Onboard detection of railway axle bearing defects using envelope analysis of high frequency acoustic emission signals

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A B S T R A C T

Railway wheelsets consist of three main components; the wheel, axle and axle bearing. Faults can develop on any of the aforementioned components, but the most common are related to wheel and axle bearing damages. The continuous increase in train operating speeds means that failure of an axle bearing can lead to very serious derailments, potentially causing human casualties, 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. The rail industry has focused on the improvement of maintenance and online condition monitoring of rolling stock to reduce the probability of failure as much as possible. This paper discusses the results of onboard acoustic emission measurements carried out on freight wagons with artificially damaged axle bearings in Long Marston, UK. Acoustic emission signal envelope analysis has been applied as a means of effective tool to detect and evaluate the damage in the bearings considered in this study. From the results obtained it is safe to conclude that acoustic emission signal envelope analysis has the capability of detecting and evaluating faulty axle bearings along with their characteristic defect frequencies in the real-world conditions.

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1. Introduction

Due to the increasing demand for safer and quicker rail transportation, rolling stock wheelsets operating under high axle loads, speed and heavy usage require more rigorous and reliable maintenance and inspection. While in service, wheelsets are constantly operating under harsh conditions including rolling contact fatigue, thermal variations and impact [1]. Gradual deterioration of the structural integrity of wheels and axle bearings can increase the risk of failure and hence the possibility of delays, unnecessary costs and derailments, increased levels of vibration, noise and temperature produced by the axle bearing is a sign of a developing defect [2].

Acoustic emission (AE) in structural health condition monitoring 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 applied to a material, the released energy will be in the form of stress waves. These stress waves can be detected using piezoelectric sensors. In recent years, there has been much progress in on-line predictive maintenance of rotating machinery within the oil and gas and maritime industry. These advances have led to a very reliable technique based mainly on trending of vibration signals and occasionally AE waveforms [3].

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The bearing in a railway wheelset sustains part of the weight of the vehicle as the wheel rotates. If the bearing seizes, then the affected wheel will block. This will cause only the other wheel of the wheelset to continue rotating. As a result of the abnormal wheelset motion caused from the blocked wheel, the axle will eventually rupture causing the train to derail.

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 become worse gradually before final catastrophic failure occurs. The presence of a defect in axle bearings will give rise to significant changes in vibration and AE patterns and amplitude. Therefore, vibration analysis and AE are possible techniques for the continuous and efficient condition monitoring of axle bearings.

Faults in axle bearings can be categorised as distributed or local [4]. Distributed defects such as surface roughness, waviness, etc., and the variation of contact force between rolling elements can increase the level of vibration and noise produced by the axe bearing. Localised defects, such as cracks, pits, spalls, etc., can generate impulses which can give rise to short duration vibration or AE signals [5].

Relevant research on diagnosis of faulty railway axle bearings using vibration analysis technique was reported by C. Yi et al. Vibration data were acquired using a sampling frequency of 10 kS/s. Vibration data analysis was carried out using Ensemble Empirical Mode Decomposition (EEMD) and Hilbert marginal spectrum [6].

2. Theoretical background

Certain bearing defects, such as roller and race defects, give rise to a fundamental frequency. Knowing the fundamental frequency of the defects is paramount in diagnosing the exact nature of the problem rather than only identifying a faulty axle bearing from a healthy one. When an axle bearing rotates, any irregularity in the race surfaces or in the roundness of rolling elements will excite periodic frequencies or otherwise fundamental defect frequencies. The amplitude of these frequencies or tones is an indication of the severity of the defect detected. Ball bearings illustrate four distinct tones (frequencies). These frequencies depend on the bearing geometry and rotational speed [7]. Once the type of the bearing and the shaft speed are identified, the defect frequencies can be calculated. The information regarding the characteristic frequencies of an axle bearing are generally provided by the manufacturer of the bearing. The formulas for calculating these specific frequencies are [8]:

$$BPFI = \frac{N}{2} \times F \times \left(1 + \frac{B}{P} \times \cos\theta \right)$$

$$BPFO = \frac{N}{2} \times F \times \left(1 - \frac{B}{P} \times \cos\theta \right)$$

$$FTF = \frac{F}{2} \times \left(1 - \frac{B}{P} \times \cos\theta \right)$$

$$BSF = \frac{P}{2B} \times F \times \left[1 - \left(\frac{B}{P} \times \cos\theta \right)^2 \right]$$

Where
BPFI = Ball pass frequency inner race (Hz)
BPFO = Ball pass frequency outer race (Hz)
FTF = Fundamental train frequency – Frequency of the cage (Hz)
BSF = Ball spin frequency circular frequency of each rolling element as it spins (Hz)
N = Number of balls
F = Shaft frequency (Hz)
B = Ball diameter (mm)
P = Pitch diameter (mm)
θ = Contact angle.

3. Acoustic emission signal envelope analysis technique

Typically, when an impact occurs in a defective rolling element as it rotates an impulse will occur. This impact will give rise to excitation of the characteristic frequencies of the structure [9]. The main idea of the AE signal envelope analysis technique is to eliminate the disturbance influence and highlight the fault feature using the envelope spectrum. In practical applications the characteristic frequency may vary due to different types of bearings being used. At early stages of evolution of an axle bearing defect, the chance of detecting it reliably using conventional power spectral analysis (FFT) is low. Signal envelope analysis provides an effective extraction method from low Signal to Noise Ratio (SNR) when vibration or AE signals are considered [10].
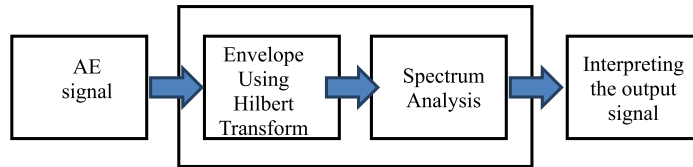
Fig. 1. Schematic of acoustic emission signal envelope analysis technique.
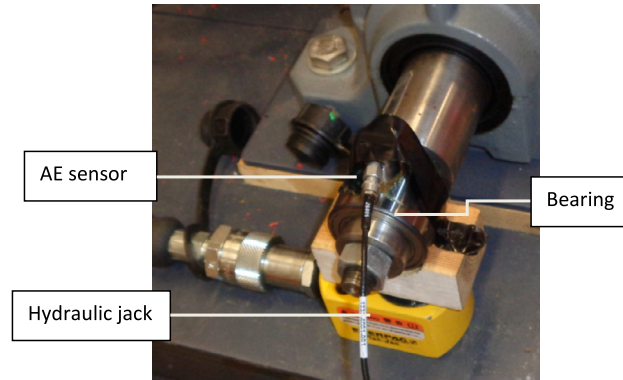

Fig. 2. Photograph of the customised test rig built at the University of Birmingham where the experiments on healthy and faulty bearings were performed.

Vibration or acoustic emission signals in operating rotating mechanical systems can be produced not only from bearings but also from others components such as gears, shafts, couplings, whether in good condition or fault condition [11]. Fig. 1 shows the schematic of envelope analysis applied to demodulate a vibration or AE signal.

The Hilbert transform is a transformation of a signal from time-domain to time-domain. Positive frequency and negative frequency components are shifted by $+90$ and -90 degrees. The Hilbert transform of $g(t)$ is the convolution of $g(t)$ with the signal $\frac{1}{\pi t}$. Which results in the equation below [12]:

$$\left[g(t)\right] = g(t) * \frac{1}{\pi t} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g(\tau)}{t - \tau} d\tau = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g(t - \tau)}{\tau} d\tau$$

Hilbert transform represents the analytical signal and it is the magnitude of the envelope of the original signal. Envelope detection or amplitude demodulation is the technique in extracting the modulating signal from an amplitude-modulated signal.

It should be noted that the raw power spectrum of an axle bearing fault signal with low SNR will usually contain little diagnostic information, being dominated by the resonance frequencies that are excited. Whereas the envelope signal obtained by amplitude demodulation will contain the required information about the repetition frequency of impacts and any modulation caused by the impact of the fault produced during its passage through the load zone.

4. Laboratory testing

Laboratory tests were carried out on healthy and defective bearings using a customised test rig with capable of rotating sample bearing from 100 up to 1000 Revolutions Per Minute (RPM). In order to minimise the effect of the predominantly low frequency mechanical background rolling and engine noise and maximise the detection of the high frequency signals arising from axle bearing fault suitable resonant AE sensors have been employed. A piezoelectric type R50α resonant AE 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. The AE signals were digitised using an Agilent 2531A data acquisition card (DAQ) with 500 kS/s sampling rate. Data acquisition was carried out for 5 s (2×10^6 points) during laboratory testing and 12 s (6×10^6 points) during the Long Marston tests. Customised software written in MATLAB by the authors was used to log and analyse the captured data. Fig. 2 shows the test rig used for this work.

The bearing samples used in the laboratory rig tests were PFI Inc., model PW29530037CSHD automotive wheel bearing with dimensions of $28 \times 53 \times 37$ mm. The characteristic frequencies which were obtained by the manufacturer are shown in Table 1. The results from 400 RPM measurements were considered for both healthy and defective (outer race defect) bearings. Defective bearing consist of damage to one small area on the outer race, inflicted by means of a small rotary

Table 1
Fundamental frequencies of bearings in the rig test – 61.5 Hz frequency and its harmonics were expected to observe in 400 RPM rotating speed for the bearing with outer race defect.

Defect types	Speed (RPM)						
	150	250	300	400	500	600	1000
FTF	1.1	1.8	2.2	2.9	3.6	4.4	7.3
BPFO	23.1	38.4	46.1	61.5	76.9	92.3	153.8
BPFI	29.4	49.05	58.8	78.5	98.1	117.7	196.2
BSF	19.7	32.9	39.5	52.7	65.85	79	131.7
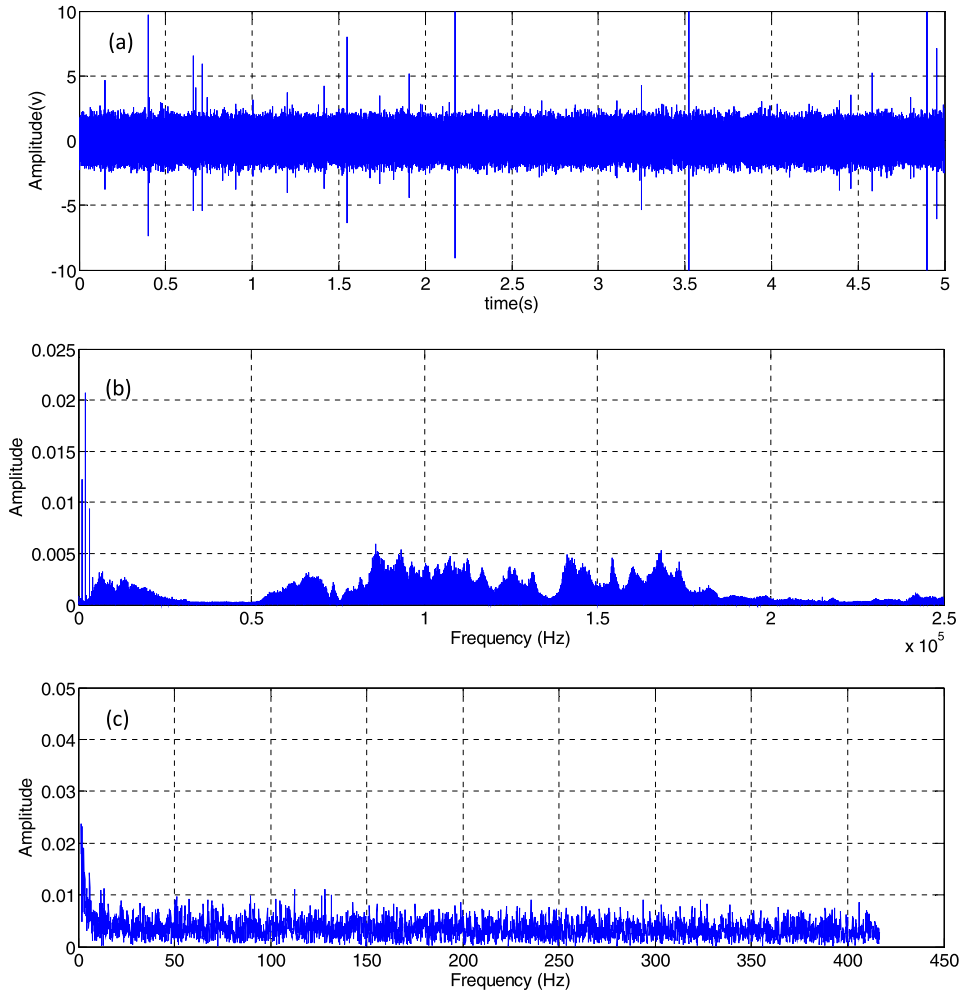
Fig. 3. Healthy bearing rig test: Raw data (a) – Power spectral analysis (b) – Envelope analysis (c).

grinder with length of 2.9% of circumference. A hydraulic jack was used to simulate the radial load acting vertically to the axis of rotation.

Fig. 3 shows the AE signal envelope and power spectral analysis on a healthy bearing from the test rig. It is evident that no indication appears in the envelope analysis approach confirming that there is no defect present. If the severity of the defect is high (in stage 3 of the bearing failure), the fundamental frequency of the defect appears in lower frequency which can be simply detected by FFT analysis. However if the severity level is low, the fundamental frequency of the defect is only visible in the resonance frequency (demodulated signal) which can be revealed by the envelope analysis.

It should be noted that the optimum bandpass frequency used in the envelope analysis was evaluated based on the resonance frequency of the bearing. An impact test, also called excitation measurement, was used to determine this frequency. A central frequency of 6 kHz with a bandwidth of 2 kHz was applied for the envelope analysis.

In the defective bearing, the fundamental frequency and its harmonics arising from the impulse caused by the impact of the bearing defect as it rotates have been excited in. The results for a sample bearing with an artificially induced roller
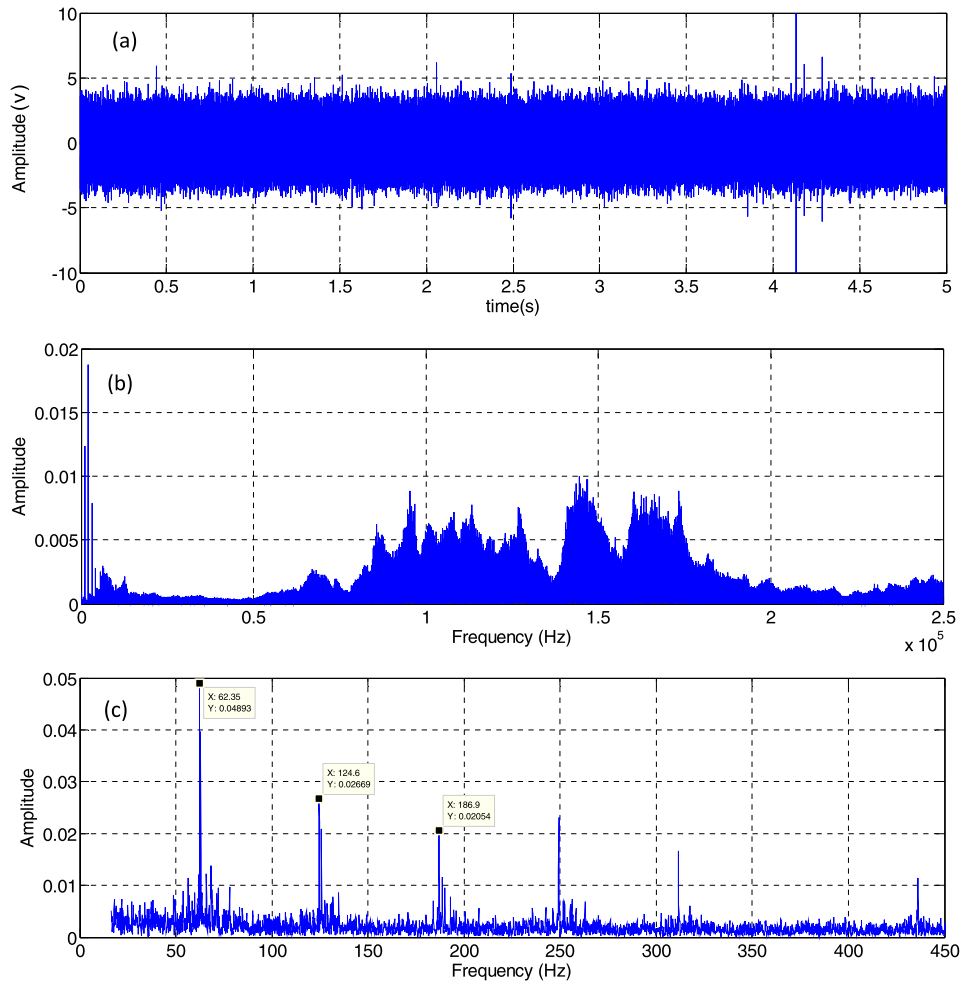
Fig. 4. Defective outer race bearing rig test: Raw data (a) – FFT analysis (b) Envelope analysis (c).

defect are shown in Fig. 4. From the envelope analysis carried out a peak at the characteristic frequency of 62 Hz is evident. The peak seen at the aforementioned characteristic frequency confirms the presence of the roller fault as it is in agreement with the fundamental frequency of the bearing at the rotating speed used during testing. There is a slight offset between the characteristic frequency given by the analysis and the table which is caused by a slight variation in the rotating speed during the test.

The laboratory experiments demonstrate the ability of the AE technique and the signal analysis approach employed to characterise the defective bearing under constant rotating speed and static loading conditions. However, the ultimate aim of this study has been to evaluate the condition of axle bearings by detecting peaks at the characteristic frequency of interest. In this case the evaluation of the axle bearings considered is far more complicated as in the field loads are dynamic, wheel tread impacts can occur stochastically and the rotating speed can vary during measurements adding considerably to the overall complexity of the problem at hand.

5. Field trial testing

Recent studies have shown that CM systems installed onboard are more likely to detect an axle bearing fault, especially at an early stage of evolution [14]. This is due to the fact that the sensors are closer to the axle bearing and hence to the source of the arising signal. Onboard systems are able to measure continuously or more often the condition of the bearings acquiring data over a larger number of revolutions of the same axle bearing. On the other hand in wayside systems can only measure the axle bearings of a passing train when they pass along the instrumented location. In addition, the wayside system is exposed to noise from the entire train being measured which is not the case when the onboard system is considered. The onboard system can record several revolutions depending on the acquisition time employed. This normally needs to be set at a sufficient length in order to capture at least a few revolutions to minimise unwanted impulse effects on the signals acquired [15].
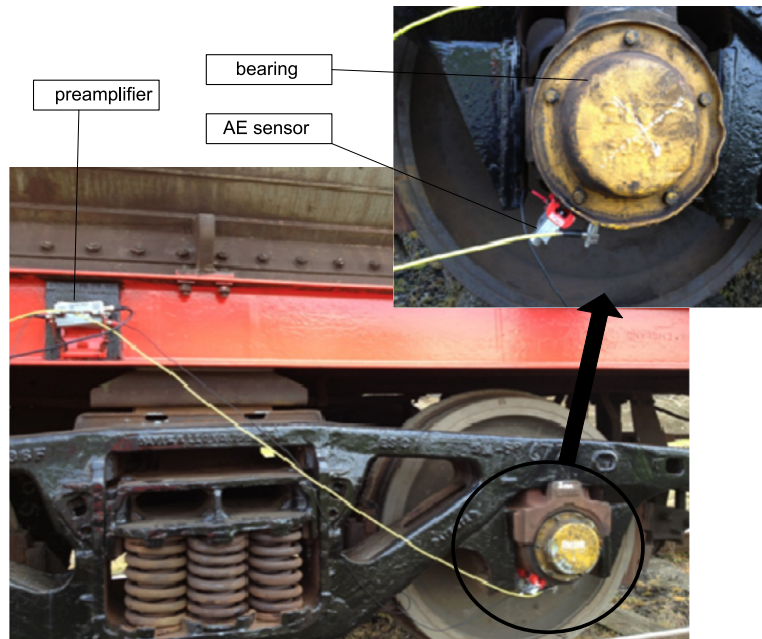
Fig. 5. Onboard mounting of the AE sensors on the bearing with 8 mm roller defect using a magnetic hold down.

Table 2
Fundamental frequencies of the Timken bearing model 99591-99100 used on the test train, Long Marston.

Frequency (Hz)	Defects
4.198	BSF – Roller/Ball Spin Freq.
11.7	BPFI – Roller/Ball Pass Freq. Inner Race
9.3	BPFO – Roller/Ball Pass Freq. Outer Race
0.443	FTFI – Fundamental Train Freq. Inner Race

Fig. 5 shows the onboard setup on the axle bearing casing of the test wagon employed. AE data were collected using the same R50α AE sensor as for the laboratory tests. There were a number of artificially induced faults include wheel flat, lubricant contamination, outer race and inner race defects. The defect on the roller and race were in three different sizes of 2,4 and 8 mm. Tests were carried out at a speed of 30 MPH forward and 20 MPH backwards pulling the freight cars over a straight section of welded track for the first and second series and continues track for third and forth series of tests. The length of the track was about 200 metres. The sampling rate for acoustic emission signals was 500 kHz. The AE sensor was attached on the axle bearing casing using magnetic hold-downs. Ultrasonic coupling was achieved using Vaseline. The AE sensor should be installed as close as possible to the bearing, this is to provide a good transmission pathway between the possible damage source and the sensor. It should also be in the maximum load zone where the maximum stresses sustained by the bearing occur. The test wagons were equipped with Timken bearing model 99591-99100.

Table 2 illustrates the characteristic frequencies of the train bearing provided by the manufacturer.

The test train speed of 48 km/h (30 MPH) corresponds to a wheel frequency of 4.2 Hz (256 RPM). According to the manufacturer datasheet for the used Timken bearings, the ratio between the frequency of the roller defect and the wheel frequency is 4.198 Hz. This results in a fundamental frequency of a defect within the rolling element of 17.6 Hz which is shown in the equation below:

4.198 Hz = Frequency of the roller defect with bearing rotating frequency of 1 Hz
4.198 Hz × 4.2 Hz (train wheel rotating speed) = 17.6 Hz

Fig. 7 demonstrates the AE data from onboard measurement carried out on a severely damaged axle bearing. Large peaks in raw data indicate the presence of a defect but not the type of defect. To find the type of the defect, data should be analysed in the frequency domain using envelope analysis. The characteristic frequencies do not appear in conventional FFT, however envelope analysis allow the detection of the fundamental frequency and its subsequent harmonics. The fundamental defect frequency obtained from the envelope analysis is 16.99 Hz followed by its harmonics, which are clearly correspond to the kinematics of the bearing provided by the manufacturer in the relevant technical data sheet. There is a slight offset between
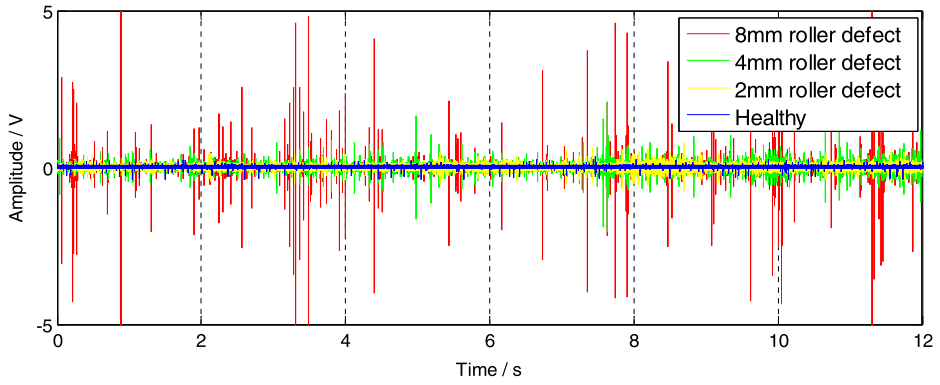
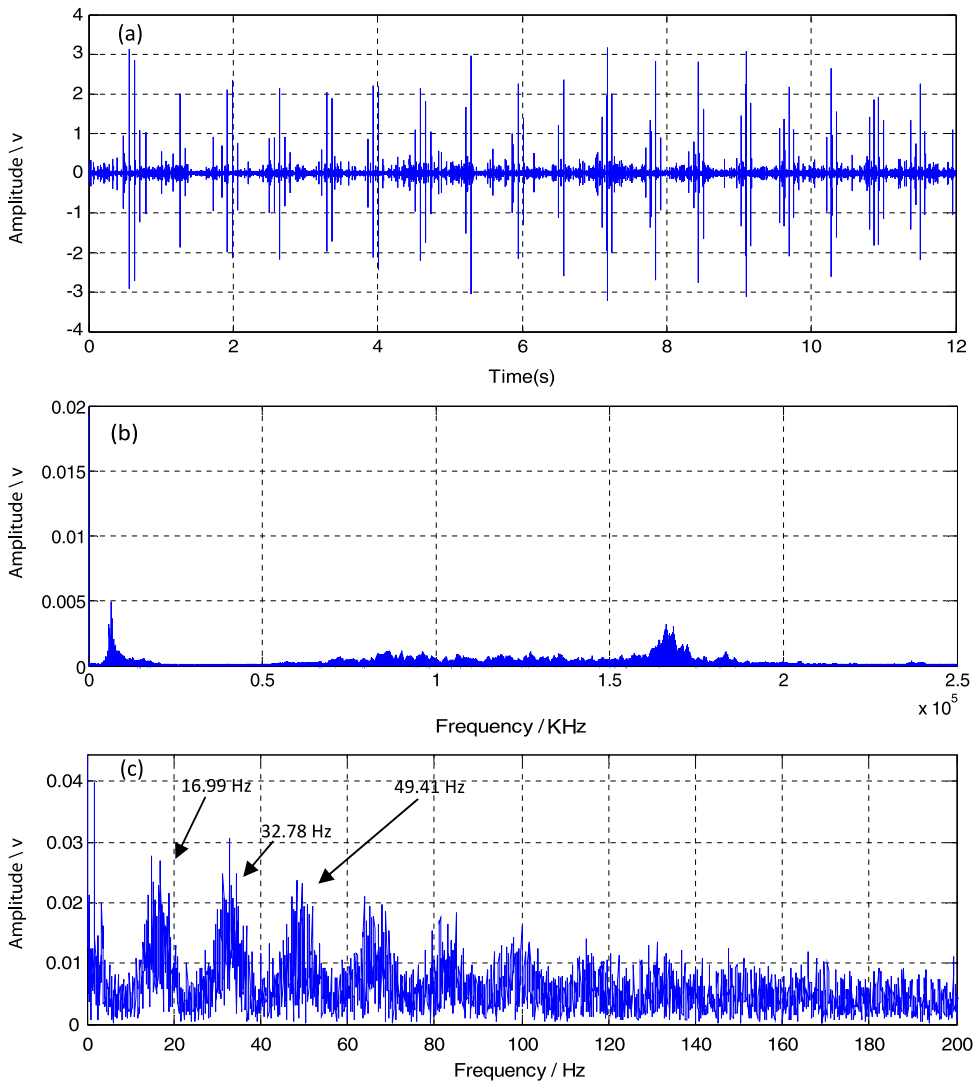**Fig. 6.** AE data comparison of the bearings with different defect sizes.

Fig. 7. Onboard AE measurement on bearing with severe roller defect: Raw data (a) – FFT analysis (b) – envelope analysis (c).
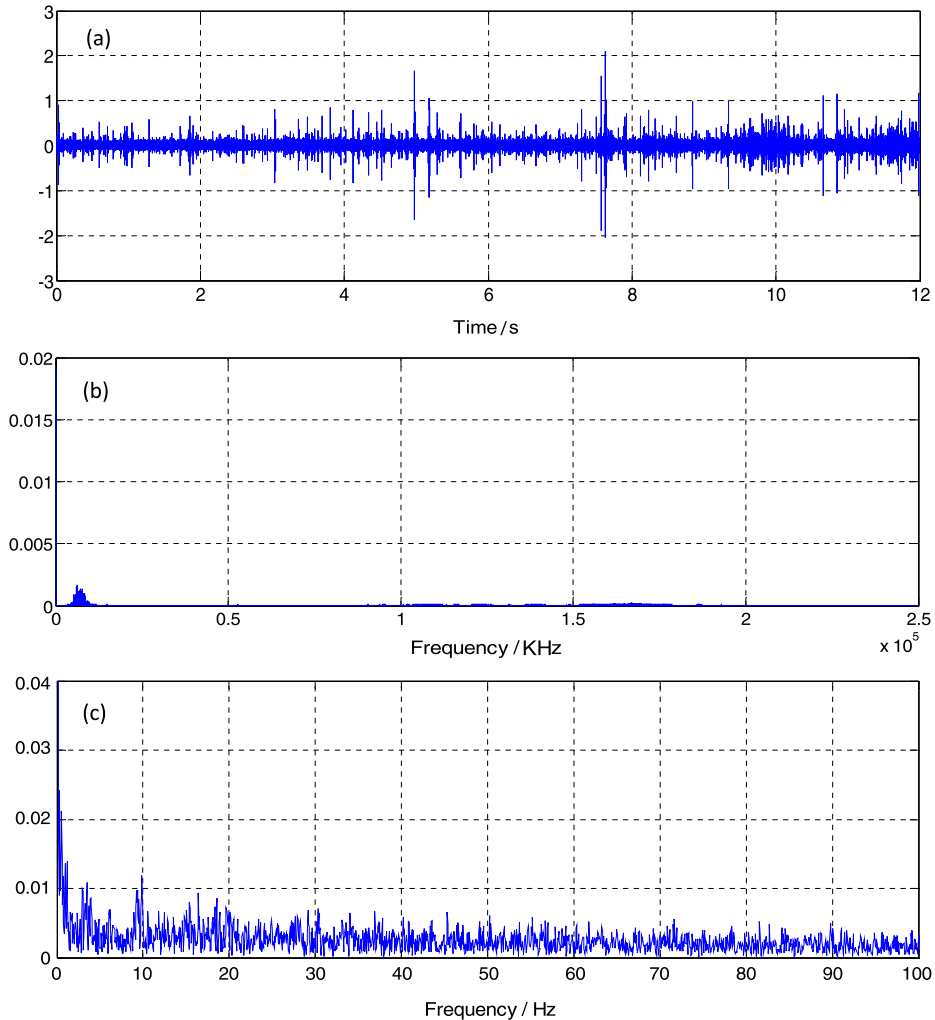
Fig. 8. Onboard AE measurement on bearing with minor defect: Raw data (a) FFT analysis (b) Envelope analysis (c).

the fundamental frequency calculated using manufacturer data sheet and the results due to the speed variation during the field test.

The plots in Fig. 8 show the same analysis on a bearing with only a minor roller defect being present. The lower amplitude in raw data compared to the severely damaged bearing should be taken into account. It is evident that despite using envelope analysis, neither the fundamental frequency nor its harmonics are evident in the signal. This is due to the fact that the signal is affected by other sources of noise (such as wheel–rail interface and brake related noises) which make more difficult the evaluation of the type of the defect. Nonetheless, it is still possible to establish that the axle bearing measured is damaged. This is due to the fact that the defective bearings contain higher AE amplitude in the raw data. Fig. 6 shows the comparison of the bearings with different defect sizes.

6. Conclusions

A number of laboratory and field tests were carried out to establish a simple and effective approach in detecting faulty axle bearings using a customised onboard AE condition monitoring system. Defective axle bearings increase the amplitude of the peaks in the power spectrum after FFT is carried out which indicates the presence of the defect. Using envelope analysis it is possible to establish the type of defect by finding the characteristic frequencies and their harmonics provided that the kinematics of the bearing are known.

The set of the laboratory tests carried out on the customised test rig developed at the University of Birmingham show effectively that the AE technique can be used together with envelope signal analysis to successfully distinguish between the defect-free and defective sample bearings considered herewith by establishing the characteristic frequencies. The same has been proven to be possible to achieve under field operational conditions as shown in the results obtained from the tests carried out at the Long Marston test track. It is shown that in the case of the mildly damaged bearing, due to the low signal

to noise ratio, AE is only able to detect the existence of the defect and in slightly severe damage it can also identify the fault.

Acknowledgements

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