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A PROPOSAL FOR A MOBILE SYSTEM OF VEHICLE AND RAIL TRACK DIAGNOSTICS

Summary. The proper technical condition of a vehicle and rail track in operation is a key aspect in terms of safety and travel comfort. This issue is of particular importance for operators and managers of rolling stock and rail infrastructure. Currently, many diagnostic systems have been developed to monitor the technical condition of selected vehicle systems or rail track from the viewpoints of both the vehicle and track. This article proposes the use of vibration signals in selected quantitative and qualitative analyses as the main diagnostic parameter. For this purpose, over a dozen vibration measurements were carried out during the normal operation of a freight wagon as part of a so-called passive experiment. Measurement points were located on the axle boxes of the wheelsets. The proposed research methodology served as a basis for comparative analyses of the selected operational cases that were investigated. The most important conclusion from the study is that it is possible to monitor the technical condition of vehicles and tracks in real time on the basis of measurements of vibration accelerations at the vehicle level. This directly increases the service life of rolling stock and optimises operating costs by changing the maintenance strategy to one that takes into account the idea of modern on-board technical diagnostics. Another important aspect is the possibility of the varied use of the proposed measurement system, depending on the purpose of the research, which is also associated with the diagnostician's experience in processing vibroacoustic signals and the utilisation of simple or complex quantitative and qualitative analyses.

1. INTRODUCTION

With the design and construction of the first steam rail vehicle in 1829, a period of technical development in the operation and organisation of rail transport began and has gone uninterrupted to this day. Sciences of operation of technical devices also include the very important field of technical diagnostics [1]. It is a field of science (part of the rail vehicle service field) dealing with issues related to the recognition of the technical condition of objects without their disassembly (or after the partial disassembly of subassemblies), which, as a whole, are subject to examination in order to assess their ability to fulfil specific operational functions [2].

However, before describing a rail vehicle as a technical object in the process of diagnosing and monitoring key parameters, it should be noted that a moving rail vehicle is an element of a mechanical system [3] consisting of a track, a wheel-rail contact zone and a vehicle. These elements are exposed to a variety of external conditions, such as weather conditions. Moreover, it should be noted that the dynamic interaction at the wheel-rail interface is the starting point for the exchange of a large number

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of different signals (e.g. vibroacoustic, forces, accelerations) between individual elements of the described mechanical system. Therefore, analysing the vehicle itself without taking into account the above-mentioned elements is a common error when operating rail vehicles.

Regarding the reliability and safety of rail vehicle transport, the operation of running and drive systems, in particular, should be monitored. Here, the most important elements are wheelsets (i.e. wheels and axles), bearings (axle boxes), primary and secondary suspension systems, gears and various types of drive units. Moreover, the dynamic influence of the technical condition of track infrastructure must be taken into account, which can also be monitored from the diagnostic equipment situated on the vehicle using vibration signals.

Many malfunctions are revealed only while driving. Therefore, dedicated on-board diagnostic systems should be used based on the analysis of vibration, temperature and the rotational speed of vehicle components and systems, among other factors [4]. This way, the service process is easier and more effective because malfunctions are located during normal operation and are detected in real time. Furthermore, and more importantly, the rolling stock operator is capable of adopting a modern approach to diagnostics and is not forced to rely only on the conventional preventative method when carrying out maintenance tasks [4, 5].

The aim of this article is to analyse vibration measurements in the context of developing a diagnostic on-board mobile system. Measurements were taken on a railway vehicle during normal operation. It is important to present the selected point measures of vibration signals as an appropriate carrier (parameter) of diagnostic information related both to the track structure and the vehicle itself.

2. SELECTED DIAGNOSTIC SYSTEMS

This chapter presents a review of publicly available literature related to existing systems and methods of diagnosing railway rolling stock. First, systems and methods of this type can be divided into on-board (called ‘on-board’ because they are permanently installed in a rail vehicle), stationary (or track-based, as they are part of railway infrastructure) and mobile (i.e. portable, as they are part of delocalised diagnostics and service).

2.1. Commercial solutions

On-board diagnostics of the running gear (called the SKF Multilog On-line system) is one of the most advanced commercial systems for monitoring the condition of a rail vehicle, particularly its running gear [5]. It was developed to detect malfunctions early and prevent their development. Its main task is to automatically notify the driver about the current technical condition. The system is based on the IMx-R platform. The running gear state is monitored by recording and analysing signals from transducers located at the main kinematic nodes of the running gear (wheelsets, axle bearing bodies) and drivetrain. Vibration and thermal signals are mainly used as diagnostic parameters.

Stationary ASDEK systems (a Voestalpine company product) track failure detection devices for rolling stock [6] and are currently the most popular systems used on major railway lines in Poland. Their greatest advantage is their automatic operation during the normal performance of a rail vehicle with a scheduled speed of up to 200 km/h. Its task is to detect wheel surface deformation, overheated axles, jammed brakes and excessive load on the railway track. The process of detecting various forms of wheel tread deformation makes use of the phenomenon of wheel-rail contact loss in the case of the above-mentioned failures [5, 7].

Based on the time of reduced load, train speed and axle load, an estimated wheel deformation value is determined. Damage to elements such as axial bearings causes increased rolling resistance and, consequently, an increase in temperature and, ultimately, further damage. Undetected and uncontrolled thermal processes within a faulty axle bearing may damage the axle and cause the train to derail. The detection process uses the phenomenon of thermal radiation of damaged rolling stock elements (infrared radiation sensors). Braking system failure in a rail vehicle may lead to the blockage (jamming) of the brakes, overheating of the wheel rim (block brake) or brake disc (disc brake); in extreme cases, the rim can loosen or even slide off the wheel. Mechanical damage to the wheel races may occur as a consequence of jammed brakes. The detection process uses the phenomenon of thermal radiation of damaged rolling stock elements (infrared radiation sensors).

Wabtec Corporation and their Bearing Acoustic Monitor (RailBAM) [8] is another trackside diagnostic system dedicated to wheelset bearing monitoring. The system is based on beamforming analysis and acoustic signal processing. The company has some other solutions for railway monitoring systems (e.g. Wheel Condition and Profile Monitoring Systems, Bogie Geometry Monitor). Similar trackside and on-board monitoring systems are offered by, among others, GRAW (Goldschmidt Smart Rail Company) [9,10], Müller-BBM Rail Technologies [11], Psiacoustic [12] and Deutzer Technische Kohle (DTK) [13].

Many other commercial companies offer measurement elements for creating dedicated mobile monitoring systems that can be mounted on the vehicle. These kinds of companies specialise in the railway research field (e.g. DTK, Müller-BBM, Siemens or Alstom) or in general measurement systems development. HBK is a producer of various vibroacoustic transducers and acquisition modules that can be mounted on the vehicle. Kistler offers dedicated mobile vibration systems which can also be placed on-board in different configurations, depending on their intended need. In sum, there are currently plenty of companies developing or producing similar measurement elements (e.g. LabView, RION, PCB).

2.2. Other methods and techniques

Later in this chapter, an analysis is presented of scientific literature on methods and algorithms for diagnosing the running and drive systems of various rail vehicles. The authors focused primarily on presenting aspects of vibroacoustic diagnostics in the context of rolling stock and infrastructure. Moreover, the presented methods and techniques, apart from simple point measures (usually used in commercial systems), typically use more complicated methods of signal processing (e.g. time-spectral analysis).

There are many methods and techniques available for monitoring and detecting flat spots on the wheels of rail vehicles. In [14], an ultrasound technique was proposed that can be implemented in stationary systems. It uses ultrasonic Rayleigh wave pulses sent at regular intervals along the rail. The pulses travel along the rail surface and reach the point of contact between wheel and rail surfaces. An echo is then generated, which is measured and analysed to determine the presence of flat spots. The proposed technique is resistant to noise disturbances, and the measurement is independent of the degree of wheel wear and its polygonisation. However, the effectiveness of the method decreases with increasing wheel rolling speed. Relative errors are lower than 4% at a maximum wheel speed of 3 m/s.

Another approach to flat spot detection in on-board systems involves measuring and processing vibration signals from axle bearing housing [15]. The study developed an algorithm for adaptive multiscale morphological filtering of the measured vibration accelerations. All simulations and tests showed very promising results, and measurement conditions (e.g. speed of a rail vehicle) were not a problem, which is an outstanding advantage. It should be added that the developed system and the method used are prototypes.

The author of this study, along with the research team, put forward a stationary system for flat spot diagnostics and monitoring using vibration and noise signals measured in close proximity to a passing rail vehicle. Research has shown that acoustic signals [16,17] and vibration [18,19] are appropriate carriers of diagnostic information. In addition, various approaches to processing measured diagnostic parameters are presented. It was shown that time-frequency analyses (i.e. STSF, signal envelope, Hilbert transform, and basic point measures) are very well suited for the purpose of diagnostics of rotating masses (in this case, flat spots of rail vehicle wheels). Also, the Doppler effect is a good example of an acoustic signal processing method for developing trackside condition monitoring systems [20, 21]. Furthermore, in addition to using the vibroacoustic signal as a main diagnostic parameter, an approach to fast signal transmission along railway networks has recently been developed using optical fibres [22–24].

Structural health monitoring is the use of sensors and transducers, actuators, data transmission systems and computing units integrated into the tested object to detect, locate, identify and predict the development of damage that may cause the object to malfunction now or in future [25, 26]. Structural health monitoring systems are based on the theory of technical diagnostics, according to which the diagnosis of technical conditions is carried out in real time during normal operation without disassembling the object. Structural health monitoring is yet another step in the evolution of diagnostic systems, which usually assess the condition of a structure by measuring and analysing technological processes or residual processes accompanying their work (e.g. vibrations, noise, temperature) [23, 25].

With the above information in mind, many monitoring and diagnostic systems have been developed for diagnostics in the main components of rail vehicle bogies. Suspension system diagnostics based on vibration measurements in specific places of bogie frames, along with active body deflection correction systems, were presented in [27] and then applied in several types of electric multiple units operated in Europe, e.g. ED250 train.

The method for monitoring and detecting bogie failures (e.g. failures in wheels or suspension systems) and track damage (e.g. corrugation) described in [28] uses measurements of body and wheelset vibration acceleration (e.g. axle bearing body) and sound. A diagram of the transducer arrangement is presented in Fig. 1. The diagnostic method is based on the interacting multiple-model. The algorithm of this model for processing measured signals mainly uses wavelet transform and Kalman filtering. It is another valuable approach to diagnostics of both the bogie and the track, using vibroacoustic signals as a real-time diagnostic information carrier. The most popular on-board railway condition monitoring systems are described in [29]; here, various types of techniques and methods of signal processing can be found. Moreover, different approaches that can be applied in cases of diagnostic signal (parameter) usage are described.

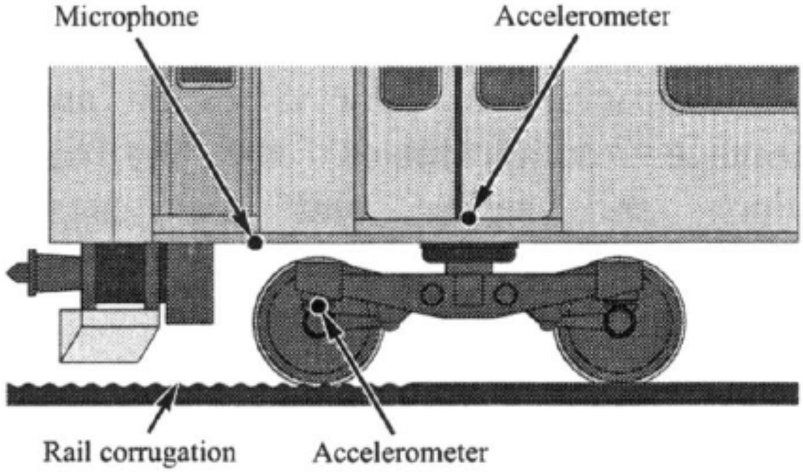

Fig. 1. Diagram of converter arrangement in a system for monitoring and detecting failure in a vehicle and track (source: [28])

Similar on-board solutions were proposed in [30], extending the research methodology to include displacement measurements with a linear sensor (connecting the axle bearing body and bogie frame) and gyroscopes situated on the bogie frame above each wheel. Other items described in the literature using this type of vibroacoustic diagnostics but slightly different signal processing algorithms are described in [31–34]. The methods of processing measured signals were primarily based on the assumptions of time-frequency analysis and successfully achieved the research objective, which was to quickly detect a bogie malfunction (in particular suspension systems) or track failure during operation.

Moving on to the summary of the final stage of literature analysis, items [4,35] present the possibility of diagnosing rotating elements on a rail vehicle bogie. A mobile and portable system was used for vibroacoustic measurements. This type of examination shows that it is possible to effectively monitor and detect malfunctions (e.g. unbalance or misalignment) of shafts, gears, clutches, motors [36], and rolling bearings [19, 37, 38] in drive systems. Considering various issues of vibroacoustic diagnostics and different methods of signal processing, simple quantitative analyses (e.g. point measures, effective values) and qualitative tests (e.g. complex time-frequency analyses) can be used to achieve the objectives mentioned above.

3. RESEARCH METHODOLOGY

3.1. Principal assumptions

A mobile vibration diagnostics system was installed on a platform type freight wagon, which was pulled by the railway drive unit (Fig. 2). The measurements were taken to obtain data on vibrations on the wheelset during the run under normal operating conditions on a first-class railway line in good technical condition at various speeds (the highest speed was approximately 85 km/h). Therefore, it can be concluded that the study was carried out in accordance with the principle of implementing a so-called passive experiment.

Fig. 2. Research object: the freight railway platform onto which the mobile diagnostic system was mounted

Vibration transducers were located on the bodies of axle boxes and recorded vibration accelerations in the vertical and transverse axes. A general diagram of the measuring path of the mobile diagnostic system is presented in Fig. 3.

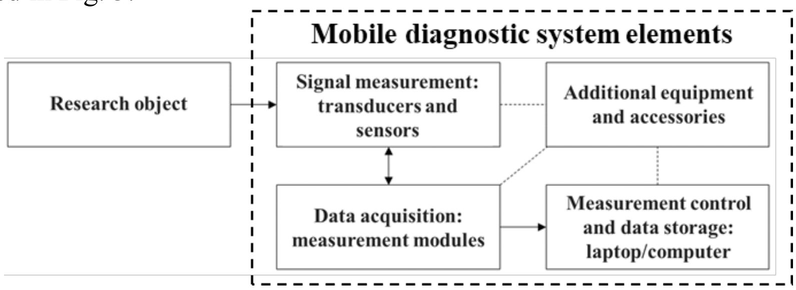

Fig. 3. Diagram of the general mobile diagnostic system elements and the measurement chain during the research

The first element of the diagram is the technical object examined (i.e. the rail vehicle system, subassembly or component and track condition). Vibration (the accompanying parameter) was measured using a vibration transducer (Brüel & Kjær, type 4504A) along different axes. Data were acquired via a measuring module (Brüel & Kjær, type 3050-A-060). The control was executed via a laptop computer onto which dedicated measurement software was installed, which enabled the lossless recording of measurement data in all measurement channels with a sampling frequency of 65,536 Hz. Additional elements included in the measurement path were cables that connected individual elements of the apparatus and special neodymium magnets that enabled the transducer to be safely attached to the steel bearing body.

Measuring the path of a mobile measurement system configured in this way enables the effective recording of data (i.e. parameters in the form of vibration signals) for many hours. Fig. 4 is an example of the recorded raw data (vertical and transverse acceleration from the left and right axle boxes) before the processing phase. This translates to subsequent measurement analysis in terms of the diagnostics of the track and vehicle.

Fig. 4. Example of the recorded raw vibration signals [m/s^2]

3.2. Measured signal processing methods

The main method of proceeding with the research is shown in Fig. 5. The vibroacoustic mobile diagnostic system mounted on the vehicle's wheelset can monitor the vehicle's and the track's technical conditions. This process is described in detail below.

Monitoring vehicle technical condition

There are many methods available for processing measured signals in technical diagnostics using an analysis of vibroacoustic signals. The authors of this article chose one of the most commonly used for wheelset condition monitoring – namely, the description of peak values of vibration acceleration. The selected parameter, apart from effective value and other point measures, such as shape factor, is very well suited for representing an increase or decrease in amplitude at a specific moment [1]. The peak value was determined for vibration accelerations (Fig. 5) measured while driving along a straight track section at speeds of 60 km/h (hereafter referred to as Case 1) and 85 km/h (hereafter referred to as Case 2). These speeds were maintained within ± 3 km/h of the target speeds.

The length of the recordings in both cases was 45 s, which is sufficient for monitoring and analysing the case examined. The track on which the vehicle ran was in good technical condition in both cases. In addition, a low-pass filter with a cutoff frequency of 100 Hz was used. The results obtained in this way were contrasted against reference (boundary) data presented by the authors in a monograph developed on the basis of the MONIT project [39].

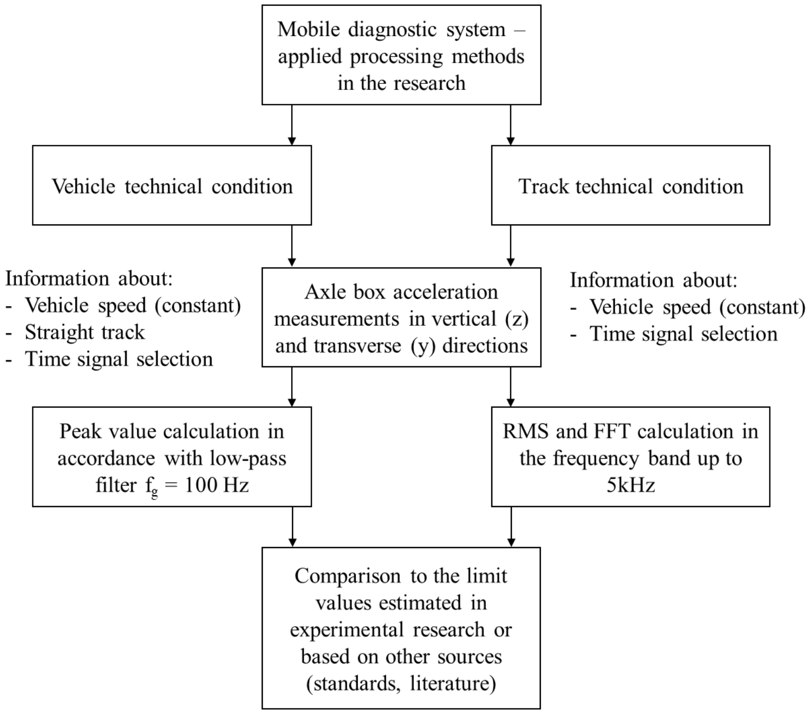

Fig. 5. The main assumptions of the mobile diagnostic system used in the research

Monitoring the technical condition of the track

In the assessment of dynamic excitation – the main sources of which are various rail infrastructure structures – the authors decided to present a comparison of effective vibration acceleration values and Fourier Fast Transform (called FFT) spectra up to 5 kHz, in accordance with the assumptions described in [40] (Fig. 5). Here, the measurement signal described as Case 2 for vehicle monitoring was used as a vehicle run along a good track. The second signal selected for comparison was characterised as a run along a track with a worse technical condition (hereafter referred to as Case 3). It is important that the speeds for both cases were very similar – specifically, 80–85 km/h. The track on which the rail vehicle travelled in both cases was straight and of the same structure. Neither track contained road or rail crossings, curves or any other rail infrastructure structures. The above assumptions minimise additional disturbances that could affect the analysis. The comparison indicated differences between values of selected point measures and FFT spectra, which suggest a deteriorated technical condition of the selected railroad.

4. ANALYSIS OF RESULTS

4.1. Monitoring the vehicle's technical condition

Table 1 shows the results of the processed measurement signals as previously described (Chapter 3.2). Vibration acceleration signals recorded in the vertical (z) and transverse (y) directions were analysed because, according to [39], they have the best characteristics (e.g. change dynamics) when used as a diagnostic parameter.

An analysis of Table 1 may lead to the conclusion that the results of the tests do not exceed the limit values specified in the MONIT project [39]. It should be noted that the estimated peak values were for an EMU type vehicle at a speed of approximately 160 km/h. The authors realise that the final results of vibration acceleration of wheelsets are influenced by many factors, the most important of which are the technical condition and speed of the tested vehicle and the technical condition of the track. In this comparison, speed was significantly diversified, but the overriding aim of the authors was to present the research methodology and a specific system of conduct in the context of vehicle condition monitoring. Moreover, this was a passive experiment, so the authors had no control of the tested object during measurements. However, prior to measurements, the operator and manager of the tested facility qualified the vehicle as good and fully operational.

Table 1

Comparison of the results of peak values of vibration accelerations

Axle box wheelset side and vibration direction	**Peak value of vibration accelerations [m/s²] for signal processing in accordance with low-pass filter f_g = 100 Hz**		
	Case 1: 60 km/h	**Case 2: 85 km/h**	**Limit values** [39]
Right, transverse; R_y	5.70	13.93	18
Left, transverse; L_y	7.74	10.43	
Right, vertical; R_z	14.50	28.21	76
Left, vertical; L_z	19.43	27.81	

The next stage of the study would be to conduct tests to determine the technical condition of the selected vehicle in the future by estimating permissible and boundary values. For this purpose, further tests can be carried out in accordance with the requirements of an active experiment (where, for example, a specific type of damage to a wheelset is simulated). Another possible method is to forecast using various estimation methods (e.g. calculating boundary values using a method that minimises the probability of failing to detect a failure with an assumed level of redundant repairs or a method based on a Gaussian distribution of a diagnostic parameter) [41]. The most important elements in this type of procedure are an appropriate amount of measurement data and (depending on the method selected) the use of statistical measures such as standard deviation or arithmetic mean. Modern approaches to diagnostic forecasting utilise machine learning or artificial intelligence.

4.2. Monitoring the track's technical condition

Table 2 shows the results of the quantitative analysis (i.e. Root Mean Square effective values) for two selected measurement cases. The selected signals were presented and processed in such a way that it was possible to compare them. It is important that the operational speeds are the same or very similar during the analysis.

Table 2

Comparison of the results of effective values of vibration acceleration [m/s²]
in the band (up to 5 kHz) for two different cases

Axle box wheelset side and vibration direction	**Case 2: 85 km/h, good track**	**Case 3: 80 km/h, bad track**
Right, transverse; R_y	11.61	22.79
Left, transverse; L_y	7.37	21.15
Right, vertical; R_z	20.80	48.52
Left, vertical; L_z	24.15	59.38

Based on quantitative analysis of the selected diagnostic point measures presented above, significant differences can be noticed between the determined effective values to the disadvantage of Case 3. The vibration in vertical and transverse directions differed significantly in Case 3 when compared to the reference case (i.e. Case 2). There was approximately a two- to three-fold increase in effective values, which indicates increased dynamic excitations from the track. The source of this may be the bad technical condition of the track, manifested as increased acoustic roughness in the rail running surface (e.g. corrugation) or another type of track wear. Precisely determining the source of presented differences was not the aim of this study; it only serves to indicate divergent measurement results of similar operational cases.

For further comparative analysis, the FFT spectra in the 5-kHz bandwidth of two selected and processed vibration signals in the vertical direction were presented (Fig. 6). A similarity can be noticed in the shape of the course of each FFT spectra determined. The first difference is a much higher amplitude of vibration accelerations in the entire frequency range, to the disadvantage of Case 3. For frequency bands of approximately 840 Hz, 1075 Hz, 2000 Hz and 2400 Hz, increases in the value of vibration accelerations tested are visible in both cases. However, it is also worth focusing on the low (i.e. up to approximately 80 Hz), medium (i.e. between 400–700 Hz) and high (above 4200 Hz) frequency ranges because the differences between the signals in these areas may indicate the wear and tear of the track and its poor technical condition.

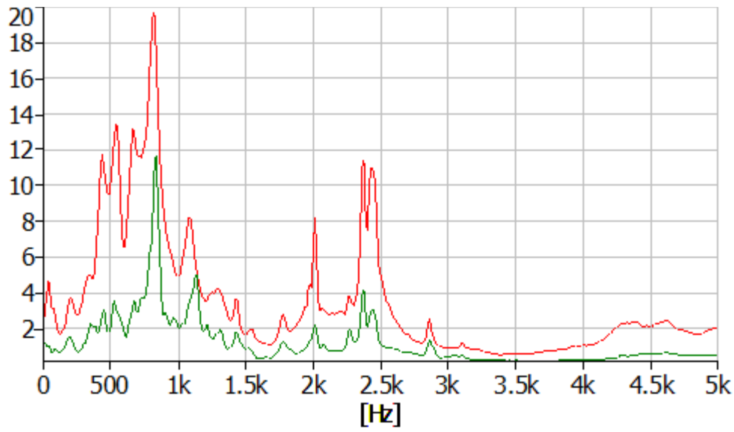

Fig. 6. Example of a comparison of FFT spectra for L_y [m/s^2] signals: red example - 3; green example - 2

The analysis above indicates the validity of using the proposed system and research methodology to monitor and diagnose the technical condition of rail tracks at the vehicle level. The use of quantitative analysis (e.g. by considering effective or peak values as a diagnostic parameter) can indicate locations on a rail network that could be utilised more often than others, thus signalling a need for additional maintenance. Apart from aspects related to safety improvement and increased running speed, this type of rail track maintenance work contributes to the improvement of passengers' travel comfort.

5. SUMMARY AND CONCLUSIONS

This article presented a research methodology and analysis for vibration measurements performed during the normal operation of a railway vehicle. The authors presented a fully justifiable proposal for a mobile system for vehicle and rail track diagnostics. This is confirmed by the following conclusions regarding the monitoring of the technical condition of a vehicle and track:

1. It is possible to monitor a vehicle's technical condition (more precisely, the elements of running and drive systems) in real time on the basis of quantitative and qualitative analysis of vibration acceleration measurements at the vehicle level. This directly increases the service life of rolling stock (as information about the change in technical condition is received early) and optimises operating costs by changing the maintenance strategy from static to quasi-dynamic (i.e. it that takes into account modern on-board technical diagnostics).
2. It is possible to monitor and diagnose the track and verify the track quality factor by measuring dynamic responses on the vehicle.
3. It is possible to verify the dynamic behaviour of the vehicle after repairs and inspections.
4. It is possible to test vibroacoustic comfort and driving safety using a mobile measurement system.
5. Owing to the collection of vibroacoustic diagnostic data about the technical condition of the vehicle, in addition to determining the wear of individual components in real time, it is possible to implement

an effective diagnostic forecast of permissible values for the future operation of rail vehicle components or systems.
6. It is possible to carry out non-normative experimental tests depending on the goals and needs of the contracting authority/manager/operator related to the measurement and analysis of vibroacoustic signals occurring in complex technical facilities. To this end, the experience and expertise of the personnel carrying out this type of research are essential.

Directions for further research on mobile systems for diagnostics and monitoring of vehicle and rail tracks should include the implementation of further measurement experiments under normal operating conditions. The most interesting research case would be the implementation of an active experiment comparing a functional and dysfunctional (controlled damage to a specific element of running or drive system) rail vehicle. This type of approach would make it possible to estimate permissible or limit values of the diagnostic parameter (i.e. vibration acceleration measured at the vehicle's position). It should be noted that the use of this type of system would depend on the classification of the exact aim of tests as determined by the client, which may also be a challenge for a diagnostician who carries out a selected quantitative or qualitative analysis of measured signals.

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