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Defect detection in deep groove ball bearing in presence of external vibration using envelope analysis and Duffing oscillator

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ABSTRACT

This paper deals with detection of local defects existing on races of deep groove ball bearing in the presence of external vibrations using envelope analysis and Duffing oscillator. Experiments have been carried out using a test rig for capturing the vibration signals of test bearing. The external vibration has been imparted to the housing of the test bearing through electromechanical shaker. In envelope analysis the centre frequency has been selected using the spectral kurtosis for the filters length of 32 and 64 for different bandwidths. Through this study, it has been revisited and confirmed that the defect detection in envelope analysis mainly depends on the selection of centre frequency and bandwidth. The spectra of selected centre frequency with several bandwidths have been studied and compared for identification of defective frequency. The system defined by the Duffing equation entered into the periodical state from the chaotic state at the critical value of disturbing periodic force in the presence of defective bearing signal. The state change has been identified using the phase plane trajectories and Lyapunov exponents of Duffing equation. It is worth to mention here that envelope spectrum reveals the information about the defect frequencies and their harmonics. However, the Duffing oscillator only confirms the presence of defect frequencies by indicating closed phase plane trajectories and negative Lyapunov exponents. Authors believe that for speedy assessment about the presence of defects on races of rolling element bearings, the use of Duffing oscillator may be preferred.

1. Introduction

Vibration measurements of rolling element bearings and its meaningful analyses play vital role in faults detections. For preventing personal and economical losses in industries, defects detection in bearings at their early stages is essential issue. The local defects on races/rolling elements of bearings generate series of impulses due to interaction of the defects with bearing elements during operations. Normally, the vibrations generated by faulty bearings have low energy; therefore, these get masked easily by higher energy vibrations generated by other components of the same machine and/or neighbouring machine. Due to weak defective bearing signals, the defect frequency of bearing may not be clearly visible in the conventional Fast Fourier Transform (FFT) of vibration signals. Thus, to detect the bearing faults from the weak signals masked by external vibrations is necessary task for condition monitoring point of view in industries.

Many researchers [1–12] have employed various methods to detect weak periodic signals using the sensitivity of system parameters. Some of these methods are shock pulse monitoring, crest factor analysis, kurtosis, spectrum analysis, envelope spectrum analysis, wavelet analysis, filtration of signal, etc. McFadden and Smith [1] have reviewed papers which have used high frequency resonance technique (HFRT) in defect detection of rolling element bearings. The authors have discussed various factors which control the appearance of a spectrum. Moreover, the authors have concluded

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that the resonance frequency should be selected based on the experimentation due to non-availability of guidelines for its selection. It has been also suggested by the authors that the bandwidth might be chosen about four times the expected characteristic defect frequency of bearings. Toersen [2] has applied an envelope technique in the detection of ball bearing defects in a laboratory study by varying the defects' size and shape at different rotational speeds. It is essential to mention here that researchers [1,2] have used band pass rectification for the envelope analysis. Ho and Randall [3] have used self adaptive noise cancellation in conjunction with envelope analysis to remove discrete frequency masking signals from the defective bearing signal. The authors have performed envelope analysis using band pass rectification and Hilbert transform. These authors have reported that for better results the band pass rectification requires extra zero padding. Tse et al. [4] have observed disadvantages in computation of envelope analysis using band pass rectification. These authors have reported that expensive equipments and experienced people are required to perform envelope analysis.

Selections of centre frequency and the bandwidth are crucial in envelope analysis. Researchers [5–9] have suggested the techniques like spectral kurtosis (SK), kurtogram, adaptive spectral kurtosis and Protrugram for the meaningful selection of centre frequency and bandwidth. The spectral kurtosis (SK) is based on the kurtosis to find the impulsiveness of the signal. The SK of the signal can be computed by the local Fourier transform at time "*t*" by moving window along the signal. The impulsiveness of band pass filtered signal is computed by the kurtosis of the complex envelope [6]. Recently, authors [7] have presented a method for optimum band selection for vibration signal demodulation. These authors have also proposed a tool called Protrugram with superior detection ability of modulating signals in the presence of heavy noise. However, the proposed methods require prior knowledge about kinematics of monitored machine and additional visual post processing to reject the discrete tones. The fast kurtogram is the extension of the spectral kurtosis. This method may not be practical because it is unrealistic to find the optimal bandwidth and frequency of filters by examining all the window lengths used in short time Fourier transform based SK technique [8]. The adaptive based SK technique for optimum selection of the bandwidth and centre frequency has been proposed in Ref. [8]. This technique is influenced by parameters such as initial window function, bandwidth and window overlap on the merged windows. Recently, an article [9] has presented a method which demonstrates the enhancement of the optimal centre frequency methods via novel "max-med" estimators. The technique enables a more robust selection of the centre frequency in comparison to the existing methods including fast kurtogram and Protrugram.

The sensitivity of nonlinear system towards its parameters is useful in finding the weak signals. Even very small perturbation of parameters in such system changes its state from chaotic to large scale periodic. Researchers [10–12] have reported that the nonlinear Duffing oscillator is a better method than the traditional denoising based on probability and evaluate the useful signal for detecting the weak signal in presence of external vibrations. Wei et al. [10] have used chaotic oscillator for bearing fault diagnosis. A 2-D approximate entropy index has been used by the authors to recognise the change of chaotic oscillator. They have concluded that their proposed method is suitable for detecting single periodic signal in a given narrow band. Moreover, numerical indication of Lyapunov exponent (LE) has been employed by Haung et al. [11] to determine the state change of Duffing oscillator in weak signal detection of global position system. Similarly, Song et al. [12] have also used the LE and golden section method to determine the state change of Duffing oscillator in a tool wear study.

Based on the literature review, it is noticed that very limited studies on bearing fault detections in the presence of external vibrations have been carried out by the researchers using envelope analysis (with Hilbert transform) and Duffing oscillator. Moreover, it is also observed that there is no clarity for selections of centre frequency and bandwidth in the envelope analysis. Therefore, in the present study the envelope analysis using Hilbert transform is employed for the improvement of the defect detection of bearing in masked noisy signal. In envelope analysis the centre frequency has been selected by using SK for filter lengths 32 and 64. However, the bandwidth has been varied in a range of marginally greater than the interested defect frequency and minimum of $(2 * \text{centre frequency},\ 2 * (\text{Nyquist frequency} - \text{centre frequency}))$. The spectra of selected centre frequency with several bandwidths are comparatively studied for meaningful visualisation of defective frequency. The ratios of the maximum amplitude of the frequency in the spectrum and the amplitude of the defective frequency for all the combinations of centre frequency and bandwidths have been compared. Moreover, for speedy and effective defect detection in bearings, Duffing oscillator is also employed in the proposed study. It is worth to mention here that the state change of the Duffing oscillator has been identified by numerical indication of Lyapunov exponent.

2. Defect detection techniques

The vibration signals captured from bearings of rotating machines normally appear very complex in the presence of external vibrations. It becomes difficult to identify the weak signal generated due to defects on bearing components in the presence of external vibrations. Due to the ability of low frequency noise removal by envelope analysis and weak signal detection of Duffing oscillator, these two techniques have been employed for defects detection in deep groove ball bearings. Functioning principles of envelope analysis and Duffing oscillator are provided concisely herein.

2.1. Envelope analysis

Vibration signals become amplitude modulated due to periodic changes in forces. In case of rolling element bearing, periodic changes in forces occur due interaction of local defects on the surfaces of bearing elements. Mod-