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Studying the structure of railway rolling stock resistance

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Abstract
The purpose of the work is to improve the structure of the resistance to movement, based on the formalization of its components related to the frictional interaction of the wheels and the rails and the vehicles directing by rail track. The formalized structure of the general resistance to movement of railway vehicles on the basis of clarifying the origin of its components associated with the direction of the vehicle by the rail track is presented in the article. The mechanism of the influence of dynamic

processes frictional interaction of wheel sets and the rail track on the resistance to movement was developed. A new terminology for the resistance to movement associated with the vehicle directing by rail track was proposed.
Key words: RAILWAY VEHICLE, RESISTANCE TO MOVEMENT, FRICTIONAL INTERACTION OF VEHICLE AND RAIL TRACK, WHEEL SET, RAIL

Problem statement

Railway Transport of Ukraine, as earlier, plays a crucial role in freight and passenger transportation of the country. For its operation up to 18% of the total consumption of diesel fuel and 4.5% of electricity are consumed. Up to 75% of energy is consumed to overcome the resistance of trains. Thus, the resistance to movement is one of the main factors influencing the energy indicators of the railway transport.

The idea of reducing the resistance to movement is very attractive due to economic factors, such as the resistance reduction just by 1% would allow annual savings of one railroad engine to 150 MW·h of electricity, or about 12 tons of diesel fuel.

Determination of unsolved problems

When designing new types of rolling stock the characteristics of resistance to movement are not analyzed due to the lack of appropriate methods [1-4]. This often leads to an unjustified increase in operating of the friction loads on the contacts of wheels and rails, which acting as friction dampers with high power dissipation level and create additional resistance to movement. The operational data on intensive flanges worn sharp and side wear of the rail heads can be the indirect proof of that [6].

The authors believe that the component of the resistance to movement connected with the vehicles directing by rail track is the most attractive to reduce it.

Analysis of recent researches and publications

The work of H. Hayman [5] can be considered as the first and the most detailed study of the vehicles directing by rail track as frictional interaction of wheels and rails. The paper laid down the basic ideas of the vehicle directing by rail track. Although the main focus was on the direction forces, the work became the basis for further research of the resistance to movement connected with directing of the wheel sets by rail track.

Relative kinematics of the wheel sets and rail track and the wear of surveying rods and wheels in the curved sections of the rail track was studied in [7]. Model of rails vehicles and rail track is considered as the system of a multi-point contact of wheels and rails. The kinematic slippages in contacts when the radial and optimum setting of wheel sets on the rail track are analyzed. It is concluded that there is significant impact of the parasitic slippages on the wheels and rails wear.

The work [8] was dedicated to evaluation of directing forces during the passage of small radius curves by the vehicle. The evaluation has been made in accordance with European standard EN 14363 or UIC 518, which is used in the development of new, reconstructed or upgraded railway vehicles. The stated method of determining the quasi-static directing force indirectly confirms the significant level of resistance to movements associated with the vehicle directing by small radius rail track.

The losses related to the impact on railway infrastructure, track condition and rolling surfaces wear of the wheels of the vehicles are one of the most urgent issues in the railway field. The work [9] was dedicated to the research of influence of rolling stock operating conditions on the evolution of the railway wheels wear and, as a result, on the change of their profiles and interaction force of the vehicle and the track. The dynamics of the train movement in the curved sections of the track was studied in [10] on the basis of dynamic multimass mathematical models. The objective of research was to determine the influence of operating conditions of the train movement on the process of degradation of wheels and rails. For this purpose the concept “working operating conditions” was introduced, as the base for comparison of studies results. Various options for the geometry of the wheels and rails were considered. According to the study results, a great influence on the degradation of the wheels and rails was noted, especially on the geometry of the wheel profile and the curve radius. It was concluded that dependence of the degradation type of wheels and rails rolling surfaces from the operating conditions, namely the fatigue failure of the rolling surfaces dominated in the large radius curves with a high level of lateral unevenness.

In the paper [11], this problem can be solved using the mathematical model of high-speed train, where wheels are considered as flexible bodies and the way has no unevenness. The wearing depth of the wheel profile has been calculated according to known Archard law. Using this model, the impact of the wheel profile, the original hardness of suspension, the way width on the wheel profile wear has been studied. Simulation results allowed us to compare the wheels profiles according to the wear resistance of rolling surfaces and to define the parameters of the "optimal" profile. XP55 type profile showed the smallest total wearing depth and the LM profile had the greatest wearing depth. It was concluded that in order to reduce the profile wear the slope of the rolling surface must be within1:35 - 1:40.

The paper [12] is devoted to analysis of factors influencing the friction processes of wheels contacting with the rails. The harmonious model of wheel wear in underridged and ridged part of the rolling surface profile was considered in details. Based on the theoretical positions of Klingel theory, the authors believe that the kinematic transverse oscillations called "wabbling" are the main cause of dynamic normal and tangential stresses during contact of the wheels with the rails. These loads should include forces of resistance to movement as related to the vehicle directing by rail track. The authors have suggested the characteristics of dependency of these forces on the geometry and material properties of the contact surfaces of wheels and rails.

Purpose of the work is improving the structure of the resistance to movement, based on the formalization of its components associated with the friction interaction of wheels and rails and the vehicle directing by the rail track.

Presentation of the main research material

According to existing classification the resistance to movement it is divided into primary and secondary (Figure 1).

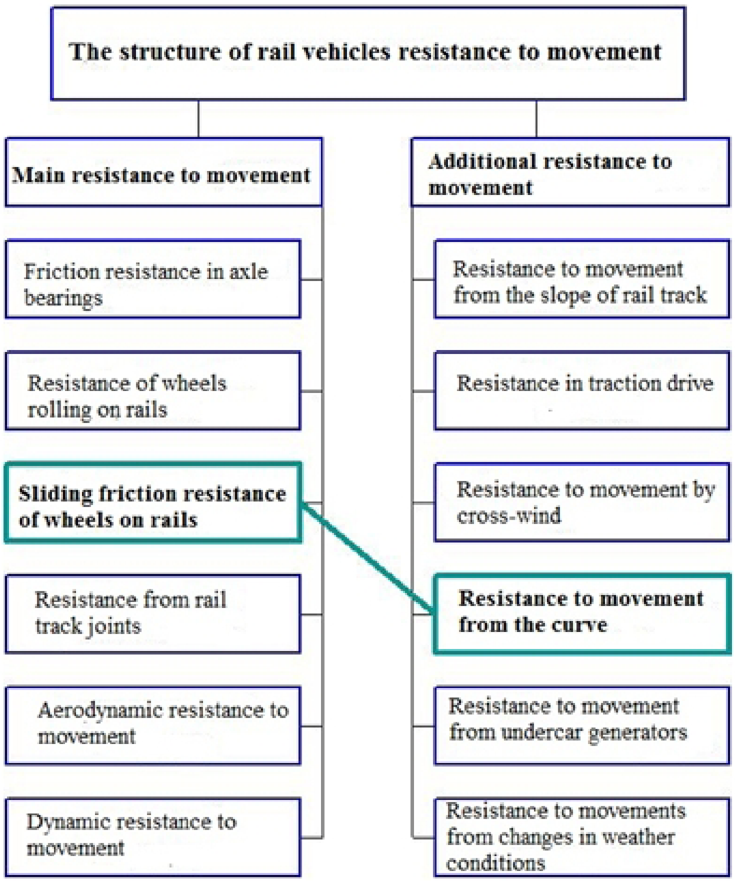

Figure 1. The structure of rail vehicles resistance to movement

The main resistance to movement includes the components always acting while moving along a straight horizontal rail track and the additional includes the components that do not always act or appear under specific conditions of movement. The system of railway vehicles directing by rail track is a grouped multiwheeled and multicontacted friction engine. Compared to the other wheel equipment the railway vehicles have three main differences. First is that railroad engine and cars have twin wheels on almost rigid axes - wheel sets. Second is that the wheel sets are formed by two or three carts with parallel axes. Third is that the vehicles directing by rail track occurs mainly due to the presence of ridges on wheel sets, which act as limiters of lateral movement within the rail track. These differences are the reason of the kinematic resistance to movement to the study, to which this article is devoted.

According to typology, the classification is built on essential characteristics and it is based on the concept of the type as the distribution unit of the classification object. The correctness of the distribution is based on two principles: the fullness and purity of distribution. According to the first principle, all terms of the division should be listed. According to the second one, the terms of the division should not be simple concepts [15].

It is considered by authors that **kinematic resistance to movement** is the resistance associated with the frictional contact interaction of vehicle and rail track occurring from the kinematic sliding in the contact of the wheels and the rails.

Theory of wheel sliding relative to the rail was proposed by Reynolds. It formed the basis of many scientific papers making this direction in the study of rolling resistance the most advanced. Forms of wheel and rail profiles determine the different rolling radii of circles as the individual wheels of the wheel set as well the various contact points of the wheel at a two-point contacting. The spatial velocities distribution leads to a differential sliding between the main and the ridge contacts within one wheel. Differential sliding is the cause of idle forces in the closed power circuits with the nodal point in the centers of frictional contact and, as a consequence, the occurrence of additional resistance to movement. The authors propose to call the resistance to the movement associated with the differential sliding in two-point contact – differential resistance to movement as a component of the kinematic resistance to movement [15].

Differential resistance to movement

Fig. 2 shows a schematic diagram of two-point contact of the wheel and the rail, which explains the nature of the differential resistance to movement occurrence. Between the main (K_1) and the ridge (K_2) contacts the four-square torque loop is created, which is the cause of parasitic sliding and occurrence of the resistance to movement force (F_r).

The system of equations of forces and moments equilibrium acting on the wheel is of the following form

$$\begin{cases} F_r = F_{bp1} - F_{bp2}; \\ F_{bp2} \cdot R_2 - F_{bp1} \cdot R_1 = 0, \end{cases} \quad (1)$$

where F_r – resistance to movement;

F_{bp}, F_{bp2}– binding powers in the main and ridge contacts respectively;

R_2, R_1 – tread circle radii for the main and ridge contacts respectively.

From the system of equations (1) an expression for the differential resistance to movement can be obtained

$$F_r = F_{bp1} \cdot \left(1 - \frac{R_1}{R_2}\right). \quad (2)$$

The binding powers are determined by the following formulas

$$F_{bpi} = N_i \cdot \Psi \cdot k_i, \quad (3)$$

where N_i – normal load in the contact;

ψ – physical friction coefficient in contacts of wheels and rails;

k_i – coefficient of binding use.

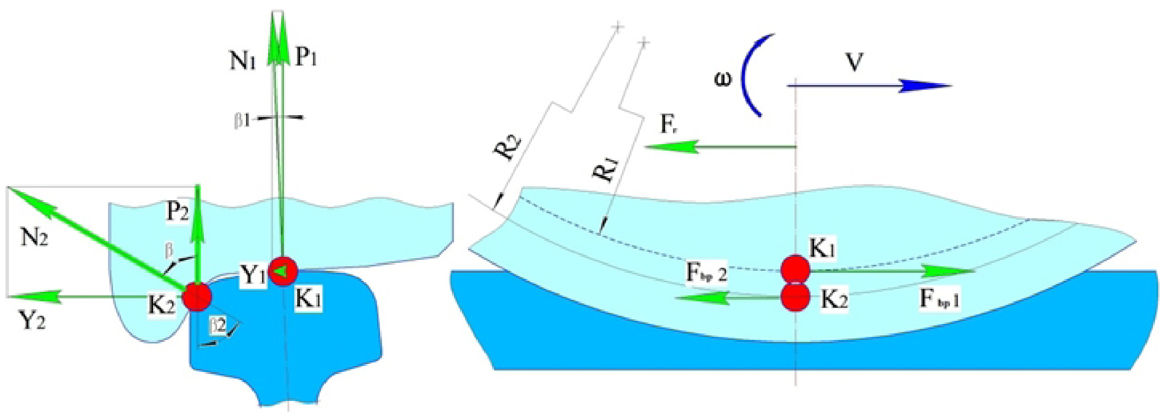

Figure 2. The scheme of the differential resistance to movement formation during the two-point contact of the wheels and the rails

The values given in equation (2) are determined by the following formulas

$$N_i = P_i \cdot \sqrt{1 + tg^2(\gamma_i)}, \quad (4)$$

where P_i– vertical loads in the contacts;

γ_i – slope angles of the rolling surface profile at the contact points.

Vertical load in the contacts is formed by the external forces acting on the wheel from the side of the rails and the bogie frame. Redistribution of the vertical load between the contacts is characterized by the re-laying coefficient of contact χ

$$\begin{cases} P_1 = (\chi - 1) \cdot P_0; \\ P_2 = \chi \cdot P_0. \end{cases} \quad (5)$$

The coefficient of binding use

$$k_i = \frac{\varepsilon_i}{a \cdot \varepsilon_i^2 + b \cdot |\varepsilon_i| + c}, \quad (6)$$

where ε_i – the relative sliding in the contacts;

a, *b*, *c* – correlation coefficients of binding characteristic *k (ε)*.

The relative sliding in the contacts

$$\varepsilon_i = \frac{\omega \cdot R_i - V}{V} = \frac{R_i - R_0}{R_0}. \quad (7)$$

Where V– velocity of the wheel center motion;

ω – angular velocity of wheel set rotation;

R_0 – average radius of the wheels tread circle.

To evaluate the level of the differential resistance to movement it should be noted that in real conditions when two-point contact the difference of radii contacts ΔR=R_1 - R_2 can reach 10…14 mm. At the same time sliding value can respectively reach 0.9 ... 1.3%, which is close to critical when k_i=1.

With taking into account (2) - (7) the differential resistance to movement can reach levels that are determined by the following formula

$$F_r = N_1 \cdot \Psi \cdot k_1 \cdot \left(1 - \frac{R_1}{R_2}\right), \quad (8)$$

Where for k_i=1 and ψ = 0.33, the specific level of the differential resistance to movement is obtained

$$w_d = \chi \cdot 6 \cdot 10^{-4} \cdot \sqrt{1 + tan^2\gamma} = 0{,}6 \cdot \chi \ {}^{H}/_{kH} \quad (9)$$

Differential resistance to movement occurs whenever the conditions for the ridge contact of wheels and rails are provided, i.e. in the following cases:

- when driving the vehicle in curved sections of the way where one or more wheels have ridge contact with the rail;
- when moving in straight sections of the rail track in the mode of impact wheel climbing on the rails. This mode is typical at medium and high speeds of rolling stock movements;
- when the faults in geometry of the wheel sets settings in the bogie frame: oblique setting, transverse deviations from the normal position.

In [13], during the tests on the experimental bench installation, a significant increase in resistance to movement of the wheel set from the difference between the wheels radii, which occurs when the transverse shift or angular rotation of the wheel set relative to the rail track axis has been confirmed.

Circulation resistance to movement

A significant part of the resistance to movement in the curved sections of the rail track is the resistance due to the circulation of the idle power in closed power circuits of the group wheeled engine, as the system of the vehicle directing by rail track. Wheels and wheel sets while driving as part of one vehicle have a mutual influence on each other through the ever-changing kinematic parameters of each individual wheel and rail contact.

The principle of vehicle direction by the rails due to the interaction forces of the vehicle and the rail track in the contact points requires the control influences from the rails, which will inevitably lead to the resistance to movement. Additional resistance to the movement, which is the result of group interaction of wheels with rails and circulation of idle power in closed power circuits of wheel sets and bogies authors propose to call the circulation resistance to movement.

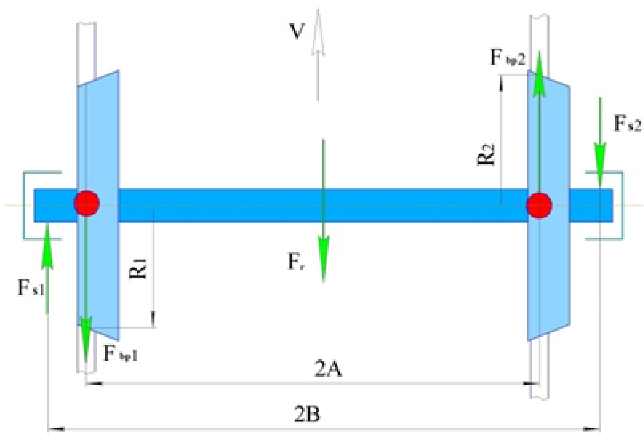

Figure 3. Scheme of circulation resistance to movement of the wheel set

Circulation resistance to movement F_r can be determined from the system of equations

$$\begin{cases} F_r + F_{bp1} - F_{bp2} = 0; \\ (F_{b1} + F_{b2}) \cdot B - (F_{bp1} + F_{bp2}) \cdot A = 0. \end{cases}$$

When driving the wheel set in rail track, its each transverse position relative to the axis of the rail track that defines the wheel rolling radii cones corresponds to the instantaneous turning radius, at which it can roll over without slipping in contact with the rails when moving in so-called equilibrium trajectory. However, as a result of interaction between the wheel sets through the bogie frame, the actual rolling trajectory of each wheel set differs from the equilibrium. Enough tight angular coupling between the wheels leads to the circulation of power in “rail track-wheel set” circuit. It also results in power flow redistribution between the wheels and, as a consequence, in the resistance to movement increase, while the railroad engine has deterioration of coupling properties [15].

In the case of group drive of wheel sets, the power circuit has multiple branched circuits. Power circuit circulation energy is absorbed mainly in the contact of the wheels with the rails, and partly in dissipative connections of bogie. The uneven redistribution of power flow between the wheels depends on several factors:

- stiffness of friction characteristics
- torsional stiffness of the axis, that is connection parameters of the wheels;
- the geometric characteristics of the wheel set including conicity and diameter of the wheels rolling surfaces, the width of the rail track and the bogie base;
- parameters of the longitudinal and transverse axle connections of the wheel set with bogie frame;
- radii of curved sections of the rail track.

Differential and circulation resistances to movement are components of kinematic resistance to movement. The kinematic resistance to movement has features of main and additional resistance, therefore, conventionally, when moving in the straight sections of the way it should be considered as part of the main, and when driving in curves, as part of the additional. Differential and circulation resistance to movement usually occurs in case of presence of closed power circuits typical not only for the case of interaction between railway vehicle and rail track, but also for many other dynamic systems with multi-threaded transfer of forces and moments. In the domestic and foreign literature information on quantitative characteristics of the kinematic resistance to movement is extremely few. Virtually as the only and far from complete, its study can be considered as theoretical and experimental works made for freight cars at the US Railroad Research Center in Pueblo in 1984-85. In the paper [14] devoted to these studies, a significant increase in the resistance to movement in the curved sections of the way even with a slight divergence in the diameter of the wheels on one wheel set is noted.

Conclusions

The existing classification of the resistance to movement is based on the principle of convenience for the experimental study and use in traction calculations, but it constrains the search for ways to reduce it. It is proposed to allocate a separate component of the resistance to movement associated with the vehicle directing by the rail track and call it a kinematic resistance to movement with the differential and the circulating components.

The above improvement of the resistance to movement structure offers prospects for reducing the resistance to movement on the basis of new technical solutions of running parts constructive performance allowing us to manage the kinematics and dynamics of frictional interaction of rolling stock wheels with the rails. It primarily relates to the study of the horizontal forces in the contacts of the wheels with the rails resulting at vehicle directing by rail track. These conclusions are fundamental for solving the problem of reduction of the rolling stock resistance to movement.

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