Applied Soft Computing 71 (2018) 36–50

Contents lists available at ScienceDirect

Applied Soft Computing

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

An integrated approach to bearing prognostics based on EEMD-multi feature extraction, Gaussian mixture models and Jensen-Rényi divergence

Akhand Rai, S.H. Upadhyay *

Department of Mechanical & Industrial Engineering, Indian Institute of Technology, Roorkee, India

ARTICLE INFO

Article history:
Received 9 June 2017
Received in revised form 30 May 2018
Accepted 21 June 2018
Available online 30 June 2018

Keywords:
Rolling element bearings
Performance degradation assessment
Remaining useful life
Gaussian mixture models
Support vector regression

ABSTRACT

This paper proposes an integrated bearing prognostics approach that is divided into two components: The first component develops a new health indicator (HI) for performance degradation assessment (PDA) of bearings. Many existing HIs suffer from certain shortcomings such as insensitiveness to incipient defects and a highly fluctuating behavior with the increase in degradation severity. To overcome these disadvantages, a HI based on Gaussian mixture models (GMM) and Jensen-Rényi Divergence (JRD) is suggested, which retains its monotonicity as the bearing condition deteriorates. Firstly, the acquired vibration signals are decomposed by ensemble empirical mode decomposition (EEMD) to extract the fault features i.e. singular values and energy moment entropies of the intrinsic mode functions (IMFs). Secondly, the feature vectors under healthy conditions are used to train the GMM. Thirdly, the test feature vectors are supplied to the trained GMM to calculate the components' posterior probabilities. Fourthly, JRD measure is used to discriminate the defective posterior probability distributions from the healthy ones. Finally, the JRD is converted into confidence value (CV) to realize bearing PDA. The second component utilizes the CV values to train the support vector regression (SVR) model. The particle swarm optimization (PSO) technique is implemented to attain the optimal values of SVR hyperparameters. The optimal SVR model is then used to forecast the CV upto predefined failure threshold and evaluate the bearing remaining useful life (RUL). The experimental results verify that the proposed CV performs better than the GMM-negative log likelihood probability (NLLP) for RUL estimation of bearings.

1. Introduction

Rotating machinery consisting of generators, turbines, rotary compressors, transmission gearboxes etc. form a huge constituent of the mechanical systems used in industries. The continuous monitoring of rotating machinery is vital to prevent the roto-mechanical equipments from sudden failures. This increases the reliability and availability of the entity and reduces the incurred maintenance costs. Rolling element bearings are one of the most damage-prone components in rotating machinery. According to the article [1], almost 40–50% of all motor failures are due to bearing faults. The literature survey by Han and Song [2], reports that 40% of the machines fail due to the bearing related issues. Consequently, if the rotating machinery is to work continually, the damage prevention in rolling bearings becomes a necessity. Diagnostics and prognostics [3] are the two widely used tools for condition monitoring of roller bearings. Many research articles [4–6] are available on the diagnosis and prognosis of faults in rolling element bearings. However, compared to diagnostics, the research available on prognostics is fewer. During the past few decades, prognostics has gained traction over diagnostics due to its greater efficacy in minimizing the abrupt collapse of rotating machinery occurring as a result of frequent bearing failures. There are two chief objectives of bearing prognostics: performance degradation assessment (PDA) and remaining useful life (RUL) estimation [7]. In PDA, a health indicator (HI) is developed to trend the degradation process in rolling bearings. Generally, the bearing degradation is categorized into four phases: normal, slight or early, severe and failure. As such, the constructed HI must be capable of predicting these phases of bearing damage in an effective manner. Qiu et al. [8] used wavelet filter and self-organizing map (SOM) for robust PDA of rolling element bearings. The minimum quantization error (MQE) obtained through SOM was used as the bearing HI. Pan et al. [9] proposed an

* Corresponding author.
E-mail addresses: raiakhand@gmail.com (A. Rai), shumefme@iitr.ac.in (S.H. Upadhyay).

https://doi.org/10.1016/j.asoc.2018.06.038
1568-4946/

approach combining second-generation wavelet transform (SWGT) and support vector data description (SVDD) for comprehensive PDA of rolling bearings. Pan et al. [10] further utilized SWGT and fuzzy c-means (FCM) for bearing PDA. While SOM and SVDD required only normal bearing data, FCM demands both normal and final failure data in order to build the HI. However, the FCM based HI was found to have a definitive range of [0,1] and possess more intuitionist capability than the SOM and SVDD based HIs. Yu [11] suggested a new approach based on locality preserving projections (LPP) and Gaussian mixture models (GMM) to assess the performance degradation degree of rolling bearings. GMM was realized to be effective in tackling the complicated bearing data distributions. Yu [12] further proposed a hybrid approach based on GMM, k-means and SOM for health assessment of rolling element bearings. Rai and Upadhyay [13] utilized k-medoids clustering, again, requiring single bearing failure history for training and realizing PDA.

The next confront in bearing prognostics is how to estimate the RUL of bearings. A number of RUL prediction schemes have been suggested in the research works available in relation to rolling bearing prognostics. Gebraeel et al. [14] used a set of back propagation neural networks (BPNNs) for anticipating the RUL of bearings. Two key methods known as weight application to failure times (WAFT) and weight application to exponential parameters (WAEP) were laid down for bearing RUL prediction. Built upon the same principle, Huang et al. [14] employed SOM derived MQE and WAFT based BPNNs for RUL anticipation of bearings. The RUL prediction techniques put forward in references [14,15] required the collection of large amount of bearing failure histories for training the BPNNs, which is quite burdensome and costly activity. Benkedjouh et al. [16] suggested a nonlinear feature reduction technique known as isometric feature mapping (ISOMAP) for obtaining bearing health indicator which was then forecasted by the support vector regression (SVR) method to anticipate the RUL of bearings. However, the proposed method was validated under the assumption that a group of bearings working under same operating conditions is used for training the SVR model and the bearing tested against the trained SVR again belongs to the same group. Soualhi et al. [17] used Hilbert-Huang transform (HHT) to extract various health indicators that were projected using SVR based one-step ahead prediction method in order to anticipate the bearing RUL. Mahamad et al. [18] employed Weibull hazard rate function (WFRF) for fitting the conventional Root mean square (RMS) and kurtosis features. The bearing age, fitted features were used as inputs and life percentage as output to learn feed forward neural network (FFNN) models and thus calculate the RUL of bearings. A major advantage of this approach was that it did not necessitate the determination of a failure threshold unlike the approaches documented in [14,16,17]. However, same failure data was used in both the training and testing phases for validation of the advocated approach thereby rendering it uncertain in nature.

The existing literature on bearing prognostics infers that there are several challenges common to bearing PDA and RUL prediction, which are discussed as follows:

1 The first and foremost challenge is to extract useful fault features from the bearing signals. Often, the impulses generated due to the bearing faults are buried heavily in the surrounding noises. Consequently, effectual signal processing techniques are needed to eliminate the unwanted noise and retain the impulsive features in bearing signals. During the preceding one-and-a-half decades, several signal-processing methods such as wavelet transform [19–21], wavelet packet decomposition [22,23] and empirical mode decomposition (EMD) [24–26] have been used extensively for the condition monitoring of rolling element bearings. Though these signal-processing methods have shown excellent potential in detecting bearing faults, they have certain disadvantages also. The wavelet-based techniques compel the selection of optimal mother wavelet, center frequency and bandwidth for effective filtering of the bearing signals. EMD being self-adaptive in nature does not require predefined basis functions for signal decomposition and therefore overcomes the problems posed by wavelet-based procedures. However, EMD suffers from the issues of false intrinsic mode functions (IMFs), mode-mixing occurrence and end effects etc. To overcome the shortcomings of EMD, the researchers have moved themselves to an improved variant of the EMD process, which is pronounced as Ensemble empirical mode decomposition (EEMD). In the recent few years, EEMD is being used tremendously [27–29] and has been established to be an efficacious modus operandi for fault diagnosis in rolling bearings. Therefore, in this paper, the authors have used EEMD for fault feature extraction from the raw bearing signals.
2 The second major challenge is the construction of artificial intelligence (AI) models for PDA and RUL inference of bearings. Generally, the AI model for bearing PDA is referred to as "assessment model" and that for RUL estimation as "prediction model". The focus of an assessment model is providing an effective HI that can detect the weak defects in bearings as early as possible. Besides, for accurate estimation of RUL, the HI should increase in a monotonic fashion and exhibit minimum fluctuations as well, with the increase in fault severity. Unfortunately, many previously used HIs fail to meet the second criteria. In this paper, GMM is employed to build the assessment model due to its ability to efficiently model the multi-modal nature of the feature distribution densities [30]. Subsequently, a novel degradation indicator based on GMM and Jensen-Rényi Divergence (JRD) is proposed to scrutinize the deterioration in bearings. After the attainment of HI, the next task is to forecast the HI to a predefined failure threshold for determining the RUL of bearings. It should be worth mentioning that the availability of HI has a major advantage in the sense that it eases the selection of failure threshold. For forecasting the HI, a prediction model based on SVR in association with iterated multi-step ahead prediction strategy [31] is adopted in this work. According to several studies [32–34], SVR based methods outperform the conventional neural networks (NNs) and Autoregressive Integrated moving average (ARIMA) etc. in time-series prediction. A major confront in the SVR based time-series prediction is to select the optimal values of the hyperparameters i.e. penalty factor (C) and kernel width (σ). The most usual approach to evaluate these parameters is the grid search method [35]. However, the grid search technique swallows a lot of time and the obtained results are often erroneous. As such in this work, the authors have exploited the well-known particle swarm optimization (PSO) algorithm developed by Kennedy and Eberhart [36] for the determination of optimal C and σ. The resultant prediction model is termed as particle swarm optimized iterated multistep ahead support vector regression (PSO-IMSSVR) model.

Thus, in this paper, a novel integrated approach based on an amalgamation of EEMD multi-feature extraction, GMM, JRD and PSO-IMSSVR is proposed for inclusive prognostication of rolling element bearings. The rest of the paper is organized as follows: In Section 2, an overview of EEMD, GMM and JRD is presented. These three techniques are used together to attain the HI for bearing PDA. Section 3 reviews the SVR algorithm and the iterated multi-step ahead prediction strategy. The PSO method applied to tune the SVR parameters is also described in this section. Section 4 outlines the framework proposed for bearing PDA and RUL prediction. In Section 5, the experimental set-up used to gather the bearing signals is described. The proposed approach is applied on the simulation