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Rolling bearing fault diagnosis and performance degradation assessment under variable operation conditions based on nuisance attribute projection

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ABSTRACT

The operation conditions are always non-stationary in the operation of rotating machinery. It is the key to realize the fault diagnosis of rotating machinery under different operation conditions by extracting the features which are irrelevant to the operation conditions and contain fault information. Nuisance attribute projection (NAP) is compensation technique to eliminate the influence of interference information in the feature space which has been used in speaker recognition and face recognition. In this paper, the rolling bearing vibration signals under different operation conditions are used to verify the nuisance removing ability of (NAP) in the feature space. Above all, after NAP are applied to the simulation and measured signals under different rotating speeds and loads, the comparisons between the original features and NAP features have shown that NAP can effectively eliminate the effect of nuisance attributes through projection. Moreover, it is verified that the information of fault pattern and fault degree are retained in the features after projection by analyzing the measured signals of different fault pattern and simulation signals of different fault degree under various rotating speeds, respectively. Furthermore, it is confirmed that the NAP can get rid of the nuisance attributes by analyzing twelve bearing tests of whole life under different operation conditions and channels. On the other hand, a feature selection method based on ranking mutual information (RMI) is used in this paper to select the features of more monotonous in bearing performance degradation assessment. The application sequences of RMI and NAP are studied for their influence on the bearing performance degradation index in the last part since the different sequence may affect the assessment results. The comparison results have shown that NAP should be used before feature selection in rotating machinery fault diagnosis.

1. Introduction

With the rapid development of science and technology and the continuous development of industrial applications, mechanical equipments are becoming more and more complex, precise and intelligent. Therefore, the requirement of industrial condition monitoring and fault diagnosis system is higher and higher in practical application. The rolling bearing is the critical element of rotating machinery since its fault probability is 30% in all faults of rotating element [1]. Thus it is

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significant to monitor the bearing healthy on the working state of rotating machine [2]. Accordingly, many researchers pay more and more attention to bearing fault pattern recognition and performance degradation assessment in recent years. Especially in bearing performance degradation assessment, lots of work about this topic such as novel performance degradation indexes, feature optimization methods and feature fusion methods had been done, which provided potential directions for future research [3–7].

Undoubtedly, the feature extraction and selection of bearing signal are the keys to accurately evaluate the bearing state. The common features include the time domain features such as mean, kurtosis, skew-ness and root mean square [8–10], frequency domain features such as mean frequency, center frequency [11–13] and time-frequency domain features such as wavelet packet energy, wavelet packet entropy and component features of empirical mode decomposition [14–19]. The effectiveness of the feature directly affects the availability of diagnosis model. However, superabundant features will not only increase the difficulty in model solution but also may swamp the effective features. To address this issue, several approaches had been proposed such as principal component analysis (PCA) [20–22] and linear discriminate analysis (LDA) [23–25] for reducing the dimensionality of the feature vectors. PCA can discriminate the directions with the globally largest variance in a data set and extract several representative components by using data projection. It had been shown that PCA is an effective dimensionality reduction method which can substitute the original features for resultant principal components via projection and has been utilized for early diagnosis of bearing defects. On the other hand, LDA is a supervised dimension reduction method which is suitable for fault degree detection online. It can preserve discriminative information by exploiting within-class and between-class scatter matrices [26]. The methods mentioned above had been proved to be effective by many actual experiments, most of which were applied to the vibration data of a stationary operation condition. However, most rotating machines are running under a time-varying operation condition and the nuisance information coming from the operation condition will cover up the available information related to the actual faults. Thus, the original feature processing methods cannot extract obvious fault information from the original features mixed with the operation condition attributes.

Nuisance attribute projection (NAP) was originally used as a compensation technique to eliminate the diversity interference among channels. It was widely used in speaker recognition, face recognition and image recognition [27–29] since it can filter out the effect of nuisance attributes in feature space. Actually, the main theory of NAP algorithm is to construct a projection matrix which makes the Euclidean distance of each feature coming from different channels minimized after projection. In rolling bearing fault diagnosis and performance degradation assessment, the vibration signal is influenced a lot by different operation conditions and the nuisance information will be presented in the feature space. Thus, NAP can be used as an operation condition compensation technique to eliminate the influence of interference information in the feature space. In this paper, the simulation and measured bearing signals under different rotating speeds are utilized to validate the validity of NAP in the beginning of this paper. Moreover, whether the projection features retain the useful information about the fault pattern and fault degree will be proved by the bearing fault pattern recognition tests and whole-life performance degradation assessment tests, respectively.

On other hand, feature selection is another feature optimal method which can improve the accuracy of fault diagnosis. In the last part, ranking mutual information (RMI) [30] is used for feature selection in the bearing performance degradation. The different appliance sequences of RMI and NAP are applied in the bearing performance assessment and their assessment results are compared because the sequences of different feature processing methods may affect the assessment results. The comparisons provide a more reasonable feature processing procedure for mechanical fault diagnosis.

2. Backgrounds

2.1. Nuisance attribute projection

Nuisance attribute projection (NAP) was initially applied to reduce the signal interfere from different channels in speaker recognition, face recognition and image recognition. Since the nuisance attributes produced by the variable conditions exist in the raw vibration signal, the features extracted from the signal cannot represent the real fault characteristics. Thus, NAP is introduced to diminish the nuisance attribute information in the feature space to obtain better diagnosis results of bearing fault pattern classification and performance degradation assessment in this paper.

The algorithm of NAP is pictorially explained in Fig. 1. The *S* represents the feature vectors containing the system independent information and other nuisance attributes from the different operation conditions and channels. The *C* represents the target attributes which include full details of bearing fault pattern and fault degree. The sub-space represents the redundant attributes and NAP is used to create a projection matrix to eliminate the nuisance attributes.

The computational procedures of NAP are shown as follows:

Consider a feature space of *N*-dim, *n* samples from different working conditions or channels can be presented as a $N \times n$ data matrix $\boldsymbol{F} = [f_1, f_2, \ldots, f_n]$, and the NAP feature matrix $\boldsymbol{F'}$ is calculated by $\boldsymbol{F}$ and a projection matrix $\boldsymbol{P}$:

$$F' = P \cdot F \tag{1}$$

where $\boldsymbol{P}$ is a $N \times N$ matrix.