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Features of Locomotive Adhesive Mass Utilization in a Braking Mode

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The magnitude of a locomotive's traction and braking forces is directly related to its adhesive mass, which largely determines its tractive and braking characteristics. Therefore, an important task is to maximize the utilization of the locomotive's adhesive mass. The degree of adhesive mass utilization is determined by more factors and is quantitatively characterized by the Adhesive Mass Utilization Coefficient (AMUC). One of the ways to increase the AMUC is to improve the locomotive's lever-type brake transmission. In braking mode, it interacts with the wheelsets and the bogie frame and may block the operation of the first stage of the suspension system. This research presents the results of a mathematical model-based study of the influence of certain parameters of the lever brake transmission on the utilization of locomotive adhesive mass in braking mode. The calculations were carried out for various values of the vertical stiffness of the brake transmission. The results indicate that the distribution of vertical loads across the locomotive's wheelsets in braking mode significantly depends on the vertical stiffness of the brake transmission.

Keywords: Locomotive Undercarriage, Coupling mass, Braking, Load redistribution, Efficiency

1 Introduction

There is difficult to imagine transporting large ammount of goods or passengres for middle and long disantces without railway transport. Rail vehicles have that advantage in comparison with other kind of transport, that there is possible to transport these goods and lot of passengers at relatively high speed together with low energy consumption. These features of rail transport relate with the principle itself of rail vehicle movement. That is, that steel wheels of rail vehicles rotate on steel rails. This results in low rolling resistance in the wheel/rail contact [1, 2]. Besides that, individual rail vehicles (i.e. wagons) form a trainset, which has favourable drag. This also contributes to favouable energy balance of railway transport. The high axleload and the high payload of freight wagons together with their many versions [3,4] including transport units for intermodal freight transport [5,6] just underlines these advantageous features of railway transport.

Wagons (except of multiple units) are towed by locomotives. Current technical solutions of locomotoves' powertrain also reflect still stricter and stricter demands to sustainability of their operation with a focus on a minimal carbon footprint. Therefore, an electrification of railway tracks is being expanded as much as possible. Where it is not possible, alternatives to standard diesel combustion engines are sought, such as gas fuels, biofules or electric batteries [7–9]. There is possible to mention regarding to certain disadvantages of railway transport, that a railway track should be built with high precission to ensure reliable and safe operation of rail vehicles in straight lines as well as in switches [10–12]. And, the key factor of safe and reliable rail vehicles' running is the wheel/rail contact mentioned above. This is only a small area, through which traction and brakeing forces are transmitted form a vehicle to a track. Safety and a risk of derailment of a rail vehicle directly depends on geometrical and tribotechnical state of this contact [13–16]. As it is detailed described below, transmission of traction and braking frces is very impoetant for locomotives.

The development of next-generation locomotives with improved dynamic, traction, and braking characteristics is a relevant scientific and practical task. When designing next-generation locomotives, it is necessary to ensure the maximum possible value of safely realizable traction and braking forces. The traction and braking forces realized by a locomotive are directly related to its adhesive mass and its distribution across the wheelsets [17–19]. Thus, maximizing the utilization of the locomotive's adhesive mass is a crucial task, as it largely determines its tractive and braking performance [20].

2 A problem of wheel/rail adhesion

The degree of adhesive mass utilization is determined by the chosen design layout scheme, the characteristics of the connections between running gear elements, and the geometric dimensions of the running gear components [21]. It is quantitatively characterized by the Adhesive Mass Utilization Coefficient (AMUC). The AMUC improvement is possible to improve all the components of the running gear. A key element of this system is the locomotive's lever-type brake transmission. This transmission system represents a relatively rigid spatial structure. It is characterized by the fact that, it interacts with the wheelsets and the bogie frame and may block the operation of the first stage of the suspension system in a braking mode. Therefore, it is of interest to study the dependence of AMUC distribution across the locomotive's wheelsets in braking mode based on the parameters of the lever brake transmission. To conduct this study, a mathematical model was developed to describe the locomotive's behavior in braking mode. This model consists of a system of algebraic equations describing the equilibrium conditions of the running gear components in the longitudinal-vertical plane under the influence of corresponding force interctions during braking [22]. The components of the running gear are represented as absolutely rigid bodies connected by elastic links with specified characteristics, modeling the locomotive body, two three-axle bogies, six wheelsets, and traction motors.

A key area of improvement in locomotive running gear is the application of design solutions and layouts that enable full utilization of the locomotive's adhesive mass in traction and braking modes. Developing modern locomotives is a complex task since these machines operate under a wide range of operating conditions with various types of trains. Field studies of locomotive traction and braking characteristics are costly and may disrupt train schedules on real railway lines. Therefore, many aspects of railway vehicle behavior and performance characteristics can be evaluated using computer modeling [23]. Mathematical models can be developed with varying degrees of complexity [24], detailing wheel-rail interaction conditions or focusing on the structural features of railway vehicle running gear components [25]. Models may contain for different number degrees of freedom. For example, [26] several mathematical models of varying complexity have been proposed to simulate locomotive traction effort. A significant portion of studies focus on modeling traction and braking force implementation using various models of locomotive wheel adhesion with rails [27].

Due to the structural features of locomotives, the realization of traction or braking forces leads to the unloading of some wheelsets while overloading others. In other words, locomotive weight is redistributed among its wheelsets. This weight redistribution can be mitigated by ensuring vertical connections between the locomotive's bogies through the vertical reactions of elastic elements or using inclined rods in the running gear [28]. Various mechatronic systems have also been proposed to enhance the traction and dynamic qualities of modern locomotives [29]. Traction force distribution across the wheelsets can also be managed through traction motor control [30].

It should be noted that the issues of the adhesion qualities of locomotives and the use of their adhesion mass in the implementation of traction force have been studied quite fully and comprehensively. For example, in the study [31] a control system for the adhesion of rail vehicles based on an observer is proposed, which allows determining the maximum traction moment based on the optimal adhesion force between the wheels of a rail vehicle and the rails depending on the weight load from the wheel to the rail, friction conditions in the contact zone and lateral displacement of the wheel pair. As a result, it allows the movement of a rail vehicle in traction mode at the maximum adhesion force for real friction conditions.

The work [32] is devoted to the problems of unloading the axles of industrial railway locomotives using the example of operation in open-pit mining conditions. It was established that the displacement of the center of mass of a quarry locomotive depends primarily on the height of the center of gravity, the height of the locomotive coupling hook above the rails, and the slope of the track. Therefore, to increase the coefficient of use of the coupling weight and ensure rational operating conditions, it is necessary to provide for an adjustable shift of the locomotive's center of mass, considering the actual operating conditions. Analysis of the calculation results showed that for the traction unit when moving in the traction mode under conditions close to the limit, it is necessary to provide a design solution for shifting the locomotive's center of mass up to 0.5 m along the direction of the locomotive's center of mass.

In [33] the existing options for testing the performance of rail vehicles and their braking efficiency under low adhesion conditions are considered: laboratory tests, which are not representative of field conditions, and expensive track tests using fully equipped vehicles. A third option is proposed: low-cost track testing. The minimum equipment and resources required to conduct the research are identified. A methodology and some initial results are presented, showing that it can generate different braking adhesion scenarios. This can be used to develop solutions to mitigate the effects of low adhesion.

At the same time, the processes of redistribution of axle loads during locomotive braking are rather poorly covered in scientific and technical literature. Most of the research is devoted to general issues related to the operation of braking equipment. For example, article [34] is devoted to the topic of increasing the reliability and analysis of the causes of failures of locomotive braking equipment. The article presents an analysis of the causes of failures of the brake equipment of rolling stock of the railways of Uzbekistan. It is shown that the main reasons for the decommissioning of brake shoes are their wear, including scuffing of friction surfaces, malfunction of the air distributor, brake line, brake cylinders and lever mechanism.

The article [35] examines methods for increasing the use of the locomotive's adhesive mass during braking. The possibility of using rail magnetic brakes to increase the efficiency of the process is considered. The processes of braking a train using a magnetic rail device to increase the locomotive's axle load are examined using a mathematical model. The results of calculating the braking efficiency using a mathematical model allowed us to conclude that the magnetic rail device used to increase the locomotive axle load can significantly improve the braking characteristics of the locomotive while increasing the permissible train weight.

One of the important components of the undercarriage of rail vehicles is the lever brake transmission. This transmission is a fairly rigid spatial structure. In the braking mode, it interacts with the wheel pairs and the bogie frame and can block the operation of the first stage of the spring suspension.

The main part of the known studies of brake lever transmissions of rail vehicles is devoted to the braking equipment of wagons. For example, in the article [36] the points of application of load on the shoes and other parts of the bogie of a freight car during braking are theoretically considered. Special differences in the operating conditions of the units of the brake lever transmission of a wagon and their influence on the wear of the shoes during the movement of the train without braking are described. Various operating conditions of triangles are described to establish a cause-and-effect relationship regarding the abnormal wear of the brake shoes of three-element bogies. A algorithm of a more accurate approach to theoretical calculations for determining the actual forces of pressing the brake shoes on the wheels of bogies is proposed. The obtained algorithmic equations can help to estimate the wear of brake shoes and its effect on the stress-strain state in order to ensure the safety of train traffic when conducting relevant theoretical and practical studies.

The paper [37] examines the stress-strain state of the brake lever transmission of the wagon bogie model 18-100 car. The authors analyze the causes of the destruction of the triangle elements, which leads to failures in the operation of cars and significant financial losses. It is proposed to improve the design by replacing the triangle string with a round pipe filled with an energy-absorbing material - aluminum foam. The calculation carried out using the finite element method showed that the maximum equivalent stresses in the modernized string do not exceed the permissible values, which indicates an increase in the reliability and durability of the design.

The aim of the study [38] is to determine a rational method for upgrading the brake lever transmission elements of freight car bogies. The authors conducted theoretical and operational studies aimed at identifying design limitations that lead to abnormal wear of brake shoes, and propose technical solutions to improve the existing design. The proposed changes in the brake lever transmission design reduce brake shoe wear and improve the efficiency of the freight car braking system.

There are relatively few scientific papers on locomotive brake transmissions. They are also mainly devoted to the strength characteristics of brake systems. For example, in [39], the stress distribution and weak points of the lever transmission were identified using theoretical and structural analysis. Various designs of lever brake transmissions were investigated for high-speed trains and for electric locomotives. Fracture tests were carried out to study the relationship between vertical stress and bending stress during braking. The results were used to determine the strength factor and develop proposals for quantitative minimum recommendations.

The locomotive's brake lever transmission interacts with the wheelsets and the bogie frame in the braking mode and can block the operation of the first stage of the spring suspension. The distribution of vertical loads across the locomotive's wheelsets in braking mode significantly depends on the vertical stiffness of the brake transmission. When designing locomotive lever brake transmissions, it is necessary to consider this dependence and implement structural solutions that prevent blocking of the first-stage suspension during braking. This will allow for a more accurate consideration of the redistribution of vertical loads across the locomotive's wheelsets in braking mode and enable the application of the necessary braking forces on specific wheelsets to ensure effective braking [40–44]. Obviously, in the locomotive's braking mode there are some features of the use of its adhesive mass, which are determined by the design and parameters of the brake transmission. Therefore, it is of interest to study the dependence of the distribution of the adhesive weight on the locomotive's wheel pairs in the braking mode on the parameters of its brake lever transmission.

The purpose of this work is to study the features of the influence of the brake lever transmission parameters on the use of the locomotive's adhesive mass in the braking mode.

3 Materials and research methods

Let us consider some of these specified features using the example of the brake transmission of the 2TE116 locomotive [45] (Fig. 1). The lever brake transmission of the three-axle bogie of the locomotive consists of six identical groups (according to the number of wheelpaars), connected in pairs for each wheel pair by axles or U-shaped beams (Fig. 2).

Fig. 1 *The locomotive 2TE116 [46]*

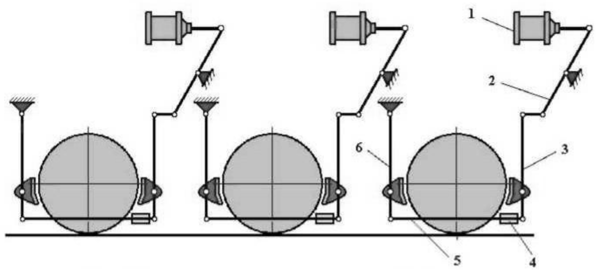

Fig. 2 *A scheme of the brake lever transmission of the bogie locomotive 2TE116 (one side of the bogie)*

Each group is driven by a brake cylinder 1, fixed to the outside of the bogie frame sidewalls. When the brake cylinder is filled with compressed air, its rod acts on a horizontal balance beam 2, passing through an opening in the bogie frame. The balance beam, via the upper fork and suspension lever 3, presses the brake shoe to the wheel pair tread. Then, the force via the lower end of the brake shoe suspension lever and the lower fork of the triangle sets in motion the rod 5 and the second triangle, which in turn is connected to the brake shoe suspension lever 6. Each brakeblock is secured with a pin to the brake shoe and is equipped with a ratchet mechanism that ensures that the brake-block surface is equidistant from the wheel rolling surface. All brake cylinders operate synchronously.

Due to the use of ridgeless brakeblocks in the locomotive braking system, the brake shoes on the left and right sides of the bogie (one wheel pair) are connected by triangles to give the lever transmission the necessary lateral rigidity, prevent the brakeblocks from slipping off the bandage and ensure synchronous operation of the brake.

Thus, it is obvious that in order to successfully perform its functions, the lever brake transmission in question must be a sufficiently rigid spatial structure, which, in the braking mode, when interacting with the wheel pair and the bogie frame, can block the operation of the first stage of the locomotive's spring suspension. The degree of this blocking depends on many factors: the design parameters of the lever transmission, the features of its technical content (the flexibility of the levers and balancers, the presence of grease in the joints, gaps, etc.), which determine its rigidity in the vertical direction. The spread of values of this indicator can be quite large and is a random value. The blocking of the spring suspension can significantly affect the distribution of vertical loads on the wheel pairs of the vehicle, which, in turn, will affect the braking characteristics of the locomotive.

Taking into account the above, the assessment of the influence of the parameters of the locomotive brake lever transmission on the use of his adhesive mass during braking is of both scientific and practical interest. The study of this issue was carried out on a mathematical model, which is a system of algebraic equations that determine the conditions of equilibrium of the elements of the running gear under the action of appropriate additional forces and moments in the braking mode of the locomotive. The calculation scheme of the mathematical model included a body, two three-axle bogies and six wheel-motor units. These components were represented as absolutely rigid bodies connected by elastic connections. The body rests on each of the bogies through four supports of the second stage of the spring suspension. The suspension of the traction electric motors is support-axial. The main geometric, rigidity and weight parameters of the considered running gear were taken close to the corresponding parameters of the running gear part of one section of the 2TE116 locomotive [45].

4 Research results

The system of equations was solved on a personal computer using the Mathcad mathematical package [47]. Some calculation results are presented below. Thus, Fig. 3 and Fig. 4 present graphs showing the change in the values of the coefficients of use of the adhesion mass η_i on the vehicle wheel pairs and the corresponding vertical loads Y_i from the wheel pairs on the rails depending on the vertical rigidity G_T of the brake lever transmission (at the maximum value of the coefficient of adhesion of the wheels to the rails Ψ=0.33).

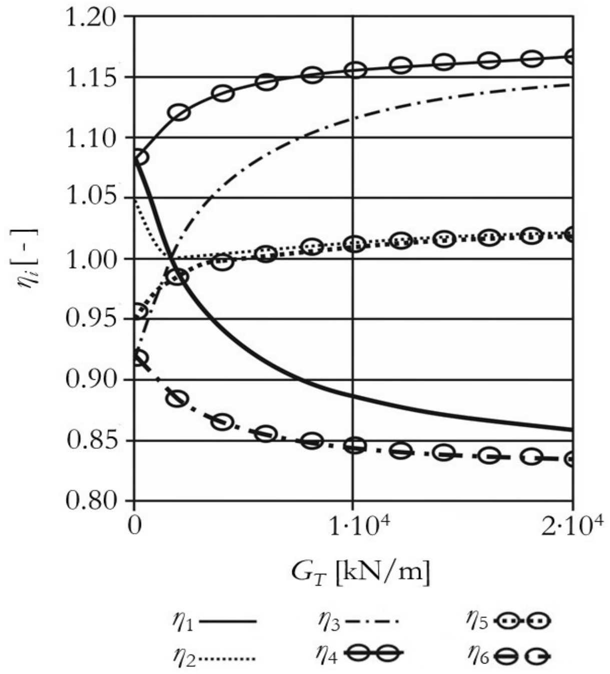

Fig. 3 *Dependences of the coefficients of use of the adhesive mass along the locomotive axles during braking on the vertical rigidity of the brake lever transmission (Ψ =0.33)*

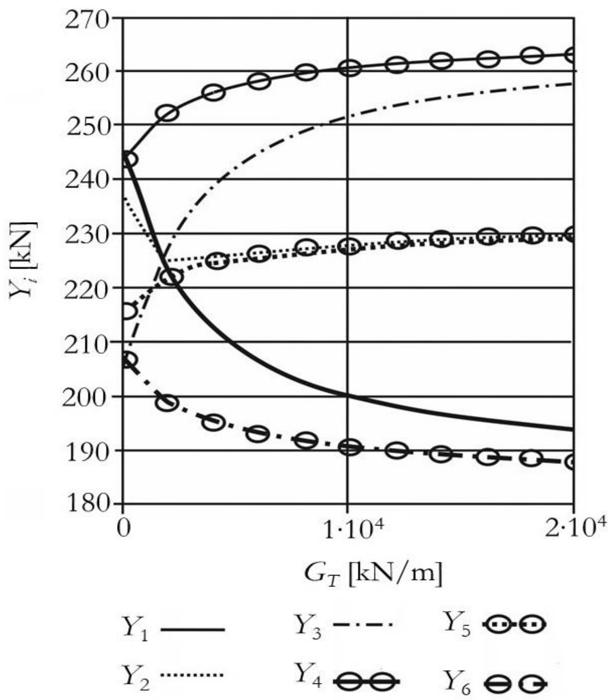

Fig. 4 *Dependences of changes in vertical loads from locomotive wheel pairs on rails during braking on the vertical rigidity of the brake lever transmission (Ψ =0.33)*

Numbers 1 to 6 in the figures indicate the values of the calculated indicators for the corresponding vehicle wheel pairs.

As a result of the analysis of the obtained calculation results, it can be noted that the distribution of the coefficients of the use of the adhesive mass on the locomotive wheel pairs during braking depends significantly on the value of the vertical rigidity of the brake lever transmission. Moreover, if at the value $G_T = 0$ the first and fourth wheel pairs along the way were the most overloaded, and the third and sixth wheel pairs were the limiting ones in terms of vertical load, then with an increase in the value G_T, the first wheel pair along the way is unloaded, which at a value G_T of more than $2.5 \cdot 10^3$ kN/m already becomes the limiting one together with the sixth wheel pair. With a further increase in the value , this pattern is preserved.

Based on this, it is possible to conclude that when designing and calculating brake lever transmissions, it is necessary to take into account the noted dependence of the redistribution of the vertical load on the locomotive wheel pairs on the value of the vertical rigidity of the brake lever transmission. Considering the large number of the above random factors affecting the value of the vertical rigidity of the brake lever transmission, determining the value of this rigidity by calculation seems to be a rather complex task. When designing brake lever transmissions, it is necessary to provide for structural elements (eyelets, suspensions, gaps, etc.) that reduce the vertical rigidity of the brake lever transmission to zero and prevent the first stage of the spring suspension from locking during braking. This will allow for a more accurate redistribution of vertical loads on the vehicle wheel pairs during braking and taking this into account, set the appropriate brakeblocks pressure on the wheels of certain wheel pairs to ensure effective braking.

5 Conclusions

- The locomotive brake lever transmission is a sufficiently rigid spatial structure, which in the locomotive braking mode, interacting with the wheel pairs and the bogie frame, can block the operation of the first stage of the locomotive spring suspension.
- The distribution of the coefficients of use of the adhesive mass on the locomotive wheel pairs in the braking mode depends significantly on the value of the vertical rigidity of the brake lever transmission.
- When designing locomotive brake lever transmissions, it is necessary to consider the presence of the specified dependence and

provide for design solutions that prevent the blocking of the first stage of the spring suspension during braking. This will allow more accurately considering the redistribution of vertical loads on the vehicle wheel pairs in the braking mode and set the corresponding forces of pressing the brakeblocks on the wheels of certain wheel pairs to ensure effective braking.

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