Journal of Sound and Vibration 371 (2016) 406–433

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Detection of gear cracks in a complex gearbox of wind turbines using supervised bounded component analysis of vibration signals collected from multi-channel sensors

Zhixiong Li [a,b,c,*], Xinping Yan [d], Xuping Wang [e], Zhongxiao Peng [c,**]

[a] School of Mechatronic Engineering & Jiangsu Key Laboratory of Mine Mechanical and Electrical Equipment, China University of Mining & Technology, Xuzhou 221116, China
[b] State Key Laboratory of Tribology, Tsinghua University, Beijing 100000, China
[c] School of Mechanical & Manufacturing Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[d] School of Power & Energy Engineering, Wuhan University of Technology, Wuhan 430063, China
[e] Xi'an Research Institute of Hi-Tech, Xi'an 710025, China

ARTICLE INFO

Article history:
Received 6 August 2015
Received in revised form
19 January 2016
Accepted 10 February 2016
Handling Editor: L. G. Tham.
Available online 24 February 2016

Keywords:
Wind turbine
Gear crack
Fault detection
Bounded component analysis
Order tracking

ABSTRACT

In the complex gear transmission systems, in wind turbines a crack is one of the most common failure modes and can be fatal to the wind turbine power systems. A single sensor may suffer with issues relating to its installation position and direction, resulting in the collection of weak dynamic responses of the cracked gear. A multi-channel sensor system is hence applied in the signal acquisition and the blind source separation (BSS) technologies are employed to optimally process the information collected from multiple sensors. However, literature review finds that most of the BSS based fault detectors did not address the dependence/correlation between different moving components in the gear systems; particularly, the popular used independent component analysis (ICA) assumes mutual independence of different vibration sources. The fault detection performance may be significantly influenced by the dependence/correlation between vibration sources. In order to address this issue, this paper presents a new method based on the supervised order tracking bounded component analysis (SOTBCA) for gear crack detection in wind turbines. The bounded component analysis (BCA) is a state of art technology for dependent source separation and is applied limitedly to communication signals. To make it applicable for vibration analysis, in this work, the order tracking has been appropriately incorporated into the BCA framework to eliminate the noise and disturbance signal components. Then an autoregressive (AR) model built with prior knowledge about the crack fault is employed to supervise the reconstruction of the crack vibration source signature. The SOTBCA only outputs one source signal that has the closest distance with the AR model. Owing to the dependence tolerance ability of the BCA framework, interfering vibration sources that are dependent/correlated with the crack vibration source could be recognized by the SOTBCA, and hence, only useful fault information could be preserved in the reconstructed signal. The crack failure thus could be precisely identified by the cyclic spectral correlation analysis. A series of numerical simulations and experimental tests have been conducted to illustrate the advantages of the proposed SOTBCA method for fatigue crack detection. Comparisons to three representative techniques, i.e. Erdogan's BCA (E-BCA), joint approximate diagonalization of eigen-matrices (JADE), and FastICA, have demonstrated the effectiveness of the SOTBCA. Hence the proposed

* Corresponding author at: School of Mechatronic Engineering, China University of Mining & Technology, Xuzhou 221116, China.
** Corresponding author at: School of Mechanical & Manufacturing Engineering, The University of New South Wales, Sydney, NSW 2052, Australia.
E-mail addresses: zhixiong.li@unsw.edu.au (Z. Li), z.peng@unsw.edu.au (Z. Peng).

http://dx.doi.org/10.1016/j.jsv.2016.02.021

approach is suitable for accurate gear crack detection in practical applications.

1. Introduction

Wind energy is one of the most promising renewable and clean energy sources [1–3]. Under severe pressure of energy security and climate change, the development of wind energy grew steadily from 23.0 GW in 2001 to 369.6 GW in 2014 [4]. However, several technique challenges limit further development of wind power globally [5–7]. One of them is the maintenance of wind turbines [6]. In many cases, without proper maintenance the wind turbines would fail in five years in average although their design life is 20 years [6]. Hence, in order to improve maintenance efficiency and to reduce costs, it is crucial to implement a reliable condition monitoring and fault detection/diagnosis (CMFD) program for wind turbines [8–10].

Gearboxes are the most frequently failure components in wind turbines [7]. Faults occurred in the gearboxes account for about 60% of overall failures in wind turbines [7,9]. In a gearbox, the least desirable fault type is the gear crack [11], because it often leads to other severe failure of the gear unit and hence to the break-down of the unit. The effects of crack size, initial position, and propagation direction will determine the fault characteristics in the time and frequency domains [12]. Theoretically, if a crack occurs in the gear root, it will eventually develop to a broken gear tooth. Consequently, the gear root crack is often more difficult to detect in comparison to the broken gear tooth due to weaker impact and modulation effects in the fault vibration response [13,14]. Also, a crack on the tooth surface may lead to a pitting or a chipping [15]. Generally, in the early stage of a crack, its fault symptoms are not obvious, often buried in background noise. It is always difficult to detect a gear crack. Therefore, large amounts of studies have been done on gear crack detection. Pioneer works include the filtering function [16], adaptive amplitude and phase demodulations (AMFM) [17], and FRacture Analysis Code model [18]. Their analysis results indicate that vibration analysis is efficient and feasible for gear crack detection. More recently, Baydar and Ball [19] used Wigner–Ville distribution to identify gear crack. Wang [20] applied the resonance demodulation technique to detection of gear tooth cracking. The bispectrum was used for gear crack detection by Li et al. [21] and the chaotic theory was introduced for gear crack detection by Li and Qu [22]. The empirical mode decomposition (EMD) [23,24], Wavelet [25–27], *K*-nearest neighbor [28], principal component analysis [29], and manifold learning [30] were employed to detect gear crack. Existing literatures have shown that significant progress was made on this topic [31,32]. However, most of previous work for gear crack detection analyzed vibration data collected from one channel sensor in one computation cycle [33]. For a simple gearbox structure, e.g. a one-stage spur gearbox, a single sensor could provide sufficient vibration information of the gearbox dynamic response. However, for a complex gearbox configuration, such as a wind turbine gearbox, the transmission paths of the gear meshing movements are complex and it is not easy to determine the best monitoring position of the sensors. Considering that the vibration response of the cracked gear can be weak and its energy distributes along its transmission paths, it may be necessary that multi-channel sensors be used at different locations and in different directions to collect the vibration responses. By making full use of multi-channel signals, the vibration signals of the cracked gear can then be reconstructed, and the energy (fault information) of the cracked gear vibration will be enhanced significantly for effective crack detection [33].

To achieve the above objective, the connection between multi-sensor signals from different locations and/or directions of the vibration sources needs to be studied. Independent component analysis (ICA) has the ability to reconstruct signals collected from multiple sensors [34] and was used to extract useful vibration signals in relation to fault source(s) [35]. However, the ICA approach bases on the assumption that fault vibration sources are independent to each other in the gearbox vibration. This is often not true for a real world vibration signal because in a multi-shaft running system the coupling and crossing effects between vibration sources are generated due to simultaneous amplitude and phase demodulations [36]. As a result, the ICA would fail in the reconstruction of the fault vibration source if the mutual independence is not satisfied. To address this issue, recently the bounded component analysis (BCA) was proposed to relax the mutual independent requirement [37]. In that research, Cruces showed that the present BCA based blind source extraction (BSE) algorithm was able to separate dependent sources correctly when the ICA failed to recover them. Furthermore, the BCA based blind source separation (BSS) algorithms were developed for communication signal analysis [34,35]. The difference between the BSE and BSS is that the BSS separates all the sources contained in the sensor records in one computation cycle while the BSE only extracts one source in one operation. Since the strict constraint of the mutual independence assumption of the ICA has been relaxed to a weaker hypothesis, i.e., the domain separability in the BCA [38,39], the BCA is more suitable than the ICA in dealing with real vibration signals.

Since the BCA is a recently developed method, very limited work has been done to further develop and apply this approach for fault detection using vibration analysis techniques. Basically, it is inefficient to directly apply the BCA to vibration signal unless some suitable pre/post treatments are cooperated. This is because, on one hand, the fault characteristics are likely to be corrupted by the vibration components of health gears and background noise. Particularly, the gear shafts in wind turbines always run at a non-constant rotational speed. The speed variation may cause a frequency smearing effect on the gear dynamics with fixed sampling frequency. A noise cancellation process is therefore required before performing the BCA analysis. On the other hand, in the vibration source separation process the BCA based BSS