Research of Mathematical Model of Movement of Six-Axle Locomotives with Controllable Wheelsets Installation

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Abstract

Research of mathematical model of movement of six-axial locomotive with controllable wheelsets installation. Based on the general system of nonlinear variable coefficient differential equations of the vehicle movement in a rail track with inequalities in plan, the mathematical model of movement dynamics of locomotive of improved design with the axial formula 3_0-3_0 as an object of automatic control of the wheelsets position in the rail track is considered. Movement simulation is performed on the example of a six-axle locomotive at the speeds of movement and parameters of the curvilinear track sections, which coincide with the conditions of the experiment presented in the thesis work of V. N. Yazykov. The article presents research results of the mathematical model of movement of the improved locomotive bogie with controllable wheelsets installation in the curvilinear track sections using the Matlab/Simulink software package. The results of experimental studies of the All-Russian Scientific-Research and Design Technological Institute of Rolling Stock and the performed theoretical studies show that the efficiency of the improved system for controlling the wheelset position is higher than that of the serial design, in all modes of movement. The improved system of automatic control of wheelsets position makes it possible to reduce guiding forces by 35%. The possibility of using the mathematical model of locomotive movement of the axial formula 3_0-3_0 of improved bogie design with axle-box links of adjustable length, taking into account the dynamics of the automatic control system of the wheelsets installation in the rail track, is theoretically substantiated. The theoretical research found out the reduction of lateral forces in the improved bogie design during the passage of curvilinear track sections. The use of the explored mathematical model of locomotive movement reduces the volume and complexity of research works, as well as increases the reliability of engineering calculations when designing new and improving existing designs of the locomotive underframe.

Keywords: *mathematical model, dynamics, curvilinear track section, radial installation, wheelset, controllable movement, numerical methods.*

1. Introduction

In modern operating conditions of the existing rolling stock there is a problem of intensive tread reduction of wheelsets, which is related to the force interaction of the wheel and the rail, especially in the curvilinear track sections. Speed increase of the railway rolling stock increases the dynamic component of the forces acting in the wheel-rail system, which leads to unproductive energy consumption for traction and premature wear of the running gear of locomotive and rail track [1]. In this regard, the task is to reduce the force action of the wheel tread on the rail, the wear of wheels and rails, as well as to ensure the movement safety and stability.

Theoretical studies and practice of domestic and foreign experience have established that 80% of the causes of tread damage are due to imperfect design of rolling stock and about 20% – for the reasons dependent on the track condition.

Dynamic properties of a vehicle in the horizontal plane and side wear of the wheel flange and rail head depend on the wheel climbing angle on the rail, condition of the locomotive underframe, which can be effectively influenced by automatic control of the wheel movement process. Bogies with passive installation of the wheelsets are subjected to increased undulatory movement in the straight track sections and do not allow wheelset to turn in horizontal plane when passing the curvilinear track sections [2, 3, 4–7].

2. Problem statement

In modern operating conditions of the existing rolling stock there is a problem of intensive tread reduction of wheelsets, which is related to the force interaction of the wheel and rail, especially in the curvilinear track sections. This results in the increased costs for repair and maintenance of locomotives and track.

Solution of this problem is connected with the creation and research of fundamentally new vehicle designs.

3. Analysis of research and publications

The promising direction of reducing the force interaction of wheel and rail and, as a consequence, of reducing the intense wear in the wheel-rail system is the application of rational designs of locomotive underframe, completed by a system of active control of the wheelsets` turning in the horizontal plane when moving in the curvilinear track sections [8–11].

4. Purpose

The article is aimed at theoretical investigation of the dynamic processes occurring in the mechanical part of the improved bogie of the locomotive and the wheel-rail contact when passing the curvilinear track section.

5. Methodology

Movement simulation is performed using the example of six-axle locomotive at the speeds of movement and parameters of the curvilinear track sections, which coincide with the conditions of the experiment presented in the thesis work of V. N. Yazykov [12].

6. Main material

The modern approach to the development of any technical system with a mechanical part involves performing theoretical studies of its behavior in the conditions close to the real ones. The most commonly used research method at the stage of designing a system or machine is the computer simulation method. The basis of this method is a mathematical model and software tools. The software complex, developed on the basis of the proposed models and algorithms, makes it possible to conduct research of the railway vehicle dynamics when moving in the track of arbitrary profile. The study of dynamic processes of curve negotiation is of significant interest. Using the developed computer model of the six-axle locomotive movement, the calculations on curve negotiation were made.

According to the mathematical model, the research of dynamic processes was carried out both during controllable and uncontrollable curve negotiation of the diesel locomotive and the results reliability was assessed.

During the tests, a number of parameters were measured, of which the value of the frame and side forces when passing a curved track sections are of interest. Frame forces were determined by the transverse displacements of the box relative to the bogie frames, which were multiplied by the rigidity of the transverse connection of the box with the bogie frame. The rigidity of transverse connection was determined by the calibration. Friction forces of the bearings were excluded.

The task of studying the locomotive dynamics in a full spatial position when moving along the curvilinear track sections requires the creation of the complex mathematical model. Necessary mathematical apparatus includes positions of analytical and differential geometry, mathematical analysis, differential equations, numerical methods for solving the systems of differential, differential-algebraic, non-linear, and linear algebraic equations.

The mathematical model of the six-axle vehicle movement is considered using the example of the locomotive 2TE116.

The underframe of the locomotive 2TE116 (axial formula $2(3_0–3_0)$ consists of four three-axle bogies. Each wheelset is with motor. The springing is individual. In the axle box stage of spring suspension, four spring kits and two friction dampers as oscillation damper were applied for each axle box. The jawless type of axle box is connected to the bogie frame with the help of axle-box link located skew-symmetrically. The axle-box links are equipped with joints with rubber-metal elements, allowing elastic vertical and transverse displacements of the boxes.

During simulation, underframe of the locomotive 2TE116 is represented as a nonlinear mechanical system consisting of solid bodies, connected by joints or elastic elements, with which the oscillation dampers of viscous or dry friction are paralleled.

The rail track is considered as two beams lying on a homogeneous elastic base; in the transverse direction the rails are presented as a spring with viscous friction. It is considered that the load, evenly moving along one of the rail beams, does not affect the other and the rail deformation under adjacent wheels; reciprocal displacements of rails and bases, as well as their longitudinal displacements are absent. The track weight is reduced to the wheel in the area of its contact with the rail. By the moment of the flange contact with the side edge of the rail, the transverse component of the friction force in the wheel and rail contact does not cause rail displacement. Such assumptions simplify solution of the problem without significant loss of the calculation accuracy.

It is assumed that the position of the mass centers of locomotive elements does not depend on the oscillations of the sprung parts, the load is evenly distributed on the wheels, the profile contour form of all the treads is the same, and the forces of traction or braking are constant at a given movement speed.

Elastic and dissipative elements are taken as weightless. When setting the elastic-dissipative parameters, the following assumptions were taken: the body pivots are elastically connected with the bogie frames in the longitudinal direction. For the description of the dissipative properties of the rubber body mounts, a linear model of viscous friction was taken. The friction of friction dampers of the axle-box suspension and the traction motors` noses along the crossbar of the elastic suspension is described by the Coulomb model.

When describing the macrogeometry of the rail track, the ratios of differential geometry are used. The random vertical and horizontal inequalities of the rails are imposed on the ideal track geometry. The model of force interactions in the wheel-rail contact is based on the nonlinear theory of the Kalker`s creep.

The friction forces at the contact points of the wheel and rail are determined as the forces of dry friction, they are constant when moving in the curvilinear track section.

The proposed improved bogie design and the automatic control system (ACS) for the wheelset installation is presented in the works [13, 14].

The system of automatic control of the wheelset position contains the control object, the measuring block, the computing device and the actuating unit.

The climbing angle is measured by the method of acoustic emission. The sound intensity is determined by microphones, and the speed of the locomotive by the tachometers installed on the bearing bodies of the traction gearbox. Parameters of the curved track section are determined by the track model based on the data of the GPS-receiver.

The functions of the control device include the processing of information coming from the microphones, tachometers and the GPS-receiver, forming a controlling influence of the regulator, which is fed to the actuating unit.

The controlling influence of the regulator is formed taking into account the undamped centrifugal acceleration of the locomotive movement and the direction of its turning in the track section. The climbing angle is controlled by the actuating unit through the corresponding rod movement.

The actuating unit with the help of power cylinders pivotally connects the axes that do not turn with the bogie frame and the body. As a source of energy, it is proposed to use a pneumatic reservoir of the brake system of the locomotive connected to the actuating unit by means of pipelines equipped with adjustable electromagnetic valves. Pneumatic cylinder was selected as the actuating mechanism of this unit. Hydraulic cylinders are installed on the last wheelsets of the bogie.

Determination of the climbing angle of the wheel on the rail is performed by processing the acoustic signal arising in the wheel-rail contact, the processing algorithm of which is given in the work [14].

Based on the general system of nonlinear variable coefficient differential equations of the vehicle movement in the track with inequalities in plan, the mathematical model of movement dynamics of locomotive of improved design with the axial formula 30-30 as an object of automatic control of the wheelsets position in the rail track is considered. The mathematical model of the locomotive movement with the axial formula 3_0-3_0, proposed in the works [8, 15, 16], is taken as the basis.

The modes of locomotive movement with constant speed are studied; it is considered the steady movement of a vehicle at constant curvilinearity value and the superelevation of the outer rail: the track has geometric inequalities in the rails in plan, which are set according to the recommended real random disturbances from the rail track [12, 17–19].

According to the Lagrange algorithm of the second kind, the operations of differentiation of the expressions for the kinetic, potential energies and the energy dissipation function of the system are carried out.

Given that the solution of the problem in the time domain entails a large amount of calculations when integrating differential equations, the Runge-Kutta integration algorithm of the fourth order with a variable step of integration is used.

In the process of modeling to determine the radius of the curvilinear track section, the following dependence was used:

$$1/R = \Omega/V, \tag{1}$$

where R – is the radius of the curvilinear track section; Ω – is the angular speed of the bogie frame turn; V – is the linear speed of locomotive.

Inertial properties of the vehicle with such a system of radial installation of wheelsets (RIWS) do not change, that is, the matrix of inertial coefficients of the model varies according to the determined turning angle of the wheelset. In the basic mathematical model [8] the equations describing the hunting of the wheel-motor blocks are changed:

$$I_{ijZ} = \ddot{\varphi} + I_{ijZ}\ddot{\varphi}_i + I_{ijZ}\ddot{\varphi}_{ij} = -K_{Б\xi}(y_{Бij}^2 - y_{ij}y_{Бij})\varphi_{ij} + M_{Tij} + M_{ij}pg, \tag{2}$$

where I – are the main central moments of inertia of these masses; i – is the bogie number; j – is the wheelset number; z – is the number of the wheel-motor block; $\ddot{\varphi}_{ij}$ – is the turning angle of the i-th wheelset of the j-th bogie relative to the body; $K_{Б\xi}$ – is the rigidity coefficient and damping in the longitudinal direction; $y_{Бij}$ – is the distance from the bogie axle to the oscillation dampers; y_{ij} – is the distance from the bogie axle to the wheelset axle; M_{Tij} – is the moment of forces in the wheels and rails contact; M_{ij} – is the weight of the wheel-motor block; p – is the vector projection of instantaneous angular velocity; g – is the gravitation acceleration.

The functional dependence of the turning angle of the wheelset relative to the bogie, depending on the parameters of the actuating unit, is substituted in the mathematical model of the movement of the improved six-axle railway vehicle.

The functional dependence of the turning angle of the wheelset relative to the bogie, according to the ACS installation of the wheelset in the railway track, has the form:

$$a_3\frac{d^3\varphi_{ij}}{dt^3} + a_2\frac{d^2\varphi_{ij}}{dt^2} + a_1\frac{d\varphi_{ij}}{dt} + \varphi_{ij} = a_1\frac{dM(t)}{dt} + M(t); \tag{3}$$

$$a_3 = \frac{T_1T^2}{k_2k_3k_5};\ a_2 = \frac{2\xi T_1T}{k_2k_3k_5};\ a_1 = \frac{k_4}{k_3};\ T = \sqrt{\frac{J}{c}};\ \xi = \frac{b}{2\cdot c};\ k_5 = \frac{M_н - M_с}{c},$$

where J – is the inertia moment of the wheelset; c, b – are the elastic and dissipative components of the springing; $M_н$ – is the moment of external load; $M_с$ – is the moment of friction when turning the wheelset; $M(t)$ – is the difference between the moment of friction when turning the wheelset and the moment of external load; k_2 – is the coefficient of the sensor transmission; k_3, k_5 – is the coefficient of the regulator transmission; T_1 – is the time constant; ξ – is the constant of spring suspension.

The sequence of movement in track sections is as follows: straight track section, incoming transition curve, arc of radius circle, outgoing transition curve, and straight track section. Superelevation in the transition curve varies according to the linear law.

The length of the original straight track section was taken equal to 100 m, the length of the transition curves is 75 m, and the length of the curve arc of the constant radius is 300 m.

Transverse elasticity of the rail is taken as a constant value.

In the second case, the movement in the track with inequalities is considered. Vertical and horizontal inequalities of the track were constructed in accordance with the methodology of simulation of random disturbances in the railway vehicle-track system.

As a result of movement simulation of the 2TE116 locomotive`s bogie of the serial production and the improved system in the Matlab/Simulink package, the results are shown in Fig. 1, 2.

7. Findings

The comparison of the values of the frame and lateral forces obtained as a result of calculations and measured during the tests makes it possible to conclude that the presented mathematical model of the mechanical part of the locomotive 2TE116 provides reliable results. It can be used for further study of dynamic processes during movement in the curvilinear track sections.

The results of experimental studies of the All-Russian Scientific-Research and Design Technological Institute of Rolling Stock and the performed theoretical studies show that the efficiency of the improved system for controlling the wheelset position is higher than that of the serial design, in all modes of movement. The improved system of automatic control of wheelsets position makes it possible to reduce guiding forces by 35%.

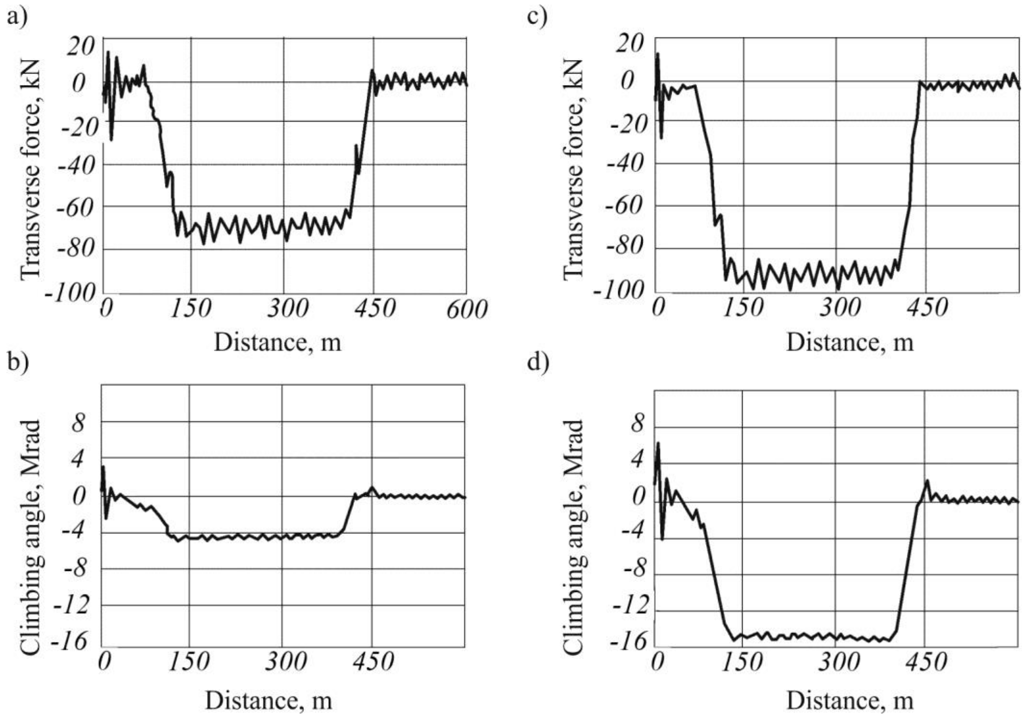

Fig. 1. Results of movement simulation of locomotive 2TE116 (R = 300 m, V = 90 km/h):
a), b) – proposed design; c), d) – serial design

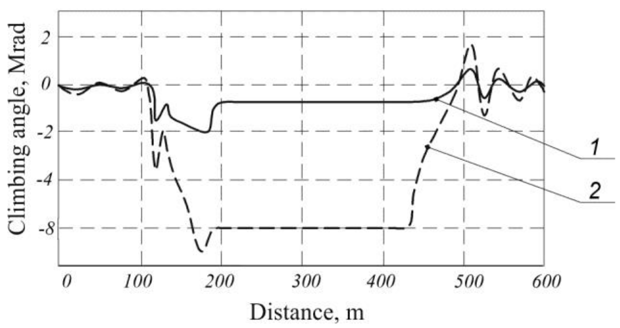

Fig. 2. Theoretical values of the hunting angle of the first wheelset of the locomotive during controlled and uncontrolled passage of the curvilinear track section:
1 – during controllable movement; 2 – during uncontrollable movement

The results of the tests are confirmed by the calculation data obtained in the theoretical studies of the six-axial locomotive 2TE116. The calculated values of the frame forces in a curve with the radius of 300 m at the speeds of 70 km/h were 56 kN (maximum) and 33 kN (quasistatic), and the horizontal body accelerations – 0.21 g.

As one can see from the presented graphs, the use of the improved bogie design of the locomotive and the developed ACS installation of the wheelsets in the rail track makes it possible to reduce simultaneously the guiding force values within 30%, the climbing angle of the wheel in 3.2 times. Reducing the lateral forces increases the locomotive traffic safety in terms of derailment [9, 12].

The climbing angles of the guiding wheelsets decreased to 3.2 times, depending on the curve radius and the mode of locomotive movement. The greatest effect from the developed ACS installation of the wheelsets in the rail track is observed in the curves with radius from 300 m to 600 m, and slightly less – in the curves with radius in the range of 125-200 m and more than 600 m. Also, the lateral forces between the wheels, wheel flanges and rails when passing the curvilinear track sections with radius from 300 to 600 m decreased in 1.3-1.9 times.

The wheelset trajectories coincide with the trajectory of the guiding wheelset. Oscillations of the second wheelset lag behind the first about a quarter of the period, the amplitudes of its oscillations are less, and the contact between the flanges and rails is not observed. The frequency of oscillations of the third wheelset is slightly higher than the first, the amplitude is less, the contact between the flanges and rails is also absent.

The locomotive body also makes transverse oscillations in plan with a frequency close to the oscillation frequency of the front wheelsets of bogies with the amplitudes within a few millimeters.

The movement of such a locomotive in a straight track section with a speed of up to 100 km/h can be considered as stable, as the development of lateral oscillations of its elements is not observed.

8. Originality and practical value

The possibility of using the mathematical model of locomotive movement with the axial formula 3_0-3_0 of the improved bogie design with the links of adjustable length, taking into account the dynamics of the ACS installation of the wheelsets in the rail track was theoretically substantiated. The theoretical research found out the reduction of lateral forces in the improved bogie design during the passage of curvilinear track sections.

9. Conclusions

The results of experimental studies of the All-Russian Scientific-Research and Design Technological Institute of Rolling Stock and the performed theoretical studies show that the efficiency of the improved system for controlling the wheelset position is higher than that of the serial design, in all modes of movement. The improved system of automatic control of wheelsets position makes it possible to reduce guiding forces by 35%. The developed mathematical model of the movement of improved six-axial locomotive, taking into account the link of adjustable length makes it possible to predict and compare the dynamic and operation indicators with the reference design. As well, it allows determining the prospects of their application in different railway sections and scientifically substantiating the design of devices for controlling the wheelsets` position in the curvilinear track sections with the confidence coefficient of 0.98.

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