Applied Acoustics 104 (2016) 101–118

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Roller bearing acoustic signature extraction by wavelet packet transform, applications in fault detection and size estimation

Farzad Hemmati [a,*], Wasim Orfali [b], Mohamed S. Gadala [a]

[a] Mechanical Engineering Dept., University of British Columbia, 2054-6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada
[b] Faculty of Engineering, Taibah University, Al Madina Al Munawara, Saudi Arabia

ARTICLE INFO

Article history:
Received 15 December 2014
Received in revised form 3 July 2015
Accepted 10 November 2015

Keywords:
Rolling element bearing
Acoustic emission signals
Condition monitoring
Wavelet packet transform
Statistical analysis
Defect size calculation

ABSTRACT

Continuous online monitoring of rotating machines is necessary to assess real-time health conditions so as to enable early detection of operation problems and thus reduce the possibility of downtime. Rolling element bearings are crucial parts of many machines and there has been an increasing demand to find effective and reliable health monitoring technique and advanced signal processing to detect and diagnose the size and location of incipient defects. Condition monitoring of rolling element bearings, comprises four main stages which are, statistical analysis, fault diagnostics, defect size calculation, and prognostics. In this paper the effect of defect size, operating speed, and loading conditions on statistical parameters of acoustic emission (AE) signals, using design of experiment method (DOE), have been investigated to select the most sensitive parameters for diagnosing incipient faults and defect growth on rolling element bearings. A modified and effective signal processing algorithm is designed to diagnose localized defects on rolling element bearings components under different operating speeds, loadings, and defect sizes. The algorithm is based on optimizing the ratio of Kurtosis and Shannon entropy to obtain the optimal band pass filter utilizing wavelet packet transform (WPT) and envelope detection. Results show the superiority of the developed algorithm and its effectiveness in extracting bearing characteristic frequencies from the raw acoustic emission signals masked by background noise under different operating conditions. To experimentally measure the defect size on rolling element bearings using acoustic emission technique, the proposed method along with spectrum of squared Hilbert transform are performed under different rotating speeds, loading conditions, and defect sizes to measure the time difference between the double AE impulses. Measurement results show the power of the proposed method for experimentally measuring size of different fault shapes using acoustic emission signals.

1. Introduction

Condition monitoring of heavy rotating machinery and equipment such as turbines, compressors and generators, is gaining importance in various industries since it keeps the plant at healthy condition for maximum production; helps in detecting faults at early stages; avoid serious accidents and damage; and reduces downtime. Bearings are the common elements used in heavy rotating machinery and equipment because of their high reliability. Bearings start to malfunction due to machine overload, shaft misalignment, rotor unbalance, overheating, etc. Many different techniques based on vibration methods have been developed to extract bearing fault features [1]. However, vibration signals are not sensitive to incipient faults and they are usually masked by background noise caused by mechanical vibration signals from rotating machinery. Hence, it is normally difficult for the vibration techniques to detect bearing faults at an early stage. Acoustic emission (AE) is the phenomenon of transient elastic wave generation due to a rapid release of strain energy caused by relative motion of small particles under mechanical stresses [2]. Interaction of rolling element bearing components and movement of bearing rollers over defects will produce AE's. The frequency content of acoustic emission (AE) is typically in the range of 100 kHz to 1 MHz, so AE is not influenced or distorted by imbalance and misalignment which are at low frequency ranges. The high sensitivity of AE technique and AE parameters in detecting the incipient bearing faults has become one of the significant advantages of AE over vibration measurement [3]. A comprehensive review of AE application for bearing fault detection was presented by Mba and Rao [4]. Al-Ghamd and Mba [5] investigated the relationship between AE

* Corresponding author. Tel.: +1 (604) 649 4574.
E-mail addresses: farhemmati@gmail.com (F. Hemmati), orfaliwasim@hotmail.com (W. Orfali), gadala@mech.ubc.ca (M.S. Gadala).

http://dx.doi.org/10.1016/j.apacoust.2015.11.003
0003-682X/

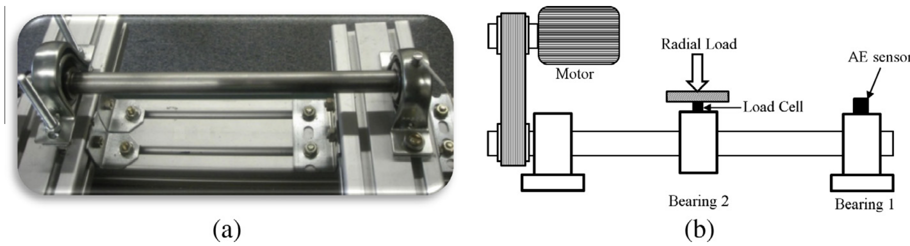

Fig. 1. (a) Experimental test setup, (b) experimental setup sketch.

Table 1
Bearing parameters.

Bearing specification	Timken 09074
Ball diameter (B_D)	7.2 (mm)
Pitch diameter (P_D)	33.5 (mm)
Number of rollers (n)	12
Contact angle (β)	8.3°
Bearing dynamic load capacity (C_{90})	10300 (N)

parameters in time domain and defect size. They concluded that AE burst duration is an effective parameter for identifying defect size on the outer race. However, in recent work performed by researchers there is no sensitivity analysis presented to analyze the most sensitive statistical parameter to incipient faults and defect growth. Acoustic based diagnostic signals in real industrial environments associated with high temperatures, rotating speeds, and pressures are always masked by high levels of noise. Desirable de-noising of these signals is not achievable with conventional techniques. Therefore, to overcome this challenge adaptive signal processing techniques need to be developed to enhance signal to noise ratio of AE signals. Dyer and Stewart [6] first presented the use of kurtosis parameter for bearing fault diagnosis and it was suggested to use kurtosis value in selected frequency bands. Antoni and Randall [7] presented the use of Spectral Kurtosis (SK) to extract transient components from a noisy signal. Sawalhi and Randall [8] proposed minimum entropy deconvolution (MED) technique along with SK to enhance the results of envelope analysis from a vibration bearing fault signal. Discrete wavelet transform (DWT) has been used in signal denoising due to its high resolution in time and frequency domains [9]. For instance, Qiu et al. [10] utilized wavelet filter-based denosing method to enhance weak periodic impulse signature masked by standard Gaussian white noise. In DWT, a digitized signal is decomposed into its low-pass approximation and high-pass detailed signals and further decompositions only apply to the detailed components. Hence, it suffers from insufficient treatment of the high frequency components where the bearing fault impulses exist [11]. Thus, wavelet packet transform (WPT) has been introduced to overcome this issue by treating both low and high frequency components [11]. Lei et al. [12] proposed an improved kurtogram method for diagnosing bearing faults. Even though, this method finds the frequency band which has the maximum value of kurtosis using WPT, the optimal wavelet function is not selected along with kurtosis value does not provide any information regarding periodic behavior of bearing fault impulses. In this paper, an experimental study

Table 2
Parameters range for sensitivity analysis of case study I.

	(−)	(+)
Defect size (D)	0 (mm)	1 (mm)
Rotating speed (R)	300 (rpm)	1100 (rpm)
Radial load (L)	0 (N)	100 (N)

Table 3
Parameters range for sensitivity analyses of case study II.

	(−)	(+)
Defect size (D)	1 (mm)	2 (mm)
Rotating speed (R)	300 (rpm)	1100 (rpm)
Radial load (L)	0 (N)	100 (N)

Table 4
Example of Plackett–Burman design objective function with three parameters.

	Defect size	Speed	Load	Statistical parameter (R)
Exp.1	+	+	+	$R_1 = 5$
Exp.2	+	+	–	$R_2 = 10$
Exp.3	+	–	+	$R_3 = 15$
Exp.4	+	–	–	$R_4 = 2$
Exp.5	–	+	+	$R_5 = 4$
Exp.6	–	+	–	$R_6 = 17$
Exp.7	–	–	+	$R_7 = 22$
Exp.8	–	–	–	$R_8 = 12$
Sum	A_1	A_2	A_3	

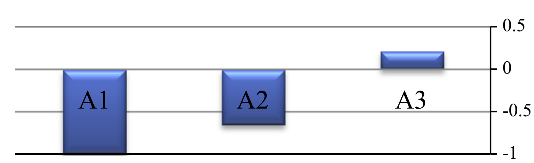

Fig. 2. Bar diagram of normalized objective function using Plackett–Burman design.

is presented to investigate the most sensitive statistical parameters for diagnosing defect growth and incipient faults in time domain analysis utilizing DOE method. A new approach based on selecting the optimal band-pass filter using WPT and selecting the optimal wavelet function is used in acoustic emission (AE) analysis to extract fault features, location of faults, and defect sizes. The outline of this paper is as follows: In Sections 2 and 3 the experimental setup and the experimental procedure for statistical analysis are explained. In Section 4 the background of DOE method is explained. In Section 5 the results of applying DOE method on the measured AE signals for sensitivity analysis are shown. In Section 6, the concept of wavelet packet transform (WPT), Shannon entropy, kurtogram, and Hilbert transform are reviewed. In Section 7, a new approach to select the optimal mother wavelet function is explained. In Section 8, the proposed method based on optimizing the kurtosis to Shannon entropy ratio of band-pass signal using WPT is discussed in detail and it is applied on a noisy impulse like signal. In this section, the proposed method is applied to the experimentally acquired signals of a faulty bearing where the faults are artificially introduced on a rolling element bearing to find the location and size of the defects. The results demonstrate that by selecting an optimal band-pass filter, bearing defects can be