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Using multi-sensor data fusion for vibration fault diagnosis of rolling element bearings by accelerometer and load cell

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ABSTRACT

This paper presents a new method for bearing fault diagnosis using the fusion of two primary sensors: an accelerometer and a load cell. A novel condition-based monitoring (CBM) system consisting of six modules: sensing, signal processing, feature extraction, classification, high-level fusion and decision making module has been proposed. To obtain acceleration and load signals, a work bench has been used. In the next stage, signal indices for each signal in both time and frequency domains have been calculated. After calculation of signal indices, principal component analysis is employed for redundancy reduction. Two principal features have been extracted from load and acceleration indices. In the fourth module, K-Nearest Neighbor (KNN) classifier has been used in order to identify the condition of the ball bearing based on vibration signal and load signal. In the fifth module, a high-level sensor fusion is used to derive information that would not be available from single sensor. Based on situation assessment carried out during the training process of classifier, a relationship between bearing condition and sensor performance has been found. Finally, a logical program has been used to decide about the condition of the ball bearing. The test results demonstrate that the load cell is powerful to detect the healthy ball bearings from the defected ones, and the accelerometer is useful to detect the location of fault. Experimental results show the effectiveness of this method.

1. Introduction

Bearing is a key element in rotating machinery and any defect can cause malfunctioning of machine. Normally, defects initiate and grow during bearing operation. Detection of defects at an early stage is of great importance because it can prevent the progression of defects to other parts of machine. Condition-based monitoring (CBM) procedure is established to improve quality inspection, and predictive maintenance. So far, a variety of methods are used for the diagnosis of bearing defects. The methods are broadly classified as acoustic measurements [1], current and temperature monitoring [2], wear debris detection [3], and vibration analysis [4]. Acoustic Emission (AE) is considered as the most effective acoustic-based bearing health monitoring technique. It is a high frequency, transient impulse emitted by the rapid local stress redistributions in solid material under working load condition. Examples of AE application are crack growth, corrosion and wear. The measurement of transient sound waves in a machine element such as bearing and analysis of acoustic signal properties can be used to detect and localize defects. Al-Ghamd and Mba [5] reported several studies on the application of AE to bearing diagnosis and compared the AE method with vibration based method. Although in compare to other techniques, this technique is considered when structural integrity monitoring is required but its accuracy is limited by the number of used sensors.

Current monitoring for bearing fault detection is relatively new method. It has become an attractive technique for condition monitoring of induction motor ball bearings. This method is simple and available in many applications but the major drawback of this method is the presence of noise and the difficulty of separating bearing faults from non mechanical faults. Another approach is using infrared thermography for detection of bearing degradation. A bearing failure can cause excessive heat generation in the rotating components. Bearing fault detection based on thermography has some limitations such as expensive equipment and hard to detect fault at an early stage. A review of infrared thermography for condition monitoring [6] discussed in details various applications.

Wear debris detection sensor is also used for damage detection in rotating machinery such as gearbox and bearing. The most common oil debris sensors can detect abnormal wear in gearboxes. A disadvantage of this technique is that it does not localize the failure in complicated gearboxes.

Vibration measurement and analysis is widely considered as the most effective condition diagnosis method for rotating

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machinery. A local fault in a machine such as spalling on balls/rollers or cracked race in a bearing generates a shock impulse every time the local fault contacts another part of the machine. Thus, the vibrations produced by shock impulses can be analyzed to identify the machine fault. The main advantage of vibration based machine diagnosis is the ability to detect different types of defects, either distributed or localized. Furthermore, low-cost sensors, accurate results, simple setups, specific information on the damage location, and comparable rates of damage are other benefits of the vibration measurement method.

Even a fault-free bearing generates vibration; thus, studying the base-line behavior of bearing oscillation is necessary to find the abnormality in the damaged vibration signature. The principal source of vibration in roller element bearings is varying compliance, caused by the continuous change of position and the number of load carrying elements. Based on this phenomenon, different models have been proposed to represent the periodic vibration of bearings [7,8]. The periodic vibration of bearings can be transformed to chaotic through a quasi-periodic, period doubling, and intermittency routes [4]. Recently, some studies have even shown a possible relation between chaotic parameters and bearing faults. For example, it has been shown that the correlation integral of bearing vibration data [9,10], and the modified Poincare map of vibration data [11] are potential features for fault diagnosis.

The majority of the research on the diagnosis and prognosis of bearings is based on signal processing techniques, independent of bearing vibration characteristics. In these works, first a localized or distributed defect is created on a bearing by means of grinding, acid etching, drilling, overloading, or over speeding to intentionally introduce defects in the bearing components. An accelerometer is usually used to measure vibration signal of the defective bearing. The bearing vibration signal is then analyzed by different signal processing techniques to extract the fault sensitive features that will later be used as the monitoring indices. This procedure is quite similar among the published literature. The reported signal processing methods are categorized as time domain, frequency domain, and time–frequency domain. These techniques are not totally independent, and in many cases, they are complementary to each other. Time domain analysis has been widely employed. Successful results of Root Mean Square (RMS), Kurtosis, skewness, peak value, crest factor (CF), and synchronous averaging [12] have been reported in the low frequency range of less than 5 kHz. Band pass filtering has also been conducted in the time domain. It is based on the fact that the strike between the damage and the rotating component can excite high frequency resonances (10–100 kHz). The generated energy from this impact is not sufficient to excite the entire rotor's assembly, but is enough to excite vibration sensor resonance. Monitoring the vibration amplitude at the resonant band pass filtered frequency is the principle of the shock pulse method [13]. It is implemented in shock pulse meters which are the most accepted diagnostic instrument in the industry.

Time domain analysis has the advantage of simple calculations, straightforward signal pre-processing, and speed independency. However, insensitivity to early stage faults and deeply distributed defects are drawbacks of this approach. Perhaps, frequency domain, also called spectral analysis, is the most reported signal processing method for bearing diagnosis. Each bearing component has a characteristic frequency, which is calculated from the kinematics of the rotating parts. Monitoring these frequencies or their harmonics at a low frequency range (<5 kHz) has been successful in bearing diagnosis [14]; however, some research draws attention to the weakness of this method for detecting small defects [15]. To decrease the effect of the noise level and frequency side bands, some researchers have adopted the amplitude demodulated or enveloped signal. The spectral analysis of a low and/or high frequency range enveloped signal is repeatedly reported as an efficient method for bearing diagnosis. A number of frequency domain features, based on simple or complex signal processing methods such as power cepstrum [12], adaptive noise cancellation [16], and denoising [17], are also proposed for bearing diagnosis. The frequency domain approach is sensitive and robust to detect bearing defects and to identify the localized damage location. However, the accuracy of this method highly depends on the bearing dimensions and rotational speed. In addition, frequency domain methods give good results if the frequency band is carefully selected.

Time–frequency methods can provide useful information regarding energy distribution of a signal in time and frequency domain. In signal processing, a number of time–frequency analysis methods such as the short time Fourier transform, Wigner–Ville distribution, and wavelet transforms [18] have been proposed. Due to its flexibility and computational benefits, wavelet transform is widely used for bearing diagnosis and prognosis [19]. Some researchers have suggested the use of diagnostic features, obtained from wavelet decompositions [20], and wavelet packets [21].

In many cases, particularly in speed and load variable systems, a simple inspection of the monitoring index does not provide reliable information regarding the condition of the machine. Therefore, there is still a demand for reliable, flexible, and automated procedures for the diagnosis of such systems. Artificial Neural Networks (ANNs) with their flexibility and learning capabilities are the best candidates for a decision-making engine of a diagnostic scheme. The input to such a scheme is monitoring indices obtained from signal processing, and the output corresponds to the level of the bearing's health. Different kinds of ANNs are proposed for bearing condition monitoring with time and/or frequency domain features. The multi-layer feed-forward [22], radial basis function [23], wavelet neural networks [24], adaptive resonance theory network, and Adaptive Neuro-Fuzzy Inference System (ANFIS) [25] are among the most referenced networks in bearing condition monitoring. Also, other types of intelligent systems such as pattern recognition models [26], cascade correlation algorithms [27], automated fuzzy inference [28], support vector machine [29], and genetic algorithms [30] have also been employed, to extract the condition of the bearing. Bearing prognosis refers to the adoption of current and previous monitoring indices to forecast machine's future states. Bearing prognostic methods are either model-based life perdition, or intelligent systems. The first category focuses on a model to predict the fatigue life of a bearing, whereas the second category involves statistical or intelligent systems to estimates the future state of a bearing. A few prognostic methods are recently proposed based on Recurrent Neural Network (RNNs) [31], Multi Layer Perception (MLP) [32], and self organizing map [33] with limited applications.

However, the above researches only used the vibration measurements from individual sensors. Integrating the diagnostic tools with different measurement technologies into one system can potentially improve the detection capabilities and probability that damage is detected.

The objective of this research is to combine load and vibration based fault detection techniques using decision fusion in order to obtain a bearing monitoring system with greater efficiency in detection and decision making capabilities than the individual diagnostic tools. The experimental load and vibration measurements will be used to verify this hypothesis.

2. Experimental set-up and measurements

2.1. Test rig

The test rig used in this study is illustrated in Fig. 1. It consists of a single-phase induction motor driving the V-belt drive. The V-belt