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Cyclostationarity of Acoustic Emissions (AE) for monitoring bearing defects

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ABSTRACT

Cyclostationarity is a relatively new technique that offers diagnostic advantages for analysis of vibrations from defective bearings. Similarly the Acoustic Emission (AE) technology has emerged as a viable tool for preventive maintenance of rotating machines. This paper presents an experimental study that characterizes the cyclostationary aspect of Acoustic Emission signals recorded from a defective bearing. The cyclic spectral correlation, a tool dedicated to evidence the presence of cyclostationarity, was compared with a traditional technique, the envelope spectrum. This comparison showed that the cyclic spectral correlation was most efficient for small defect identification on outer race defects though the success was not mirrored on inner race defects. An indicator, based on this cyclostationary technique, has also been proposed. It is concluded that its offers better sensitivity to the continuous monitoring of defects compared to the use of traditional temporal indicators (RMS, Kurtosis, Crest Factor).

1. Introduction

Over the last 20 last years the Acoustic Emission (AE) has been proved as a powerful method for the detection of incipient defects on rotating machines [1]. The technology offers several significant advantages over conventional vibration analysis [1]. Acoustic Emission (AE) results from rapid release of strain energy, which causes transient elastic waves in a solid material [2]. In particular for bearing monitoring, AE results from micro-shocks and friction between the rotating elements of the bearing. AE differs from vibration analysis as the frequency band used for AE is between 100 and 1000 kHz.

AE offers earlier detection than vibratory analysis for outer race defects [1] though this is not mirrored for inner race defects. Some studies used the principle of AE to identify bearing defects over a wide range of operating speeds. McFadden and Smith [3] showed the effectiveness of AE in detecting small defects at low speeds (10 rpm) whilst Rogers [4] applied AE to monitor offshore cranes. For small defects, Tandon and Nakra [5] have demonstrated the usefulness of parameters associated with AE, such as peak amplitude or counts, especially the ringdown counts. Bansal et al. [6] and Choudhury and Tandon [7] also exploited traditional AE analysis techniques for fault diagnosis, presenting results of AE events and maximum amplitude (peak amplitude), or, AE events and ringdown counts.

Another advantage offered by AE is the fact that it can be employed to quantify the bearing defect size in-situ. Al-Ghamdi et al. [8] and Mba [9] correlated the AE burst duration with the length and width of an outer race defect;

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however, such a correlation was not demonstrated for inner race defects. In another study Al-Dossary et al. [10] investigated the influence of the shape of the defect (length and width) on both inner and outer races and reaffirmed the findings of Al-Ghamdi et al. It should also be noted that the application of AE does have its challenges [21].

Over the last decade, primarily due to developments in computer hardware and storage systems, techniques suitable for the vibration are being applied to the AE. Liu et al. [12] used the independent components analysis, Liao et al. [13] employed wavelets analysis whilst Žvokelj et al. [14] and Li et al. [15] were interested in the empirical mode decomposition and Gabor transform, respectively, on AE signals. Chiementin et al. [16] used time domain indicators RMS, Kurtosis, and proposes to improve the signal-to-noise ratio by applying denoising techniques (wavelet, spectral subtraction, sanc) on experimental acquired AE data. The use of traditional methods of vibration analysis for AE analysis offers yet further techniques for the diagnostician. This paper first highlights the cyclostationary character of AEs associated with a defective bearing, and second, shows the effectiveness of the spectral correlation for diagnosis. Finally, a unique indicator for monitoring bearings based on cyclostationarity characteristics is presented.

2. Cyclostationarity and Acoustic Emission

Bursting of acoustic emission during bearing operation is caused by the passage of the roller over the defective race. The frequency of the AE burst will be associated with the defect location and is given by the following expressions.

Outer race defect frequency:

$$BPFO(\mathrm{Hz}) = \frac{n}{2} f_r \left(1 - \frac{BD}{PD}\cos\beta\right) \tag{1}$$

Inner race defect frequency:

$$BPFI(\mathrm{Hz}) = \frac{n}{2} f_r \left(1 + \frac{BD}{PD}\cos\beta\right) \tag{2}$$

Ball (roller) defect frequency:

$$BDF(\mathrm{Hz}) = \frac{PD}{BD} f_r \left[1 - \left(\frac{BD}{PD}\cos\beta\right)^2\right] \tag{3}$$

where n is the number of balls or rollers, f is the relative rotation frequency between inner and outer races, BD is the ball (roller) diameter, PD is the pitch diameter and β is the contact angle.

Similar to vibrations, AE signals from a damaged bearing will include periodicities associated with the defect frequency, and, usually the signal is considered to be amplitude modulated. Hence, it can be expected that the use of envelope analysis would highlight the bearing defect characteristics [17]. In addition, the similarity of structure between the vibration signal and the AE signal (a sequence of impulse responses at natural frequency) suggests expecting the same cyclostationarity properties for AE signal arising from a defective bearing. Nevertheless, it is judicious to mention that in spite of the fact that bearing fault frequencies are not constant because of small random variations in the spacing of the rolling elements due to slip, bearing signals can be usefully treated as cyclostationary.

2.1. Cyclostationarity

By definition, a signal is cyclostationary if some of its statistics present periodicities. Each period or cycle can be regarded as a realization of the same random process. Averaging can make it possible to extract the deterministic part of the signal. If the signal obtained after subtracting this deterministic part does not exhibit cyclostationarity, the signal is said to be cyclostationary at an order '1'. In general terms, a signal is cyclostationary at an order 'n' if its statistical properties at order 'n' are periodic. The cyclostationarity property that is a particular case of non-stationarity allows discovery of hidden periodicities within a signal. As rotating machines intrinsically generate periodicities, one may find it beneficial to exploit cyclostationarity properties for fault detection and diagnosis. In this section, we recall the main definitions and properties of a cyclostationary processes. The reader is referred to Antoni [18] for a full explanation and definition on cyclostationarity.

The construction of cyclostationarity concepts is essentially based on statistical moments. The latter are defined as mathematical expectations. The nth order moment of a signal $x(t)$ is given by

$$m_n(t) = E\{x^n(t)\} \tag{4}$$

where E is the mathematical expectation. If this moment presents a periodicity T, the signal is said to be cyclostationary at order n. Hence, one can write:

$$m_n(t) = m_n(t+T) \tag{5}$$

An interesting quantity deduced from the concept of statistical moments is the instantaneous autocorrelation. It is defined by

$$R_{xx}(t,\tau) = E\{x(t-\tau/2)x^*(t+\tau/2)\} \tag{6}$$