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A novel approach for incipient defect detection in rolling bearings using acoustic emission technique

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ABSTRACT

Bearings are critical components of rotating machinery and monitoring their condition is important to avoid catastrophic failures and reduce the machinery down-time. Acoustic emission (AE) is gaining ground as a complementary condition monitoring technique as it offers earlier fault detection compared with other more established techniques, such as vibration analysis or oil analysis. However, AE signals always include a significant level of noise reducing the potential of defect detection at early stage. For this reason, this paper proposes a novel envelope analysis method for bearing incipient defect detection. This method is able to identify localized defects in an incipient stage, in which the signal-to-noise ratio (SNR) is extremely low. This method combines Wavelet packet, for AE signal denoising, the Hilbert Transform (HT) for envelope extraction and autocorrelation function, to find patterns in the AE signal. An extensive experimental investigation was carried out in order to evaluate the performance of the proposed method under extremely low SNR, adding high level of noise to the signals. The results indicate that the proposed enhanced envelope method is able to detect incipient defects with 9 dB lower SNR than traditional envelope analysis.

1. Introduction

Rolling element bearings are found widespread in both domestic and industrial applications (i.e. turbines, compressors, pumps, motors, etc.) and they are critical components of rotating machinery [1]. The purpose of bearing diagnostics is to detect the defect at its incipient stage and inform the operator before catastrophic failure occurs. The typical failure mode of a rolling element bearing is a localized defect, which occurs when a sizeable piece of material on the contact surface is dislodged during operation, mostly by fatigue cracking under cyclic contact stressing [2].

Bearing monitoring has received considerable attention as the majority of the rotating machinery problems are caused by faulty bearings [3]. Therefore, there is a need in the industry for bearing incipient defect detection found in for example wind turbine industry. The most established technique for bearing condition monitoring is vibration analysis. However, it has some drawbacks such as (i) the low sensitivity to fault detection in low speed rotating machines and (ii) limited capability of defect detection in early stage. On the other hand, AE is gaining ground in bearing defect detection as it overcomes the two drawbacks previously presented for vibration analysis [4]. AEs are defined as transient elastic waves generated from a rapid release of strain energy, caused by a deformation of damage within, or on the surface of a material [5]. This mechanical process can be produced by different sources such as cracks, plastic deformation, rubbing, cavitation, and leakage [6]. Particularly, AE in rotating machinery is produced by two surfaces in relative motion, i.e. asperity contact. An extensive review of AE applied to rotating machinery (bearings, gearboxes and pumps) was carried out by Mba and Rao [7]. In addition, AE has also been applied for the detection of rotor-dynamic faults [8].

Several studies have been carried out to detect defect in bearings using AE technique such as flaking or spalling [9,10]. Mba [4] studied the changes produced in AE signals by changing the speed, load and defect size in the outer and inner race. The experiments showed that increasing rotational speed and load can cause an increase in RMS value. Small and large defects introduced in the outer race also resulted also in an increase in RMS value. However, in the case of defects in the inner race, the same tendency was not observed. In [11] the application of AE to monitor rolling contact fatigue tests using a test-rig running under constant load and speed for detecting the incipient damage and damage location was investigated. The test rig consisted of just a ball instead of an entire rolling bearing. Thus, the system was simpler and the fault detection complexity was reduced. The authors concluded

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that the AE hit count rate is an important parameter to define incipient damage, its detection and the size of the damage during the damage propagation. Al-Ghamd and Mba [12] observed that the primary source of AE was the material protrusions above the mean surface roughness and the burst duration was directly correlated to the seeded defect length along the race in the direction of the rolling action. Al-Dossary et al. [13] showed that the energy values correlated with increase defect severity for the inner and outer race. Furthermore, burst duration was shown to be as a good parameter to find geometric size of the outer race. However, this did not apply for the inner race defect. However, the previously mentioned techniques for bearing detection using AE are applicable in conditions in which he AE signal SNR is high.

In AE, what is considered noise varies from one application to the next. The noise in the AE signal may come from the following sources [14]:

(i) Distorted signal components beyond the limits of mechanisms in the signal acquisition process including periodic transient events, such as valve activity, electro-magnetic interference and radio frequency interference.
(ii) Residual, periodic electronic noise generated or captured in the electronic components (amplifier, power supply, filter, data acquisition card).
(iii) Quasi-periodic transient impulses such as wear of seals or bearing localized defects (when not looking for incipient seal or bearing faults).
(iv) Modulation produced at low frequency in the AE signal due to shaft or gear misalignment or reciprocating machines.
(v) AE noise from mechanisms of no interest to the analysis being performed. These include AE activity generated by the operation of healthy machines.

Due to the diversity of sources and the high level of the noise in AE signals, one of the most investigated topics in the application of AE to rotating machinery is the AE signal denoising. Thus, numerous denoising techniques haven been applied for noise suppression in the AE signal including Hilbert–Huang transform, spectral kurtosis, morphological filters, Wavelet transform (WT), etc. [15–18].

Possibly, the discrete Wavelet transform (DWT) is the most established technique for AE signal denoising. However, due to the fact that the decomposition of only the approximated component at each level using the dyadic filter bank, the results of frequency resolution in higher-level DWT decompositions are less accurate [19]. It may cause problems while applying DWT in AE signals in which the important information is located in higher frequency components. Thus, the frequency resolution of the DWT may not be precise enough to extract necessary information from the decomposed component of the signal. For this reason, the Wavelet packet transform (WPTT), which is a generalization of WT, offers better denoising ability on non-stationary signals such as the AE signals produced by a defected bearing. Several studies have been published applying WT for fault detection in rotating machinery using AE. One of them was carried out by Law et al. [20] that presented an approach based on WPT decomposition and Hilbert–Huang transform for spindle bearings condition monitoring. They concluded that AE has the advantage over vibration of ease of monitoring frequency characteristics changes by visual inspection. Bo and Yu [21] studied a defected low speed rolling bearing using WT as a denoising technique. Two different cases were studied, roller defected bearings and grease contamination. The authors concluded that the corresponding frequency of stress waves is 100 and 120 kHz for the roller defects, and the corresponding characteristic frequency of stress waves is 110 kHz for the grease contamination, with side frequencies 120 and 250 kHz.

In this paper, to further enhance the detection of the transients produced by the defected bearing in the AE signals, the autocorrelation function (ACF) is applied. The ACF is widely used to find patterns in a signal, particularly, to find periodicity in a noisy signal. This function has not been widely applied in AE bearing monitoring. One of the few studies regarding this topic was carried out by He et al. [22] who combined short-time RMS and ACF to extract the bearing fault characteristic frequency from a defected specimen. The results showed that the proposed method was very effective in estimating the bearing fault characteristic frequency from the AE signal.

Thus, in order to denoise the AE signal the proposed method (WPT-ACF) aims to reduce the AE generated from with the normal bearing operation. For this reason, this paper proposes an enhanced envelope analysis method that combines WPT as a pre-processor, HT for envelope extraction and ACF to find periodic patterns in the AE envelope prior to applying the Fast Fourier Transform (FFT) in order to denoise the AE signal and detect incipient defected bearings. Thus, although the previously described signal processing techniques have been applied in signal denoising to date, the authors propose a novel method that combines the advantages of these techniques to provide a robust and effective approach for bearing localized defect detection in low SNR conditions such as the conditions existing in the early stages of defected bearings. An experimental study was carried out to evaluate the reliability and effectiveness of the proposed method. Furthermore, the results obtained were compared with the traditional envelope analysis. The results presented in this study show that the proposed method performs significantly better than the traditional envelope recognizing the bearing defect particularly in low SNR conditions such as the conditions found during the presence of the existing in early stage defects.

2. Problem definition and proposed method

Failure alarm for a rolling element bearing is often based on the detection of the onset of localized defects [23]. Once a localized defect emerges in the inner or outer race of the bearing, an impact occurs every time the rolling element crosses the defected area of the bearing race. As a result, a high frequency AE burst is generated periodically due to (i) elastic or plastic deformation of asperities, (ii) fracture of asperities or (iii) the adhesion between asperities [24,25]. Envelope analysis is a well-known technique for bearing fault detection and it is suitable for the detection of these types of defects. It has been applied to vibration and AE signals to detect periodic increases in the amplitude of the signal caused by defected components in bearings [26–28]. Typically, envelope analysis refers to the following procedures: (i) band-pass filtering, (ii) signal rectification, (iii) HT and (iv) power spectrum extraction. Fig. 1 shows a visual explanation of the burst produced by the impact in the AE signal (blue) and the envelope of the AE signal is shown in red[2].

However, when the defect is at an incipient state, the AE background noise caused by normal operation can be of higher amplitude than the AE burst produced by the impact between the bearing race and the rolling elements. For this reason, the incipient defects are extremely difficult to be detected. As a result, the envelope spectrum will not show the peak at the frequency in which the impact is produced. As an example, three different SNR scenarios simulating the AE signal produced by a defected bearing are shown in Fig. 2. They represent the problem of the traditional envelope analysis under low SNR conditions. In high SNR condition

[2] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.