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Fault diagnosis of rotating machinery with a novel statistical feature extraction and evaluation method

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ABSTRACT

Fault diagnosis of rotating machinery is receiving more and more attentions. Vibration signals of rotating machinery are commonly analyzed to extract features of faults, and the features are identified with classifiers, e.g. artificial neural networks (ANNs) and support vector machines (SVMs). Due to nonlinear behaviors and unknown noises in machinery, the extracted features are varying from sample to sample, which may result in false classifications. It is also difficult to analytically ensure the accuracy of fault diagnosis. In this paper, a feature extraction and evaluation method is proposed for fault diagnosis of rotating machinery. Based on the central limit theory, an extraction procedure is given to obtain the statistical features with the help of existing signal processing tools. The obtained statistical features approximately obey normal distributions. They can significantly improve the performance of fault classification, and it is verified by taking ANN and SVM classifiers as examples. Then the statistical features are evaluated with a decoupling technique and compared with thresholds to make the decision on fault classification. The proposed evaluation method only requires simple algebraic computation, and the accuracy of fault classification can be analytically guaranteed in terms of the so-called false classification rate (FCR). An experiment is carried out to verify the effectiveness of the proposed method, where the unbalanced fault of rotor, inner race fault, outer race fault and ball fault of bearings are considered.

1. Introduction

Rotating machinery is widely used in many industrial fields. Usually vibration signals are used to detect the faults of the machine components and reduce the catastrophic damage and the down-time of machinery by applying fault diagnosis methods [1–4]. Generally speaking, there are two main steps in fault diagnosis: the first step is the feature extraction of vibration signals with some signal processing tools, and the second step is the fault classification based on the extracted features in the previous step.

How to extract the features from vibration signals is one of the key problems in the fault diagnosis of rotating machinery. Since vibration signals usually have non-stationary and nonlinear behaviors due to the complexity of the structure and work conditions of rotating machinery, it is difficult to achieve an effective fault diagnosis only with the time domain or the frequency domain analysis. Hence features are extracted to indicate the characteristics of vibration signals. The conventional feature extraction methods include time-domain methods, frequency-domain methods, and time-frequency methods [1].

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Time-domain methods are directly based on the time waveform, e.g. peak amplitude, root-mean-square amplitude, variance, skewness, kurtosis, correlation dimension and fractal dimension [5–8]. Most of those features are statistics of the time waveform. Frequency-domain methods are based on the transformed signal in frequency domain, i.e. Fourier spectrum, cepstrum analysis, and envelope spectrum [9–11]. Wavelet analysis, short time Fourier transform, Wigner–Ville distribution, Choi–Williams distribution and Hilbert–Huang transform are the time-frequency methods [12–17], which investigate waveform signals in both time and frequency domains.

Many studies of fault classification were also carried out [1]. Fault classification based on artificial neural network (ANN) techniques and support vector machine (SVM) techniques are popular in literatures for fault diagnosis of rotating machinery. ANN was used as a fault classifier for both binary and multi-class fault classifications [18–21]. ANN requires extensive training data and training time. It is difficult to be analytically interpreted, and it may not converge in the global optima. An alternative to ANN is SVM, which is based on the statistical learning theory [22]. The solution to an SVM is the classification hyperplane, which is well interpreted and unique. SVM has recently been applied to many practical problems [23–27]. In order to obtain the training samples of features required by ANNs or SVMs, a number of vibration signals under the same condition were processed to extract the features, or a given vibration signal was equally divided into many partitions and then certain signal processing method was applied to extract the features of each partition. The length of signals or partitions was determined by the applied signal processing method. The variation of extracted features can significantly influence the accuracy of fault classification with ANN and SVM [2]. In [28], a decoupling technique has been proposed to classify the faults based on simple algebraic computations without a training procedure, where feature vectors were projected onto a set of orthogonal directions in order to indicate the fault information. There were also other fault classification methods such as fuzzy inference method [29], genetic algorithm [30] and hidden Markov model method [31].

The effectiveness of a fault diagnosis method is indicated by the classification accuracy and the computation time. Hence finding an accurate and fast method for fault diagnosis is an essential issue [23]. However ANN and SVM based fault classification methods do not give any analytical guarantee on the accuracy. The classification accuracy of ANN and SVM is usually estimated through experiments.

In this paper, a feature extraction and evaluation method is proposed for fault diagnosis of rotating machinery. Based on the central limit theory, an extraction procedure is presented to compute statistical features with the help of existing signal processing tools. Such statistical features are close to normal distributions. The raw features which are directly computed with conventional feature extraction methods are compared with the statistical ones by using them as the inputs for ANN and SVM based fault classifiers. Then the statistical features are evaluated with a decoupling technique, and a decision logic is also given to indicate the classification results by making use of the means and variances of statistical features. The proposed evaluation method only requires simple algebraic computation, and the accuracy of fault classification is analytically guaranteed. The so-called false classification rate (FCR) can be ensured to be smaller than any given value. An experiment is carried out to verify the effectiveness of the proposed method, where the unbalanced fault of a rotor, inner race fault, outer race fault and ball fault of bearings are considered.

The rest of the paper is organized as follows. Section 2 introduces the experimental system. In Section 3, the statistical feature extraction is proposed. The statistical feature evaluation is given in Section 4. In Section 5, the experimental results are used to demonstrate the effectiveness of the proposed method. Finally, concluding remarks are given in Section 6.

2. Experimental system

The experiment is carried out with a machinery fault simulator as shown in Fig. 1, which contains a variable speed motor, a variable speed motor controller, a flexible coupling, a shaft, a rotor disk with tapped holes in the edge and two rolling element bearings. One of the bearings without defects is located in the bearing housing closer to the motor. The other bearing is located in the bearing housing farther to the motor, and it could be replaced by the testing bearings with three kinds of faults, i.e. defect in the inner race, defect in the outer race, and defect in a ball. An ICP accelerometer with a bandwidth up to 10 kHz and a 0.1 V/g output is mounted on the right bearing housing, and the vibration signals from the accelerometer are used to diagnose faults. The running speed of this simulator is set at 1198 RPM and driven by a 3-hp AC motor. The sampling frequency is 2 kHz, and the sampling time is 10 s.

In order to develop the new fault diagnosis method, five sets of vibration data were obtained from the experimental system under five health conditions: (i) under the normal condition; (ii) with the unbalanced fault of rotor; (iii) with the inner race fault of a bearing; (iv) with the outer race fault of a bearing; and (v) with a ball fault of a bearing. The bearings under different health conditions are replaced in the right bearing housing in order to simulate the faulty behaviors. The rotor is unbalanced with bolts screwed in the tapped holes. Each set of data contained vibration signals of 10 s, and it was divided into two parts: design data and test data. The design data is used to design the fault diagnosis system, while the test data is used to testify the designed system. Fig. 2 shows parts of the vibration signals under different health conditions.

Given that a discrete time vibration signal x_j is collected through the accelerometer under the j-th health condition of rotating machinery. Due to the limits of computation capacity, only a partition of x_j can be processed by computers at once. It is well known that vibration signals may with inherent non-stationary characteristics and may also interfered by unknown noises. Hence the raw features extracted from different partitions of x_j could be varying. Actually it is also difficult to determine the distributions of raw features. This is the reason why ANN and SVM techniques are employed to realize fault classification in literatures, where a number of samples of features are used to train ANN or SVM. However such fault