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Rolling element bearing defect diagnosis under variable speed operation through angle synchronous averaging of wavelet de-noised estimate

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ABSTRACT

Rolling element bearings are widely used in rotating machines and their faults can lead to excessive vibration levels and/or complete seizure of the machine. Under special operating conditions such as non-uniform or low speed shaft rotation, the available fault diagnosis methods cannot be applied for bearing fault diagnosis with full confidence. Fault symptoms in such operating conditions cannot be easily extracted through usual measurement and signal processing techniques. A typical example is a bearing in heavy rolling mill with variable load and disturbance from other sources.

In extremely slow speed operation, variation in speed due to speed controller transients or external disturbances (e.g., varying load) can be relatively high. To account for speed variation, instantaneous angular position instead of time is used as the base variable of signals for signal processing purposes. Even with time synchronous averaging (TSA) and well-established methods like envelope order analysis, rolling element faults in rolling element bearings cannot be easily identified during such operating conditions. In this article we propose to use order tracking on the envelope of the wavelet de-noised estimate of the short-duration angle synchronous averaged signal to diagnose faults in rolling element bearing operating under the stated special conditions. The proposed four-stage sequential signal processing method eliminates uncorrelated content, avoids signal smearing and exposes only the fault frequencies and its harmonics in the spectrum. We use experimental data[1] from a laboratory setup to validate the diagnosis tool for bearing raceway and rolling element faults.

1. Introduction

Faults in rolling element bearings are typically due to localized defects in the outer-race, inner-race, the rolling element, or the cage. Contact of such defects with mating surfaces generates a series of impacts or impulses which excite the entire system including the bearing, the sensor and the structure where the bearing is mounted. Through different signal processing techniques, the bearing characteristic frequencies (BCF) and/or bearing characteristics order (BCO) can be identified from vibration signals.

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[1] This article includes complete dataset as supplementary material (accessible from online version).

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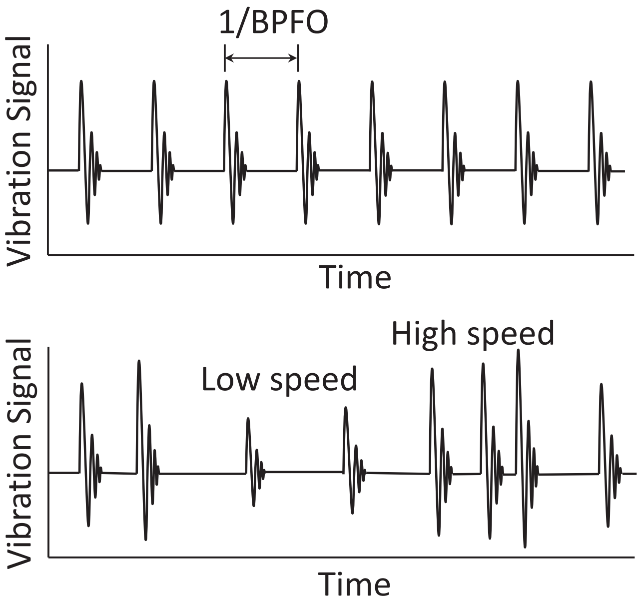

Fig. 1. Schematic representation of ideal vibration signals in constant (top) and variable speed (bottom) operation with bearing outer raceway fault.

There is abundant literature on diagnosis of rolling element faults through vibration analysis [1]. Several signal processing steps may be used to extract the relevant features from the acquired measurements before the diagnosis scheme can be applied [2]. There are many signal processing methods for diagnosis of faults in rolling element bearings in time, frequency and time–frequency domains.

For constant speed operation, ball pass frequencies for inner race (BPFI) and outer race (BPFO), and ball spin frequency (BSF) are searched in the frequency response to identify the presence of faults. These frequencies are derived from the bearing geometry and kinematics under no-slip assumption, and are given as

$$\mathrm{BPFI} = N(f_i - f_o)(1 + (d/D)\cos(\psi))/2 \tag{1}$$

$$\mathrm{BPFO} = N(f_i - f_o)(1 - (d/D)\cos(\psi))/2 \tag{2}$$

$$\mathrm{BSF} = \frac{D(f_i - f_o)}{2d}\left(1 - \left(\frac{d}{D}\cos(\psi)\right)^2\right) \tag{3}$$

where d is the diameter of ball/rolling element, D is the pitch diameter, f_o is the frequency of outer race rotation, f_i is the frequency of inner race rotation, N is the number of balls, and ψ is the contact angle. The element defect frequency (EDF) is twice that of the BSF. These are the standard ratios applicable in the case of constant race frequencies. In most cases, outer race is stationary, i.e., $f_o = 0$.

However, in slow speed operation as well as variable speed or speed reversal operations, fault induced impulses do not appear at constant time intervals but at constant angle intervals (See Fig. 1). In addition, impact of the race with fault generates different levels of vibration depending on the instantaneous speed of rotation at the time of the impact. At faster speeds, vibration levels are higher (e.g. due to unbalance) and impulses are closely spaced and the vice versa happens at slower speeds.

For variable speed operation, taking outer race of the bearing as stationary, we can rewrite the expressions (1), (2) and (3) in the angular domain to obtain the corresponding bearing characteristic orders (BCO) as

$$O_{BPI} = N(1 + (d/D)\cos(\psi))/2 \tag{4}$$

$$O_{BPO} = N(1 - (d/D)\cos(\psi))/2 \tag{5}$$

$$O_{BS} = \frac{D}{2d}\left(1 - \left(\frac{d}{D}\cos(\psi)\right)^2\right) \tag{6}$$

where O_{BPI}, O_{BPO} and O_{BS} are the orders of ball pass for inner race fault, outer race fault and of ball spin, respectively. The order for element defect is twice that of the ball spin order. The shaft spin order is denoted by $O_S = 1$.

For non-uniform and slow speed shaft rotation, the fault symptoms cannot be extracted by conventional measurement and signal processing techniques. There are few literatures available for diagnosis of fault in rolling element bearing under non-uniform speed rotation. Foremost among them are computed order tracking coupled with squared envelope spectrum