ARTICLE IN PRESS

Mechanical Systems and Signal Processing xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Bearing fault diagnosis of a permanent magnet synchronous motor via a fast and online order analysis method in an embedded system

Siliang Lu [a,b,*], Qingbo He [c], Jiwen Zhao [a,b]

[a] College of Electrical Engineering and Automation, Anhui University, Hefei, Anhui 230601, PR China
[b] National Engineering Laboratory of Energy-Saving Motor & Control Technology, Anhui University, Hefei 230601, PR China
[c] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, Anhui 230026, PR China

ARTICLE INFO

Article history:
Received 29 July 2016
Received in revised form 29 November 2016
Accepted 20 February 2017
Available online xxxx

Keywords:
Bearing fault diagnosis
Permanent magnet synchronous motor
Order analysis
Online signal demodulation
Embedded system

ABSTRACT

A permanent magnet synchronous motor (PMSM) is a typical electromechanical system widely used in industrial automation. Bearing fault diagnosis is necessary because a bearing is a key and vulnerable component in a PMSM. Order analysis (OA) methods, which include tachometer-based OA and tacholess OA methods, have been proven to be effective tools for diagnosing bearing fault under variable speed conditions. However, tachometer-based OA methods require the installation of an external sensor to obtain rotating speed, whereas tacholess OA methods are usually complicated and require massive computation cost. Traditional OA methods cannot diagnose bearing fault conveniently and timely because of such deficiencies. Thus, a novel fast and online OA (FOOA) method is proposed to realize variable-speed PMSM bearing fault diagnosis in this study. The FOOA method consists of two algorithms. (1) The rotating phase information is extracted from the sinusoidal current of the PMSM, and a series of equal-phase sampling pulses are generated. (2) The bearing signal acquired from a microphone is angular resampled based on the equal-phase sampling pulses. The resampled signal is demodulated, and the envelope order spectrum is calculated for bearing fault identification. The two algorithms are executed sequentially by two micro controller units operating in parallel. Thus, they can be implemented in an embedded system for online fault diagnosis. The effectiveness and flexibility of the proposed FOOA method are validated on both a desktop computer and an embedded system to diagnose different types of defective bearings that are installed on a PMSM test rig.

1. Introduction

Permanent magnet synchronous motor (PMSM) has been used extensively in daily life and industrial automation because of its distinct merits, such as high energy density, high efficiency, stable motion control, and low noise [1–4]. Bearings are key components in PMSM because they support the motor shaft that rotates at high speed. However, bearings are vulnerable because of the harsh working environment, which includes humidity, high temperature, and variable load. Nearly 40–50% of motor faults are induced by bearings [5]. Thus, bearing condition monitoring and fault diagnosis are important to guarantee motor safety [6,7].

* Corresponding author at: College of Electrical Engineering and Automation, Anhui University, Hefei, Anhui 230601, PR China.
E-mail address: lusliang@mail.ustc.edu.cn (S. Lu).

http://dx.doi.org/10.1016/j.ymssp.2017.02.046
0888-3270/

A number of methods has been proposed for bearing fault diagnosis under constant rotating speed, such as wavelet analysis [8,9], empirical mode decomposition [10], stochastic resonance [11–13], morphological filtering [14], cyclostationary analysis [15], and manifold learning [16]. A transient signal analysis based on Levenberg-Marquardt method was proposed for the fault feature extraction of rotating machines [17]. A general sequential Monte Carlo method-based optimal wavelet filter was introduced for extracting bearing fault features [18]. A Dempster-Shafer theory was suggested for fault diagnosis of induction motors using vibration and current signals [19]. An adaptive stochastic resonance method was introduced for impact signal detection based on a sliding window [20]. A spectral segmentation method was proposed to identify resonant frequency band for bearing fault diagnosis [21]. These methods have exhibited good performance in fault features extraction and fault recognition in the condition where the bearing runs at constant speed.

When a motor runs at variable speed, the bearing signal becomes time-varying, and the fault features shift with time, which causes difficulty for fault identification. An order analysis (OA) method can address this issue because it uses multiples of rotating speed (order) instead of absolute frequencies as frequency base; thus, OA methods have been widely used in variable-speed bearing fault diagnosis [22,23]. For instance, a method for rolling element bearing defect diagnosis under variable speed operation through angle synchronous averaging of wavelet denoising estimation was suggested in [24]. An OA method based on time frequency representation (TFR) was proposed for rolling element bearing fault diagnosis under time-varying rotational speed [25]. A rotating speed isolation method was introduced to extract the instantaneous rotation frequency and instantaneous fault characteristic frequency (IFCF) from the vibration signal in bearing diagnosis under variable speed condition [26]. Rolling element bearing defect detection using generalized synchrosqueezing transform and guided by time-frequency ridge enhancement was proposed to realize tacholess OA (TOA) in [27].

The OA methods can be classified into two classes: (1) tachometer-based methods that use a tachometer or an optical encoder to obtain rotating phase information for angular resampling, and (2) TOA methods that extract the phase information from acquired vibration or sound signal [28]. For the former, external sensors should be installed on the motor to be tested, which increases measurement cost and system complexity. Moreover, some specific cases, such as small motors, have no place for sensor installation. For the later, the stability and accuracy of the TOA method are limited because the vibration signal is usually corrupted by heavy background noise. Besides, most TOA methods are complicated and require massive computation cost because they always utilize time-frequency analysis techniques to calculate the rotating phase information, which reduces efficiency of fault diagnosis.

This study proposes a novel fast and online OA (FOOA) method to realize PMSM bearing fault diagnosis under variable speed and address these issues. The proposed method is comprised of two algorithms: (1) current analysis algorithm, through which the rotating phase information is extracted from the PMSM sinusoidal current to provide equal-phase sampling pulses, and (2) sound analysis algorithm, through which the resampled sound signal is demodulated to expose the bearing fault characteristic order (FCO) for fault identification. These two algorithms are executed sequentially by two micro controller units (MCUs) operating in parallel. Thus, they can be implemented in an embedded system for online diagnosis. The PMSM current can be obtained conveniently using either internal- or external-sensors. Therefore, the proposed method provides a simple, fast, online, and effective solution to realize bearing fault diagnosis, which is suitable for use in the worksite where the tachometer has not been installed (e.g., a sensorless-controlled PMSM).

The rest of the paper is organized as follows. Section 2 introduces the proposed FOOA method. Section 3 verifies its effectiveness and efficiency on a desktop platform in comparison with a traditional TOA method. Section 4 validates the method performance on an embedded system. Section 5 provides discussions and Section 6 draws the conclusions.

2. Method

2.1. Method overview

The framework of the proposed method is illustrated in Fig. 1. A three-phase PMSM is driven by a motor controller, and one phase current is measured by a current sensor. The test bearing is installed at the encoder-end of the PMSM. The bearing sound signal is recorded by a microphone. Current and sound signals are sampled and quantified by two analog-to-digital converters (ADCs). To balance the general purpose input/output (GPIO) ports and the computational resources, two MCUs are used for current and sound signals analysis, respectively. The sampling of ADC1 is triggered by the equal-phase pulses (1 pulse/degree in this study) provided from MCU2 to transform the time-domain sound signal to an angular-domain one, which means that the sampling rate of ADC1 is variable with respect to time. To achieve this goal, ADC2 samples the current signal at a constant sampling rate (oversampling) and then MCU2 calculates the current phase online to generate the equal-phase pulses. The detailed procedure will be introduced in the next subsection.

2.2. Current analysis

The sound signal should be equal-phase resampled rather than equal-time resampled to perform OA. The PMSM is driven by sinusoidal current. Thus, the phase information can be estimated easily from the phase current, as illustrated in Fig. 2. The discrete sampled current shown in Fig. 2(a) is denoted as $x[n]$, $n = 1, 2, 3, \ldots$. The current signal is interfered by noise and an infinite impulse response (IIR) filter is used to purify the current signal, as shown below.