UDC 006.91:681.518:629.4

Advancement of information and measurement technologies in on-board monitoring systems for railway rolling stock

V. Ravlyuk https://orcid.org/0000-0003-4818-9482
A. Lovska http://orcid.org/0000-0002-8604-1764
V. Bondarenko https://orcid.org/0000-0003-4019-4017
A. Rybin https://orcid.org/0000-0003-4430-8018
D. Skurikhin https://orcid.org/0000-0002-1122-1234

Ukrainian State University of Railway Transport, Oborony Val Square, 7, 61001, Kharkiv, Ukraine
bonvya@ukr.net

Abstract

The information and measurement component of an onboard system for monitoring the heating of axle box bearings in passenger railcars is considered. The system uses contact, integrated, and posistor temperature sensors to ensure temperature control during train operation. A method for temperature prediction was developed, accounting for metrological parameters of temperature sensors. Computer simulation of temperature dynamics of the axle box was performed, considering measurement errors of temperature sensors, and the following dependencies were obtained: temperature dynamics accounting for sensor errors, absolute temperature measurement error for different types of sensors, and the dependence of the error in predicting the time to reach a critical temperature on the heating rate. The obtained results indicate that the use of platinum resistance temperature sensors makes it possible to improve the accuracy of temperature measurements and the reliability of temperature condition assessment, as well as to reduce the error in predicting the moment of reaching the critical temperature level by approximately 3–6 times compared to integrated and posistor sensors. The results obtained can be used in the development of advanced onboard systems for continuous monitoring of the technical condition of railway rolling stock axle box bearings.

Keywords: information technology; monitoring system; metrology; sensor; accuracy; railway car; railway transport.

Received: 10.03.2026 Edited: 10.04.2026 Approved for publication: 16.04.2026

Introduction

Ensuring the safety of passenger rolling stock operation largely depends on the technical condition of axle box bearings, the failure of which may lead to accidents and significant material losses. One of the most informative parameters of the condition of axle box bearings is temperature, the variation of which reflects the intensity of friction, wear, the presence of faults, and oils degradation. Modern trends in railway car engineering are aimed at the development of on-board monitoring systems that provide continuous monitoring of parameters during operation and enable the detection of defects at early stages of their development. In the railway rolling stock of Ukraine, axle box heating monitoring systems (ABHMS) and their modifications are usually used. The most widespread are systems with contact temperature sensors, while further development of monitoring systems has led to the use of semiconductor and integrated temperature sensors. However, such sensors are characterized by parameter dispersion, temperature instability, sensitivity to vibration, and limited measurement accuracy, which complicates the implementation of algorithms for predicting the technical condition and reduces the reliability of assessment of overheating of bearings. The use of platinum resistance temperature detectors (RTDs), in particular Pt100 or Pt1000, makes it possible to improve the accuracy and reliability of the system. An urgent task of modern information and measurement systems is not only to determine the current temperature value but also to predict its change over time to ensure the timely prevention of emergency operating conditions of the axle box bearings. This requires a metrologically substantiated approach to temperature measurements, the use of mathematical models of thermal processes, and methods for processing measurement data that allow determining the heating rate of the axle boxes and estimating the time to reach critical temperature values. In this regard, the development of an approach to intelligent temperature monitoring of passenger railway cars axle boxes based on the use of platinum resistance temperature sensors and algorithms for predicting the time to bearing overheating is a relevant task.

Overview of modern foreign and domestic studies and publications

The modern development of information and measurement technologies in the field of diagnosing the technical condition of rolling stock is aimed at increasing the reliability of monitoring parameters that characterize the operability of units and assemblies. Considerable attention is paid to metrological support of measurement systems, in particular to the evaluation of measurement channel errors, the influence of operating conditions on measurement results, and the application of modern methods for processing measurement data.

In paper [1], the temperature characteristics of axle box bearings under the occurrence of wheelset defects are studied. Changes in the thermal regime the axle box bearings under dynamic loads are analysed, and relations between motion parameters and thermal processes in the bearing are determined. At the same time, the issues of temperature measurement accuracy and metrological characteristics of sensors are not considered.

In study [2], the main approaches to diagnosing freight car bearings based on temperature measurements and analysis of technical condition signals are considered. The authors study the possibilities of defect detection using on-board and trackside monitoring systems. It is shown that temperature parameters do not always ensure reliable detection of defects at early stages of their development. However, the features of bearing temperature measurement and the influence of temperature sensor errors on diagnostic results are not considered.

In paper [3], an algorithm for diagnosing electronic equipment of passenger railcars based on reliability assessment and optical monitoring is proposed. The proposed approach increases the efficiency of monitoring complex systems through integrated data processing. At the same time, issues of temperature monitoring of axle box bearings and metrological characteristics of temperature measurement channels are not considered.

In paper [4], the distribution of dynamic loads in axle box bearings of high-speed trains based on experimental measurements is studied. The obtained results assess the influence of loads on the operation of axle box bearings and the formation of its thermal regime. However, the issues of temperature measurement accuracy are not considered.

In study [5], the application of energy-saving technologies in monitoring the technical condition of rolling stock axle box bearings is considered. The author analyses possibilities for improving the efficiency of monitoring systems and optimizing operating conditions of assemblies. At the same time, metrological aspects of temperature measurement of axle box bearings are not sufficiently covered.

In paper [6], the development of an electronic system for diagnosing braking equipment of passenger railcars is presented, which increases the reliability of technical condition monitoring. The system is based on the use of electronic sensors and digital signal processing. However, the issues of monitoring the temperature condition of axle box bearings are not considered.

In paper [7], a method for predicting the temperature of high-speed trains axle box bearings based on machine learning algorithms and on-board monitoring data is proposed. The possibility of improving the efficiency of early detection of bearing faults by predicting temperature regimes is demonstrated. At the same time, the accuracy of primary measurements and the influence of sensor errors on prediction results are not analysed.

In paper [8], the use of platinum resistance temperature sensors of the Pt100 type for monitoring the temperature of railway rolling stock axle boxes is considered. High stability of metrological characteristics of such sensors and the possibility of their calibration are noted. However, temperature measurement errors under real operating conditions are not analysed in details.

In study [9], a design of an adaptive thin-film temperature sensor for measuring the temperature of bearing elements is proposed. The developed sensor provides high response speed and the possibility of measuring the temperature of bearing rollers. However, the issues of sensor application in rolling stock monitoring systems and evaluation of their metrological characteristics remain insufficiently studied.

In paper [10], a hybrid model for predicting the temperature of high-speed trains axle boxes based on a combination of physical models and machine learning methods is proposed. The obtained results indicate improved accuracy of temperature regime prediction and the possibility of early detection of bearing defects. At the same time, the influence of temperature measurement errors on the reliability of thermal process prediction is not accounted for.

The conducted analysis implies that the use of platinum resistance temperature sensors can increase the reliability of diagnostics and the efficiency of systems for monitoring the technical condition of rolling stock.

The purpose of the study is to improve the accuracy and reliability of assessing the temperature condition of axle boxes of passenger railcars by accounting for metrological characteristics and errors of temperature sensors in the information and measurement system and by developing a method for predicting the moment of reaching a critical temperature state.

To this end, the following tasks are defined:

• to analyse available information and measurement systems for monitoring the temperature of axle box bearings and their metrological features;

• to develop a method for predicting the temperature condition of axle box bearings accounting for metrological parameters of temperature sensors;

• to study the influence of the accuracy of different sensors on the reliability of temperature condition assessment and the error in predicting the time to reach the critical temperature.

Main part of the study

The safety of train operation directly depends on the technical condition of the axle box bearings of passenger railcars; therefore, considerable attention is paid to monitoring their technical condition. For assessing the condition of an axle box, the most informative parameter is temperature, in particular the temperature of the axle box, which is proportional to the bearing temperature. The following systems are used on passenger railcars of JSC "Ukrainian Railways": ABHMS with contact temperature sensors (Fig. 1, *a*), ABHMSP with posistor sensors (Fig. 1, *b*), and ABHMS-K with integrated temperature sensors (Fig. 1, *c*).

ABHMS (Fig. 1, *a*) is the most widespread monitoring system with contact temperature sensors T393M with a fusible element (Fig. 2, *a*). The sensors are installed in the axle box housings of the passenger car and connected in series. The activation temperature is 96 ± 4 °C, and the operating range is from −50 to +45 °C. When the melting temperature is reached, the

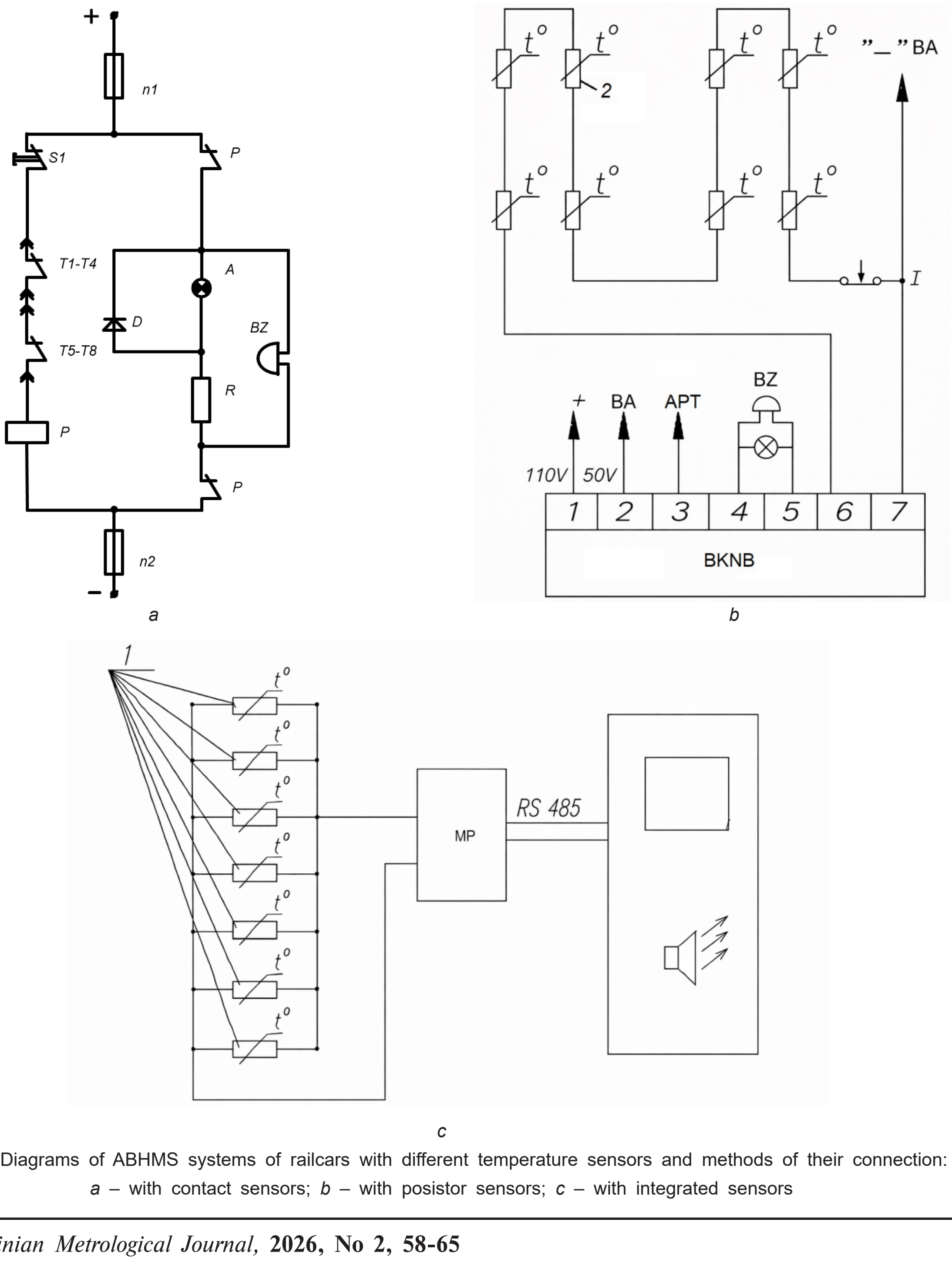


Fig. 1. Diagrams of ABHMS systems of railcars with different temperature sensors and methods of their connection: *a* – with contact sensors; *b* – with posistor sensors; *c* – with integrated sensors

contacts open and the alarm is triggered. The disadvantages of the system include the occurrence of false alarms, the inability to identify the faulty axle box, and the single-use operation of the sensor.

In the ABHMSP system (Fig. 1, *b*), posistor thermistors (Fig. 2, *b*) are used, connected to the axle box heating control unit. The activation temperature is (95 ± 5) °C, and the operating range is from −60 to +55 °C. The operating principle is based on monitoring the total resistance of the sensors. The disadvantages include parameter dispersion of the sensors and reduced operational reliability.

The ABHMS-K system (Fig. 1, *c*) uses integrated temperature sensors (Fig. 2, *c*) connected to a microprocessor-based signal processing unit. When the temperature reaches 65–70 °C, a warning signal is generated, and at (94 ± 4) °C an axle box overheating signal is triggered. The operating temperature range is from −50 to 125 °C. A disadvantage of integrated sensors is their sensitivity to vibration. Under operating conditions of rolling stock, which are characterized by significant vibration and shock loads, temperature cycling, and electromagnetic interference, a more reliable solution is to use passive resistive temperature sensors of the Pt100/Pt1000 type (Fig. 2, *d*) [8].

Platinum resistance thermometers Pt100 and Pt1000 belong to the class of resistive temperature sensors (RTD – Resistance Temperature Detector) and are widely used in industrial monitoring systems owing to their high accuracy, stability of characteristics, and long-term metrological reliability. Their operating principle is based on the dependence of the electrical resistance of the platinum sensing element on temperature, which is described by standard equations adopted for platinum resistance thermometers. The Pt100 sensor has a nominal resistance of 100 Ω at $t = 0$ °C, while Pt1000 has a nominal resistance of 1000 Ω, which ensures metrological reproducibility of measurement results and the possibility of calibration. For temperatures $T \geqslant 0$ °C, the temperature–resistance characteristic is described by the Callendar–Van Dusen equation [11]:

$$R(T) = R_0 \cdot \left(1 + AT + BT^2\right), \qquad (1)$$

where R_0 is the sensor resistance at a temperature of 0 °C; A, B is the temperature coefficients of platinum; T is the temperature. The coefficients of the equation for platinum temperature sensors are: $A = 3.9083 \times 10^3$ 1/°C; $B = -5.775 \times 10^{-7}$ 1/°C².

The normalization of the transfer function ensures metrological reproducibility of measurement results and the possibility of sensor calibration. In systems for monitoring the technical condition of rolling stock, in particular axle boxes of passenger railcars, the use of platinum resistance thermometers is advisable considering their high measurement accuracy, mechanical strength, and resistance to vibration loads. Compliance with railway standards for electronic equipment of rolling stock makes it possible to use such sensors in railway transport. The use of Pt100 sensors together with industrial controllers and RTD resistance measurement modules enables the implementation of systems for early detection of axle box overheating and prediction of the technical condition of bearings, which increases the operational safety of rolling stock and reduces the risk of accidents.

Methodology for predicting the temperature condition of an object considering metrological parameters of temperature sensors

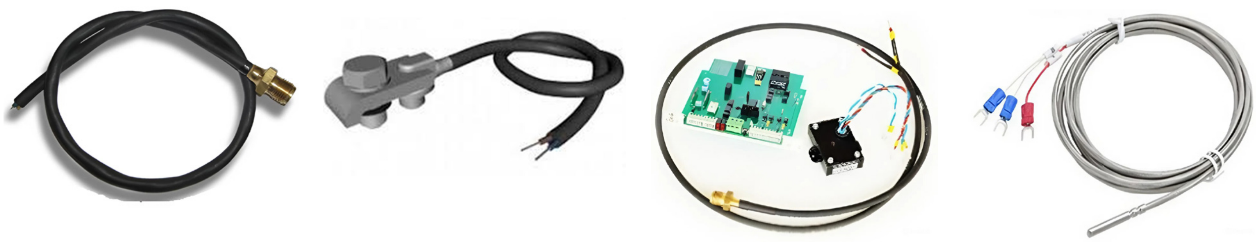
The proposed method for prediction is based on estimating the local rate of temperature change and extrapolating the time to reach the critical value, accounting for the temperature measurement error.

Physical model of the axle box heating process

The heating process of the rolling stock axle boxes is characterized by thermal inertia and can be described by a generalized first-order thermal model. In this case, the temperature variation over time is described by an exponential dependence corresponding to the lumped capacitance method and its analytical solution [12]:

$$T(t) = T_{env} + \left(T_{\max} - T_{env}\right)\left(1 - e^{-t/\tau}\right), \qquad (2)$$

where T_{env} is the ambient temperature; $T_{\max}$ is the steady-state temperature of the object under constant heat generation conditions; τ is the thermal time constant; t is the time.



a *b* *c* *d*

Fig. 2. Different types of temperature sensors for passenger car axle boxes: *a* – contact temperature sensor of the T393M type; *b* – posistor temperature sensor of the 005 type; *c* – integrated temperature sensor; *d* – platinum temperature sensor Pt100 (prospective)

Such a model makes it possible to describe the heating process without detailed consideration of the design parameters of the axle box and is sufficient for analysing temperature dynamics in prediction tasks.

Temperature measurement model considering sensor error

The measured temperature value differs from the true value due to the sensor measurement error. Given that:

$$T_m(t) = T(t) + \varepsilon_T(t), \tag{3}$$

where $T(t)$ is the true temperature; $T_m(t)$ is the measured temperature value; $\varepsilon_T(t)$ is the temperature measurement error of the sensor.

Accounting for the measurement error is necessary for assessing the accuracy of determining the rate of temperature change and predicting the moment of reaching a critical condition. During the modelling, typical metrological characteristics of sensors were used: for platinum Pt100 (Class A) – ±0.35 °C at 100 °C; for integrated sensors – ±1.0...1.5 °C; for posistor sensors – ±2.0 °C. The obtained error values were used as parameters of random deviations in the simulation of temperature measurements.

Based on the generalized exponential model of object heating and the temperature measurement model considering sensor measurement error, simulation modeling of the temperature dynamics of the axle box was performed. Fig. 3, *a* shows the simulation of the heating dynamics of the axle box accounting for temperature measurement errors of different types of sensors. As can be seen from the figure, platinum sensors provide the smallest deviations from the true temperature dependence, which ensures more accurate reproduction of the temperature dynamics of the object and increases the reliability of determining the heating rate and predicting the moment of reaching a critical temperature condition.

As can be seen from Fig. 3, *b*, platinum temperature sensors are characterized by the smallest measurement error, integrated sensors have a moderate error level, while posistor sensors demonstrate the largest deviations. The obtained results confirm the feasibility of using platinum sensors for predicting temperature conditions.

The absolute value of the temperature measurement error is determined according to the following formula:

$$\left|\varepsilon_T(t)\right| = \left|T_m(t) - T(t)\right|. \tag{4}$$

Platinum temperature sensors are characterized by lower measurement error compared to integrated semiconductor and posistor sensors, which ensures more accurate determination of the temperature condition of the object.

Determination of the rate of temperature change

To predict the development of the thermal process, the local rate of temperature change is used, which is determined based on the results of discrete measurements:

$$\vartheta = \frac{T_i - T_{i-1}}{\Delta t}, \tag{5}$$

where T_i is the temperature values at adjacent time instants; Δt is the interval between measurements.

The rate of temperature change makes it possible to assess the intensity of the thermal process and to predict the moment of reaching a critical temperature condition. In the limiting case, as the sampling interval decreases ($\Delta t \to 0$), the estimation of the rate of temperature change can be expressed in the form:

$$\vartheta(t) = \frac{\partial T(t)}{\partial t}. \tag{6}$$

Since the measured temperature value includes sensor measurement error, the error in determining the rate of temperature change also depends on the temperature measurement error. Reducing the error of the temperature sensor ensures a more accurate determination of the heating rate of the object, which increases the reliability of predicting the moment of reaching a critical temperature condition. Platinum temperature sensors provide the most accurate determination of the rate of temperature change of the object, which improves the reliability of predicting the moment of reaching a critical temperature condition compared to integrated and posistor sensors.

Prediction of the time to reach the critical temperature

The prediction of the time to reach the critical temperature is performed based on the local rate of temperature change using linear extrapolation:

$$t_{cr} = \frac{T_{cr} - T}{\vartheta}, \tag{7}$$

where T_{cr} is the critical temperature value; T is the current temperature value; ϑ is the rate of temperature change.

Such an approach makes it possible to estimate the time to reach a hazardous temperature condition without using complex thermal models of the railway car axle box structure. Since the measured temperature value includes an error, it can be represented in the form:

$$T_m = T + \varepsilon_T. \tag{8}$$

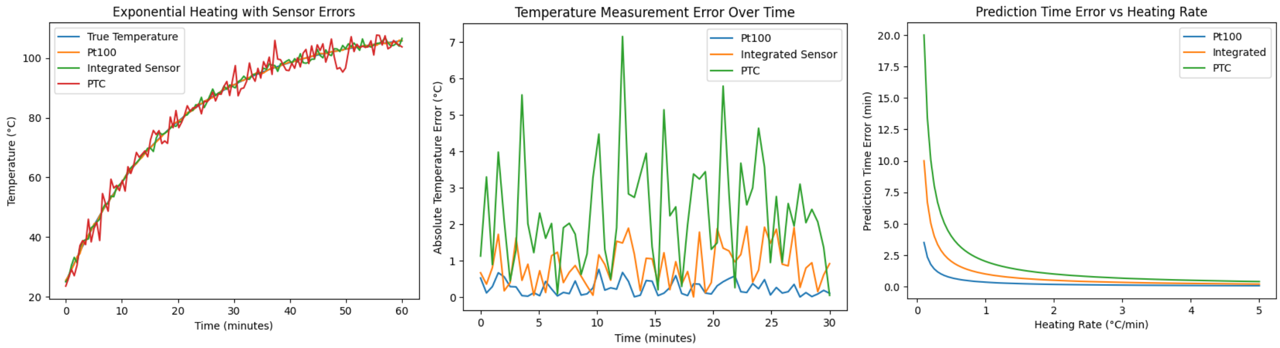
To assess the influence of temperature measurement error on the error of time prediction, the expression for the predicted time is linearized under the assumption of small measurement errors. Then, the estimate of the prediction error of time is given by:

$$\Delta t_{er} = \frac{\Delta T}{\vartheta}, \tag{9}$$

where ΔT is the temperature measurement error.

The obtained relationship shows that the error in time prediction is directly proportional to the temperature measurement error and inversely proportional to the rate of temperature change of the object. At low heating rates, the time prediction error increases sharply, which is consistent with the analytical dependence:

$$\lim_{\vartheta \to 0} \Delta t \to \infty. \tag{10}$$



a *b* *c*

Fig. 3. Results of the simulation of temperature dynamics of the axle box considering temperature sensor measurement errors: *a* – temperature dynamics considering sensor errors; *b* – absolute temperature measurement error for different types of sensors; *c* – error in predicting the time to reach the critical temperature

Table 1

Influence of measurement error of temperature sensor on the error of predicting the time to reach the critical temperature condition (at υ=1 °C/min)

Sensor Type	Temperature Measurement Error at 100 °C	Time Prediction Error	Relative Error*
Pt100 Class A (platinum)	±0.35 °C	±0.35 min (≈21 s)	1×
LM35 (integrated)	±1.0...1.5 °C	±1.0...1.5 min	3-4×
KTY83-110 (posistor)	±2.0 °C	±2.0 min	6×

*Relative to the prediction error of the Pt100 Class A sensor (reference standard).

The subsequent dependencies are obtained based on the generalized exponential heating model and the temperature measurement model accounting for sensor measurement error. The analysis of the obtained dependencies (Fig. 3, *c*) shows that as the rate of temperature change decreases, the error in determining the time to reach the critical temperature condition increases significantly.

Under such conditions, the use of sensors with lower measurement error makes it possible to improve prediction accuracy, which is especially crucial for components with high thermal inertia, such as axle boxes of rolling stock. Thus, improving sensor accuracy directly leads to an increase in the accuracy of predicting the time to reach the critical temperature condition. For a quantitative evaluation of the influence of measurement error of the temperature sensor, a comparative calculation was performed for different types of sensors in Table 1.

As can be seen from Table 1, the use of platinum temperature sensors makes it possible to reduce the error in predicting the time to reach the critical temperature condition by several times compared to posistor and integrated sensors, which confirms the feasibility of their application in temperature condition monitoring systems of rolling stock axle box bearings. Platinum sensors Pt100/Pt1000 are characterized by high accuracy, parameter stability, and reproducibility of measurement results, which ensures their advantage over posistor and integrated sensors in temperature condition monitoring systems of rolling stock.

Conclusions

1. Temperature monitoring systems of passenger railcars axle boxes and the sensors used in them were analysed. It was determined that contact, integrated, and posistor sensors are characterized by limited accuracy and significant parameter dispersion, which reduces the reliability of temperature condition assessment. It was also revealed that platinum resistance thermometers have more stable metrological characteristics and lower measurement error.

2. A method for predicting the temperature condition of an axle box was developed, based on an exponential model of thermal dynamics, determination of the rate of temperature change, and extrapolation of the moment of reaching the critical value. The method accounts for temperature measurement error, which makes it possible to assess its influence on the accuracy of determining the heating rate and predicting the time to reach the critical temperature.

3. Computer simulation of the temperature dynamics of an axle box was performed, considering measurement errors of different types of sensors. It was determined that the use of platinum resistance sensors improves temperature measurement accuracy and the reliability of temperature condition assessment and reduces the error in predicting the time to reach the critical temperature by approximately 3–6 times compared to integrated and posistor sensors.

Acknowledgement

This publication was supported by the project "Advancing Train Safety Through Integrated Lifecycle Management Technologies for Railcars" State Registration No. 0125U001907, which is funded by the Ukrainian state budget, since 2025.

Розвиток інформаційно-вимірювальних технологій у бортових системах контролю рухомого складу залізниць

В.Г. Равлюк, А.О. Ловська, В.В. Бондаренко, А.В. Рибін, Д.І. Скуріхін

Український державний університет залізничного транспорту, майдан Оборонний Вал, 7, 61001, Харків, Україна
bonvya@ukr.net

Анотація

Розглянуто інформаційно-вимірювальну складову бортової системи контролю нагріву буксових вузлів пасажирських вагонів, у якій для забезпечення контролю теплових режимів під час руху поїзда застосовуються контактні, інтегральні напівпровідникові та позисторні давачі температури.

Особливу увагу приділено аналізу точності вимірювань, що забезпечується різними типами давачів, та впливу їхніх метрологічних характеристик на достовірність оцінювання теплового стану буксового вузла. Розроблено методику прогнозування теплового стану об'єкта контролю з урахуванням метрологічних параметрів температурних давачів. Виконано комп'ютерне моделювання температурної динаміки буксового вузла з урахуванням метрологічних похибок температурних давачів, у результаті чого отримано залежності: температурної динаміки з урахуванням похибок давачів, абсолютної похибки вимірювання температури для різних типів давачів, а також залежності похибки прогнозування часу досягнення критичної температури від швидкості нагріву. Отримані результати демонструють, що застосування платинових термометрів опору дозволяє підвищити точність вимірювання температури та достовірність оцінювання теплового стану, а також зменшити похибку прогнозування моменту досягнення критичного температурного рівня приблизно у 3–6 разів порівняно з інтегральними напівпровідниковими та позисторними давачами. Запропонований підхід дозволяє враховувати вплив метрологічних характеристик температурних давачів на точність прогнозування теплових процесів у буксових вузлах в умовах експлуатації та підвищує достовірність визначення часу досягнення критичних температур. Отримані результати можуть бути використані при розробці перспективних бортових систем безперервного моніторингу технічного стану буксових вузлів рухомого складу залізниць та вдосконаленні алгоритмів діагностики для раннього виявлення перегріву буксових вузлів вагонів у процесі експлуатації.

Ключові слова: інформаційні технології; система контролю; метрологія; давач; точність; вагон; залізничний транспорт.

References

1. Yaping Luo, Fan Zhang, Zhiwei Wang et al. Temperature Characteristics of Axle-Box Bearings Under Wheel Flat Excitation. *Lubricants*, 2025, vol. 13, no. 1, 19. doi: https://doi.org/10.3390/lubricants13010019
2. Tarawneh C., Montalvo J., Wilson B. Defect detection in freight railcar tapered-roller bearings using vibration techniques. *Railway Engineering Science*, 2021, vol. 29, no. 1, pp. 42–58. doi: https://doi.org/10.1007/s40534-020-00230-x
3. Ivantsyk Ya., Bondarenko V., Bereznyi V. et al. Diagnostic algorithm for electronic equipment of passenger cars based on reliability assessment and optical monitoring methods. *Proceedings of Seventeenth International Conference on Correlation Optics*, 2025, vol. 13813, 138131S, pp. 1–5. doi: https://doi.org/10.1117/12.3092407
4. Yu Hou, Xi Wang, Jiaqi Wei et al. Measured dynamic load distribution within the in situ axlebox bearing of high-speed trains under polygonal wheel–rail excitation. *Railway Engineering Science*, 2024, vol. 32, pp. 444–460. doi: https://doi.org/10.1007/s40534-024-00344-6
5. Petukhov V.M. Vykorystannia enerhozberihaiuchykh tekhnolohii pry kontroli buksovykh vuzliv [Energy-saving technologies under the control of axle boxes]. *Collected scientific works of Ukrainian State University of Railway Transport*, 2015, issue 153, pp. 238–243 (in Ukrainian). doi: https://doi.org/10.18664/1994-7852.153.2015.64694
6. Ravluyk V., Derevianchuk I., Afanasenko I., Ravluyk N. Development of electronic diagnostic system for improving the diagnosis reliability of passenger car brakes. *Eastern-European Journal of Enterprise Technologies*, 2016, vol. 2, no. 9(80), pp. 35–41. doi: https://doi.org/10.15587/1729-4061.2016.66007
7. Wanyi Li, Kun Xie, Jinbai Zou et al. Transformer-Based High-Speed Train Axle Temperature Monitoring and Alarm System for Enhanced Safety and Performance. *Applied Sciences*, 2024, vol. 14, no. 19, 8643. doi: https://doi.org/10.3390/app14198643
8. Eisenbrand E. Hot box detection in European railway networks. *RTR Special*, 2011, pp. 2–11.
9. Yunxian Cui, Pengfei Gao, Wuchu Tang et al. Adaptive Thin Film Temperature Sensor for

Bearing's Rolling Elements Temperature Measurement. *Sensors*, 2022, vol. 22, no. 8, 2838. doi: https://doi.org/10.3390/s22082838

10. Ying Zhang, Qinghua Liu, Yaguo Lei et al. Circular Halbach negative stiffness isolating from torsional vibration: Design, modeling and experiments. *Mechanical Systems and Signal Processing*, 2023, vol. 202, 110711. DOI: https://doi.org/10.1016/j.ymssp.2023.110711
11. DSTU EN IEC 60751:2022. Industrial platinum resistance thermometers and platinum temperature sensors. General requirements and test methods (EN IEC 60751:2022, IDT; IEC 60751:2022, IDT). Kyiv, 2022. 35 p. (in Ukrainian).
12. Bergman T.L., Lavine A.S., Incropera F.P., DeWitt D.P. Fundamentals of Heat and Mass Transfer. 7th edition. Hoboken, John Wiley & Sons, 2011.