Advanced wayside condition monitoring of rolling stock wheelsets

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Abstract

The use of wayside monitoring for the detection of serious faults in rolling stock is of paramount importance for rail infrastructure managers as it contributes to the safety of rail operations. In this paper we report on the key results that have arisen from the development and implementation of a novel integrated wayside condition monitoring system based on high-frequency acoustic emission and vibration analysis which can be interfaced with existing wayside systems such as hot boxes and wheel impact load detectors. The novel system makes use of inexpensive and robust acoustic emission sensors and accelerometers which can be easily installed on the rail track with minimal intervention involved. Experimental work carried out under actual conditions in Long Marston test rail track has proven that the developed system is capable of detecting wheel and axle bearing related defects with various levels of severity.

Keywords: railway, train, axle bearing, wayside, fault detection, acoustic emission, vibration, signal analysis

1. Introduction

The increasing demand for faster and safer rail transport requires reliable passenger and freight rolling stock. While in service railway wheelsets operate continuously under adverse loading and environmental conditions involving rolling contact fatigue, accidental impacts, exposure to thermal variations and humidity. Gradual deterioration of the structural integrity of the wheels and axle bearings can cause excessive noise and vibration reducing passenger comfort and lead to higher contact stresses in the wheel-rail interface [1]. Furthermore, wheelset faults may result in delays and increase the risk of failure involving unnecessary costs and derailments (e.g. the Rickerscote accident, UK in 1996 and Eschede accident, Germany in 1998) [2-4].

Train wheelsets consist of three main components, the wheels, the axle and the bearings. A large proportion of all equipment related accidents in the rail industry is due to failed axle bearings, wheels and axles. To avoid catastrophic failure, wheelsets are inspected at regular intervals in order to detect the presence of defects or faults. Effective wheelset inspection requires its removal from the bogie train at regular maintenance intervals. However, since wheelset defects can develop in-service and evolve very rapidly the rail industry has invested heavily in the online monitoring of wheelsets to minimise the likelihood of a catastrophic derailment [5].

Various wayside condition monitoring systems are used in the railway industry for diagnosing faults in rolling stock so as to reduce delays, damage to infrastructure, serious accidents and unnecessary costs. Existing wayside monitoring systems make use of different types of sensors such as strain gauges, infrared cameras, lasers, acoustic arrays, etc. The data generated from these specialised wayside systems provide information regarding the condition of the wheel, axle bearing and bogie. However, such systems are expensive, prone
to false alarms and many of them are able to detect serious faults only just before final catastrophic failure occurs.

The profound value of wayside monitoring in helping safeguard the reliability of rolling stock operations is undeniable. However, despite significant investments by the rail industry in this sector, wayside monitoring efficiency and reliability have not reached the desired level. Axle bearing, wheel and bogie suspension faults still remain a significant problem which needs to be addressed as traffic density, train speeds and axle loads continue to increase in rail networks around the world [6].

A recent study published by DNV as part of the D-RAIL FP7 project considered the railway accidents that have been reported in 23 countries over the past years [7]. It was revealed that out of the 700 accidents considered, 36% of them were due to rolling stock faults (figure 1). Moreover, 84% of all rolling stock-related accidents were confirmed to have been caused by wheelset and bogie defects (figure 2).

![Figure 1: Railway accidents considered in the D-RAIL FP7 project by cause [7].](image1)

![Figure 2: Rolling stock related accidents by cause [7].](image2)

According to the findings of the D-RAIL FP7 project, 41% of all rolling stock accidents were due to axle failure which in the vast majority was caused by a faulty bearing. Almost 60% of all rolling stock accidents were due to wheelset failure, thus accounting for one in five of all railway accidents considered in the study.
If a wheelset defect is not detected promptly, it will gradually become more severe, leading to more serious damage to other important rolling stock components as well as the rail track [8]. Early detection of faults helps rolling stock operators to schedule maintenance activities more efficiently without compromising the minimum required fleet availability. Poor maintenance scheduling can lead to reduced number of available trains, which in some extreme cases can cause disruption of normal train services giving rise to significant fines.

2. Wayside monitoring

A wayside monitoring system is typically installed in or next to the track to detect and identify deterioration of wheelset components before failure can occur by measuring one or more parameters. Wayside monitoring technologies can be classified as reactive or predictive [9]. Reactive systems detect actual faults on the vehicles. In most cases the information from these systems is not suitable for trending, but is of importance to protect the equipment from further damage due to the fault. Examples of reactive systems are Hot Axle Box Detectors (HABDs) and Wheel Impact Load Detectors (WILDs). HABDs (see figure 3) apply infrared sensors to detect overheating bearings and stuck brakes. WILDs are able to detect flats, metal build-up and shelling in the wheel tread by measuring the loads sustained by the rail as rolling stock goes over. A reactive-based system reports only after critical thresholds are exceeded and thus they are not optimal for long-term observation.

![Figure 3: A Hot Axle Box Detector installed on the Portuguese rail network (REFER).](image)

Predictive wheelset condition monitoring systems such as Wheel Profile Detectors (WPDs) are designed to inspect and identify worn wheels on passing trains by using non-contact sensors, such high-speed cameras and lasers. WPD data analysis can provide useful wheel profile parameters, such as flange height/slope, tread hollow, wheel width and wheel diameter. Tread condition detectors are capable to detect discontinuities in the running surface of the wheel, such as surface-breaking and subsurface cracks [9]. Increased level of vibration, noise and temperature produced by the axle bearing is a sign of a developing defect. Trackside Acoustic Array Detectors (TAADs) use arrays of microphone to record the noise produced by the bearing (see figure 4). TAADs are capable of detecting the acoustic signature of early bearing defects using spectral analysis and data trending.

The maximum operational frequency range of the microphones used in trackside acoustic arrays is normally 20-40 kHz. At this operating frequency the microphones are affected by surrounding environmental noises as well as noises from the measured train itself. Noises
from the wheel-rail interface and the train engine can contaminate the signal acquired by the acoustic array resulting in false alarms or missed faults.

![Figure 4: A RailBAM trackside acoustic array detector installed on the British rail network near London. The photograph is courtesy of SIEMENS.](image)

In this paper we report the development of an integrated acoustic emission and vibration analysis system for onboard and wayside evaluation of axle bearings and wheels. The results from the analysis of acoustic emission and vibration measurements carried out on actual freight wagons with artificially damaged axle bearings at the Long Marston test track, UK are discussed. From the acquired data and subsequent analysis it is evident that acoustic emission has the capability of detecting faulty axle bearings at various stages of evolution, well before they cause final failure of the bearing.

3. Experimental Methodology

A customised integrated AE and vibration analysis system has been under development over the last two years in collaboration with Krestos Limited. The AE/Vibration analysis system consists of the following components: a) R50A resonant acoustic emission sensors manufactured by Physical Acoustics Corporation (PAC), b) 25kHz high frequency accelerometers with sensitivity 100mV/g manufactured by Wilcoxon, c) pre-amplifiers manufactured by PAC, d) digital amplifiers manufactured by Krestos, e) accelerometer power supply manufactured by Krestos, f) four-channel decoupling hub manufactured by Krestos, g) 2531A Agilent four-channel data acquisition card with a maximum sampling rate of 2 MS/s in single channel mode and h) Amplicon industrial computer with customised data logging and analysis software. An automatic triggering system based on optical sensors has also been developed and used for monitoring the speed of the test train.

In order to evaluate the capability of AE and vibration analysis in detecting and quantifying the severity of wheel and axle bearing defects tests were carried out at the Long Marston rail track using tanker freight rolling stock made available by VTG Rail. The tests were carried out using rolling stock on which defects were artificially induced in some of the wheels and axle bearings. All defects were induced only from one side of the wheelsets with the other side kept defect-free for comparison purposes. Onboard measurements were also carried out for the axle bearings of the rolling stock used in tests in order to confirm their condition prior to wayside testing.

Three different types of faults were artificially induced in a number of axle bearings during tests in Long Marston: a) sand and water jetting to simulate debris and severe lubricant
contamination, b) roller defects of different magnitudes (2, 4 and 8mm deep, signifying mild, moderate and severe defects respectively) induced using a power tool and c) outer race defects of different magnitudes (2, 4 and 8mm deep, signifying mild, moderate and severe defects respectively) induced using a power tool. Wheel flats were induced on the tread of wheels of interest using a high-speed grinding disc. The photographs in figure 5 shows the hardware used during wayside testing.
AE sensors and accelerometers were mounted using magnetic hold-downs. The area where the sensors were mounted was slightly ground to improve contact. Vaseline was used to couple the AE sensors on the surface of the rail web (wayside) or axle bearing casing (onboard). The acquisition system during testing was triggered manually. AE channels were sampled at 500 kS/s and vibration channels at 25 kS/s for 12 or 24s.

The reason for selecting a relatively low sampling rate for vibration is because the top useful frequency of the accelerometers is limited to 5 kHz since mounting has been done using a magnet rather than glue or thread. The simplified schematic in figure 6 shows the sensor installation and data acquisition architecture during testing.
During testing different test configurations were used which comprised from only one engine (shunter) and one wagon up to one engine and four wagons. The speed at which both onboard and wayside tests were carried out was moderately low, restricted at 24 km/h. Tests were carried out by running the test rolling stock back and forth over the instrumented section for a few hundred meters. This means that in some tests the engine was in front, pulling the wagons while in others the engine is in the back pushing the wagons. It should be noted that the only motorised wheelsets were those of the engine. The test track in the section were tests were carried out was jointed with concrete sleepers. The fact that the test track was jointed rather than welded does contribute to some unwanted noise and vibration being recorded during measurements. For that reason sensors were placed as nearly to the centre as possible between the joints. Moreover, the sensors were installed above a sleeper in order to minimise the effect caused by the bending of the rail as the rolling stock travelled above it. The data acquired by AE sensors is suitably amplified using the PAC pre-amplifier and Krestos amplifier.

In the tests reported herewith the test train consists of an engine and 4 tanker wagons. The first two wagons have bearing faults all from one side whilst the other side is free of defects for comparison purpose. The last 2 wagons are completely healthy and not concerned for the test. The schematic in figure 20 shows the overall experimental configuration in this case. All bearing defects in first two wagons are induced artificially using mechanical means in roller and race of the bearing, each with different severity with 2mm, 4mm and 8mm defects. A 1mm flat is induced on a wheel on the defect-free side after several runs. The schematic of the test vehicle is provided with all defects listed.

4. Results
Some typical results of bearing defects are listed below from onboard measurements. These tests have been carried out to verify the actual presence of the defects artificially induced and their severity as well as to confirm that the axle bearings considered to be in good condition are indeed so. Furthermore, onboard tests were carried out to confirm the overall capability of the AE sensors and accelerometers under a less challenging experimental configuration than wayside since the signal source is much closer to the location of the sensors. The top plot in
Figure 7 shows the onboard raw AE measurement of a healthy bearing carried out at a speed of 24 km/h. The bottom plot is the moving RMS of the signal filtered using a time window of 60 µs.

Figure 7: Raw AE data acquired from a healthy bearing (top plot) and its moving RMS plot using a filtering time window of 60 µs (bottom plot).

Figure 8 shows the onboard AE measurement for a 4mm roller defect which was artificially induced using a power tool.
Figure 8: Raw AE data acquired from a bearing with a 4 mm roller defect (top) and RMS processed results (bottom). Notice the amplitude of the strong RMS peaks.

Figure 9 presents the raw AE data and moving RMS from an 8mm roller defect. Note the increasing amplitude of the RMS signal indicating a higher severity.

Figure 9: Raw AE data acquired from a bearing with a 8 mm roller defect (top) and RMS processed results (bottom). Notice the amplitude of the strong RMS peaks which is much higher than the RMS for the 4mm roller.

Figure 10 shows the raw AE data and moving RMS acquired from a bearing with an 8mm race bearing defect. It is noticeable that the raw AE response varies significantly from measurement to measurement but the RMS provides a consistent analysis method for
evaluation the severity of the defects. It is also independent of the gain used for amplification as long as the signal is not saturated.

![Graph showing raw data and moving RMS processed results](image)

Figure 10: Raw data of 8 mm race defect (top) and moving RMS processed results (bottom).

Following the onboard assessment of the axle bearings of the test wagons, wayside measurements were carried out. It should be noticed at this point that the impact of defective bearings recorded by the wayside system does not necessarily happen at the exact location of the sensor.

This actually varies in one rotation of the specific wheel. Given that the diameter of the wheel is 0.93 m and the train speed is around 24 km/h, the spike of the impact may be located within several seconds from the position of the sensor. In some cases, two impacts generated by the same defect can be recorded by the sensor.

This is the method of timing to locate the defects and identify the defect either as bearing defect or wheel flat. A comparison between defective and healthy side from the same wagon is provided.

It can clearly show that the AE not only can effectively detect the bearing defects, but also shows the severity. The detection of bearing defects is then validated by windowed FFT for the presence of the resonance frequency of the AE sensor. Figure 11 shows the results for the healthy and defective sites revealing the presence of three roller bearing defects. The race defects have not been detected in this run although they were equally detectable during the onboard measurements.
Figure 11: RMS results of defective side (top); RMS results of healthy side (bottom). Note that the raw data are from different runs as the tests were not carried out on both rails at the same time. The movement of the train for the top plot is with the engine in the back whilst in the bottom it is with engine in the front.

Vibration results are shown below for the detection of wheel flat. The results clearly show that wheel flat is recorded by vibration. The smaller spike which detected after the larger one can be the second impact of the wheel flat as it is at 0.4 s.
Another example is presented with two vibration sensors applied next to each other, called Channel 1 and 2. The results in figure 12 show good consistency between the two accelerometers. The fact that the amplitude of the spike from Channel 2 is larger indicates that the impact was closer to this sensor. The smaller peak at around 6.5s is a previous impact. Timing or larger number of accelerometers can be a solution to generally locate the wheel flat. This is an important parameter which needs to be accurately determined if the severity of the flat is also to be ascertained accurately. Thus although detection may appear straightforward, meaningful results will require to ascertain the severity of the flat.

Figure 12: Moving RMS from two acceleration sensors detecting a wheel flat during a single run. The flat is no deeper than 1mm.
5. Conclusions
It is obvious that existing wayside monitoring technology involves high costs and has several limitations which need to be addressed in the foreseeable future. From the experiments carried out in Long Marston in collaboration with Krestos Limited, VTG Rail, Motorail Logistics and Network Rail it has been found that by integrating high-frequency acoustic emission data with vibration data wheel and axle bearing defects can be classified and potentially evaluated in terms of their severity as long as an appropriate signal analysis methodology is used. It is evident that the signal difference between healthy bearing and damaged bearings containing relatively mild fault is significant. This means that with relatively simple analysis methods such as RMS the axle bearing defect can be easily identified. Further analysis can enable the type of the defect to be also ascertained. Moving RMS provides a sound methodology for assessing the severity of the axle bearing defects and potentially wheel flats. Comparison of the severity of the defects is only possible when the speed of the train is similar between measurements.

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