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Identification of railway track damage using vibration signal characteristics

Adrianna **Łomżyńska** [a], Klaudia **Strugarek** [b], Malwina **Nowak** [c], Aleksander **Ludwiczak** [b], Mikołaj **Klekowicki** [b, *], Grzegorz M. **Szymański** [b]

[a] *Łukasiewicz Research Network – Poznan Institute of Technology, 6 Ewarysta Estkowskiego St., 61-755 Poznań, Poland*
[b] *Faculty of Civil and Transport Engineering, Poznan University of Technology, Poland*
[c] *Faculty of Chemical Technology, Poznan University of Technology, Poland*

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The study focuses on the identification of railway track damage using vibration signal characteristics. It presents the identification of vibration signals generated by the bogie system during passage over selected track sections in two different technical conditions. A literature review on rail infrastructure and its maintenance is provided, along with a description of modern diagnostic systems employed by companies responsible for track maintenance. The research involved analyzing vibration signals in both the time and frequency domains. Based on the obtained results, the feasibility of detecting damage using vibration signals recorded from a vehicle was confirmed, allowing for the assessment of the impact of infrastructure damage on passenger comfort.

1. Introduction

Early diagnostics of rail infrastructure enable the identification of damage to critical components essential for the safe and efficient operation of the railway system. Such early detection facilitates the implementation of remedial actions before the damage progresses, positively impacting the condition of the infrastructure. The contemporary advancement of technology necessitates the development of modern methods for maintaining and servicing railway equipment. Through data analysis and continuous monitoring, it becomes possible to track the wear processes of individual components over time, thereby enhancing diagnostics and maintaining them in optimal condition.

The primary goals of diagnostics are to increase durability, improve reliability, and enhance the efficiency of technical solutions. Accurate assessment of the technical condition enables comprehensive analysis, which serves as the foundation for making informed maintenance decisions. Advanced diagnostic techniques, based on the analysis of impulse signals and their comparison with reference damage data, allow for precise identification of technical issues.

In the context of rail infrastructure, key components subject to frequent damage include rails, sleepers, and rail fastenings, all of which are continuously subjected to heavy loads. Damage to these elements directly affects both the condition of rolling stock and the organization of the entire railway system. In response to the demands of modern transportation, engineers have focused on designing vehicles capable of achieving very high speeds, necessitating the adaptation of rail infrastructure to withstand increased loads without excessive wear of critical components. Consequently, regular monitoring of the technical condition and wear levels of individual components has become an indispensable element of railway operations, encompassing both transport organization and the production of rolling stock components.

* Corresponding author: mikolaj.klekowicki@student.put.poznan.pl (M. Klekowicki)

2. Railway infrastructure

2.1. Components of railway infrastructure

Railway infrastructure is a complex system that plays a crucial role in transportation, enabling the efficient and safe movement of people and goods. It forms the foundation of rail transport, providing the necessary stability and protection against external factors. Railway infrastructure encompasses a range of components, including tracks, sleepers, traffic control systems, and engineering structures, which together create a cohesive system that ensures the safe operation of trains. Additionally, the infrastructure includes various solutions aimed at enhancing energy efficiency, such as railway networks that enable electrification and reduce emissions.

Regular maintenance and monitoring of infrastructure conditions are essential for ensuring safety. Advanced diagnostic techniques, such as measurement vehicles and vibroacoustic systems, enable real-time assessment of track and other component conditions, minimizing the risk of failures and unplanned service interruptions.

The components of railway infrastructure form a system that ensures the safe and stable operation of trains. Rails, as a primary component, are made from durable materials such as steel or cast iron and are mounted on wooden or concrete sleepers using spacers and fasteners that dampen vibrations and reduce noise. Sleepers transfer the load from the rails to the ballast, which provides stability and ensures proper drainage of the trackbed [9].

Engineering structures, such as bridges, viaducts, and tunnels, are also integral to railway infrastructure, enabling trains to overcome natural obstacles. Depending on the terrain, tracks may be single- or multi-line and adapted to speed and transport type. Modern railway networks often incorporate track electrification, which enhances energy efficiency and reduces environmental impact.

This study focuses on analysing phenomena occurring on the railway track surface, the most visible part of railway infrastructure. It consists of elements that enable the movement of rail vehicles, such as rails, fasteners, sleepers, and ballast (Fig. 1).

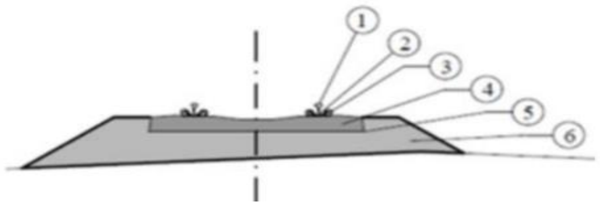

Fig. 1. The structure of the railway track surface comprises: 1 – rail, 2 – rail fastening baseplate, 3 – rail fastening connectors, 4 – sleeper, 5 – under-sleeper pad, 6 – ballast [1]

Railway rails are a fundamental component of rail infrastructure and play a crucial role in ensuring the safe and efficient operation of railway systems.

2.2. Railway infrastructure damage

The railway track surface undergoes natural wear and damage caused by dynamic loads generated by train operations. As part of regular maintenance, the infrastructure is inspected to prevent major failures [4]. Rail damage, such as cracks or deformations, is classified according to national and international standards, including the UIC 712 Rail Defects Catalogue [2] and the Rail Defects Catalogue of Polish Railway Lines [3].The most common types of damage include:

- Head checks – micro-cracks forming on the inner surface of the rail head, particularly in areas of intensive wheel-rail contact (Fig. 2). These defects result from variable dynamic loads and material fatigue [5].
- Squats – deformations on the lower edge of the rail head caused by improper load distribution. These lead to surface bulging and deformations, potentially causing track failure (Fig. 3) [7].

Fig. 2. Example of a "head checks" defect [15]

Fig. 3. Example of a "squat" defect [8]

If undetected and unaddressed, these defects can lead to track failures and potential collisions. Defects in rail fastenings, in turn, destabilize the track, posing a risk to railway traffic safety. Both concrete and wooden sleepers are also susceptible to damage. In concrete sleepers, cracks, fractures, and surface spalling occur, while wooden sleepers are vulnerable to moisture and temperature fluctuations, resulting in reduced durability and fungal growth. These defects affect the stability of the entire track structure and may require replacement during regular inspections.

2.3. Vibrations generated at the wheel-rail interface

Rail vibrations are a critical factor in the diagnostics of railway infrastructure. The passage of a train generates vibrations that can serve as indicators of the track's technical condition. Various diagnostic parameters are employed in vibration analysis, including amplitude, frequency, harmonic composition, and impulsive indicators (Fig. 4). These parameters are compared with reference values to determine whether the vibrations generated in the rails are within acceptable limits or if deviations indicate potential damage.

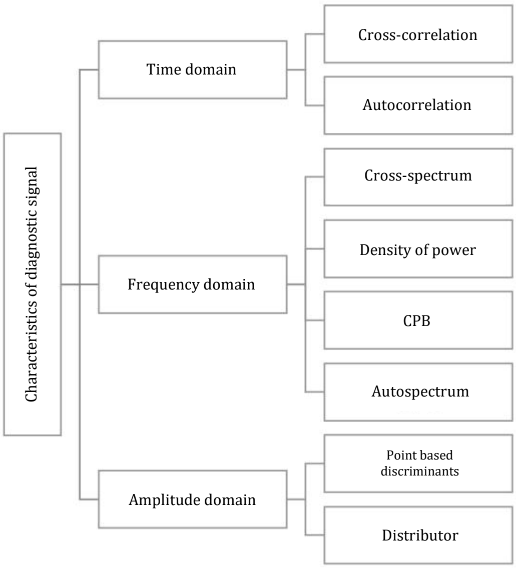

Fig. 4. Selected parameters of vibration diagnostics signals

Vibrations caused by rail contact are recorded using piezoelectric sensors, which convert mechanical motion into electrical signals. These parameters can then be analysed in real time, providing data for evaluating track conditions. Vibrations not only indicate track wear but also help identify areas requiring maintenance before more severe damage occurs [8].

3. Railway infrastructure diagnostics

3.1. Inspection using a measurement trolley

A specialized diagnostic vehicle of PKP PLK (Fig. 5) utilizes laser technology for precise and contactless measurement of track geometry, rail head profile, and the condition of sleepers, rail fastenings, and track stability. The collected data is automatically recorded and transmitted to stationary diagnostic computers, enabling rapid analysis and response to potential infrastructure issues. A notable innovation is the inclusion of railway network diagnostics, which allows for a comprehensive assessment of the entire railway line.

The vehicle is equipped with an ETCS Level 2 system, enabling verification of compatibility with the European Rail Traffic Management System (ERTMS) on main lines, thereby enhancing compliance with European safety standards. Powered by a diesel engine, the vehicle can reach speeds of up to 120 km/h, facilitating the efficient monitoring of extensive network segments. Bogies with pneumatic suspension ensure stability and measurement accuracy while also improving crew comfort.

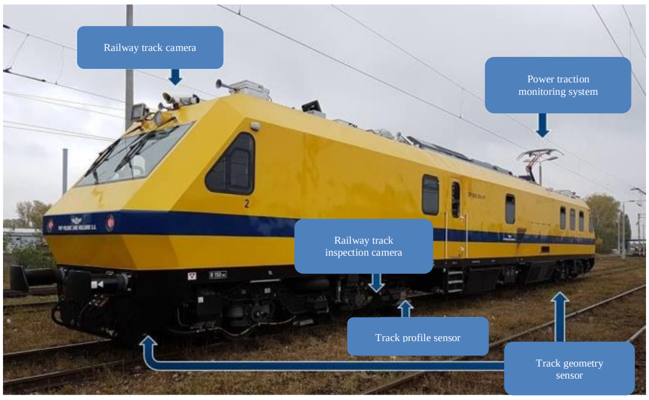

Fig. 5. Railway measurement trolley [10]

The vehicle is equipped with onboard facilities, including sleeping areas, a shower, a toilet, and a small kitchenette, allowing the crew to work independently for extended periods across the entire PKP PLK railway network. This mobile diagnostic unit, functioning as a "laboratory on wheels," provides near-instant access to results, enabling rapid decision-making regarding necessary repairs or upgrades. For passengers, this translates to improved travel quality –- enhanced comfort and reduced delays or schedule disruptions.

3.2. Inspections and technical assessments of infrastructure

The inspection of railway infrastructure involves regular reviews and assessments of all components comprising the railway system, such as tracks, platforms, signals, bridges, tunnels, signalling devices, and power lines. The primary aim of these activities is to ensure the functionality and safety of the entire railway network, which is crucial for uninterrupted and secure train operations. These inspections are carried out by trained personnel using specialized tools and technologies to monitor the condition of the infrastructure.

During inspections, various aspects of the infrastructure are analysed, including track wear and potential damage, deformations, as well as the stability and condition of rail fastenings to sleepers. Special attention is given to track sections with curves of radii smaller than 800 meters, as these are more prone to deformations and damage. Inspections also check for cracks in rails or fishplates, and whether sleepers provide adequate support and maintain the correct track gauge. Inspectors closely examine for signs of rail creep or track shifting, which could pose safety risks.

Detecting any irregularities that may threaten safety is a key objective of these inspections, as is taking corrective action. If immediate repairs are not feasible, hazardous sections must be secured using warning signals, and specialists should be notified for necessary intervention. Inspection and repair activities must be conducted in a way that ensures the safety of both personnel and trains operating on the affected section.

Regular inspections of railway infrastructure enable early detection of problems, prevention of failures, and enhancement of railway traffic safety.

3.3. Defectoscopic testing

Defectoscopic testing of active railway tracks encompasses detailed procedures and non-destructive techniques aimed at detecting material discontinuities such as cracks, corrosion, voids, delaminations, or fissures. These methods enable the assessment of the technical condition of rails without causing any damage. The most commonly employed techniques include:

- Ultrasonography, which utilizes ultrasonic waves to penetrate the material's structure, allowing for the detection of cracks, inclusions, or other internal defects within the rails.
- Magnetoscopy, used to inspect metal structures such as rails by analyzing the magnetic field. This method is particularly effective in identifying surface discontinuities in metallic materials.
- Radiography, which employs X-rays or gamma rays to generate images of the internal structure of rails. This technique allows for the precise detection of hidden defects and damage that may not be visible to the naked eye.
- Thermography, which examines the thermal emission on the rail surface. Variations in the temperature distribution can indicate potential structural defects, facilitating the early detection of problems.
- For manual defectoscopic testing of rails, specialized single-probe ultrasonic devices are used, enabling precise inspection of individual track sections (Fig. 6).

The testing is conducted according to a schedule that depends on the specific characteristics of the tracks, such as the maximum allowable train speed on the section or the annual track load. Defectoscopic testing is carried out with varying frequencies, with more frequent inspections on lines with higher loads or speeds. For instance:

- Inspections are conducted four times a year on lines where train speeds reach at least 160 km/h.
- For lines with speeds between 120 and 160 km/h, inspections are performed three times a year.
- For speeds ranging from 100 to 120 km/h, inspections occur twice a year.
- On lines where train speeds are below 100 km/h, inspections are carried out once a year.

Fig. 6. Defectoscope for single rail inspection

Similar guidelines apply to inspections based on the annual track load, measured in ton-hours (Tg). For loads of at least 20 Tg, inspections are performed three times a year; for loads between 10 and 20 Tg, twice a year; and for loads below 10 Tg, once a year.

All these activities are carried out by specialized teams equipped with appropriate tools, including radiotelephones operating on railway network channels, to ensure smooth communication and safety while working on active tracks.

3.4. Challenges related to railway infrastructure diagnostics

Diagnostics of railway infrastructure using vibration acceleration measurements is an advanced method for assessing the technical condition of railway tracks and other critical infrastructure components. By recording vibration accelerations, this approach enables the detection of minor damages, such as microcracks, deformations, or slight rail distortions, which may pose risks to the safety and continuity of railway operations.

The diagnostic process is based on comparing vibration signals from a track section with a known defect (the test condition) to signals from a reference section that is free of defects. For each measurement point, a vibration signal is generated, influenced by the passage of trains. The key to technical assessment lies in measuring the similarity between signals from the tested area and the reference section, which allows for the identification and evaluation of potential damage.

Vibroacoustic diagnostics consider three primary aspects of signal analysis: time, frequency, and amplitude. Vibration acceleration measurements are performed using accelerometers mounted directly on rails, near tracks, or on vehicles. These accelerometers record vibrations caused by train passages as well as other stress factors affecting the infrastructure. Unusual vibrations resulting from microcracks or more prominent damages are captured by transducers, enabling the detection of deviations in the track system, such as rail displacements, deformations, or irregular spacing.

Measurement data is collected and digitally analysed using advanced computational tools. The analysis focuses on identifying specific signal characteristics that indicate potential structural issues. In the time domain, the analysis examines signal shapes, acceleration values, velocities, and displacements over time, providing a detailed representation of events at each measurement stage. Correlation analysis is also conducted to evaluate the temporal consistency between different signal fragments or signals recorded simultaneously.

In the frequency domain, power spectral density is used to determine vibration characteristics by transforming data from the time domain into the frequency spectrum using Fourier transforms (both DFT and FFT). This analysis allows for the precise identification of irregularities in track structures, indicating early stages of damage. As a result, this method serves as an effective tool for monitoring railway infrastructure conditions, supporting maintenance activities, and enhancing the safety of railway systems.

4. Methodology

4.1. Measurement methodology and scope of research

The research was conducted based on vibration signals recorded on a vehicle passing through the analysed points of railway infrastructure. The applied methodology relied on a comparative analysis of two track sections. Following a visual inspection, one section was identified as damaged, while the other was considered a reference standard. Both segments were located on a railway siding.

The analysis was carried out using measurements recorded on the tested sections of varying lengths, necessitating the standardization of the data for comparison. The signals were normalized in the time domain. During the study, the vehicle maintained a constant speed of 10 km/h.

After the measurements, time-domain waveforms were obtained, representing vibration accelerations on the test sections. The results were presented as time-domain plots, including maximum amplitude values, amplitude ratios, and FFT (Fast Fourier Transform) analysis.

4.2. Measurement equipment

The measurement equipment was mounted on a vehicle traversing the test infrastructure, with its parameters detailed in Table 1. The vehicle consists of two sections differing in relation to the dual-drive type. The first section is designated as the machine module, while the second is electric. Each section is equipped with a powered bogie and a trailing bogie. A distinctive feature of this setup is the placement of the powered bogies at the center of the trainset. The primary difference between the sections lies in the mass distribution and the structural design of the trailing bogies, significantly influencing the homologation tests of such a vehicle.

Table 1. Basic technical data of the vehicle

Clearance gauge	According to PN-EN 15273-2:2013+A1:2017-03, sketch G2
Axle arrangement	2'Bo'+Bo'2'
Track gauge	1435 mm
Overall length	53,652 mm
Minimum curve radius	150 m
Curb weight	112,500 kg
Wheel diameter on the rolling circle	850 mm
Maximum speed	160 km/h

Two types of piezoelectric transducers were used for the measurements, with their characteristics detailed in Tables 2 and 3. The first transducer (Table 2, Fig. 7) was mounted on the vehicle's bogie, while the second (Table 3, Fig. 8) was installed on the floor of the passenger compartment.

Table 2. Technical specifications of the MEAS EGCS-A2-5-/C transducer

MEAS EGCS-A2-5-/C	
Parameters	up to 4000 Hz
Mechanical features	
Sensor base material	anodized aluminum
Sensor axes	single-axis
Sensor weight	50 g (1.75 oz)
Mechanical attachment	
Mounting type	screw
Operating conditions	
Operating temperature range	–40°C to 120°C
Other features	
Sensitivity	5 mV/g
Nonlinearity	±1% FSO

Fig. 7. Piezoelectric transducer MEAS EGCS-A2-5-/C

Table 3. Technical specifications of the MEAS EGCS3-A transducer

MEAS EGCS3-A	
Parameters	up to 4000 Hz
Mechanical features	
Sensor base material	anodized aluminum
Sensor axes	triaxial
Sensor weight	50 g (1.75 oz)
Mechanical attachment	
Mounting type	screw
Operating conditions	
Operating temperature range	–40°C to 120°C
Other Features	
Sensitivity	5 mV/g
Nonlinearity	±1% FSO

Fig. 8. Piezoelectric transducer MEAS EGCS3-A

A PC-class computer equipped with the LabVIEW measurement system from National Instruments was used for data recording, processing, and analysis. The data acquisition software, also LabVIEW by National Instruments, utilized digital filters provided by National Instruments for enhanced signal processing.

4.3. Localization of measurement points

The measurement points were strategically located on the machine module to ensure optimal representativeness of dynamic measurement results. The first measurement point was placed on the vehicle's bogie frame (Fig. 9), while the second was positioned on the floor as close as possible to the aforementioned bogie (Fig. 10). This selection of measurement locations is crucial, as it allows for the comparison of two acoustically distinct regions of the vehicle, providing a more comprehensive insight into the distribution of vibrations across different parts of the structure.

Fig. 9. Measurement point 1 localized on the train bogie

Fig. 10. Measurement point 2 localized on the train floor

The measurement point on the bogie frame reflects the vibration levels experienced by the working parts of the vehicle, particularly components directly related to the drivetrain and suspension systems. Conversely, the measurement point located on the floor enables the evaluation of vibration levels perceived by passengers, which directly impacts ride comfort. This approach facilitates an analysis from both the perspective of the vehicle's technical operation and passenger comfort. Consequently, it becomes possible to identify sources of potential operational issues and assess the effectiveness of vibration isolation implemented in the vehicle's design.

Furthermore, comparing the measurement results between the bogie and the floor forms the basis for identifying vibration propagation phenomena and energy losses at various stages of transmission through the vehicle's structure.

5. Data analysis

The recorded vibration acceleration values for the vertical Z-direction (on the vehicle's floor and bogie) during the object's operation at a speed of v = 10 km/h on a railway siding were subjected to further analysis. Initially, the amplitude values of the time-domain signals were compared to establish preliminary differences. These waveforms are presented in Fig. 11 and 12.

Table 4. Comparison of maximum amplitude values (A_max) for bogie (W) and floor (P)

	Damaged	Undamaged
A_max(W)	17.07 m/s^2	10.08 m/s^2
A_max(P)	1.84 m/s^2	0.73 m/s^2

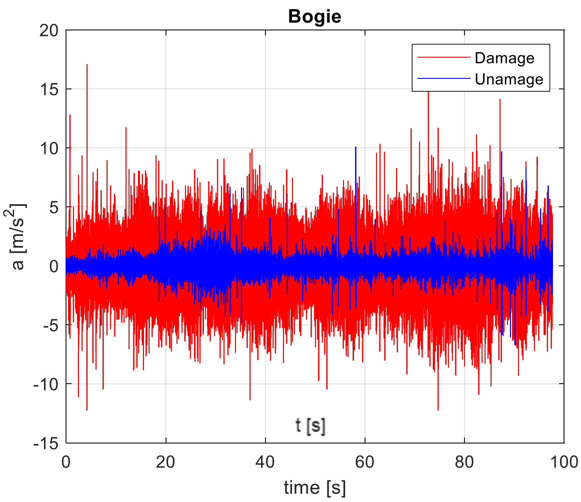

Fig. 11. Comparison of time-domain waveforms for damaged and undamaged tracks in the case of bogie measurements

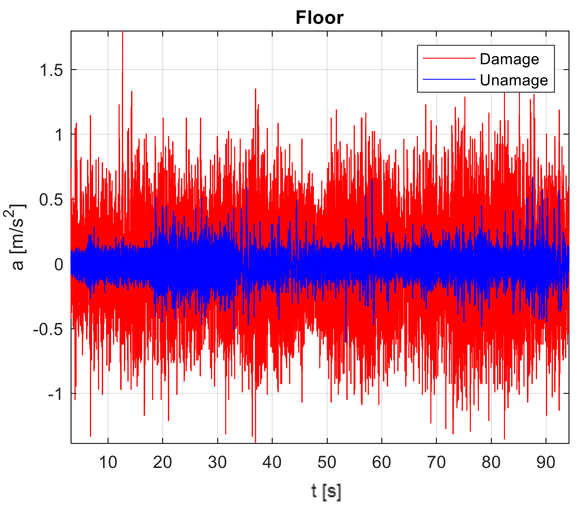

Fig. 12. Comparison of time-domain waveforms for damaged and undamaged tracks in the case of floor measurements

In Figures 11 and 12, it can be observed that the vibration amplitude values for the signal measured on the floor are comparatively lower than those for the signal measured on the bogie. However, the amplitude ratio of the signals (Table 4) is higher for the floor measurements than for the bogie measurements.

The next step of the study involved performing a frequency analysis of the recorded measurements using the Fast Fourier Transform (FFT), also known as spectral analysis. FFT enables the rapid identification of a signal's components by representing it as a sum of sinusoidal signals with varying frequencies and amplitudes. Changes in vibration amplitudes as a function of frequency were analyzed, allowing for the identification of potential vibration sources and an assessment of their impact on the overall dynamics of the vehicle [10].

The relationships describing the Fourier Transform are expressed in the following equations (Equations 1–3):

$$s(t) = a_0 + \sum_{k=1}^{\infty} \left[a_k \cos\left(\frac{2\cdot\pi\cdot k\cdot t}{T}\right) + + b_k \sin\left(\frac{2\cdot\pi\cdot k\cdot t}{T}\right) \right] \quad (1)$$

$$a_k = \frac{1}{T}\int_0^T s(t)\cdot\cos\left(\frac{2\cdot\pi\cdot k\cdot t}{T}\right)\, dt \quad (2)$$

$$b_k = \frac{1}{T}\int_0^T s(t)\cdot\sin\left(\frac{2\cdot\pi\cdot k\cdot t}{T}\right)\, dt \quad (3)$$

where: t – time, T – time interval, k – harmonic order (k = 1, 2, 3…), f – frequency, a_0 – constant component of signal, a_k, b_k – coefficients for expanding the function into a Fourier series.

The amplitude spectrum is defined by the formula:

$$A=\sqrt{a_k^2 + b_k^2} \quad (4)$$

The FFT analysis for the bogie (Fig. 13) includes the vibration amplitude spectrum comparing the reference and damaged states. In the damaged state, significantly higher amplitude peaks can be observed at both low and high frequencies, indicating an increased level of harmonic vibrations in these ranges.

Characteristic peaks appear in the low-frequency range (approximately 0–100 Hz), which may adversely affect the bogie's performance, potentially leading to reduced operational lifespan and a more frequent need for maintenance activities.

Figure 14 illustrates the differences in amplitude levels between the reference and damaged states. However, due to the damping properties of the working section connected to the passenger compartment, a significant reduction in vibration levels can be observed for both damaged and reference tracks. This indicates a positive impact of the vehicle's design on passenger comfort in terms of vibration perception during travel.

Table 5. Dynamics of signal changes for different frequency bands

Measurement point	Frequency range [Hz]	Dynamics [dB]
Bogie	40–90	12
	130–180	15
	250–300	14
Floor	40–90	13
	130–180	8
	250–300	6

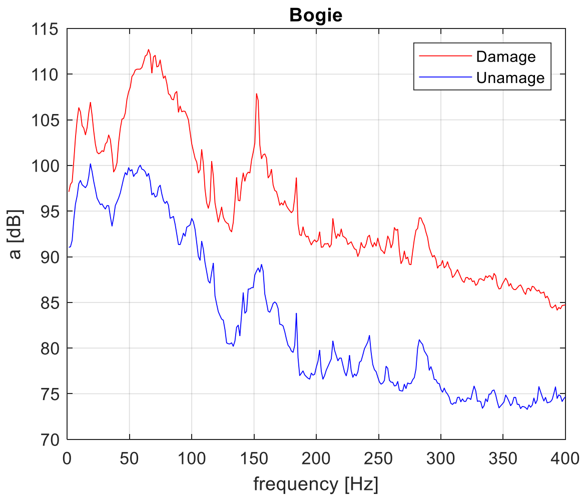

Fig. 13. FFT characteristics for results recorded on the bogie

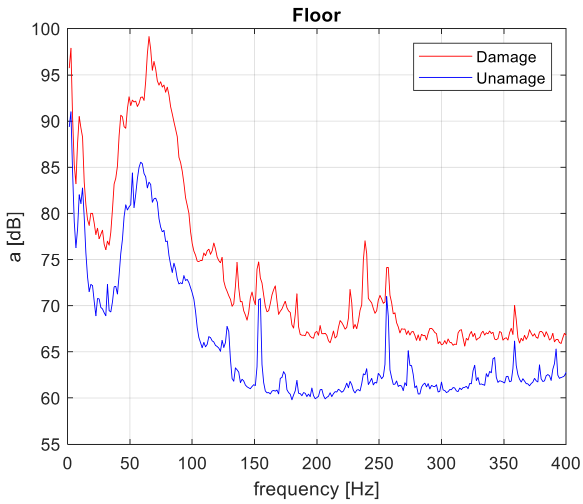

Fig. 14. FFT characteristics for results recorded on the floor

The FFT analysis results indicate that the damaged state of the vehicle is characterized by a significant increase in vibration levels within the low-frequency range. This increase is predominantly observed at the bogie level and is negligible at the floor level (Table 5). While this may negatively impact the overall dynamics and operational aspects of the vehicle, it is likely imperceptible to passengers.

6. Conclusions

Based on the conducted research, it was concluded that vibration signals generated during the passage of a rail vehicle can be effectively used to identify damage to railway infrastructure. A comparison of maximum vibration acceleration amplitudes between the reference and damaged states revealed significant differences at both the bogie and floor levels.

On the bogie, the vibration amplitude values were 17.07 m/s^2 for the damaged state and 10.08 m/s^2 for the reference state, indicating an increase of approximately 69%. On the floor, the amplitudes were lower, measuring 1.84 m/s^2 and 0.73 m/s^2 respectively, which corresponds to an increase of approximately 152%.

The FFT analysis showed that the damaged state is characterized by a significant increase in vibration amplitudes within the 130–180 Hz range for the bogie (15 dB of signal dynamics) and at 40–90 Hz for the floor (12 dB of signal dynamics). The increased vibration levels in these ranges on the bogie may negatively impact vehicle operation, accelerating the need for maintenance work.

At the same time, the vehicle's structural vibration damping effectively reduced the vibration levels perceived by passengers, indicating a well-designed passenger compartment and its positive influence on ride comfort.

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Nomenclature

DFT Discrete Fourier Transform

FFT Fast Fourier Transform

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