Tribology International 96 (2016) 289–306

Contents lists available at ScienceDirect

Tribology International

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

A review on signal processing techniques utilized in the fault diagnosis of rolling element bearings

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ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form
19 November 2015
Accepted 28 December 2015
Available online 2 January 2016

Keywords:
Rolling element bearings
Signal processing
Diagnosis
Prognosis

ABSTRACT

Rolling element bearings play a crucial role in the functioning of rotating machinery. Recently, the use of diagnostics and prognostics methodologies assisted by artificial intelligence tools such as artificial neural networks, support vector machines etc. have increased for assessing the health of the rolling element bearings. The effectiveness of these approaches largely depends upon the quality of features extracted from the bearing signals. Keeping this in mind, the authors have presented the various signal processing methods applied to the fault diagnosis of rolling element bearings with the objective of giving an opportunity to the examiners to decide and select the best possible signal analysis method as well as the excellent defect representative features for future application in the prognostic approaches. The review article first quotes some of the condition monitoring tools used for rolling element bearings and then the importance of signal processing methods in diagnosis and prognosis of rolling element bearings. Next, it discusses the various signal processing methods and their diagnostic capabilities by dividing them into three stages: first stage corresponding to the articles published before the year 2001, second stage refers to the articles published during the period 2001–2010 and lastly the third stage pertains to the articles issued during the year 2011 to till date. To focus more on the recent developments in the signal processing methods, the third stage has been partitioned further into several sections depending upon the methodology of signal processing. Their relative advantages and disadvantages have been discussed with regard to the fault diagnosis of rolling element bearings.

1. Introduction

Rolling element bearings (REBs) are the most common machine elements playing an exceptionally vital role in almost all kinds of rotating machinery and as such used at length in industries due to their relatively lower price and operational ease. The maneuver of rotating machinery is entirely dependent upon the health state of the REBs, which accounts for almost 45–55% of these equipment failures [1–3]. The presence of bearing faults [4] such as galling, spalling, peeling, subcase fatigue or failure of the bearings due to misalignment, shaft slope, surface roughness, high extent of waviness and inclusions, etc causes a catastrophic collapse of the system thereby reducing the reliability and availability of the plant. This in turn increases the production downtime causing a massive financial loss to the organization and may every so often prove dangerous to the safety of the workers. Thus, it becomes a requisite to implement and expand effective maintenance strategies to minimize the impact of failures due to malfunctioning of the rolling element bearings. The literature [5,6] divides the maintenance strategies primarily into three types – Corrective maintenance, Preventive maintenance and Predictive maintenance (or Condition based maintenance CBM). Huang et al. [6] presented a tabular comparison of the various maintenance strategies and confirmed that the downtime and the extended damages are minimal in CBM. CBM is a decision-making strategy, which aims to avoid unexpected catastrophic failures by early detection of embryonic faults and implementing the necessary maintenance actions for their isolation, thus attempting to re-establish the health of a machine, component or system. Recently, Shin and Jun [7] reviewed the diverse definitions of CBM and presented a new definition of CBM as a maintenance policy that do maintenance action before product failures happen, by assessing product condition including operating environments, and predicting the risk of product failures in a real-time way, based on gathered product data. In addition, it has been stated that the term CBM is often referred to as Prognostics and Health Management (PHM). The three main aspects of a condition-based maintenance are as shown in Fig. 1.

It should be worth mentioning that the three components of CBM depicted in Fig. 1 are interconnected to each other and none

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http://dx.doi.org/10.1016/j.triboint.2015.12.037
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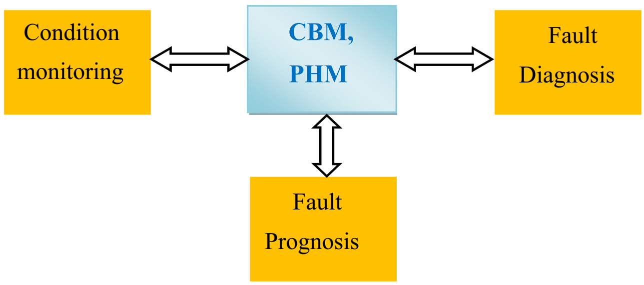

Fig. 1. Components of condition based maintenance.

of the task can be accomplished effectively without the existence of other. However, there is a clear distinction between the diagnosis and prognosis practices, which will be discussed in the upcoming sections. At the same time, it must be recognized that the condition monitoring tools such as vibration, acoustic emission, oil debris, motor current signature analysis etc. supply the failure data for bearings in uncooked form that has to be treated precisely to execute apposite diagnosis and prognosis of rolling element bearings. For instance, the widely used implement for the health inference of rolling element bearings i.e. vibration condition monitoring yields the fault information in the form of signals, which are often perturbed by surrounding noises and interferences due to the presence of mechanisms such as shaft rotational speed, gear noises, etc. Consequently, more and more reliable signal processing are required to extract and distinguish the fault features contained in the raw signals with a high degree of accuracy. The stimulus behind this paper is to review the signal processing methods that have been applied until now to extract as well as augment the defect characteristics incorporated into the signals produced by the rolling element bearings. The article thus provides an opportunity to the researchers to select the perfect signal processing techniques for the unambiguous diagnosis and prognosis of rolling element bearings.

Several review articles on signal processing methods utilized for the fault diagnosis in mechanical systems have been reported in the literature. Howard [8] reviewed the various signal processing techniques for the detection, diagnosis and prognosis of REBs upto the year 1994. Tandon and Chaudhary [9] presented the signal processing approaches applied to the vibration and acoustic emission signals for identification of defects in REBs. Jardine et al. [10] provided a summary of the data acquisition, data processing, diagnosis and prognostics algorithms implemented in the CBM of machines. The literature [11,12] explained the wear mechanisms; wear monitoring and diagnosis methods in REBs. Majority of the signal processing methods cited into these papers are customary in nature and have been modified or used in combination with certain advanced signal processing methods over the last fifteen years to improve their efficiency and accuracy.

This review paper addresses the earliest works on signal analysis to provide a background to the researchers and further focuses on the successive upgrading in the signal processing techniques, which have been applied so far for the diagnosis of faults in REBs. The remainder of the paper has been partitioned into the following sections; Section 2 presents a brief summary of the condition monitoring techniques applied to rolling element bearings; Section 3 discusses the difference between diagnosis and prognosis in addition to the role played by feature extraction processes in diagnosis and prognosis of rolling element bearings; In Section 4, the articles related to signal processing methods have been reviewed and discussed; Section 5 presents a summary of the survey highlighting the future research opportunities; Finally, the Section 5 summarizes the conclusions drawn from the work highlighting the current challenges and future research opportunities.

2. Condition monitoring techniques

A variety of machine condition monitoring techniques such as acoustic emission (AE), vibration (VR), oil debris (OD), electrostatic (ES) and ultrasound (US) are being used meticulously by the industrial enterprises. Petersen et al. [13] made use of the vibrations generated in the self-aligning ball bearings on gearbox and fan test rigs to analyze the load distributions and variations in stiffness due to presence of defects in the ball bearings. Patel et al. [14] utilized the simulated and experimental vibration measurements to study the effect of multiple local defects on the vibrations generated by the rolling element bearings. Saruhan et al. [15] conducted vibration studies on the rolling element bearings with inner race defect, outer race defect, ball defect and a mixture of the three under different load and speed combinations. Jena and Panigrahi [16] developed an experimental set up to capture the bearing vibration signals and exercised it to measure the width of the defects seeded in the inner and outer races. The literature [17–21] provides some more insight into the applications of vibration condition monitoring with regard to rolling element bearings. Further, it should be noted that majority of the signal processing methods discussed in Section 4 have been employed to the vibration signals produced by the rolling element bearings. Another extensively used condition monitoring technique is the acoustic emission, which has been reported in the articles [22–26]. Pandya et al. [27] processed the AE signals with Hilbert–Huang transform and used a K-nearest neighbor based classifier for the diagnosis of faults in rolling element bearings. Recently, Chacon et al. [28] collected the AE signals from the bearing with an outer race defect and processed it with a wavelet based signal processing method to identify the bearing faults in its early stages, when the signal to noise ratio is squat. The other condition monitoring techniques i.e. OD, ES and US have been figured out in the publications [11,29–31] and [32,33] respectively. Recently, an increasingly used condition-monitoring tool known as motor current signature analysis has gained significance in the fault diagnosis of rolling element bearings. Motor current signature analysis has been widely used in the areas where the faulty components are difficult to access such as the centrifugal pumps buried in the grounds [34,35], nuclear power plants [36], induction motor drives [37,38] etc. Zarei and Poshtan [39] treated the stator current signals with a Park's vector predicated approach to detect the fault frequencies generated by the rolling element bearings in three phase induction motors. Amirat et al. [40] applied the signal processing method famous as ensemble empirical mode decomposition to the homopolar current signals produced by the induction machines (generator) for the monitoring of wind turbine bearings. Alwodai et al. [41] unified the stator current analysis with another signal processing method pronounced as bispectrum analysis to diagnose the bearing faults in induction motors. The encouragement behind the motor current signal analysis is that the vibrations induced by the presence of bearing defects results in a modulation of the stator current and provides the similar warnings as the vibration measurements [42].

Though a variety of condition monitoring methods are available, the vibration and acoustic emission techniques are the most commonly applied techniques for gathering the data conducive to the detection of the bearing faults in addition to estimating the remaining life of rotating machinery. The existing literature classifies the condition monitoring data into three categories: value data, waveform data and multidimensional data. The data collected from oil debris analysis and electrostatic analysis can be