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Online condition monitoring of rolling stock wheels and axle bearings

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Abstract
The early detection of faults in rolling stock wheels and axle bearings 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 condition monitoring system based on high-frequency acoustic emission and vibration analysis installed onboard. The novel system makes use of inexpensive and robust acoustic emission sensors and accelerometers which can easily be installed on the axle bearing box with minimal intervention required. Experimental work carried out under actual conditions in Long Marston rail track and on Lisbon – Cas-Cais suburban line has proven that the developed system is capable of detecting wheel and axle bearing related defects with various levels of severity.

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, humidity and natural wear. Gradual deterioration of the structural integrity of the wheels and axle bearings can cause excessive noise and vibration reducing passenger comfort whilst resulting in higher contact stresses in the wheel-rail interface [1]. Wheel and axle bearing faults can cause delays and increase the risk of failure involving unnecessary costs and derailments (e.g. the Summit tunnel, UK, 1984 and Rickerscote accident, UK in 1996) [2-4]. The derailment and subsequent fire in the Summit tunnel resulted in the closure of the rail line for 8 months until the damage had been repaired.

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 [5]. 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 train bogie at appropriate maintenance intervals. However, since wheel and axle bearing defects can develop in-service and evolve very rapidly the rail industry has invested heavily in wayside monitoring to minimise the likelihood of a catastrophic derailment [6].

Various wayside 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 sensors, lasers, acoustic arrays, etc. The data generated

from these specialised wayside systems provide information regarding the condition of the wheels, axle bearings and bogie suspension. However, such systems are expensive and prone to false alarms. Moreover, some of them, such as hot axle box detectors, are able to detect 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 [7]. 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.

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 [5]. It was revealed that out of the 700 accidents considered, 37% 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-related defects (figure 2).
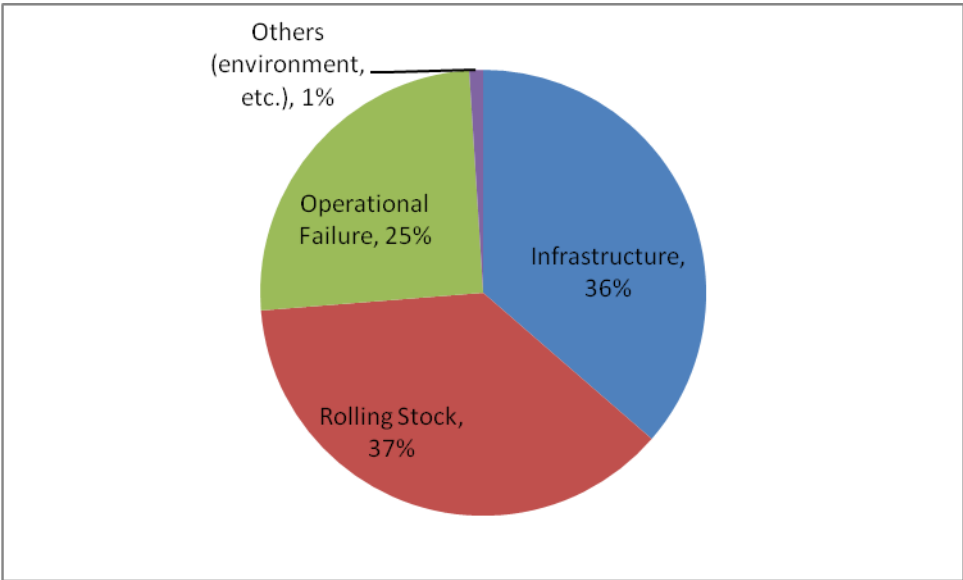

Figure 1: Railway accidents considered in the D-RAIL FP7 project by cause [taken from reference 5].
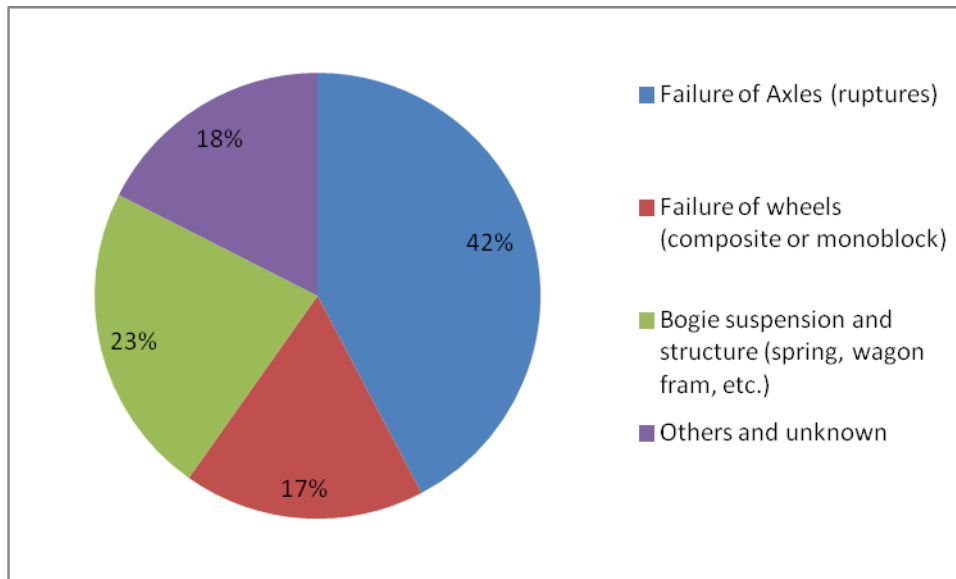
Figure 2: Rolling stock related accidents by cause [taken from reference 5].

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 wheel or axle bearing 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 wheel and axle bearings before failure can occur by measuring one or more parameters. Wayside monitoring technologies depending on their nature 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 such as the one shown in figure 3 employ 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 the instrumented rail track section. Reactive-based systems raise an alarm only after the critical threshold set has been exceeded and thus they are not appropriate for historical trending. However, it is possible to use reactive systems to follow a particular wheelset during a single run as the rolling stock of interest passes from each check-point.

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

A failed axle bearing for example, will gradually start getting hotter as the rolling stock continues to travel through the rail network. Although it may not immediately trigger an alarm at the first or second or even third HABD installed along the track, it may be possible to trend the temperature for each axle bearing as it passes through each checkpoint. The rising temperature trend detected by a series of HABDs may be sufficient for the signalling engineers to alert the train driver of the existence of a potential axle bearing fault.

Predictive wheel 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. An example of TAADs is shown in figure 4. TAADs are capable of detecting the acoustic signature of early bearing defects using spectral analysis and data trending [10].The maximum operational frequency range of the microphones used in trackside acoustic arrays is normally 22-44 kHz. At this operating frequency range the microphones can be 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 possibly 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).

In this paper we report the development of an integrated acoustic emission and vibration analysis system for onboard evaluation of axle bearings and wheels which can be rapidly installed and removed from the train tested using magnetic hold-downs. The results from two independent sets of experiments carried out involving passenger and freight rolling stock in Portugal and the UK respectively are presented and discussed.

The first set of experiments were carried out on tanker freight wagons with artificial damage induced on several axle bearings. The test wagons are shown in figure 5a. Testing took place in the Long Marston rail track, UK. 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.

The second set of experiments were carried out on the Portuguese Rail Network managed by REFER on an Electric Multiple Unit (EMU) operated by Comboios de Portugal (CP) for suburban passenger services on the line between Lisbon City Centre and Cas-Cais. The test vehicle concerned in this paper is shown in figure 5b. It comprises of three carriages and operates at a maximum speed of 90 km/h. One of the wheels of the EMU considered in this study has developed shelling on the tread naturally during normal operation shown in figure 6. Vibration measurements carried out during a normal operational run from Cas-Cais to Lisbon showed that the tread defect could easily be detected and evaluated using appropriate signal processing.

a)   b)

Figure 5: a) Tanker freight wagons with several axle bearings artificially damaged in the roller or race using a power tool, b) EMU with one defective wheel (tread shelling) used for experiments in Portugal.

Figure 6: Photographs showing shelling on the tread of the damaged wheel of the EMU tested.

3. Experimental Methodology

A customised integrated AE and vibration analysis system under development over the last two years was employed for the evaluation of various types of axle bearing defects including lubricant contamination, roller and race defects of different severity. Tests were carried out in Long Marston using freight rolling stock supplied by VTG Rail as shown in figure 7. All roller and race defects were artificially induced using a suitable power tool. Surface wear of different magnitude was caused in each case. In Long Marston test wagon No.1, three of the axle bearings had roller defects of different magnitude induced. In Long Marston test wagon No.2 three of the axle bearings had race defects of different magnitude induced. All defects were induced from the same side of the wagon with the other side kept defect free for comparison purposes. All axle bearings considered in the study were of the tapered type.

The customized 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 developed by the authors. The AE sensors and accelerometers were mounted using magnetic hold-downs as shown in figure 8a.

Figure 7: The customised data acquisition equipment used during trials in Long Marston.

For the tests carried out in Portugal different hardware was employed for measuring the acceleration of the axle box. A 10 kHz Endevco Istron 7251A-100 accelerometer was used instead which was installed on the axle boxes of interest with a threaded mounting plate as shown in figure 8b. Vibration data were logged using the Test Point software package through a PCMCIA board. A sampling rate of 5 kS/s was used. Nonetheless, data analysis was carried out using the same customised software as for the Long Marston tests.

The main purpose of the onboard tests in Long Marston was to evaluate the capability of the customised AE and vibration analysis system in detecting and potentially quantifying the severity of axle bearing defects. The sensitivity of the system to the different sizes of the defects was also a key part of the assessment during the tests in Long Marston. Further work will focus in evaluating the type of the axle bearing defect detected using spectral analysis.

The pre-amplifiers used employ plug-in filters in order to optimise unwanted noise rejection. A band pass filter of 100kHz to 1.2 MHz has been used in this case. Thus any frequencies below 100kHz are filtered out. The R50a sensor is a piezoelectric sensor which has an operational frequency of 100kHz to 700kHz. R50a is ideal for testing in environments with high levels of mechanical noise producing low frequency signals that need to be rejected in the measurement. The resonant frequency of interest in these tests is approximately at 164kHz. According to the Nyquist-Shannon sampling theorem, the sampling rate should be at least twice the maximum frequency component of the signal of interest [11]. In other words,

the maximum frequency of the input signal should be less than or equal to half of the sampling rate. By sampling at 500kSamples/s oversampling is achieved thus aliaising near the original low Nyquist frequency can be removed during signal processing using a digital filter such as Fast Fourier Transform (FFT).

Onboard AE and acceleration measurements were carried out in order to confirm the condition of the healthy and defective axle bearings while the tankers were pushed or pulled using a shunter over a straight section of rail track for 500 meters at a speed of 24 km/h.

In Long Marston test wagon No. 1, roller defects of different magnitudes 2, 4 and 8 mm deep, signifying mild, moderate and severe defects respectively were induced using a power tool. In Long Marston test wagon No. 2 outer race defects 2, 4 and 8mm deep, signifying mild, moderate and severe defects respectively were also induced using a power tool.
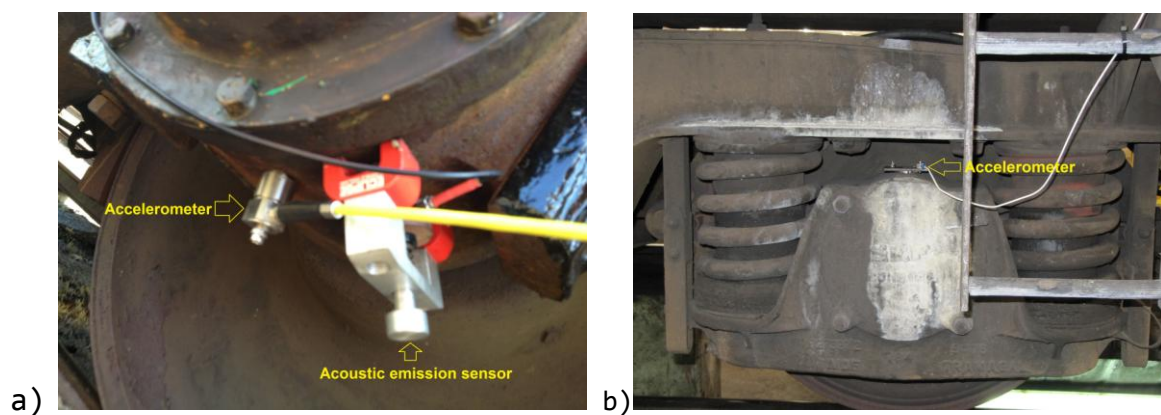

Figure 8: a) AE sensor and accelerometer installed in one of the axle bearing of the tanker freight wagons tested in Long Marston, UK and b) accelerometer installed in one of the two wheels of the EMU tested in Cas-Cais, Portugal.

AE sensors and accelerometers were mounted using magnetic hold-downs. The area were the sensors were mounted was slightly ground to improve contact. Vaseline was used to couple the AE sensors on the surface of the axle bearing casing in order to maximize the transmissibility of ultrasonic waves produced from axle bearing to the piezoelectric sensing element. 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.

During the experiments in Portugal a relatively low sampling rate (5 kS/s) was used to assess the condition of the tread of one healthy and one defective wheel due to the prolonged duration of the measurement (1200 seconds or 20 minutes). The main reasons of these measurements were two-fold. Firstly, to assess the level of vibration and its effect on passenger comfort during the entire run of the line served and secondly to assess whether the defect could be successfully and reliably detected. Testing took place during normal runs from Cas – Cais to Lisbon City Centre and vice versa.

4. Results

Some typical results of bearing defects are listed below from onboard measurements carried out in Long Marston. These tests have been carried out to verify the actual presence of the artificially induced defects and their severity as well as to confirm that the axle bearings considered to be in good condition are indeed healthy. The plot in figure 9a shows the onboard raw AE measurement of a healthy bearing carried out at a speed of 24 km/h. The plot in figure 9b is the normalised moving RMS of the signal filtered using a time window of 60 μs. It is evident that the AE signal contains very little noise. This is manifested also in the RMS plot of the raw signal where peaks below 100 arbitrary units are seen.
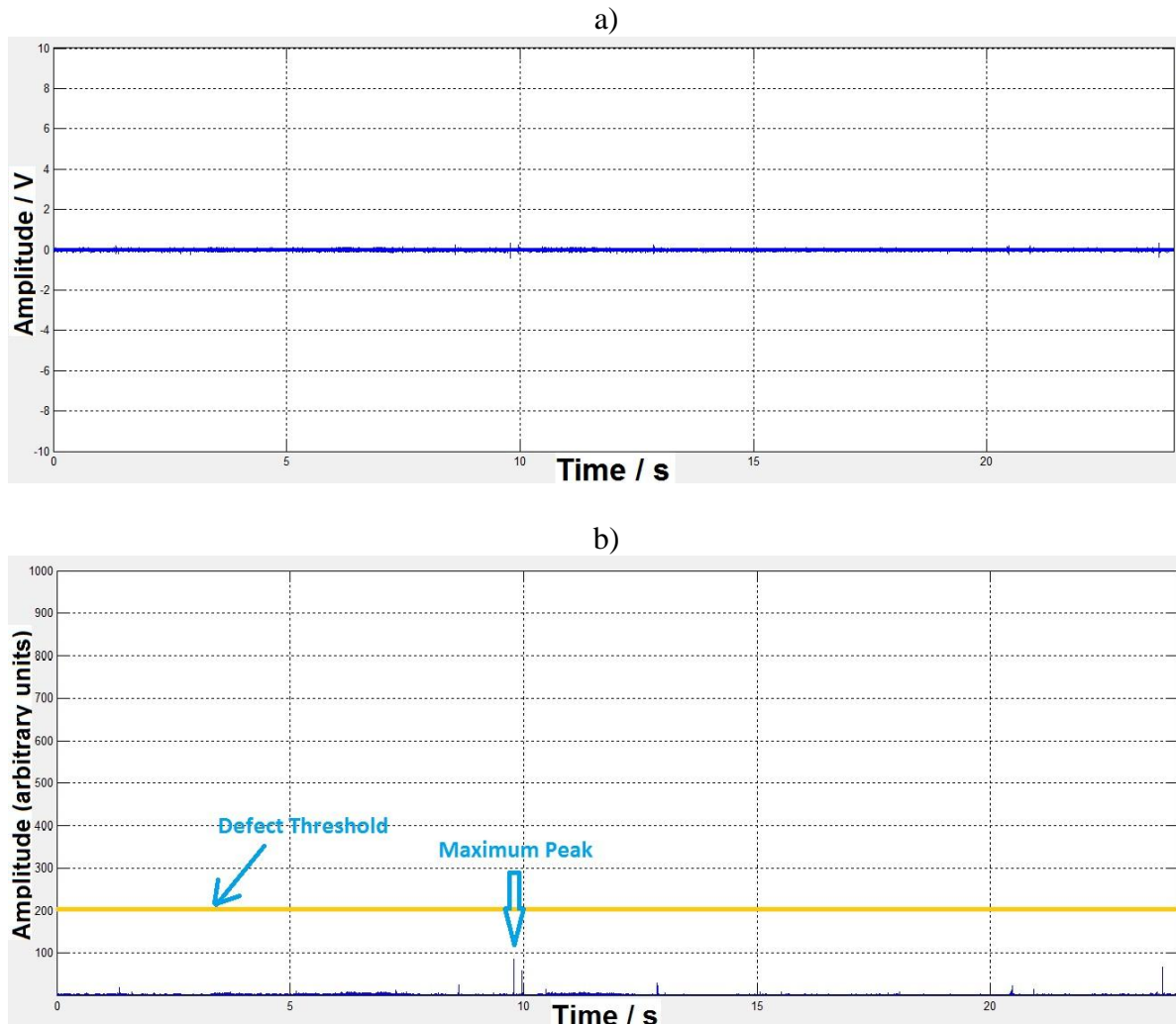
a)

b)

Figure 9: a) Raw AE data acquired from a healthy bearing and b) its moving RMS plot using a filtering time window of 60 μs.

Figure 10a shows the onboard AE measurement for a 4 mm roller defect which was artificially induced using a power tool. The signal appears to be slightly noisier than the healthy one. The peaks seen in the raw AE dataset correspond to the impact of the defective roller as the bearing rotates. By converting the raw data to normalised moving RMS we can see that a number of peaks are evident in the plot, some of which exceed significantly 200 units indicating the presence of a defect. Peaks no more than 200 units have been determined after the analysis of several tests in the field and laboratory to be associated with noise rather than actual defects. The highest peak for the 4 mm roller defect has maximum RMS

amplitude of 2000 units, well above the predefined threshold. The variability in the resulting moving RMS maximum peak per location should be taken into consideration. Although in the raw dataset amplitude variations seem to be smaller the energy of the impact is not the same and depends on the speed of the train as well as the quality of the rail track and the wheel. The more the bearing is loaded as it rotates the more energy will be released.
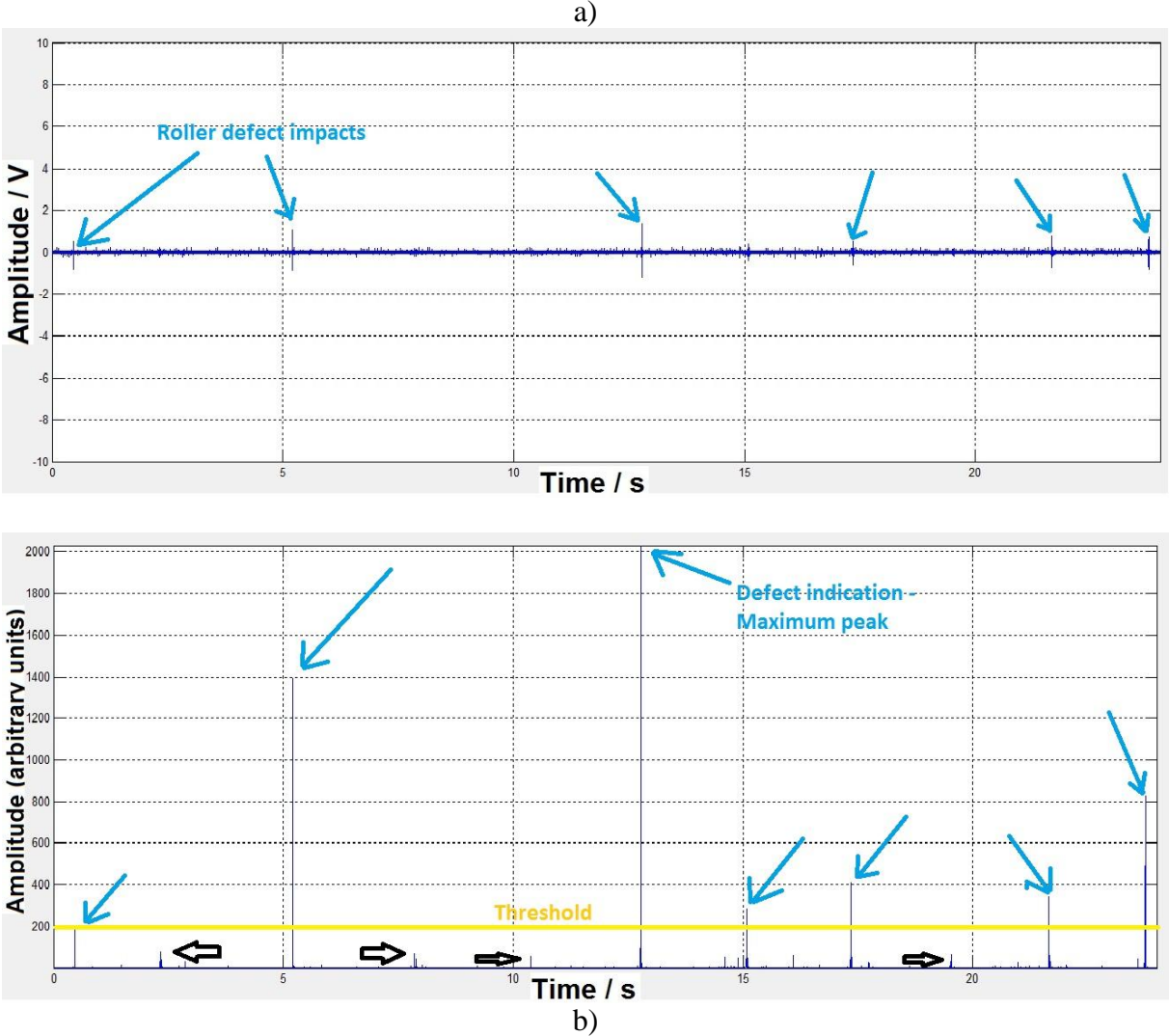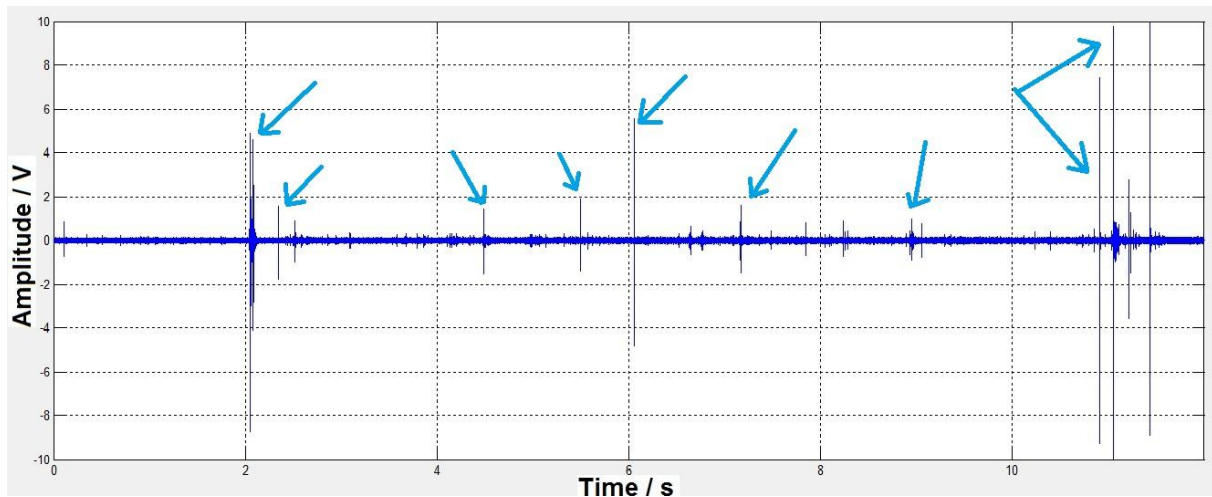
a)

b)

Figure 10: a) Raw AE data acquired from a bearing with a 4 mm roller defect and b) RMS processed results. Notice the amplitude of the strong RMS peaks.

Figure 11a presents the raw AE data and 11b the moving RMS from an 8mm roller defect. Note the increasing maximum peak amplitude (~5100 arbitrary units) of the RMS signal indicating the higher severity. However, the variability in each axle bearing rotation remains with some of the peaks falling even below the threshold limit despite the much higher amplitudes recorded in the raw signal. This is another indication that the amplitude is not sufficient indicator and the energy the signal carries need to be considered. Also in order to safely assess the severity of the signal we need to trend the maxima from several measurements in order to reach a reliable conclusion.
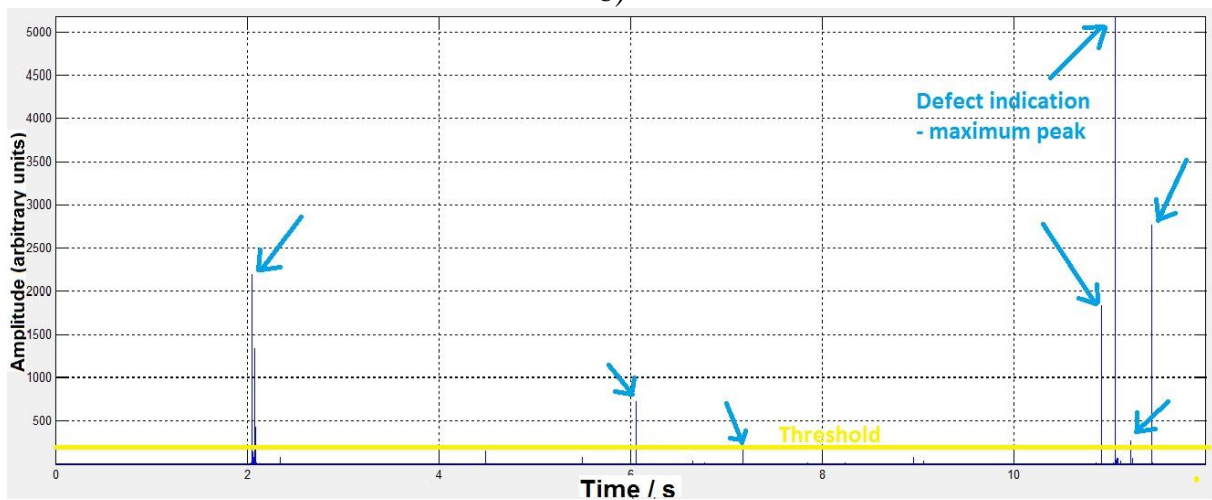
a)

b)

Figure 11: a) Raw AE data acquired from a bearing with a 8 mm roller defect and b) RMS processed results. Notice the amplitude of the strong RMS peaks which is much higher than the RMS for the 4mm roller.

Figure 12a shows the raw AE data and 12b the moving RMS acquired from a bearing with an 8 mm race bearing defect. It is noticeable that the raw AE amplitude varies significantly from measurement to measurement but the moving RMS provides a consistent analysis method for evaluating the severity of the defects provided that the maxima are trended and compared.
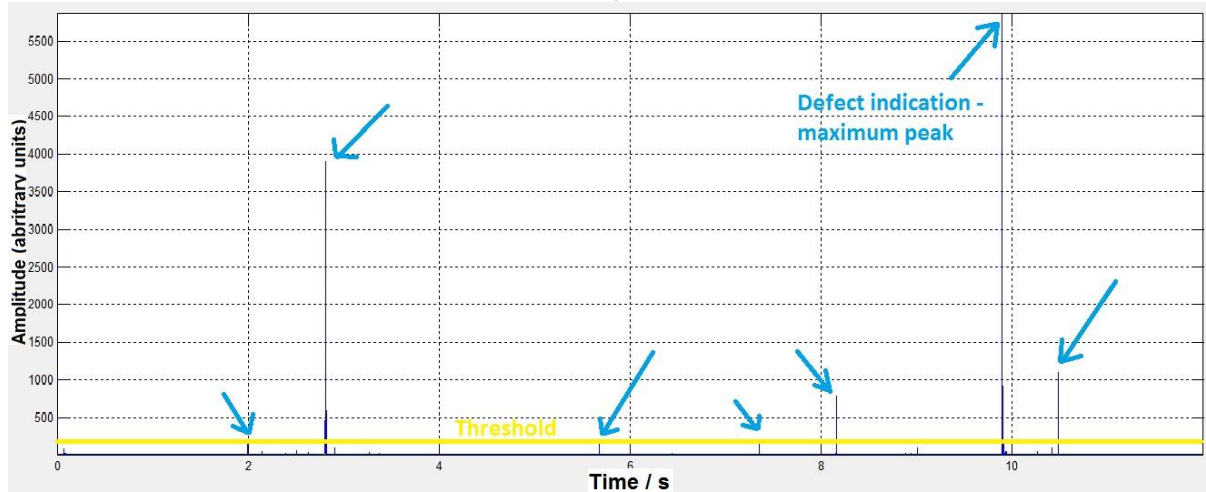
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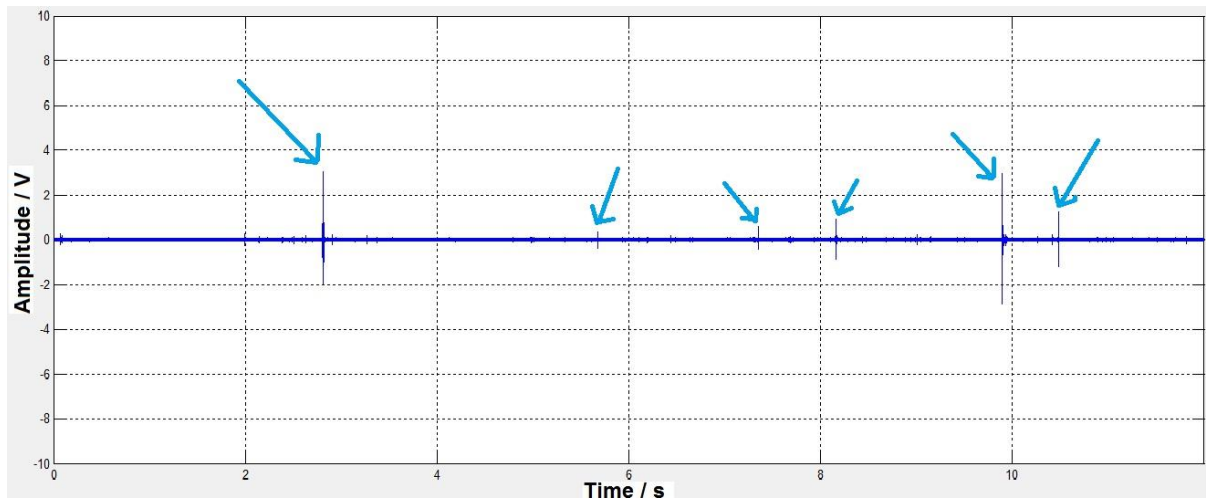
b)

Figure 12: a) Raw data of 8 mm race defect and b) moving RMS processed results.

The results for the various AE measurements are tabulated in the following table 1.

Defect type	Defect size in mm	Maximum raw AE signal amplitude in Volts	Maximum Moving RMS peak in arbitrary units
No defect	-	0.25	90
Roller	4	1.7	2000
Roller	8	9.8	5600
Race	8	3	5850

Figure 13a shows the raw vibration response for a healthy bearing and 13b for the axle bearing containing a 2 mm roller defect. The raw acceleration appears to be a bit more noisier for the defective axle bearing. However, it is not possible to arrive into safe conclusions by just looking into the raw measurements.
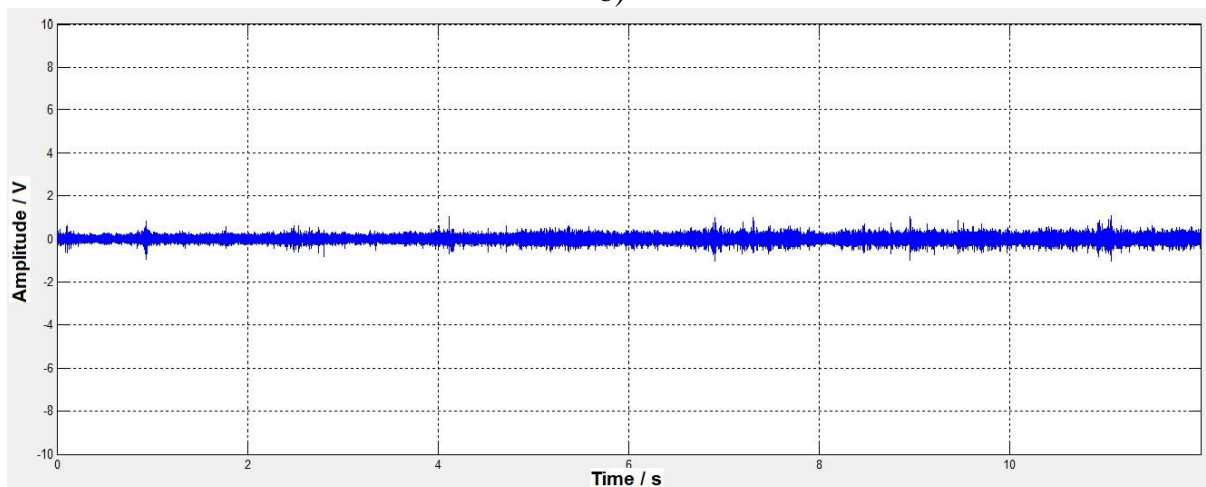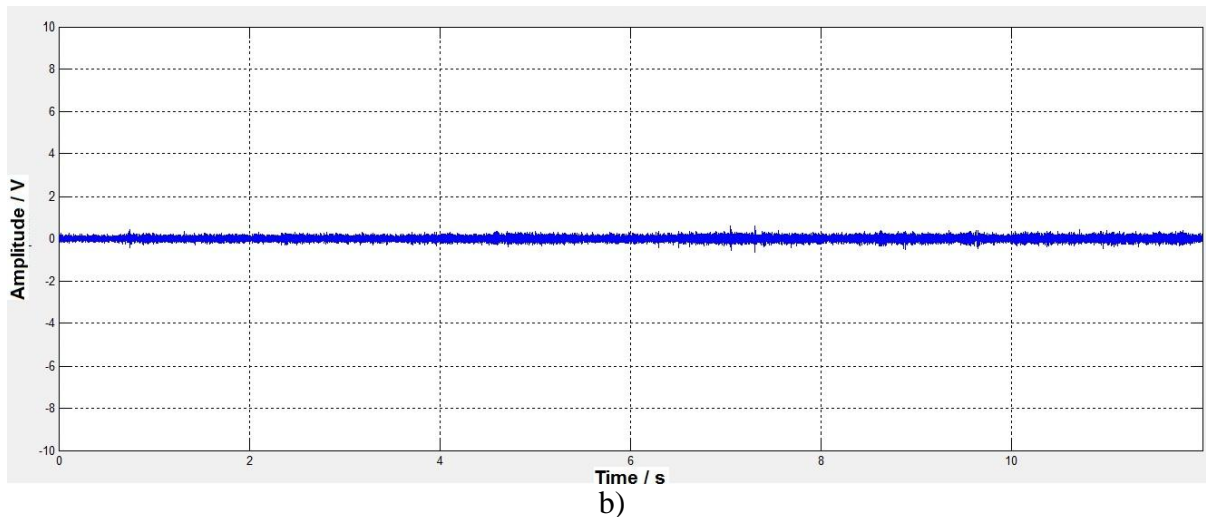
a)

b)

Figure 13: a) Raw acceleration for a healthy axle bearing and b) raw acceleration for an axle bearing containing a 2mm roller defect.

By converting the time-domain signal into frequency-domain using Fast Fourier Transform (FFT) it is evident that for the faulty axle bearing a considerably strong peak appears in the power spectrum plot in figure 14b at approximately 3800 Hz. This peak also exists in the healthy axle bearing power spectrum in figure 14a but its magnitude is significantly lower. The repeated measurements carried out on both axle bearings indicated the persistence of the strong peak at 3900 Hz in the power spectrum of the signal for the defective axle bearing. This suggests that the significant increase in the 3800 Hz peak is likely to be associated with the roller defect present. However, it is not possible to evaluate the severity of the defect using the vibration measurements and through this analysis it is only possible to qualitatively evaluate the possible presence of a problem in the axle bearing under evaluation.
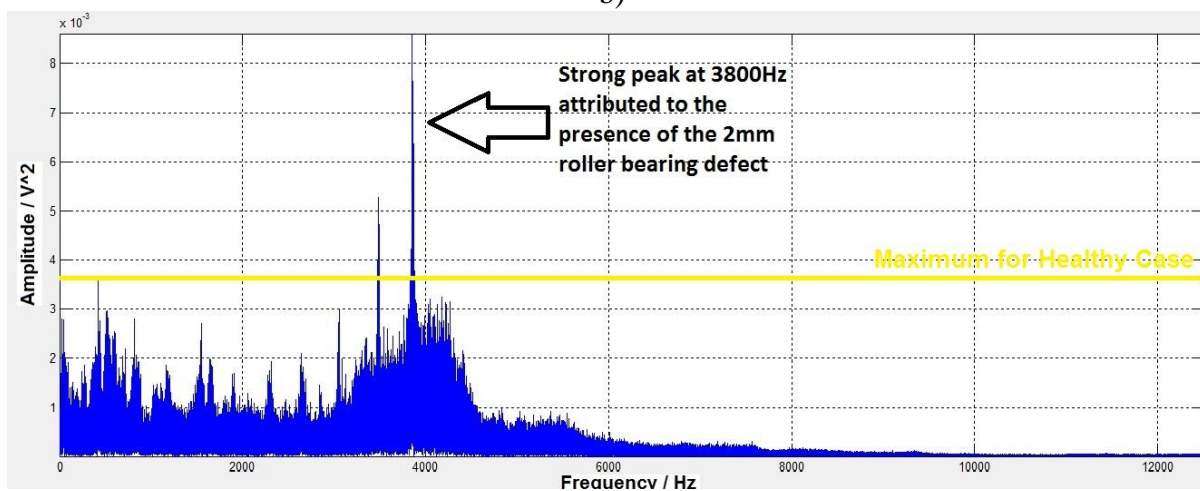
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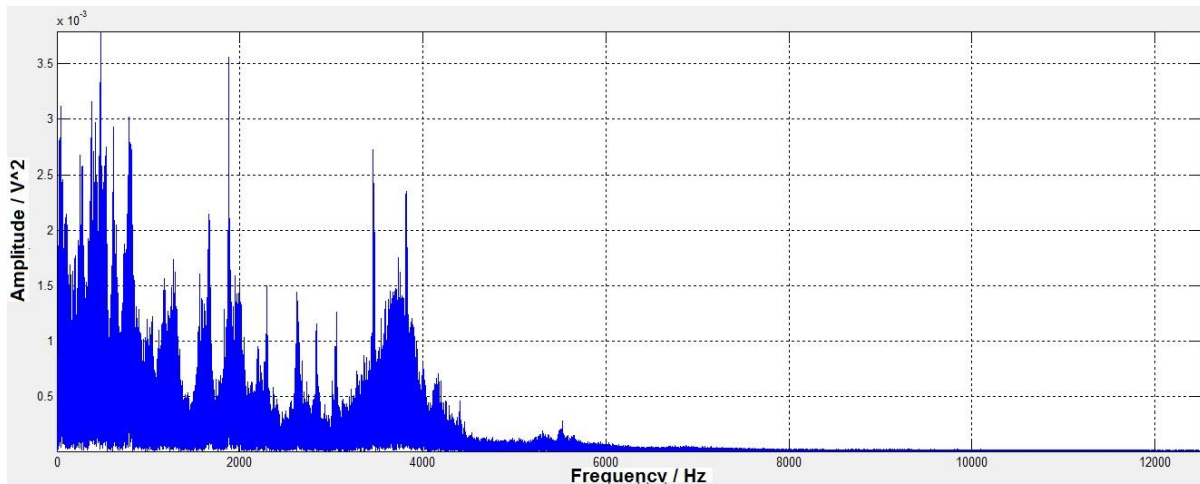
b)

Figure 14: a) Power spectrum of the healthy axle bearing and b) power spectrum of the faulty axle bearing containing a 2 mm roller defect.

During the EMU trials in Portugal, acceleration measurements were collected for a wheel free of defects and a defective wheel containing shelling on the tread surface. The average train speed during tests was 75 km/h or 20.70 m/sec. The plot in figure 15a shows the raw vibration signal for the healthy wheel and 15b for the wheel in the deteriorated condition. Although the raw vibration plots generally differ in each wheel condition, it is not sufficient to arrive in a safe conclusion since the vibration data will differ from wheel to wheel regardless of their actual condition. It is crucial to be able to identify from the vibration measurements the origin of the fault. A flat or spalling should give different pattern from a bearing defect. Approaches based on peak to peak levels alone should be considered more dependable on the measurement conditions as load, speed, wheel profile quality and rail track quality.

Thus it is impossible to assess the severity of the defects present on the damaged wheel based on the raw data alone. For this reason further analysis was carried out using moving RMS, spectral analysis (FFT) of the raw signal and spectral analysis of the demodulated signal (FFT of the envelope of the signal).
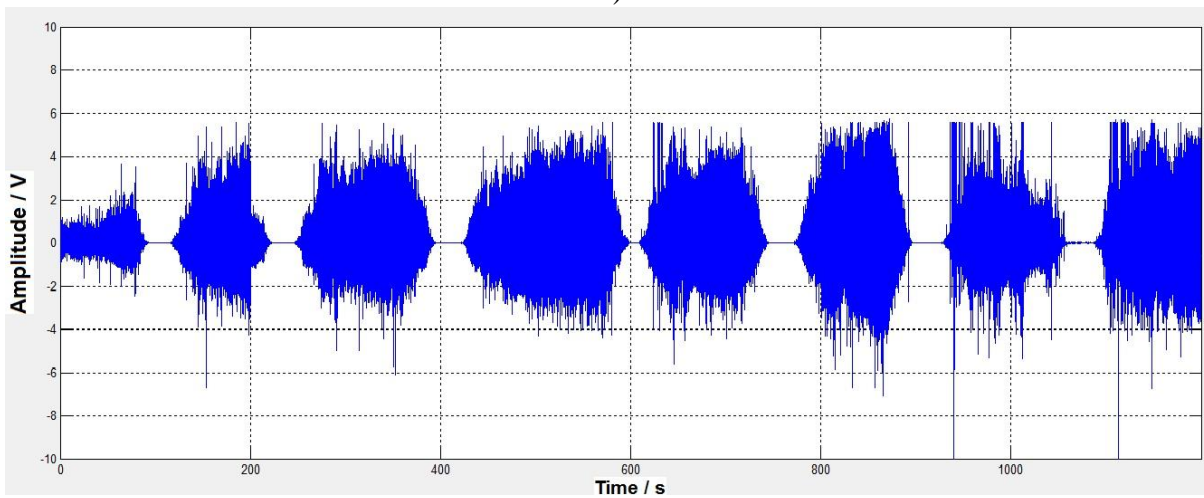
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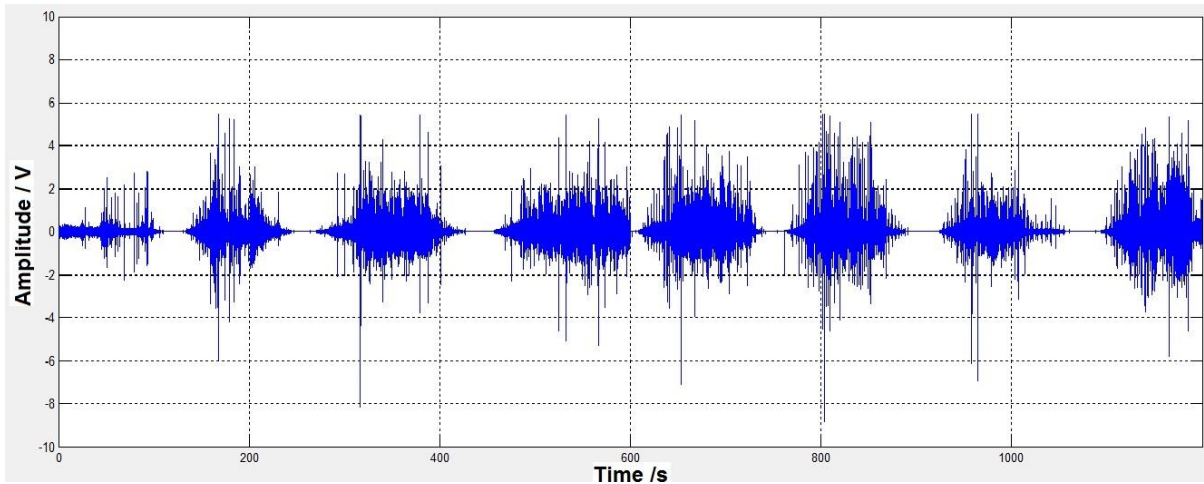
b)

Figure 15: a) Raw vibration data for healthy wheel and b) raw vibration data for defective wheel.

Figure 16 shows the power spectra for the healthy (16a) and defective wheel (16b). A new significant peak is evident at approximately 1600 Hz in the power spectrum for the defective wheel which is not present in the power spectrum of the healthy bearing. Furthermore, the peaks at approximately 700 Hz and 900 Hz are much stronger in the power spectrum of the defective bearing in comparison to the one for the healthy bearing indicating a potential problem as expected which indeed indicates the presence of a problem but does not provide an indication of the fault's origin.
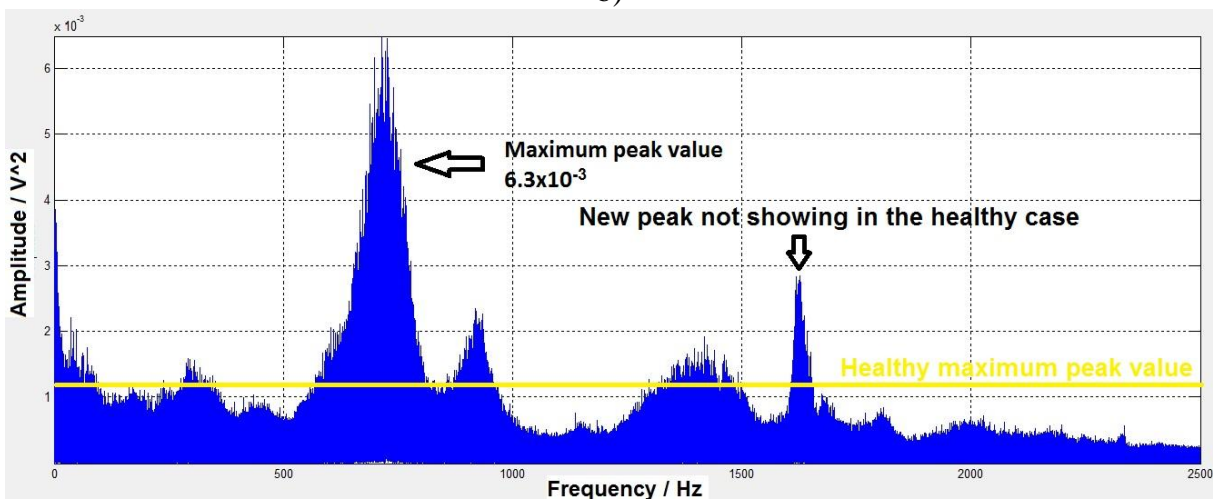
a)
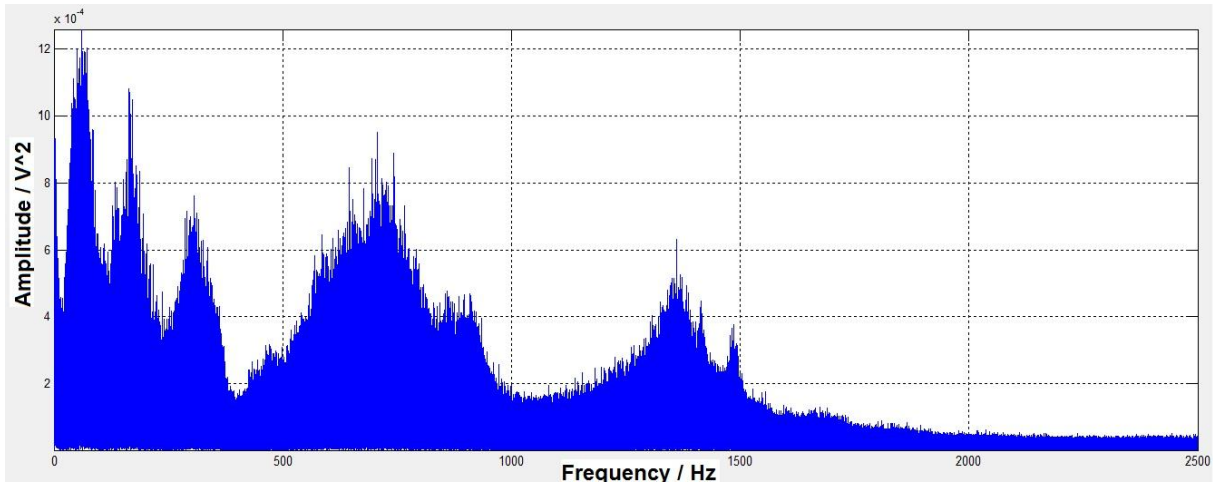
b)

Figure 16: a) Vibration power spectrum for the healthy wheel and b) vibration power spectrum for the defective wheel.

The plots in figure 17 show the moving RMS of the raw vibration signal for the healthy (17a) and defective wheel (17b). Although in the case of the defective wheel the moving RMS is far more noisier due to the vibrations caused by the defective tread area of the damaged wheel than the moving RMS of the healthy wheel it is not possible to ascertain safely the defect and its nature. More in depth analysis is required.
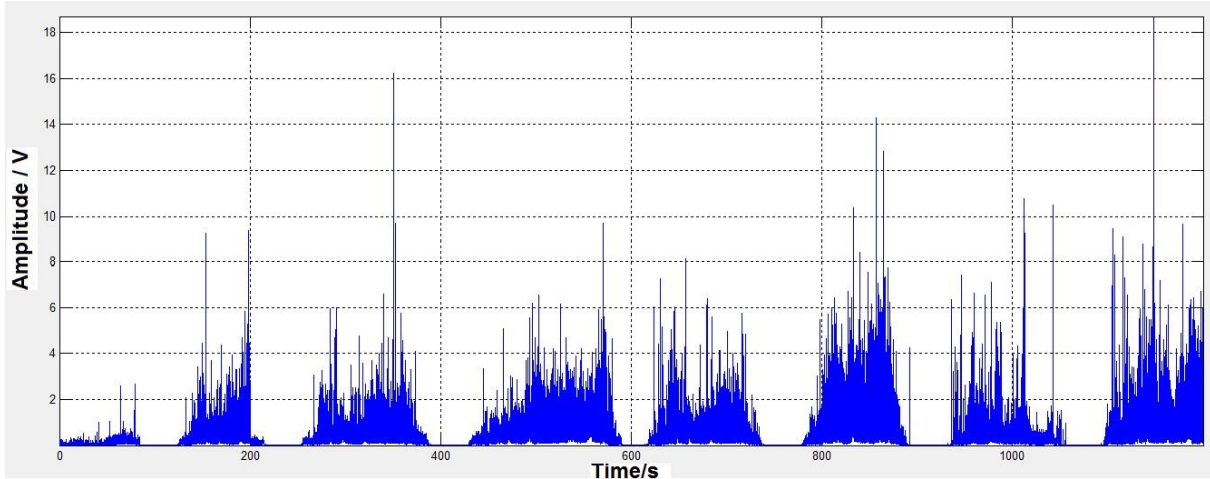
a)
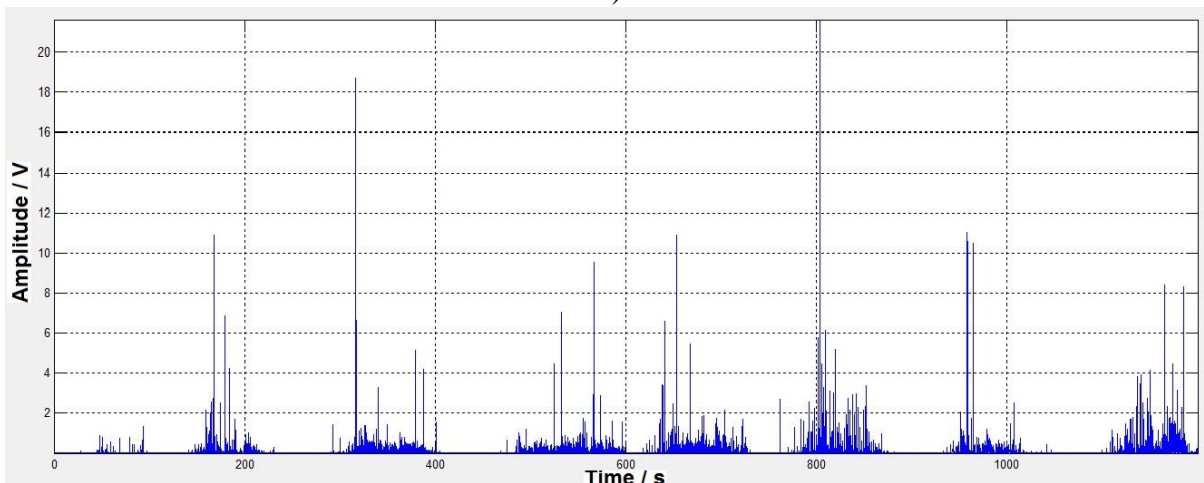
Figure 17: a) Moving RMS for healthy wheel and b) moving RMS for defective wheel.

Since shelling is expected to impact on the rail during each wheel revolutions or 1X the low frequency power spectrum and harmonics should be employed in order to identify this specific fault. The plots in figure 18 show the low frequency demodulated power spectrum of the acceleration signal up to 7 wheel revolutions (7X) for both the healthy (18a) and defective (18b) wheels. The demodulated power spectrum signal in figure 18b shows clearly the 1X peak and associated harmonics up to 4X for the defective wheel indicating the presence of a fault on the tread. In the plot of figure 18a these harmonics are not present for the healthy wheel. Thus, this analysis clearly identifies wheel faults and a clear separation between healthy and deteriorated condition has been achieved. It is possible to relate the result directly to any wheel problems present thanks to the multiple harmonics showing up if the train speed is taken into account.
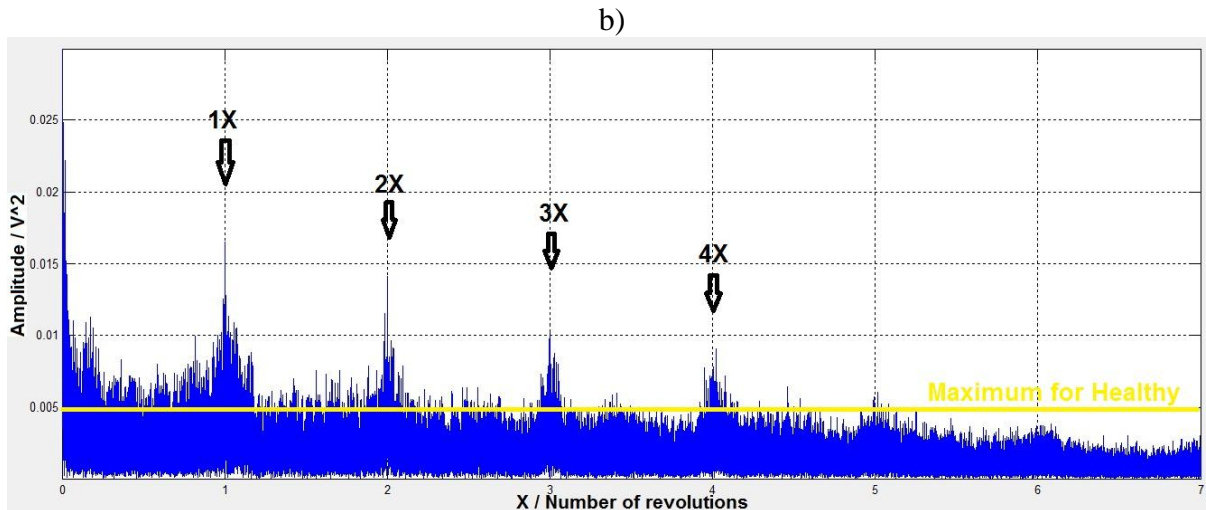
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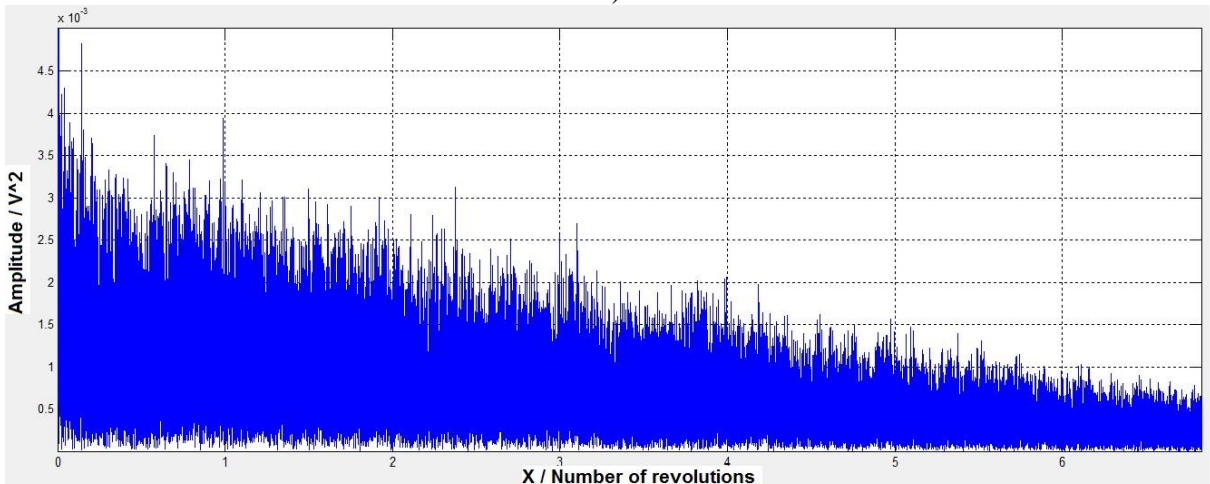
Figure 18: a) Demodulated power spectrum for the healthy wheel showing no harmonics and b) demodulated power spectrum for the defective wheel showing clear evidence of multiple harmonics up to 4X. Note also the significant difference in the amplitude of the two signals.

From the results obtained, analysed and discussed in this paper, acoustic emission and vibration analysis can be used for onboard detection of various wheel and axle bearing defects. Wheel defects such as single and multiple flats, shelling and other tread defects are detectable using vibration analysis. Their range size can also be potentially quantified by trending the maxima of the measurements. Vibration measurements may be extended to monitor the quality of wheel and rail geometry as well as broken bogie suspensions. Acoustic emission is more effective in axle bearing detection. The results discussed herewith have shown that the technique is capable of detecting roller and race defects of various sizes. The quantification of the defect severity is highly complicated but trending the maxima is a plausible method for assessing the likely size range of the defect. The type of the defect can be assessed using spectral analysis as long as the bearing frequency characteristics are known. In this case the bearing characteristics were not known to the authors. Other axle bearing defects that are detectable using onboard acoustic emission, include lubricant contamination, fretting and corrosion. The applicability of the acoustic emission in detecting axle bearings using wayside measurements will be discussed in a follow up paper.

The raw acoustic emission signal is influenced by several factors including the type of defect present, the speed of the train, the quality of the coupling, the quality of the wheel and track geometry. As shown in the results for the same defect during the same measurement different amplitudes arise each time there is a defect impact as the axle bearing rotates. However, the key parameter for the analysis is not to consider the amplitude alone but take into consideration the amount of energy the signal contains. For this reason the moving RMS peaks show considerable variability within the same measurement as well as from measurement to measurement that are directly related to the energy that the AE signal contains. In order to arrive to safe conclusions regarding the size of the defects it is necessary to trend the maxima of the measurements. By knowing the bearing frequency characteristics it is possible to also determine the type of the defect present.

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 onboard experiments carried out on freight and passenger wagons in Long Marston, UK and Lisbon,

Portugal respectively, in collaboration with Krestos Limited, VTG Rail, Motorail Logistics, Network Rail, EMEF, NOMAD TECH and REFER 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 moving RMS the axle bearing defect can be easily identified. However, it is also important to note that defect sizing requires trending of the maxima and it is important to note the influence of the energy of the signal rather than the amplitude alone. Further analysis can enable the type of the defect to be also ascertained as shown in the case of the wheel defects assessed on the EMU tested in Portugal. Moving RMS provides a sound methodology for assessing assess 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. Demodulated spectral analysis is useful when the nature of the defect requires more in depth investigation in order to enable reliable identification.

6. Acknowledgements

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