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Rail vehicle axle-box bearing damage detection considering the intensity of heating alteration

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Highlights

- Axle-box temperature change intensity as criterion of the technical state was provided.
- Comparative analysis of assessment methods of axle-box temperature change was performed.
- Three cases to assess the intensity of axle-box temperature change were examined.
- The applying of Sharp criterion method as the most appropriate of the three is proved.

Abstract

The article observes problems of detection of rolling bearing damages in rail vehicles. Two methods of bearing damage detection are examined – according to heating of axle-boxes and by vibro-diagnostic manner. The disadvantage of vibro-diagnostic method is that a contact vibration sensor is used for vibration diagnostics, intervention into rail vehicle structure is required. The method according to heating of axle-boxes also has drawbacks. The same temperature value of axle-box in various conditions may characterize different bearing technical state. The Authors studied a possibility to use temperature change intensity parameters as the diagnostics criteria. Based on the examples of axle-box temperature measurement data, Authors developed and proposed a methodology for detecting axle-box bearings defects. The Authors suggest the use the method according to heating of axle-boxes. The given example proofs that the fact of the presence of their damages can be unambiguously identified by the intensity of temperature change of the axle-boxes.

Keywords

rolling stock, axle-box, bearing damage, vibro-diagnostic method, heating alteration.

1. Introduction

One of the most important structural components to ensure the rail vehicle running safety of is the running gear. Wheelsets are the main elements of running gear directly contacting the rail rolling surface, guiding and supporting the dynamic stability in the track [18]. Wheelsets are fastened in axle-boxes of bogies and rotate in installed bearings. Thus, the technical condition (repair condition) of axle-box bearings has a decisive impact on the safety and smoothness of rolling stock running, and it is constantly monitored and controlled. Monitoring the technical condition of axle-boxes is an integral part of the maintenance system of rolling stock as a whole. The problems of detection of axle-box bearing damages in rolling stock is significant and extensively discussed in the scientific publications [13, 23].

In the scientific literature, the issues of bearing diagnostics are examined taking into account the peculiarities of their operation. A separate issue is when the bearings are loaded very intensely for a short time [11]. Also an important issue is the effect of bearing friction noise on working conditions [20]. It is important whether it is possible to install the measuring equipment on site or whether a remote method is required [9]. Sometimes it is easier to detect acoustic phenomena and sometimes – thermal ones [12]. Rail vehicle axle-box bearing damage detection has its own peculiarities.

Many technologies, such as temperature determination [22], acoustic analysis [24], acoustic emission technology [1] and vibrational signal analysis [25] have been investigated for many years to detect damage to the axle-box bearing [7]. For this purpose can be applied online conduction monitoring of rolling stock wheels and axle bearing [16] or Rolling Element Bearing Activity Monitoring [5]. Sometimes fault diagnosis of train axle bearing is based on multiple-feature parameters [14]. Special algorithms have been developed for this purpose [26]. Some measures make it possible to determine not only the fact of the failure but also its extent [27]. Observing early stage rail axle-box bearing damage for diagnostics are currently available as 'state-of-the-art', a trackside system, e. g. Railway Bearing Acoustic Monitoring (RailBAM) by Siemens or Trackside Acoustic Detection System (TADS) developed by the American Transportation Technology Centre, Inc. (TTCI) both employing microphones to listen to passing axle-box bearings or an on-board system by Perpetuum Ltd [15]. The latter approach (the subject of this paper) provides each wheel bearing with local real-time vibration monitoring using accelerometers [19]. Kazakh researchers have examined the possibility of diagnosing rolling stock based on its noise and vibration [3, 4]. A typical example of the test equipment described above is given in Figure 1.

A wireless sensor node (WSN) bolted to a wheel bearing housing is shown in Figure 1. It is important to note that the sensor is sited

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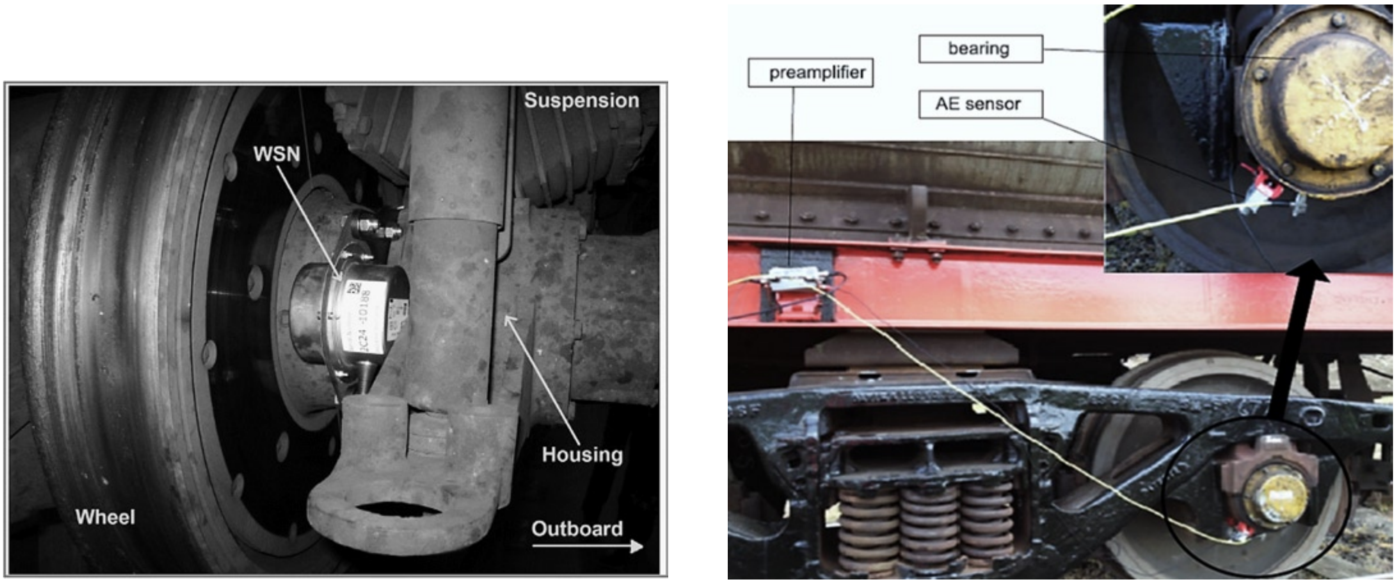

Fig. 1. Mounting of sensors systems [1, 19]

on the inboard side of the housing which is on the outboard side of the wheel. This unit forwards the data to an Internet Cloud Database. The WSNs are self-powered by vibration harvesting. This emerging technique has been made possible by the decreasing power budget of sensor and wireless technologies. By the way, the authors do not analyse vibration parameters.

Recent studies have shown that measurement systems installed on-board are more likely to detect an axle-box bearing fault, especially at an early stage of evolution [17]. This is due to the fact that the sensors are closer to the axle bearing and hence to the source of the arising signal. On-board systems are able to measure continuously or more often the condition of the bearings acquiring data over a larger number of revolutions of the same axle bearing [1].

New methods of rail vehicle axle box fatigue crack were analysed [28]. The high-speed railway bearing fault diagnosis is important for prevent unexpected accidents and has been a hot topic in last decades [10]. The new criteria for bearing crack detection during fatigue tests were developed [8]. Vibration measurements were recorded during the tests, and the evolution of certain frequency bands with the number of cycles was analysed. Change in frequency behaviour could therefore be used for crack detection.

Further Authors consider three possible ways to estimate the intensity of axle-box bearing damage definition with intention to propose the mostly appropriate and rational one.

2. Theoretical background and methodology of investigation of axle-box bearing technical condition

Once the type of the bearing and the shaft speed are identified, the defect frequencies can be calculated. The information regarding the characteristic frequencies of an axle bearing are generally provided by the manufacturer of the bearing. The formulas for calculating these specific frequencies are [6]:

$$BPFI = \frac{N}{2} \cdot F \cdot \left(1 + \frac{B}{F} \cdot \cos\theta\right); \tag{1}$$

$$BPFO = \frac{N}{2} \cdot F \cdot \left(1 - \frac{B}{F} \cdot \cos\theta\right); \tag{2}$$

$$FTF = \frac{F}{2} \cdot \left(1 - \frac{B}{F} \cdot \cos\theta\right); \tag{3}$$

$$PFS = \frac{N \cdot P}{2 \cdot B} \cdot F \cdot \left(1 - \left(\frac{B}{F} \cdot \cos\theta\right)^2\right); \tag{4}$$

where: *BPFI* – ball pass frequency inner race, Hz; *BPFO* – ball pass frequency outer race, Hz; *FTF* – fundamental train frequency or frequency of the cage, Hz; *BSF* – ball spin frequency circular frequency of each rolling element as it spins, Hz; *N* – number of balls; *F* – shaft frequency, Hz; *B* – ball diameter, mm); *P* – pitch diameter, mm; *Θ* – contact angle, rad.

The presented theory shows that the critical values of diagnostic parameters (for instance, oscillation frequencies and accelerations) depend on bearing design. It complicates the versatility of the diagnostic process fundamentally. On the other hand, it is not known whether these frequencies can be identified in practice. Not only the vibration excitation frequency but also the systems' own oscillations operate in practice. In addition, it is not easy to purify the required oscillation frequency modes in a dynamic system. The answers to these questions are further sought through practical researches by two methods:

1. Defect detection by vibro-diagnostic method.
2. Defect detection according to heating of axle-box.

The vibro-diagnostic stand of axle-box bearings of railway wagons is used for the research. It draws axle-box vibration acceleration and frequency diagrams. The practice of article authors showed that acceleration axis in diagrams must include a scale no less than from 0 to 2 m/s^2 and frequency scale from 0 Hz to 400 Hz. Acceleration increases are observed depending on the nature of the defect in one or another frequency range. These frequency ranges can determine the nature of the damage.

Three possible ways to estimate the intensity of the temperature change of the axle-boxes of rolling stock mathematically are examined: first – by estimating the axle-box temperature change in degrees per kilometre (change intensity), second – by estimating the axle-box temperature change in percentage (during the selected mileage range), and third – by using Sharp criterion. Axle-box temperature change is the difference of *i* axle-box temperatures T_{n+1} and T_n in heating detection station:

$$\Delta T_i = T_{i,n+1} - T_{i,n} \ . \tag{5}$$

Temperature change in degrees per kilometre is calculated by dividing i^{th} axle-box temperature change by distance X between axle-box heating detection stations (HABD):

$$\Delta T_{km,\,i} = \frac{\Delta T_i}{\mathrm{X}} \,. \tag{6}$$

The axle-box temperature change in percentage is calculated according to the formula:

$$\Delta T_{\%} = 100 \cdot \frac{T_{i,n+1} - T_{i,n}}{T_{i,n}} \,. \tag{7}$$

Sharp criterion *SH* [21] assesses how the variance deviation of considered parameter (temperature, in this case) of examined objects (axle-box, in this case) from the average $\Delta\overline{T}_{\%} - \Delta T_{\%,i}$ complies with the standard square deviation σ (through all examined objects):

$$SH = \frac{\Delta\overline{T}_{\%} - \Delta T_{\%,i}}{\sigma} \,. \tag{8}$$

The above methods for the analysis of the intensity of the temperature change of the axle-boxes of rolling stock are analysed and compared. In this study, the measurement results gained by two different methods are not directly compared interdependently. The study goal is to examine and prove the possibility of applying the considered methods.

3. Detection of bearing damages by vibro-diagnostic method

The general view of vibro-diagnostic stand of railway wagon axle-box bearing of series CV-TK-03 [2] used for research is provided in Figure 2.

Three axle-boxes with rolling bearings have been selected for the research. One of them was without bearing defects, the bearing roller of the second axle-box had 1 mm width and 1 mm depth cut, and the third axle-box had front bearing external bearing ring crumbling of 4,5 mm width and 1,5 mm depth (12 mm from the edge). Vibration frequency and acceleration diagrams of the said cases are provided in Figure 3.

As is seen in Figure 3, the obvious increase of vibration acceleration in 200-250 Hz frequency range when the bearing roller has a cut ("a" case). If the front bearing has external ring crumbling ("b" case), the increase of vibration acceleration in 300-350 Hz frequency range is observed. However, the diagram without bearing defects ("c" case)

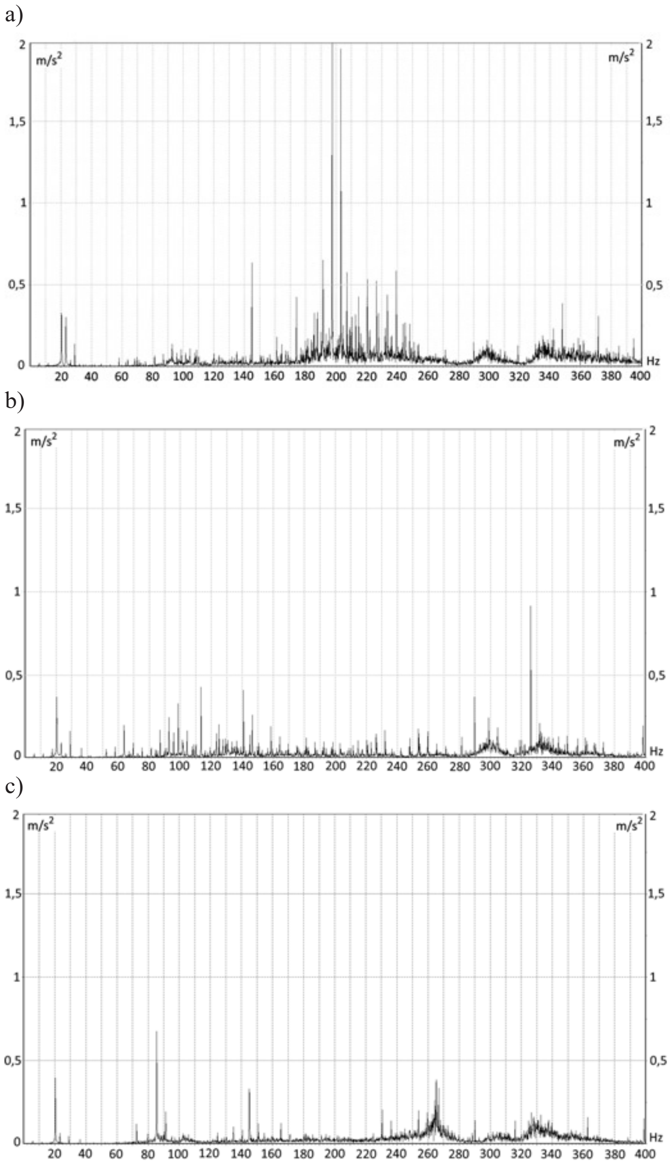

Fig. 3. Axle-box vibration frequency and acceleration diagrams a) diagram of bearing roller with cut, b) diagram of front bearing with external ring crumbling, c) diagram of bearing without damage

also shows cases of vibration acceleration. After having examined the diagrams of vibration frequency and acceleration of bearing roller with cut and damaged roller, it can be preliminarily concluded that

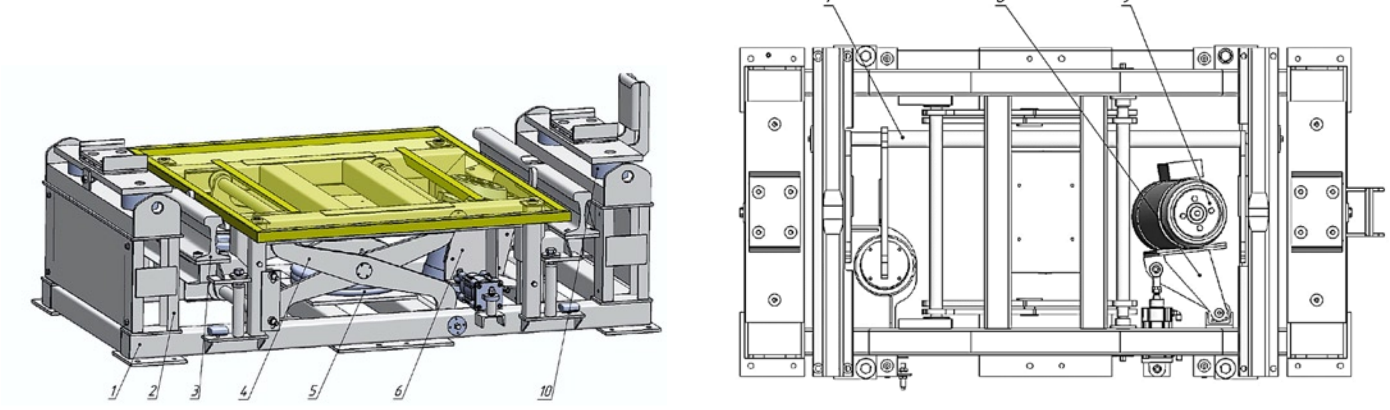

Fig. 2. General view of stand used for research:

1 – stand basis frame, 2 – stand frame rack, 3 – railway, 4 – axle-box lifter, 5 – compressed air balloon, 6 – winch for axle rotation, 7 – pneumatic winch pusher, 8 – winch holding bracket, 9 – device for torque transmission to axle, 10 – vibration damping supports.

the vibro-diagnostic method can not only successfully detect defects in the axle-box bearings of rolling stock, but also the frequency ranges of increase in vibration acceleration can be used to determine the type of damage. The disadvantage of the vibro-diagnostic method is that a contact vibration sensor is usually used to measure the vibration parameters and it requires intervention into rolling stock structure or use of special stand (Fig. 1 and Fig. 2 respectively). The possibilities of sensor use are very limited due to abundance and variety of rolling stock in operation and the test in stand during rolling stock operation is not possible at all. Also, we have to keep in mind that the critical values of diagnostic parameters (oscillation frequencies and accelerations) depend on bearing structure. All this complicates the versatility of the diagnostic process in all cases.

4. Bearing damage detection according to temperature

The track side equipment – Hot Axle Box Detectors (HABD) – installed on railway track for axle-box body temperature measurement is provided in Figure 4.

a)

b)

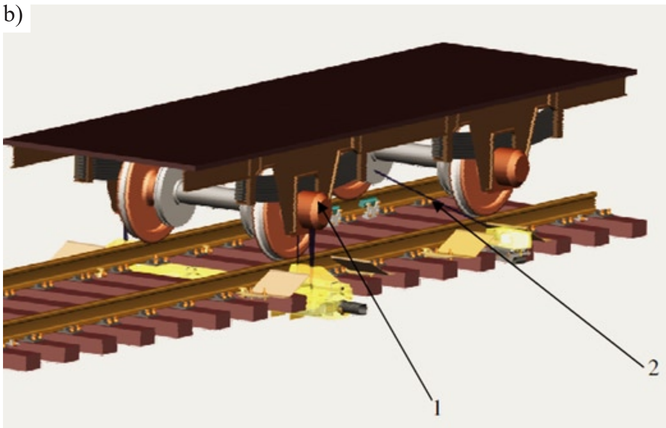

Fig.4. Axle-box temperature measurement equipment [22]: 1– axle-box temperature detectors, 2 – wheel temperature detectors

Temperature sensors are installed on the rail line section in every (20–40) km (actual distance of device displacement depends on infrastructure specific conditions). Temperature sensors are mounted in a special railway sleeper. An optical temperature sensor measures the temperature with accuracy in 0.1 degree (the system reports to the accuracy in 1.0 degree). The equipment is applicable to measure temperature in the range from minus 40°C to plus 50°C. During normal operation of HABD, if a higher temperature of axle-box than the permissible value is recorded, corresponding measures (train stopping, train speed limiting, etc.) are taken on which are regulated in the norm documents. The measurement data are collected in a common system database and this information is be used both for axle-box condition monitoring and for research purposes.

Two-axle bogie of freight car where three of four axle-boxes were serviceable and one was not serviceable was used for temperature test. The temperatures of all four axle-boxes of bogie were measured while running through four HABD at 0°C ambient temperature. The distance from the beginning of route to the first HABD was 28,2 km, from first to second HABD – 29.8 km, later – 22.3 km and 40.6 km respectively. Rail track curves and slopes were not assessed during the test (these values were not essential). Train axle-box temperature values were fixed by HABD sensors during train passing the corresponding devices. Axle-box temperature differences ΔT_i between the values fixed in adjacent heating detection stations HABD is calculated by Formula (5). Axle-box temperature values according to HABD stations are provided in Figure 5.

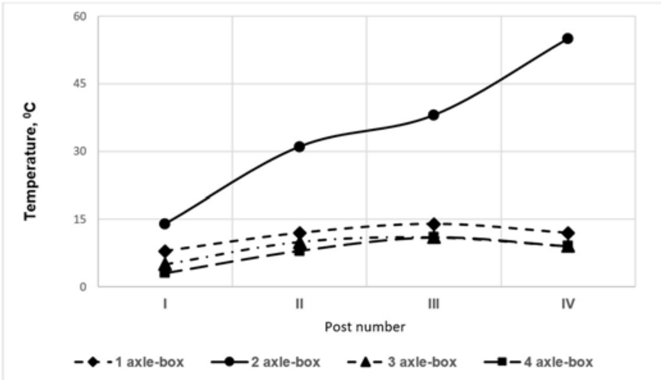

Fig. 5. Axle-box temperature values according to HABD stations

As is seen in Figure 5, the second axle-box gets heater more intensively than other axle-boxes. One of the indicators of the intensity of heating of axle-boxes is their temperature change per kilometre. The said temperature changes per kilometre according to intervals between stations is provided in Figure 6. The temperature changing per kilometer is calculated according to Formula (6).

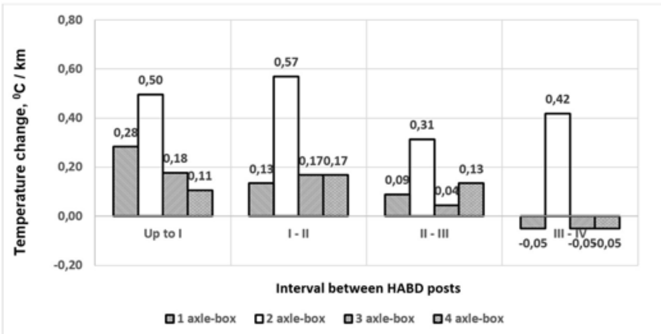

Fig. 6. Axle-box temperature changes per kilometre according to intervals between HABD stations

Diagrams of Figure 6 show that the temperature change per kilometre of the second axle-box is dominant compared to the values of the corresponding indicators for the other axle-boxes. The thermal effect of the environment on all axle-boxes is estimated as the same. During the study, the temperature change of the axle-boxes is compared with each other interdependently. In this way, the impact of the ambient temperature on the calculated final results is eliminated.

Another indicator of heating intensity – axle-box temperature changes in percentage according to intervals between stations is provided in Figure 7. The percentage change of axle-box temperature is calculated according to Formula (7).

Diagrams of Figure 7 show that it is even easier to name more intensively heating axle-box according to axle-box temperature change in percentage (the second in this case). Sharp method is widely used to compare the intensity of indicator value change. It can also help

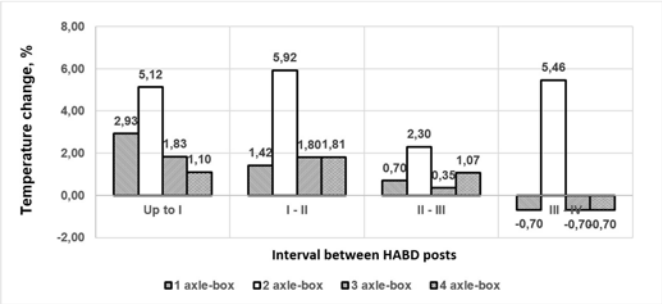

Fig.7. Axle-box temperature changes in percentage according to intervals between stations

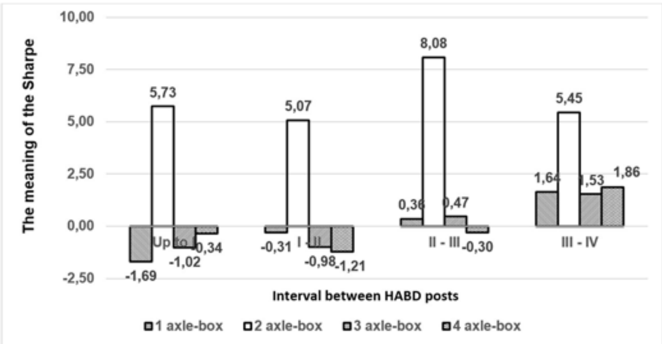

Fig. 8. Sharp criterion values for intervals between stations

to compare the values of indicators of axle-box temperature change intensity. Sharp criterion values for intervals between stations are provided in Figure 8. Finely, the Sharpe criterion to assess the variance deviation of considered parameter is calculating by equation presented in Formula (8).

Diagrams of Figure 8 display that the result of Sharp criterion is the most informative of examined results. After having the summarised results shown in diagrams of Fig. 6, Fig.7 and Fig.8, it can be seen that temperature change is suitable diagnostic criterion for rolling stock axle-box bearings and one of several mathematical methods can be selected to process the data of the values of this parameter.

Vibro-diagnostic and temperature variation methods can be used together in combined manner. Monitoring of axle-box temperature change does not require intervention in the vehicle structure. That makes this method more convenient in practice.

Conclusions

1. The research of identification methods of axle-box bearing damage of rolling stock confirmed that two methods of bearing defects diagnostics are possible in the physical sense: vibro-diagnostic method and temperature change intensity method.
2. The advantage of the vibro-diagnostic method is that it allows identifying not only the fact of bearing failure, but also its nature according to the peculiarities of oscillation frequency and acceleration diagrams. The disadvantage of this method is that the measurement of the vibration parameters requires an intervention in the rolling stock structure (or requires the use of special stand), but such possibilities are very limited due to abundance and diversity of rolling stock in operation. In addition, critical values of diagnostic parameters (oscillation frequencies and accelerations) depend on bearing structure. All this complicates the versatility and accessibility of the diagnostic process.
3. The research showed that the temperature change is suitable diagnostics parameter of axle-boxes of rolling stock and one of several mathematical methods can be selected to process the data of the values of this parameter.
4. Three possible methods to assess the temperature change intensity of axle-boxes of rolling stock mathematically were provided: first – by estimating the axle-box temperature change in degrees per kilometre, second – by estimating the axle-box temperature change in percentage (during the selected mileage range), and third – by using Sharp criterion.
5. The simplest way is to estimate the axle-box temperature change in degrees per kilometre. The most informative results were obtained by applying Sharp criterion, however, this method is the most complex. It must be noted that this circumstance (complexity) is not essential when using computer software.

References

1. Amini A, Entezami M, Papaelias M. Onboard detection of railway axle bearing defects using envelope analysis of high frequency acoustic emission signals. J Case Stud Nondestruct Test Eval 2016; 6: 8-16, https://doi.org/10.1016/j.csndt.2016.06.002.
2. An automated complex for vibration diagnostics of bearings of axlebox units of wheelsets of railway cars. JSC "Technocom". Watched: 2020-03-05: http://texnokom-nn.ru/katalog/kolesno-rolikovyi-uchastok/komplex-vibrodiagnostiki-sv-tk/?utm_source=google&utm_medium=text&gclid=EAIaIQobChMI2ou1__6C6AIVyPhRCh30TAtWEAAYASAAEgJvXvD_BwE
3. Aliev T, Babayev T, Alizada T, Rzayeva N. Control Of The Beginning Of Accidents In Railroad Operation Safety Systems In Seismically Active Regions Using The Noise Technology. Transport Problems - Problemy Transportu 2019; 14 (3): 155 - 162, https://doi.org/10.20858/tp.2019.14.3.14
4. Aliev T, Babayev T, Alizada T, Rzayeva N. Noise control of the beginning and development dynamics of faults in the running gear of the rolling stock. Transport Problems - Problemy Transportu 2020; 15 (2): 83 - 91, https://doi.org/10.21307/tp-2020-022.
5. Bently D E. Rolling element bearing defect detection and diagnostics using REBAM® probes. Orbit 2001; 22:12-25.
6. Bosso N. A modular monitoring system for on-board vehicle diagnostic. Mater Eval 2012: 78-85.
7. Cao P, Fan F, Yang X. Wheel-bearing fault diagnosis trains using empirical wavelet transform. Measurement 2016; 82: 439-449, https://doi.org/10.1016/j.measurement.2016.01.023.
8. Gomez M J, Castejon C, Garcia-Prada J C. New stopping criteria for crack detection during fatigue tests of railway axles. Engineering Failure Analysis 2015; 56: 530-537, https://doi.org/10.1016/j.engfailanal.2014.10.018.
9. Han T, Jiang D. Fault diagnosis of multistage centrifugal pump unit using non-local means-based vibration signal denoising. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2019; 21 (4): 539-545, https://doi.org/10.17531/ein.2019.4.1.

10. Huang Y, Lin J, Liu Z, Wu W. A modified scale-space guiding vibrational mode decomposition for high-speed railway bearing fault diagnosis. Journal of Sound and Vibration 2019; 444: 216-234, https://doi.org/10.1016/j.jsv.2018.12.033.
11. Huang H-Z, Yu K, Huang T, Li H, Qian H-M. Reliability estimation for momentum wheel bearings considering frictional heat. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2020; 22 (1): 6-14, https://doi.org/10.17531/ein.2020.1.2.
12. Karabacak Y., Gürsel Özmen N, Gümüşel L. Worm gear condition monitoring and fault detection from thermal images via deep learning method. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2020; 22 (3): 544-556, https://doi.org/10.17531/ein.2020.3.18.
13. Li X, Jis L., Yang X. Fault diagnosis of train axle bearing based on multiply feature parameters. Dissert Dynamics in Nature and Society 2015. Article ID 846918: 8, https://doi.org/10.1155/2015/846918.
14. Li Y, Liang X, Li J. Train axle bearing fault detection using a feature selection scheme based multi-scale morphological filter. Mech Syst Signal Pr 2018; 101: 435-448, https://doi.org/10.1016/j.ymssp.2017.09.007.
15. Owen R. No bearing no acoustics? Think again. Acoustics Bulletin. Institute of Acoustics 2014; 39 (4): 35-37.
16. Papaelias M, Amini A, Huang Z. Online conduction monitoring of rolling stock wheels and axle bearing. J. Rail Rapid Transit 2016; 230 (3): 709-723, https://doi.org/10.1177/0954409714559758.
17. Papaelias M. Interoperable monitoring, diagnosis and maintenance strategies for axle bearings. Maxbe report 2012; 34 p.
18. Steišūnas S, Bureika G, Gorbunov M. Effects of rail-wheel parameters on vertical vibrations of vehicles using a vehicle-track-coupled model. Transport Problems - Problemy Transportu 2019; 14 (3); 27-39, https://doi.org/10.20858/tp.2019.14.3.3.
19. Symonds N, Corni I, Wood R. Observing early stage rail axle bearing damage. Eng Fail Anal 2015; 56: 216-232, https://doi.org/10.1016/j.engfailanal.2015.02.008.
20. Urbaś A, Szczotka M. The influence of the friction phenomenon on a forest crane operator's level of discomfort. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2019; 21 (2): 197-210, https://doi.org/10.17531/ein.2019.2.3.
21. Vaičiūnas G, Bureika G, Steišūnas S. Research on metal fatigue of rail vehicle wheel considering the wear intensity of rolling surface. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2018; 20 (1): 24-29, https://doi.org/10.17531/ein.2018.1.4.
22. Vale C, Bonifacio C, Seabra J. Novel efficient technologies in Europe for axle bearing condition monitoring - the MAXBE project. Transport. Res. Proc. 2016; 14: 635-644, https://doi.org/10.1016/j.trpro.2016.05.313.
23. Wang Z, Cheng Y, Allen P, Zhonghui Yin Z, Zou D, Zhang W. Analysis of vibration and temperature on the axle box bearing of a high-speed train. Vehicle System Dynamics, International Journal of Vehicle Mechanics and Mobility 2019, https://doi.org/10.1080/00423114.2019.1645340.
24. Wang C, Shen C, He Q. Wayside acoustic defective bearing detection based on improved Doppler-let transform and Doppler transient matching. Appl. Acoust. 2016; 101: 141-155, https://doi.org/10.1016/j.apacoust.2015.08.014.
25. Yi C, Lin J, Zhang W, Ding J. Faults diagnostics of railway axle bearings based on IMF's confidence index algorithm for ensemble EMD. Sensors 2015; 15: 10991-11011, https://doi.org/10.3390/s150510991.
26. Yi C, Wang D, Fan W, Tsui K-L, Lin J. EEMD-Based Steady-State Indexes and Their Applications to Condition Monitoring and Fault Diagnosis of Railway Axle Bearings. Sensors 2018; 18(3), 704: 1-21, https://doi.org/10.3390/s18030704.
27. Zhao M, Lin J, Miao Y. Detection on recovery of fault impulses proved harmonic product and its application in defect size estimation of train bearings. Measurement 2016; 91: 421-439, https://doi.org/10.1016/j.measurement.2016.05.068.
28. Zhou Y, Lin L, Wang D, He M, He D. A new method to classify railway vehicle axle fatigue crack AE signal. Applied Acoustics 2018; 131: 174-185, https://doi.org/10.1016/j.apacoust.2017.10.025.