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SYSTEM FOR MONITORING THE STRENGTH AND DYNAMIC CHARACTERISTICS OF FREIGHT WAGONS IN OPERATION

Purpose. Improvement of methods and tools for experimental evaluation of the quality and safety indicators of freight wagons by enhancing the theoretical foundations, methodological approach, and instrumental support for testing. It is proposed to implement software and hardware systems instead of laboratory wagons to determine the quality indicators of wagon movement, as well as to provide recommendations for assessing the dynamic performance of rolling stock.

Methodology. The paper examines the features of monitoring the strength and dynamic characteristics of freight wagons using modern measurement systems under operating conditions. It describes a method for measuring wheel-rail interaction forces by determining deformations at control points and highlights the general requirements for force measurement systems to ensure traffic safety. The study provides recommendations for direct measurements to assess the stability margin of wheelsets (quality indicators of movement), which will help prevent transport incidents. Additionally, emphasis is placed on the need to improve methodological and software support for evaluating movement quality indicators.

Findings. A transition from laboratory wagons to mobile software and hardware systems for rolling stock testing has been proposed, which will enhance the efficiency and accuracy of movement quality evaluation. The dependency areas of stress formation in the disk of a standard freight wagon wheel under vertical and horizontal force loads have been identified. An improved strain gauge scheme for measuring wheel-rail interaction forces has been proposed.

Originality. General requirements for a mobile software and hardware system for measuring and evaluating the quality indicators of freight wagon movement under operating conditions have been developed, and field tests using this system have been conducted.

Practical value. The obtained research results make it possible to formulate general requirements for a mobile software and hardware system for measuring and evaluating the quality indicators of freight wagon movement under operating conditions. These results should be used in the development and design of systems for railway rolling stock aimed at monitoring traffic safety by measuring strength and dynamic parameters. This, in turn, will enhance the safety of railway transportation.

Keywords: *testing, traffic safety, freight wagons, mobile system*

Introduction. Traffic safety is a combination of organizational and technical measures that ensure accident-free operation and the maintenance of railway infrastructure, tracks, rolling stock, equipment, and mechanisms in proper working condition.

The operation of rolling stock and complex technical systems is often subject to failures caused by factors such as non-compliance with manufacturing technological requirements, harsh operating conditions, violations of usage regulations, as well as aging and wear of individual components.

With the advancement of measurement technology and systems, new opportunities arise for implementing modern instrumental and software-based approaches to assessing train movement quality and safety, as well as for taking preventive measures against emergency situations.

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Thus, improving methods and tools for the experimental evaluation of freight wagon movement quality and safety indicators is highly relevant, particularly through the enhancement of methodologies, software solutions, and instrumental testing systems.

Literature review. In study [1], the authors describe the features and methodology for measuring the interaction forces between wheelsets and rails by assessing wheel deformations at control points in passenger cars. However, this study does not address such measurements for freight wagon wheelsets.

Study [2] discusses railway rolling stock testing using modern measurement systems that evaluate the quality indicators of wagon movement based on frame forces. However, the work does not consider simultaneous measurement of movement quality indicators in multiple test zones of the rolling stock.

Study [3] examines the key criteria for the interaction process between the pantograph and the contact wire. It also analyzes the causes and consequences of

current collection disruptions. Based on the research results, the authors developed an experimental system to determine interaction parameters for different types of rolling stock pantographs with the contact network under operational conditions. However, this study does not explore the possibility of measuring other safety indicators, such as the stability margin coefficient of a wheel against derailment.

In study [4], the authors describe the dynamic interaction between wheels and rails and assess wheel wear in freight wagons and metro wagons. However, the study does not examine the overall impact of wheel wear on traffic safety indicators.

In study [5], the authors propose an innovative diagnostic method using an indicator called the Hunting Coefficient (HC). This method is based on analyzing the transverse amplitude and frequency of wheelset oscillations, allowing for continuous monitoring of the technical condition of freight wagons. However, the authors do not describe the potential application of this method for acceptance testing of newly manufactured railway products.

Study [6] presents an algorithm for reverse determination of wheel-rail interaction forces, specifically the derailment coefficient, based on measurement signals obtained from instrumented wheelsets. The approach utilizes Blind Signal Separation (BSS) and Independent Component Analysis (ICA). The verification was conducted on a freight wagon wheelset using an MCE-based wheel model. The results demonstrated high efficiency and accuracy of the developed algorithm, with the estimated error of reverse identification being less than 5 %.

Study [7] calculates the quality indicators of freight wagon movement with a Y25 bogie using simulation. The calculations were performed for both empty and loaded wagons moving along curves of different radii and at various speeds. However, the study does not assess wheel-rail interaction parameters.

In study [8], the dynamic characteristics of three different types of freight bogies are compared. The results showed no significant differences among the three bogie types when operating at speeds of 40 to 120 km/h on a straight tangent track section. The study also suggests improving the dynamic performance of freight wagons by optimizing the suspension component parameters. However, the methodology for comparing dynamic indicators is not described in detail.

Study [9] describes a system that enables real-time monitoring of train parameters such as speed, wagon weight, and the number of train axles. This weigh-in-motion system, using optical sensors, measures dynamic axle loads and calculates the corresponding static values.

In study [10], the authors propose using sandwich panels for freight wagon sidewalls to reduce operational loads on the wagon body. The findings indicate that stress levels in the wagon body remain within permissible limits and are 3.5 % lower than those in a typical structure. However, the study does not address how using sandwich panels affects the dynamic performance of freight wagons.

Study [11] presents an improved design of a hopper wagon to enable the simultaneous transportation of different types of cargo. The enhancement involves dividing the body into two separate sections that interact through a vertical wall and horizontal connecting bands. The structural strength of the two-section hopper wagon was assessed using the finite element method in SolidWorks Simulation. However, the study does not examine how these design modifications impact the wagon's dynamic performance.

Study [12] investigates the effect of lateral bogie displacement in open-top wagons on their primary dynamic parameters and wheel-rail interaction characteristics. The research established dependencies of freight wagon dynamic indicators on the body rotation angle and speed. Additionally, the study identifies the influence of lateral displacement of the running gear on rolling stock dynamic performance and wheel-rail interaction, considering speed and track curvature.

In study [13], the authors explore methodological improvements for identifying potential causes of freight wagon instability and derailment. Using a basic computational model of freight wagon dynamics, a numerical experiment was conducted to analyze the impact of the running gear and track condition on empty wagon derailment stability. The study concluded that excessive wedge height in damping mechanisms poses the highest risk to empty freight wagon stability on the track.

Study [14] examines the nonlinear damping characteristics of friction wedges in the suspension system of a freight wagon, considering unilateral contact, multi-axial motion, slip conditions, and wedge geometry. The resulting 114-degree-of-freedom wagon model included constraints related to side bearings, axle boxes, and center plates, while wheel-rail contact forces were calculated using the FASTSIM algorithm. However, the study does not describe the actual measurement and evaluation process for safety indicators.

Study [15] focuses on railway safety, emphasizing the fact that railway companies and equipment manufacturers must ensure the highest quality, service, and reliability. The authors suggest that a motion detection support system could be developed to improve railway crossing safety. This support system should be independent of existing control devices. The article presents the concept of using vibrational wave propagation as a source of train or vehicle detection information.

In study [16], the authors evaluate railway rolling stock safety conditions using computer modeling. The paper analyzes possible derailment causes by assessing the effectiveness of rolling stock and track interaction. It also examines how the technical condition of damping devices affects the safety of passenger wagons. However, this study focuses exclusively on passenger railcars.

Study [17] investigates how different types of rolling stock and train speeds affect key dynamic indicators and track-vehicle interaction parameters. The research is based on mathematical and computer modeling of dynamic loads in freight wagons, using a spatial variation model for a five-wagon train. Theoretical studies were conducted for different types of freight wagons, but the paper does not address evaluating these parameters under real operating conditions.

In study [18], the authors present an experiment to determine the typical stress spectrum in parabolic leaf springs of freight wagons. The stress spectrum in the leaf spring is correlated with the load spectrum acting on the wheelset. Data is collected using strain gauges and po-

tentiometers mounted on the leaf spring and axle box. However, the study is limited to identifying stresses in leaf springs and does not examine their impact on movement quality indicators.

Study [19] describes a simulation analysis of freight wagon dynamics with two types of damping: dry friction and viscous damping. The paper details the differences between these damping mechanisms, but it does not explore how different damping types affect the wheelset stability margin against derailment.

In study [20], the authors examine sorting modes for freight trains with different types of freight wagons and their impact on longitudinal forces during rainy conditions. An imitation model for mixed freight trains was developed, along with several typical mixed sorting modes. However, this model does not assess the movement quality indicators of freight cars.

Unsolved aspects of the problem. The goal of increasing the speed of freight trains necessitates the implementation of new methods for assessing train safety indicators and the technical condition of freight wagons. The stability of rolling stock on the track is determined by the ratio of forces arising in the wheel-rail contact. Calculating these forces is a complex task due to the constant movement of the contact zone along the rolling surfaces of the wheels and rails.

Furthermore, ensuring wheel stability and preventing wheel climb onto the rail requires continuous analysis of the ratio between horizontal and vertical contact forces over a certain period. Addressing this challenge demands the development of a modern system for determining the movement quality indicators and the technical condition of freight wagons in operation.

Purpose and task statement. The objective of this article is to present the results of developing general requirements for a mobile software and hardware system designed to measure and evaluate the movement quality indicators of freight wagons under operating conditions.

This study aims to explore the feasibility of integrating mobile diagnostic systems into existing rolling stock and to assess their performance in real-world operational environments.

The mobile software and hardware system should include the following technical and functional features:

1. Implementation of a mobile approach – The system enables data collection directly in field conditions, reducing the need for stationary equipment.
2. Integration of IoT technologies – The system can utilize IoT sensors for real-time wireless data transmission to a server for further processing.
3. Comprehensive data analysis – The system combines multiple data types (vibration analysis, mechanical stresses, etc.) for more accurate diagnostics.
4. Autonomy and energy efficiency – The system can be equipped with autonomous power sources, ensuring its usability in various conditions.

Presentation of the main material with a description of the software and mathematical support. The software and mathematical support is designed to assess and record the movement quality indicators of railway rolling stock during operation. Experimental data processing is carried out using the LabVIEW software environment, where algorithms for analyzing and processing the results of dynamic tests are implemented.

The main function of the software is to determine the relationships between the vibrational processes of load-bearing structures, identify interaction frequencies, and evaluate the levels of these interactions. To achieve this, correlation and spectral analysis methods are applied to various structural elements.

The data obtained during measurements is represented as a multidimensional time series, where each row corresponds to a one-dimensional time series derived from an individual measurement channel.

Fig. 1 presents the software scheme, which consists of five main modules, each responsible for a specific stage of data processing.

This solution enables an in-depth analysis of the dynamic properties of rolling stock, improving the accuracy of its condition diagnostics.

One of the standard functions of LabVIEW used for analyzing rolling stock test data is digital signal filtering. A digital filter (DF) is defined as any digital system that transforms an input additive mixture $\tilde{x}(n) = x(n) + \xi(n)$ (where $\tilde{x}(n)$ is the desired signal and $\xi(n)$ represents noise) according to a given operator $y(n) = F\{\tilde{x}(n)\}$.

In our case, for evaluating dynamic and safety indicators, we use the Butterworth filter, which provides a maximally flat frequency response in the passband, ensuring smooth and distortion-free filtering.

The transfer function of the Butterworth filter prototype is given by

$$K(\omega) = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_0}\right)^{2n}}}, \quad (1)$$

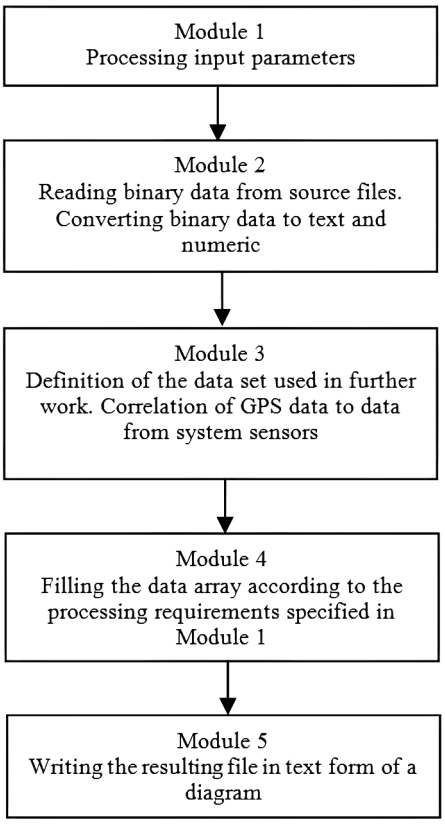

Fig. 1. Scheme of the software

where ω_0 is cutoff frequency (for the prototype filter it is 1 rad/s); n – filter order. The transmission coefficient at zero frequency is 1, and at the cutoff frequency, regardless of the filter order, is $1/\sqrt{2} \approx 0.707 \approx 3$ dB. As $\omega \to \infty$ the amplitude-frequency response (AFC) approaches zero. The frequency response of the Butterworth filter is maximally flat at $\omega = 0$ and $\omega = \infty$. In general AFC monotonically from unity to zero as the frequency changes from zero to infinity (Fig. 2).

One of the key indicators of running quality is the wheelset stability margin coefficient. It evaluates the wheelset's resistance to derailment in the event of the wheel flange climbing onto the rail head.

To predict situations that pose a risk of wheelset derailment, stability is assessed in the track based on the coefficient k_{st}.

The calculation of k_{st} is performed for the most unfavorable combinations of horizontal and vertical forces acting on the wheelsets during movement, using the formula

$$k_{st} = \frac{\mathrm{tg}\beta - f_{sf}}{1 + f_{sf} \cdot \mathrm{tg}\beta} \cdot \frac{P_v}{P_h} \geq \left[k_{st}\right], \qquad (2)$$

where β is the angle of inclination to the horizon of the generating conical surface of the wheel crest; f_{sf} – the coefficient of sliding friction of the interacting surfaces of wheels and rails; P_v – a vertical component of the forces acting from the wheels on the rails; P_h – a horizontal component of the forces of interaction of the wheel with the rail, which acts simultaneously with the force P_v.

Presentation of the main material on the identification of deformation sensitivity zones of the wheel disc to force loading. The placement of strain gauges on the wheelset disc and their connection in the measurement circuit must be designed to ensure sufficient sensitivity to the measured force while eliminating the influence of forces acting in other directions.

Thus, for the separate registration of forces acting on the wheelset, it is necessary to determine the optimal locations for strain gauges, ensuring that each gauge is sensitive only to the force acting in a specific direction.

The determination of sensitive zones on the wheel disc was carried out through stress-strain state calculations of the wheelset using the finite element method (FEM).

Fig. 3 presents the refined locations of sensitive points on the wheel disc, which are responsive to vertical and lateral loads, as determined from the FEM calculations. These locations were selected to maximize measurement accuracy and minimize cross-sensitivity to unwanted force components.

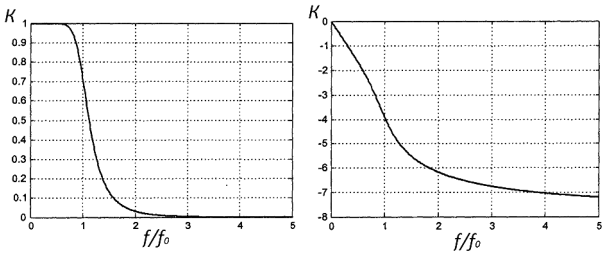

Fig. 2. Characteristics of the Butterworth filter

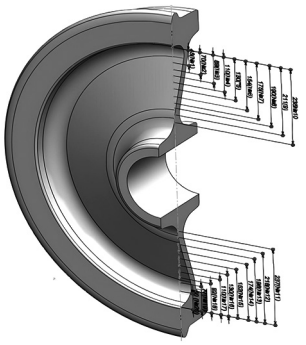

Fig. 3. Sensitive areas to vertical and lateral loads

The obtained experimental data allow for identifying zones of maximum stresses occurring on the wheel disc under lateral (horizontal) and vertical loads. Based on these findings, an optimal strain gauge placement scheme on the wheel discs is proposed to accurately determine the vertical and lateral forces acting on the wheelsets (Fig. 4).

For the calibration of strain gauge circuits mounted on the wheels, specialized devices should be used – one for applying lateral loading to the wheel in the area closest to its contact with the rail and another for applying vertical loading.

Presentation of the main material: description of the hardware component of the control system. The mobile system for monitoring the strength and dynamic characteristics of freight wagons in operation consists of primary transducers, a global positioning system (GPS) receiver, analog signal transmission lines, subsystems for collecting measurement data, express processing of safety indicators, and determining dynamic stresses.

The primary transducers include strain gauges, low-frequency accelerometers, and displacement sensors. The analog signal transmission lines consist of cables that connect the primary transducers to recording devices operating at voltages up to 10 V and are integral components of the measurement system. The cables are shielded, resistant to oils, have six conductors, and possess flexibility corresponding to Class 2, maintaining their properties at temperatures ranging from –40 to +80 °C.

The system performs two main functions: real-time assessment of strength and safety indicators, as well as autonomous measurement of physical parameters (displacement, acceleration, and deformation) with subsequent statistical data processing. To analyze the influence of speed on changes in the monitored parameters,

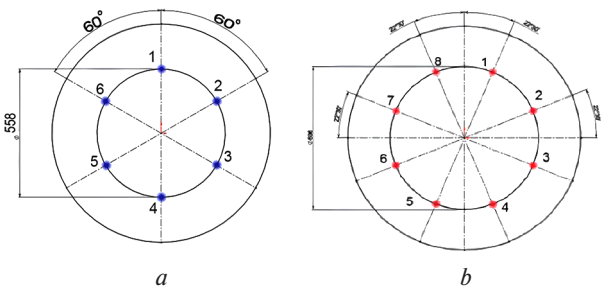

Fig. 4. Layout of strain gauges for measuring deformations:
a – from vertical load; b – from lateral load

as well as to determine precise time and current coordinates, data obtained from the GPS module is utilized.

The mobile system enables autonomous control tests for the dynamic diagnostics of rolling stock units. This is essential for assessing the load on running gear, which is a key factor in verifying the quality of major repairs, determining the remaining service life of load-bearing structures, conducting control tests as part of service life extension procedures, and analyzing loads on running gear during operation.

The general block diagram of the mobile system for monitoring the strength and dynamic characteristics of freight wagons in operation is shown in Fig. 5.

Application of the mobile system in operational conditions. For field tests, a hopper wagon was selected for bulk transportation of grain and other similar food-grade loose cargo, with key technical characteristics optimized for transporting corn (a priority crop for Ukraine). This wagon was designed and manufactured by the Panyutynsky Railcar Repair Plant, a branch of JSC "Ukrzaliznytsia", and adapted for operation on the railways of European countries and Ukraine (Fig. 6).

To measure dynamic stress indicators, strain gauges were installed on the load-bearing structures of the wagon. For recording safety indicators (stability margin coefficient), strain gauges were mounted on the wheelset discs according to the proposed placement scheme (Fig. 4), and accelerometers were installed on both the sprung and unsprung parts of the wagon. The installed recording sensors were connected to the mobile system using cables.

To determine the most stressed areas of the grain hopper wagon's load-bearing structure, a standard strength calculation was performed in accordance with DSTU 7598 requirements.

Figs. 7 and 8 show the control zones (strain gauge installation points) on the load-bearing structure of the grain hopper wagon, identified based on the normative strength calculation using SolidWorks Simulation software.

An example of a wagon with a mobile system is shown in Fig. 9.

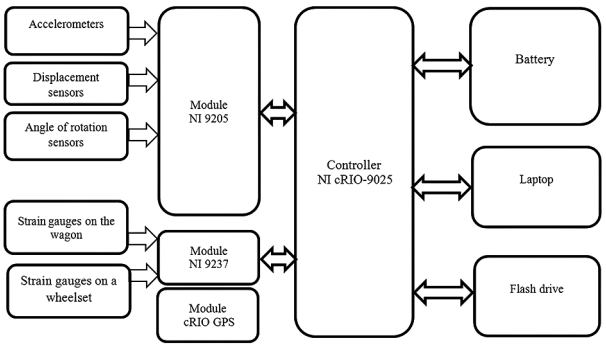

Fig. 5. Block diagram of a mobile system for monitoring strength and dynamic characteristics

Fig. 6. Grain wagon on 1,520 and 1,435 mm tracks

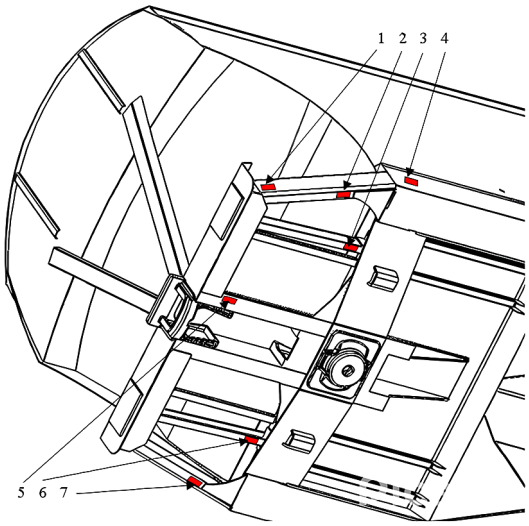

Fig. 7. Installation locations of strain gauges

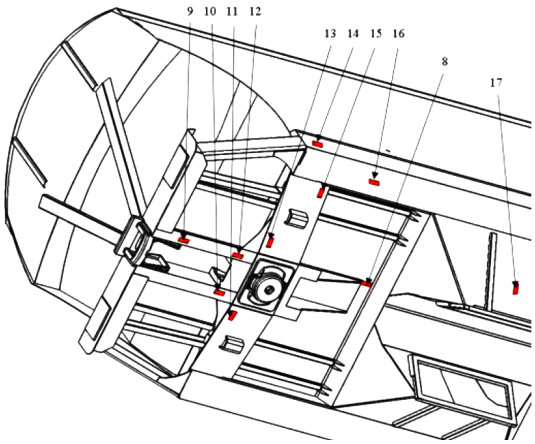

Fig. 8. Installation locations of strain gauges

Fig. 9. The wagon is equipped with a mobile measuring system

Table 1

Results of dynamic stress determination

Indicator	Normative value, MPa	Actual value, MPa	
		For 1,520 mm track	For 1,435 mm track
Dynamic stresses:	for steel S355		
Channel 1	319.5 according	41.8	40.5
Channel 2	to DSTU 7598	14.3	19.1
Channel 3	for steel 09G2S	6.4	7.4
Channel 4	310.5 according	1.7	4.3
Channel 5	to DSTU 7598	5.7	3.1
Channel 6		11.1	16.4
Channel 7		16.7	12.1
Channel 8		20.4	14.3
Channel 9		11.8	10.9
Channel 10		7.8	7.4
Channel 11		14.3	13.5
Channel 12		23.8	21.4
Channel 13		19.8	20.4
Channel 14		3.3	2.5
Channel 15		13.9	11.7
Channel 16		4.0	4.6
Channel 17		15.4	14.8

Strength and dynamic running tests were conducted on the experimental grain hopper wagon in a loaded state on 1,520 and 1,435 mm track gauges. The purpose of these tests was to determine the quality and safety indicators of movement, including dynamic stresses, stability margin coefficient, and acceleration of wagon elements, using the mobile system under operational conditions.

The test results are presented in Tables 1–3.

Presentation of the main material and obtained scientific results.

1. A software-mathematical framework has been developed for determining movement quality and safety indicators, ensuring measurements with an expanded uncertainty of 2.1 % (compared to the maximum allowable 5 %) using mobile systems during operation. This is achieved through the use of high-precision accelerometers for vibration acceleration measurements and modern recording equipment.

2. The stress distribution on the disc of a standard freight wagon wheel under vertical and horizontal force loads has been determined. The obtained results formed the basis for developing an improved strain gauge placement scheme, enabling direct measurement of wheel-rail interaction forces.

Table 2

Results of determining the quality of movement indicators (running dynamic tests on 1,520 mm track)

Indicator	Normative value	Parameters at speed, km/h				
		40	60	80	100	120
Coefficient of vertical dynamics of the body, no more	Perfectly 0.20 Good 0.35 Satisfactory value 0.40 Acceptable value 0.65	0.11	0.15	0.20	0.25	0.3
Coefficient of vertical dynamics of unsprung bogie frame, no more	Perfectly 0.50 Good 0.70 Satisfactory value 0.80 Acceptable value 0.85	0.2	0.22	0.30	0.33	0.37
Coefficient of horizontal dynamics of the body, no more	Perfectly 0.20 Good 0.25 Satisfactory value 0.30 Acceptable value 0.38	0.07	0.08	0.07	0.09	0.11
Wheel derailment safety coefficient, not less	1.3	2.5	2.2	2.2	2.3	2.0

Table 3

Results of determining the quality of movement indicators (running dynamic tests on 1,435 mm track)

Indicator	Normative value	Parameters at speed, km/h				
		40	60	80	100	120
Coefficient of vertical dynamics of the body, no more	Perfectly 0.20 Good 0.35 Satisfactory value 0.40 Acceptable value 0.65	0.13	0.17	0.21	0.24	0.33
Coefficient of vertical dynamics of unsprung bogie frame, no more	Perfectly 0.50 Good 0.70 Satisfactory value 0.80 Acceptable value 0.85	0.3	0.32	0.34	0.34	0.39
Coefficient of horizontal dynamics of the body, no more	Perfectly 0.20 Good 0.25 Satisfactory value 0.30 Acceptable value 0.38	0.06	0.08	0.07	0.10	0.13
Wheel derailment safety coefficient, not less	1.3	2.4	2.3	2.2	2.0	1.9

3. A strain gauge placement scheme has been proposed to determine the contact forces of wheel-rail interaction. This allows for a direct assessment of the actual stability margin of wheelsets against derailment.

4. General requirements for the mobile system used to determine movement quality and safety indicators of freight wagons in operation have been established and implemented. This system enables the monitoring of movement quality and safety indicators of experimental rolling stock in operational conditions without the need for laboratory wagons.

5. Dynamic and strength running tests of a hopper wagon for bulk grain transportation have been conducted. The measurements of experimental movement quality and safety indicators were carried out using the developed mobile hardware-software complex, designed for measuring and assessing the movement quality of freight wagons in operational conditions.

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Система для контролю міцності та динамічних характеристик вантажних вагонів в експлуатації

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Мета. Удосконалення методів і засобів експериментальної оцінки показників якості та безпеки руху вантажних вагонів шляхом покращення теоретичних основ, методологічного підходу та інструментального забезпечення випробувань. Запропоноване впровадження програмно-апаратних комплексів замість вагонів-лабораторій для визначення показників якості руху вагонів, а також надані рекомендації для оцінки динамічних показників рухомого складу.

Методика. У роботі розглядаються особливості контролю міцності й динамічних характеристик вантажних вагонів сучасними вимірювальними системами в умовах експлуатації. Описано спосіб вимірювання сил взаємодії коліс із рейками через визначення деформацій у контрольних точках, а також висвітлені загальні вимоги до систем вимі-

рювання сил для забезпечення безпеки руху. У роботі викладені рекомендації щодо безпосередніх вимірювань для оцінки запасу стійкості колісних пар (показників якості руху), що сприятиме попередженню транспортних подій. З іншого боку, акцент зроблений на актуальності вдосконалення методологічного та програмного забезпечення для оцінки показників якості руху.

Результати. Запропоновано перехід від вагонів-лабораторій до мобільних програмно-апаратних комплексів для випробувань рухомого складу, що підвищить ефективність і точність оцінки якості руху. Визначені області залежності виникнення напружень у диску стандартного вагонного колеса від дії вертикальних і горизонтальних силових навантажень. Запропонована уточнена тензометрична схема, призначена для вимірювань сил взаємодії коліс із рейками.

Наукова новизна. Розроблені загальні вимоги до мобільного програмно-апаратного комплексу для вимірювань і оцінки показників якості руху вантажних вагонів в умовах експлуатації, проведені натурні випробування за допомогою такої системи.

Практична значимість. Отримані результати досліджень дають можливість сформувати загальні вимоги до мобільного програмно-апаратного комплексу для вимірювань та оцінки показників якості руху вантажних вагонів в умовах експлуатації. Такі результати доцільно використовувати при розробці та проєктуванні систем для залізничного рухомого складу, що спрямовані на контроль безпеки руху, шляхом вимірювання міцності й динамічних показників. Це, у свою чергу, дозволить підвищити безпеку руху на залізничному транспорті.

Ключові слова: *випробування, безпека руху, вантажні вагони, мобільна система*

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