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A robust detector for rolling element bearing condition monitoring based on the modulation signal bispectrum and its performance evaluation against the Kurtogram

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ABSTRACT

Envelope analysis is a widely used method for rolling element bearing fault detection. To obtain high detection accuracy, it is critical to determine an optimal frequency narrowband for the envelope demodulation. However, many of the schemes which are used for the narrowband selection, such as the Kurtogram, can produce poor detection results because they are sensitive to random noise and aperiodic impulses which normally occur in practical applications. To achieve the purposes of denoising and frequency band optimisation, this paper proposes a novel modulation signal bispectrum (MSB) based robust detector for bearing fault detection. Because of its inherent noise suppression capability, the MSB allows effective suppression of both stationary random noise and discrete aperiodic noise. The high magnitude features that result from the use of the MSB also enhance the modulation effects of a bearing fault and can be used to provide optimal frequency bands for fault detection. The Kurtogram is generally accepted as a powerful means of selecting the most appropriate frequency band for envelope analysis, and as such it has been used as the benchmark comparator for performance evaluation in this paper. Both simulated and experimental data analysis results show that the proposed method produces more accurate and robust detection results than Kurtogram based approaches for common bearing faults under a range of representative scenarios.

1. Introduction

Bearings are at the heart of almost every rotating machine, and they have received a lot of attention in the field of vibration analysis because they are a common source of machine faults [1,2]. For accurate diagnosis of a bearing fault, a number of techniques have been proposed in recent years to detect and identify specific bearing fault features (bearing frequencies) from within monitored data. Darlow explored the use of a high frequency resonance technique, widely known as envelope analysis [3]. Antoni applied cyclostationary spectral analysis [4,5], and cepstrum analysis, bispectrum analysis and time-frequency analysis have also been used. Ho and Randall investigated the application of self-adaptive noise cancellation in conjunction with envelope analysis to remove discrete frequencies masked within bearing vibration signals [6]. Barszcz

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applied the same approach to denoise wind turbine vibration signals for bearing outer race fault diagnosis [7]. Sawalhi, Randall and Endo presented an algorithm for enhancing the surveillance capability of spectral kurtosis by using the minimum entropy deconvolution technique. This technique deconvolves the influence of the transmission path and clarifies the impulses, even when they are not separated in the original signal [8]. Zhao applied empirical mode decomposition and the approximate entropy method for severity assessment of a spall-like fault in a rolling element bearing [9]. A recent significant advance in envelope based rolling element bearing fault detection has been the Kurtogram [10] and this has received considerable attention in recent months [11–13]. For this reason, the Kurtogram has been used as the benchmark comparator in this study.

The researchers above, and more, have achieved considerable progress in improving the accuracy of bearing fault detection and diagnosis. Most of the fault detection schemes presented in the literature are based on tracking the amplitude of the characteristic fault frequency but with little attention given to the utilisation of modulation characteristics and noise suppressing which are inherent in measured signals. Recently, Rehab et al. explored using the MSB to extract fault features from the envelope signal, exploiting its noise suppression capabilities, and in doing so showed more reliable bearing fault severity assessment compared to power spectrum approach [14]. This approach, however, still requires optimisation of the filter's parameters for envelope analysis. In this paper a more straightforward and robust MSB detector is proposed, which does not rely on envelope analysis, and which is shown to provide reliable detection features based only on the demodulation and noise suppression characteristics of the MSB.

Section 2 develops the detector and outlines the theoretical basis for bearing fault diagnosis. Section 3 presents performance studies based on simulated signals, and Section 4 validates the practical application of the detector via two application case studies.

2. The modulation signal based detector

2.1. A bearing vibration signal model

The vibration signature of a rolling element bearing with local defects can be typified by an amplitude modulation process. For a rolling bearing with a local defect of fault characteristic frequency $f_F = 1/T_0$, its vibration acceleration response containing $2M+1$ impulses can be modelled according to [15–17], as follows:

$$x(t) = \sum_{m=-M}^{M} A_m(t_i)e^{-\beta(t_i)}\cos(\omega_r t_i)u(t_i) + n(t) \tag{1}$$

where A_m is the amplitude of the m th fault impulse which includes cage and load modulation, M is the number of impulses, $u(t)$ is a unit step function, T_0 is the time period corresponding to the fault characteristic frequency, β is the structural damping characteristic, ω_r is the excited resonance frequency, $n(t)$ is typical noise which includes both stationary Gaussian noise and aperiodic impulses as would inevitably be encountered in any real measurement environment, and where $t_i = t - \left(mT_0 + \sum_{i=-M}^{m}\tau_i\right)$ in which τ_i represents the effect of random slippage of the rollers as the ith realisation of a zero mean uniformly distributed random variable, with standard deviation within a range $< 0.02T_0$.

This represents the fault signature of a local bearing defect comprising not only periodic components but also nonlinear modulation effects between fault frequencies, structural resonances and load distribution. Moreover, the signal is contaminated by noise and interference, and this is especially relevant when the fault signature is weak during the early stages of fault development. On this basis, to extract fault signatures effectively, the signal must be both denoised and demodulated.

As the effect of random slippage is relatively small, the deterministic part of $x(t)$ in Eq. (1) represents predominately a series of impulse responses to local bearing defects such as a small dent on deferent components of a bearing, with a repetition frequency which reflects the contact of the bearing fault with another part of the bearing (e.g. an area of fatigue damage on a raceway and the periodic interaction of the rolling elements with this), this is called the defect frequency of the bearing. For a typical rolling element bearing there are four possible characteristic defect frequencies and these are determined by the bearing dimensions, the shaft speed and the defect location, in addition to an installation-dependent feature called the contact angle [18]. The repetition frequency for an outer race defect is denoted f_o, that for an inner race defect is f_i, for a rolling element defect is f_b and for a cage defect is f_c. The repetition frequency can be modulated by loaded zone effects on rotating elements, as shown in Fig. 1. For an inner race defect, the modulating frequency is the shaft rotational frequency f_r, but for a rolling element defect it is the ball spin frequency f_{bs} (where $f_{bs} = f_b/2$). The theoretical characteristic frequencies of a rolling element bearing can be calculated with Eqs. (2)–(5) [18].

Outer race fault frequency (aka the Ball Pass Frequency for a Fault on the Outer Race – BPFO):

$$f_o = \frac{N_r}{2} f_r \left(1 - \frac{D_b}{D_c}\cos\varphi\right) \tag{2}$$

Inner race fault frequency (aka the Ball Pass Frequency for a Fault on the Inner Race – BPFI):

$$f_i = \frac{N_r}{2} f_r \left(1 + \frac{D_b}{D_c}\cos\varphi\right) \tag{3}$$