Mechanical Systems and Signal Processing 94 (2017) 14–32

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

A novel vibration-based fault diagnostic algorithm for gearboxes under speed fluctuations without rotational speed measurement

Liu Hong [a,b], Yongzhi Qu [a,b], Jaspreet Singh Dhupia [c,*], Shuangwen Sheng [d], Yuegang Tan [a,b], Zude Zhou [a,b]

[a] School of Mechanical and Electronic Engineering, Wuhan University of Technology, China
[b] Hubei Digital Manufacturing Key Laboratory, Wuhan University of Technology, China
[c] Department of Mechanical Engineering, University of Auckland, New Zealand
[d] National Renewable Energy Laboratory, United States

ARTICLE INFO

Article history:
Received 5 October 2016
Received in revised form 10 February 2017
Accepted 16 February 2017

Keywords:
Gear fault diagnosis
Tacho-less algorithm
Speed fluctuations

ABSTRACT

The localized failures of gears introduce cyclic-transient impulses in the measured gearbox vibration signals. These impulses are usually identified from the sidebands around gear-mesh harmonics through the spectral analysis of cyclo-stationary signals. However, in practice, several high-powered applications of gearboxes like wind turbines are intrinsically characterized by nonstationary processes that blur the measured vibration spectra of a gearbox and deteriorate the efficacy of spectral diagnostic methods. Although order-tracking techniques have been proposed to improve the performance of spectral diagnosis for nonstationary signals measured in such applications, the required hardware for the measurement of rotational speed of these machines is often unavailable in industrial settings. Moreover, existing tacho-less order-tracking approaches are usually limited by the high time-frequency resolution requirement, which is a prerequisite for the precise estimation of the instantaneous frequency. To address such issues, a novel fault-signature enhancement algorithm is proposed that can alleviate the spectral smearing without the need of rotational speed measurement. This proposed tacho-less diagnostic technique resamples the measured acceleration signal of the gearbox based on the optimal warping path evaluated from the fast dynamic time-warping algorithm, which aligns a filtered shaft rotational harmonic signal with respect to a reference signal assuming a constant shaft rotational speed estimated from the approximation of operational speed. The effectiveness of this method is validated using both simulated signals from a fixed-axis gear pair under nonstationary conditions and experimental measurements from a 750-kW planetary wind turbine gearbox on a dynamometer test rig. The results demonstrate that the proposed algorithm can identify fault information from typical gearbox vibration measurements carried out in a resource-constrained industrial environment.

* Corresponding author.
E-mail address: j.dhupia@auckland.ac.nz (J.S. Dhupia).

http://dx.doi.org/10.1016/j.ymssp.2017.02.024
0888-3270/

1. Introduction

The characteristic frequencies of gear faults in the measured vibration spectrum are harmonically related to the shaft rotational speed. A localized gear failure results in periodic amplitude and phase modulations in which spectral sidebands are spaced around the gear-mesh harmonics at a distance equal to the shaft rotational harmonics [1,2]. Assuming a constant shaft rotational frequency, the sidebands can be easily identified in theory through the spectral analysis of cyclo-stationary signals [3,4]. However, in practice, though rotating machines can be operated at a relatively stationary condition, the gearboxes—especially those employed in high-powered applications—are often characterized by significant speed fluctuations. For instance, Ref. [5] presents the rotational speed during the controlled operation of an 850-kW variable-speed wind turbine drivetrain in which 18–32% speed variations with respect to the nominal operational speed can be observed within 85 s. Such speed fluctuations can smear the frequency components in the measured vibration spectrum, which makes it difficult to recognize the sidebands introduced by a gear fault.

This spectral smearing phenomenon occurring as a result of speed fluctuations can be alleviated by order-tracking (OT) methods. Conventional OT techniques employ additional sensors to provide the information of rotational speed or angular position of the shaft, which increase costs and are often unavailable in industrial applications [6]. The first tacho-less OT algorithm for gear diagnosis was presented in [7], which estimated the shaft angular position using a narrow-band phase demodulation at one of the harmonics of the gear-mesh frequency. The required harmonic of the gear-mesh frequency was extracted by an appropriately designed band-pass filter. This algorithm was further mathematically investigated in [8]. It was proven that the gear-mesh harmonics (the higher-order harmonics of shaft rotational frequency), instead of the shaft rotational frequency or any of its low harmonics, should be extracted to conduct the phase demodulation for lowering the estimated shaft phase error. However, the use of a high-order harmonic of shaft rotational frequency (i.e., gear-mesh harmonics) restricts the maximum allowed speed fluctuation of the algorithm (typically to less than 1%) [7,8]. To compensate for larger speed variations, the time frequency distribution (TFD) algorithms that evaluate the instantaneous frequency (IF) of gear-mesh harmonics on the basis of ridge searching of TFD have attracted significant attention recently [9–11]. Though the TFD-based methods are also capable of estimating the rotational speed of the shaft, they are usually limited by a high time-frequency resolution requirement in practice, which is a prerequisite for the precise estimation of IF [12]. Moreover, several gear-mesh harmonics are not even present in the vibration spectrum of an equally spaced sequential planetary gearbox [13,14]. Generally, these issues deteriorate the efficacy of the existing tacho-less OT methods during their applications in an industrial environment.

To address such aforementioned issues and advance the state of the art of tacho-less diagnostic techniques, a novel fault-diagnostic algorithm for gearboxes under speed fluctuations is developed in this paper. The proposed approach alleviates the problem of spectral smearing by resampling the measured acceleration signal of the gearbox based on the optimal warping path evaluated from the fast dynamic time warping (Fast DTW) algorithm, which dynamically aligns a filtered shaft rotational harmonic with a reference signal assuming a constant shaft rotational speed. The reference signal is chosen as a simple monocomponent sinusoidal function in which frequency and amplitude are estimated from the approximated operational speed and vibration characteristics of either the input or output shaft. Thus, the presented diagnostic method requires only an approximate knowledge of the operational speed besides the measured gearbox vibration signal. The capability of the approach is first demonstrated through a simulation study of a fixed-axis gear pair under nonstationary conditions. Later, the effectiveness of this approach is also experimentally validated through the measured vibration signal from a commercial 750-kW planetary wind turbine gearbox.

The rest of the paper is organized as follows. Section 2 gives a brief background of the Fast DTW algorithm. The detailed procedure for the proposed tacho-less fault diagnostic technique is described and discussed in Section 3. Section 4 investigates the effectiveness of the proposed method using MATLAB simulation studies. Section 5 presents the experimental validation of a 750-kW planetary gearbox that was damaged during the field operation while installed in a wind turbine. Finally, Section 6 concludes the paper.

2. Review of fast dynamic time warping

The proposed fault diagnostic procedure for gearboxes proposed in this paper alleviates the effect of spectral smearing due to speed fluctuations by resampling the data based on the optimal warping path evaluated from the Fast DTW algorithm. This approach demonstrates a promising performance to identify fault signatures using captured vibration data without any rotational speed measurement. DTW and Fast DTW are reviewed briefly in this section to provide greater understanding.

2.1. Dynamic time-warping algorithm

A simple compression or expansion along the timescale is not enough to accurately align two similar time-domain vibration signals from practical rotating machineries, which differ because of the random nonlinear fluctuations in speed. DTW can find the optimal alignment between the corresponding data points from the two series yielding minimum residue, which allows the timescale to be warped nonlinearly by stretching or shrinking. Thus, DTW is a useful tool to determine the similarity between two given time series [15]. It was recently employed to detect faults in a reciprocating compressor using