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The use of vibroacoustic signals to assess the condition of a railroad railway switch

KEYWORDS
Vibrations, STFT analysis, diagnostics, railwaysirst, signal SNR.

ABSTRACT
The work concerns the assessment of the technical condition of the turnout sleeper with the use of research methods based on the analysis of the vibration signal. The tests were carried out in a selected place of the railway infrastructure with a turnout sleeper with visible signs of wear. Three three-axis sensors made in the MEMS technology were used to record the vibration parameters. Registrations were carried out on the basis of the proprietary program developed in the LabView package. The original script developed in the Matlab calculation package was used to analyze the data recorded during the research. For the signal analysis, the short-term Fourier transform (STFT) was used and the value of the SNR coefficient for the adopted measurement points was determined. As a result, there is a visible differentiation of the SNR coefficient at the point of wear of the switchboard.

1. Introduction

The development of railroad infrastructure helps to increase the speed of train traffic. This, in turn, requires rail infrastructure managers to increase spending on diagnostics and maintenance of rail lines to ensure the safety of rail travelers. Railroad infrastructure is a complex system of dependencies in which the weakest element determines the safety level of the entire system. As a result of analyses of the risks posed by the increase in the speed of rail traffic, a key element of the system is the technical condition of the elements of the rail system and the proper diagnostic and maintenance procedure.

Railroad system components include turnout and crossing systems, which have a very complex structure. It requires not only a large number of components (such as rails, switches, crossovers, turnout supports, slide runners, etc.), but also different types of components and technologies (mechanical devices for operating switches, electrical devices for controlling, etc.). This complexity of railroad systems makes them susceptible to failures that can ultimately cause delays and even fatal accidents. It is therefore important to develop appropriate condition monitoring techniques to detect and diagnose faults in railroad systems. Statistics from the Zhuzhou to Hengyang railroad in China showed that more than 40% of all failures were related to S&C equipment failure [1].

The System failures can be caused by changes in environmental conditions and/or human error. Any malfunction during the maintenance process, such as lack of lubrication, improper handling, or loose fasteners can lead to infrastructure system failure [2]. The article [3] presents a vision system that, in combination with image processing analysis tools, can detect wear and distance between key components of a railroad switch. As a result of the simulation, it was shown that when passing through a switch at speeds above 250 km/h, the amount of wear on the switch increases tenfold. These results indicate the need for online frequency diagnostics. The article [4] presented the results of a study of the dynamics of a typical vertical railroad turnout under the load of moving trains. The analysis referred to constant-speed crossings where only vertical dynamics (including rocking and tilting movements) were studied. For uneven crossings, the intensity of impact loading at the crossing strongly depends on the speed of the train. The increase in contact force compared to static force is on the order of 100% at 70 km/h and 200% at 150 km/h. Authors of the study [5] presented a methodology for simulating the degradation of rail profiles in switches and crossings. The methodology presented includes: simulation of dynamic vehicle-track interaction considering stochastic changes in input data. The authors found that increasing the axle load from 25 tons to

30 tons increased the change in the vertical profile by 27%, and the numerical value of the RCF [Rolling Contact Fatigue] criterion was increased by 10%.

In the paper [6], methods were proposed for image processing using Canny edge extraction and Hough transform. The solution presented is aimed at early diagnosis of failures at switch crossings and prevention of potential accidents based on image processing. Márquez et al. [7] proposed a solution for monitoring (detecting) major failures related to wear of turnout system mechanisms. The authors considered various failures caused by the wear of the displaced components (including dry and with varying lubrication) and the value of the current drawn by the control (switching) components. In the article [8] an analysis of various forecasting methods for railroad turnout systems is presented. Five different sensors, installed in an actual turnout system used by the Turkish Railways, are individually analyzed using different predictive methods. In [9], the authors presented the possibility of identifying a passing rail vehicle using vibroacoustic methods. In the study they used a measurement system on a triaxial acceleration sensor and a sensor measuring acoustic pressure. The obtained waveforms show an apparent increase in vibration and sound pressure with the approach of the rail vehicle.

2. Test methodology and measurement system

The presented examples of the methodology of conducted research in the context of the analysis of the technical condition of elements of railroad infrastructure illustrate the diversity of research work carried out in this area. Their core is the possible early detection of damage and not leading to serious disasters in railroad traffic. The authors of this paper used selected methods of vibration analysis of the elements of a railroad switch sleeper to assess its technical condition as a component of the railroad surface. The conducted tests took place under the conditions of normal operation of the turnout for varied trainsets.

The methodology is based on recording vibrations at selected points of the switch sleeper (Fig. 1) using three triaxial acceleration sensors connected to an original application developed in LabView. The recorded data are subjected to analysis in the time and frequency domains. The time-domain analysis allowed a preliminary assessment of the vibrations occurring in terms of peak values and the shape of the vibration waveform. Short time Fourier transform (STFT) was used for analysis in the frequency domain.

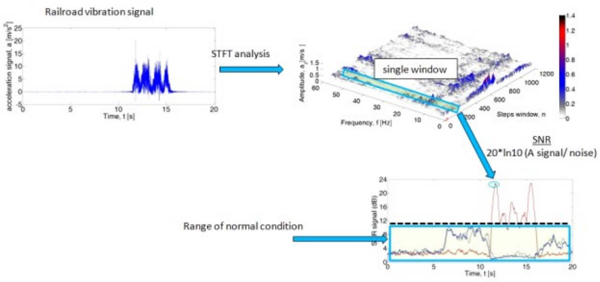

Fig. 1. Data analysis diagram

For this purpose, an application was developed in the LabView environment. A computational script in the MatLab environment was used to analyze the recorded data. The developed program makes it possible to present the results in the time domain and frequency domain (short-time Fourier transform- STFT) presented in the form of spectrograms. On their basis, the results of the measured accelerations are presented and the value of the SNR [signal-to-noise ratio] is determined. The obtained SNR values as a function of time formed the basis for developing inferences about the technical condition of the switch sleeper.

3. Measurement system

3.1. A Subsection Sample

The measurement system (Fig. 2) consists of acceleration sensors, power supply systems, and application for recording current parameters. The measurement system uses two AHRS 3DM-GX5-25 sensors and one 3DM-GX3-25 sensor. The technical data of the sensors are listed in Table 1.

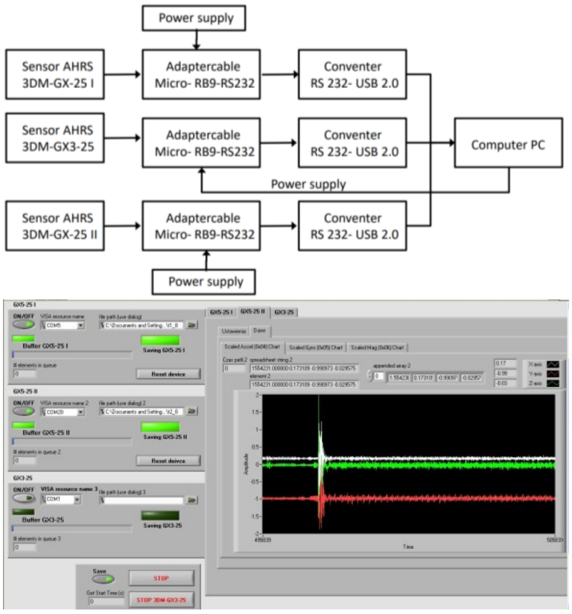

Fig. 2. Block diagram of the measurement system and front panel of the measurement

The developed own measurement application developed in the LabView program allows you to view the current parameters from three measuring sensors and save data to a text file. An external battery system was used to power the sensors. Due to the varied sampling frequency of the sensors used, a data synchronization system was developed.

Table 1. Parker LORD 3DMGX5-AHRS sensor specifications

Name	3DMGX5-HRS	3DM-X3-25
Measurement range	±8g	+/- 8g
Non-linearity of measurement	±0,02% fs	±0,1% fs
Resolution	0,02 mg	80 μg/√Hz
Frequency band	225 Hz	225 Hz
Sampling frequency	1000 Hz	530 kHz
Mechanical shock limit	500 g/1 ms	500 g/1 ms

4. Testing under real conditions

Tests carried out under conditions of normal operation of railroad infrastructure on a classic railroad turnout of the Rz 60E1- 300-1:9Psb type. The turnout is located in the city of Ozimek in the area under the Ozimek railroad switch tower (railroad line No. 144 at the distance of 55 km 800 m). The permissible speed of a train on the straight track of this turnout is 140 km/h.

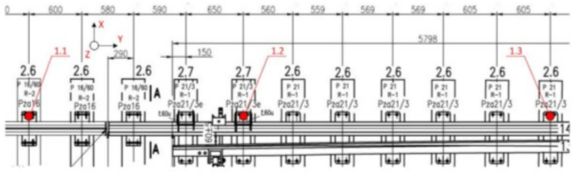

Fig. 3. Schematic diagram of the distribution of measurement points on a section of the drawing of the left railway

Before the measurements were taken, measurement points were selected. It was assumed that increased vibration and vertical deflection of the structure during train wheel run could occur in this part. Due to the use of three sensors, the measurement points were divided into subpoints. Their exact locations are shown in Fig. 3: 1.1 – sensor 3DM-GX5-25 I, before facing point lock, – 1.2 – sensor 3DM-GX3-25, facing point lock, – 1.3 – sensor 3DM-GX5-25 II.

All acceleration sensors were mounted to the switch sleepers at the measurement points (on ribbed baseplate) using magnetic elements. This allowed measuring vibrations occurring on the turnout with the exclusion of the direct influence of rail vibrations. The measurement axes of the sensors were oriented in the following directions: X-axis indicates longitudinal vibrations of the turnout, Y-axis transverse vibrations, and Z-axis vertical vibrations. Relating the axes to the train path, the X axis will indicate transverse vibrations of the turnout, and the Y axis will indicate longitudinal vibrations.

Information on the masses of trainsets and speeds was obtained from the traffic officer on duty. It doesn't matter whether the train will be in the run-in or run-out phase, as its mass and inertia are too large and the measurement section too short for the speed to change drastically.

5. Analysis of measurement results

Sample waveforms in the time domain for an example measurement are shown in Fig. 4. They show the components of the amplitudes of the x, y, z axes at measurement points 1.1, 1.2 and 1.3. Analyzing the two measurements, there were clearly visible differences in the obtained waveforms made at point 1.2. The amplitudes of longitudinal and transverse vibrations occurring for the tested turnout have higher acceleration values relative to the values recorded at the other measurement points. The situation is similar for vertical vibrations, but the differences are not as significant. Very significant, however, are the waveforms of vertical vibrations obtained for point 1.2. At the moment of the arrival of the train wheel at the area of the selected measurement point, bilateral vibrations (of sinusoidal nature) are recorded. In the case of vibrations of the Z axis of point 1.2, the waveforms have the character of a shock phenomenon. This phenomenon occurs for all measurements carried out within measurement point 1.1 For the switch sleeper tested in point 1.2, it is also noted that it falls into vertical vibrations even before the wheel arrives. Many measurements show that their onset occurs before the wheel is registered by sensor 1.1 or 1.3. There are characteristic ascending and descending slopes for this phenomenon, as can be seen in Fig. 6.9. The above factors indicate that the ballasting of the switch sleeper in point 1.2 is poor, resulting in increased longitudinal and transverse vibrations and the occurrence of vertical impacts at the moment of the train wheel's arrival.

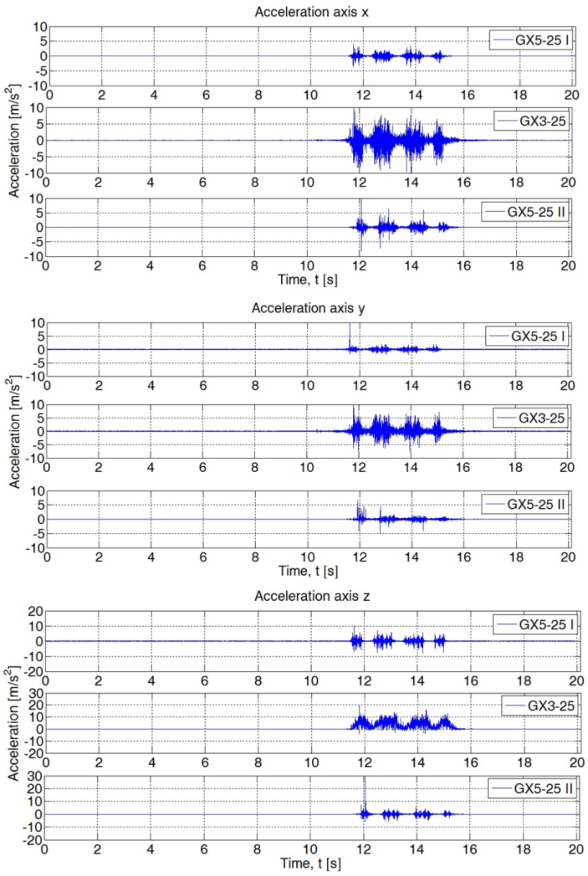

Fig. 4. Acceleration waveforms in the time domain for an example measurement

Analyzing the recorded signal in the frequency domain (Fig. 5), one can clearly see the presence of components of vibration amplitudes in the entire frequency band (up to 250 Hz). However, they are characterized by relatively low intensity. For measurement point 1.1, a visible trend was found, consisting in the appearance of vertical dominant vibrations with frequencies within the 100÷150 Hz band. For the rest of the measurements taken at points 1.1 and 1.3 the dominant amplitudes reach varying values. Their character does not indicate the presence of anomalies in the area of the tested switch sleepers. In this case, the most representative waveforms are the results obtained at point 1.2.

Performing a comparative analysis of the transverse and longitudinal vibrations of this point along with the others, it is apparent that the intensity of the vibrations is clearly higher. This difference is one of the factors indicating the abnormal condition of the railroad turnout. However, taking into account the vertical vibrations (z-axis), significant differences are noticeable. The strongest vibrations are recorded within the facing point lock. They occur in the low frequency range up to 20 Hz, in contrast to the other measurements.

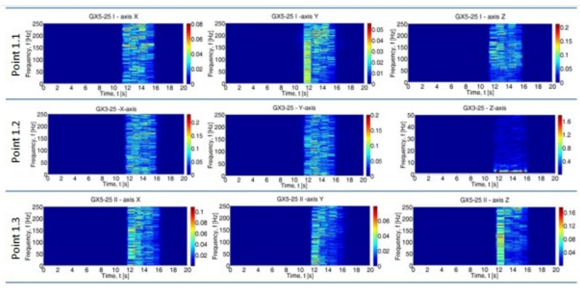

Fig. 5. Periodograms for a sample study

For the vertical component (z-axis) in the range up to 100 Hz, it is apparent that the bands of concentration of dominant amplitudes vary depending on the measurement point (Fig. 6). At point 1.1, the occurring amplitudes are random in nature. An increase in their value is seen from 60 Hz onward. A noticeable increase in the amplitude is seen when the wheel runs over the measuring point. The peak value is 0.16 m/s^2. Amplitudes of similar value are maintained over the entire range of the train's passage. As a result, it can be concluded that there is no significant damage to the track at this location. At measurement point 1.2 located at the facing point lock, a band of dominant amplitudes with a frequency of 3 Hz can be seen over the entire range of train passage. The values of the amplitudes range from 1.2 m/s^2 to 1.8 m/s^2. In the rest of the frequency range, the amplitude value does not exceed 0.2 m/s^2. This indicates that there are impacts between track elements, as a result of the run of the wheels of the trainset. According to the authors, this can provide important information about the occurrence of wear and tear of the elements of the facing point lock.

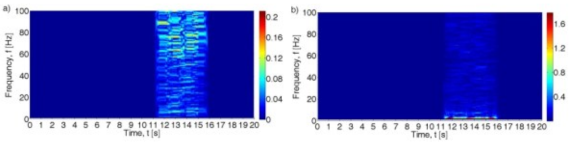

Fig. 6. Periodograms of Z-axis measurement 1: a) point 1.1, b) point 1.2.

On the other hand, at point 1.3, located behind the facing point lock, an increase in amplitudes up to 0,16 m/s2 is evident when the wheels run over the measuring point (particularly noticeable in the 80 Hz and 90 Hz range). Thereafter, the amplitudes fade to no more than 0,12 m/s2 with no apparent dominant band.

Based on the results shown in Fig. 6, it was found that when a malfunction occurs, there is an apparent increase in the value of the dominant amplitude in a given band relative to the remaining frequency band (noise). The analyzed malfunction refers to wear and tear causing the depletion of mating surfaces, resulting in the formation of a gap.

In order to obtain information that can provide a diagnostic symptom, the SNR (Signal to Noise Ratio) described by equation (1) was determined. In the issue under consideration, the ratio refers to the values of the dominant amplitudes in the band up to 10 Hz and the average value of the amplitudes in the range up to 100 Hz.

$$SNR = 20\log_{10}\frac{A_{\text{signal}}}{A_{\text{ratio}}} \tag{1}$$

As a result of applying SNR to analyze the z-component (vertical axis) of the recorded passages at points: 1.1, 1.2, 1.3, the waveforms shown in Fig. 7 were obtained.

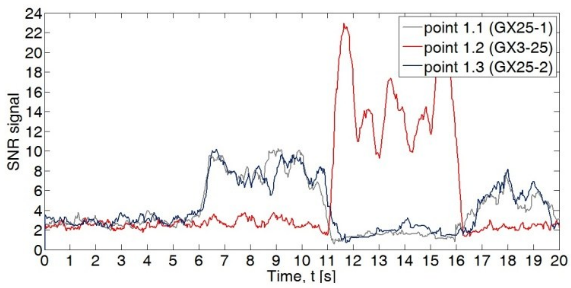

Fig. 7. SNR signal for an exemplary train passage

Analyzing the obtained SNR values for the passages at points 1.1, 1.2, 1.3, it was found that 1.1 does not exceed 10 dB. This is due to the significant random noise occurring over the entire frequency range which was found when analyzing the STFT periodograms in the earlier description. At point 1.2, a significant increase in the ratio's value is seen during the beginning of the train's run over the measurement point. The SNR values are then 22.5 dB for passage 1 and 17.5 dB for passage 13. In the course of the passage, the SNR value decreases and then increases to values similar to those obtained at the time of the wheel contact. The SNR values at point 1.3 are smaller, not exceeding 8 dB.

Within the study, the obtained SNR values were analyzed. A comparison of sample SNR waveforms for the studied points 1.1, 1.2, 1.3 is shown in Fig. 8. For the substituted waveforms, the variation in SNR values is evident. For an well maintained track, the value does not exceed 10 dB. For waveforms with a defective element, the value of the coefficient is above 10 dB.

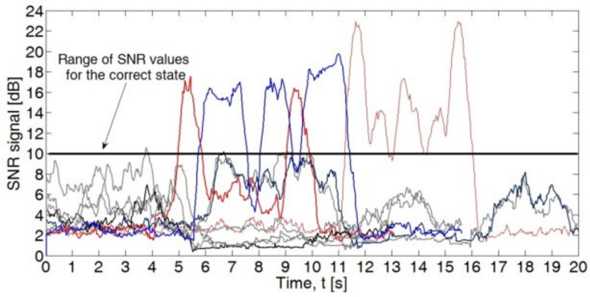

Fig. 8. Range of correct technical condition of the switch sleeper

In view of this, the value of the diagnostic range for the case under consideration was set at 10 dB. Then exceeding this value can be an alert signal about the occurrence of a process of significant wear of cooperating elements. This signal can form the basis for further analysis of the considered measurement point.

6. Conclusion

Based on the analysis of vibrations of selected points of the railroad turnout structure, i.e. the facing point lock, the range of the diagnostic parameter indicating the occurrence of wear of the mating elements was determined. Carrying out a comparative analysis of the obtained time and frequency waveforms, significantly increased values of acceleration were observed at the point of the facing point lock (point 1.2). The value of the vibration amplitude is several times greater than in the other points studied. This is particularly evident for the Z axis. For points 1.1 and 1.3, the recorded acceleration signals have a sinusoidal shape relating to the vibrations caused by the rolling wheels of the carriages on the rail. This is evident in the obtained STFT spectra, where the band of dominant amplitudes is not visible. The spectrum has the character of noise caused by the rolling wheels of carriages on the track surface. For measurement point 1.2, the waveform of vibrations is characterized by the occurrence of rising slopes as the wheel arrives and falling slopes as the wheel moves away. This pattern relates to the impact of the mating elements of the switch sleeper. This indicates the wear and tear of the mating elements. Analyzing the obtained frequency spectra presented as spectrograms in point 1.2, it was found that there was a band of amplitudes dominating in the low-frequency band (from 2 to 3 Hz). The occurring amplitudes are characterized by several times higher value with respect to the vibrations recorded in points 1.1 and 1.3.

As a result of further signal analysis, SNR (signal-to-noise ratio) values were determined in the range up to 100 Hz. The obtained signal waveforms at the analyzed points illustrate how the value of the useful signal (excitation from the train carriage wheels) is shaped against the noise in the signal spectrum. At points 1.1 and 1.3, the SNR value does not exceed 10 dB. While in point 1.2 it ranges from 16 to 22 dB for all analyzed crossings.

The developed method of measurement and analysis of the results allows a preliminary determination of the occurrence of railroad turnout failure based on vibration measurement and evaluation of the value of the SNR coefficient. The authors note the need for further studies to determine the effect of ambient temperature, travel speed and wear and tear on the value of the analyzed coefficient.

References

1. Cheng, Y.; Zhao, H. Fault detection and diagnosis for railway switching points using fuzzy neural network. In Proceedings of the 10th Conference on Industrial Electronics and Applications (ICIEA), Auckland, New Zealand, 15–17 June 2015; pp. 860–865.
2. Rail Safety and Standards Board. Formal Inquiry: Derailment of Train 1T60, 1245 hrs Kings Cross to Kings Lynn at Potters Bar on 10 May 2002, Appendix; RSSB: London, UK, 2005; pp. 1–164.
3. Kisilowski, J., Kowalik, R.: Railroad Turnout Wear Diagnostics. Sensors 2021, 21,6697. https://doi.org/10.3390/s21206697.
4. Andersson, C.; Dahlberg, T. Load Impacts at Railway Turnout Crossing. Int. J. Veh. Mech. Mobil. 1999, 33, 131–142.
5. Johansson, A.; Palsson, B.; Ekh, M.; Nielsen, J.C.O.; Ander, M.K.A.; Brouzoulis, J.; Kassa, E. Simulalion of wheel-rail contact and damage in switches & crossings. Wear 2011, 271, 472–481.
6. Karakose M., Yaman O., Akin E.: Detection of Rail Switch Passages Through Image Processing on Railway Line and Use of Condition-Monitoring Approach; Conference: International Conference on Advanced Technology & Sciences (ICAT'16) At: Konya, Turkey Volume: 99-105.
7. Márquez, F.P.G.; Tercero, D.J.P.; Schmid, F. Unobserved component models applied to the assessment of wear in railway points: A case study. Eur. J. Oper. Res. 2007, 176, 1703–1712.
8. Camci, F.; Eker, O.F.; Baskan, S.; Konur, S. Comparison of sensors and methodologies for effective prognostics on railway turnout systems. Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 2016, 230, 24–42.
9. Burdzik R., Słowiński P., Konieczny Ł.: „Preliminary studies of vibroacoustic signal images in the context of identification of a passing rail vehicle", Silesian University of Technology, Transport Department 2018, doi: 10.5604/01.3001.0014.4552.