Application of Time-Frequency Analysis of Acoustic Signal to Detecting Flat Places on the Rolling Surface of a Tram Wheel

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Abstract The article presents the problematic aspects of detection of flat places on tram wheels using time-frequency analysis of acoustic signals. A number of pass-by tests were conducted during real life exploitation. The objects of research are light rail vehicles exploited in Poznan. Some of them were characterized by flat places on tram wheels. The research aimed to apply the wrought method for detection of flat places on tram wheels.

Keywords Wheel flats monitoring · Time-frequency analysis · Acoustic signal processing

1 Introduction

Public rail transportation is one of the most attractive modes of transportation in larger European agglomerations. Comfort is a very important factor on the basis of which passengers choose their mode of transportation. Vibroacoustic phenomena generated during a ride have a significant impact on the comfort of both the passengers and the nearby city dwellers. Number of inhabitants and passengers complain on annoyance vibroacoustic signals emitted by Poznan public rail transport during passage rise up [4]. Also public transportation operators and cities authorities are noticed the noise problem and the scale of this issue has to be reduced. The noise requirements for

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Fig. 1 The wheel flat on the examined tram

producers and also tram maintenance operators are increasing in terms of reduce the main sound sources—rolling and traction noise [5, 8]. Particularly important is a correct interaction between the rolling surface of a wheel and the rail. Imperfections on rolling surfaces of wheels and rails—flat places in particular—contribute to the increased level of noise and vibrations. One of the most annoying sounds during rail journeys is the impact rolling noise which is caused by rail joints, switches and crossings or irregularities on rail and wheel surfaces, called wheel/rail flats [7, 9, 10]. The example of the wheel flat, which was located on the both wheels on the last bogie axis of examined tram, is shown in Fig. 1. When only wheel flats will be taken to consideration, it is worth to diagnose and monitor them by the acoustic signal processing in normal technical conditions. Another aspect confirming the necessity of detection of flat places on tram wheels is minimizing tram exploitation costs. Moreover, early detection of the problem increases the dependability of the transportation process. Those are essential factors to rail vehicles and rail infrastructure managers.

The aim of the article is detection of tram wheel flats using the time-frequency method on acoustic signals processing. Firstly, several exterior acoustic measurements in pass-by test were carried out. Trams, which are still operated on Poznan tram infrastructure, were taken as the research objects. Some of light rail vehicles were equipped with wheels where the flat places are. Secondly, the acoustic signals processing using proposed method based on the STFT (Short Time Fourier Transform) analysis was performed. The results of research are presented and the proposed method is applied on.

2 The JTFA Analysis Method

Joint Time-Frequency Analysis is an analysis method for non-stationary signals. This kind of method includes the STFT analysis and Wavelet Transform. Short Time Fourier Transform concerns short signal sequences FFT analysis in which it can be treated as quasi stationary. Extraction of the input signal of subsequent data segments for the FFT analysis is performed by means of the floating window method [2]. The comparison of spectra achieved in this manner gives, as a result, a time-spectra map of the analyzed process. Definitional STFT record can be presented by means of the dependence (1).

The STFT result can be treated as a series of spectra determined for local, short time segments of time history. The advantages of this method include, among others, short calculation time necessary to define time-frequency map, easy, intuitive interpretation of results and constant resolution within the whole frequency range.

$$STSF[x_w(t,\tau)] = X_w(f,\tau) = \int\limits_{-\infty}^{\infty} w(t,\tau)x(t)\cdot e^{-i2\pi ft}\,dt \tag{1}$$

where: x(t)—time course representing analyzed input signal; w(t)—time window function (tapering function); τ—position of time window in time domain.

The form of analysis result depends on the assumed time window function and signal processing parameters: the number of samples in data segment and time step of the analysis. There are some limitations of this method which include, for example, lack of possibility to achieve, at the same time, high resolution in time and frequency domains. Resolution in time domain can be improved by applying overlapping which is partial covering of analyzed segments of the signal. The error of amplitude and frequency estimations for local maximum values of a map can be minimized by applying amplitude—frequency AFC correction [1, 3].

In Wavelet Transform, any functions [6] can be used as mother functions. Due to the simplification of the calculation process, in many cases Morlet's function is used as mother function. Its application allows using the FFT procedure which effectively accelerates the calculation process. The result form, to a great extent, depends on the assumed mother functions. The definition of Wavelet Transform is presented by the following dependence (2) [6]:

$$WT(a,b) = \frac{1}{\sqrt{a}}\int\limits_{-\infty}^{\infty} x(t)\Psi^*\left(\frac{t-b}{a}\right)dt \tag{2}$$

where: Ψ (t-τ)—mother function (wavelet); a—scale, parameter connected with localization in frequency domain (dilation, scale); b—parameter indicating position in time domain (translation); Ψ^*—conjugate function of Ψ function (.).

This type of analysis can be compared to filtration with the constant relative width of the Δf/fs band. The position of filter on the time-frequency map is defined by scale and translation parameters (a—dilation, b—translation). Together with the translation towards higher frequencies, analysis band width increases (analysis resolution is decreased in domain of frequency), whereas, resolution in domain of time is increased and the other way round. This feature can be very useful in case of simultaneous analysis and observation with a different time step of quick-changing high frequency (e.g. vibrations of car body or vibrations of the wheel) and slow-changing low-frequency processes. One of the disadvantages of this method is dependability of the result form on the assumed mother function, and not always intuitive interpretation of the graphical form of result.

To summarize the overview of vibration signals analysis methods, it has been concluded that in order to obtain diagnostics opinion about examined object, simple analysis methods e.g. assigning point measures, as well as highly advanced methods—from the signal processing point of view, e.g. time-spectrum analysis, can be used. In this work, to monitor the impact noise caused by wheel flat during tram passage, the analysis of acoustic signals was used.

3 Research Methodology

3.1 Measurements Assumptions

The experimental research stage involved exterior acoustic measurements during pass-by test. Measurements were carried out on a straight section of the track, located in the Poznan Franowo depot. The tram's speed was about 10–20 km/h. Furthermore, measurements have performed during late evening hours, when all trams were going back to depot. Thus, all types of light rail vehicles, which are operated on Poznan tram infrastructure, were a research objects. Among all research objects, one of the trams had wheels flat, which was very important aspect in case of next research analysis. Furthermore, there was made few more acoustic measurement series on the selected tram, with different tram's speed −20, 30 and 40 km/h. Impact noise emitted by this tram was taken to further signal processing.

3.2 Measurement Points

In Fig. 2 is shown the scheme of measuring position. Three microphones were used to acoustic measurements, located in proximity of 2 m from the track. All electroacoustic transducers were spread along the track at a distance of 2.04 m which is the length of each tram wheel circumference. It means one full wheel rotation period during passage will be made at this distance. Thus, authors have made sure that all acoustic signals caused by wheel flats will be recorded in proper way.

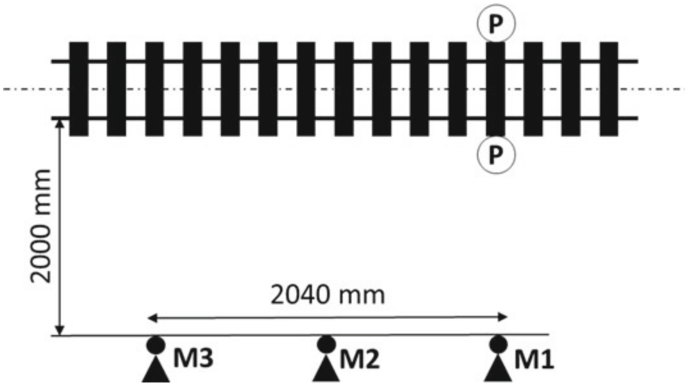

Fig. 2 The scheme of measuring position in the pass-by test; M—Microphones, P—photocells

In the measurement cross section, between the tracks, a transmitter-receiver type photocell was placed (Fig. 2). It allowed for introduction of time selection of the processed signals, in which the tram was found in the measuring cross section of the track—on the microphone1-photocell line. Also, the speed of tram's ride was calculated on the basis of the recorded signal.

3.3 Measurement Devices

Recording of acoustic signals was conducted with use of measurement devices from a Danish firm Brüel and Kjær Sound and Vibration A/S. The measuring equipment scheme is shown in Fig. 3.

To acoustic measurements were used following equipment:

- microphones type 4189-A-021,
- two Autonics Photocells type BX15M-TDT,
- the data acquisition system PULSE LAN-XI type 3050-A-060,
- mobile computer,
- router Wi-Fi.

Before the measurements, the calibration process of each measuring devices, was performed.

3.4 Parameters of Recording Acoustic Signals

Registering of acoustic signals for exterior measurements was conducted constantly in a full measurement spectrum of 25.6 kHz, with sampling frequency of 65,536

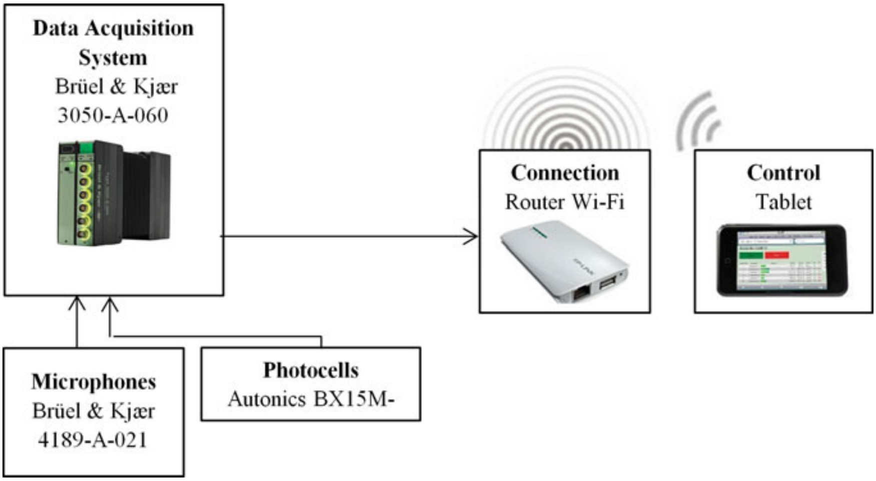

Fig. 3 The measuring equipment scheme used to research

samples per second. The signals were recorded synchronously in all measurement points and channels. Duration of signals was dependent on the speed and length of the tram passing through the measurement cross section, and was about 4–10 s.

4 Research Results

4.1 Research Analysis

After acoustic measurements, authors have picked four sound records for further analysis. The four STFT analyses are shown in Fig. 4. Sound records from the first microphone were taken to all analysis. The Mik1_Good chart presents the reference sound recorded during the Moderus Beta No. 916 ride. There was no wheel flat problem in this case. While next three charts (Mik1_20, Mik1_30 and Mik1_40) show the Moderus Beta No.920 rides with different tram's speed. The sound pressure was much higher than in the first example. Especially in the low and medium frequency range, the regular brighter stripes (higher sound pressure) can be observed. Wheel flats are the reason of the impact noise occurring.

Based on the STFT analysis, two main frequency bands were chosen: 100–300 and 1150–2125 Hz. The filtered FFT analyses of four acoustic signals are shown in Figs. 5 and 6. Sound pressure of Mik1_30 and Mik_40 are the highest on both figures. While the sound pressure of Mik1_20 is higher than Mik1_good only in the Fig. 5. It means that tram's speed has influence on the impact noise magnitude and

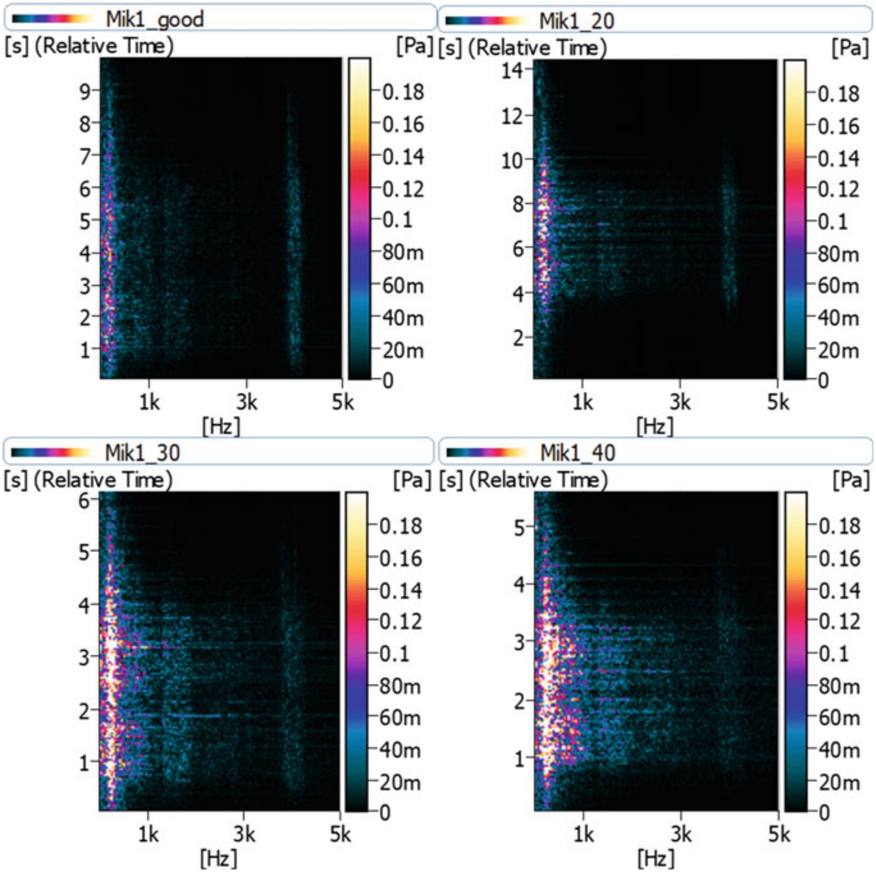

Fig. 4 The first step of acoustic data processing—the STFT analysis

frequency. Therefore, if tram's speed is about 20 km/h and lower it will be hard to find the wheel flat based on the second filtered FFT analysis.

All RMS values were calculated in accordance to the Eq. (3)—which is an energetic averaged root mean square value taken from filtered FFT analysis:

$$S_{rms} = \sqrt{\sum_{i=1}^{n} |x_i|^2} \tag{3}$$

where: x_i—is the sound pressure value in the *i*th frequency band.

The reference RMS value S_{ref} was calculated from Mik1_good sample and it is equal to 11 mPa (nearly 55 dB) in case to the first filtered FFT range (Tables 1 and 2). This is 1.5 times (3.5 dB) less than in the Mik1_20 case and about 3 times (about 9.5 dB) less than next two examined cases. It means the wheel flat problem has

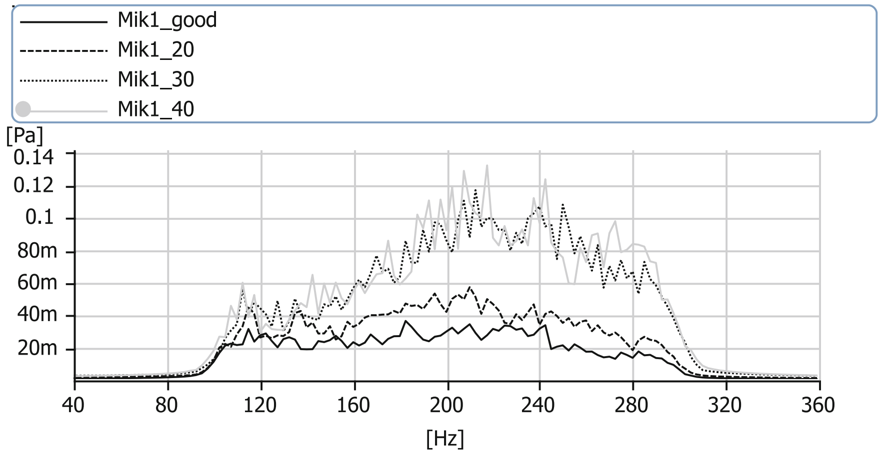

Fig. 5 Filtered FFT analysis in the first frequency range: 100–300 Hz

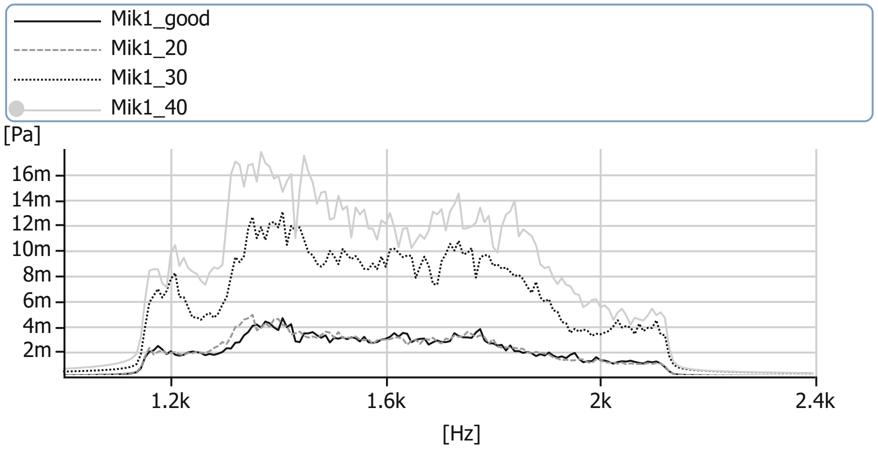

Fig. 6 Filtered FFT analysis in the second frequency range: 1150–2125 Hz

occurred and tram wheels should be serviced. In case to the second filtered frequency range, only the S2 and S3 RMS values are significant higher (by 3–4 times) than S_{ref} which means the impact noise problem. The differences expressed in decibels unit are even higher—nearly by 10 and 13 dB (Table 2).

Table 1 Root mean square values and differences related to the reference value S_{ref} in mPa

		RMS values			
		f: 100–300 Hz		f: 1150–2125 Hz	
		mPa	S_{ref}/S_i	mPa	S_{ref}/S_i
Mik1_good	S_{ref}	10.97	–	1.44	–
Mik1_20	S1	16.48	1.50	1.49	1.03
Mik1_30	S2	32.04	2.92	4.45	3.09
Mik1_40	S3	33.84	3.09	6.24	4.33

Table 2 Root mean square values and differences related to the reference value S_{ref} in dB

		RMS values			
		f: 100–300 Hz		f: 1150–2125 Hz	
		dB	$S_{ref} - S_i$	dB	$S_{ref} - S_i$
Mik1_good	S_{ref}	54.78	–	37.15	–
Mik1_20	S1	58.32	3.54	37.44	0.29
Mik1_30	S2	64.09	9.31	46.95	9.80
Mik1_40	S3	64.57	9.79	49.88	12.74

4.2 Algorithm of the Acoustic Signals Processing

Authors elaborated the algorithm for sound pressure processing in case to monitor and diagnose wheel flats (Fig. 7). Based on recorded acoustic signals and proposed time-spectrum analysis method, the decision can be made if tram wheels should be serviced. First step is to carry out acoustic measurements s(t) during tram ride. Authors used three measurement points however one microphone placed near track should also be good for further analysis. Also tram's speed is very important parameter and has to be calculated or measured. If tram's speed is less than 30 km/h, the tram's ride should be repeated with higher speed, to make sure of proposed method validity. The STFT analysis in the full range of signal spectrum is the next step of the algorithm. Characteristic frequency bands, where sound pressure amplitude increased in unnatural way (in comparison to reference acoustic signals where no wheel flat problem occurred), are pointed. The frequency filter to reject unwanted bands is applied in next algorithm step. Then, energetic root mean square value is calculated. Critical RMS value S_c should be averaged from the same types of vehicle. Also the standard deviation should be added. If examined RMS sound pressure value S is bigger than critical value S_c, it means there is a wheel flat problem and service or technical checking of tram wheels should be made.

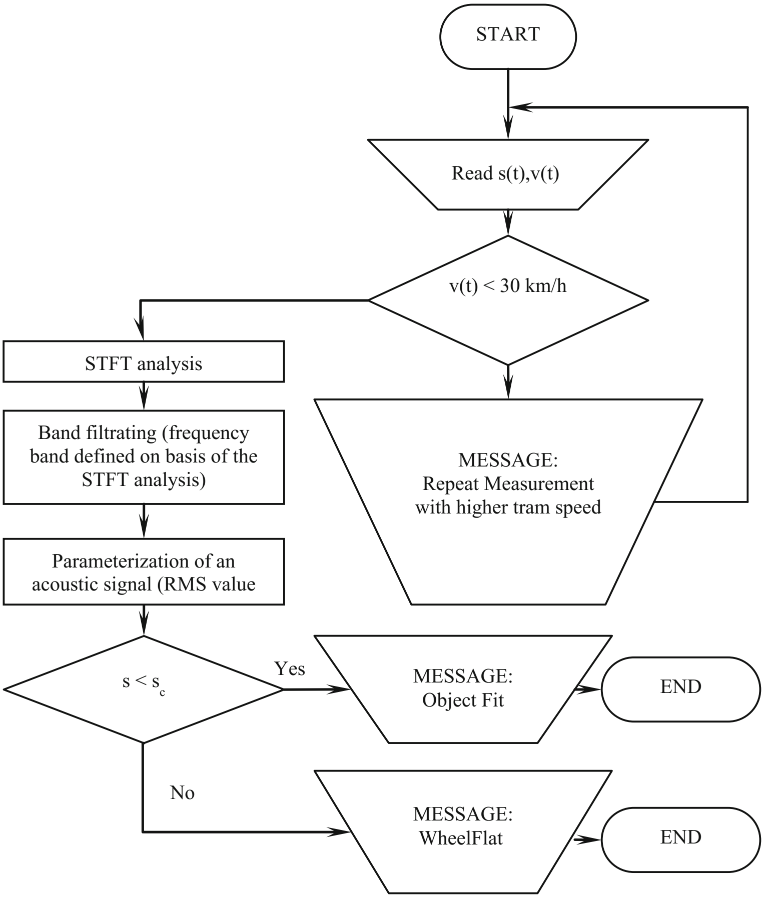

Fig. 7 Algorithm of the acoustic signal processing to diagnose wheel flats

5 Conclusions

Based on the research, authors proved that there is a possibility to monitor and diagnose wheel flats using acoustic signal processing—the algorithm of analysis was proposed. The time-spectrum method allows locating the wheel flat on the rail vehicle. Furthermore, the STFT analysis enables the frequency band detection, in which the system response to the impact excitation. Here, the impact excitation means dynamic wheel-track interaction when the wheel flat appears. The 100–300 and 1150–2125 Hz frequency bands are characteristic spectrum for examined tram. Research shows that analysis is not suitable when rail vehicle velocity is about 20 km/h because the difference between examined RMS sound pressure and critical sound pressure S_c should be at least 6 dB (in the research it was equal to 3.5 dB). Above the rail vehicle velocity of 25–30 km/h, proposed algorithm is well-founded.

There is a lot of different kind of methods and approaches for detection of rail wheel defects. A vibration technique (where vibration signal is processed) seems to be the most popular one. In this article authors proposed acoustic approach which is also easy in usage and cheap in production. Based on proposed method can be designed the monitoring system which can be applied on every tram depot. This could successfully contribute to decrease vibroacoustic emission around tram infrastructure and improve the passengers' comfort.

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