Energy xxx (2016) 1–9

Contents lists available at ScienceDirect

Energy

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

Early fault detection and diagnosis in bearings for more efficient operation of rotating machinery

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A R T I C L E I N F O

Article history:
Received 30 September 2015
Received in revised form
17 July 2016
Accepted 11 August 2016
Available online xxx

Keywords:
Energy efficiency
Fault detection and diagnosis
Rolling bearings
Wavelet transform
Energy entropy
Quadratic classifiers

A B S T R A C T

Early fault detection and diagnosis plays an increasingly important role in various energy systems where it is critical to avoid deteriorating condition, degraded efficiency and unexpected failures. Rolling-element bearings are among the most common components of rotating machinery used for transformation of energy. Mechanical wear and defective bearings cause rotating machinery to decrease its efficiency, and thus increase energy consumption. A new technique for early fault detection and diagnosis in rolling-element bearings based on vibration signal analysis is presented. After normalization and the wavelet transform of vibration signals, the standard deviation as a measure of average energy and the logarithmic energy entropy as a measure of the degree of disorder are extracted in sub-bands of interest as representative features. Then the feature space dimension is optimally reduced to two using scatter matrices. In the reduced two-dimensional feature space the fault detection and diagnosis is performed by quadratic classifiers. Accuracy of the new technique was tested on four classes of the recorded vibrations signals, i.e. normal, with the fault of inner race, outer race and balls operation. An overall accuracy of 100% was achieved. The new technique will be further tested and implemented in a real production environment.

1. Introduction

Predictive maintenance together with an early fault detection and diagnosis (FDD) plays an increasingly important role in various systems used for transformation, distribution, and storage of energy. The ability to detect degraded efficiency and predict unexpected failures reduces maintenance costs, improves productivity and increases availability of such systems. Salahshoor et al. [1] use a data fusion method based on support vector machine and adaptive neuro-fuzzy inference to detect and diagnose faults in steam turbines. Similarly, Liu et al. [2] study fault diagnosis in a solar assisted heat pump system while Rostek at al [3]. deal with early detection and prediction of leaks in fluidized-bed boilers. Daisy and Dashti [4] propose a hybrid method for fault detection in distribution feeders to support power distribution system to restore rapidly. Tylman et al. [5] also uses artificial intelligence but to detect leaks of dielectric fluid in underground high-pressure cables. Shao et al. [6] propose an artificial neural network system for fault diagnosis in proton exchange membrane fuel cells. Kusiak et al. [7] give an overview of techniques used for condition monitoring and fault detection in various parts of wind turbines including their bearings as well. Rolling-element bearings are among the most common components of rotating machinery available in various industries from agriculture to aerospace. They operate under high loading and severe conditions. As shown in Fig. 1 their faults often occur gradually and represent one of the foremost causes of failures in rotating machinery. Defective bearings generate various forces causing high amplitude of vibration and thus increasing energy consumption. For example, in the case of a water pumping station

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http://dx.doi.org/10.1016/j.energy.2016.08.039
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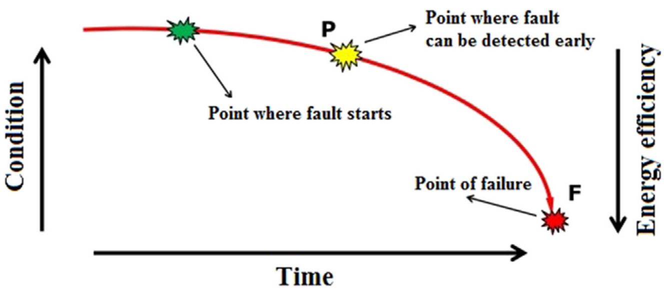

Fig. 1. Predictive maintenance Potential to Functional Failure (P–F) curve.

bearing faults can increase vibration level up to 85%, where power consumption increases 14% and efficiency decreases 18% [8]. Power consumption, maintenance and initial costs represent around 85%, 10% and 5% of the pumping station life cycle cost, respectively [9]. Therefore it is very important to avoid deteriorating condition, degraded efficiency and unexpected failures of rotating machinery using a reliable, fast and automated technique for early FDD in bearings.

Many techniques for FDD in bearings based on vibration signal analysis have emerged in recent years. Generally, an FDD can be decomposed into three steps: data acquisition, feature extraction, and classification. An effective feature extraction as the key step represents a mapping of vibration signals from their original measured space to the feature space which contains more valuable information for FDD. Even though time-domain features such as peak, mean, root mean square, variance, skewness and kurtosis have also been employed as input features to train a bearing FDD classifier the fast Fourier transform (FFT) is one of the most widely used and well-established feature extraction methods [10]. However, the FFT-based techniques are not suitable for analysis of non-stationary signals. Since vibration signals often contain non-stationary components, for a successful FDD it is very important to reveal such information as well. Thus, a supplementary technique for non-stationary signal analysis is necessary. Time-frequency techniques such as the Wigner–Ville distribution (WVD) [11] and the short-time Fourier transform (STFT) [12] also have their own disadvantages. The WVD bilinear characteristic leads to interference terms in the time-frequency domain while the STFT results in a constant resolution for all frequencies since it uses the same window for the analysis of the entire signal. The wavelet transform very accurately resolves all these deficiencies and provides good frequency resolution and low time resolution for low-frequency components as well as low frequency resolution and good time resolution for high-frequency components. Therefore the wavelet transform has been widely applied in the field of vibration signal analysis and feature extraction for bearing FDD [13,14]. A precise classification as the next step directly depends on previously extracted features, i.e. there is no classifier which can make up for the information lost during the feature extraction. As in the case of the feature extraction, we can come across a wide range of classifiers used for FDD in bearings. The classifiers based on artificial neural networks [15–17] and fuzzy logic [18,19] demonstrated a highly reliable classification. However, one of the disadvantages of these classification approaches is that they require the availability of a very large training set and a large number of parameters, which have to be selected or adjusted to obtain good results [20]. Therefore, there is a strong need to make the classification process simpler, faster and accurate using the minimum number of features and parameters.

2. Materials and methods

In this paper a new technique for early FDD is proposed. As shown in Fig. 2 it has several steps. The first step is acquisition of vibration signals as well as their preprocessing which includes normalization and segmentation. In the next step and after the wavelet transform of vibration signals 12 representative features such as the standard deviation and the logarithmic energy entropy are extracted in the time-frequency domain. In the third step the feature space dimension is optimally reduced to two using scatter matrices while in the final step in total three quadratic classifiers are designed [21], the one for detection and the other two for diagnosis of bearing faults. Using this new approach, the overall complexity of FDD is decreased and at the same time a very high accuracy maintained compared with already available techniques which employ more complex training algorithms.

2.1. Acquisition and preprocessing of the vibration signals

In order to test the capability of the new technique the bearing data obtained from the Case Western Reserve University (CWRU) Bearing Data Center [18] is used since it has become a standard reference in the field of FDD in bearings. A ball bearing as one shown in Fig. 3 was installed in a motor driven mechanical system shown in Fig. 4. A three-phase induction motor was connected to a dynamometer and a torque sensor by a self-aligning coupling. The dynamometer was controlled so that desired torque load levels can be achieved. An accelerometer with a bandwidth up to 5000 Hz and a 1 V/g output was mounted on the motor housing to acquire the vibration signals from the bearing.

The data collection system consisted of a high bandwidth amplifier particularly designed for vibration signals and a data recorder with a sampling frequency of 12000 Hz. The sampling rate is ample having in mind that the frequency content of interest in

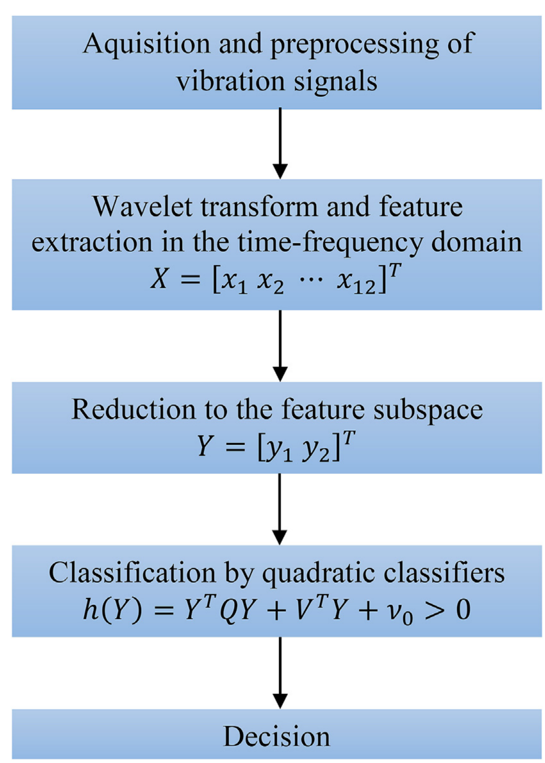

Fig. 2. Flowchart of the new technique for early FDD.

Please cite this article in press as: Brkovic A, et al., Early fault detection and diagnosis in bearings for more efficient operation of rotating machinery, Energy (2016), http://dx.doi.org/10.1016/j.energy.2016.08.039