Mechanical Systems and Signal Processing 117 (2019) 16–32

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Signal processing techniques for rolling element bearing spall size estimation

Aoyu Chen *, Thomas R. Kurfess

George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA

ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form 28 February 2018
Accepted 5 March 2018

Keywords:
Rolling element bearing
Spall size estimation
Variational Mode Decomposition (VMD)

ABSTRACT

This paper proposes signal processing techniques to extract entry and exit points from the bearing vibration signal for spall size estimation. The entry point is the start point of a low frequency response when a rolling element enters a localized defect on the raceway, which is contaminated with background noises and difficult to identify. An empirical model based signal processing method is proposed to effectively identify the entry point. The Variational Mode Decomposition (VMD) is applied to the bearing entry signal for more accurate estimation. Differentiation technique is used to identify the high frequency exit point with more reliable threshold values for automatic diagnostics. Then, based on defect size estimation models for both inner and outer race defects, the spall size can be estimated. The proposed methodology is validated on a machine tool spindle's bearing system. Experimental results show that the proposed signal processing techniques provide less biased results with respect to spindle speed and more precise estimation.

1. Introduction

Bearing diagnostics provide valuable information related to a bearing's health used in Condition Based Maintenance (CBM) for rotary machines. CBM is an effective method to minimize unnecessary cost and downtime resulting from unanticipated machine spindle failure. Researchers have proposed that when a rolling element passes a spall on the raceways, a repeatable response pattern corresponding to the entry and exit events arises in the vibration signal, as shown in Fig. 1(a) [1]. In this plot, the shaft speed is 500 rpm and the defect width is 1.530 mm. The time separation between these two events can be used to estimate the defect size [2–5]. Thus, characterizing the impact event is a promising candidate to quantify the severity of a spall-like damage for a CBM algorithm.

Fig. 1(b) shows the correlated physical process when the ball passes the line-spall defect, shown as a rectangular profile on bearing races. Due to the contact deflection, two elliptical contact areas exist between ball/inner and ball/outer race. When the deflected area arrives at the entry edge, the ball center is at location A, which is associated with the entry point A on the vibration signal. From A, the contact force starts to decrease, which is defined as the "destressing" process. During this process, the vibration signal decreases to the local minimum at point D. At this moment, the ball center is between A and B. Since the location of D is not used to estimate defect size, it is not labeled in Fig. 1(b) to show A, B and C more clearly. Then, the vibration signal begins to increase and reaches the dominant peak at point B, which corresponds to the moment when the ball loses contact with both raceways and the deflection between ball and raceways fully recovers [6]. After B, the ball

* Corresponding author at: Room 104, Love Building, Georgia Institute of Technology, GA 30332, USA.
E-mail addresses: achen75@gatech.edu (A. Chen), kurfess@gatech.edu (T.R. Kurfess).

https://doi.org/10.1016/j.ymssp.2018.03.006
0888-3270/

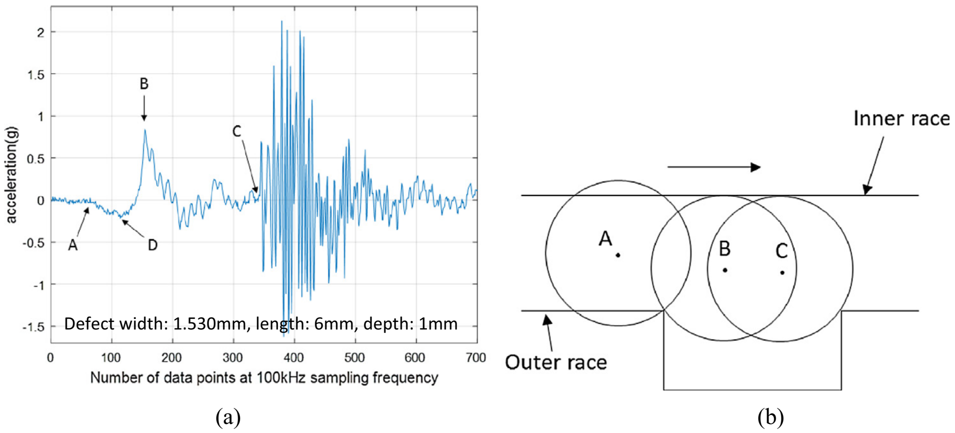

Fig. 1. (a) Typical bearing defective response. (b) A ball passes a defect on the outer race.

collides with the exit edge and a high frequency response occurs at point C, which corresponds to the ball center location C. Upon C, the "restressing" process begins and the ball re-enters the space between the inner and outer races. Given the ball center velocity, the defect size can be estimated based on the time information of point A, B and C in the vibration signal. Therefore, an accurate signal processing method is required to extract key points from the vibration pattern. However, available signal processing techniques for entry and exit characterization are limited. For point A, because the destressing process between the ball and races is continuous, the initial part of the entry signal exhibits a small slope and low signal-to-noise ratio. Therefore, precisely identifying point A is difficult, especially when the signal is contaminated with background noises. For points B and C, previously proposed methods are threshold sensitive and therefore are difficult to calculate a reliable threshold value for automatic diagnostics. To address these issues, an empirical model of the bearing entry signal and the signal processing methods to extract point A, B and C are described in this paper. The Variational Mode Decomposition (VMD) is applied to the bearing entry signal to remove the high frequency noise for more accurate estimation. The proposed signal processing techniques provide less biased results with respect to spindle speed and more precise estimation results. Thus, the proposed technique is suited for an automatic bearing diagnostic system. The proposed methodology is validated on a machine tool spindle's bearing system. The spall width is estimated at varying spindle speeds using the proposed signal processing methods. Results show that the proposed signal processing techniques provide an enhanced method to more accurately extract the time information from the vibration data, thus improving the estimation result.

In this paper, previous bearing dynamic modeling and signal processing methods for defect size estimation are summarized in Section 2. The signal processing techniques to extract points A, B and C are described in Section 3. The defect size estimation model is introduced in Section 4 to calculate the defect size from the extracted time information. Section 5 describes the experimental setup, results and discussion. Section 6 summarizes the conclusions of this research.

2. Prior work

Dynamic models have been studied for rolling element bearings with localized defect. The first non-linear multi-body dynamic bearing model was derived by Harsha in 2005 [7]. To explain the vibration pattern due to a localized defect on bearing raceways, Randall improved this model by considering the slip between bearing components [8]. Moazen and Ahmadi [9,10] further improved this model by considering the finite size of the rolling elements, and the results demonstrated an increased accuracy when compared to previous models. Jing Liu and Yimin Shao [11,12] proposed a new twelve-DOF dynamic model to analyze the influences of the housing support stiffness and localized defect sizes. The relationship between defect edge shapes and the vibration response with or without lubrication is also studied. Based on prior bearing dynamic modeling work, various signal processing methods have been proposed by previous studies for defect size estimation. These methods are summarized in the following paragraphs.

Sawalhi and Randall proposed two approaches to enhance the weak entry event [2]. In the first approach, pre-whitening and wavelet analysis are used to balance the energy between low and high frequencies during the impact events. The second approach treats the entry and exit events separately so that they can be represented equally. Then the power cepstrum is calculated to estimate the average separation of the two pulses. Using the proposed signal processing method, the two peaks related to the entry and exit events can be separated successfully. Randall considered the most dominant peak in the entry signal as the moment when the ball starts to enter the defect zone (point B in Fig. 1). However, other work has demonstrated this assumption to be inaccurate and shown that the full entry signal starts near point A rather than point B in Fig. 1 [6].

Smith proposed a more accurate method to identify the entry point by shifting the start point in Randall's research to an earlier time in the signal [13]. He demonstrated a consistent roll-off after the entry point in the pre-impact vibration signal