Mechanical Systems and Signal Processing 116 (2019) 370–391

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Fault detection of rolling element bearings using optimal segmentation of vibrating signals

Theodor D. Popescu [a,*], Dorel Aiordachioaie [b]

[a] National Institute for Research and Development in Informatics, 8-10 Averescu Avenue, 011455 Bucharest, Romania
[b] "Dunarea de Jos" University of Galati, 47 Domneasca Street, 800008 Galati, Romania

ARTICLE INFO

Article history:
Received 19 February 2018
Received in revised form 9 May 2018
Accepted 18 June 2018

Keywords:
Fault detection and diagnosis
Rolling element bearings
Optimal segmentation
Monte Carlo simulation
Vibrating signals
Case study

ABSTRACT

Change detection and diagnosis are important research directions and activities in the field of system engineering and conditional maintenance of equipments and industrial processes. The paper promotes a new method for change detection and optimal segmentation of vibrating data obtained during operation of rolling element bearings (REB). After a description of the bearing faults and dynamic simulation of REB, the paper makes a review of the change detection and segmentation approaches, that could be used in REB fault detection and diagnosis. A new approach for change detection and optimal segmentation of vibrating signals, aiming to determine the change points in signals generated by the faults, produced during REB operating, is presented; the efficiency of the segmentation method is proven using Monte Carlo simulations for different signal models, including models with changes in the mean, in FIR, and AR model parameters, frequently used in processing vibrating signals. In the final part, the paper analyses some experimental results obtained using this approach and data from the Case Western Reserve University Bearing Data Center.

1. Introduction

The rolling element bearings (REB) are present in many industrial and domestic machines. The existence of some defects of the bearing components can lead, in time, to machine failure, with costly consequences. The great majority of bearing failures occur due to inappropriate use (e.g. imbalance, improper lubrication) or manufactory errors, hardly ever to wear. Bearings are critical elements in rotating machines, since they support the rotating structure and much of the energy during operation is transferred through the bearings. Bearing failures may easily lead to other, more expensive damages in a machine. Hence, most machines are periodically serviced, and replacement of the bearings is a routine matter to prevent major problems.

In this case the problem of fault modeling and predictive health monitoring of REB is one of great interest and includes detection, diagnosis and prognosis, in order to extract the features related to the fault produced. A study reviewing such methods, which explore their capabilities, advantages and disadvantage in monitoring of REB makes the object of [1]. Implementation of such procedures implies signal analysis methods (statistical measures, frequency domain methods, feature extraction) features diagnosis methods (artificial neural network, fuzzy logic, support vector machine, model-based approach), and prognosis analysis (statistical approach, artificial intelligence approach, physic-based approach).

---

* Corresponding author.
E-mail addresses: Theodor.Popescu@ici.ro (T.D. Popescu), Dorel.Aiordachioaie@ugal.ro (D. Aiordachioaie).

https://doi.org/10.1016/j.ymssp.2018.06.033
0888-3270/

A general overview of various condition-monitoring and fault diagnosis techniques for REB in current practice are discussed in [2]. The presented techniques include data acquisition techniques, major parameters used for bearing condition monitoring, signal analysis techniques, and bearing fault diagnosis techniques using either features or artificial intelligent tools.

A tutorial to guide the reader in REB diagnostics using vibrating signal analysis, with different case studies is presented in [3]. Its purpose is to explain the background for a very powerful procedure, used with great success in many cases. The final diagnosis is based on "envelope analysis" of the optimal filtered signal, using digital implementation.

Usually in condition monitoring (CM) of machines and industrial equipments, techniques like vibration and acoustic measurement, temperature measurement, and wear debris analysis are frequently used. Vibration monitoring proved to be a reliable and effective technique to detect the changes in REB. The most used vibration analysis techniques in this case are time domain analysis, frequency domain analysis, high frequency resonance technique and wavelet transform methods [4]. These approaches can lead to improving of the fault detection.

The problem of REB diagnosis, or faults localization, has been analysed in many papers, among which we mention [2,5–8], etc. with very convincing conclusions.

The change detection and diagnosis (CDD) methods proved to be useful tools in fault detection and diagnosis of vibration signals produced during REB operating, and received a considerable attention during the last two decades. They operate in time and frequency domain, and make use of theories based on statistics [9,10], which provide the theoretical instruments of solving the problem of early detection. This theory assumes that a mathematical model of the monitored system is available. The hypothesis is reasonable, the physical principles of many industrial processes are known, with available equations as analytical models. When the models are very complicated or unknown, the local approach still can use semi-physical models or black-box models.

The matter of monitoring the rolling element bearings plays a crucial role in the assessment of the overall health state of a rotating machine, with consequences on the in machine's operation efficiency, the maintenance/replacement costs, and extending its lifespan. The problem is still a challenge, but in the last two decades on can notice convincing results in this field.

The paper is organized as follows. In Section 2 we present the bearing faults categorised by components: outer race, inner race, bearing cage and ball (roller), as well as the dynamic simulation of REB. Section 3 presents a review of change detection and segmentation approaches, that could be used in REB fault detection and diagnosis. Section 4 presents a new approach for change detection and optimal segmentation of vibrating signals, aiming to determine the change points in signals generated by the faults, during operation of rolling element bearings; the efficiency of the segmentation method is proven using Monte Carlo simulations for different signal models, including models with changes in the mean, in FIR, and AR model parameters. Section 5 discusses some experimental results obtained using the proposed approach and data from the Case Western Reserve University Bearing Data Center [11].

2. Bearing faults and dynamic simulation of REB

Usually, during the rolling bearing operation, some defects are produced. In the case of *distributed* defects developed in bearings, sinusoidal vibrations will be produced inside the structure. Distributed defects are faults like misalignment, eccentricity and geometrical imperfections, where the magnitude of the ball-race contact force varies continuously and periodically as the bearing rotates. According to [12], examples of geometrical imperfections are: race or element waviness and offsized rolling elements. Incipient *discrete* defects in bearings can be detected with vibration monitoring: they will appear as irregularities or modifications in the rolling surfaces of the bearings, which will lead to (semi-) periodic impacts that will excite the bearing and machine resonances. Deviations from exact periodicity were observed and will lead to continuous phase shifts, i.e. phase randomization.

To understand the dynamic behavior of healthy and defective bearings, dynamic models of REB have been developed. All rolling bearings consist, practically, of four basic parts: inner ring, outer ring, cage, and rolling elements (see Fig. 1). So, the bearing faults may be classified based on their location as outer, inner, cage and rolling elements faults. A summary of fault modeling of rolling element bearings is given in [1]. Also, a review of the dynamic modeling for REB, in healthy state and with a possible fault is given in [4,13].

The vibration signal produced in the case of a fault for a REB can be analyzed in time and frequency domain. Usually in the time domain the following statistical parameters are estimated: crest factor, skewness, kurtosis, probability density, etc. The fundamental information in monitoring bearing conditions is the characteristic of bearing defect's frequency. In the frequency domain a fault in the vibration signal can be identified with bearing fundamental frequencies, function of the bearing geometry and rotor speed. Approximations to the average defect frequencies are shown in Table 1, where the following parameters have been used for the geometry and dimensions of a roller element bearing, presented in Fig. 1: N – shaft speed in revolution per minute (RPM), n – number of roller elements in a bearing, ϕ – contact angle, d – roller diameter, D – bearing diameter.

The generation of vibrations by a single localized defect in a REB can be modeled as a function of the rotation speed of the bearing, the distribution of load in the bearing, bearing-induced resonant, exponential decay due to damping and noise. So, a simulated bearing defect signal can be generated by using the following equations [2,13]: