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Fault diagnosis of rolling bearing based on feature reduction with global-local margin Fisher analysis

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A R T I C L E I N F O

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A B S T R A C T

The primary task of rotating machinery fault diagnosis is to extract more fault feature information from the measured signals, so that its diagnostic result is more accurate and more reliable. To obtain much more inherent global and local fault information from the mechanical operating data, a novel fault diagnosis approach of rolling bearings based on feature reduction that uses Global-Local Margin Fisher Analysis (GLMFA) is firstly proposed. First of all, the proposed fault diagnosis approach transforms the vibration signals of rolling bearings into a multi-domain statistical feature dataset. The constructed feature dataset is then trained by the proposed GLMFA algorithm, which is a novel manifold learning algorithm aim to extract the low-dimensional sensitive features subset with global information and local information of rolling bearing. Finally, the various health conditions of rolling bearings are diagnosed by using the improved Euclidean Weighted K-nearest neighbor (EW-KNN) classifier. The core of this method is that the proposed GLMFA can overcome the shortcoming of Margin Fisher Analysis (MFA) that it cannot juggle global fault information and local fault information of the data. Therefore, the global and local structure information of vibration signals are described by adding two kinds of regularization items. And the proposed EW-KNN weights the different features in the classification process of K-nearest neighbor (KNN) by using standardized Euclidean distance to highlight the sensitivity of different features for the classification. The experimental datastes of rolling bearings verify the effectiveness of this novel method. The experimental results indicate that this method can comprehensively extract global-local discriminant fault information, which can make its extracted fault features more sensitive and significantly improve classification accuracy rate.

1. Introduction

Rotating machinery has always been played an important role in modern industrial production and technological development [1–3]. Once a failure occurs, it will cause huge economic losses and even safety accidents. Therefore, it is necessary to perform effective condition monitoring and fault diagnosis on key components of rotating machinery [4,5]. At the present stage, rolling bearings are still the most important powerful transmission and supportive components for rotating machinery [3–5]. According to statistics, 30% of the failures of rotating machinery are caused by local damage or defects of rolling bearings [5,6]. Hence, it is needed to have an effective intelligent rolling bearing fault diagnosis technology to diagnose the existing or potential failures of rotating machinery [4–6].

As we all know, the vibration signals of rolling bearings contain a large number of information which can reflect the working conditions of rotating machinery [7–9]. Therefore, the rolling bearing fault diagnosis based on vibration signals analysis as one of the main diagnostic approaches is widely used in the field of condition monitoring and fault diagnosis [7,10,11]. In order to enhance the completeness of mechanical information, the collected mechanical information and data have been increasing [8,9], which will inevitably lead to data redundancy and information sparseness. It is conceivable that the follow-up classification and decision-making are difficult, that is, 'dimension disaster' issue [10–12]. This issue requires us to effectively reduce and compress the massive data resources to extract valuable information and knowledge [9–11].

In a broad sense, the data-driven intelligent fault diagnosis of rotating machinery usually includes three steps: (1). Signal acquisition and segmentation; (2). Feature extraction and reduction; (3). Fault recognition and prediction. Among them, signal acquisition and segmentation is the basis, feature extraction and reduction is the key step of fault diagnosis, and its fault recognition is the ultimate goal [8,9, 13–16]. The purpose of fault feature reduction is

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to extract low-dimensional feature information which reflects the intrinsic information from high-dimensional data, i.e. dimensionality reduction [12, 16–18]. Correspondingly, the conventional fault feature reduction methods can be divided into global model and local model according to data structure [19]. The typical global methods are Liner Discriminant Analysis (LDA) [20], Principal Component Analysis (PCA) [21], Kernel Principal Component Analysis (KPCA) [22] which is aimed to extract global fault feature information from vibration signals of rotating machinery.

Additionally, manifold learning has been used to extract local fault feature information for fault diagnosis [1]. And manifold learning assumes that the local structure information of data is maintained by using manifold geometric embedding. Especially, Locality Preserving Projections (LPP) [23] and Margin Fisher Analysis (MFA) [24] were used to extract local manifold fault information by preserving local manifold structure of data.

However, the traditional fault feature reduction methods cannot take both global information and local information of data into account. Refs. [25–29] suggested that the global and local structural information of data are both beneficial for fault feature reduction and fault classification. As a comparison, both local and global information should be adequately considered for dimension reduction and fault diagnosis. The global structure defines the outer shape of the process dataset, while the local structure provides its inner organization of dataset. In order to juggle more global and local fault information, Local Global Principal Component Analysis (LGPCA) in Ref. [25] was proposed by establishing local and global objective functions. It was and then successfully applied in fault detection. And Chen et al. [26] proposed Laplacian Liner Discriminant Analysis (Lap-LDA) algorithm based on least squares LDA theory. LapLDA not only contains the global structure information of LDA, but also can obtain the local structure information of data by using Laplacian map. Zhang et al. [27] proposed a new fault detection and identification scheme that is based on the global-local structure analysis (GLSA) model. And it combines the advantages of both Locality Preserving Projections (LPP) and Principal Component Analysis (PCA). Yu [28] aimed at the issue that the sensitivity of various physical features that are characteristics of bearing performance may vary significantly under different working conditions. And a local and nonlocal preserving projection (LNPP)-based feature extraction algorithm was proposed. And LNPP is capable of discovering both local and nonlocal structures of data manifold. Furthermore, a LNPP-based quantification index was proposed for the assessment of bearing performance degradation.

Actually, the above-mentioned global-local feature reduction methods cannot establish a unified objective function, which increases the complexity of algorithm. Thus, it is critical to extract the most valuable information from the vibration signals for intelligent fault diagnosis and health assessment of rolling bearing. According to the Ref. [24], MFA is a supervised localized manifold learning algorithm based on graphical embedding. As a local linear approximation of LDA, MFA not only overcomes 'outing of sample problem', but also solves the limitation that the data of LDA must meet the Gaussian distribution of same labeled samples. However, MFA only uses labeled samples to extract local information and ignores global information. In order to make MFA juggle more global and local information, the regularization techniques of UDP-based Discriminant Analysis (UDA) algorithm [29,30] are used to generalize the global information and local information of data. In this paper, the neighboring and non-neighboring regularization items are introduced to maintain global and local structure information, so a new manifold learning model-Global Local Margin Fisher Analysis (GLMFA) algorithm is put forward.

In order to quantify fault diagnosis results intuitively and accurately, it is needed to select an efficient and stable pattern recognition method to implement the mapping between low-dimensional feature subset and fault conditions after feature reduction of GLMFA [31–35]. KNN (K-nearest neighbor) classifier [34,35] is a nonparametric pattern recognition method based on mathematical statistics. And KNN is widely used in fault diagnosis and other fields without complicated training. However, KNN is based on the Euclidean distance metric membership degree in the classification process, and it only gives equal contribution to the neighboring sample features, and its classification effect depends heavily on Euclidean distance measure, which cannot effectively highlight the contribution of different features for the classification [36,37]. On the other hand, the standardized Euclidean distance, as an improvement of Euclidean distance, can weight and highlight the sensitivity of different features [36,37]. For this purpose, this paper introduces standardized Euclidean distance into KNN classifier and uses standardized Euclidean distance to weight different features, so a novel Euclidean Weighted K-nearest neighbor (EW-KNN) classifier is proposed.

Based on the proposed GLMFA and improved EW-KNN, a novel fault diagnosis method of rolling bearings based on dimensionality reduction with Global-Local Margin Fisher Analysis (GLMFA) is proposed. Firstly, the vibration signals are transformed into an high-dimensional fault dataset, the constructed high-dimensional feature dataset is and then input into GLMFA for global and local feature information extraction. And the extracted low-dimensional feature subset is finally input into EW-KNN classifier for fault diagnosis. The validity of this fault diagnosis method is verified by application of rolling bearing fault dataset.

The main contributions of this paper are outlined as follows.

1) Aimed at the present issue that conventional fault feature reduction method cannot juggle local and global fault feature information, the Global-Local Margin Fisher Analysis (GLMFA) is firstly proposed. The proposed GLMFA can overcome the shortcoming that MFA cannot juggle global and local fault information of data. Therefore, the global and local structure information of vibration signals is described by adding two kinds of regularization items.
2) A novel fault diagnosis method of rolling bearing based on GLMFA is presented. First of all, the proposed fault diagnosis approach transforms the vibration signals of rolling bearing into a multi-domain statistical feature dataset. The feature dataset is and then trained by the proposed GLMFA algorithm. Finally, the various health conditions of rolling bearing are diagnosed by using the improved Euclidean Weighted K-nearest neighbor (EW-KNN) classifier. And the proposed EW-KNN can weight the different features by using standardized Euclidean distance to highlight the sensitivity of different features for the classification.
3) Two cases of rolling bearing vibration signals verify the effectiveness of the GLMFA model and fault diagnosis method of rolling bearing based on dimensionality reduction with GLMFA

The remainder of this paper is organized as follows. In Section 2, the theoretical background of MFA and regularization technique are briefly introduced, respectively. The GLMFA algorithm is then proposed in Section 3. In Section 4, a novel EW-KNN classifier and rolling bearing fault diagnosis method based on GLMFA are proposed. Vibration signals of rolling bearing verify the validity of this fault diagnosis method in Section 5. Finally, some conclusions are drawn in Section 6.

2. Theoretical background

The basic theory of Margin Fisher Analysis (MFA) and regularization technique are briefly introduced in this section, respectively.

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