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Wheel flat detection algorithm for onboard diagnostic

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ABSTRACT

The paper describes an algorithm to detect wheel flat defects by measuring the vertical acceleration on the axle-box. The algorithm operates in the time domain and it is suitable to define an index to discover the presence of wheel flats at the early stage and to estimate the severity of the problem. In order to verify the algorithm both numerical simulations and experimental tests have been performed on a freight vehicle. The results show that the wheel flat index proposed in this work is able to detect small flats and to estimate its severity. The algorithm has been integrated on a monitoring system for onboard application and it has been developed in order to be able to run on a light hardware architecture.

1. Introduction

A wheel flat is one of the defect occurring to the wheels of railway vehicles during service life. This defect is related to the occurrence of anomalous braking events leading to the locking of axle rotation, with the consequence of a complete sliding at the contact and heavy wear of the wheel surface. Most of modern railway passenger vehicles are nowadays equipped with wheel slide protection devices (WSP) acting on the pneumatic circuit of the brake system. Therefore this kind of vehicles are not often subject to this wheel defect, except in the case of malfunction of the wheel slide protection system. Freight vehicles are commonly equipped with a simpler brake system, based on brake blocks acting directly on the wheel tread and not usually equipped with a WSP. The use of brake blocks on the tread, has however some benefits on the wheel tread surface condition since their action provide a sort of grinding of the surface being able to remove small surface defects, with the cost of an higher wear of the surface with respect to vehicles equipped with brake disks. However since those vehicles are not equipped with a wheel slide protection system, the only method adopted to prevent wheel locking during braking is given by the limitation of the brake force in relation with the weight acting on the bogie and measured with a device usually linked to one of the suspensions. This method is not able to prevent the wheel locking in all conditions; therefore freight vehicles are subject to the formation of wheel flats. The presence of wheel flat on the wheel surface has the consequence to generate severe impact loads during wheel rolling [1–5]. Those loads cause heavy stresses on the components of the vehicle and of the infrastructure and are responsible of an important increment of rolling noise [6]. Heavy loads and stresses at the contact are also related to phase variations in the material of the wheels with martensite formation [7], and can play an important role in the generation and grow of defects due to the rolling contact fatigue (RCF).

During the service life of the railway vehicle, the action of repetitive braking can produce out of roundness of the wheel also when a complete wheel locking does not occur. This event, also if is not severe as a wheel flat, is related to the polygonalization of the wheel, that leads to an increment of the dynamic load on the track [1,8,9] and to an increase of the noise.

The dynamical behavior of a railway vehicle with a wheel flat can be properly simulated only considering also the effect of the track flexibility [10], since the impact load generated by the wheel flat excites the mode shapes of the track, and it is mitigated by the flexibility of track and contact. The role of track irregularities must be also taken into account since it is superimposed to the vibration produced by the wheel flat [11]. Steenbergen has analyzed in detail [12,13] the dynamic of a vehicle with a wheel flat providing a model able to predict the impact load also considering the effect of mitigation occurring on the wheel flat due to wear produced at successive passages of the flat on the rail.

Wheel corrugation and wheel flat play an important role in noise generation, therefore, in the effort to reduce the noise of freight vehicles, railway administrations in the European Community are requested to limit the circulation of vehicles with wheel flats, this became mandatory after the approval of directive 91/440/EC. The strategy adopted to solve this problem is to detect the presence of wheel flat on the vehicle [14] and to remove defective vehicles from circulation. In the last years different techniques have been developed to detect wheel flat, based on systems installed on the infrastructure [14–23]. Track

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side monitoring system can be based on different techniques [15,16], the most common are based on the measurement of the wheel/rail force (strain gauge) or of the track deflection or deformation. The latter can be performed with a wide range of sensors, including accelerometers [17–20], geophones, LVDT, custom measuring solutions [21] and more recently Fiber-Bragg gratings [22]. Data analysis can be performed in the time domain [17–19], eventually adopting techniques to enhance the detection of the presence of the local defect, in [23] digital wavelet transform is adopted to obtain threshold level from the analyzed signal. An alternative method is based on the analysis of the signal in the frequency domain; [20] adopts the power Cepstrum of the signal to identify the presence of the defect. Other techniques are based on ultrasound measurements [24], where the variation of the round-trip time of Rayleigh waves is adopted to detect a defect on the wheel, or based on acoustic measurements [25].

Onboard monitoring systems are installed on some vehicles for diagnostic and maintenance purpose [26]. Those systems have been primarily developed to solve issue related to safety and more recently to detect components deterioration and improve the maintenance process. The use of onboard monitoring systems can also be adopted to detect wheel flat occurrence on a vehicle, with the benefit that the detection can be performed immediately after the wheel flat formation, without requiring a passage on a track side monitoring site. The immediate detection of the flat formation can be also correlated to the braking occurrence if the braking system is also monitored, in order to develop strategies to reduce the occurrence of this event.

Wheel flat monitoring with an on board diagnostic system can be essentially based on acceleration measurements. Liang and others [27] simulated the wheel flat with experiment on roller-rig and numerical models and compared three different methods in the frequency domain to analyze the measured data to detect the presence of the defect. Acceleration versus acoustic signal are also compared and the former appears to be the most effective method. Li and others [28] developed a method of analysis of the accelerations in the frequency domain, able to improve the detection of the wheel flat with respect to the rolling noise, the method is tested with experiments on roller-rig. Sun and others [29] proposed to use acceleration measurements on the wagon body to detect the presence of wheel flat, the method is tested using different numerical simulations.

This paper proposes to use acceleration measured on the axle-box of a vehicle and to analyze it in the time domain to detect wheel flats. A specific algorithm has been developed and tested using numerical simulations and measurements on a real vehicle. Aim of this work is to develop an effective but computationally simple algorithm, able to run on low power embedded systems or μ-controllers. This allows its use on self-powered systems that eventually can be installed directly on the axle-box and operate as a WI-FI sensor node. The system has been tested on a monitoring system that has been developed by the authors [30] and already used to perform measurements of the track condition [31]. This system has been improved in order to act as an independent onboard monitoring system [32] and can be used to perform specific tests to detect also the presence of wheel-flat. The adoption of an algorithm in the time domain can be of interest also together with other algorithms developed in the frequency domain [27,28] in order to improve the level of accuracy of the detection and increase the SIL level of the system. The novelty of this approach is the definition of a simple but effective algorithm that can find practical application on real time, low cost and low power systems to be installed onboard. The existing systems or algorithms, which have been analyzed from the literature usually require complex data acquisition systems or a fixed installation on the track. Therefore they are not suitable to cover the entire range of railway vehicles (freight, regional or refurbished passenger trains).

2. Wheel flat detection algorithm

The algorithm used to detect the wheel flat phenomenon is based on the measurement of the vertical acceleration in the axle-box relative to the considered wheel of the vehicle and of the angular position of the wheel. The concept beneath this approach consists in the consideration that a flat portion of the wheel produces a high vertical acceleration at each revolution of the wheel, when the flat surface comes in contact with the rail. The severity of the problem depends on the depth of the flat surface and determines the amplitude of the acceleration, together with the velocity of the vehicle.

Considering a vehicle running at a certain speed V, the time t_c required to the wheel to complete an entire revolution is given by Eq. (1).

$$t_c = \frac{2\pi R}{V} \tag{1}$$

where R is the wheel radius. The acceleration is measured using an accelerometer located in the axle-box and its signal is acquired using a data acquisition system with a specific sampling frequency. Therefore the acceleration measured on the axle-box during a single revolution of the wheel is not known continuously, but it is quantized in a vector, that for the first revolution is given by Eq. (2).

$$\ddot{A}_1 = [\ddot{z}_1, \ddot{z}_2, \ldots, \ddot{z}_{k1}] \tag{2}$$

The dimension of the vector ($k1$), is given by the product of the time t_c times the sampling frequency f_s, rounded to the integer value. Since t_c depends on the vehicle velocity V, while the sampling frequency is constant, the dimension of the vector of the accelerations is in general different for each revolution as shown in Eqs. (3)–(5) for the second, third, and j-th revolution respectively.

$$\ddot{A}_2 = [\ddot{z}_{k1+1}, \ddot{z}_{k1+2}, \ldots, \ddot{z}_{k1+k2}] \tag{3}$$

$$A_3 = [\ddot{z}_{k1+k2+1}, \ddot{z}_{k1+k2+2}, \ldots, \ddot{z}_{k1+k2+k3}] \tag{4}$$

...

$$\ddot{A}_j = \left[\ddot{z}_{\sum_{i=1}^{j-1} ki+1}, \ddot{z}_{\sum_{i=1}^{j-1} ki+1}, \ldots, \ddot{z}_{\sum_{i=1}^{j-1} ki+kj}\right] \tag{5}$$

The dimension of the vector in those cases is given by $k2$ for the second revolution, k_3 for the third and kj for the generic j-th revolution. The angle of rotation of the wheelset is measured using an incremental encoder.

The first element of the angular rotation vector is given by the initial measurement of the angle, θ_0 (6) and must be synchronized with the first measurement of the acceleration.

$$\theta_1 = \theta_0 \tag{6}$$

The angle, measured at the same time of the last element $k1$ of the acceleration vector, is one revolution forward as described in Eq. (7). The angle measured in correspondence of the last element of the j-th acceleration vector (5) is given by Eq. (8).

$$\theta_{k1} = \theta_0 + 2\pi \tag{7}$$

...

$$\theta_{kj} = \theta_0 + 2 \cdot j \cdot \pi \tag{8}$$

In the general case where the vehicle velocity is variable, described by Eqs. (2)–(8), it is rather complex to determine the extent of the wheel flat problem. At first, the acceleration vectors 2–5 need to be resampled to obtain vectors of the same dimension. Then, it is necessary to determine the relation between the vehicle velocity and the acceleration amplitude.

However, considering that the railway vehicle often maintain a constant velocity for long periods of time due to its high inertia, the wheel flat detection algorithm can be conveniently executed during those periods. In case the vehicle runs at a constant velocity $V = V_0$, the Eqs. (2)–(8) are still valid, but all the vectors are of the same length k given by Eq. (9).

$$k1 = k2 = k3 = \cdots = kj = k = f_s \cdot t_c \tag{9}$$