ASSESSMENT OF THE QUALITY INDICATORS OF THE CARRIAGE MOVEMENT BY DIRECTLY MEASURING THE FORCES OF INTERACTION BETWEEN THE WHEELS AND RAILS

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Resume
This work describes the features and methods of measuring the forces of interaction between the wheel pairs and rails by measuring wheel deformations at control points. The work also contains recommendations for direct measurements of the forces of interaction between the wheels and rails to determine the actual margin of stability of wheel pairs from derailment. The result of the work is general requirements for the system of direct measurement of the strength of interaction of the high-speed rolling stock wheel pairs with rails and scientifically based recommendations for direct measurement of the interaction forces of wheels and rails. The problems of interaction between the wheel pairs and rails do not significantly depend on the track width and are general in nature for different countries of the world.

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1 Introduction

The task of increasing the speed of passenger rolling stock requires new approaches to the assessment of the safety indicators of train movement and the smoothness of carriages. The conditions of stability on the track of rolling stock can be defined as the ratio of forces acting upon contact of the wheel with the rail. Determining these forces is an extremely difficult task, since the contact zone is constantly moving along the rolling surfaces of the wheels and rails. In addition, to assess the stability of the wheel against rolling onto the rail, it is necessary to constantly calculate the ratio of horizontal and vertical contact forces over a certain period of time, because even isolated cases of exceeding the permissible values of this ratio can cause a violation of traffic safety conditions.

It should be noted that the existing methods of the full-scale tests of rolling stock provide for the determination of traffic safety indicators based on the ratio of forces acting on the wheel pairs from the frame structures of the running parts, the so-called "frame forces". That is, the values of the forces of direct interaction between the wheels and rails, which depend on the ratio of the stability of the wheel pair in the rail track, are essentially not used. In addition, this method of determining the dynamic forces acting on the wheels at the points of contact with the rails, based on deformations of the side frames of the bogies, due to a number of assumptions, does not have high accuracy.

Therefore, this work substantiates recommendations regarding direct measurements of the forces of interaction between the wheels and rails to determine the actual margin of stability of wheelsets from derailment. This approach will improve the level of safety of train traffic and increase the effectiveness of forecasted evaluations of dynamic indicators of the rolling stock, which will generally improve the conditions for the prevention of traffic events associated with derailment of wheelsets.

Problems of interaction between the wheelsets and rails do not depend significantly on the width of the track and are of a general nature for different countries of the world.

2 Literature review

Railway transport is rapidly developing and is a component of the high-speed transport system. The safety of train operation is becoming a more acute issue. To assess the safety quality of the movement of wagons, locomotives and other types of rails rolling stock, there are various approaches to assessing the safety conditions and solving this problem.

The study [1] describes the development of a finite element model for simulating the descent of trains moving in a curved section of the track located on a bridge during earthquakes. The simulation results showed that the risk of derailment of trains moving on curved bridges is greater than that of trains moving on straight bridges. But this study does not take into account and does not describe determination of performance of the wheelset with rails along the entire train tracking route.

The work [2] gives the results of studying and establishing the mechanism of interaction between the railway wheel and a rail. The modeling is based on the fundamental theory of circular motion kinematics. The proposed method makes it possible to determine the characteristic of the interaction kinematics criteria of the wheel pairs tire cross-section of the rolling stock with the lateral sides of the rail heads. However, the work does not describe the process of interaction between the railway wheel and rail from the point of view of traffic safety.

In document [3], the authors propose a new strategy for improving the dynamics of railway cars and reducing the energy consumption during the transportation, by optimizing the position of the center of gravity of the car during the cargo loading. However, the authors do not indicate how the optimized center of gravity affects the general indicators of the safety of railway carriages.

The paper [4] presents a theoretical basis for modeling the interaction of a railway car and a track, in which the dynamic equations of motion of car-track systems are composed by effectively connecting linear and nonlinear dynamic characteristics. The result of this study is determination of the critical speed of a railway train and the localization of track irregularities through the effective integration of a dynamic modeling model, a probabilistic model of track irregularities and a time-frequency analysis method. However, the work does not consider the possibility of developing a mobile system for determining the indicators of the interaction of a railway car and the track based on the conducted research.

The authors of the work [5] investigate the longitudinal forces acting on a railway car for different loading conditions of the cars in the train. Three different types of wagons are considered in the work, namely fully loaded, partially loaded and empty wagons. The purpose of this work is to determine the best place for their location in a freight train where the smallest longitudinal forces occur, regardless of the wagon loading scheme. However, the work does not assess the influence of horizontal forces on the railway car, which significantly affect the safety of the movement of railway cars.

The article [6] presents a study of the freight wagons derailment in symmetrical turnouts. A dynamic model of the open wagon and a model of a flexible turnout, which undergoes derailment when the wheel flange is lifted, was created. In addition, a full-scale wheel-rail interaction test was conducted to verify the dynamic model. As a result of the simulation of derailment during the lifting, the wheels are consistent with the research data, and the safety of the bogie depends on the condition of both the front and rear wheels.

In the article [7], the authors describe the concept of a smart wagon consisting of various components. This concept meets the safety requirements of a modern railway system. Self-diagnosis functions in a wagon significantly reduce the risk of accidents. This paper also presents the concept and functional model of this railway wagon and illustrates the utility of this concept based on investigated railway accidents.

Research [8] describes the behavior of dynamic derailment caused by the failure of rail connections of a railway switch, as well as the assessment of the impact of such parameters on the safety of train operation. The developed model takes into account the transverse difference between the sections of the rail connection, which directly cause the lifting of the wheel. The conducted research indicates that the proposed derailment model is able to effectively evaluate operational safety as a result of various wheels and track defects, and thus provide a basis for providing a cost-effective platform for future optimization of railway track and rolling stock parameters.

In [9], the authors study the effect of gaps between the blocks, changes in the wheel-rail friction coefficient, and the radius of the track curve on the nonlinear critical speed of a railway vehicle. The influence of the gaps between the axle boxes on the wear of the wheels and the interaction of the wheels with the railway track was also investigated.

The paper [10] describes the dynamic behavior of the wheel-rail interaction under various surface contaminations of the rail track, using the methodology of experimental and numerical modelling. The results of the study showed that the wheel-rail creep force drops sharply when the wheel enters the low adhesion zone, and when the adhesion is restored, there is a sudden increase in the creep force, which negatively affects the dynamics of the railway car.

In the study [11], a refined wheel-rail contact formula was proposed for analysis of the nonlinear train-track interaction, which takes into account the geometry of the wheel and rail. While most of the existing methods consider contact forces as external forces, the work uses modeling of the behavior of the contact surface based on Hertz's theory and Kalker's laws. The proposed refined mathematical model is confirmed by experimental data.

In the article [12] three-dimensional numerical modelling of the moving load of the wheel-rail interaction for high-speed and heavy trains is investigated. Simulations were performed in ANSYS with a hybrid model involving a flexible wheelset moving on a pair of rigid rails, which helped in estimating the frictional stresses at the wheel-rail interface during the train motion. As a result of the work, it was found that contact pressure and frictional stress increase quadratically with increasing train speed.

In the article [13], the authors proposed a three-dimensional (3-D) model of train-track interaction. As a result of the study of the developed dynamic model, it was found that this model demonstrates high computational stability, accuracy and efficiency in comparison to traditional solutions; in addition to some key parameters, such as bridge element length, the length of the track and bridge section in numerical integration can be conveniently refined using this model.

In work [14], the authors developed a dynamic model for studying the vertical interaction of a rail track and a system of cars. The developed model is verified using several test data and other numerical models.

In the article [15], the authors presented an analysis of the influence of creep paths on the contact forces of the wheel and rail. The simulation results showed that the maximum normal wheel-rail contact stresses are less than 1600 MPa in the range of typical conditions of normal operation.

The article [16] presents the features and results of the cataloging of the supporting system of semi-cars, the application of this approach for the end wall of one of the basic models of wagons.

In [17], the authors described the problem of various deformations at all the stages of operation of freight wagons. The main type of these deformations are residual deformations that occur during welding as a result of thermal exposure.

The authors of the article [18] describe the process of conducting the control tests of tank wagons for dangerous goods. The testing methodology described in this work was used during the research.

In the article [19], the author highlights the results of work on determining ways to increase the degree of ideality of freight wagons and forecasting the evolution of the chassis of new generation wagons. A review of examples of the idealistic strategy of improving the undercarriage of railway universal freight open wagons.

In the studies [20-21], the authors elucidate a method to enhance the efficiency of the braking system by regulating the cooling of friction surfaces through adaptive air supply. A mathematical model has been devised to govern the air pressure supply to the brake's frictional interface, determining the optimal diameters of friction lining holes and the velocity of air delivery.

According to the findings from the examination of literary sources [1-21], it can be inferred that the exploration of directly measuring the forces of interaction between the wheel pairs and rails through assessing the wheel deformations at specified control points is pertinent and necessitates further investigation.

3 Methodology

3.1 Systems for measuring the forces acting on the running parts of the rolling stock

As traffic intensity continues to rise and the inclination to increase the speed of passenger trains persists, there is a growing need to experimentally assess the power modes of wheel pair elements and the proportions of vertical and lateral forces at the points where wheels make contact with rails. These factors determine the resistance to rolling of the wheel on the rail head, a crucial aspect for ensuring traffic safety.

Measuring tools, currently used in testing the rolling stock, there are no standard systems suitable for determining the forces directly in contact between the wheels and rails. Instead, the force responses of the rail crew to the interaction of wheels and rails in the form of mechanical stresses are measured in the elements of the load-bearing structures, that is, in the rails, wheels, axles or axle assemblies.

There are two ways of measuring the interaction forces between the wheels and rails:

1 - due to deformations of the elements of the upper structure of the track;

2 - due to deformations of elements of running parts.

The first method is used mainly in tests regarding the effect of rolling stock on the track and consists in equipping a certain section of the rail track with measuring devices. That is, the measurements are carried out on a limited section of the track. A significant drawback of this method is the difficulty of ensuring sufficiently high insulation of measuring circuits, especially when they are used for a long time on sections of operating railway lines. However, this method has been improved in recent years. It became possible to continuously measure the vertical forces acting on the rail on a certain section of the track. It is successfully used to detect defects on the rolling surface of the wheels, which cause an increased effect of dynamic forces on the track and axle assemblies of cars. Thus, the localization of stationary means of measuring force action on the track is, in a certain sense, useful from the point of view of detecting defects on the rolling surfaces of the wheels, to evaluate them and make decisions regarding the removal, of wagons from trains for repair if necessary.

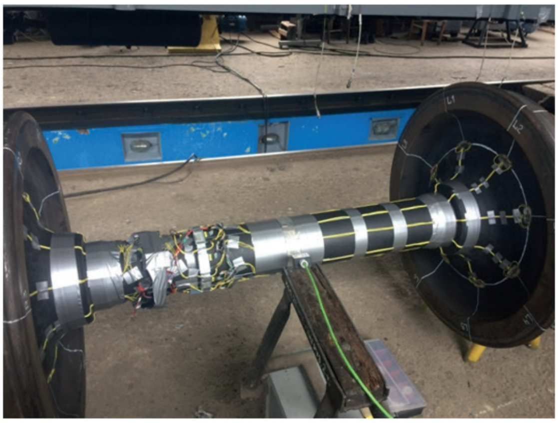

Figure 1 *General view of the tensometric wheelset*

In contrast to measurements by stationary devices, which are carried out on a fixed section of the track at the same time, systems for measuring force actions by deformations (tensions) of the load-bearing elements of the running parts provide for the current collection of data on dynamic processes accompanying the movement of the crew.

3.2 Measurement of data of elements of load-bearing structures

To measure the mechanical stresses in the surface layers of the elements of the load-bearing structures of the rolling stock, the methods and means of tensometry are used, that is, strain gauges and registration equipment. The operation of the strain gauge is based on the tensile effect of the conductor or semiconductor, which is attached to the surface of the supporting element of the structure with a special glue. Thus, deforming together with the metal element when it is loaded, the strain gauge changes its electrical resistance.

The change in resistance of the strain gauge during deformation is very small, usually of the order of several hundreds of Ω. One of the most convenient means of measuring such changes is the Wheatstone bridge. It includes four resistors connected to a DC power supply.

3.3 Direct measurements of the interaction forces between the wheels and rails

From the point of view of determining the dynamic properties of some researched rail crew and assessing the conditions of its safe operation, the most effective is the use of measuring wheel pairs, that is, wheel pairs equipped with devices for direct measurement of the interaction forces between wheels and rails. According to this method, the forces of interaction between the wheel and a rail are measured with the help of strain gauges installed on the elements of the wheel pair and combined in the corresponding strain gauge schemes.

The use of measuring wheel pairs gives a number of advantages. Such instrumentation provides direct measurement of instantaneous values of contact forces in the wheel-rail system. Direct measurement is opposed to indirect or approximate, which involves determining the forces of interaction of wheels with rails due to deformations of the supporting structures of the running parts.

Methods of measuring the forces of interaction of wheels with rails by wheel deformations can be divided into two technologies:

1 - measurement of stresses in spokes of spoked wheels;
2 - measurement of stresses in the wheel disc, i.e. between the axle and the rim.

The method associated with the equipment of tensometric schemes of spoked wheels is not used often, mainly due to the need to manufacture wheels of a special design. At the same time, with proper design, manufacture and appropriate calibration, strain gauge wheel pairs with spoked wheels provide high measurement accuracy.

Among the methods of experimental determination of the wheel-rail interaction forces, the method based on the deformation measurements of the wheel discs is nowadays gaining widespread use. There are a number of different projects within this method. The basic principle is measurement of stresses in specific places on the wheels.

An important problem of force-measuring wheel pairs is the need to compensate for "parasitic" effects and to prevent mutual influences between forces acting in different directions. Parasitic effects include the influence of wheel rotation, temperature, and the position of forces on the wheels. It is also necessary to take into account the influence of magnetoelectric phenomena, since the very strong currents (1000-2000 A) sometimes pass only at a distance of 50-100 mm from the wheels and cable lines. In addition, the effects of humidity, temperature and mechanical impact of a shock nature should be taken into account. Thus, the ultimate goal is to achieve output signals proportional to

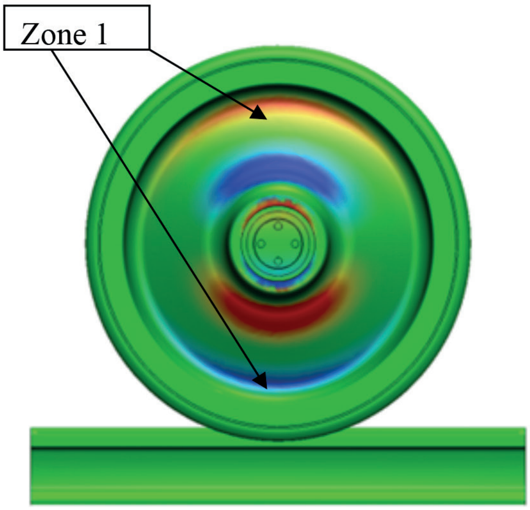

Figure 2 *Chart of wheel surface stresses under vertical load*

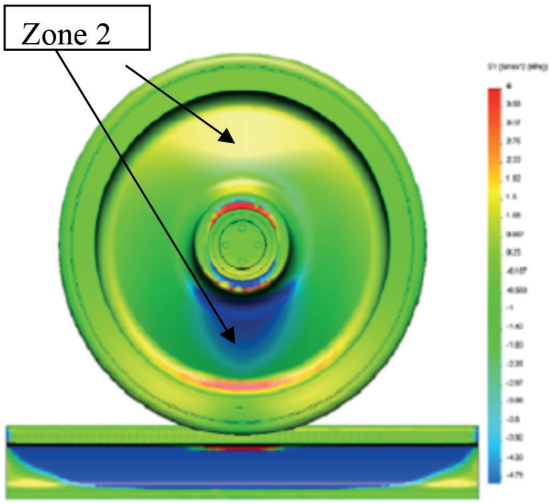

Figure 3 *Chart of wheel surface stresses under vertical load and under the simultaneous action of vertical and lateral forces*

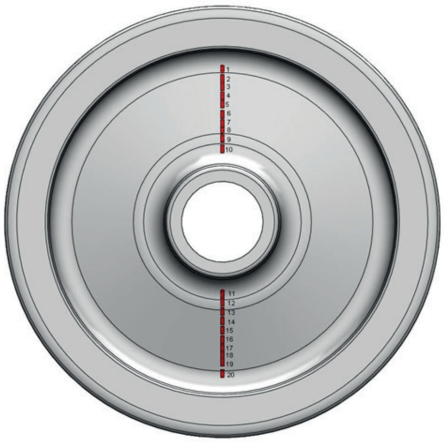

Figure 4 *Schematics of stress gauge placement on the wheel disc*

the applied load with a minimum of mutual influences and parasitic effects.

The main advantage of this method is that it provides an opportunity to measure horizontal (Y) and vertical (Q) forces continuously and close to the wheel-rail interface. It is also possible to measure fairly high-frequency force processes (at least up to 100 Hz). The accuracy of measurements can be quite high (at least within 5-10%).

Figure 1 shows the general view of the tensometric wheelset for measuring miles of interaction between wheel pairs and rails.

3.4 Determination of zones of deformation sensitivity of the wheel disc to force load

Places of tensor resistors on wheel disks and ways of including them in the measuring scheme should be such that, with sufficient sensitivity of the scheme to the action of the measured force, the influence of the force in the other direction is as small as possible. Therefore, studies on the determination of the zones on the surface of the wheel disk, the deformations of which are caused by the action of purely vertical and horizontal contact forces, are necessary to substantiate the recommendations for equipment with strain gauge schemes.

To carry out calculations of the stress-strain state of the wheelset using the finite element method, 3D models of individual elements of the wagon wheelset and rails of the R65 type were created, from which a general 3D model of the wheelset installed on the rails was made.

The determination of the zones of deformation sensitivity of the wheel disc is carried out according to the following calculated cases of the wheel pair load:

a) vertical load;
b) loading by vertical forces and forces from the action of the tare system (horizontal load).

The vertical loads were set based on the mass of the wagon of 52 tons. The lateral load scheme simulated the application of horizontally directed forces from the tare

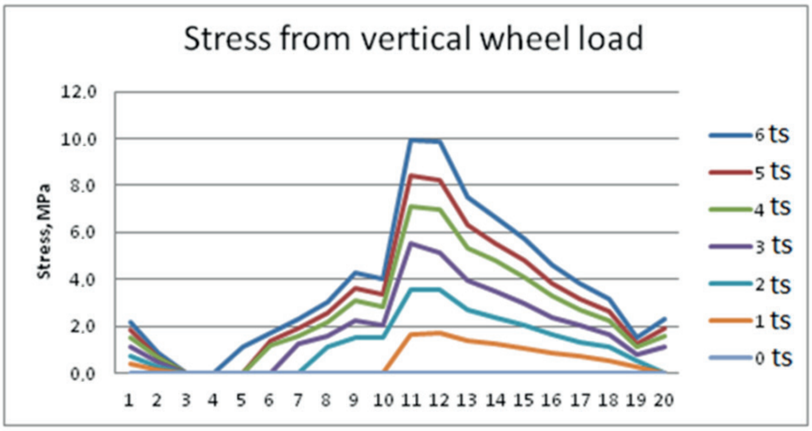

Figure 5 *Distribution of stresses from the vertical load of the wheel*

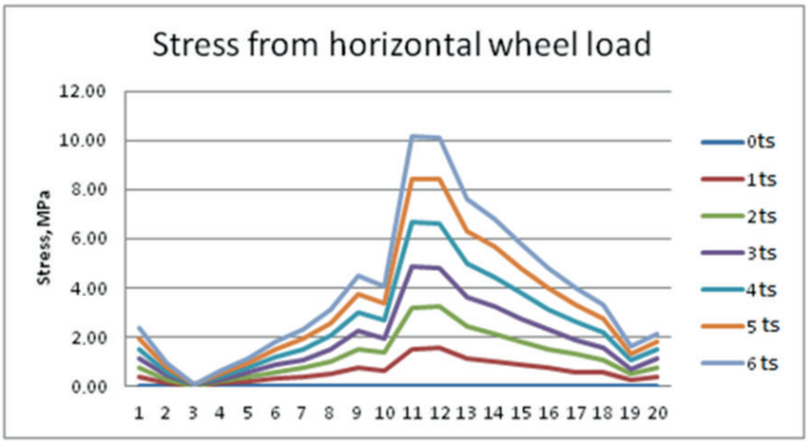

Figure 6 *Stress distribution from horizontal wheel load*

device to the outer face of the wheel above the contact with the rail. In the calculations, the value of the lateral force was set at the level of 50 kN.

The results of the calculation of the surface stresses distribution of the wheel under vertical load (Figure 2) and simultaneous action of vertical and lateral forces (Figure 3) are presented. As can be seen, the greatest stresses in the wheel disc under vertical load occur in the transition zone of the disc to the rim (zone I), as well as in the place adjacent to the hub (zone III). In the case of lateral loading, deformations spread to the middle part of the disk (zone II) near the area of attachment to the hub.

Thus, according to the results of VAT calculations of the wheel disc, zone III was the most sensitive in terms of deformations to both vertical and lateral loads. Therefore, for the lateral load measurement, zone II should be chosen, which is practically sensitive only to lateral forces, and zone I should be chosen for vertical load measurement.

Places of tensor resistors on the disc of a wheel pair and methods of their inclusion in the measuring scheme should be such that, with sufficient sensitivity of the scheme to the measured force, influence on the scheme of the force of the other direction is excluded. To clarify the locations on the wheel disk of the points of sensitive zones to the action of vertical and lateral loads, appropriate experimental studies were conducted. Tensor resistors were placed on the wheel disc in the radial direction with a step equal to the base of the tensor resistor. The diagram of placing tensor resistors on the wheel disk is presented in Figure 4. A total of 20 tensor resistors were installed along the diametrical direction of the wheel.

The vertical load of the wheel was created by the weight of the wagon body. Figure 5 shows the stress distribution from the vertical load of the wheel, measured at the placement points of each tensor. As can be seen, in this case the greatest stresses occur at points 9-12.

The results of stress measurements, when the wheel is loaded with lateral forces, are presented in Figure 6. Here, the stress distribution graphs correspond to the power-level values of the forces. As with vertical loading, points 9 to 12 turned out to be the most sensitive in this case.

The obtained experimental data allow to identify the zones of maximum stress that occur on the wheel

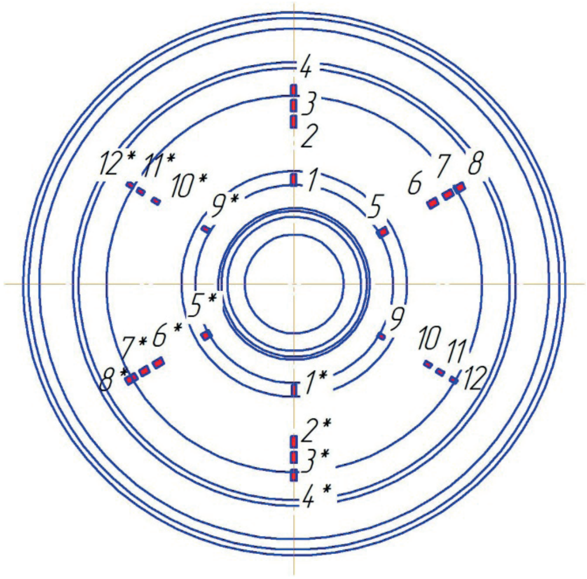

***Figure 7** The diagram of placement of tensor resistors for determining the forces of interaction of wheels and rails*

***Figure 8** Measuring scheme on the experimental wheel pair*

disc under the action of lateral (horizontal) and vertical loads. Experimental data, taking into account the results of computer modelling of the wheel load, provide the basis for the development of a refined tensometric scheme for direct measurements of the interaction forces between wheels and rails.

Based on the calculations and experimental data for determining the zones of deformation sensitivity of the disk of a standard wagon wheel to vertical and lateral loads, a scheme for placing strain gauges for determining the contact forces of the interaction of wheels and rails is recommended, which is shown in Figure 7.

Points 1-1*, 5-5*, 9-9* indicate the places where the greatest stresses occur. Points 2-2*, 6-6*, 10-10* are selected for measuring lateral forces, and 3-3*, 7-7*, 11-11* for vertical ones. Measurement of deformations at points 4-4*, 8-8*, 12-12* is intended to determine the momentary position of the wheel during the carriage movement.

3.5 An experimental study on measuring the interaction forces of a wheel pair with rails

Experimental studies on the direct measurement of forces in the wheel-rail system were carried out on the carriage of a passenger car. Stress gauges were installed on the wheel pair of the experimental cart according to the proposed scheme (Figure 7). After installing the strain gauges on the wheel disc, measuring circuits were installed (Figure 8). The measuring equipment and batteries were mounted on the axle of the wheel pair using a special mount.

To establish the relationship between the readings of the strain gauges and the load in the vertical direction, the measurement system was calibrated.

The test trip was conducted on a section of the track with a length of about 20 km. The position of the wagon on the site and the speed of its movement were

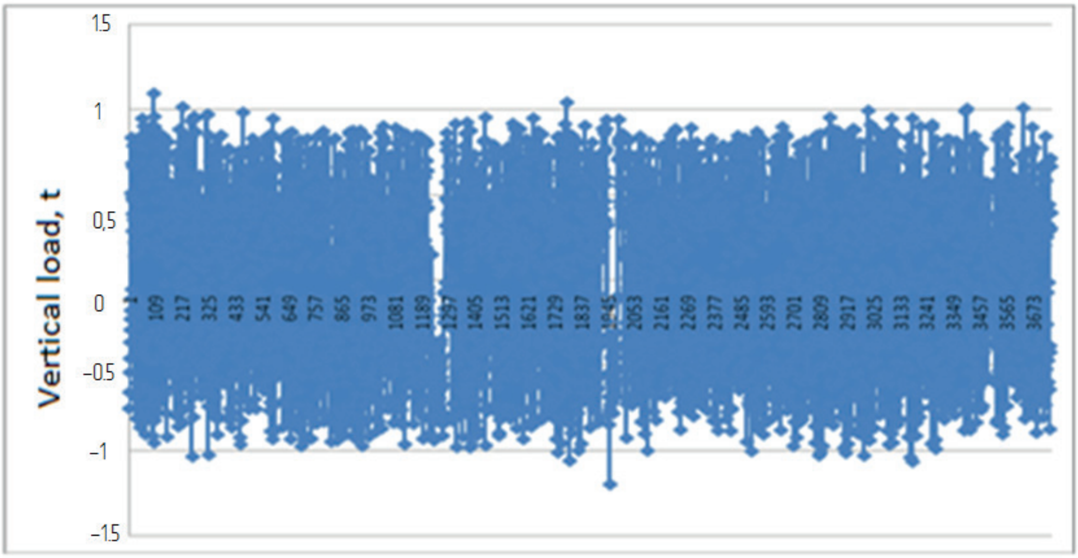

Figure 9 *Recording of vertical forces*

Figure 10 *Recording of horizontal forces*

determined with the help of a GPS-Logger. The GPS survey was conducted once per second.

Strain measurement data was recorded using a software-hardware complex, which consists of a hardware part based on the NI cRIO 9012 controller, an eight-slot NI cRIO 9104 chassis with NI9237 modules, and a software-virtual recorder developed in the LabView software shell.

The software of the complex performs the following functions:

a) configuration of measuring channels;
b) selection of the strain gauge connection scheme;
c) autonomous registration of signals on the internal FLASH storage device;
d) data recording in a text file (for further processing).

Signals were recorded on a local FLASH drive. Figure 9 and Figure 10 provide a complete record of the forces that occurred during the test ride.

4 Results and discussion

4.1 General requirements for the system of direct measurement of the interaction forces of wheel pairs of high-speed rolling stock with rails

A mobile system for measuring the interaction forces of wheel pairs of high-speed rolling stock with rails should include:

- sensors primary converters;
- GPS receiver;
- cables for signal transmission;
- system of collection and registration of measurement indicators;
- transfer of data about the location and status of the system to the server;
- determination and assessment of traffic quality and safety indicators in the modeexpress processing.

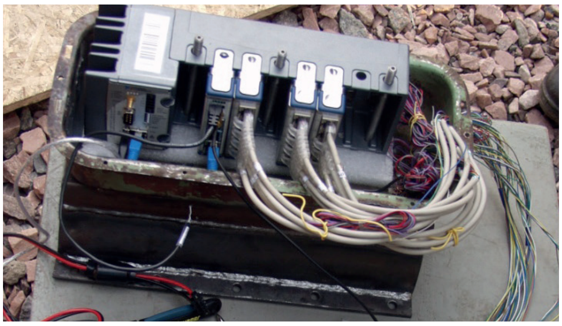

Figure 11 *The direct measurement system for assessing the forces involved in the interaction between the wheel pairs and rails*

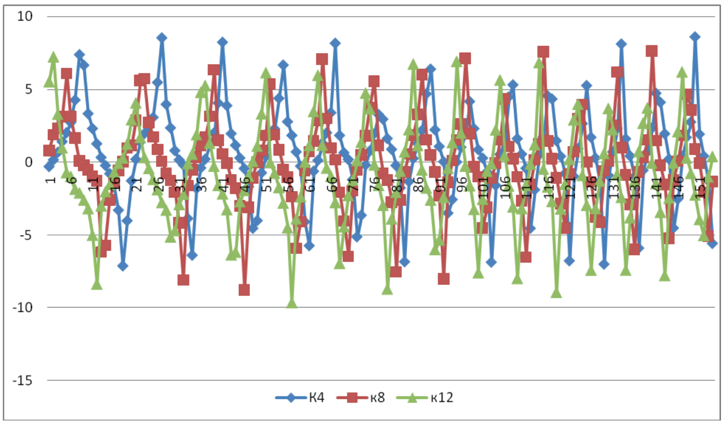

Figure 12 *A fragment of the vertical load record*

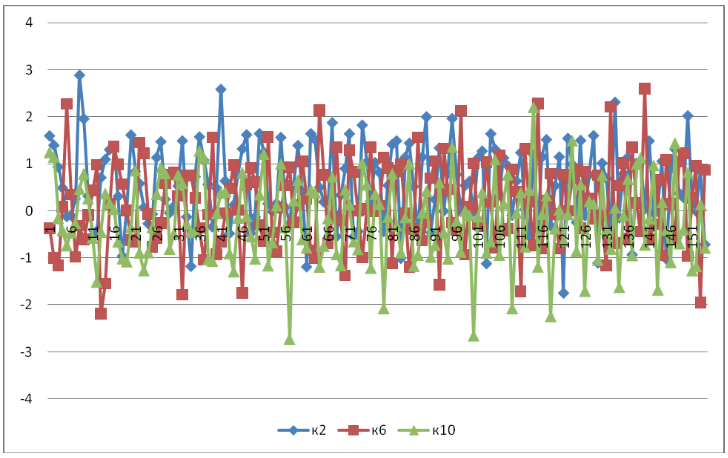

Figure 13 *A fragment of the lateral load record*

The mobile system for measuring the interaction forces of wheel pairs of high-speed rolling stock with rails based on National Instruments CompactRIO solves a wide list of tasks aimed at monitoring the technical condition of rolling stock during tests and in normal operation.

The software of the software-hardware logger is developed in the LabView FPGA software shell.

The application software is designed to read measurement data from channels selected by the user at the hardware level with a specified sampling frequency, select the type of connection of the outputs of the primary measuring transducers, and set the voltage measurement limits.

The NI 9012 controller application software consists of two parts. The first part reads data from NI 9237 and NI 9205 ADC modules, performs data processing and writes to the non-volatile memory of the controller. The second part transmits data using the Transmission Control Protocol (TCP) to an external computer.

The general view of the system for the system of direct measurement of the forces of interaction of wheel pairs of high-speed rolling stock with rails is shown in Figure 11.

Results of the study are now analyzed in more details on measuring the forces of interaction between the wheel pair and the rails. Figures 12 and 13 show

Table 1 *Results of statistical processing of contact force values*

Estimation of magnitude	Q (ton-force)	Y (ton-force)
Mean square deviation	0.47	0.33
Maximum value	9.77	0.99

fragments of vertical and lateral load processes at a speed of 36 km/h, respectively.

Based on the results of taring, calculations and experimental research of the stress-strain state of the wheel disks, the actual value of the interaction forces was determined by the readings of those sensors that were in a vertical position relative to the track plane.

Representative parts of the records of dynamic processes at v = 36 km/h were subjected to statistical processing. The results of this processing are shown in Table 1. Here, the maximum values of the studied quantity are determined by the expression:

$$\bar{x}_{\max} = \bar{x} + ks\,, \tag{1}$$

where:
$\bar{x}$ - arithmetic mean (mathematical expectation),
s - root mean square deviation (RMS),
k - is a coefficient that depends on the given level of reliability.

For values ΣY and Y/Q, which are important for evaluation of the traffic safety, k = 3, for other calculated quantities, k = 2.2, except for quasi-static, for which k = 0. Since the values of contact forces are important for evaluation of the traffic safety, then is taken equal to three.

5 Conclusions

The outcomes of the research focused on directly measuring the forces between the wheel pairs and rails, support the following scientifically grounded conclusions:

1. The approach to measuring the forces involved in the interaction between the wheels and rails, which relies on the deformation of elements in the upper track structure, is constrained to short track sections. Consequently, it does not facilitate continuous monitoring of the force exertion on the moving parts of rolling stock when traversing track sections that exhibit heterogeneity in terms of plan, profile, and condition. At the same time, this method is becoming widely used to identify wagons in trains with deviations in the technical condition of elements of running parts.
2. Theoretically and experimentally, the zones of dependence of the occurrence of stresses on the disk of a standard wagon wheel under the action of vertical and horizontal force load have been determined, which provide grounds for the development of a refined tensometric scheme for direct measurements of the interaction forces between wheels and rails.
3. A scheme for placement of tensoresistors is proposed for determining the contact forces of the interaction of wheels and rails to determine the actual margin of stability of wheel pairs from derailment in a direct way.
4. A comparison of the values of rms deviations obtained by computer simulation and from the experiment was carried out and it was established that the discrepancy in the lateral load is 0.22%, and in the vertical - 9.34%. Thus, these data confirm, on the one hand, the reliability of the developed computer model, and on the other, the effectiveness of the method of direct measurement of the contact forces of the interaction of wheels and rails.
5. The developed general requirements for the system of direct measurement of the interaction forces of wheels with rails provide for the following:
   5.1. For the high-speed passenger wagons, it is mandatory to assess the interaction forces using wheel pairs equipped with strain gauges;
   5.2. Determining the locations of the strain gauges on the wheel discs must be accompanied by calculations of the stress-strain state of the wheel pairs under the complex loading by forces that correspond to the operating conditions in terms of magnitude and points of application;
   5.3. Specialized devices should be used to calibrate the strain gauges placed on the wheels of the measuring wheel pairs - to implement the lateral load of the wheel in the part that is as close as possible to the zone of its contact with the rail, and to apply the vertical load.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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