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Reliable fault diagnosis for incipient low-speed bearings using fault feature analysis based on a binary bat algorithm

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ABSTRACT

In this paper, we propose a highly reliable fault diagnosis scheme for incipient low-speed rolling element bearing failures. The scheme consists of fault feature calculation, discriminative fault feature analysis, and fault classification. The proposed approach first computes wavelet-based fault features, including the respective relative wavelet packet node energy and entropy, by applying a wavelet packet transform to an incoming acoustic emission signal. The most discriminative fault features are then filtered from the originally produced feature vector by using discriminative fault feature analysis based on a binary bat algorithm (BBA). Finally, the proposed approach employs one-against-all multiclass support vector machines to identify multiple low-speed rolling element bearing defects. This study compares the proposed BBA-based dimensionality reduction scheme with four other dimensionality reduction methodologies in terms of classification performance. Experimental results show that the proposed methodology is superior to other dimensionality reduction approaches, yielding an average classification accuracy of 94.9%, 95.8%, and 98.4% under bearing rotational speeds at 20 revolutions-per-minute (RPM), 80 RPM, and 140 RPM, respectively.

1. Introduction

Bearings have played a significant role in low-speed machines that are widely utilized in heavy industries, such as paper mills, steel pipe foundries, and wind-turbine power plants, for supporting heavy loads and providing stationary rotational speeds [56]. Unanticipated bearing defects can therefore lead to severe motor breakdowns and significant economic losses. To address this issue, reliable fault diagnosis for incipient bearing failures is important. Vibration signal analysis has been widely utilized for bearing fault diagnosis because it provides the most intrinsic information about diverse bearing defects [3,4,7,26,36,45,47,50]. Moreover, current signature analysis has been an alternative for condition monitoring of bearings and offers two advantages [18,23,32,43,65,66]: high sensitivity to diverse mechanical failures with its non-intrusive monitoring ability, and failure diagnosis that is low-cost on account of its lack of requiring special devices to be installed on the motor. Although these analysis methods have shown satisfactory performance for diagnosing diverse bearing failures, they have focused only on identifying bearing faults under high rotational speeds, which are hundreds to thousands of revolutions-per-minute (RPM). This is because they are limited in capturing useful descriptions about low-speed bearing failures from

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very feeble vibration and current signals. To address this problem, acoustic emissions (AEs) have been attractive for use in fault diagnosis in low-speed bearings because they are very useful for capturing low-energy signals [6,10–13,41,44,54,56,57,60]. More specifically, according to Tandon and Chaudhary [54] and Yoshioka and Fujiwara [60], AEs can capture intrinsic symptoms of diverse bearing defects before they appear on the bearing's surface. Hence, in this study, we exploit AE signals for early identification of incipient defects in low-speed rolling element bearings.

During the past few decades, signal processing-based fault diagnosis methodologies have been popular in studies for identifying bearing failures, such as a crack or spall on raceways of a bearing. The following steps are crucial for bearing fault diagnosis using these methodologies: fault feature calculation, discriminative fault feature analysis, and fault classification. In the fault feature computation phase, calculation of statistical parameters, including mean, standard deviation, kurtosis, and skewness, is performed to describe diverse symptoms of bearing defects by exploring time domain analysis [26,41,44,45,56,57], frequency domain analysis [4,7,10,24,51,56,57], and time–frequency domain analysis [1,5,6,14,17,19,21,22,27–29,31,32,34–36,46,50,53,55,62,64,68]. Owing to the fact that signals (e.g., vibration, current, AE) acquired for bearing defect diagnosis have non-stationary properties, time–frequency domain analysis has been of increasing interest in recent research on revealing the most informative description of bearing failures. Hence, fault feature extraction has been performed via time–frequency domain analyses, including the wavelet transform (WT) and empirical mode decomposition (EMD). Specifically, wavelet-based fault features have been extensively utilized for failure diagnosis [14,16,27–29,31,46,53,55,59].

In general, the dimensionality of a feature vector that includes these wavelet-based fault features is high. However, this high-dimensional feature vector may have unsuitable fault features, which can increase the number of misclassifications among different bearing failures. Accordingly, dimensionality reduction of the feature vector is therefore required, while the most useful information about diverse bearing failures is retained. To address this issue, several methods, such as principal component analysis (PCA) [8,15,20,26,42,56,69] and linear discriminant analysis (LDA) [9,26,56,63,67], have been introduced to reduce the dimensionality of the feature vector [25,61]. An unsupervised analysis method, PCA is effective for dimensionality reduction; the resultant principal components via PCA can be alternatives to optimal fault features for early diagnosis of bearing defects. However, PCA has a shortcoming in terms of preserving discriminative properties of bearings because it lacks an interclass separability estimation process. LDA, on the other hand, which is a supervised analysis technique, can preserve discriminative information by exploiting within- and between-class scatter matrices. As a result, it generally offers better classification results for fault diagnosis than those obtained by the PCA-family approaches, such as PCA and kernel PCA [26,63].

In addition, Jin et al. [26] and Zhao et al. [63] presented trace ratio linear discriminant analysis (TR-LDA), which is an orthogonal variant of LDA and eliminates redundant information from the scatter matrices in LDA. Although TR-LDA yields satisfactory performance in identifying various bearing defects, it is limited in analyzing fault features without a Gaussian distribution. In practice, non-Gaussian fault features are often observed in many machinery diagnosis problems. Accordingly, TR-LDA has been extended to effectively analyze non-Gaussian fault features. Extended TR-LDA exploits two new scatter matrices that characterize interclass separability and intra-class compactness, which are generated from intrinsic and penalty graphs. Nevertheless, extended TR-LDA often has difficulty characterizing interclass separability because the penalty graph cannot reflect neighborhood relationships among various classes. Furthermore, this inherent property in extended TR-LDA can be a major cause of degraded classification performance.

To overcome these limitations in conventional dimensionality reduction approaches, we herein propose a discriminative fault feature analysis based on a binary bat algorithm (BBA), which cooperates well with one-against-all multiclass support vector machines (OAA MCSVMs), wherein the SVM is a binary classifier using labeled information. The proposed discriminative fault feature analysis identifies an optimal set of fault features in an initially produced feature vector for diagnosing low-speed bearing failures. This proposed methodology then discriminates various bearing defects by using an optimal set of fault features as an input for OAA MCSVMs, which are generally effective for achieving higher classification performance with limited training data [58].

The remainder of this paper is organized as follows. In Section 2, we introduce diverse bearing defects and illustrate a test rig for experiments. In Section 3, we present the proposed fault diagnosis methodology that employs fault feature analysis based on a BBA. In Section 4, we evaluate its effectiveness in terms of classification performance and compare its classification accuracy with that of other state-of-the-art methods. Our conclusions are provided in Section 5.

2. Diverse rolling element bearing defects and experimental setup

To identify incipient rolling element bearing defects, we developed a low-speed machinery fault simulator that enables modeling of bearing faults under different load conditions at different rotational speeds, as shown in Fig. 1(a). In addition, an AE sensor (R3α type from Physical Acoustics Corporation) with a frequency range of 25–530 kHz was attached to the top of the bearing housing to capture continuous AE signals, as shown in Fig. 1(b). Fig. 1(c) illustrates a data acquisition system for recording and analyzing AE signals. The system was capable of an 18-bit 10-MHz analog-to-digital conversion with a laptop connected to a PCI board. To diagnose multiple bearing defects, various seeded bearing defects were produced by using a diamond bit and a grinder with an air-grinding tool. Fig. 2 shows cracks and spalls on either raceways or the roller of cylindrical roller bearings (i.e., SKF NF307). In addition, a defect-free bearing was utilized as a reference case in this study. In total, we acquired six different types of AE signals under various load conditions (i.e., 500-N and 2-kN) at different rotational speeds (20, 80, and 140 RPM). We recorded 90 1.5-s AE signals sampled at 500 kHz for each case.