' = (1.05 - 1.1)F''$$  \hspace{1cm} (20)
The dynamic resistances arising during unsteady motion (Wo) depend on the magnitude of the acceleration (deceleration) of the rope movement and the reduced mass of the moving parts of the installation.

\[ W_0 = \pm a \cdot \sum M, \]  
\[ \sum M = M_c + M_r + 2 \cdot m_{pr} + \sum m_p, \]

where:  
- \( M_c \) is the mass of the transported cargo;  
- \( M_r \) with is the mass of the ropeway rolling stock;  
- \( m_{pr} \) - reduced weight of the cable car drive to the pulley rim;  
- \( \sum m_p \) - the sum of the masses of the guides, deflecting and end rollers reduced to the rope.

When calculating transport installations with a flexible traction element, the resistance forces are determined by the method of bypassing the contour "by points". In this case, the tension is found at any point of the flexible traction circuit, the tension in the incoming and outgoing branches of the circuit at the drive, and from them the total resistance and traction force is calculated.[7-8]

The calculation by the "point-by-point" method is as follows. The contour of the traction element is crossed out and divided into straight and curved sections, while the points of conjugation of these sections are numbered, as shown in Figure 4. The drive is usually started from the point where the traction element comes off the drive pulley. Further, the characteristic points are numbered sequentially along the movement of the traction body.

\[ S_1 = S_{EB} \]  
\[ S_2 = S_1 + W_{1-2} \]  
\[ S_3 = 1,02 \cdot S_2 \]  
\[ S_4 = S_3 + W_{3-4} \]

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Figure 4. Scheme of the traction contour with characteristic points.

The calculation must start from point 1, where the tension is equal to \( S_1 \). The tension of the rope at each point following along the course of its movement is equal to the tension at the previous point plus the resistance force in the section between these points. I.e.:
The total resistance \( W \) and tractive effort \( F_t \) on the drive drum shaft is equal to

\[
W = F_t = S_4 - S_1 \tag{27}
\]

or

\[
W = F_t = S_{SB} - S_{EB} \tag{28}
\]

In transient modes, the dynamic component of the moving and rotating masses of the transport system should be taken into account. In this case, the total resistance is

\[
W_\Sigma = S_{SB} - S_{EB} \pm a \cdot \sum M \tag{29}
\]

where \( \sum M \) is the total mass of all translationally moving masses (bogies, cargo, rope) and rotationally moving masses (rollers, drive and end pulleys, gear wheels and, in the case of a hydraulic drive, rotors of drive hydraulic motors ), reduced to the pulley rim ;

\( a \) - acceleration (or deceleration) of the movement of the rolling stock. The minus sign is adopted when the system slows down, and the plus sign is taken when the system is started.

Acceleration and deceleration are chosen from the range of allowable accelerations and decelerations, safety regulations on limited cargo-people transportation at coal mines [9].

As mentioned earlier, the Euler-Zhukovsky formula is widely used in practical calculations. Transforming this formula 2.1 and using equation 29, we get the following expression:

\[
F_{tr} = S_{EB} \cdot \left( e^{\mu \alpha} - 1 \right) \tag{30}
\]

where \( F_{tr} \) is the friction force that the drive pulley can transmit.

The condition for the absence of slipping of the rope along the pulley in the transient mode.

\[
S_{SB} - S_{EB} \pm a \cdot \sum M \leq F_{tr} \tag{31}
\]

3. Discussion

The mode of operation during acceleration and deceleration of the transport system is more dangerous in terms of slippage than at a steady speed, therefore, the condition of no slip in unsteady modes is always checked. This selects the acceleration and deceleration values.

The traction drive is driven by a traction wheel. A steel cable is suspended from a traction wheel. The method of winding the traction rope mainly depends on the position of the traction device, the rated load and the rated speed. When selecting and determining the cable winding mode, high transmission efficiency, reasonable power consumption, and long service life should be taken into account. For this purpose, the calculated parameters of the tractive effort are used.

Determining the rational parameters is one of the main tasks in the study of the operation of the surface rope way drive. The fact that the length of the surface rope way changes periodically during its operation is of particular importance is. At the same time, the resistance to the movement of the rolling stock and the rope changes, based on which the necessary traction force is calculated, which must be provided by the surface rope way drive. Therefore, it is necessary to vary the main parameters of the drive, which affect its traction force. As mentioned earlier, these are the coupling coefficient \( \mu \), the angle of rope contact and catenary tension \( S_{ss} \). Obviously, it is not possible to change the friction ratio by technical means during the operation of the drive, since it depends more on the materials of contact surfaces. The use of high-friction materials as a lining for friction sheave is due to the fact that in light operating conditions, the drive has a large margin of friction forces. At the same time, when working in severe conditions, there will be no margin and under certain conditions (for example, when starting the system), the selected margin may not provide a stable coupling of the rope with the sheave. This raises the question of increasing the traction force of the drive, which can be influenced by devices that allow changing the angle of rope contact. It is also possible to use a tensioner to increase the tension in catenary, which will allow using the drive with a lower traction factor. This follows from the Euler-Zhukovsky relation. Thus, changing the angle of rope contact and catenary tension, as well as determining their optimal values for various working conditions, are the most promising directions when
studying the operation of a rope drive. In addition, there is a problem of coupling the rope with the sheave during transients of the drive. Therefore, determining the value of the transport system acceleration is also one of the main tasks when designing an endless-rope haulage. To determine the rational values of the drive, it is necessary to consider their dependence on such factors as the length of transportation, the slope of the workings, the weight of transported cargo, etc.

4. Conclusion

The maximum effective pulling force that can be generated in a tow wheel groove is the coefficient of friction between the steel rope and the wheel groove and the function of the steel rope around the corner of the tow wheel. Measures to increase traction capacity are:

- to change the shape of the rope groove and the material of the rope groove to improve the coefficient of friction,
- to increase the angle of the envelope.

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