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Hidden Markov model and nuisance attribute projection based bearing performance degradation assessment

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ABSTRACT

Hidden Markov model (HMM) has been widely applied in bearing performance degradation assessment. As a machine learning-based model, its accuracy, subsequently, is dependent on the sensitivity of the features used to estimate the degradation performance of bearings. It's a big challenge to extract effective features which are not influenced by other qualities or attributes uncorrelated with the bearing degradation condition. In this paper, a bearing performance degradation assessment method based on HMM and nuisance attribute projection (NAP) is proposed. NAP can filter out the effect of nuisance attributes in feature space through projection. The new feature space projected by NAP is more sensitive to bearing health changes and barely influenced by other interferences occurring in operation condition. To verify the effectiveness of the proposed method, two different experimental databases are utilized. The results show that the combination of HMM and NAP can effectively improve the accuracy and robustness of the bearing performance degradation assessment system.

1. Introduction

As reliability has been playing a more and more important role in the industrial production, performance degradation assessment, the base of prognosis which is more efficient than fault diagnosis to realize the condition-based maintenance, has been attracting more and more attentions [1]. Bearings are one of the most widely used elements in rotary machines and their failures are one of the most frequent reasons for machine breakdown [2]. Many research works on bearing performance degradation assessment have been published [3–7].

Recently much research work has been reported on the application of HMM in the bearing fault diagnosis and performance degradation assessment [8–11]. Hidden Markov model (HMM) is a time series model with a doubly embedded stochastic process, which was initially introduced and studied in the late 1960s and early 1970s [12]. HMM has simple model interpretation, which is a competitive edge over the commonly used black-box modeling techniques, such as neural network [13]. Many improvements in HMM have been proposed, such as factorial hidden Markov model (FHMM), segmental hidden semi-Markov models (HSMMs) and coupled HMM and so on. FHMM forms a dynamic belief network through several layers. For FHMM, each layer has the independent dynamics, and the observation vector depends upon the current state in each of the layers. Li [14] utilized FHMM for fault diagnosis of the speed-up and speed-down process of rotating machinery. And the experimental data showed the FHMM based method had better performance than HMM. An

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HSMM is constructed by adding a temporal component into the well-defined HMM structures. The duration of a state was modeled by an explicit Gaussian probability function to cope with the inaccurate durational modeling in the HMM, which extended the use of HMMs for prognostics [15]. CHMM is utilized for multichannel fusion a lot in bearing performance degradation assessment. Xiao [16] utilized a two-chain CHMM to integrate the two-channel vibration signals, which improved the classification rate of bearing fault diagnosis. Liu [17] used a three-chain CHMM to assess the degradation process of bearing. These extensions overcome some inherent limitations of the regular HMM, but the major drawback of them is that the computational complexity may increase for the inference procedures and parameter estimations [18]. Furthermore, many new algorithms are combined with HMM for better performance and more applications [19]. However, these applications generally do not consider the feature transformation method to improve their performance significantly.

As a machine learning-based method, the accuracy of HMM based performance degradation assessment system, subsequently, is dependent on the sensitivity of the features used to evaluate the health condition of bearings. Many data analysis techniques have been proposed for bearing fault diagnosis and performance degradation assessment [20–25]. They can be classified into three categories, which are frequency domain, time domain and time–frequency domain analysis. From these three analysis domains, a lot of features can be generated from vibration data. However, various factors influence the effectiveness of the features, e.g., location of sensors, operation environment issues, etc. [26]. As a result, it is difficult to estimate which features are more sensitive to defect development and propagation in the condition monitoring system. In this paper, feature transformation is implemented to better serve as a preprocessor for the HMM based bearing performance degradation assessment system.

In order to improve the effectiveness of features, many feature transformation methods have been utilized in the performance degradation assessment system. As one of the representative feature extraction techniques, principal component analysis (PCA) has the ability to discriminate directions with the globally largest variance in a data set, and extract several representative features (i.e., principal components (PCs)) through using data projection [26]. PCA is utilized to extract features from the wavelet packet node energy generated from vibration signals of bearings to be effective inputs of the bearing performance degradation assessment system in Ref. [27]. Zhang et al. utilized PCA to handle the features extracted from both time and frequency domains of vibration signals to assist condition prognosis [28]. As a nonlinear extension of a PCA, kernel principal component analysis (KPCA) first maps the input space into a feature space via nonlinear mapping and then computes the principal components in that feature space [29]. PCA has been discussed by many authors emphasizing its limitation dealing with large data sets, because it seeks for a global structure of the data [30]. So locality-based learning methods represented by locality preserving projections (LPP) that seek to discover the nonlinear structure of the manifold existing in the given data set appeared in the last few years. In many situations, LPP is capable to recover important aspects of the intrinsic linear or nonlinear manifold structure by preserving local structure. Yu [6] utilized LPP to extract the most useful features as inputs of the bearing fault diagnosis and performance assessment model. The effectiveness of the proposed approach for bearing defect and severity classification was evaluated experimentally on bearing test-beds. Although these mentioned methods have been proved to be effective by experimental data, new methods are needed to tackle the practical issues in engineering condition monitoring. In this study, a new feature transformation method is introduced into the HMM based bearing performance degradation assessment system.

Different from the mentioned methods, nuisance attribute projection (NAP) is originally used as a channel compensation technique. NAP can be used for the compensation of channel effects, session variation, speaker variation, and general mismatch in speaker recognition [31]. NAP can filter out the effect of nuisance attributes in feature space. The nuisance attribute can be some quality or attribute that effects the appearance of an observation without being correlated with the target attribute. If the vibration signal is influenced a lot by one certain condition issue, the NAP can effectively remove its influence based on two databases sampled from situations with two different kinds of this condition issue. It's easy to implement and has got excellent performance. For the HMM based bearing performance degradation assessment, NAP can be used to diminish some certain nuisance attribute information the feature space contains. The operation condition issues introduce nuisance attributes into the bearing feature space, which is similar to situations where different channel types are utilized for a speaker identification system [32] and illumination induces appearance changes for face recognition system [33]. NAP is widely applied for two obvious reasons, one of which is the simplicity of applying a projection and another is that it does not require trying to learn the nuisance attribute value [32]. In practical applications, many condition issues affect the effectiveness and accuracy of the performance degradation assessment system. So better performance is expected for the NAP and HMM based bearing performance degradation assessment.

The rest of the paper is organized as follows: Section 2 introduces backgrounds of hidden Markov model and nuisance attribute projection; Section 3 describes the proposed bearing performance degradation assessment scheme based on HMM and NAP. The effectiveness of the proposed scheme is verified through two bearing lifetime tests in Section 4. Then in Section 5, a conclusion is drawn.

2. Backgrounds

2.1. Hidden Markov model

Hidden Markov model, as a powerful tool to characterize a time series stochastics sequence, was initially introduced and studied in the late 1960s and early 1970s [12]. Due to its strong mathematical basic theory and well developed algorithms,