A practical approach to tramway track condition monitoring: vertical track defects detection and identification using time-frequency processing technique

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Abstract

This paper presents an automatic method for detecting vertical track irregularities on tramway operation using acceleration measurements on trams. For monitoring of tramway tracks, an unconventional measurement setup is developed, which records the data of 3-axes wireless accelerometers mounted on wheel discs. Accelerations are processed to obtain the vertical track irregularities to determine whether the track needs to be repaired. The automatic detection algorithm is based on time–frequency distribution analysis and determines the defect locations. Admissible limits (thresholds) are given for detecting moderate and severe defects using statistical analysis. The method was validated on frequented tram lines in Budapest and accurately detected severe defects with a hit rate of 100%, with no false alarms. The methodology is also sensitive to moderate and small rail surface defects at the low operational speed.

Key words: tramway track condition monitoring, time-frequency signal processing, vibration, wheel-rail interaction, wavelet transform

1 Introduction

The detection of track irregularities in their early stage and their timely maintenance can increase the reliability of railway operation and minimize the long-term cost of the railway infrastructure. The methods and instruments applied for track condition monitoring have been steadily developed over the years. Track condition monitoring and assessment have been a deeply studied problem for many years and extensive literature is now available. Basically, four different monitoring systems exist [1]: infrastructure-based infrastructure monitoring, rolling-stock-based infrastructure monitoring, rolling-stock-based rolling stock monitoring, and infrastructure-based rolling stock monitoring. Dedicated measurement trains are normal in many railway administrations for assessing the condition of the track [2], and there are

some examples, where simplified versions of these measuring systems have been fitted to service vehicles [3].

In the case of dedicated track measurement trains, the typical six-month schedule of inspection is too long to apply corrective measures, because it is not able to identify the rapid degradation of track. Recently modern electronics and the development of robust sensors, which are compact and robust enough to be mounted underneath in-service vehicles, made the rolling-stock-based infrastructure monitoring possible. It provides an effective system for monitoring railway track on a daily basis with continuous updates and relative low cost.

This article is concerned with tramway track monitoring based on measurements made by sensors fitted to an in-service vehicle. The axle-box, bogie side-frame and car body mounted inertial sensors are commonly used for identifying poor track quality from vehicle dynamics behaviour in conventional railway. However, due to the fact that in tramway operation the sensors cannot be mounted on axle-boxes, a not-commonly used vehicle dynamic measurement set-up is developed by the Authors [4], in which accelerometers mounted on the wheel discs are also applied, in addition to conventional solutions to detect poor track geometry and structural problems.

In the next section details are given about the measurement set-up adopted for experiments with the in-service tram. In *section 3* the applied signal processing techniques are discussed. *Section 4* presents the algorithm applied for detecting vertical track irregularities. Then, *section 5* is intended to face the test results and to give the main conclusions on the considered possibilities for development of the currently used tramway track condition monitoring.

2 Measurement set-up

A prototype of the measurement system has been installed on a dedicated recording tram. A GANZ type articulated tramcar was instrumented, which has 3 body sections, two not-driven Jacobs-type bogies and two driven bogies, one at each end of the vehicle. This vehicle has poor riding behaviour, which means that it has high-level resonance vibration during operation due to its old constructional arrangement.

Three-axes accelerometers are mounted on the one hand on each wheel disc (named WA: Wheel Acceleration) within a not-driven bogie, on the other hand, on the middle part of the bogie side-frames (named BA) under the pivot point of car body. The position, ID-s and sensing directions of the sensors are given in **Fig. 1**. The sensors WA sense the a_z *axial acceleration* pointing outward from the plane of wheel, the a_x *tangential acceleration* and a_y *radial acceleration*. The sensors BA on bogie-side frame measure the a_y *vertical* and a_z *lateral accelerations*. The sensors have odd and even sensor ID-s depending on which side of the vehicle they are located: on left side odd sensor ID-s, while on right side even sensor ID-s are used according to **Fig. 1**.

2.1 Data acquisition

Taking the speed range between 0-50 km/h, the maximum scale of acceleration recorded by this measurement set-up is $\pm 20g$ on a rotating wheel and bogie side-frame and $\pm 1g$ on the car body. Therefore, the scale of sensors on the wheels and the bogie side frame were set to $\pm 24g$ and the car body sensors to $\pm 6g$.

Figure 1: The sensor positions, the sensor ID-s and sensing directions on the instrumented Jacobs-type bogie; (BA: bogie-mounted accelerometer; WA: wheel-mounted accelerometer)

The applied sensors are capable of measuring accelerations with output data rates from 0.5 Hz to 1 kHz. At vehicle speed v , a periodic wheel/track irregularity with wavelength λ will generate a dynamic excitation at frequency $f = v/\lambda$. Considering the rolling stock as a multibody dynamic system, it consists of some unsprung masses (wheel), located below the primary suspension and whose natural frequencies usually range between 20 and 1000 Hz; semi-sprung masses (bogie), above the primary suspension with natural frequencies usually from 5 to 20 Hz; and sprung masses (car body), located above the secondary suspension, with natural frequencies usually ranging from 0.5 Hz to 5 Hz.

Table 1: Relation between track irregularity wavelength [m] and excitation frequency [Hz] at a given vehicle speed [km/h]: ■ Track elements; ■ Unsprung masses (wheel); ■ Semi-sprung masses (bogie side frame), ■ Sprung masses (car body)

		Wavelength [m]							
		0.035	0.06	0.25	0.6	2	25	70	120
Speed [km/h]	50	397	231	56	23	7	0.56	0.20	0.12
	40	317	185	44	19	6	0.44	0.16	0.09
	30	238	139	33	14	4	0.33	0.12	0.07
	25	198	116	28	12	3	0.28	0.10	0.06
	20	159	93	22	9	3	0.22	0.08	0.05

Taking the measuring speed range between 20-30 km/h (used in tramway operation), the maximum excitation frequency is 238 Hz according to **Table 1**. Simple accelerometers are used with the maximum sampling frequency of 400 Hz. These tools are suitable to record the impact of track irregularity with the wavelength between 0.035 and 25 m according to the **Table 1** introduced above and considering Nyquist–Shannon sampling theorem.

2.2 Localisation

The location of recorded data is mostly identified by using tachometer and GPS navigation systems. However, there is a way to directly identify the position information without GPS by using rotating wheel mounted accelerometers, but this solution is not commonly used for condition monitoring purposes recently. The travelled route is computed from both the rotated angle and number of revolution based on previous research of the authors [4]. After applying a low-pass filter ($f_c = 5$ Hz) or moving average on both y and x axes of WA sensors to isolate the gravitational component, the rotated angle can be computed by using these components, because they are sinusoid signals with constant g amplitude and the ω angular velocity of wheel. During the calculation the real wheel diameter is considered. The accuracy of the computed position information depends on both the total travelled route, the number of wheel slips and the vehicle riding quality.

3 Signal processing & track defects

The track irregularities can be estimated by the data recorded on various parts of the vehicle suspension system based on the vibration analysis of vehicle-track interaction. Single transients with large amplitude refer to severe local defect, while periodic transients relate to a defective track section [5]. Furthermore, the recorded acceleration signals, when the vehicle passes on different track defects, have various characteristics depending on the defect type. In that case, when multiple defects exist together, the usage of signal processing is required. The proper frequency content of the signals must be used to separate the different type of track defects. There are numerous solutions in literature to investigate the frequency content of the signal by using the techniques of signal processing, for instance conventional Fourier Transform [5] and wavelet approaches [6] [7].

An automatic detection algorithm is applied for localization of the isolated track defects, which appear as outstanding values (transients) in the measured signal. Wavelet analysis is used in this paper, because it provides high time and frequency resolution, so it is appropriate for the investigation of nonstationary phenomena with local changes in the frequency components, such as structural damage detection and crack identification. The Continuous Wavelet Transform (CWT) is a time–frequency analysis tool in which the observed function is multiplied by a group of shifted and scaled wavelet functions. For a more detailed discussion on wavelets, see [7]. In this paper, the Morlet function is used as a mother wavelet (center frequency $\omega_0 = 5$), because it provides that the Wavelet scale is equal to the Fourier period. The power spectrum of a wavelet transform (WPS) is defined as the square of the wavelet coefficients $|W_n^2(s)|$. The WPS is presented as a two-dimensional contour plot (see an example on **Fig. 4b**), which defines the time–frequency relationship of track defects with the recorded signal. The *Scale-Averaged Wavelet Power* (SAWP see **Fig. 4d**) is used for the automatic detection of isolated track defects. This function captures the variation of the spectrum in a signal, and thus, the system triggers the detection when the power spectrum of the frequencies related to the defects is higher than a given threshold. The SAWP is defined as the weighted sum of the WPS [7] i.e. (1),

$$\overline{W}_n^2 = \frac{\delta_j \delta_t}{C_\delta} \sum_{j=j_1}^{j_2} \frac{|W_n^2(s_j)|^2}{s_j} \quad (1)$$

where n is the time index, δ_j is a scale step, δ_t is the time step, and C_δ is an empirically derived constant for each wavelet function. To detect isolated defects, the SAWP is calculated in the whole frequency band between 0 and 250 Hz. Because the SAWP is a time series, “hammering effects” can be identified by finding the local maxima of the SAWP that exceed a certain threshold. In general, a higher SAWP indicates a more severe defect. Different constant thresholds were used for the analysed tracks. Thresholds are determined to maximize the hit rate and reduce the number of false alarms. The thresholds can be adapted to satisfy the requirements of the infrastructure managers depending on the track properties.

4 Automatic detection

The process for detecting isolated track defects includes data acquisition, pre-processing of the measured data to reduce the noise and vibration and remove periodicity, detection of faults, and assessment. The main steps of this algorithm are described below.

4.1 Quasi-vertical wheel acceleration

The recorded acceleration data on wheel can be decomposed into four independent components: on the one hand there is an acceleration component from translational motion (≤ 0.5 Hz) and a sinusoid acceleration signal component caused by the gravity (0.5–10 Hz), on the other hand the accelerometer senses the radial- and tangential accelerations, when the wheel is rotating. Furthermore, there is a noise component from wheel-rail vibration (see Fig. 2).

Figure 2: a.) component from the acceleration of gravity; b.) component from translational acceleration; c.) Radial - and tangential acceleration components from rotation

The sensed data can be computed with the superposition of the (a), (b); (c) and the remaining “noise” acceleration components:

$$\begin{aligned} a_x &= -g \sin \theta + \ddot{p} \cos \theta - \frac{r_s}{R} \ddot{p} + w_x, \\ a_y &= -g \cos \theta - \ddot{p} \sin \theta - \frac{r_s}{R^2} \dot{p}^2 + w_y, \end{aligned} \quad (2)$$

where θ is the angle of rotation; g is the acceleration of gravity [m/s^2]; r_s is the radius of

inertial sensor on the wheel [m]; R is the wheel radius [m]; p is the travelled distance [m]; w_x and w_y are noise [m/s²]; a_x and a_y are the sensing axes of the accelerometer [m/s²]. The recorded data on *sensors* WA are periodic signals due to the rotation and the forming gravity. Therefore, a pre-processing is required for *sensors* WA to remove this periodical part. The Quasi-vertical wheel acceleration is calculated from the recorded tangential and radial accelerations in order to remove periodicity from rotation. The first step is to calculate the gravity components of the recorded tangential and radial accelerations by using 4th order Butterworth high-pass filter with a cut-off frequency of 0.5 Hz. The rotated angle is computed by using the following formula (3):

$$\theta_{angle} = \arctan \left(\frac{a_{gy}}{a_{gx}} \right) \quad (3)$$

Where θ angle rotated angle [rad], a_{gy} gravity component on y axis [m/s²], a_{gx} gravity component on x axis [m/s²]. Then the Q vertical acceleration can be computed using the following formula (4):

$$Q = a_{gy} \cdot \sin \theta_{angle} + a_{gx} \cdot \cos \theta_{angle} \quad (4)$$

Fig. 4a, Fig. 7b and Fig. 7c show the computed *Quasi-vertical wheel acceleration*.

4.2 Background noise reduction (global wavelet spectrum)

For denoising purposes the iCWT was applied, because the wavelet transform is essentially a bandpass filter of uniform shape and varying location and width. After filtering on frequency domain the reconstruction of the filtered signal can be established from its wavelet coefficients. The expression for the inverse wavelet transform iCWT is (5):

$$x'(n) = \frac{\delta_j \delta_t^{1/2}}{C_\delta \psi_0(0)} \sum_{j=j_1}^{j_2} \frac{\Re\{W_n(s_j)\}}{s_j^{1/2}} \quad (5)$$

The factor $\psi_0(0)$ removes the energy scaling, while the $s_j^{1/2}$ converts the wavelet transform to an energy density. The factor C_δ comes from the reconstruction of a δ function from its wavelet transform using the function $\psi_0(\eta)$. This C_δ is a constant for each wavelet function.

This filter has a response function given by the sum of the wavelet functions between scales j_1 and j_2 . This filtering can also be done on both the scale and time simultaneously by defining a threshold of wavelet power. This “denoising” removes any low-amplitude regions of the wavelet transform, which are presumably due to noise. This technique has the advantage over traditional filtering in that it removes noise at all frequencies and can be used to isolate single events that have a broad power spectrum or multiple events that have varying frequency. During the calculation 10% significance level is used (see **Fig. 4a** red filtered signal).

4.3 Detection

The track defects are predicted by calculating the SAWP of the recorded signals. Recently there are no sufficient measurement data from vehicle dynamics measurements available to identify exact frequency bands with the maximum power spectrum related to the defects. Therefore, we investigate the whole frequency range between 1 and 200 Hz. The locations of the vertical track irregularities are predicted by the values of the SAWP that exceed a certain threshold. **Fig. 3** shows the investigated welded joint and **Fig. 4** illustrates the steps of the detection algorithm. The instrumented vehicle runs at 20 km/h on a newly-built track, where the welded joints caused significant outstanding values. **Fig. 4** can be decomposed into four traces: the first one presents the time history of the calculated quasi-vertical wheel acceleration and its filtered version (see eq. 5), where the background noise is reduced; the second shows the Wavelet Power Spectrum (WPS), where the left axis is the Fourier period (in meter), the bottom axis is Travelled route. The shaded contours are at normalized variances of 1, 2, 5, and 10. The thick contour encloses regions of greater than 95% confidence for a red-noise. Cross-hatched regions on either end indicate the “cone of influence,” where edge effects become important. The third illustrate the global wavelet spectrum, which shows 1.23 cm average periodicity. The blue dashed curve illustrates the 95% confidence level for a red-noise. One can see the broad set of Q peaks between period of 2^{-5} and 2^{-7} m, well above the background spectrum. The last diagram presents the Scale Average Wavelet Power (SAWP) over all scale between 2^{-1} and 2^{-8} , which gives a measure of the average Q variance versus time. This variance plot shows a distinct period between 220 and 220.5 m when Q variance was significantly higher the average variance and the given threshold. The localisation is done by taking the highest peak of the exceeding part of the signal. The ● symbol denotes the location of the identified defects.

Figure 3: Faulted welded joint in embedded rail system in a new-built track

A constant threshold of $1g^2$ ($\sim 10 m^2 s^4$) was used for the analysed welded joints, which provided a good trade-off between maximizing the hit rates and minimizing the false-alarm rate. To validate the proposed method, the track was visually inspected to properly quantify the false alarms and hit rate.

Figure 4: Faulted welded joint: (a) The Quasi-vertical wheel acceleration time history used for the wavelet analysis; (b) The local wavelet power spectrum (WPS) of (a) using the Morlet wavelet, normalized by $1/\sigma^2$ ($\sigma^2 = 0.09g^2$); (c) Global Wavelet spectrum with the 95% confidence level; (d) Scale averaged Wavelet Power (SAWP) (1) over all scales between 2^{-1} and 2^{-7} m, with the applied $1 g^2$ threshold (● symbol denotes the location of the identified defects).

5 Measurement results

The test of the algorithm has been performed in a tram depot and on the tram line 41 in Budapest. The instrumented tram used in this study ran at nearly constant speed in the range between 25 and 30 km/h. When a wheelset rolled over the crossing part of turnout significant outstanding values (1 - 8g) are sensed in recorded signal depending on the both the vehicle velocity and the condition of turnout frog. Travelling through a vertical track irregularity or rail corrugation, periodic excitation showed up in the recorded signals. The detection algorithm is used to determine whether track section needs to be repaired. Two different thresholds are used for detecting isolated track defects and for identifying track irregularities. The $8g^2$ SAWP (see **Fig. 5b**, **Fig. 7b** and **Fig. 7c**) threshold is applied to identify moderate and severe hitting effect forming between wheel and rail, while $1g^2$ threshold is used the determine vertical track irregularity computed along a certain track length (6 m) of SAWP signal (see **Fig. 5b** and **Fig 7d**).

Figure 5: Homogeneous track sections and turnouts along right-sided track of the investigated tram line (S: straight segment, C: curve segment): a.) Cumulative sum of SAWP corresponding to Q_{left} ; b.) SAWP with the $1g^2$ and $8g^2$ thresholds (● symbol denotes the location of isolated track defects exceeding $8g^2$ threshold)

A.) Detecting isolated track defects

On the investigated track section 5 turnouts and 3 crossings can be found. The turnouts between 0 and 400 m (vPh 30/50/30, 48 100/100e) were recently rebuilt and have spatial partial flange bearing frogs. **Fig. 5** shows the results of the detection algorithm used on the first-left wheel's quasi-vertical acceleration data. The hit rate in the case of turnouts (severe and moderate isolated defects) is 100% (from 8 frogs 8 was identified). It is clearly seen that the special frogs have lower outstanding values than the traditional ones. **Fig. 6** represents the variance of the SAWP signal at the turnouts and crossings. Along the whole investigated track section the 48 100/60 and 48 XIX 50/50 eg. type turnouts are in the poorest condition (see **Fig. 6**), but in the case of the second turnout the vehicle must brake (at 700 m position), which significantly reduced the recorded accelerations. The last turnout within the section is the 48 100/100e type, whose fastenings are loosened and its wooden sleepers are deteriorated, which resulted in significant hitting effects.

B.) Detecting vertical track irregularities

The investigated track section is divided into homogeneous track sections according to the cumulative sum of SAWP signal (see **Fig. 5a**) calculated from the first-left wheel Quasi vertical acceleration. The homogeneous sections do not contain the crossings and turnouts, they are separately analysed. The cumulative sum curve has a “jump” at the locations where a significant hitting effect is formed between wheel and rail (for instance: frog of turnouts and crossings). The amount of the jump depends on the intensity of the hitting effect, which can be characterised by

the corresponding SAWP value. The segments with nearly constant inclination of the cumulative sum, refer to homogenous sections. These sections are sub-classified according to the horizontal alignment of track. The “S” symbol means straight, while, “C” refers to the curve segments (see **Fig. 5a** on top axes and **Fig. 7e** on bottom axes). The track segments between 0 and 400 m (*Section S1*) were renovated this year, so they are in excellent condition. On these segments only, the turnouts and crossings are identified based on threshold exceeding of SAWP signal. Straight *Section S2* is in moderate condition, water beds, faulted rail joints and moderate size rail corrugation can be found on this segment. On straight *Section S3* there is a foundation problem, which is caused by a creek located directly next to track. On the acceleration time history corresponding this section (see **Fig. 7a** between 1050 and 1200 m) and on the computed SAWP signal (see **Fig. 5b**), periodic excitation can be observed, which refer to the above-mentioned problem. On the curved *Segment C1* the outer rail sank and its fastenings are loosened, which result in numerous hitting effects with large amplitudes in SAWP signal. On curve *Segment C2* there is no significant rail corrugation and the SAWP signal is below the given threshold with only some transients exceeded it. The applied track structure within this section is the MAV48 type rail profile with wooden sleepers. On the curve *Segment C3*, there is significant vertical track irregularity and intensive rail corrugation. The significant part of the corresponding SAWP signal exceeds the given $1g^2$ threshold. Within this section there is a level crossing, where the rail is sank and has significant vertical wear, which cause the periodic vertical excitation of the wheel and the large number of hitting effect between wheel and rail.

Figure 6: SAWP variance of the turnouts and crossings along the investigated track section: a.) the variance separately per track structures b.) Total variance of all turnout and crossing along the section

Fig. 7 can be decomposed into 6 diagrams: the first one illustrates the vehicle velocity, the second and third one shows the computed *Quasi-vertical wheel acceleration* corresponding to first-left and right wheel in addition to detected defects, which exceeds the $8g^2$ SAWP threshold. The identified defects are denoted by filled red circle on top axes. The fourth one is the histogram of detected isolated defects exceeding the $1g^2$ thresholds. The fifth diagram shows the low-pass filtered ($f_c = 5$ Hz) lateral wheel acceleration, which represents the horizontal alignment of the track. The last diagram gives information about the applied track system along the whole section. (BTWS: Ballasted Track with Wooden sleepers; BTWC: Ballasted Track with Concrete sleepers; WSEC: Wooden Sleepers Embedded in Concrete)

Figure 7: Detecting isolated vertical track defects and irregularities: a.) vehicle velocity; b.) and c.) Quasi-vertical acceleration of first-left and right wheel (● symbol denotes the location exceeding $8g^2$ threshold); d.) histogram of detected isolated defects exceeding the $1g^2$ thresholds; e.) lateral wheel acceleration representing the track horizontal alignment

6 Conclusion

Although the introduced vehicle dynamics measurement system does not provide exact data of track geometry, but sections with poor track geometry or structural problems (faulted welds and turnout frogs, foundation problems) can be identified and located with algorithms like the one discussed in this paper. Regarding the identification of vertical track irregularities, it can be concluded that severe defects can be easily identified without using signal processing. But in that case, when multiple defects exist together, the usage of signal processing is required. The wavelet transform is an excellent tool to separate multiple-formed track defects, because it can reduce the background noise and keeps the transient values. This vehicle dynamic measurement system is cheap to implement and no significant modification of the vehicle is required. Therefore, in-service vehicles equipped with this system may serve a good opportunity for monitoring tramway track, while it is running. Multiple passes over the same track section can contribute to establishing safer transport systems.

Acknowledgements

The Authors intend to thank the Budapest Public Transport Ltd. (BKV) and METALELEKTRO Measuring Technique Ltd. for assuring of the tramcar and the accelerometers as well as to B. Figura for assistance in the measurements.

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