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PECULIARITIES OF MOVEMENT SIMULATION OF ELECTRIC VEHICLE TAKING INTO CONSIDERATION THE DEPENDENCE OF LOADING ON RELIEF

There had been shown the reason why the known methods for optimization of movement of electric vehicle under loading, depending on relief, on which the railway in tracked, cannot be applied for solution of specific practical tasks. There had been suggested the method for simulation of such vehicles, suitable for solution of practical tasks of optimization of their movement.

***Key word**: simulation, optimization, electric vehicle, railway track, relief.*

Task setting and initial background

Optimization tasks from vehicles, moving within significant time duration, have to be solved under conditions of dependence of motion path on relief. Fig. 1 shows one of possible paths of such a motion from point A, where vehicle starts moving in time t_A, to the point B, to which this vehicle arrives according to schedule in time t_B. This figure also shows the path projecting of movement on coordinate space x Oy and x Oz. the figure shows that from point A to point B there is a down line, from point C to point D there is a curved track in horizontal plane, from point D to point M – straight up line, from point M to point N there is a curved track in horizontal plane and from point N to point B the movement continues in horizontal plain but on the straight line.

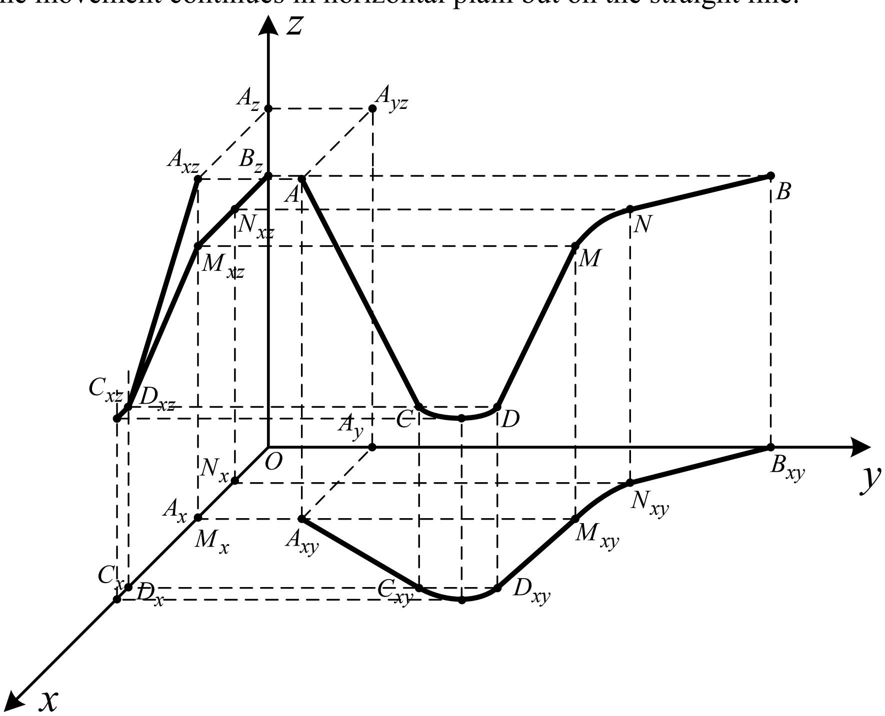

Fig.1. Example of motion path of vehicle on the road with complex relief

The member of works, for example [1], describe the approach to the solution of such class of optimization tasks using mathematical model of vehicle motion in the form of the second Newton's law, that is, in the form

$$m\frac{d^2l(t)}{dt^2} = F_T(t) - F_\Gamma(l,t), \tag{1}$$

where m – mass of vehicle, $l(t)$ – length of way, covered by vehicle from the beginning of motion, which depends on time t, and $F_T(t)$, $F_\Gamma(t)$ – correspondingly, vehicle tractive force and braking force, influencing the vehicle at the time of movement.

However, as we realized during the attempt of using this approach for solution of specific optimizational task, it is not efficient, since first, braking force is not constant even during the movement on horizontal plane, because any drag and tangential air resistance depend on speed $v(t)$ of vehicle movement, that is

$$F_\Gamma(l,t) = \mu_0(l,t) + \mu_1(l,t)\cdot v(l,t) + \mu_2(l,t)\cdot\left(v(l,t)\right)^2, \tag{2}$$

Second, the value of braking force only depends on whether the vehicle moves on horizontal plane or slopes up or down, and third, the travelled path, with the availability of road length rises, falling gradients and turns, becomes function of rectangular coordinates x, y, z (fig. 1), which, with their approximation by type-dimension function

$$\begin{cases} x(t) = x_a f_x(t), \\ y(t) = y_a f_y(t), \\ z(t) = z_a f_z(t) \end{cases} \tag{3}$$

leads to the appearance of non-linear dependences from their derivatives in expressions, which simulate the travelled, since

$$dl = \sqrt{(dx)^2 + (dy)^2 + (dz)^2} = \sqrt{\left(x_a \frac{df_x}{dt}\right)^2 + \left(y_a \frac{df_y}{dt}\right)^2 + \left(z_a \frac{df_z}{dt}\right)^2}\, dt, \tag{4}$$

$$l(t) = \int_{t_A}^{t} \sqrt{\left(x_a \frac{df_x}{d\tau}\right)^2 + \left(y_a \frac{df_y}{d\tau}\right)^2 + \left(z_a \frac{df_z}{d\tau}\right)^2}\, d\tau, \tag{5}$$

$$\frac{d^2 l}{dt^2} = \frac{x_a^2 \frac{df_x}{dt}\cdot\frac{d^2 f_x}{dt^2} + y_a^2 \frac{df_y}{dt}\cdot\frac{d^2 f_y}{dt^2} + z_a^2 \frac{df_z}{dt}\cdot\frac{d^2 f_z}{dt^2}}{\sqrt{\left(x_a \frac{df_x}{dt}\right)^2 + \left(y_a \frac{df_y}{dt}\right)^2 + \left(z_a \frac{df_z}{dt}\right)^2}}. \tag{6}$$

It is quite obvious that movement optimization according the electric energy E minimum-cost criterion by electric locomotive, which receives voltage $u(t)$ from contact system, creating current $i(t)$, that is, according to the minimum criterion of an expression

$$E = \int_{t_A}^{t_B} u(t) i(t) dt, \tag{7}$$

suggested in work [2], on condition of movement program run between stops in points A and B (fig. 1)

$$l_{AB} = \int_{t_A}^{t_B} v(x, y, z, t) dt \tag{8}$$

and restrictions (1), which use the correlation (2) – (6), is impossible to perform the way, which will allow to build analytical mathematical model for current $i(t)$ of electric locomotive drive, which insures minimum of criterion (7) during program run (8). It is also impossible to build the analytical model for this current with the use of models of dynamic of electric train as presented in works [3, 4]. Therefore the paper is aimed at searching for an approach which will allow to build the above analytical mathematical model.

Solution of the task

It is known from the departmental procedure for railway road laying on surfaces with complex relief, that railroad specialists have to lay the curved track on horizontal surfaces and make as falling gradient as well as rise of road of rectilinear. Operating rules for railway vehicle require steady speed for curved track, the value of which ensures no derailed carriage as well as their no-capsizing. Consequently, relying on these rules and methods, allows to state that the decomposition of task of movement optimization of railway vehicle on surface with complex relief into the totality of sub-tasks for optimization of this vehicle's movement on rectilinear horizontal sections (section NB on fig. 1), on curves in horizontal planes (arcs MN and CD on fig. 1), on rectilinear rise of road (section DM on fig. 1) and rectilinear falling gradient (section AC on fig. 1) is expedient, applying at the same time the conditions of uniformity of those values of movement parameters in points of detachments of the specified sections and arcs, which ensure not only the smoothness of movement path from the initial (point A on fig. 1) to the terminal (point B on fig. 1) station, but smoothness of curves, reflecting the timetable of movement rate of vehicle from point A to point B, since the noticeable linear dimensions, of vehicle and the availability of minimum two wheel pairs make if impossible the appearance of breaking points on continues path of its movement, and noticeable mass makes the jumping change of its speed impossible.

It is known that function is called a smooth one when it is a continuous function with the continuous first derivative. Therefore the mechanical trajectory of vehicle will be a smooth function only when its first derivative, that is the rate of movement, will represent the continuous function. In its turn, rate of movement of vehicle will be a smooth function only when its first derivative, that is the acceleration, will also represent the continuous function.

Therefore, the smoothness conditions for the mechanical trajectory from point A to point B, presented on fig.1, will be the fulfillment of correlations:

$$\begin{cases} v_{AC}(C) = v_{CD}(C); \\ v_{CD}(D) = v_{DM}(D); \\ v_{DM}(M) = v_{MN}(M); \\ v_{MN}(N) = v_{NB}(N), \end{cases} \tag{9}$$

in which the double lower index near the symbol of speed indicate the section of the trajectory, the vehicle approaches to the point, indicate in brackets, vehicle movement rate smoothness on this trajectory will be the fulfillment of correlations:

$$\begin{cases} \dfrac{dv_{AC}}{dt}(C) = \dfrac{dv_{CD}}{dt}(C); \\ \dfrac{dv_{CD}}{dt}(D) = \dfrac{dv_{DM}}{dt}(D); \\ \dfrac{dv_{DM}}{dt}(M) = \dfrac{dv_{MN}}{dt}(M); \\ \dfrac{dv_{MN}}{dt}(N) = \dfrac{dv_{NB}}{dt}(N), \end{cases} \tag{10}$$

which adopt the same symbolism relating to derivatives of speed.

Since the unique determination of mechanical trajectory requires setting its value on boundaries of movement section, the correlations (9), (10) need to be supplement with correlations:

$$\begin{cases} v(A) = v_A; \\ v_{NB}(B) = v_B \end{cases} \tag{11}$$

– for speeds, in which v_A, v_B are their specified numerical values, and with correlations:

$$\begin{cases} \frac{dv}{dt}(A) = v_A^1; \\ \frac{dv_{NB}}{dt}(B) = v_B^1 \end{cases} \tag{12}$$

– for accelerations, in which v_A^1, v_B^1 are also their specified numerical values.

For the unification of further considerations, we specify the places for location of points A and B. For inland railway electric trains these points are easy to locate in places with signal posts. Point A we will place on departure signal post of the initial station and time reading t_A we will begin at the moment of passing the signal post by the last carriage of electric train. Point B we will place on the entras signal post of the last station and time reading t_B we will begin at the moment of meeting the signal post by the body end of the towing electric locomotive. As for the underground electric trains and overground city trams, the point A we will connect to the initial cut of the platform and time t_A we will begin at the moment of passing the outgoing cut of the platform by the end of the last carriage, and point B we will connect to the entrance cut of the last platform. The time reading t_B we will begin at the last platform by the body end of the first carriage.

It follows from the above that the task of optimization of electric train movement from the initial station to the final one, formulated for the general case of mechanical trajectory, presented on fig. 1, is expedient to solve by optimization of movement on separate sections of the way (AC, CD, DM, MN, NB) on condition of satisfying the limits (9) – (12). The solution of this task to begin with the optimization of movement on curved tracks (CD, MN), reasoning from the fact, that the main criterion of optimality during the movement of electric vehicle on curved track, placed on the horizontal plane, is the reserve of no-derailing, which is ensured by no-overspeeding the admissible speed value by this vehicle, which is determined by derailing conditions of the carriage with the highest center of mass which is indistinctly defined. Therefore, considering, that the curved tracks should be passed by electric vehicles with constant speed, we find on this stage the specific values of restrictions (9), (10), and it is quite obvious that the speeds in the determined points will be constant and accelerations-zero.

The second stage in solution of the set task is to determine the restrictions (11), (12). It is also necessary to take into account the fact that speed and acceleration of electric vehicle on the signal post of the initial station are set by its processing, and speed and acceleration of this very vehicle on the signal post of the station shall be determined from the dynamic equation on condition of its halting on the specific length of the platform.

The third stage solves the task of optimization of electric vehicle movement on straightway (NB), tracked on horizontal plane. Thereby, instead of restrictions (1), (2), (8), it is possible to use more simple ones:

$$m\frac{d\ v(t)}{dt} = F_T(t) - F_\Gamma(v,t), \tag{13}$$

$$F_\Gamma(v,t) = \mu_0 + \mu_1 v(t) + \mu_2 (v(t))^2, \tag{14}$$

$$l_{NB} = \int_{t_N}^{t_B} v(t)\, dt. \tag{15}$$

The fourth stage selves task of optimization of electric vehicle movement during its downward journey (straightway section AC) and during its upward journey (straightway section DM).

In this case, what concerns the tractive and braking force in models (13), (14), it is necessary to consider all those peculiarities, which are disclosed in work [4], and restriction (15) shall se formed as:

$$l_{AC} = \int_{t_A}^{t_C} v(x_A, x_C, y_A, y_C, z_A, z_C, t)\, dt\,, \tag{16}$$

$$l_{DM} = \int_{t_D}^{t_M} v(x_D, x_M, y_D, y_M, z_D, z_M, t)\, dt\,, \tag{17}$$

where Cartesian coordinates of final points set the length of the corresponding way section in space.

Conclusions

1. There had been shown why the known methods for optimization of electric vehicle movement with loading, depending on relief on which the railway is tracked, cannot be applied for the solution of specific practical tasks.

2. There had been suggest an approach to the simulation of movement of electric vehicle, fit for solution of practical task of improvement optimization, based on decomposition of movement optimization task along the whole trajectory into the aggregate of subtasks of movement optimization on sections, limited by points of mode change.

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