

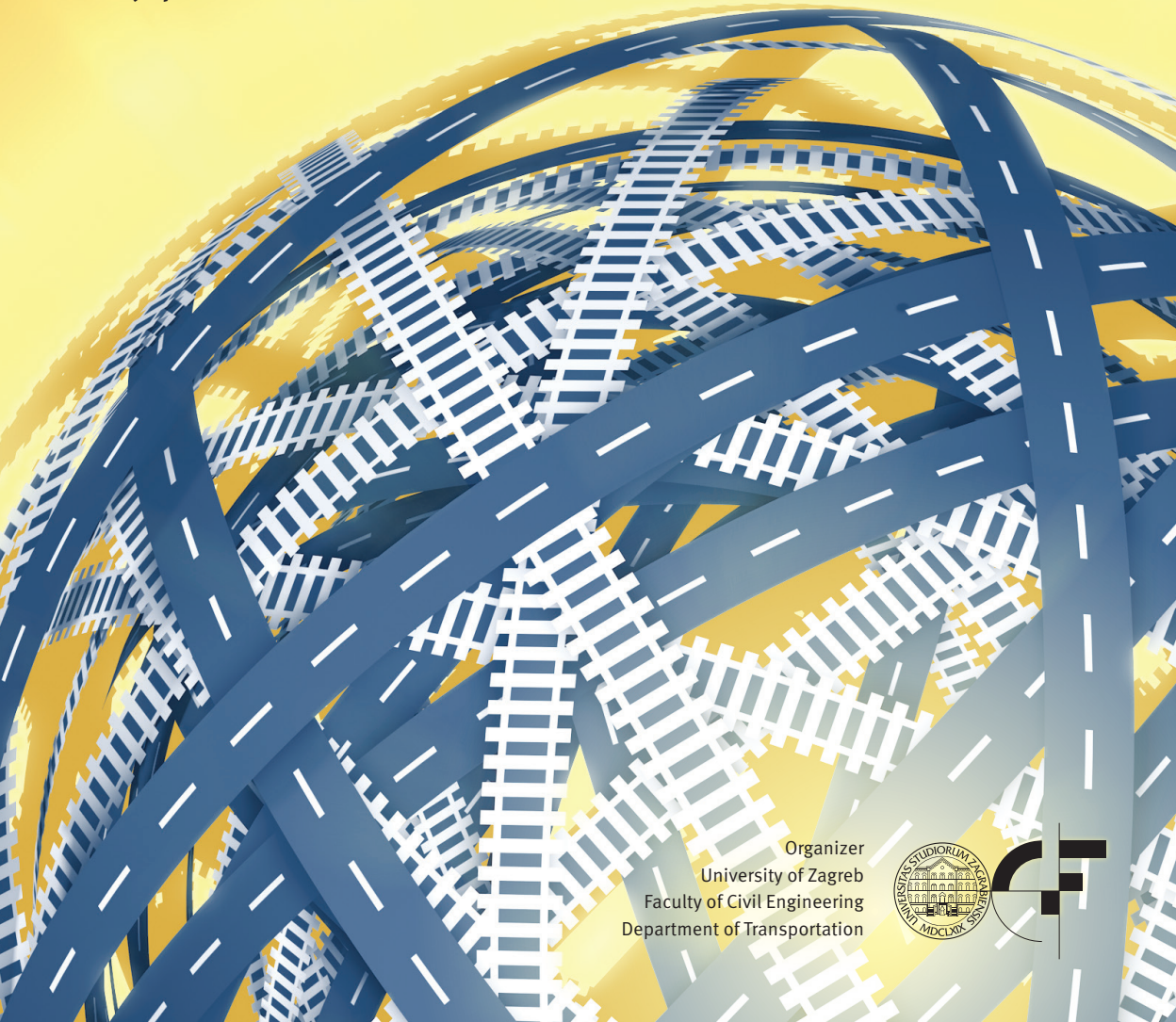


**CETRA** 2016

4<sup>th</sup> International Conference on Road and Rail Infrastructure  
23-25 May 2016, Šibenik, Croatia

## Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



Organizer  
University of Zagreb  
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## PRACTICAL EXPERIENCE AND IN-SERVICE VEHICLE DYNAMICS MEASUREMENTS BASED MAINTENANCE STRATEGY FOR TRAMWAYS INFRASTRUCTURE

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### Abstract

In the case of guided transportation systems the acting cyclical loads in track-vehicle interaction can change in wide range depending on both the type and technical state of the vehicle and the track. Due to the urban traffic-control constraints significant additional loads can be formed from the combined effects of weather conditions and driving style. The infringement of tram traffic regulation especially exceeding the speed limit or both sudden start and braking can easily cause premature degradation of the track. The intensity of addition load between the wheel and rail was estimated by wheel modal analysis, which input data are recorded by wheel-mounted accelerometers on an in-service tramcar.

*Keywords: Wheel-mounted accelerometer, Tramway track, Condition monitoring, Wheel vibrations, In-service tramcar*

### 1 Introduction

The exact knowledge of track technical state is highly important for every railway company. Nowadays there is a great variety of track measuring devices available: from track geometry recoding trolley to track recording cars. The measurement systems can be divided into two large groups depending on which part of the track-vehicle system is measured: Geometric Measuring System (GMS) and Vehicle Dynamics Measurement System (VDMS). [1] [2] [3] GMSs provide good information about the current technical state of tracks, because there is a close relation between the current geometrical deviation of track structural elements and track deterioration level.

VDMSs give information about irregular vehicle movements (vehicle dynamic behaviour), from which poor track technical state can only be concluded indirectly. Therefore only derailment safety and travel comfort features are characterized. The axlebox mounted accelerometers and forcemeters are commonly used for measuring vehicle dynamics behaviour. The irregular vehicle movement can refer to track irregularities and depending on the defect type different exciter frequency components are registered in the measured signal. There are numerous solutions in literature to detect different wavelength-track defects by using the techniques of signal processing. The localisation of recorded data is mostly identified by using GPS navigation devices or combined systems. However, there is a way to directly identify the position information without GPS by using rotating wheel mounted accelerometers [4] [5] [6], but this solution is not commonly used for condition monitoring purposes recently.

The existing solutions, which have demonstrated to be reliable, are too expensive for tramway operators currently. Therefore this paper is aimed to introduce an accelerometer based low-cost measurement system, which is mounted on in-service vehicle's wheels and ensures

the automatic detection of faulted track sections. The authors have carried out an extensive experimental activity with an instrumented city-tram on homogeneous structured track sections. The next sections describe results and the system on which tests have been performed.

## 2 Vehicle-track interaction

The dynamic interaction between vehicle and track can be described by a mass-spring system and it can be excited by failure of both track and vehicle. In order to detect rail defect or predict failure, the tram track and the vehicle should be analysed together, because the deterioration of track is a self-exciting cyclical process between the vehicle, the track and the substructure. Running through a track defect the dynamic response of different type vehicles can change in wide range due to their variant structural arrangement. Furthermore, travelling at low speed the vehicle often makes irregular oscillation, which is not caused by track defect, but also due to their own inertial mass of parts of vehicle mass-spring system. Only one old tram type was used for the test, but the comparison behaviour of different tram types will be necessary in the future.

### 2.1 Characteristics of the tramcar

The GANZ type 8 rigid-axle articulated tramcar, which does not have slip protection and torque control traction motors, was used for the test. It has a semi-automatic drum starter, which reduces the adverse results of the sudden starts. The two powered wheelsets are situated at both ends of the vehicle. The drum-brake is located on the driven wheel-sets, and the disc-brake on the not-driven wheel-sets.

### 2.2 Investigated track section

The line test was performed in operation along the Budapest tram line 49, which is one of the most frequented lines in the downtown. Along this tram line different track types can be found. The significant part of the track is grooved rail formed embedded fastening system (ERS: Embedded Rail System), but there are special track structures on sharp curves, on the bridge and on turnouts.

## 3 Measurement set-up

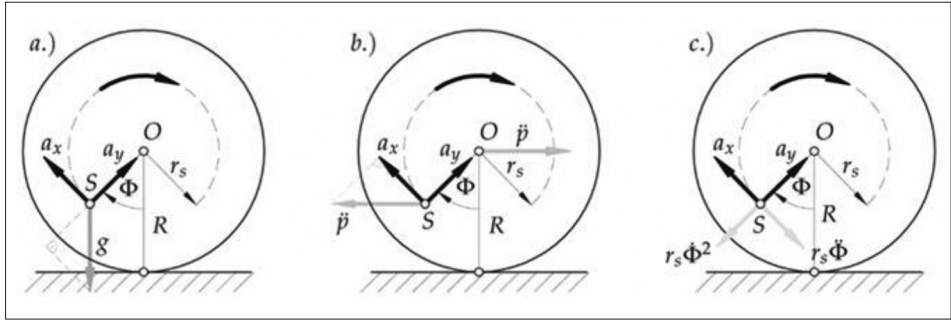
Digital USB 3-axis accelerometers have been used for vehicle dynamic measurements. Only two tools are available this time, so one accelerometer is mounted on a not-driven-wheel and another one on the driven wheel on the opposite side. The investigated conical tramway wheelset is rigid and free, so it does not have additional loads from propelling. A steel plate provides fixing accelerometers on the wheel. It has two conical structured spacers, which fit into the two bore-holes of wheel rim. These spacers expand and get stuck in the hole for torsion. The holes on the steel plate provide fixing of the accelerometers by using cable tie. The longitudinal axis of the accelerometers is perpendicular to the wheel radius, so the axis measures the  $a_x$  tangential,  $a_y$  radial and  $a_z$  lateral acceleration (see Fig. 1).

## 4 Theory & method

Dynamic accessory forces are developed by the forming acceleration during movement of the vehicle, which cause damaging vibrations of the track and vehicle components. The magnitude of forming loads can be computed by the measured data of wheel mounted accelerometers. Several independent methods were used to determine the position information, to analyse and filter the relevant frequency components of the measured signals.

#### 4.1 Kinematical model of the running wheel

The recorded acceleration data 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 (5 – 10 Hz), on the other hand the accelerometer senses the radial- and tangential accelerations, when the wheel is rotating (Fig. 1). Furthermore, there is a noise component from wheel rail vibration. No slipping situation is assumed during the motion of the wheel.



**Figure 1** Sensing directions  $a_x$ ,  $a_y$ ,  $a_z$  and the kinematical model of the running wheel: 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:

$$\begin{aligned} a_x &= -g \sin\theta + \ddot{p} \cos\theta - \frac{r_s}{R} \ddot{p} + w_x, \\ a_y &= -g \cos\theta - \ddot{p} \sin\theta - \frac{r_s}{R^2} \dot{p}^2 + w_y \end{aligned} \quad (1)$$

where  $\theta$  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 [ $m/s^2$ ];  $a_x$  and  $a_y$  are the sensing axes of the accelerometer [ $m/s^2$ ]. Figure 2 shows the above mentioned components of the sensed signal on running wheel  $a_y$  axis.

In contrast to traditional filtering methods only the known Signal components (See Fig. 1 (a) (b) (c)) are filtered, so the outstanding values of the residual component can refer to forming additional loads between the wheel and rail. Therefore the modal analyses of measured signals will be present in the next section.

#### 4.2 Modal analyses of the wheel-rail vibration

The residual vibration accelerations ( $w_x$ ,  $w_y$ ) on x and y sensing axes are determined by filtering the known component of the recorded signals. These consist of the vibration of the wheel-rail interaction and the impact of forming additional loads too (Fig. 3). Decomposing of the residual acceleration component the additional loads can be separated from the wheel-rail vibrations. Running on track defect gives a broad band excitation at the wheel [7], which means an outstanding value in the residual noise components, as well as this causes a vertical line in its spectrogram around the location of track defect (Fig. 3c). In any other cases there is a low- (Fig. 3a) or “high”-frequency vibration (Fig. 3b) of the vehicle track interaction. There are several methods to analyse the frequency components of a time domain signals.



The Short-Time Fourier Transform (STFT) allows to determine the power of frequency components of a signal by using Fourier Transform. In the function of time and frequency the power (PSD) of coherent values can be represented on a spectrogram Fig. 3. Due to the sampling frequency of the applied sensors being 400 Hz, the power spectrum can be accurately determined until 200 Hz (Nyquist–Shannon sampling theorem [8] [9]).

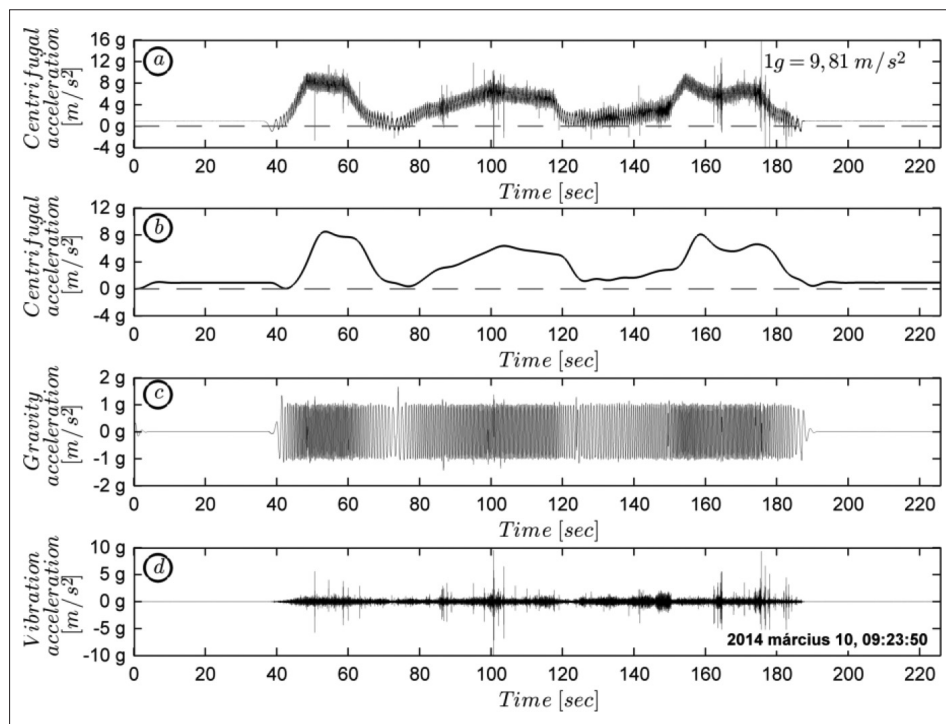


Figure 2 Extraction of the sensed signal on running wheel  $a_y$  axis: a) Measured centrifugal acceleration; b) centrifugal acceleration without its gravity component; c) gravity acceleration components; d) “noise” (vibration acceleration)

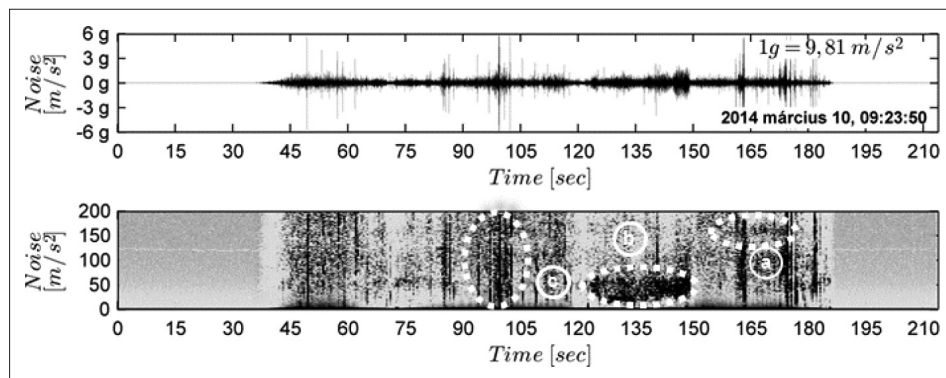


Figure 3 Dominant frequencies at place of the outstanding values of “noise”  $w_y$ : a) 150-200 Hz; b) 0-50 Hz; c) 0-200 Hz



### 4.3 Localization

Localization of outstanding values can be achieved by data of wheel mounted accelerometers. One way is the Extended Kalman Filter (EKF), which [5] in the case of an appropriate chosen physical model is suitable to compute not measured vehicle parameters from the measured data ( $a_x, a_y$ ). It should be noted, when the forming accelerations exceed the range of the sensors, the EKF is not applicable. The next way is to compute both the rotated angle and revolution [4]. After applying low pass filter (5 Hz) or moving average on y and x axes to remove signal from gravity ( $a_{gy}$  and  $a_{gx}$ ) (see. Fig. 2c), the rotated angle can be computed by using these components, because they are sinusoid signals with constant g amplitude and the  $\omega$  angular velocity of wheel. The rotated angle is computed by using this formula:

$$\theta_{\text{angle}} = \arctan\left(\frac{a_{gy}}{a_{gx}}\right) \tag{2}$$

Where  $\theta_{\text{angle}}$  rotated angle [rad],  $a_{gy}$  gravity component on y axis [ $m/s^2$ ],  $a_{gx}$  gravity component on x axis [ $m/s^2$ ].

The travelled distance can be computed by sampling the revolutions based on rotated angle. Figure 4 shows the measured accelerations on both x and y axes, the computed rotated angle as well as the travelled distance. In the case of travelled route calculation the real wheel diameter is taken into account. The accuracy of the computed position information is between about 2 and 5 m thanks to the poor riding quality of the investigated tramcar. There is a significant sudden irregular vehicle movement at every start and stop, which causes that the first and last revolution of the rotating wheel can't be detected between two stops. The vehicle velocity is computed from the travelled route by derivation.

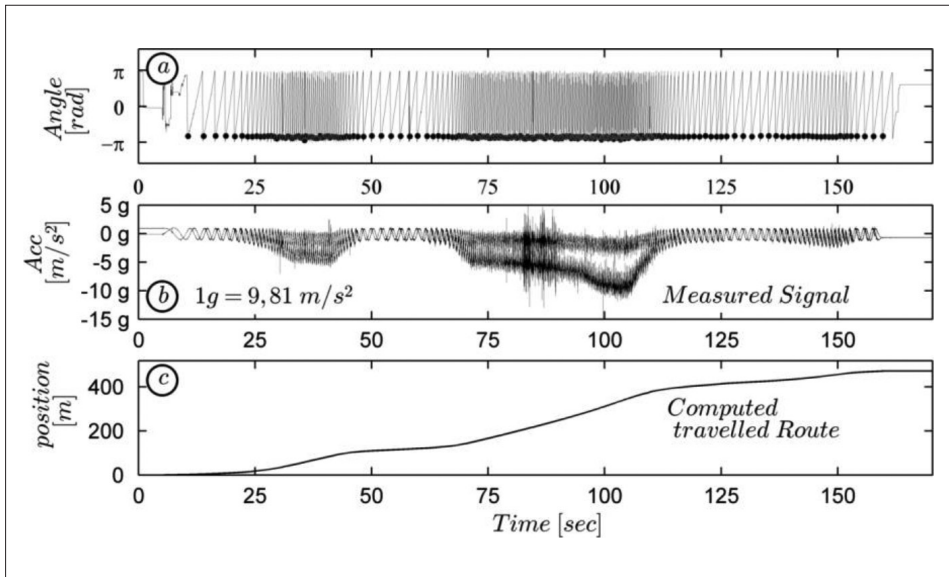


Figure 4 Position information: a) Computed rotated angle with the identified revolutions; b) Sensed data on x and y axes; c) Computed travelled route by sampling revolutions

## 5 Measurement results

During the line tests the instrumented tramcar travelled about 10 km along the tramline 49 in Budapest. In contrast to the previous section, the power spectrum of the measured signals is represented in the function of travelled route. Figure 5 is composed of 5 diagrams: In the first one the vehicle velocity [km/h] is represented in the function of travelled route, in the second one there is residual acceleration after decomposition on different sensing axes, in the third diagram the spectrogram of signal is reported, in the fourth one there is average power of frequency domain signal along the whole travelled

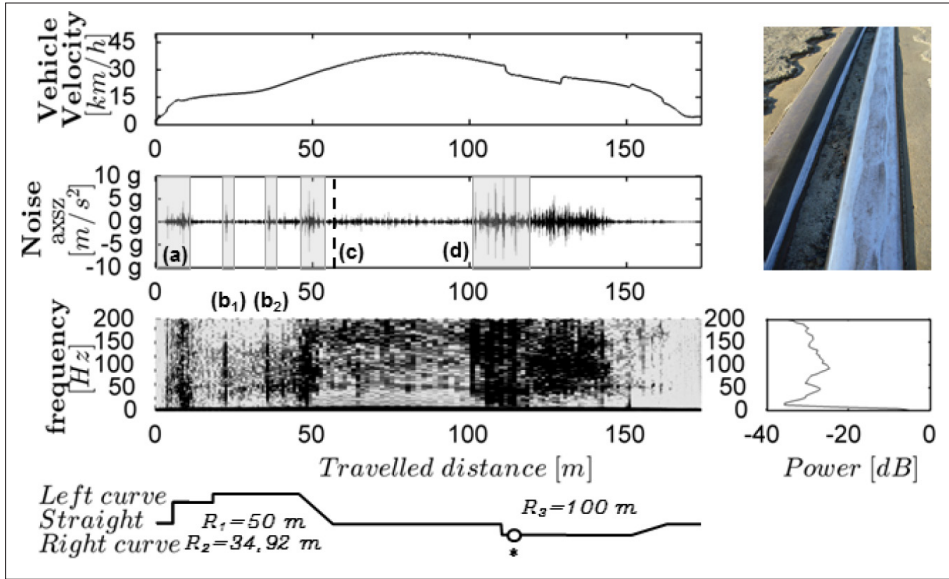


Figure 5 Investigated track section between Szent Gellért Square and Kelenhegyi Street, along the tram line 49 in Budapest. (running wheel acceleration on the rim in axial direction).

section. In the last diagram the curvature of the line section alignment is represented. This information cannot be identified from the measured signal, but adding to the diagram makes it possible to analyse the recorded data easily. Furthermore, specific points of the turnouts and crossings are signed by \* on the curvature diagram.

Figure 5 shows an about 170 m long investigated track section. After the instrumented tramcar started, it travelled on a diverging track of turnout, then ran on a 34 m radius curve section, afterwards went on a straight section for about 50 m. And then meanwhile it was running on a left-sided 100 m radius curve section, it travelled through a crossing too. The residual noise component can refer to poor track technical state and the existing structural element of the track too (turnouts, crossings). The outstanding values at position (a) are recorded at travelling through crossing and switch part of the turnout. The outstanding values at (b<sub>1</sub>) and (b<sub>2</sub>) refer to two failed rail weldings. On the travelled route section between 15 and 50 there are significant corrugations on both rail running surfaces, which result in periodical vertical lines in spectrogram of the measured signal during the whole curved section. Before and after the 55 m position information there are two different sub-structures. On Figure 5 the differences in both elastic features and vibration-absorbing capability of the two sub-structures can be seen clearly, because after 50 m chainage the high-frequency-components (over 100 Hz) are more powerful than in the previous section. At the position of approximately 110 m, when the tram travelled through a crossing, there is significant broad band excitation, lasting for about

10 m. In this section the average power spectrum of the measured signal has two peaks: one of them is at 50 Hz and the other one is at about 100 Hz. The 50 Hz component dominates at curved sections mainly, while the 100 Hz component is significant, when the tram braked intensively. The statements above are also true in the case of both radial and lateral accelerations. It is important to note that the average power spectrum of lateral acceleration (sensed on z axis) is significantly higher (about twice) than the power of the accelerations recorded on x and y axes ( $a_x$ ,  $a_y$ ).

## 6 Conclusion

It can be stated that the introduced measurement set-up is suitable to detect poor technical state track section. Besides its low cost, another important advantage of this system is that the travelled route can be determined from the measured signal directly due to the existing gravity acceleration, which causes the sensors to be able to work as a revolution counter. The accuracy of travelled distance is from 2 to 5 m in 300 m, which is enough for track inspectors to find the location of the track defect. It should be noted that the using same velocity during measurement is absolutely necessary for comparison of monitored results in the case of the same track sections.

## References

- [1] Weston, P., Roberts, C., Yeo, G., Stewart, E.: Perspectives on railway track geometry condition monitoring from in-service railway vehicles, *Vehicle System Dynamics, International Journal of Vehicle Mechanics and Mobility* 53 (2015) 7, pp. 1063–1091, doi: 10.1080/00423114.2015.1034730
- [2] Hitoshi, T., Yasukuni, N., Akira, M., Takeshi, M., Hirotaka, M.: Condition monitoring of railway track using in-service vehicle, *Journal of Mechanical Systems for Transportation and Logistics* 3 (2010) 1, pp. 154–165, doi: 10.1299/jmtl.3.154
- [3] Boccione, M., Caprioli, A., Cigada, A., Collina A.: A measurement system for quick rail inspection and effective track maintenance strategy, *Mechanical Systems and Signal Processing* 21 (2007) 3, pp. 1242-1254, doi: 10.1016/j.ymssp.2006.02.007.
- [4] Huang, J., Wang, T.: Accelerometer Based Wireless Wheel Rotating Sensor For Navigation Usage, 2011 5<sup>th</sup> International Conference on Sensing Technology, Palmerston North, pp. 565-568, 2011.
- [5] Bernd, G., Udo, F.: A Kalman-filter for odometry using a wheel mounted inertial sensor, 10<sup>th</sup> International Conference on Informatics in Control, Automation and Robotics, Reykjavík, pp. 388–395, 2013.
- [6] Sonenblum, S. E., Sprigle, S., Caspall, J., Lopez, R.: Validation of an accelerometer-based method to measure the use of manual wheelchairs, *Medical Engineering & Physics* 34 (2012) 6, pp. 781-786, doi: 10.1016/j.medengphy.2012.05.009.
- [7] Corradi, R., Crosio, P., Manzoni, S., Squicciarini, G.: Experimental investigation on squeal noise in tramway sharp curves, 8<sup>th</sup> International Conference on Structural Dynamics, Leuven, pp. 3214-3221, 2011.
- [8] Shannon, C. E.: Communication in the presence of noise, *Proc. IRE* 37 (1949) 1, pp. 10–21
- [9] Nyquist, H.: Certain topics in telegraph transmission theory, *AIEE Trans.* 47 (1928), pp. 617-644