Design of a Haulage System Operating on a Downward Curvilinear Track

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Abstract: One of the most important problems met in cable downward installations is the considerable unbalance between tensions of two cable bits caused by load variation. This variation mainly caused by downward cable bit mass which induces amplitude in torque variation applied to control group. To maintain skip speed in recommended limits and limit the motor drive power as well as operation mode, dynamic balancing of downward system is carried out. This system acts as to limit the difference between tensions of the two downward system cable bits. In this study, it is recommended the application of downward track having a variable slope angle to realise a dynamic balancing system. Thus, because of track curvilinear shape, the decomposition of forces acting on each cable bit is such that to realize tensions equality between the two cable bits. The other advantage of this balancing type is the application of a constant braking torque which is an important factor for the choice and rational use of control group.

Key words: Cinematic-dynamic-braking-cable-balancing-skip

INTRODUCTION

In the installations of ore downward transport by skips, the load creates a motor-carriage force and the system operates because of gravitation force. An electrical control operates in a state of current regeneration braking limiting skip downward speed and stopping at the unloading point.

The cinematic of this type of installation is characterized by transient states at the start and the stop causing important dynamic overloads at the organs of control system and cable oscillations with its elastic nature can favour the amplification and consequently cause its rupture.

One of the most important problems met in cable downward installations is the considerable unbalance between tensions of two cable bits caused by load variation.

This variation mainly caused by downward cable bit mass which induces amplitude in torque variation applied to control group. Sudden torque evolution in a limited cycle time induces an installation control system oversized and a lower exploitation rate[1].

Many processes were used to limit the unbalance between cable bits tensions and consequently to size rationally the power of control group.

To overcome these difficulties, the use of vertically curved tracks may have a great advantage. This study explores a possible solution of calculating design parameters of such rail track.

When operating on a vertically curved rail track system where the main function is loading the load, it can also be employed in raising supplies[2]. Generally it is the load that generates the necessary moving effort in systems working by gravity[3]. A suitable electrical drive can operate as a braking and speed controlling unit when regenerating and may hold the moving speed of the skip within the prescribed limits and stop it at the dumping point.

When operating on a vertically curved rail tracks the ratio between regenerated and normal power remains poor[2]. This is due to the important variation on transmissible strength during downward motion, accelerating and decelerating periods. During these periods, important consecutive load surges are transmitted to different parts of the system which may reduce their life duration.

MATHEMATICAL MODEL DEVELOPMENT

Taking in consideration different physical parameters influencing the downward movement, the model is

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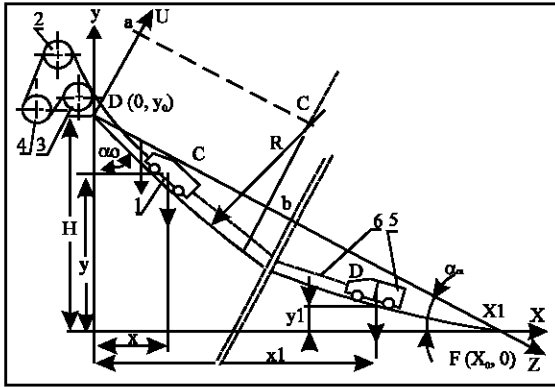
Fig. 1: Diagram of descent system having a curvilinear track 1. Container charged 2, 3: guidance pulleys 4: inversion Pulley 5: Empty container 6: Cable a, b: Co-ordinates of circle center C: Center of circle R: radius
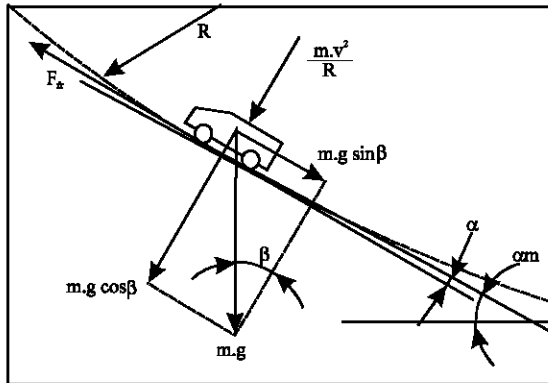

Fig. 2: Diagram of calculation of the static forces and friction for the skip
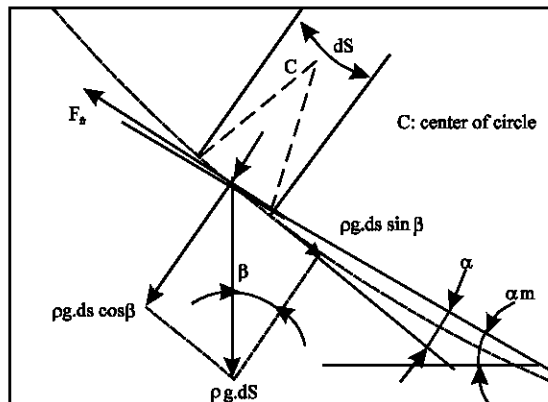

Fig. 3: Diagram of calculation of the static forces and of friction for the cable

developed in order to limit the transmissible strength variation[4]. For this purpose the curvilinear rail track is considered.

Firstly, let us consider the geometry of the curved rail track or guide-ways Fig. 1 as a mean of improving the transmissible strength.

It will be seen that if the slope is increased for upper portion of the rail track and is reduced for the lower portion, the gravitational forces applied to the downward system will vary so that the forces due to velocity increase at the beginning of the cycle and decrease at the end of the cycle.

In this study, the approach used is limited to choose vertical curves that ensure a regular slope variation.

Problem description: Emphasis is placed on finding a curve where effective gravitational components are well distributed throughout the track length. This distribution must ensure a free downward motion of the loaded conveyance with minimum rough transmissible loads and with a constant braking strength (retarding force).

Let the points D $(0, Y_0)$ and D $(X_0, 0)$, corresponding to the beginning and the end of the curved guide-ways Fig. 1. A curve $y = f(x)$ (Track of the curved guide-way) connects two points D and F. Two skips connected by a rope moving at the same speed.

Considering the downward installation as a mono-mass system. While referring to the equilibrium equation from d'Alembert[5] and if the braking strength (retarding force) F_{fc} is assumed constant, the equation of dynamic equilibrium of the system is:

$$\sum F_{st} - \sum F_{fr} - F_{fc} = \sum F_{dyn} \qquad (1)$$

The static forces $\sum F_{st}$ and friction $\sum F_{fr}$ are determined by the position of the considered element (skip or cable) and in particular the slope angle β. Knowing that this angle is variable, one will express these forces according to Fig. 2 and 3:

Expressing, respectively the elementary portion of the cable dS, the radius of curvature at the considered point of the track R, cos β and sinβ according to the Eq. of the curve[6].

$$dS = \sqrt{1 + (y')^2} \; dx \quad R = \frac{\left[1 + (y')^2\right]^{3/2}}{y''}$$

$$\cos \beta = \frac{1}{\sqrt{1 + (y')^2}} \quad \sin \beta = \frac{y'}{\sqrt{1 + (y')^2}}$$

Then by breaking up the static forces and system friction, one develops the equation of d'Alembert (1). The dynamic equilibrium equation is obtained following the downward system on a curvilinear track[4].

$$g(m_s+m_u)\frac{y'-f_1}{\sqrt{1+(y')^2}} - (m_s+m_u)f_1.v^2\frac{y''}{\sqrt{(1+(y')^2)^3}} -$$

$$g\,m_s\frac{y'_1+f_1}{\sqrt{1+(y'_1)^2}} - m_s f_1.v^2\frac{y''_1}{\sqrt{(1+(y'_1)^2)^3}} -$$

$$\rho.g.f_2.v^2(x+x_1) - k_f.g.m_u\sin\alpha_m - \qquad (2)$$

$$F_{fc} - m_i.\frac{dv}{dt} = \rho.g(\int_0^{x_i} y'dx - \int_0^x y'dx)$$

$$+ \rho.f_2.v^2(\int_0^x\frac{y''}{(1+(y')^2)}dx + \int_0^{x_i}\frac{y''}{(1+(y')^2)}dx)$$

Where: m_s, m_u are, respectively the mass of the empty skip, the main load m_i reduced mass: conventional mass replacing all mobile element mass of downward installation. It is situated on the axis of the inversing pulley and having the same action as replaced masses. f_1 et f_2: friction coefficient between the skips, the rail and the rope.

ρ : metric rope mass (mass per unit length)

k_f: proportional coefficient[7] which consider the friction between the rope and the pulley and also the aerodynamic resistance; $k_f = 0.5$ at 0.2.

$$\alpha_m = \text{arctg}\frac{X_0}{Y_0}$$

In order to solve this equation and simplify calculations[4,8], it is necessary to find relations between y, y_1 and x, x_1 and the reduced mass; the expressions of the speed, acceleration and braking strength are deduced.

Curve's equation $y = f(x)$ must be previously defined so that the analytical solution will be possible to find.

MATHEMATICAL MODEL RESOLUTION: THE TRACK AS AN ARC

Let us consider the curved guide-ways as an arc. Slope variation (α) is proportional to distance covered S. Let U.O.Z Fig. 1 is chosen as co-ordinate; to limit the circles passing by the points (0, 0) and (X_0, 0). Supposing that slope tangent at the point (0, 0) is known and its angle is α_0.

It is specified that α_0 is negative and varies in the interval:

$$0 \le \alpha_0 \le \alpha_m$$

Curve Eq. (0, X) is:

$$y = b - \sqrt{(R^2 - (x-a)^2)} \qquad (3)$$

Where: a, b: co-ordinates of the circle centre, R: Radius From Eq. 3, it can be deduced $y_1 = f(y)$ and $x_1 = f(x)$. We substitute these two functions into (2) and solve the new differential equation, we find:

Speed expression:

$$v = \sqrt{\begin{array}{l}p(e^{m\overline{s}}-1)+q(e^{m\overline{s}}\cos\alpha_0-\cos((2\overline{S}-1) \\ \alpha_0))+k((e^{m\overline{s}}\sin|\alpha_0|+\sin((2\overline{S}-1)|\alpha_0|)\end{array}} \qquad (4)$$

Acceleration expression:

$$a = 0.5me^{m\overline{s}}(p+q\cos\alpha_0+k\sin|\alpha_0|)+|\alpha_0| \qquad (5)$$
$$(q\sin((2\overline{S}-1)|\alpha_0|)+k\cos((2\overline{S}-1)\alpha_0))$$

Constant braking strength (retarding force) expression:

$$F_{fc} = A_2 + m_i(\frac{BX_0}{2} - kD\frac{1+e^m}{1-e^m}\sin|\alpha_0|+qD\cos\alpha_0) \qquad (6)$$

Downward duration:

$$v = \frac{dS}{dt} \Rightarrow dt = \frac{dS}{v} \Rightarrow t = \int_0^s\frac{dS}{v}$$

By considering the speed expression, one concludes that the downward duration $T = f(S)$ will be a transcendent equation for which a numerical solution is required. The first two parameters are given as a function of the relative distance covered, $\overline{S} = S/S_0$

S_0: Total length

For terms p, q, m, k, A_1, B and D (Appendix 1).

Appendix 1:

$$A = \frac{1}{m_i}(g(m_s+1.5m_i)\cos a_m\sin a_0 - ?gH+(m_s+0.5m_u)f_1g\sin a_m\sin a_0 - \rho gf_2.X_1 - \rho gf_2H.tga_0 - km_u\sin a_m - F_{fc}$$

$$B = \frac{1}{m_i}(2\rho g\sin\alpha_m - 2\frac{g}{X_0}(m_s+1.5m_u)\cos\alpha_m\sin\alpha_0 - \frac{2g}{X_0}(m_s-0.5m_u)f_1\sin\alpha_m\sin\alpha_0)$$

Appendix 1: Continue

$$C = \frac{1}{m_i}(g(m_s + 0.5m_u)\sin\alpha_m - (m_s + 1.5m_u)$$

$$f_1 g\cos\alpha_m + \rho g f_2(\frac{H}{\sin\alpha_0}))$$

$$D = \frac{1}{m_i}(-2\rho f_2\alpha_0 - 2\frac{f_1}{X_0}(m_s + 1.5m_u)\sin\alpha_0)$$

$$k = \frac{2R(C - 2R^2DB)}{1 + 4R^2D^2} \quad q = \frac{2R^2(B + 2CD)}{1 + 4R^2D^2} \quad m = \frac{2DX_0\alpha_0}{\sin\alpha_0}$$

$$p = \frac{A + B.a}{D} \quad A_2 = m_i A + F_{fc}$$

MODEL APPLICATION TO A DOWNWARD INSTALLATION (CASE OF OUENZA MINE)

In order to show and estimate parameters variation (speed, acceleration and constant braking strength) obtained in this theoretical analysis, the data (Appendix 2) of an Algerian mine (OUENZA) were used[4].

Appendix 2:

Difference in altitude H = 162 m	Total height X0 = 432 m
Angle of inclination am = 22 °	Payload (tons) mu = 50
Mass skip ms = 35 tonnes	Mass counterweight (tons) mc = ms + 0.5 mu = 60
Metric mass of the cable ρ = 13.65 Kg/m	Reduced mass of the system (tons) mi = 250

Five forms of the track guide-ways are considered by varying α_0 from 3 to 15° with a step of 3°.
Braking strength results $F_{fc} = f(\alpha_0)$

RESULTS AND DISCUSSION

From the diagram of speed variation shown in Fig. 4 it can be noticed that the skip downward speed takes a parabolic form with a progressive increase up to a maximum value corresponding to the medium in layout. Then speed decreases regularly up to the point of unloading where it becomes equal to 0. Thus, one obtains the automatic stop of the skip at the end of the descent $V = 0$ if $\bar{S} = 1$.

Contrary to the rectilinear track, where limited periods are located at the beginning and the end of the descent; for a curvilinear track, the transitional stage is distributed on all the cycle with a progressive reduction in acceleration until the median position of the track becomes null, then negative until the stopping of the skip at the final point Fig. 5. This shape of the transient
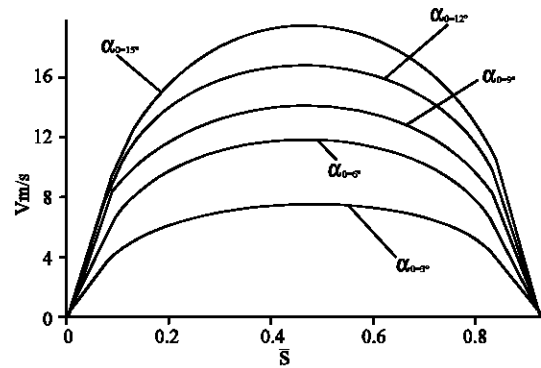

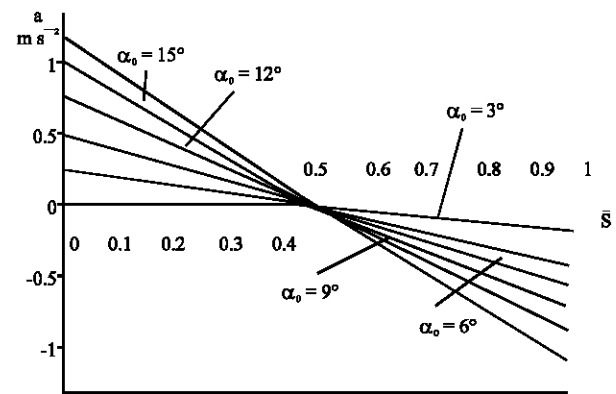Fig. 4: Diagram of speed variation for α_0 = 3 to 15°
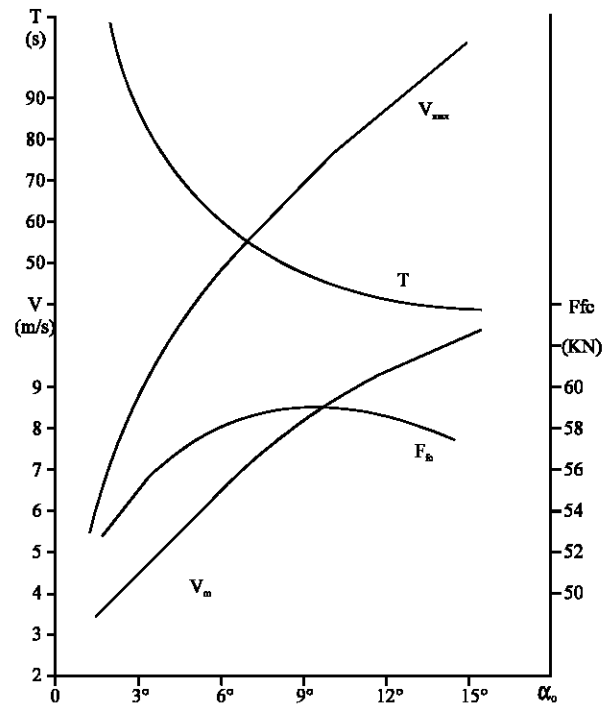

Fig. 5: Diagram of acceleration variation

Fig. 6: Diagram of parameters variation V_{max}, V_m, T and F_{fc}

movement will inevitably have a positive effect on the reliability of the installation since with blows and dynamic shocks appearing during the passage from the transient movement to the uniform movement are removed.

By considering the expressions of operation parameters before deduction, it is indicated on Fig. 6 the interval of general variation of these average parameters (speed V_m, maximum speed V_{max}, downward time T, braking force F_{fc}) according to the angle α_0 . Thus, it is noticed that for the downward installations, the angle α_0 should not exceed 15° to respect the speed limit imposed by the safety conditions[7,8].

CONCLUSION

The theoretical analysis as well as the obtained results has showed that the application of curvilinear track has many advantages such as to ensure the realization of dynamic balancing of skips downward installations. The main advantage of this solution is the progressive acceleration variation. This will improve the installation reliability by avoiding the dynamic shocks characterized by an abrupt variation of transmissible forces.

In addition, with this process, it can be obtained a flattening of transmissible efforts. Thus, in the installation of OUENZA mine, the application of a track in arc of circle where α_0 is equal to 3°, the amplitude of variation of transmissible forces decreases by 43 %.

Finally, if the variations of transmissible efforts during the cycle are attenuated, the electrical power of the group will be weaker and the utilisation ratio will be more significant. By comparing, the downward installation of OUENZA mine, the required power will be lower 22 % compared to the working installed capacity.

From this analysis and referring to integral parameters evolution Fig. 6, the limiting angle α_0 should not exceed 18° to respect the speeds imposed by Tolba and Grichko[1,7] for this type of installations.

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