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Control method for vehicles on base of natural energy recovery

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Abstract. This paper is devoted to vehicle movement control method based on the natural energy recovery [1] and position-path control approach [2,3,4]. This method ensures the fullest use of kinematic energy of the controlled vehicle. Method is applied for path profile with variable height. Vehicle velocity is changed to minimize kinematic energy losses. The time of the path passage is accounted in the designed method. In this report typical profiles of the controlled vehicle are considered. In general case the vehicle velocity program is developed on base of solutions for typical profiles. The vehicle velocity program is changing while vehicle is moving. The developed method is applied for control of trains implemented with electrical power drives. On base of train model studying it is proved that optimal mode of trains acceleration is maximal traction. The maximal traction ensures minimum energy consumption of train drives. But the traction of trains is extreme function of the speed wheel slip [5, 6]. Therefore the new extreme control for the train drives is developed. This method supports trains traction in extreme value. The developed method is implemented in simulator based on Matlab and Universal Mechanism. Movement of a freight train on a real track section is simulated.

Introduction

Usually control of vehicles movement is planned to ensure constant vehicle speed. Usually if path is not horizontal then the average speed is less than the maximal speed for the given vehicle. Due to constant vehicle speed the vehicle thrust is increased when driving on the rise. But deceleration occurs when driving downhill. Thus if assuming reduction in speed when driving on the rise then the subsequent movement downhill speed can be increased at lower energy costs. Decreasing the energy costs is able due to better utilization of the vehicle kinetic energy.

Energy Saving Movement Planning

Consider the quantitative relations, which can occur when the natural recovery. Let us consider energy effect from the natural recovery.

Assume that path profile is known. For example consider the path profile from point *A* to point *B* shown on fig. 1. There is a hill on the way from point A to point B. Parameters of the hill are altitude h_1 *m*, and altitude h_2 *m*. The main peculiarity of the hill is $h_2 < h_1$. The rest of the path is horizontal. Assume that average vehicle speed V_0 is known. Average vehicle speed V_0 is calculated on base of traveling time from point A to point B.

It is necessary to calculate speed V2, speed V3, distance Sy, and acceleration α. For the given profile we obtain

$$V_2 = \sqrt{V_0^2 - 2gh_1}\,. \tag{1}$$

$$0{,}5mV_0^2 - mgh_1 > 0\,. \tag{2}$$

$$V_3 = \sqrt{V_0^2 - 2gh_2}\ . \tag{3}$$

$$S_y = \frac{1}{(V_0 - V_3)}\left[V_0(2S_3 - S_1 - S_2) - V_2(S_3 - S_1) - V_3(S_3 - S_2)\right]. \tag{4}$$

$$\alpha = \frac{1}{2S_y}[3V_0^2 - 4V_0V_3 + V_3^2]\ . \tag{5}$$

Herein g is gravity acceleration, m is a mass of vehicle.

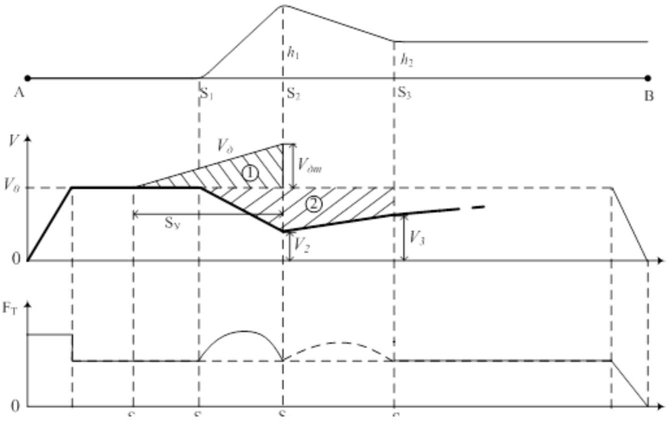

Fig. 1 Path profile, speed, and thrust of vehicle

Similar expressions are obtained for other profiles.

Consider the next example: S1=2000 m, S2=2300 m, S3=2500 m, h1=20 m, h2=12 m, V0=25 m/s, g=10 m/s^2. It is necessary to calculate distance Sy, and acceleration α so that both average vehicle speed as well as vehicle speed at point S3 are equal to V0.

1. From expression (1) and (3) we obtain: V2 = 15 m/s, V3=19,62 m/s. Thus vehicle speed decreasing is V0-V3=5,38 m/s.
2. From (4) we obtain distance Sy=1129 m.
3. From (5) we obtain the acceleration required 0,131 m/s^2.
4. Therefore the point of vehicle acceleration start is: Soa=S2-Sy=2300-1129=1171 m.

Thus to maintain the given average vehicle speed it is necessary for the point Soa increase thrust to give the vehicle acceleration equal 0,131 m/s^2. This acceleration is constant from point Soa to point S2. At the the top of the hill a vehicle thrust is reduced to the value given by movement on the horizontal path with speed 25 m/s.

Let us evaluate energy saving followed from vehicle moving with variable speed.

If vehicle speed is constant for path presented on the fig. 1, then additional energy for vehicle climbing to 20 meters is

$$E_{12}=mgh_1= 200m\ Nm. \tag{6}$$

In addition the energy required to braking vehicle is

$$E_{23} = mg(h_1-h_2) = 80m\ Nm. \tag{7}$$

Assume that 50 % of this energy is provided by the work of the motion resistance forces. Another 50 % of this energy is provided by active breaking. Therefore the complete additional energy costs for the given example is 240m Nm.

If vehicle speed is variable for path presented on the fig. 1, then additional energy for vehicle climbing to 20 meters is

$$Ead=mgh_2=120m\ Nm. \tag{8}$$

Thus energy efficiency of the developed method for the given example is

$$\eta_{эк} = \frac{240m - 120m}{240m} = \frac{120}{240} = 0{,}5\,. \tag{9}$$

Extreme Control for Electrical Traction Train

On the base of proposed method it is possible to develop power saving control system for electrical traction train.

Consider the equation of train movement

$$\dot{V}_{tr} = \left(F_{trac} - F_{mr0} - F_{mr1}V_{tr} - F_{mr2}V_{tr}^2\right)/\,m\,. \tag{10}$$

Herein F_{mr0}, F_{mr1}, F_{mr2} are constants depending from train parameters and weight, F_{trac} is traction of train, V_{tr} is speed of train.

A first approximation of a train resistance force is quadratic function of train speed. This force is [1]:

$$F_{mr}(V_{tr}) = F_{mr0} + F_{mr1}V_{tr} + F_{mr2}(V_{tr})^2\,. \tag{11}$$

If train traction is constant then train speed for horizontal path in the steady state mode is

$$V_{tr}^{*} = \frac{F_{mr1}}{2F_{\mathrm{mr2}}}\left(-1 + \sqrt{1 + \frac{4F_{\mathrm{mr2}}}{F_{\mathrm{mr1}}^2}(F_{\mathrm{trac,max}} - F_{\mathrm{mr0}})}\right). \tag{12}$$

From (12) it is clear that train speed in the steady state mode is determined by the difference between the maximum possible traction force $F_{\mathrm{trac,max}}$ and the trait moving off resistance force F_{mr0}.

If F_{trac} is constant then equation (7) takes the form

$$\dot{V}_{\mathrm{tr}} = f(V_{\mathrm{tr}})^2 + gV_{\mathrm{tr}} + h\,. \tag{13}$$

Herein $f = -F_{\mathrm{mr2}}/m$, $g = -F_{\mathrm{mr1}}/m$, $h = (F_{trac} - F_{mr0})/m$ are constant.

Equation (8) is Riccati equation. If $f \neq 0$ then for constant coefficients solution of equation (8) is:

$$V_{tr}(t) = \frac{C[\exp(p_2 t) - \exp(-\overline{p}_1 t)]}{[C_1\exp(-\overline{p}_1 t) + C_2\exp(p_2 t)]}\,. \tag{14}$$

Herein $C = \frac{F_{\mathrm{mr1}}}{4F_{mr2}}\frac{a}{\sqrt{1+a}}$, $\overline{p}_1 = F_{\mathrm{mr1}}(1+\sqrt{1+a})/2m$, $p_2 = F_{\mathrm{mr1}}(-1+\sqrt{1+a})/2m$, $a = 4F_{\mathrm{mr2}}(F_{trac} - F_{\mathrm{mr0}})/F_{\mathrm{mr1}}^2$.

From investigation of solution (14) it is clear that for constant traction train energy costs is

$$Q_c(V_{\mathrm{c,tr}}) = \frac{F_{\mathrm{trac}}\,mV_{\mathrm{c,tr}}^2}{2(F_{\mathrm{trac}} - F_{\mathrm{mr0}})} = \frac{mV_{\mathrm{c,tr}}^2}{2}\left(1 + \frac{F_{\mathrm{mr0}}}{F_{\mathrm{trac}} - F_{\mathrm{mr0}}}\right). \tag{15}$$

From (10) it is clear that the most power saving acceleration of train is the acceleration by maximal traction. In other side traction of train is linear function of the friction coefficient $k_{\mathrm{fr}}(V_{\mathrm{sl}})$. But $k_{\mathrm{fr}}(V_{\mathrm{sl}})$ is extreme function of slipping speed V_{sl}. Maximum of the adhesion force is corresponding to optimal value of slipping speed V_{sl}. Thus the most power saving mode oft rain acceleration is acceleration with optimal slipping speed V_{sl}^{*}.

Necessary condition of the adhesion force F_{ad} extreme value is

$$dF_{\mathrm{ad}} / dV_{sl} = 0 . \tag{16}$$

Extreme value of the slipping speed V^*_{sl} can be calculated on base of measuring the acceleration of train wheels, acceleration of train, and the time rate of change of the traction motor. But errors of train wheels acceleration $\dot{\omega}_{wh}$, acceleration of train $\dot{V}_{tr}$, and the time rate of change of the traction motor $\dot{M}_{dr}$ calculation cause unacceptable large error of the derivative $\dot{V}_{\mathrm{sl}}$ calculation. Practically the errors of measurements do not allow calculate value of V^*_{sl} correctly.

Therefore to calculate the extreme value of F_{ad} we used method based on comparison differences of the extreme function with its argument [7].

In the developed train control system the rising differences are used. These rising differences are

$$\Delta F_{\mathrm{ad},k} = F_{\mathrm{ad},k} - F_{\mathrm{ad},k-1} . \tag{17}$$

$$\Delta V_{\mathrm{sl},k} = V_{\mathrm{sl},k} - V_{\mathrm{sl},k-1} . \tag{18}$$

Symbol k is discrete time. Symbol k^* is time of the maximal value $F_{ad,\max}$ of the adhesion force F_{ad}. If $k \le k^*$ then sign of the difference $\Delta F_{\mathrm{ad},k}$ (17) and sign of the difference $\Delta V_{\mathrm{sl},k}$ (18) are same. If $k > k^*$ then sign of the difference $\Delta F_{\mathrm{ad},k}$ (17) and sign of the difference $\Delta V_{\mathrm{sl},k}$ (18) are different. In other words slipping speed is optimal if product $\Delta F_{\mathrm{ad},k} \cdot \Delta V_{\mathrm{sl},k}$ changes sign.

Therefore we can propose the new method of detecting and supporting the extreme value of train slipping speed. Assume that train is moving due to initial voltage applied to motors. Control system measures slip speed and adhesion force and calculates differences $\Delta F_{\mathrm{ad},k}$ (17) and $\Delta V_{\mathrm{sl},k}$ (18). Extreme algorithm starts from time k_s. The extreme algorithm is:

$$u_{\mathrm{m},k} = u_{\mathrm{m},k-1} + u_\Delta \mathrm{sign}\,(\Delta F_{\mathrm{ad},k-1}) \cdot \mathrm{sign}\,(\Delta V_{\mathrm{sl},k-1}) , \; k = k_s, k_s + 1, k_s + 2, \; \dots . \tag{19}$$

Herein u_Δ is positive constant (trial motion). Usually value of the trial motion u_Δ is determined by experiments.

The effectiveness of this method was carried out by computer simulation equations trains in MATLAB. To reduce the time slicing effect we used averaged over several periods of the variables.

On fig. 2 we can see graph of voltage on the test locomotive engines. On fig. 3 we can see graph of slip speed on the test locomotive. On fig. 2 and fig. 3 the trial motions are shown good. The trial motions are changing the voltage on the motor and changing the slip speed. From fig. 3 it is clear that the slip speed first is approaching the optimal value. Thereafter the slip speed is oscillating in the neighborhood of the optimal value.

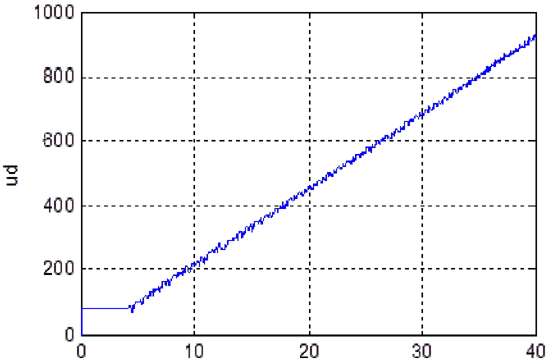

Fig. 2 Graph of voltage

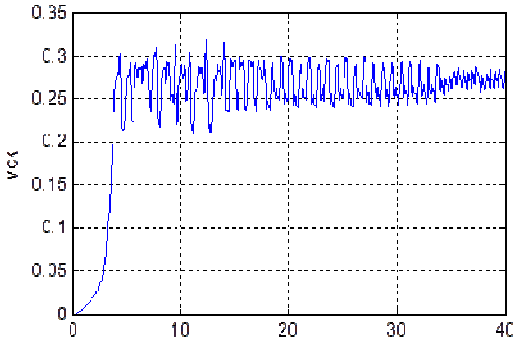

Fig. 3 Graph of slip speed

Simulation Complex

Simulation complex is based on complex for modeling and trials used at [2, 3, 8, 9, 10, 11]. This complex was adapted by including program "Universal Mechanism". Universal Mechanism allows modeling detiled mechanics of trains. The block diagram of the developed complex is presented on fig. 4.

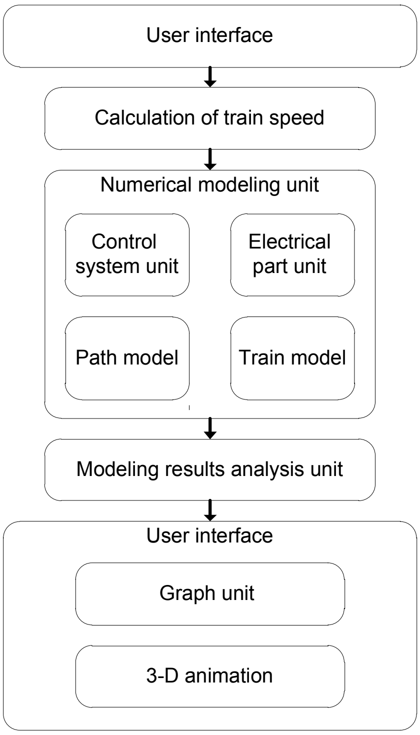

Fig. 4 Block diagram of the modeling complex

On base of presented on fig. 4 complex energy effectiveness of the proposed method is checked. On fig. 5 profile of section from 1785 km to 1777 km of path Tuapse – Armavir is shown. The section length is about 8 km. The maximal train speed is 47 km/h.

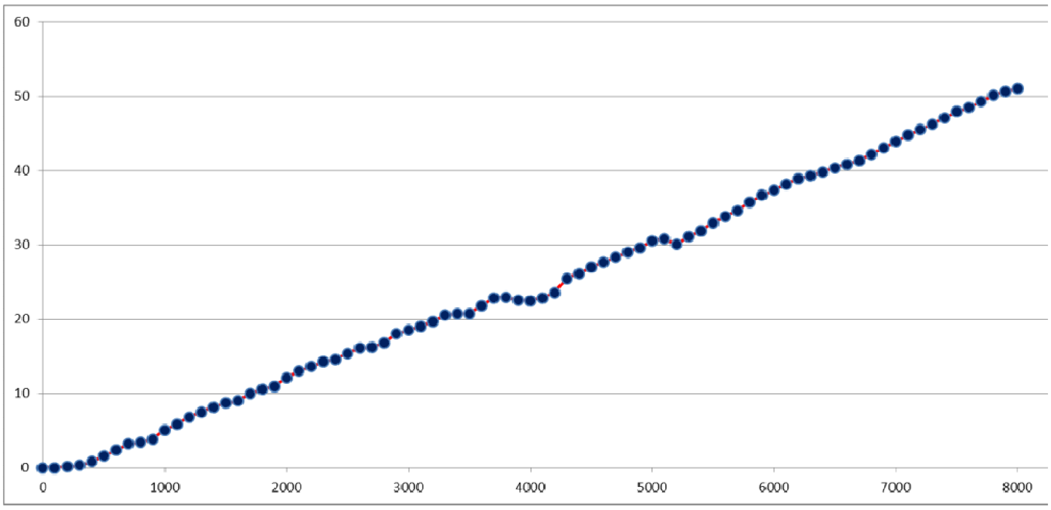

Fig. 5 Profile of the path section

For the given path profile energy effect of the developed method is about 5 %. If path profile consists of hills and dells, then power saving effect increases.

Summary

Proposed method can be used for another types of vehicles because dynamics model of the vehicles is not used to calculate speed reference. But it is necessary account peculiarities of the vehicle. For example power saving control of airship needs model of aerodynamics and wind model. [12, 13]. If we have detailed information about vehicle model, then position path adaptive or robust control can be used [4, 14].

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