Detection and evaluation of rolling stock wheelset defects using acoustic emission

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INSIGHT

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Non-Destructive Testing and Condition Monitoring

This month's cover

This month's front cover features a prototype cobot system at TWI Wales scanning a 3D blade shape using an ETher NDE AeroCheck+ as part of the CFLUX Project.

CFLUX is a project for the eddy current inspection of carbon fibre raw materials and cured parts used in the aerospace industry. 3D woven structural parts are stronger than conventional fabric lay-up parts, as the carbon fibre is continuous throughout the product structure.

Consortium members include TWI Wales (robotics and data management), ETher NDE (eddy current hardware and probes), M Wright & Sons (3D woven carbon fibre-reinforced polymers (CFRPs) and test-pieces), FAR Composites (finite element analysis (FEA), reference samples and tool design) and AHS (eddy current field measurement (ECFM) sensors). The project is funded by Innovate UK.

The CFLUX consortium has developed innovative sensor technology that can give sensitivities 1000 times greater than before, retrieving high-quality high-resolution signals that were previously unachievable.

CFLUX Project
www.cfluxproject.com

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Detection and evaluation of rolling stock wheelset defects using acoustic emission

E Giannouli, M Papaelias, A Amini, Z Huang, V L Jantara Junior, S Kerkyras,
P Krusuansombat, F P Garcia Marquez and P Valley

Acoustic emission (AE) can be employed for the early fault detection of rolling stock wheelset components. Research has been carried out on the development of a remote condition monitoring (RCM) technology for monitoring online rolling stock wheelset defects. Railway axle bearings and wheels are critical components that can develop faults at any time when in service. AE is a reliable passive RCM technique that can be employed for the quantitative evaluation of the structural integrity of rolling stock wheelsets. The emphasis of this study is placed on the results obtained from experimental work performed under laboratory and field testing conditions. Several laboratory tests were carried out using different axle bearing defects. In addition, a customised online RCM system installed on the Chiltern Rail Line, adjacent to a hot box axle detector, was used for comparison purposes. Using this, AE signal analysis was carried out in order to detect potential rolling stock faults. Defect type evaluation and quantification can also be achieved, leading to effective diagnosis of the structural rolling stock integrity of rolling stock wheels and axle bearings.

Keywords: remote condition monitoring, axle bearings, acoustic emission, structural integrity, signal processing.

Introduction

Operational efficiency is a point of focus for the rail industry. Increases in speed and heavy loading conditions enhance the risk of degradation at rolling stock wheelset components. Rail transport capacity has increased due to growth in passenger numbers and freight carried. In order to support this growth, the structural health of railway axle bearings and wheels needs to be monitored using appropriate systems. Unfortunately, axle bearing faults and failures still occur, resulting in disruption and unnecessary costs. Hence, the development of reliable remote condition monitoring (RCM) technology is of paramount importance for the rail industry.

State-of-the-art RCM technology used for the online evaluation of railway rolling stock components fails to detect defects early enough. Due to the harsh environmental conditions, thermal variations and severe axle loading conditions, railway rolling stock components are at risk of failure at any time while in service^[1]. The effect of speed and load on the acoustic emission (AE) signal of rolling bearings has been investigated by Couturier and Mba^[2]. This study found that an increase in running speed generates higher AE activity in comparison with an increase in the bearing load condition.

Acoustic emission is a well-established and versatile condition monitoring (CM) technique that can be employed in order to monitor the damage initiation and degradation in mechanically loaded structures and components. The energy released from a structure when it is loaded can be detected by piezoelectric sensors. More specifically, high-frequency passive piezoelectric transducers operating in the frequency range of 100 kHz to 1 MHz (above the audible range) are mounted on the surface of the material in order to convert the stress waves generated from a possible defect into electrical signals. Electrical signals can be recorded and digitised by an appropriate data acquisition system and then analysed using advanced signal processing techniques. The AE signals are amplified using appropriate preamplifiers and amplifiers and filtered out

before the digitisation. AE, in conjunction with advanced signal processing techniques, can be effective for accurate decision-making. The proposed AE RCM system improves the rolling stock health assessment and allows a predictive maintenance approach to be implemented.

AE testing is now widely used for the assessment of structural health integrity. Several researchers have used AE testing in order to detect bearing faults. Some recent studies are discussed below.

Amini *et al*^[3] employed AE and vibration testing in order to discuss the effect of speed and defect severity on signal amplitude. Bearings with outer race and roller faults were used as test bearings in this work. From the results obtained, the signal amplitude increased along with the rotational speed. Furthermore, several statistical parameters such as peak-to-peak, root mean square (RMS), kurtosis and crest factor values were calculated in cases of varying bearing fault severity. The peak-to-peak and RMS values increased in proportion to defect severity.

Elasha *et al*^[4] demonstrated the capability of AE testing in early fault detection compared to vibration signal analysis. A heavily damaged

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bearing, a slightly damaged bearing and a healthy bearing were the three different bearing conditions that were used in the experimental part of this study. According to the results reported, small bearing defects can only be detected by AE signal analysis. Elforjani^[5] also compared AE and vibration signal analysis using faulty bearings. The same conclusions were reported; AE is more sensitive to the early detection of bearing faults than vibration analysis.

Liu *et al*^[6] proposed a new method based on the use of a kurtogram in order to enhance the early detection of bearing faults. This signal processing technique was applied on simulated and real acoustic emission signals. Outer race bearing faults were considered as test bearings in order to assess the proposed signal processing technique. The effectiveness and reliability of the new method were demonstrated by the results. AE is a high-frequency inspection technique that is capable of detecting axle bearing and wheel faults at an early stage without the influence of noise. Therefore, a reliable and cost-effective wayside RCM system should prevent rather than detect an imminent wheelset failure^[7]. However, in AE measurements the useful information contained in signals captured can be masked by background noise, resulting in certain defects not being detected.

Signal processing techniques

Three different signal analysis approaches are discussed in this section. Time-domain, frequency-domain and time-frequency analysis are combined in order to achieve accurate axle bearing and wheel fault diagnosis at the initial stage. Wheelset defects can be detected using time-domain signal analysis. Peak-to-peak analysis, moving RMS (discussed below)^[8,9] and moving kurtosis^[4] are time domain-based signal processing algorithms that are commonly used. Defect quantification can be achieved by moving RMS. In addition, defect type evaluation can be established by frequency-domain processing^[10]. Fast Fourier transform (FFT)^[11-13], cepstrum analysis^[14,15] and the high-frequency resonance technique (HFRT)^[16-21] are the algorithms most commonly used for frequency-domain analysis. Time information is lost in frequency-domain analysis. Thus, there is a significant need for a time-frequency signal representation. The ability of the time-spectral kurtosis (TSK) algorithm to distinguish between axle bearing defects and random noise was discussed in^[1,21-23].

Moving RMS

RMS is a non-dimensional statistical indicator of the energy of a signal. The RMS value for a given signal $X = \{X_1, X_2, \dots, X_n\}$ with length n is described by Equation (1)^[8]:

$$RMS = \sqrt{\frac{\sum_{i=1}^n X_i^2}{n}} \dots\dots\dots (1)$$

The main limitation of RMS analysis is that the time information is lost. Moving RMS is an analytical approach that reverses the time information. In this type of process, the RMS value is calculated in terms of moving window analysis.

In moving RMS signal analysis, high amplitude peaks are most likely related to bearing defects^[9]. In this study, defect quantification can be achieved by moving RMS signal analysis.

Cepstrum analysis

Multiple faults in rolling element bearings or gearboxes may not be detectable using power spectrum or envelope analysis.

Cepstrum analysis has been considered as the most appropriate method for detecting and distinguishing the families of harmonics in a power cepstrum^[14]. The power cepstrum of a signal $x(t)$ is defined by Equation (2)^[15]:

$$C(\tau) = IFT \left\{ \log \left\{ FFT \left\{ x(t) \right\} \right\}^2 \right\} \dots\dots\dots (2)$$

The power cepstrum is described as the inverse Fourier transform of the natural logarithm of the power spectrum of the original signal. The horizontal axis is the quefrequency that is the reciprocal of the frequency and it is measured in seconds.

High-frequency resonance technique

Rolling element bearings consist of four main components: an outer and inner race, a cage and a rolling element. Balls, rollers and tapered rollers are the most common railway rolling elements at present.

Bearing defects can be present in any of these four components. A series of vibration impacts are generated periodically when the rolling element passes over the defect. These impacts recur at bearing fundamental frequencies^[16]. According to rolling bearing kinematics the four bearing fundamental frequencies can be calculated when the bearing geometry and the shaft speed are known in advance^[17].

Early-stage bearing damage may not be detectable by the conventional spectrum analysis due to wide energy distribution^[10,16]. The HFRT (also known as envelope demodulation processing) provides superior sensitivity to bearing fundamental frequencies in AE and vibration applications^[10]. The main idea of the HFRT is to separate the signal generated by the defective part within the envelope spectrum from the signal generated by the other machine elements using the band-pass filter around the resonance frequency^[18]. This approach of analysis shifts the frequency analysis from the high-frequency range to a lower frequency, allowing a better resolution to be achieved^[10].

Before the HFRT algorithm is presented, the Hilbert transform (HT) is described.

For a signal $g(t)$, the HT is defined by Equation (3)^[19]:

$$H[g(t)] = g(t) * \frac{1}{\pi t} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{g(\tau)}{t - \tau} d\tau \dots\dots\dots (3)$$

The Hilbert transform of $g(t)$ is the convolution of $g(t)$ with the signal $\frac{1}{\pi \cdot t}$.

The HFRT process is employed for AE and vibration signals in this study and is shown in Figure 1.

The HFRT algorithm consists of three main steps in order to locate the fault characteristic frequency in the envelope spectrum^[20]. The band-pass filter is applied to the raw data. The bandwidth of the filter is crucial to guarantee the results. The bandwidth is suggested to be at least four times the highest fundamental fault frequency^[18]. The band-passed signal is then subjected to envelope analysis. In this work, the Hilbert transform has been used to calculate the envelope signal. The HT extracts the amplitude-modulating signal from the amplitude-modulated signal^[21]. The repetition rate of the impact is revealed in this step. In the third step, the envelope spectrum is estimated using the FFT algorithm.

Figure 1. Schematic showing the high-frequency resonance technique process

Experimental procedure

A customised integrated AE and vibration system was employed for the laboratory and in-service tests (Figure 2). This novel system consisted of the following components:

- A 25 kHz high-frequency accelerometer with a sensitivity of 100 mV/g manufactured by Vibrametrics;
- A 2531A Agilent four-channel data acquisition card with a maximum sampling rate of 2 MS/s in single-channel mode;
- A four-channel decoupling hub manufactured by Krestos;
- Digital amplifiers manufactured by Krestos;
- A preamplifier provided by Physical Acoustics Corporation (PAC);
- An accelerometer power supply manufactured by Krestos;
- An R50a resonant AE sensor provided by PAC; and
- A computer with customised data logging and analysis software developed in collaboration with other colleagues.

Figure 2. The customised data acquisition equipment used during laboratory trials, developed in collaboration with Krestos Limited

An R50a resonant AE sensor was connected to the preamplifier, which in turn was connected to an amplifier. The amplifier was connected to a data acquisition board, which converted the voltage excursion generated by the AE sensor into digital data that were fed to the acquisition software. The data acquisition board was linked to a computer via a USB connection. The preamplifier's gain was set to 40 dB and the amplifier's gain ranged between 22 dB and 40 dB, according to the test requirements. The sampling rate of the acquisition software was set to 500 k samples per second (500 kS/s). The duration of data recording was set to 5 s and 8 s for laboratory and field tests, respectively. The acquired AE and vibration data were analysed using signal processing tools developed using the MATLAB software in collaboration with other researchers.

Laboratory and in-field trials

Laboratory tests were carried out on several types of defective bearing, such as those with outer race and roller defects and those with multiple defects, using a customised test-rig in order to evaluate the performance of the AE testing. Figure 3 shows the customised test-rig and the AE and vibration logger.

Figure 3. Customised test-rig (left) and AE and vibration logger (right)

Table 1 describes the different induced bearing faults employed in the test-rig experiments and Figure 4 shows these faults.

Table 1. Description of different induced bearing faults used during the on-board test-rig experiments^[24]

Lab test ID	Description
F0 (healthy)	Good condition, no induced defects
F1	Minor damage to one small area on each outer race, consisting of surface roughening by means of an electrical discharge engraver. Fault length is 1.7% of the circumference
F2	Minor damage to one small area of one roller in each cage, again consisting of surface roughening by an electrical discharge engraver. Fault length is 10% of the circumference
F4	Similar to F2 above. Single faulty roller in each cage. Small rotary grinder. Fault length is 50% of the circumference
F7	Significant damage to both races and six rollers on each side. Debris from grinding left in bearing. Fault length is 35% of the race circumference and 12% of the roller circumference

Figure 4. Induced bearing faults used during the test-rig experiments

Wayside measurements were also performed at the instrumented Cropredy site (Chiltern Rail Line), adjacent to a hot box axle detector, for comparison purposes. These trials serve as blind trials.

The Cropredy wayside integrated system consists of six channels (four AE and two vibration). A mechanical treadle is used in order to activate the data logging system. Measurement data are recorded and stored automatically. Figure 5 shows a schematic of the sensor layout used in the Cropredy trials. The gain used for Cropredy measurements was set up to 29 dB in order to decrease

the environmental noise that affects the raw AE signal.

A custom-built integrated AE condition monitoring system was employed for both tests. The sampling rate of the acquisition was set at 500 k samples per second. The time duration was 6 s due to the high speed of trains on this particular line. The captured data were analysed using time-, frequency- and time-frequency domain analysis with MATLAB.

Figure 5. Schematic showing the sensor layout used in the Cropredy trials. A mechanical treadle was used to activate the data logging system^[9]

Results

In order to evaluate the capability of AE testing to detect faulty bearings, several sets of experiments were carried out. Some representative examples are presented in the current study. In the first part of the experiments, on-board AE signals were recorded using the customised test-rig. Different types of bearing fault (F1, F2, F4 and F7) were used. Generally, the manufacturer of the bearing provides the bearing fault frequencies for a known speed (see Table 2). Therefore, the type of defect can be identified if the bearing fault frequency is presented in the results. There is a slight offset between the theoretical and observed bearing fault frequency due to a slight variation in the actual rotational speed during the experiments. Figure 6(a) shows a raw AE signal from a bearing with a defective outer race (the F1 test bearing) at 500 r/min. The raw signal was processed using the HFRT technique (Figure 6(b)). A characteristic fault frequency of 74 Hz and its harmonics (148.1 Hz, 225 Hz) are identified. This frequency corresponds to a known race fault frequency for this model of bearing. Defect type evaluation can be achieved by this signal analysis method. Furthermore, a dominant peak of 7.987 is illustrated in the HFRT plot due to the first order of turning speed of the test-rig.

Table 2. Bearing fundamental frequencies in the customised test-rig^[24]

Defect type	Speed (r/min)						
	150	250	300	400	500	600	1000
Fundamental train frequency (FTF)	1.1	1.8	2.2	2.9	3.6	4.4	7.3
Ball pass frequency outer (BPFO)	23.1	38.4	46.1	61.5	76.9	92.3	153.8
Ball pass frequency inner (BPFI)	29.4	49.05	58.8	78.5	98.1	117.7	196.2
Ball spin frequency (BSF)	19.7	32.9	39.5	52.7	65.85	79	131.7

Figure 7 shows an example of cepstral analysis. The raw data is a vibration signal from a defective bearing (F7) from the test-rig at 500 r/min rotational speed. Damage in both races and in the roller is artificially induced. The fundamental frequencies of the bearing are BPFO = 76.9 Hz, BPFI = 98.1 Hz and BSF = 65.85 Hz (see Table 2). The peaks at $0.01288 = \frac{1}{77.64}$, $0.01008 = \frac{1}{99.2}$ and

$0.01588 = \frac{1}{62.97}$ confirm the presence of the faults. There is a slight offset between the theoretical and the observed fundamental frequencies due to the slight variation in the rotational speed during the test. Therefore, multiple bearing faults can be detected using cepstrum analysis.

The plots in Figure 8 show three raw AE measurements acquired from two bearings with defective rollers (F2 and F4 test bearings) of different defect severity and a healthy bearing (F0) at 500 r/min. As it can be

seen, the width of the signal is proportional to the defect severity. It should also be noted that the amplitude of the AE signals increases as the condition of the bearing deteriorates.

Figure 6. (a) Raw AE signal from a defective bearing; and (b) HFRT plot of the signal

In Figure 9, the normalised moving RMS of previous signals is presented. The RMS is connected with the energy of a signal. Greater energy not only indicates the presence of bearing defects but also defect propagation. A number of peaks exceed the healthy threshold, indicating the presence of a defect. It is also noticeable that the amplitude of signals in AE measurements is connected with the fault length. Therefore, moving RMS analysis is capable of defect quantification.

A series of wayside measurements were carried out at the instrumented Cropredy site. The raw signals were analysed using different advanced signal processing techniques. The AE signal and the corresponding HFRT plot collected from a passenger train passing through the instrumented Cropredy site are shown in Figures 10(a) and 10(b), respectively. This particular signal may indicate a suspected inner race defect. The side-bands and harmonics indicate the presence of a bearing defect.

Figure 7. Defective bearing F7 test-rig: (a) raw signal; and (b) power cepstrum analysis

Figure 10. (a) AE signal; and (b) corresponding HFRT plot collected from a passenger train passing through the instrumented Croppedy site

Figure 8. Raw AE signals from two bearings with roller defects of different severity and a healthy bearing at 500 r/min

Figure 9. Normalised moving RMS of the signals

Conclusions

This paper presents a brief summary of the development of an online RCM system for rolling stock wheelsets. Laboratory and in-service trials have been carried out. On-board and wayside measurements have been performed and compared with laboratory-based experimental

results and analysis. Time and frequency analysis has been considered for processing the captured data. From the results obtained to date, it has been safely demonstrated that defect type evaluation can be achieved using the HFRT method. The bearing fundamental frequency and its harmonics have been observed in the HFRT plot. In addition, defect quantification has been shown to be possible by applying a normalised moving RMS method to raw signals. Furthermore, during laboratory trials involving bearings with multiple defects, cepstrum analysis has been considered as the appropriate signal analysis methodology in order to confirm the presence of all the defects. Three different fundamental fault frequencies have been detected. During the experimental part of this project, in-service trials were carried out at Croppedy and potential bearing faults were detected. The Croppedy tests were blind trials as they were performed on in-service rolling stock. A representative example has been presented in this work. The results still need to be confirmed with the help of Network Rail. High-frequency AE testing has been shown to be a useful technique for railway axle bearing fault detection, providing superior capabilities over state-of-the-art techniques.

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