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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).

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

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.

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

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

...

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

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).

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

Table 1
Samples measured inside a wheel section of 30 mm affected by the flat phenomenon at different velocities (grayed: not usable).

Vehicle velocity	20 Km/h	50 Km/h	90 Km/h
fs	Samples inside the section of the wheel affected by the flat problem (L=30 mm)		
250 Hz	1,35	0,54	0,3
500 Hz	2,7	1,08	0,6
1000 Hz	5,4	2,16	1,2

The event of wheel flat could be detected also considering a single revolution of the wheel, in this case only Eq. (2) is required. However, during a single revolution of the wheel also a defect or discontinuity present on the rail can produce an increment in the measured acceleration similar to the one due to a wheel flat and the effective cause cannot be disambiguated. To detect the wheel flat problem it is possible to consider the fact that, at constant speed, its effect is repeated each turn in the same way. The adopted algorithm considers a mean acceleration vector, given by Eq. (10), obtained averaging N subsequent vectors, taken at the same vehicle velocity. The presence of high accelerations due to defects of the track are not repeated with the same period of the wheel revolution, therefore those values are attenuated in the mean vector.

$$\ddot{A}_m = \frac{1}{N}\sum_{j=1}^{N}\ddot{A}_j = [\ddot{z}_{m,1},\ddot{z}_{m,2},\ldots,\ddot{z}_{m,k}] \tag{10}$$

In order to detect the presence and the severity of the wheel flat event, at first the root mean square value of the accelerations of the mean vector (11) is calculated. This value is adopted as a reference of the base acceleration environment due to the presence of irregularities on the considered track.

$$\ddot{A}_{m,rms} = \sqrt{\frac{1}{k}\sum_{i=1}^{k}\ddot{z}_{m,i}^2} \tag{11}$$

The rms value is compared with the maximum value of the mean acceleration vector (12).

$$\ddot{A}_{m,max} = Max_i(|\ddot{z}_{m,i}|) \tag{12}$$

The wheel flat severity index (WFI) is then defined according to Eq. (13), subtracting from the maximum acceleration value the rms value. This index is directly related to the acceleration level produced by the wheel flat and can be adopted to estimate the presence of the flat and its severity. In a very noisy/vibratory environment, such as measurements performed on the vehicle frame a different and more selective index can be used, according to Eq. (13b). This index is obtained dividing the maximum acceleration value by the rms value and it is more effective to detect the presence of wheel flats, but its value is not directly related to the severity of the flat.

$$WFI = \ddot{A}_{m,max} - \ddot{A}_{m,rms} \geqslant 0 \tag{13}$$

$$WFI_M = \frac{\ddot{A}_{m,max}}{\ddot{A}_{m,rms}} - 1 \geqslant 0 \tag{13b}$$

The indexes can be made more sensitive, by considering as a reference the rms value depurated by the effect of the maximum acceleration, according to Eq. (14).

$$\ddot{A}_{m,rms} = \sqrt{\frac{1}{k-1}\sum_{i=1}^{k}\ddot{z}_{m,i}^2 - (\ddot{A}_{m,max})^2} \tag{14}$$

The ability of the method to detect a wheel flat and to exclude other causes can be improved by increasing the value of N in Eq. (10). This strategy meets the only limit due to the duration of the process, and the requirement that the vehicle maintains constant the speed for the required time.

Another important aspect is the selection of an appropriate sampling frequency (f_S) in order to be able to detect the passage of the wheel flat through the acceleration measurement.

The wheel flat can be represented by a chord of the circular tread of the wheel and can be expressed as a function of the angle α, that is the angle of the sector containing the chord, according to Eq. (15). This equation is obtained assuming that the chord approximates the correspondent arc length and it is then suitable for small angles.

$$L = 2\cdot R_0\cdot sin\left(\frac{\alpha}{2}\right) \rightarrow \alpha = 2\cdot arcsin\left(\frac{L}{2\cdot R_0}\right) \tag{15}$$

The length of the wheel flat L is an important parameter, and railway administrations establish a limit of the flat length to allow the circulation of the vehicle. In Italy and most of EU countries, this limit is fixed to 60 mm. The purpose of this work is to define a method able to detect wheel flats lower than the limit, therefore wheel flat of 15/30/60 mm will be considered.

The number of measurements performed during the passage inside the section of the wheel affected by the flat phenomenon (*spf*) can be calculated with the Eq. (16), where ω represents the angular velocity of the considered wheelset and the acronym *spf* stands for sample points for flat.

$$spf = \frac{2\cdot f_S}{\omega}\cdot arcsin\left(\frac{L}{2\cdot R_0}\right) \tag{16}$$

Table 1 shows the measurements acquired during the passage of the wheel flat at different velocities, it is evident that in order to detect the phenomenon the distance between consecutive measuring points must be comparable with the length of the flat on the wheel surface. As a reference at least one measuring sample inside the length of the flat is considered to be necessary in Table 1. The sampling frequency adopted during the test is 1000 Hz, and this theoretically allows to detect wheel flat up to 90 km/h, with better angular accuracy at lower velocities. Of course the use of higher sampling frequency during acquisition (2 kHz or more) improves the detection, especially considering that the behavior of the acceleration during the passage on the wheel flat is related to the interaction with the vehicle and the infrastructure whose mode shapes can be excited and produce dynamic responses at high frequency.

For this reason values in Table 1 must be considered as the minimum values to be adopted for the sampling frequency of the acceleration, then the effective possibility to detect the phenomenon must be proved during an experimental test, where also the dynamic of the system is involved.

This process has been adopted because the aim of this work is the development of a simple algorithm requiring the lowest possible hardware solution for the data acquisition. In particular a monitoring system, already developed for vehicle dynamic measurements (where frequency up to 250 Hz are usually sufficient), is used in this case to detect the presence of wheel flats.

If the measurement is performed at low speed, lower sampling frequency (and low cost data acquisition systems) can be adopted. The main drawback is that at very low speed it is possible that the vehicle does not keep an absolutely constant speed. Fig. 1 shows the algorithm, that has been improved with respect to the Eqs. (1)–(14), in order to be able to manage a variation of the velocity of the vehicle during the test. This is obtained by considering directly the measurement of the angle of the wheel θ_i at each time step. The required resolution of the sensor

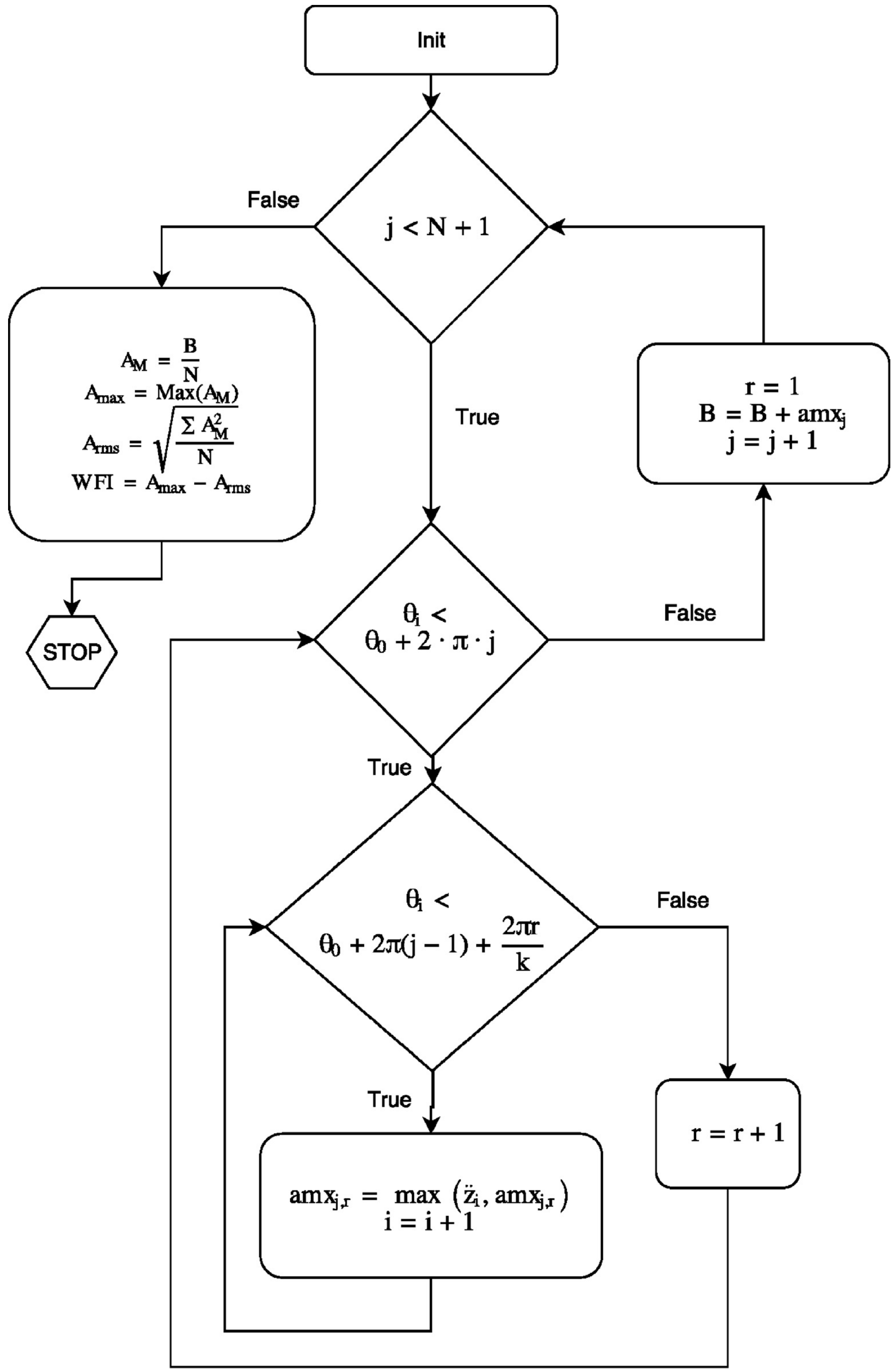

Fig. 1. Wheel flat detection algorithm.

must be adequate to detect the angular position of the wheel at the considered time step. The number of measured angular positions inside the section of the wheel affected by the flat problem of length L (PPF), with an encoder with a resolution of "PPR" pulse per revolution, is given by equation Eq. (17). For the most critical case of Table 1 (20 Km/h, 1000 Hz) at least 512 PPR are required to have the same number of points acquired for the acceleration measurement. During the tests an encoder with 1024 PPR has been used.

$$PPF = \frac{L{\cdot}PPR}{2{\cdot}\pi{\cdot}R_0} \tag{17}$$

3. Experimental tests

The experimental tests have been performed on the test circuit of Velim in the Czech Republic, adopting an unloaded flat freight vehicle

Fig. 2. Vehicle used during the tests, with mounted the monitoring system.

(Res type), with Y25 Bogies. The monitoring system has been installed on one of the bogies and on the vehicle frame, as shown in Fig. 2. On the first wheelset of the instrumented bogie a small flat (15 mm in length) was present.

The tests have been performed considering different vehicle velocities, in particular the cases at 25, 35 and 60 km/h are considered in this paper.

4. Numerical model

In order to understand the behavior of the accelerations and forces due to the presence of wheel flats versus speed and flat length, a numerical model has been developed with a multibody code. The numerical model is based on rigid bodies and concentrated stiffness elements, therefore the response of the system at high frequency, and the excitation of flexible modes of the structures are not considered. It is expected that the numerical model has a stiffer and less damped response with respect to the real case, as shown in the literature [4,7,26] where often the vehicle is considered as a rigid element. The numerical model is only used to understand the effect of the considered parameters on the accelerations, and the obtained results (e.g. Fig. 4) can be expected to differ from real case in terms of frequency (lower in real case) and damping. The damping in the wheel/rail contact has been tuned to achieve similar results respect to the results shown in the analyzed literature.

The numerical model of the vehicle has been realized using Simpack 2017 and the final model is shown in Fig. 3. A single freight car with the same characteristics of the one used in the experimental test has been developed on a discrete flexible track.

The vehicle has been modeled in detail, also considering the non-linear behavior of friction elements in the same way already made by the authors in [33]. The vehicle is modeled in load condition using only rigid bodies: one vehicle frame, two bogie frames, 4 wheelsets and 8 axle-boxes. Only elastic elements have been used to connect the bodies, except the axle-boxes, that have been connected to the corresponding wheelsets using rigid revolute joints.

The track flexibility has been modeled using a discrete model (Simpack native) including only a tie with three degrees of freedom (vertical-lateral and roll) placed under each wheelset.

The data of interest for the vertical dynamic, used in the model, are shown in Table 2. The wheel/rail contact damping has been decreased with respect to the default used by Simpack otherwise the jump on the flat would be immediately damped. The reduction produces a vibration that vanishes after 5–6 peaks as shown in Fig. 4, and in accordance with the results seen in literature [4,7,11,12].

It is evident that the actual value of the overall damping depends from many factors including the real characteristics of the track that is used, in this case the adoption of a less damped environment has been chosen since it is more critical for the algorithm. In fact, in this case the acceleration response is spread over a wider angular portion of the wheel.

The wheel flat has been modeled using the out-of-round modeling capability of the Simpack code, and a set of input function has been generated to describe the five types of flat considered (20/30/45/

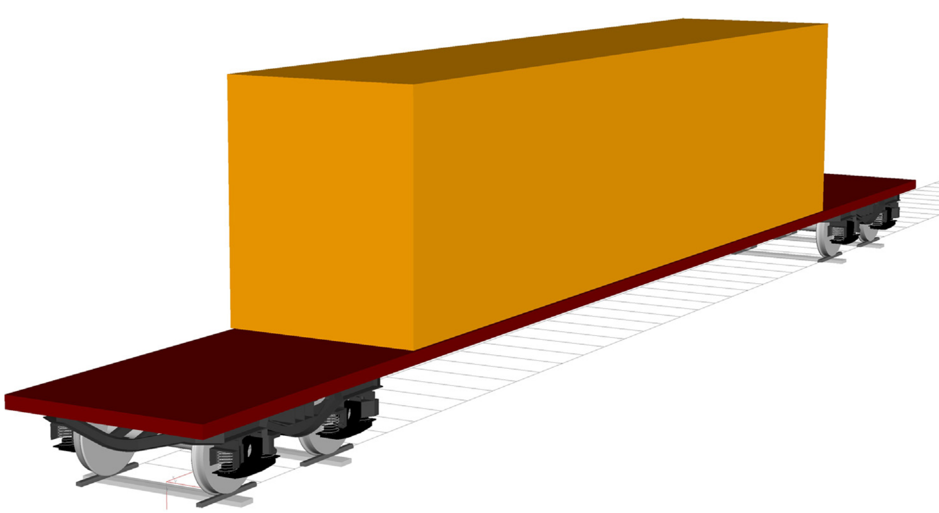

Fig. 3. Vehicle model realized using Simpack 2017.

Table 2
Relevant model data for vertical dynamics.

Parameter	Value	Unit
Tie-Ballast Stiffness	150,000	[kN/m]
Contact Stiffness	According to the non-linear simpack wheel/rail contact model	
Primary suspension Stiffness	300/1210 (per axle-box, tare/load)	[kN/m]
Secondary suspension Stiffness	4600 (center pivot) + 1142 (side-bearers)	[kN/m]
Contact Damping	10	[kNs/m]
Tie-Ballast Damping	188	[kNs/m]
Primary suspension Damping	Non linear, according to the Lenoir Link model with μ = 0.3.	
Secondary suspension Damping	46	[kNs/m]
Vehicle Frame Mass	71,190	[Kg]
Bogie frame Mass	2070	[Kg]
Wheelset Mass	1225	[Kg]
Tie Mass	330	[Kg]
Axleload	20	[ton]

60 mm). Each input function describes the wheel radius as a function of the wheel angle. The flat has been modeled as a theoretical non smoothed flat.

5. Detection of wheel flats

In order to validate the algorithm, it has been applied both to the results of the numerical simulation and to the experimental tests considering different vehicle velocities.

5.1. Numerical simulation

The numerical simulation is useful to compare in similar conditions more flat lengths at a wide range of vehicle velocities. Fig. 4 shows the behavior of the acceleration on the axle-box in the numerical simulation considering different wheel flat lengths (20/30/45 and 60 mm) at 30 km/h.

It can be observed that, in the considered case, where a fresh flat has been realized on the wheel, two positive and negative peaks of acceleration can be observed for each flat passage (at the beginning and end of the defect). The oscillation is then damped in a short time. The maximum and minimum value of acceleration, indicated with “M” and “m” in Fig. 4, have been found for all the simulations performed and the behavior of their absolute maximum values as a function of the velocity and of the flat length is shown in Fig. 5.

The numerical model also allows analyzing the wheel/rail contact forces during the passage on the wheel flat. The maximum and minimum value of the wheel/rail contact force simulated by the code is shown in Fig. 6 as a function of the vehicle velocity, for each of the wheel flat considered.

It can be observed that the maximum force shows a behavior that is similar to that of the maximum acceleration. The minimum value of the contact force shows the event of complete wheel unloading over a certain value of the velocity, depending on the length of the flat. At higher value of the flat length, the wheel unloading occurs earlier.

The simulations, shown in Figs. 4–6, are performed on a perfect track, without irregularities, in order to obtain clean diagrams and to be able to understand the wheel flat phenomenon. In order to apply the wheel flat detection algorithm on the numerical simulations in more realistic conditions, the same simulations have been performed again with the introduction of track irregularities, generated using a power spectral density defined according to the typical European spectrum for large defects (ERRI B176). The wheel flat detection algorithm is then applied to the data obtained from the numerical simulations with irregularities. The results are summarized in Table 3.

The wheel flat detection algorithm has been applied to the data obtained from numerical simulations considering two different vehicle velocities suitable for performing the real tests with good accuracy (15 and 30 km/h). The algorithm has been performed considering 10 revolutions of the wheel (N = 10) and the results are shown in Table 3 for

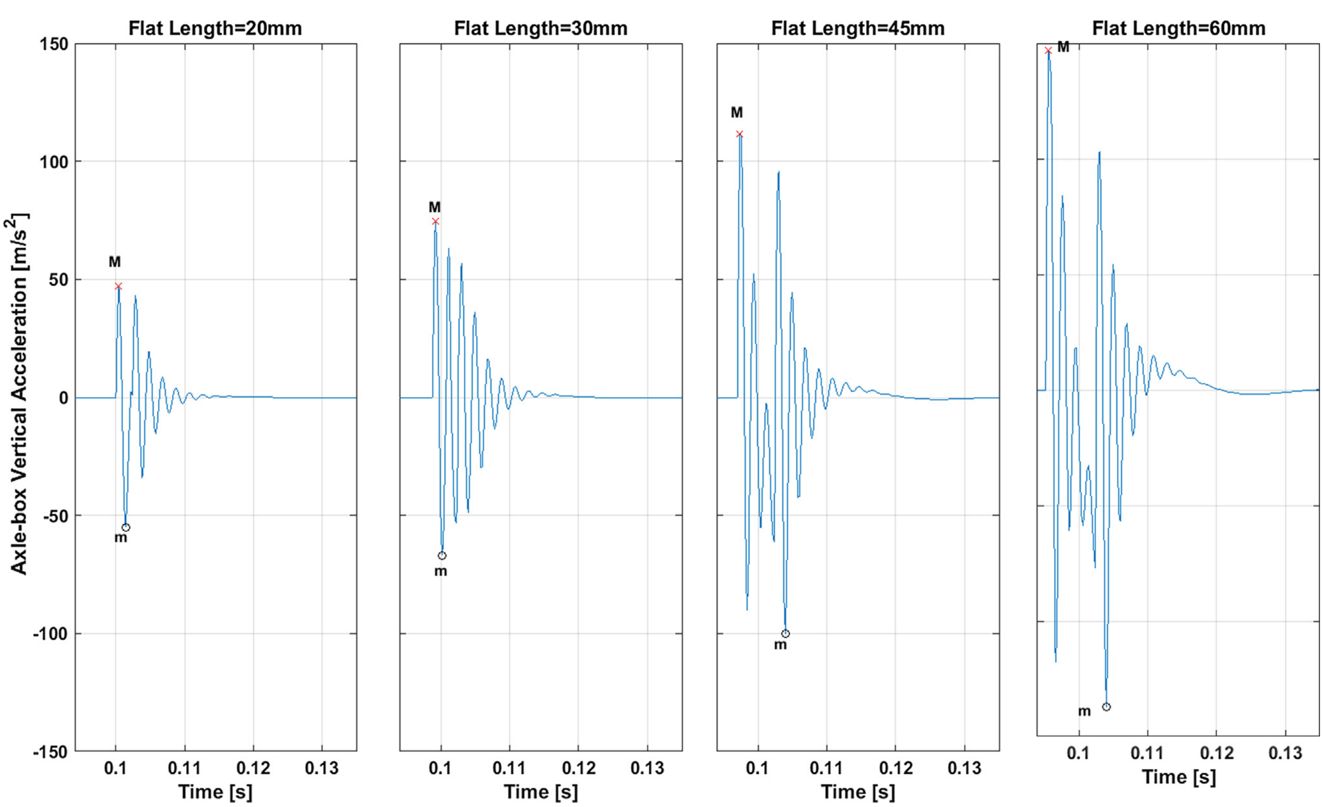

Fig. 4. First passage of the wheel on a flat with different lengths at 30 Km/h.

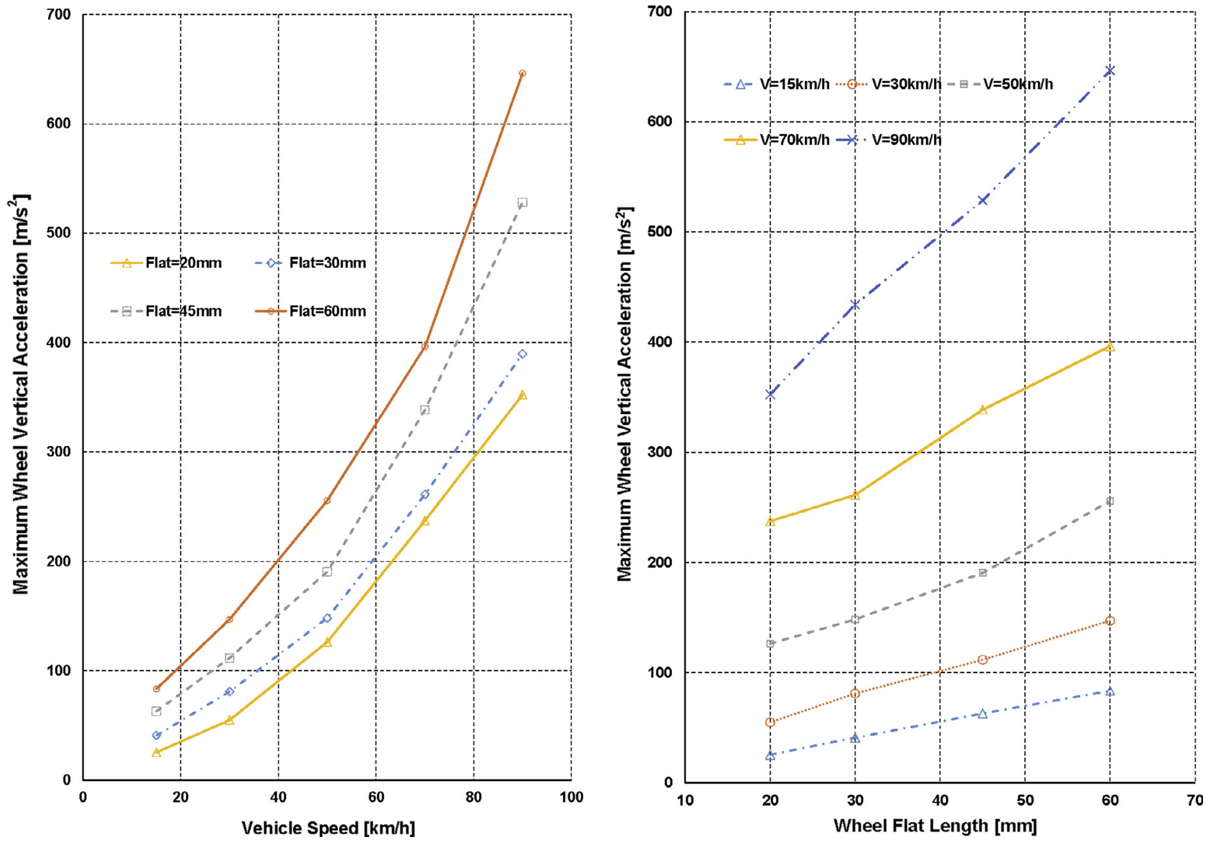

Fig. 5. Maximum value of acceleration during the passage on a wheel flat as a function of the vehicle velocity (left) and of the flat length (right).

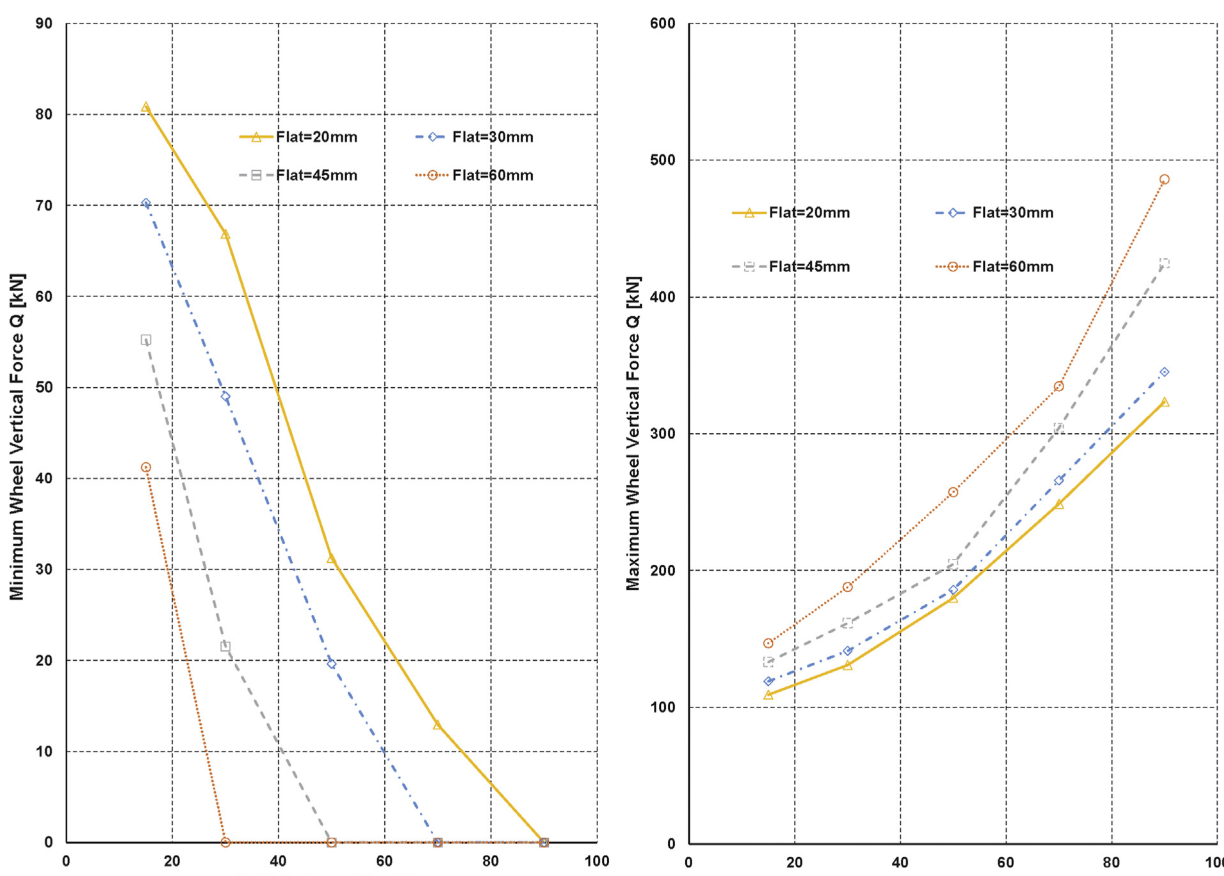

Fig. 6. Minimum (left) and maximum vertical wheel/rail contact force versus velocity for different flat lengths.

Table 3
Wheel flat index calculated from the numerical simulations for different flat lengths and velocities.

Velocity	k[a]	Flat length [mm]				
[Km/h]	[/]	0	20	30	45	60
		WFI (Wheel Flat Index)				
15	60	0,05	16,64	32,15	42,76	67,58
15	30	0,05	16,56	31,88	43,10	67,02
30	60	0,17	21,55	44,49	77,60	116,30
30	30	0,17	34,48	58,16	86,61	118,99

[a] Sectors per revolutions.

different flat lengths, and for a vehicle without flat (flat length = 0). A time step of 1 ms has been used for all the simulations and a k parameter (Eq. (10)) of 30 and 60 has been adopted. The k parameter represents the number of sectors taken for each revolution of the wheel.

The application of the algorithm exhibits an almost linear behavior of the index with the dimension of the wheel flat. The increase of the vehicle velocity leads to an increment of the index as well, therefore the index is coherent with the behavior of the maximum acceleration shown in Fig. 5, and it is suitable to detect the presence of the wheel flat and to estimate its severity, that is linearly related to the value of the index at each considered velocity.

5.2. Experimental test

The algorithm has been also validated considering an experimental campaign on the vehicle described in paragraph 4. On the first wheelset of the vehicle was present a small wheel flat (approximately 15 mm) realized by grinding the wheel surface. The choice to use a small flat is due to the requirement to use the vehicle for several tests without compromising the track, the riding noise and the dynamic behavior. The flat was not recently generated (it was smoothed by the normal running of the vehicle). Therefore this test is suitable to verify the ability of the algorithm to detect small flats.

Fig. 7 shows the acceleration detected on the axle-box, that is

Table 4
Wheel flat index calculated from the experimental tests on the axle-box.

Velocity	k – Sectors per revolutions	WFI (Wheel flat index)	
[Km/h]	[/]	Flat (Wheelset 1)	Noflat (Wheelset 2)
25	30	10,48	0,57
25	60	10,77	0,57
37	30	13,1	0,47
37	60	13,59	0,54

mounted on the wheel with the flat, and on the vehicle frame in correspondence of the bogie centre. The peaks of the flat are clearly visible on the axle-box and they are still present on the vehicle frame, but in this case their value is not much different from the vibration level.

Table 4 shows results obtained by applying the algorithm to the experimental measurements. Two tests are considered, the first at the average velocity of 25 Km/h and the second at 37 Km/h. The index has been calculated on the first wheelset, where the flat was located and on the second wheelset of the same bogie where no flat was present. The flat on the first wheelset produces a vibration on the bogie structure that in small portion can return also on the second wheelset.

In this case it is evident that the index for the second wheelset differs slightly from the base rms level, so no flat is detected. The index calculated on the first wheelset shows an increment with the vehicle velocity and its value is correspondent to a fresh wheel flat of about 7–8 mm, which appears to be reasonable considering that the flat was worn and smoothed.

The application of the wheel flat algorithm considering the acceleration measured on the vehicle frame is less effective, as shown on Table 5. The main problem is that the impulse produced by the flat is reduced by the suspension and the corresponding peak of acceleration is largely reduced and it is difficult to disambiguate from the base vibration level of the bogie for small wheel flats. If the modified wheel flat index WFI_M, defined according to Eq. (13b), is adopted the presence of the wheel flat is more clearly detected (this index, without flat is usually close to 0). Anyway the measurement on the vehicle frame does not allow to understand where the flat is located. Moreover the

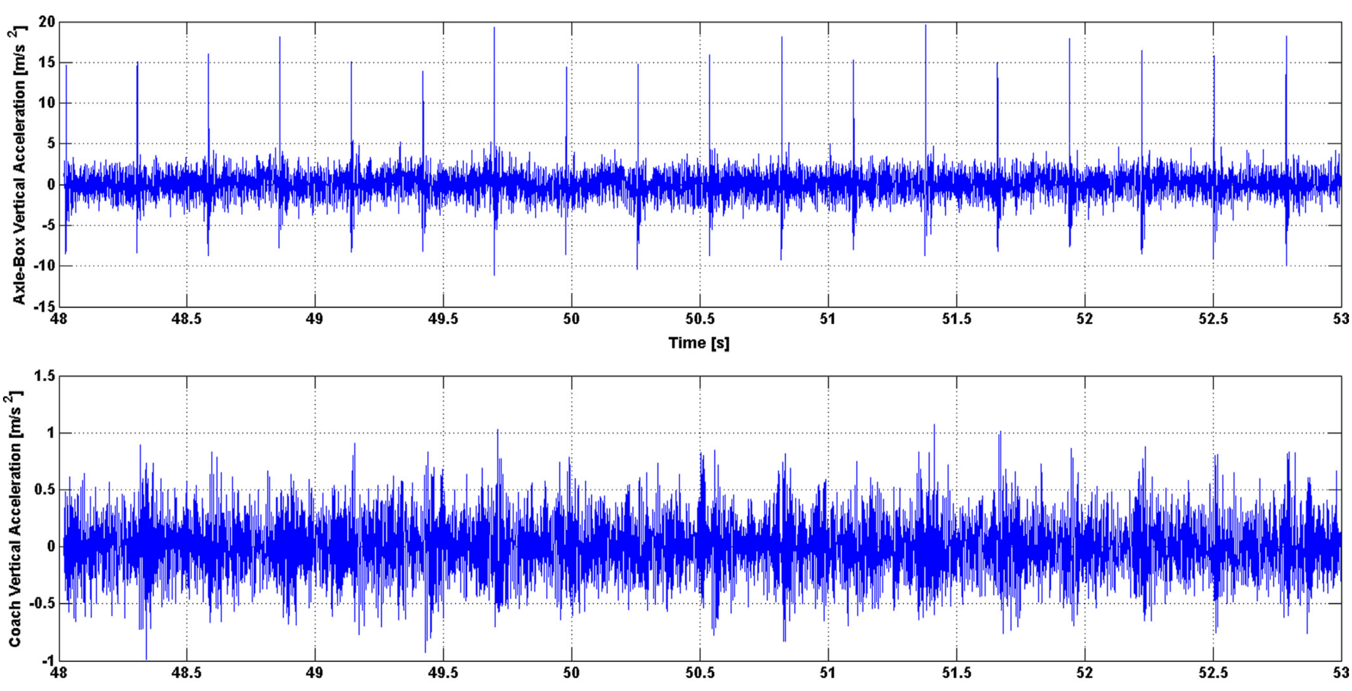

Fig. 7. Acceleration measured on the axle-box and on the vehicle frame at 37 Km/h.

Table 5
Wheel flat index calculated from the experimental tests on the coach.

Velocity	*k* – Sectors per revolutions	WFI (Wheel flat index)	
[Km/h]	[/]	WFI	WFI_M
25	30	0,51	2,11
37	30	0,37	1,09

estimation of the flat severity is much more complex, since the base vibratory level at the vehicle frame is more affected by the track condition, making difficult to relate the value of the index on the coach with the flat length.

In this work, an incremental quadrature encoder was used and it was acquired on demand by a digital counter with the X4 encoding, therefore the value of the angle of the considered wheelset was immediately available. If an angular velocity sensor is used, the angle can be obtained by integration, but the accuracy must be enough to reproduce the angle over at least 10 rotations of the wheelset.

6. Discussion

According to theoretical studies on ideal flats [12,13], the acceleration occurs when the trailing edge of the flat impacts on the rail. The length of the flat has however, also in the theoretical case, a strong influence on the value of the initial acceleration.

The dynamic response depends on the characteristics of the system composed by the vehicle and the track and it is characterized by a damped oscillation. The acceleration detected after a certain number of periods also depends on the initial value of acceleration, and therefore on the flat length. Furthermore, on a real track (with non perfect surface), considering a non-ideal (smoothed) wheel flat, the impact can result as a sum of multiple impacts of lower amplitude, and can appear with a wider duration.

Therefore it is not possible to establish a simple correlation between the defect length (wheel-flat) and the duration of the detectable acceleration signal. In any case it is clear that close to the defect the signal is more intense.

Moreover, since this is a localized phenomenon, it is convenient to associate the presence of the defect to the angular position of the wheel. In this work the wheel has been discretized in angular sectors whose width has been here associated to the size of the defect itself, since this length determines the initial acceleration level and the duration of the detectable response.

The data available in the literature show that in any case the response of the system is generally quite rapid and such to be contained within the considered arc length.

The numerical simulations and the experimental tests carried out have also highlighted the effectiveness of this approach, demonstrating an excellent ability to discriminate the presence of wheel flat even considering the presence of the irregularities of the track and its flexibility.

In fact, the numerical simulations have been carried out considering the presence of track irregularities defined by the typical European spectrum (PSD) corresponding to a line with large defects.

Experimental tests were instead performed on a real track that naturally presents track irregularities and that allows to take into account further environmental effects and non-linearity of the system that cannot be easily predicted using a numerical model.

It is evident that for the application of the proposed method during real operations it is necessary to perform a specific calibration of the algorithm to adapt it to the particular vehicle and line being used. The proposed algorithm is particularly simple to adapt to the specific application by acting on a limited number of parameters that allow to modify its sensitivity (k, N, fs).

7. Conclusions

The work shows an algorithm acting on the time domain to detect wheel flats using accelerations measured on the axle-box. The algorithm has been tested using a multibody numerical model and different type of flats at different velocities. Experimental tests on a real vehicle have been also used to validate the results. The algorithm has demonstrated to be able to detect wheel flats of small dimensions and to measure the severity of the flat with an index which is proportional to the length of the flat. The algorithm is simple enough to be used even on wireless monitoring systems based on low power microcontrollers.

Declarations of interest

None.

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