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Overview and analysis of instrumented wheelset designs

Alexander A. Migrov[1], Aleksander V. Tretiakov[2], Mariya V. Zimakova[3]✉

[1, 2, 3] Emperor Alexander I St. Petersburg State Transport University (PGUPS); Saint Petersburg, Russian Federation
[1] amigrov@gmail.ru; https://orcid.org/0000-0001-8630-9209
[2] avtretiakov51@yandex.ru; https://orcid.org/0000-0003-4820-9535
[3] m.zimackova@yandex.ru✉; https://orcid.org/0000-0002-3354-7243

ABSTRACT The article provides an overview and analysis of the designs of instrumented wheelsets used to measure lateral, longitudinal and vertical forces at the point of contact between the wheel and the rail. The use of instrumented wheelsets is an important tool for conducting research and certification tests on rolling stock. The relevance of this tool increases with higher axle loads and higher speeds. In addition, the instrumented wheelsets currently in use allow for the implementation of various (piecewise continuous or continuous) methods for recording vertical and lateral interactive forces in the wheel-rail system in a single turn of a wheel. Point methods of measuring the impact of rolling stock on the railway track by deformation in the rail allow for measuring the force between the wheel and the rail only at the moment when the wheel is above the measuring section of a railway track. The main disadvantage of using existing instrumented wheelsets for estimating the condition of a railway track is that measurements depend on the speed of movement and the discreteness of the measuring equipment. When using an instrumented wheelset for assessing the condition of a railway track, the probability of detecting a section of the track that presents a risk of derailment is not high enough and needs to be increased.

Methods: A retrospective analysis of the use of instrumented wheelsets was conducted; the main stages of the evolution of instrumented wheelsets were identified. The features of the designs of modern Russian and foreign instrumented wheelsets and methods for recording measurements of vertical and lateral forces acting between the wheel and the rail were considered.

Findings: Conclusions were made about the main directions of development and requirements for instrumented wheelsets. A description was provided for the design and characteristics of the instrumented wheelset with continuous measurement recording developed by scholars of PGUPS and NVC Vagony JSC, which features the lowest measurement pitch among the currently known Russian systems and is provided with special software used to detect sections of the railway track that present the risk of derailment.

KEYWORDS: stress-strain state of the wheel plate; wheel-rail system; instrumented wheelset; diagnostics of railway track; continuous measurement recording; monitoring of technical condition

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Научная статья

Обзор и анализ конструкций тензометрических колесных пар

А.А. Мигров[1], А.В. Третьяков[2], М.В. Зимакова[3]✉

[1, 2, 3] Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС); г. Санкт-Петербург, Россия
[1] amigrov@gmail.ru; https://orcid.org/0000-0001-8630-9209
[2] avtretiakov51@yandex.ru; https://orcid.org/0000-0003-4820-9535
[3] m.zimackova@yandex.ru✉; https://orcid.org/0000-0002-3354-7243

АННОТАЦИЯ Выполнен обзор и анализ конструкций тензометрических колесных пар, применяемых для измерения поперечных, продольных и вертикальных сил в точке контакта колеса и рельса. Использование тензометрических колесных пар — важный инструмент для проведения исследований и испытаний подвижного состава. Актуальность его применения возрастает при повышении осевых нагрузок и увеличении скоростей движения. Кроме того, применяемые в настоящее время тензометрические колесные пары позволяют реализовывать различные методы регистрации (кусочно-непрерывные, непрерывные) вертикальных и боковых сил взаимодействия в системе «колесо — рельс» за один оборот колеса. Точечные методы измерения воздействия подвижного состава на железнодорожный путь по деформациям, возникающим в рельсе, позволяют измерить силу между колесом и рельсом только в момент расположения колеса над измерительным сечением, расположенным на участке железнодорожного пути. Основным недостатком применения существующих тензометрических колесных пар для диагностики состояния железнодорожного пути является ограничение в шаге регистрации силового воздействия. Для диагностики состояния железнодорожного пути с использованием тензометрической колесной пары вероятность обнаружения сходоопасного участка пути недостаточно высока и возникает задача ее увеличения.

Выполнен ретроспективный анализ истории применения тензометрических колесных пар, определены основные этапы эволюции конструкций. Рассмотрены особенности конструкций современных отечественных и зарубежных тензометрических колесных пар и методы регистрации измерений вертикальных и боковых сил, действующих между колесом и рельсом.

Сделан вывод об основных направлениях развития и требованиях к тензометрическим колесным парам. Описана конструкция и характеристики тензометрической колесной пары с непрерывной регистрацией измерений, разработанной учеными ПГУПС и сотрудниками АО «НВЦ “Вагоны”», обладающей минимальным расстоянием шага регистрации силового воздействия из известных в настоящее время отечественных конструкций, а также специальным программным обеспечением, применяемым для обнаружения сходоопасных участков железнодорожного пути.

КЛЮЧЕВЫЕ СЛОВА: напряженно-деформированное состояние диска колеса; система «колесо-рельс»; тензометрическая колесная пара; диагностика состояния железнодорожного пути; непрерывная регистрация измерений; мониторинг технического состояния

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INTRODUCTION

When designing and launching production of new rolling stock models, it is necessary to determine the forces acting at the contact point between the wheel and the rail. It is not difficult to calculate static loads at the contact point. But it is much more difficult to determine the forces arising from the dynamic interaction between the rolling stock and the rail. Measuring these interactive forces is crucial in safety certification and testing of new and upgraded high-speed rolling stock in Europe and many other countries. The European standard for testing is EN14363; the standard in use in the United States is 49 CFR 213. Russia has two fundamental methods for determining force action: by using strain gauge circuits located on the rails or an instrumented wheelset with strain gauges.

An instrumented wheelset (IWS) is a railway wheelset equipped with primary transducers and a data transmission system that uses a measuring and computing system to measure forces at the wheel-rail interface during movement.

BRIEF HISTORY OF IWS USE AND DEVELOPMENT

In 1946, in the USSR, Mikhail F. Verigo proposed to perform continuous recording of forces exerted by the wheel on the rail by measuring vertical and horizontal components of the wheel-rail interaction forces using the stress state of the wheel plate [1].

The method of measuring forces using instrumented wheelsets became widely known after it was described in papers by Olson and Johnsson (1959, 1960) [2, 3]. Olson and Johnsson found that radial deformations of the wheel plate were very sensitive to lateral forces and almost insensitive to vertical forces. This allowed them to develop a method of continuous recording of lateral (horizontal, transverse) forces between the wheel and the rail by measuring radial deformations of the wheel plate and design instruments for statistical recording of the average force values.

In 1962, the Electro Motive Division (EMD) of General Motors (GM) created an instrumented wheelset on a locomotive with the measuring equipment that measured lateral force proportional to the average deformation of the wheel plate [4]. Vertical wheel load data was obtained using sensors installed through holes drilled in the wheel plate. The arrangement enabled obtaining a peak signal proportional to the vertical wheel load per revolution. The wheelset was recalibrated in 1968 and was in use until 1972.

In Japan and the United Kingdom, methods for measurement of forces using a arm wheel-based IWS have been developed and refined since 1952 [5]. The greatest contribution to the development of arm wheel-based IWS was made by the British Railways in the 1970s and 1980s [6]. In these instrumented wheelsets, strain gauge sensors are positioned on certain sections

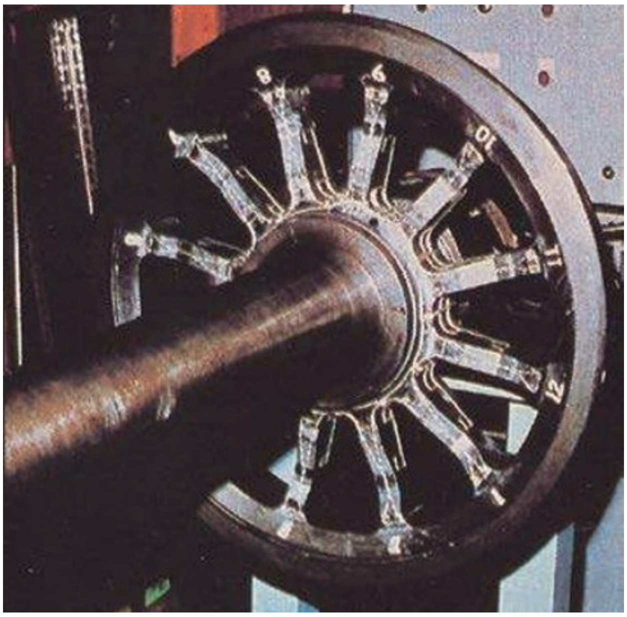

Fig. 1. Arm wheel-based IWS [6]

of the spokes (*Fig. 1*) and connected into bridge circuits. The advantage of this method of measurement is that it provides better sensitivity to vertical force due to higher vertical elasticity. Its main drawback is that machining of spokes is very complicated and expensive and requires high precision. Currently, this method is occasionally used in the United Kingdom and Switzerland [7].

Depending on the position of sensors, there are two types of instrumented wheelset designs: with sensors placed on the axle or on the plate. Instrumented wheelsets with sensors on the axle appeared in the early 1970s. They are based on measuring bending and torsional moments in particular cross-sections of the axle. By measuring bending moments in cross-sections it is possible to estimate approximate vertical and transverse forces on the wheels, with neglect of wheelset mass forces. By also measuring two torsional moments, it is possible to calculate the approximate longitudinal forces. Thus, six forces — two longitudinal, two transverse, and two vertical forces — can be determined from the six moments measured. *Fig. 2* shows a diagram of an instrumented wheelset for measuring bending and torsional moments. Bending moments and torques are measured using strain gauge bridges. Signals are transmitted to the axle via slip rings installed in one of the stub axles of the axle or by radio.

At first sight, the principle of measuring moments and torques of the axle seems quite simple, effective, and precise. Another advantage is that the wheels on the measuring axle can be replaced.

However, the method has two main drawbacks [8].

- Forces can be applied to the wheel in different positions. Since the position of the contact point may change, the position of the vertical force application point will change, too. A change in the position will change the moments measured on the axle, thereby introducing errors that cannot be compensated for, as the actual position where the force is applied is unknown.
- Axle moments depend on the unsprung mass of the axle and other unsprung parts of the wheelset. Thus, it is impossible to fully assess the impact of the unsprung mass on vertical forces.

These drawbacks hamper the use of IWS with sensors on the axle.

In 1973, EMD developed a new instrumented wheelset that used sensors in other positions to minimize the effects of lateral orientation of the wheel/rail on the lateral output, and some new wiring schemes. The strain gauge bridge was configured to make its output sensitive to symmetric bending [10].

In 1973, FRA made a contract with the Association of American Railroads (AAR) to use four CK-36 cast steel wheels of the 100-tonne Barber S-2 bogie for measuring lateral and vertical forces [11]. The wheelsets continuously measured lateral forces, but vertical load measurements were limited by the spatial resolution of one-quarter of the wheel circumference.

The Canadian National Research Centre developed an instrumented wheelset using standard disc plate wheels, however they used cast, rather than forged, wheels. This was done to achieve a uniform 1/16 inch thickness of the wheel, which is greater than that of forged wheels [12].

Both General Electric on its U30C locomotive [13] and EMD on its SPD-40 used instrumented wheelsets with radially oriented strain gauges in separate bridge circuits that only received a signal within a narrow arc of maximum sensitivity. On these locomotives, only one IWS was used, usually placed as the drive axle of either the leading or trailing bogie of the locomotive.

In 1976, Amtrak tested the Rc4A locomotive built by ASEA using two instrumented wheelsets on a single bogie to read signals of vertical and lateral wheel-rail contact forces, as well as lateral wheel-bogie contact forces.

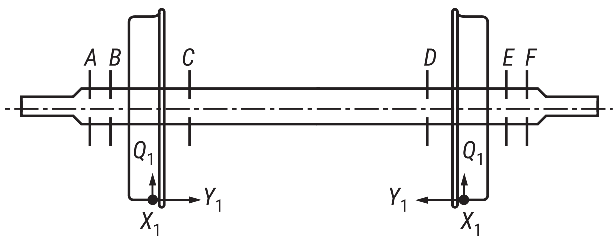

Fig. 2. IWS with sensors located on the axle [9].
A, *B*, *C*, *D*, *E*, *F* are cross-sections at which measuring sensors are installed

FRA concluded a contract with ENSCO Inc. to build an instrumented wheelset on a locomotive where each wheel had two vertical and two lateral measuring bridges. Vertical bridges consisted of strain gauges installed on both upper and lower parts of the holes drilled through the wheel plate, similar to EMD wheelsets [14]. The wheelset was used for testing Amtrak's SPD-40F train in 1977 [15].

In 1977, Amtrak and FRA purchased three instrumented wheelsets in Sweden. ASEA AB, Sweden, collaborated with the Swedish State Railways to build instrumented wheelsets. Continuous measurement of vertical force was achieved by combining two triangular waveforms [16]. These wheelsets were used by FRA for tests at the Transportation Test Center (EEC) in Pueblo, Colorado, in November–December 1978.

Paper [17] reported on experimental studies where the sensitivity of measurement of vertical force was increased by providing small "dummy spokes" by drilling the wheel plate close to the rim, where strains are low.

OVERVIEW OF CURRENT FOREIGN IWS DESIGNS

TÜV SÜD has developed the fifth-generation instrumented wheelset, IWT5 (*Fig. 3*), featuring numerous advantages over IWT4. They used a standard wheelset without any modification. This means that no special test wheels need to be manufactured, simplifying logistics, reducing the time required to produce IWS, mitigating risks, and reducing costs of testing. IWT5 allows for measuring all (vertical, transverse, and longitudinal) forces simultaneously in all three directions. Vertical and transverse forces are important for assessing dynamic characteristics of rolling stock and the track condition, while longitudinal forces are essential for assessing the wear of the contact area.

What distinguishes IWT5 from other solutions is its unique telemetry system. The fifth-generation telemetry system has increased performance and robustness while also using a "plug and play" architecture that allows for fast replacement of elements. The main benefit of using the telemetry system is that there is no need for slip-ring devices, improving the reliability and simplifying the installation of the system as IWT5 is using an inductive telemetry system designed specifically for railway transport. This helps avoiding electromagnetic interference problems that are normally typical of radio-based telemetric systems. IWT5 does not need additional batteries, as an advanced inductive power transfer system ensures IWT5 is powered whenever the vehicle is turned on. Technical specifications of IWT5 are listed in *Table 1*.

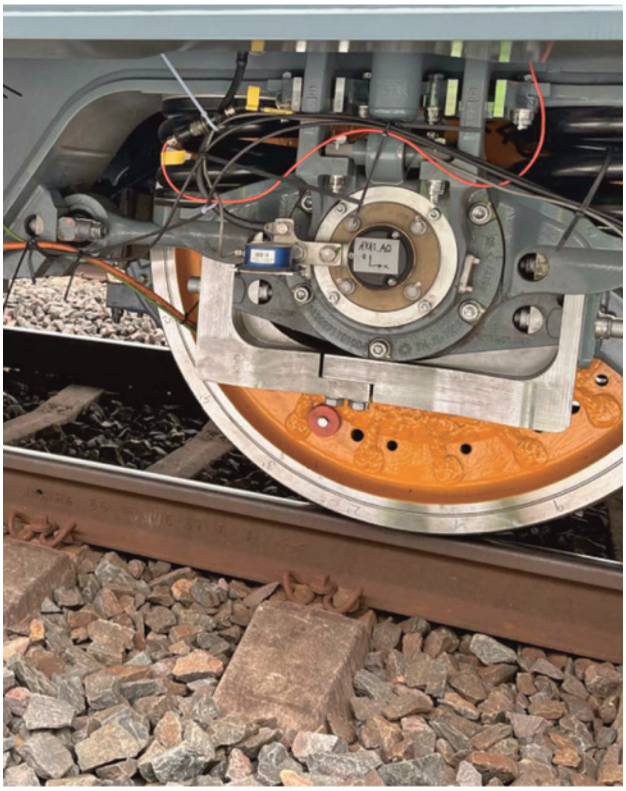

Fig. 3. IWT5 instrumented wheelset from TÜV SÜD, Germany[1]

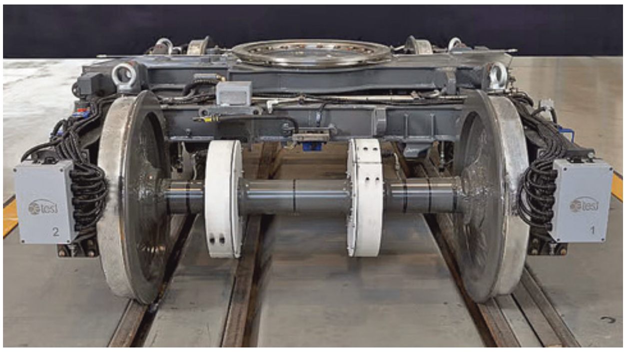

Fig. 4. Instrumented wheelset from CETEST, Spain[2]

Test center, CETEST, Spain, presented a proprietary IWS system (*Fig. 4*). It allows for measuring vertical, transverse, and longitudinal forces in real time with the measurement uncertainty of 4%. The sampling rate

[1] Instrumented wheelset technology IWT 5. [Electronic media]. — URL: https://www.tuvsud.com/en/-/media/global/pdf-files/brochures-and-infosheets/rail/220830_tuv_sud_iwt5_infosheet_final.pdf (дата обращения: 11.03.2025).
[2] Railway technology. Instrumented Wheelset. URL: https://www.railway-technology.com/products/instrumented-wheelset/

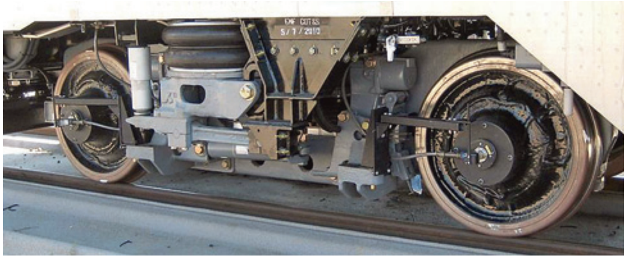

Fig. 5. Instrumented wheelsets from ENSCO, USA, on a bogie[3]

is up to 1 kHz. The IWS can identify the wheel-rail contact point position and provides compensation for errors (signal drift, thermal effects, rotation effects, and interferences). Communication is provided by optical telemetry systems without batteries.

ENSCO, USA, has been manufacturing and using its own proprietary IWS since 1975 (*Fig. 5*). ENSCO's IWS systems are designed to measure vertical, transverse, and longitudinal forces at the wheel-rail contact point in real time, along with the contact location.

OVERVIEW AND ANALYSIS OF RUSSIAN INSTRUMENTED WHEELSET DESIGNS

Several IWS systems have been designed in Russia to date. These allow for up to eight measurements per wheel revolution and record only two components of the force interaction between the wheel and the rail: vertical and lateral forces, as distinguished from their foreign counterparts providing the possibility of recording longitudinal forces and determining the coordinates of the contact area in the wheel-rail system, which improves the accuracy of measurement [18].

Paper [19] notes that IWS systems developed in Russia differ by the location of the measurement circuits (the outer or inner side of the wheelset plates) and the number of strain gauges used for arranging measurement circuits with different angular intervals. Depending on the arrangement, IWS can produce a continuous function of interaction forces with the measuring resolution of 0.18 m to 0.75 m. The smaller the resolution, the more strain gauges and measuring circuits are required, which makes the device too complicated and detrimentally affects its reliability, manufacturing complexity, maintenance, and repair.

An IWS developed by VNIKTI JSC (*Fig. 6*) [20] is provided with LY11-10/350 strain gauges manufactured by HBM, Germany, with a measuring grid length of 10 mm and nominal resistance of 350 Ohm. To measure vertical and lateral forces, the strain gauges are glued to the inner sides of the wheel plates and connected to a half-bridge circuit. Two groups of circuits are used to determine vertical and lateral forces in a single line; each line is positioned at 90° to the other, thus enabling point measurements of vertical and lateral forces [21].

PGUPS and NVC Vagony JSC developed an instrumented wheelset with strain gauges positioned on two concentric diameters of the inner side of the wheel plate at a pitch of 22.5° along the circular arc (a total of 64 half-bridge circuits of strain gauges). The IWS ena-

Table 1

Technical specifications of IWT5

Specifications	Value
Vertical and transverse force measurement uncertainty	Less than 3% at 20 Hz
Frequency of longitudinal force measurement	Over 10 Hz
Contact point position measurement accuracy	Typically ± 2 mm. Accuracy is degraded in two-point contact conditions
Capabilities for handling two-point contact forces	Equivalent global values for the contact forces. Individual contact forces for individual points of contact are not measured
Operating temperature	−25 °C to +50 °C
Permissible test speed	4,500 km/h
Output interfaces	Analogue connections BNC or D-Sub, EtherCAT, CAN, TCP/IP, digital interfaces for imc Cronos and HBK Quantum X. Other interfaces are available on customer demand
Compatibility	P32 Telemetry System, PROSE IWT

[3] ENSCO. Official web-site. URL: https://www.ensco.com/rail/instrumented-wheel-sets-iws

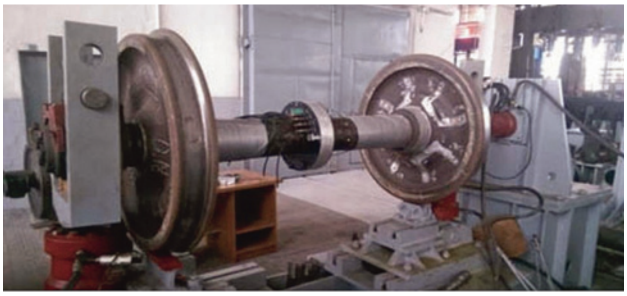

Fig. 6. Instrumented wheelset of VNIKTI JSC on a test bench [24]

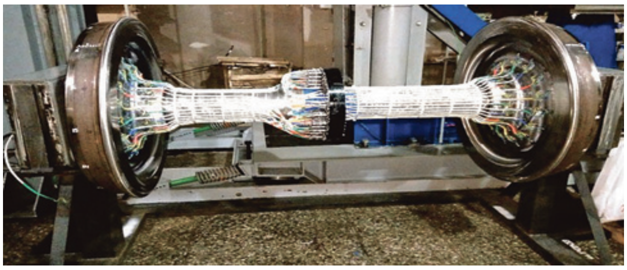

Fig. 7. Instrumented wheelset of PGUPS and NVC Vagony JSC

bles the implementation of the piecewise continuous method for recording of vertical and lateral forces in the wheel-rail system with a minimum pitch of 190 mm per wheel revolution (*Fig. 7*) [22].

Patent No. 2682567 for "Data collection device and method for assessing the results of wheel-rail interaction" [23] was obtained in 2017, and a prototype instrumented wheelset was produced in 2018. The developed IWS was tested on the high-speed test site of the Railway Research Institute (VNIIZhT) on the Belorechenskaya–Maikop railway section during the dynamic performance tests and the track impact tests of 12-9548-01 heavy-haul open wagons on 18-6863 bogies with an axle load of 27 tonnes on the Smychka–Kachkanar railway section.

This pitch of force recording is sufficient when it comes to testing rolling stock for analysing the forces arising during traveling at different speeds on representative sections of a railway track. However, there is a technical solution for the creation of a digital software and hardware platform for monitoring the technical condition of a railway track using IWS [24]. When using these IWS systems to assess the condition of a railway track, the probability of detecting a section of track that presents the risk of derailment is not sufficiently high and needs to be increased.

To address this problem, scholars of Emperor Alexander I St. Petersburg State Transport University and NVC Vagony JSC developed an instrumented wheelset with the lowest pitch among the currently available Russian IWS designs. It enables continuous recording of forces [25]. When the distances between the measuring sections at which strain gauges are located are reduced, the accuracy of measurement increases, and this can significantly increase the probability of detecting a section of track with the risk of derailment. Dynamic processes in the wheel-rail system can be recorded at a predetermined distance per wheel revolution. Therefore, the use of the IWS with continuous recording of dynamic processes makes it possible to detect dangerous defects in railway track.

Special-purpose C#software was developed for monitoring the technical condition of a railway track by the IWS with continuous recording. It uses GPS navigation to determine precise geo-coordinates of the identified track sections with the risk of derailment, generates and stores large amounts of recorded data, including geo-coordinates, and relies on modern big-data and cloud-computing capabilities for real-time computer-aided data processing, enabling identification of track sections with the risk of derailment.

CONCLUSION

The above overview and analysis have shown that instrumented wheelsets allow for measurements in a broad range of operating conditions, but have certain drawbacks, such as the complexity and high cost, the need for preliminary calibration of wheelsets, and impossibility to account for changes in the geometry of the wheel tread during operation.

The main challenge in measuring the wheel-rail contact forces is that wheel deformations are caused not only by the lateral, longitudinal and vertical forces being measured, but are also influenced by various other parameters. Apart from the forces, wheel deformations during movement are also caused by the varying position of the contact point, wear of the wheel profile, the angular velocity of the wheel, and changes in temperature. Taking into account the influence of all these parameters is a major prerequisite for developing a method for measuring the wheel-rail contact forces and achieving a high accuracy of measurement.

Over the more than 65-year-long period of IWS systems existence we can identify several key periods of their development. It can be stated that the evolution of IWS follows a few main lines:

- Increasing structural capabilities. For example, modern IWS can not only measure all vertical, transverse, and longitudinal forces simultaneously in all three directions, but also determine the position of the wheel-rail contact point;
- Increasing the signal transmission speed by introducing optical telemetry systems;
- Improving the accuracy of measurement through the use of improved signal processing algorithms;

- Increasing self-sufficiency of IWS without the use of batteries by special power transfer systems, etc.

The instrumented wheelset for continuous measurement with the specialized software developed by PGUPS and NVC Vagony JSC can be used for assessing the condition of railway tracks and can significantly increase the probability of detecting track sections that present the risk of derailment.

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Bionotes

Alexander A. Migrov — Cand. Sci. (Tech.), Associate Professor, Department of Ground Transportation and Technological Complexes; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky pr., St. Petersburg, 190031, Russian Federation; RSCI ID: 683999, SPIN-code: 7560-2776, Scopus: 57447079000, ORCID: 0000-0001-8630-9209; amigrov@gmail.ru;

Aleksander V. Tretiakov — Dr. Sci. (Tech.), professor of the Department of Railway Cars and Railway Car Facilities; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky pr., St. Petersburg, 190031, Russian Federation; RSCI ID: 453745, SPIN code: 8854-1727, ORCID: 0000-0003-4820-9535; avtretiakov51@yandex.ru;

Mariya V. Zimakova — Cand. Sci. (Tech.), Associate Professor of the Department of Railway Cars and Railway Car Facilities; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky pr., St. Petersburg, 190031, Russian Federation; RSCI ID: 727390, SPIN code: 1113-0677, Scopus: 57866003500, ORCID ID: 0000-0002-3354-7243; m.zimackova@yandex.ru.

Об авторах

Александр Алексеевич Мигров — кандидат технических наук, доцент кафедры «Наземные транспортно-технологические комплексы»; **Петербургский государственный университет путей сообщения Императора Александра I**; 190031, Санкт-Петербург, Московский пр., д. 9; РИНЦ ID: 683999, SPIN-код: 7560-2776, Scopus: 57447079000, ORCID: 0000-0001-8630-9209; amigrov@gmail.ru;

Александр Владимирович Третьяков — доктор технических наук, профессор кафедры «Вагоны и вагонное хозяйство»; **Петербургский государственный университет путей сообщения Императора Александра I**; 190031, Санкт-Петербург, Московский пр., д. 9; РИНЦ ID: 453745, SPIN-код: 8854-1727, ORCID: 0000-0003-4820-9535; avtretiakov51@yandex.ru;

Мария Викторовна Зимакова — кандидат технических наук, доцент кафедры «Вагоны и вагонное хозяйство»; **Петербургский государственный университет путей сообщения Императора Александра I**; 190031, Санкт-Петербург, Московский пр., д. 9; РИНЦ ID: 727390, SPIN-код: 1113-0677, Scopus: 57866003500, ORCID: 0000-0002-3354-7243; m.zimackova@yandex.ru.

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Corresponding author: Mariya V. Zimakova, m.zimackova@yandex.ru.
Автор, ответственный за переписку: Мария Викторовна Зимакова, m.zimackova@yandex.ru.

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