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On-Line evaluation of structural degradation of train wheels using vibration analysis techniques

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Abstract

The condition of the wheels of a train was evaluated using vibration analysis techniques. The bogies of the train were instrumented with accelerometers. Vibration was sampled on-board both in good and deteriorated condition. Analysis of acquired signals was then performed in order to correlate signal characteristics with wheel defects. The high frequency spectrum showed a significant increase of energy content in the deteriorated condition but could not be directly correlated with wheel flats. The low frequency spectrum of the demodulated acceleration signal was proved to be a suitable transformation that could directly relate wheel flats to signal characteristics producing a spectrum with a characteristic spike at 1 wheel revolution (1X) which is directly related with wheel flat impact on rail.

1. Introduction

Today, rail networks worldwide are getting busier with trains travelling at higher speeds and carrying more passengers and heavier axle loads than ever before. The combination of these factors has put considerable pressure on the existing infrastructure, leading to increased demands in inspection and maintenance of rail assets. The expenditure for inspection and maintenance has thus, grown steadily over the last few years. The immediate key challenges faced by the rail industry are: a) the improvement in the safety of the railway systems, b) the development of new railways to accommodate the continued growth in demand, and c) contributing to a more sustainable railway, in both environmental and financial terms, by delivering further efficiencies and exploiting technological innovation.

Although, severe rail accidents are relatively rare, they do occur. Classification of rail accidents depends on their causative factor, which can be either a human error or equipment failure. A number of all rail accidents are equipment-related, with some of these occurring due to failed train wheelsets. The continuous increase in train operating speeds means that
catastrophic failure of a wheelset may result in very serious derailments, such as the one that took place in Eschede, Germany in 1998. This heavy rail accident caused loss of life, injuries, severe disruption in the operation of the network, damage to the tracks, unnecessary costs, and loss of confidence in rail transport by the general public. In the Eschede accident, a single failed wheel initiated a chain of events that led to the severe derailment of a high-speed train on the route from Munich to Hamburg, causing the death of more than 100 passengers and the severe injury of many others.

The most common wheel defects encountered in the rail industry are wheel flats, shells and cracks. Failure of the wheel due to such defects can be avoided by careful inspection of the wheelsets during maintenance. Nevertheless, the existence of wheel flats and shells alone poses a severe problem to the rail industry. This is due to the fact that these types of wheel defects are known to cause abnormally high forces and stresses on the railway track and on the vehicle components, leading to significant damage on the rail network and reduced operational lifetime for the rail. Depending on the size and shape of the defect, axle load and speed, the stresses may be sufficient to initiate fatigue cracks, or even cause final failure, leading to derailment of the train. In addition to safety and economic considerations, these defects reduce passenger comfort and significantly increase the level of noise produced at the wheel-rail interface. It is believed that locking the wheels during braking causes wheel flats and therefore, they can occur without warning at any time. The flat spot, possibly starting as chord of the wheel circumference, tends to get longer and rounded after a few cycles of wheel rotation. Then the basic flat shape may stay on the wheel tread for a long time and repeatedly generate large impact forces. Wheel shells are mainly developed from micro-cracks, initiated by high strains in the wheel-rail interface due to high axle load and creep forces. Even though the appearances of wheel shells are different from those of wheel flats, the measured irregularity functions are similar and therefore the basic characteristics of the impact loads are analogous. Hence, the damage caused by wheel shells on rails is similar.

The importance of detecting defects in wheelsets as early as possible is therefore of paramount importance for the rail industry in order to reduce maintenance costs and improve safety standards. In this paper the authors report an online methodology based on vibration analysis for the assessment of the condition of the wheels of an in-service passenger train operated by CP on the Cais-do-Sodré and Cascais line in Portugal.

## 2. Experimental Background

CP uses Electric Multiple Units - EMU for passenger suburban services throughout Portugal. The vehicle concerned in this paper (shown in figure 1) consisted of three carriages and had a maximum speed of 90km/h. The wheelsets of the train consist of solid axles and monobloc wheels with a diameter of 850mm. The maximum axle load permitted is 12.5 tonnes. The braking mechanism of the train is based on brake blocks which act directly on the wheels.

This type of vehicles was rehabilitated during the 90s. The refurbished vehicles re-started their commercial service in 2001. Before the refurbishment some wheel problems (mainly spalling) were already known, but after refurbishment these problems became more severe.
As mentioned earlier, braking on this train is achieved by applying the braking pads directly on the wheel tread pneumatically. During the refurbishment the pneumatic brake system was replaced with a new one. A slight rise in braking cylinders pressure values was observed during the operation of the new brake system.

The existing bogies and timonerie were kept and overhauled during refurbishment, with weight pressure valves introduced as a new function of the vehicles. The pressure of the braking cylinders was measured in order to dismiss any anomalous shift made by weight valves. Evaluation of braking pads in motor wheels revealed that their geometry was out of tolerance, and thus, led to incorrect efficiency and dispersion of braking effects. Although this problem was overcome, a new arose in the form of thermal fissures in the outer border of the wheel tread. The synthetic brake pads employed on the vehicle had high dispersion in the friction coefficient values. An investigation was carried out on the thermal effects using thermography during normal operation. As UIC released new types of braking pads to replace the old iron cast ones, tests were carried out with sinterized brake pads that seem to have more uniform and stable friction coefficient.

The train vehicles used for suburban service need to brake often due to the large number of stations they stop at. Therefore the quality of braking is of utmost importance since overheating of the wheels can lead to the development of thermal fissures and spalling.
Vibration analysis is a valuable tool which can be employed online to evaluate the development of damage on the wheels. During the vibration tests reported herewith, a damaged wheelset with visible spalling on the wheels was present on the train employed (figure 2). The remaining wheelsets had been recently turned for reprofiling and were in good condition. Vibration measurements were conducted on both the damaged and good wheelsets as the train moved at 70km/h.

The wheelsets evaluated were instrumented with a commercial Endevco Isotron 7251A-100 accelerometer. The vibration data were acquired using the Test Point software package through a PCMCIA board. The sampling rate was 5kHz with $1 \times 10^6$ number of samples.

The accelerometer was mounted on the axle box using a magnetic base as shown in figure 3. Data were collected during normal vehicle operation. Tests were performed on “good” wheels and “bad” wheels in order to compare the obtained signals.

![Figure 3: Photograph of the accelerometer installation during testing. The accelerometer has been mounted on the axle box of the wheelset concerned.](image)

3. Results

Raw vibration data were collected for both wheels free of defects as well as wheels with surface defects (spalling) present. The average train speed during tests was 19.44m/sec. The diagrams in Figure 4 show the raw vibration signal for wheels in good and deteriorated condition with the train accelerating from complete stance to 19.44 m/s and then back to complete stance for several times. All signals differ from each other thus, does not provide clear condition indication.
Although the raw vibration data differ for the good and bad condition wheels, this is not sufficient to arrive in a safe conclusion regarding the condition of the wheel being tested since the vibration data will differ from wheel to wheel regardless of its actual condition. Moreover, it is also impossible to assess the origin of the defects present on the damaged wheel based on the raw data alone. Therefore further analysis was carried out using customized software produced by Feldman Enterprises.

The diagrams in figure 5 show the high frequency FFT analysis of good (top) and deteriorated (bottom) wheel conditions up to 2.5KHz. Some characteristic resonant frequencies can be seen. The Mean Spectrum Energy of the good condition wheel is approximately 0.0000881 units whilst in the deteriorated wheel condition the Mean Spectrum Energy is 0.00033 units. This is considerably increased as expected thus, showing a problem but does not provide an indication of the fault’s origin. The deteriorated wheel condition also exhibits a considerable increase in energy around the 700 Hz region mostly related to structural resonance.
The diagrams shown in figure 6 show the low frequency spectrum up to 14 wheel revolutions for both the good and deteriorated wheel condition signals. Although, more energy is concentrated in the area around of 1X (where X is 1 wheel revolution) in the deteriorated condition compared to good condition, this analysis fails to clearly highlight the problem.
The diagrams in figure 7 show Low Frequency Spectrum of amplitude modulated vibration signal for both good and deteriorated conditions. The deteriorated condition signal shows clearly the 1X, 2X up to almost 8X harmonics of wheel speed whilst in the good condition signal these harmonics are not present. Thus, this analysis clearly identifies wheel faults and a clear separation between good and deteriorated condition has been achieved and is directly related to wheel problems since they appear as multiple harmonics of wheel speed. Results of this analysis can be directly related to physics of fault formation and thus, clearly identify the origin of the fault. According to traditional vibration analysis charts, this pattern resembles to imbalance and looseness. In this application this effect is caused by several wheel surface defects impacting on the rail with a periodicity of 1 wheel revolution, causing the axle to move similar as having imbalance and looseness.

![Figure 7: Demodulated low frequency FFT for a) good and b) deteriorated wheel condition.](image)

The deteriorated condition signal shows clearly the 1X, 2X up to almost 8X harmonics of wheel speed whilst in the good condition signal these harmonics are not present.

The diagrams in figure 8 show a truncated part of initial good wheel condition entire signal of raw vibration (a) and demodulated spectrum (b). The diagrams in figure 9 show the same thing for the deteriorated wheel condition. The appearance of 1X harmonic in the deteriorated wheel condition is evident but it is clearly absent in the good condition. This is indicative of wheel surface problems related to wheel revolution thus, showing the 1X harmonic.
Figure 8: a) Raw vibration and b) demodulated low frequency FFT of raw signal for good wheel condition. 1X is not evident in the good wheel condition.
4. Conclusions

Vibration analysis is a useful online tool for the evaluation of train wheels. From the tests and analysis carried out herewith it is concluded that amplitude modulated signals give a clear indication of fault presence when the low frequency power spectrum is calculated. Characteristic harmonics at a point do not resemble to those well defined in traditional vibration analysis [1] used in rotating machinery as pumps, compressors, gearboxes etc. thus, an experimental database of faults in train monitoring applications will significantly improve system ability to distinguish fault origin.

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6. References
