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Evaluation of the effect of speed and defect size on high frequency acoustic emission and vibration condition monitoring of railway axle bearings

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Abstract

The rail industry has focused on the improvement of maintenance strategies through effective online condition monitoring of critical rolling stock components. The aim is to increase the reliability and minimise the probability of failures. Wheelset defects can develop in-service and evolve rapidly. For this reason, the rail industry has invested tremendously in the development of online wayside wheelset monitoring techniques to minimise the likelihood of a catastrophic derailment caused by wheel and axle bearing defects. This paper discusses the results obtained from condition monitoring tests carried out under laboratory conditions and field trials on actual rolling stock with healthy and faulty axle bearings using acoustic emission (AE) and vibration analysis techniques. Various Key Parameter Indicators (KPIs) are used as a means of verifying the presence of bearing defects and evaluation of their severity together with the effect of speed on the AE and vibration measurements.

Introduction

Railway wheelsets consist of three main components; the wheels, axle and axle bearings. Wheelset failures, although relatively rare, are common and can occur unexpectedly. Wheelset faults can develop on any of the aforementioned components. The most common wheelset failures are related to undetected wheel and axle bearings defects.

Axle bearing failure can occur at any time and possibly before the bearing reaches its intended design lifetime. The continuous increase in train operating speeds means that failure of an axle bearing can lead to very serious derailments causing 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.

Acoustic emission (AE) in Structural Health Monitoring (SHM) is defined as the generation of elastic waves made by a sudden redistribution of molecules inside or on the surface of a material. When an external stimulus, such as temperature or load, is subjected on a material energy can be released in the form of stress waves. These stress waves are detectable using sensitive and passive piezoelectric sensors which are capable of detecting surface displacements as small as 25 pm. In recent years, much progress has been made in on-line predictive maintenance of rotating machinery within the oil and gas and maritime industry.

The development of Condition Monitoring (CM) techniques for rotating machinery has been mainly based on trending of vibration signatures and occasionally AE [1].

The overall physical movement or motion of a rotating machine is normally referred to as vibration. Vibration analysis is used to detect the early faults or precursors to machinery failure. Through the effective application of vibration analysis, rotating machinery can be monitored and evaluated for the presence of faults and their evolution. This permits repair or replacement of the affected components to be carried out before a catastrophic failure occurs.

Direct detection and spectral analysis of vibration signals from bearings, gears and shafts in rotating machinery are well developed techniques and have been widely used in many industries. Examples of these applications are electromechanical motors and industrial pumps. However, the evaluation of rolling stock wheelsets and axle bearings using an online condition monitoring system is still under development [2, 3].

Due to the increasing demand for higher availability of rail transport, rolling stock wheelsets need to be rigorously and reliably monitored during the operation in order to subsequently optimise maintenance effectiveness. In-service wheelsets are constantly operating under harsh conditions which can lead to damage related to rolling contact fatigue (RCF), thermomechanical fatigue [4].

Gradual deterioration of the structural integrity of wheels and axle bearings can increase the risk of failure and therefore the possibility of delays, unnecessary costs and potentially catastrophic derailments. The presence of wheel and axle defects can be recognised as increased levels of vibration, noise and temperature produced during normal operation.

The bearing in a railway wheelset carries part of the weight of the carriage as the wheel rotates. If the bearing seizes, it will block the wheel, however, the other wheel of the wheelset will continue to rotate. As a result of the abnormal wheelset motion caused from the blocked wheel, the axle will eventually rupture causing the train to derail [5]. Therefore, in the railway industry axle bearings are considered as a critical rolling stock component. Any axle bearing defect, unless detected in time, will almost certainly deteriorate with time and eventually result in final catastrophic failure [6].

The presence of a defect in an axle bearing will give rise to significant changes in vibration and AE patterns and amplitude. Therefore, vibration and AE analysis techniques can be applied for online CM of axle bearings. Bearing defects can be categorised as distributed or local [3]. Surface roughness and waviness can be considered as distributed defects. The variation of contact force between rolling elements can lead to an increase in the level of vibration or AE [7]. Cracks, pits and spalls can be considered to be local defects. Local defects generate short duration impulses causing vibration or noise which can be detected using accelerometers and AE sensors respectively thus revealing the presence of the defect in the bearing [8].

N.A. Thakkar and et al. have shown that the AE signals from normal rail-wheel interaction is dependent on load amplitude [9]. Defect size and rotating speed are the other parameters that

affect the AE and vibration signals. The main purpose of this paper is to evaluate the effect of these parameters on vibration and AE measurements. Analysis of AE and vibration signals based on peak-to-peak, RMS (root-mean-square), crest factor and kurtosis values can be used to diagnose axle bearing faults.

The simplest approach in time domain-based analysis is to evaluate the RMS level of the raw vibration or AE signal. The RMS value of a signal is a time domain feature that measures the energy content. Equation 1 is used to calculate the root mean square value of a data series [10]:

$$RMS = \sqrt{\frac{1}{N} \sum_{n=1}^{N} x_n^2}$$

(1)

where N is the number of data points (x).

Kurtosis is the degree of sharpness of peaks in a signal. It measures the relative peakedness or flatness of a distribution as compared to a normal distribution. For an undamaged rotating machine, the kurtosis value is close to 3. Any value greater than 4 indicates the presence of an abnormality which may lead to a failure in system [3].

To find the kurtosis, the difference between each value and average of all values should be calculated (X_i - X_{avg}) as shown in equation 2. The fourth moment about the mean is the sum of each value deviation from the mean powered of 4 which is then divided by number of values:

$$m_4 = \frac{\sum_{i=1}^{n}(X_i - X_{avg})^4}{n}$$

(2)

The calculation formula for kurtosis is K = m_4 / σ_4 where m_4 is the fourth moment about the mean and σ_4 is the fourth moment about standard deviation of the signal. Therefore, K is given by equation 3:

$$K = n \frac{\sum_{i=1}^{n}(X_i - X_{avg})^4}{(\sum_{i=1}^{n}((X_i - X_{avg})^2)^2}$$

(3)

In order to detect the presence of a defect, a threshold can be chosen and any achieved value above this threshold would represent a problem in the system [11]. The kurtosis value increases significantly for relatively low level severity defects but decreases when the fault severity exceeds a certain level [12].

Crest factor is the peak to average ratio and can be calculated by dividing the peak amplitude over the RMS value of a waveform as shown in equation 4. The purpose of calculating the crest factor is to measure the impacts captured within the recorded waveform. These impacts are often associated with wheel flats, metal built-up or bearing defects.

$$Crest\ Factor = \frac{Peak}{RMS} \qquad (4)$$

In an ideal sine wave, with amplitude of 1, the RMS value is equal to 0.707 and the crest factor is equal to 1.41 [10]. The crest factor is sensitive to sharp peaks which do not last very long and have low energy [10]. A typical vibration signal from a machine with severe imbalance and no other problems will have a crest factor of approximately 3. As the bearings gradually wear, impacts will occur resulting in a significant increase of the crest factor value. This is due to the sensitivity of the crest factor to extreme peaks present in the waveform. In some case the RMS value of a defective system may remain low, the crest factor may be much higher due to the presence of extreme peaks in the measured signal [11]. This is particularly useful when dealing with signals involving significant background noise levels.

Laboratory experiments

Laboratory experiments were carried out on healthy and defective bearings using a customised test rig capable of rotating sample bearings from 100 up to 700 Revolutions per Minute (RPM). A R50A resonant AE piezoelectric sensor procured from Physical Acoustics Corporation (PAC) was mounted on top of the bearing case using a magnetic hold-down [13]. The AE sensor was coupled on the bearing case using Vaseline. The AE signals were amplified using a pre-amplifier and amplifier also from PAC by 43 dB. In addition, a high frequency industrial accelerometer with sensitivity 100 mV/g, manufactured by Wilcoxon, was used for the vibration measurements. The accelerometer was mounted using a magnetic pad. The AE and vibration signals were digitised using an Agilent U2531A data acquisition system (DAQ). Customised software developed in MATLAB by the authors was used to log and analyse the captured data.
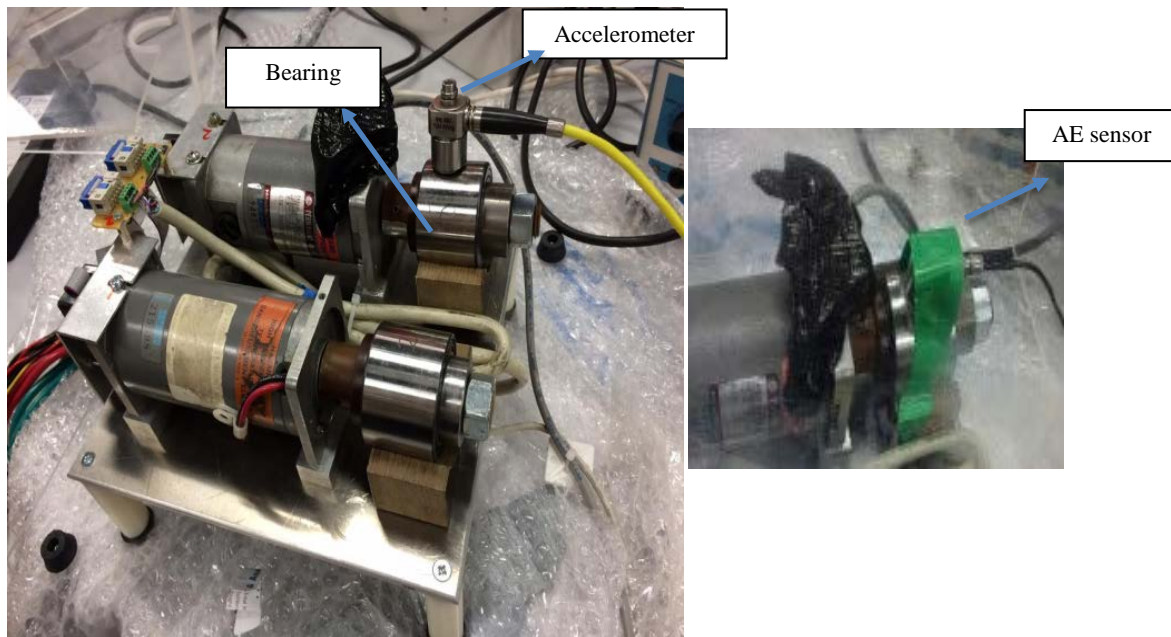
Figure 1: Laboratory bearing test rig at the University of Birmingham.

The bearing samples used during the laboratory rig tests were manufactured by PFI Inc., model PW29530037CSHD automotive wheel bearing with dimensions of 28 mm x 53 mm x 37 mm. These bearings were disassembled in order to artificially induce race and roller defects of interest before being reassembled and installed on the test rig. Figure 2 shows the bearing samples employed for the test rig tests.

Figure 2: Example of a double-row tapered roller bearing using in the test rig laboratory experiments.

Bearings used in the rig test include healthy, outer race and roller defective in different defect sizes. Table 1 shows bearings with different induced defect used in the laboratory experiments.

Table 1: bearings with different induced defect used in the laboratory experiments.

Lab Test ID	Description
F0 (H)	Good condition, no introduced defects.
F2	Minor damage to one small area of one roller in each cage, consisting of surface roughening by electrical discharge engraver. Fault length 10% of circumference.
F3	Damage to one small area on each outer race, consisting of surface roughening by means of an electrical discharge engraver. Fault length 2.9% of circumference.
F5	Single ground and roughened fault, same position on each outer race. Damage inflicted by small cutting wheel and engraver. Fault length 6.6% of circumference.

Field experiments

Onboard CM based on vibration and AE can be used to detect an axle bearing fault much easier in comparison to wayside detectors. The onboard CM is particularly useful when the fault is still at an early stage of evolution [14]. This is due to the fact that the sensors are much closer to the axle bearing and hence to the source of the vibration and noise signals [15]. Onboard systems are able to measure continuously or at predetermined intervals the condition of the axle bearings with data acquisition being possible over a longer period of time in comparison to wayside measurements. Through onboard CM, it is possible to record several revolutions of the wheel and axle bearing hence adjusting the acquisition time according to the measurement requirements. The signal acquisition time needs to be set at a sufficient length in order to capture at least a few revolutions in order to minimise unwanted impulse effects during subsequent analysis [16].

Field experiments were carried out using a freight wagon travelling forward (engine in front) with 48 km/h and backward (engine in the back) 32 km/h speed over a straight length of rail track in Long Marston. The length of the track used was a few hundred metres and the tested freight wagons had axle bearings procured from TIMKEN (Timken model 99591-99100). All defects used in the experiments were artificially induced using power tools. The sampling rate employed for AE measurements was 500 kSamples/s and for the vibration 25 kSample/s.

Figure 3 shows the onboard non-intrusive experimental setup with the AE sensor and accelerometer mounted magnetically on the bearing case of one of the wheelsets monitored during testing. The sensors were located as close to the monitored bearing as possible and hence the source of interest. This allowed a good mechanical pathway between the bearing and the sensors enabling good transmissibility of vibrations and noise from the source. Data were recorded using the same hardware and software as for the laboratory configuration.
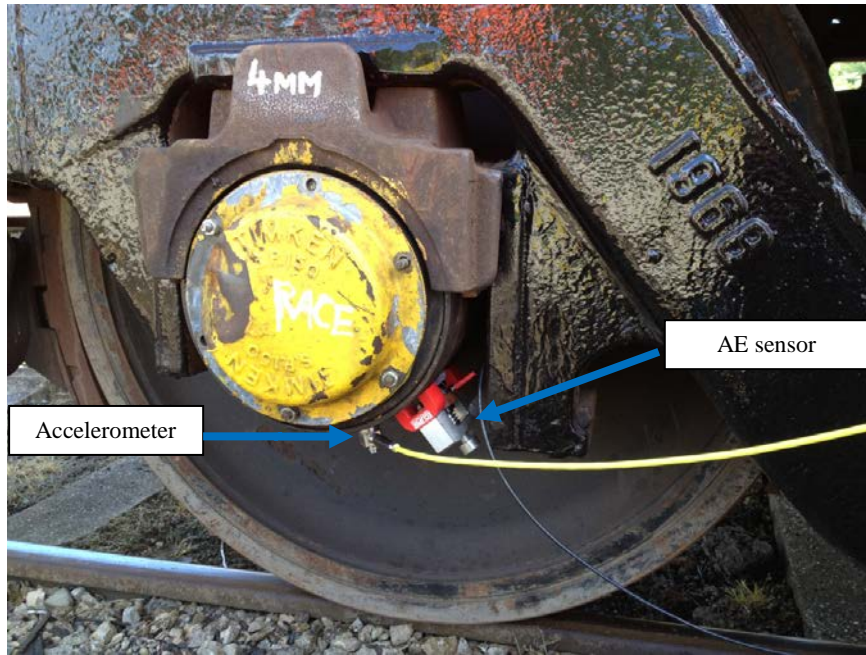
Figure 3: The accelerometer and AE sensor mounted using a magnetic pad and magnetic hold-down respectively on the axle box of an axle bearing with a 4mm artificially induced race defect during onboard testing [7].

Results and discussion

The peak-peak data from both vibration and AE test rig measurements at different rotational speeds are shown in Figure 4. The amplitude of the vibration and AE signals increases with increasing rotating speed of the bearings. This is due to the fact that the impact produced by the defect has more energy as rotating speed increases.
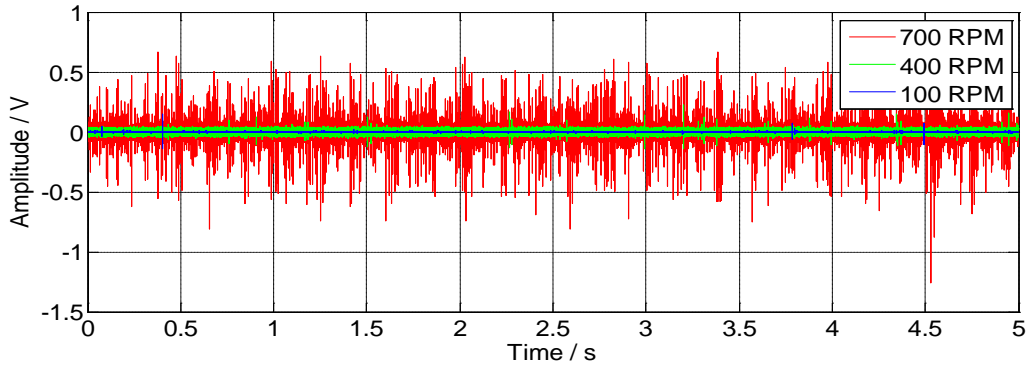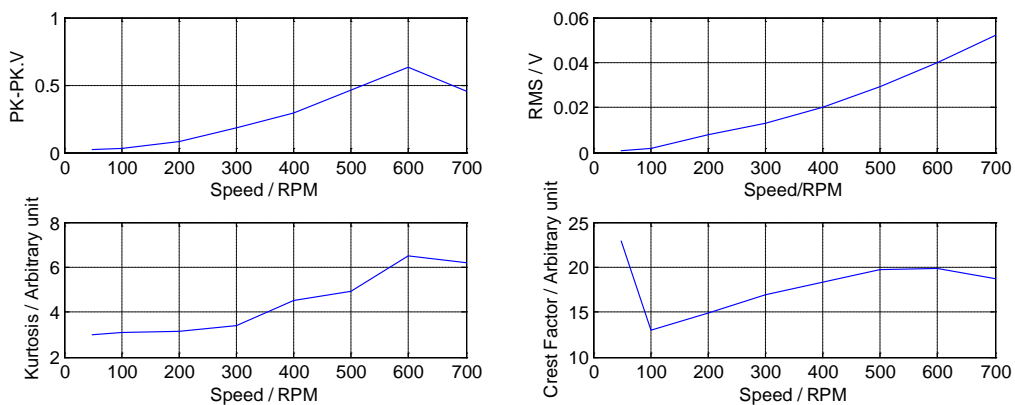

Vibration measurements
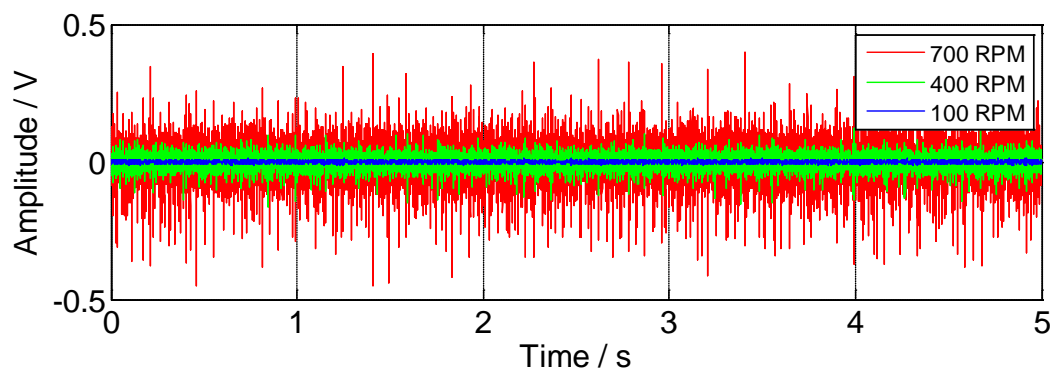
AE measurements

Figure 4: Peak-peak data comparison of the bearing with outer race defect (F3) in rig test by changing rotating speed for a) vibration and b) AE measurement.

The plots shown in Figure 5 show the overall peak-to-peak, RMS, kurtosis and crest factor values with increasing rotating speed. In vibration analysis, the overall kurtosis value shows a constant increase with increasing speed. However, in AE, because of high frequency non-Gaussian noises, which occur in the data, the overall kurtosis value becomes minimal with increasing speed. Crest factor shows slightly better results than kurtosis in both vibration and AE data with increasing rotating speed. It should be stressed here that the analysis is based on the calculation of the overall RMS, kurtosis and crest factor values from each of the measurements considered. The analysis based on the use of a suitable moving window (i.e. moving RMS, moving kurtosis and moving crest factor) would provide better results but of course requires significantly higher computational time [7].
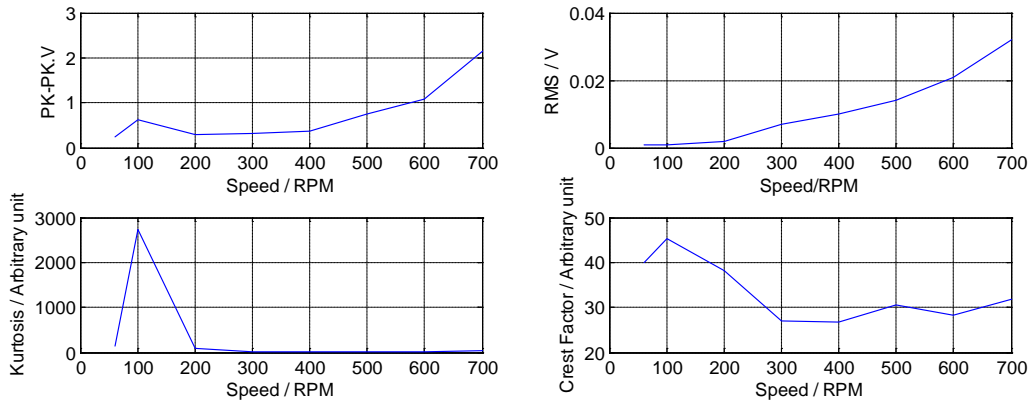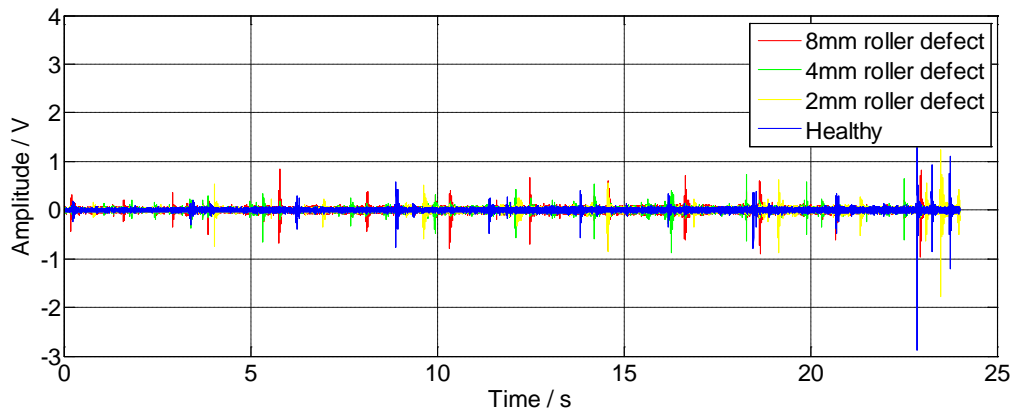
(a) Vibration measurements

Figure 5: Overall value changes of the bearing with outer race defect (F3) by changing the test rig speed for a) vibration and b) AE measurements.

The amplitude difference in raw data of the onboard vibration and AE experiments can be observed in Figure 6. Unfortunately, due to the accelerometer cable length limitation of the experimental configuration employed vibration measurements could not be carried out on the bearings with over 8mm size of roller defect.

There is no significant change in the amplitude and overall values of the vibration data by increasing the size of the defects. This is due to the fact that relatively smaller defects (defects in the early stages) do not produce sufficient vibration variations in order to be detectable with an accelerometer. However, from the raw data AE results it is evident that the larger defect size results in an AE signature with greater amplitude. The peak-to-peak, RMS values in the bearing with 8 mm roller defect are significantly higher than the ones containing smaller defect sizes. Kurtosis and crest factor without the use of a suitable moving window are not able to clearly separate the bearings with different defect size (Figure 7). Random dynamic effects during the movement of the rolling stock may also have influenced the resulting calculations of the kurtosis and crest factor values.

Vibration measurement
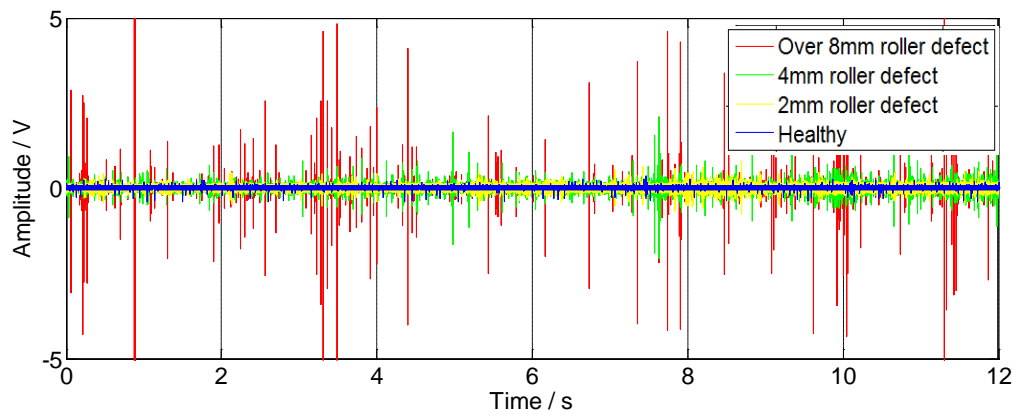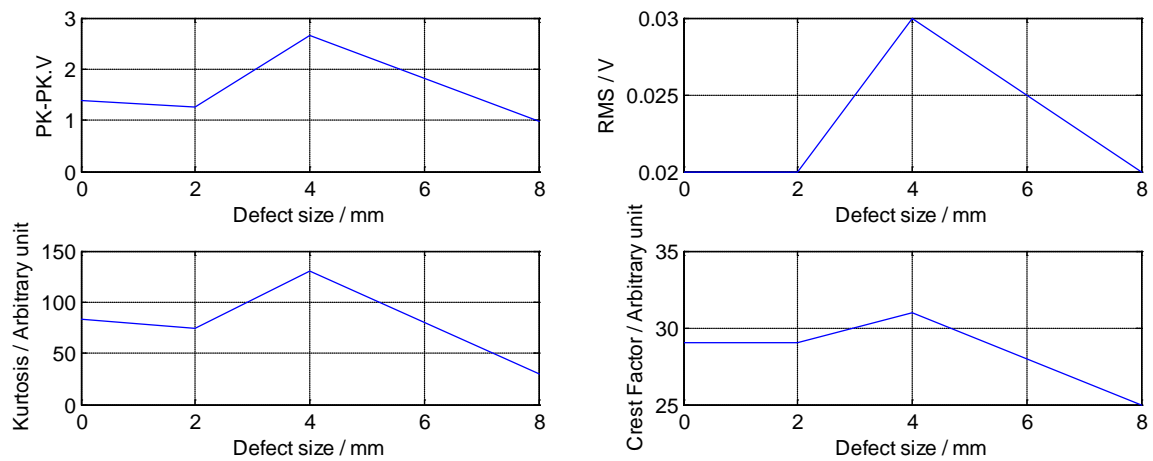
AE measurement

Figure 6: Raw data comparison for different defect sizes during Long Marston onboard test
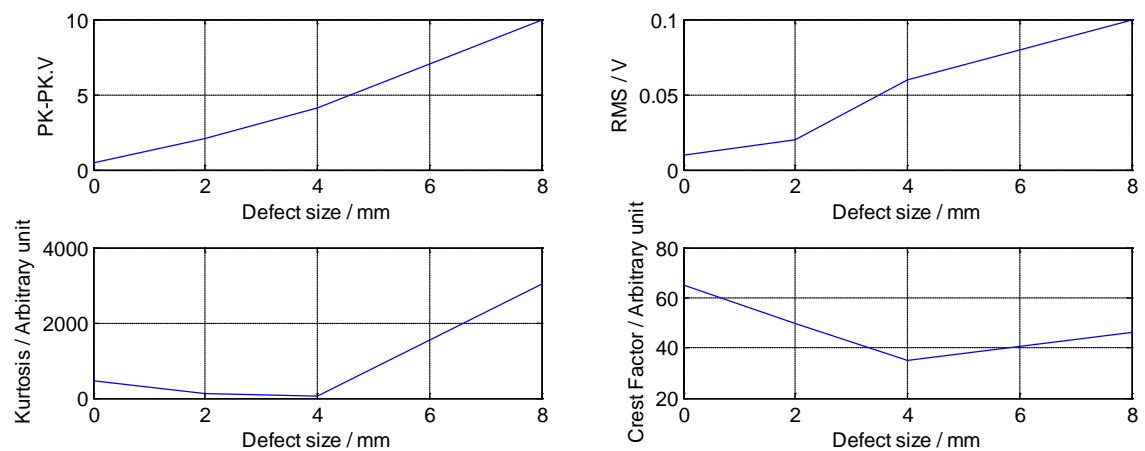
Vibration measurements

AE measurements

Figure 7: Overall signal value changes with increasing roller defect size

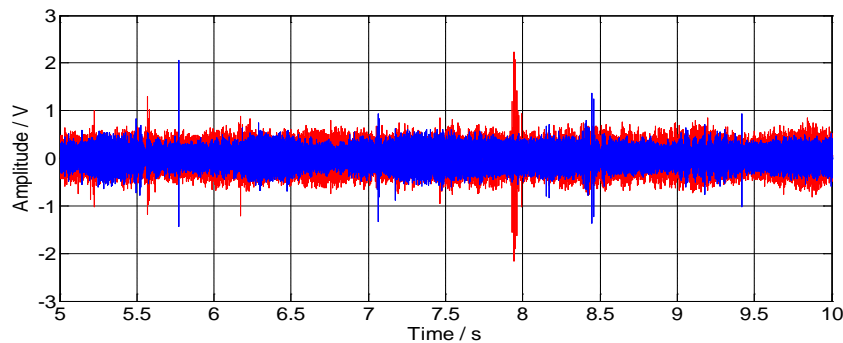The amplitude difference in the AE signature for the Long Marston tests at 32 km/h and 48 km/h is shown in

Figure **8**. The vibration measurement does not show noticeable changes in this case. This is attributed to the smaller effect on the vibration signature in comparison to the effect on the noise signal. The AE signature shows a slight increase with increasing speed. On the other hand, the amplitude of the vibration signal does not show any appreciable change with increasing speed.

(a) Vibration measurements
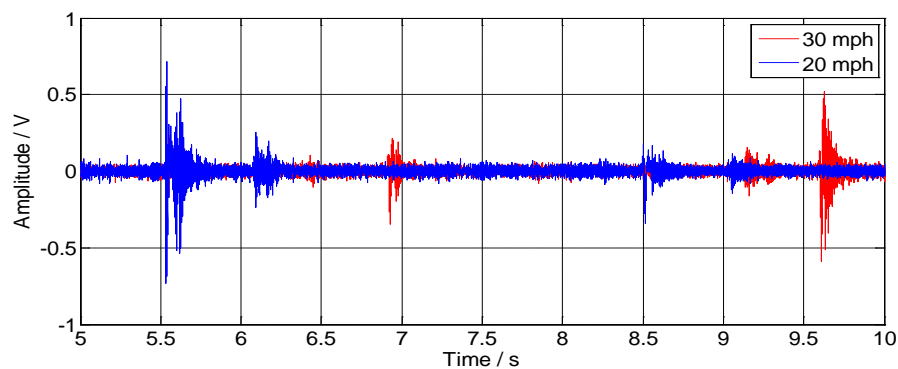
(b) AE measurements

Figure 8: Data comparison from the onboard bearing with 2mm roller defect, Long Marston test at two different train speeds (32 km/h and 48 km/h).

Error! Reference source not found.2 summarises the vibration and AE results for the 2mm roller defect obtained during the field tests in Long Marston at two different speeds. The

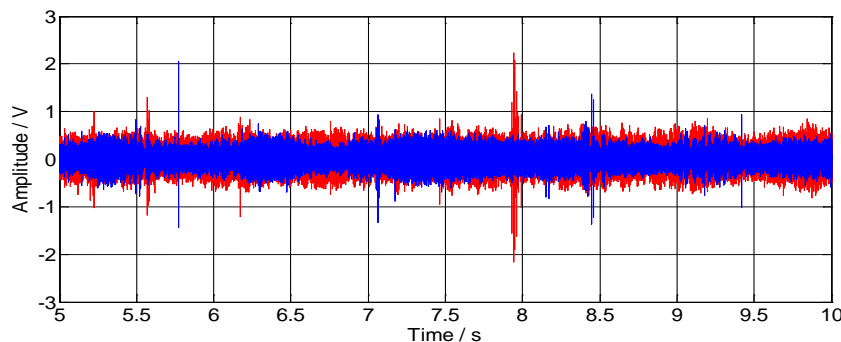overall values for AE confirm the previous results in the laboratory test. Yet again the peak-to-peak and RMS values increase when the train runs faster. The calculated kurtosis and crest factor overall values show evidence of the defect presence but do not increase with increasing train speed. On the other hand, there was small difference in overall values of vibration measurement. Therefore, vibration shows lower sensitivity to speed changes compared to AE technique. This can be caused by existing low frequency noises which affect the vibration data.

Table 2: Comparison of vibration and AE signals for the 2mm axle bearing roller defect at two different train speeds during testing at Long Marston.

	AE		Vibration	
	backward (20 mph)	forward (30 mph)	Backward (20 mph)	forward (30 mph)
PK-PK / V	3.4	4.4	1.44	1.1
RMS / V	0.11	0.15	0.03	0.02
Crest factor	25	23	27	26
Kurtosis	4.2	3.9	59	53

Conclusions

A number of laboratory and field tests have been carried out in order to examine the effect of defect size and speed on AE and vibration measurements during onboard monitoring of railway axle bearings. Rotating speed was changing from 100 to 700 RPM in the laboratory test and from 20 to 30 MPH in the field test and the defect sizes in the field test varied from 0mm to 8mm. In the bearing vibration analysis, RMS and peak-to-peak values tended to be proportional to the running speed and size of the bearing defect if the recording gain remains the same. In the laboratory vibration tests with less background noise and more stable speed, kurtosis is capable to indicate the fault. However, the value of kurtosis and Crest Factor were affected by the surrounding noises in the field experiments.

Acknowledgements

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Appendix

Table 2: Overall value changes of the bearing with outer race defect by changing the speed

VIB				
speed	kurtosis	Crest factor	RMS	pk-pk
48	3	22.9	0.001	0.022
100	3.09	13	0.002	0.026
200	3.13	14.9	0.008	0.08
300	3.42	16.88	0.013	0.18
400	4.5	18.3	0.02	0.29
500	4.93	19.75	0.029	0.46
600	6.5	19.85	0.04	0.63
700	6.21	18.77	0.052	0.45

AE				
speed	kurtosis	Crest factor	RMS	pk-pk
60	131.9	39.9	0.001	0.247
100	2727	45.22	0.001	0.62
200	92.93	38.06	0.0018	0.29
300	4.07	26.9	0.007	0.31
400	4.09	26.7	0.01	0.36
500	12.12	30.56	0.014	0.75
600	24.48	28.34	0.021	1.07
700	33.64	31.88	0.032	2.14

Table 3: Overall value changes of the bearing with outer race defect by changing the size of the defect.

AE	Healthy	2mm roller	4mm roller	Over 8mm roller
PK-PK / V	0.5	2.07	4.15	19.99
RMS / V	0.01	0.02	0.06	0.27
Crest factor	65.99	50.7	34.78	36.08
Kurtosis	446.07	125.21	40.72	578.2

Vibration	Healthy	2mm roller	4mm roller	8mm roler

PK-PK / V	1.39	1.27	2.66	0.98
RMS / V	0.02	0.02	0.03	0.02
Crest factor	29	29	31	25
Kurtosis	83	75	130	30