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Technical Paper

Multi-bearing remaining useful life collaborative prediction: A deep learning approach

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ABSTRACT

Rolling bearing health analysis and remaining useful life prediction have become an increasingly crucial research area that can promote reliability and efficiency in the modern manufacturing industry. Internet-of-Things and cyber manufacturing techniques make it convenient to collect large volumes of sensor data that can provide powerful support for efficient data analytics such as deep learning. The combination of a massive amount of available data and advanced machine learning models brings new opportunities for bearing remaining useful life prediction. This paper proposes an integrated deep learning approach for multi-bearing remaining useful life collaborative prediction by combining both time domain features and frequency domain features. The method can extract high-quality degradation patterns of rolling bearing from vibration signals. Regarding features extracted from bearing vibration signals, in addition to three conventional time domain features, a novel frequency domain feature is adopted in the proposed method as well. Based on the extracted features, the deep neural network model is introduced to predict the remaining useful life of rolling bearing. We evaluate the performance of the proposed method on a real dataset and compare it with several commonly used shallow prediction methods Numerical experiment results show the effectiveness and superiority of the proposed approach.

1. Introduction

Rapid development of Internet-of-Things as well as cyber manufacturing [1–6] techniques are changing modern manufacturing industry dramatically. A massive amount of industrial data are generated from sensors in cyber manufacturing environment, providing new possibilities for further improvement of reliability and efficiency for manufacturing industry. In addition, advances in AI (Artificial Intelligence) oriented big data analytics are creating new research opportunities for large-scale manufacturing data processing and analysis.

As an indispensable element of modern factory machines, rolling bearings play a critical role in industrial manufacturing systems, especially where rotating machinery and equipments serve as the essential components. Bearing faults are usually considered as one of the most frequent causes of mechanical failures [7,8]. Bearing reliability has a crucial impact on dependability, durability and efficiency of the equipments in manufacturing industry. In recent years, research related to bearing degradation process analysis and service time prediction has become an increasingly important area [9].

The health status of a rolling bearing is influenced by a wide variety of factors, i.e., running load, operating temperature, lubrication, installation, corrosion, material defects, and operation mode, during the whole service life of the bearing. Each of these factors has a unique effect on bearing health status, thus making bearing remaining useful life prediction a rather complex problem [10]. In fact, multi-bearing collaborative analysis introduces more challenging issues in remaining useful life prediction, which aims at predicting remaining useful life of a bearing by considering a group of bearings with the same type under similar operating conditions. Indeed, there often exist differences between respective degradation patterns in a group of bearings, so multi-bearing remaining useful life collaborative prediction still faces great challenges.

Current existing bearing remaining useful life prediction approaches can be generally classified into three categories, model-based method, knowledge-based method, and data-driven method [11]. Model-based method usually requires constructing control equation to describe the operation principles [12]. Precision of a model-based method depends on the accuracy of the established model. Since it is difficult to describe the complex process

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of bearing degradation clearly and comprehensively, mechanism model for bearing remaining useful life prediction is usually hard to construct and has drawbacks from the perspective of prediction accuracy. Knowledge-based method makes prediction based on expert systems which take advantages of empirical knowledge. Typically, knowledge-based methods are good at qualitative evaluation rather than quantitative prediction [13]. Therefore, knowledge-based methods are more suitable to make qualitative predictions but have limitations in forecasting bearing remaining useful life with high accuracy. Data-driven method, featured data mining and machine learning, need not establish complex control equations at the initial analytical stage. In addition, data-driven methods are able to provide quantitative prediction results or probabilistic distributions of predictive variables. Building appropriate learning models for machine learning algorithms plays an essential role in data-driven approaches [14]. Both quantity and quality of available data have an effect on the prediction precision of a data-driven method.

In recent years, data-driven methods have become increasingly popular by leveraging the advantages of data analytics methodology [15]. The development and application of deep learning approach [16] have a tremendous impact on big data analysis technique research. Deep learning approach features high precision [17] and big data processing capability [18], allowing the decrease of modeling complexity [19]. Therefore, deep learning based data-driven approach has the potential to provide new opportunities for multi-bearing remaining useful life prediction. In addition, the development of high-performance computing also supports the implementation of complex machine learning algorithms to process the large-scale data efficiently.

To address the issues of multi-bearing remaining useful life prediction, this paper proposes an integrated deep learning approach based on collaborative analysis of monitoring data from multi-bearing vibration signals by combining both time domain features and frequency domain features. The feature parameters system consists of three features of time domain and one feature of frequency domain. The time domain features include root mean square (RMS), crest factor and kurtosis. All these three features derive from classical time domain features for bearing vibration signals analysis. The frequency domain feature is a newly defined feature, named as frequency spectrum partition summation (FSPS), which is represented as a six-dimensional vector in this paper. The features extracted from the bearing vibration signals almost cover a whole process of bearing degradation. The frequency domain parameter is sensitive to the earlier stage and the later stage, while the time domain features have advantages in representing the middle stage of bearing degradation process. The fully connected deep neural network is adopted in the proposed multi-bearing remaining useful life prediction model. And the deep neural network related parameters are determined according to a series of grid search experiments.

In order to validate the effectiveness of the proposed method, numerical experiments are implemented on a real dataset, which is provided by AS2M department of FEMTO-ST Institute, for performance comparison with the gradient boosting decision tree (GBDT) method, the support vector machine (SVM) method, BP neural network, Gaussian regression method and Bayesian Ridge method. Experimental results show the effectiveness and superiority of the proposed approach.

The remaining paper is organized as follows. Section 2 investigates the related work. Section 3 presents descriptions of the problem and the proposed methodology. Numerical experiment details and result analysis are given in Section 4. Section 5 concludes the paper.

2. Related work

In general, solutions for rolling bearing remaining useful life prediction could be classified into three categories, model-based prediction approach, knowledge-based prediction technique, and data-driven prediction method.

System mechanism model is the foundation of model-based prediction method. System state equations or control equations for rolling bearing degradation process are established by analyzing the complex relationships among bearing health status and the main affect factors. Based on the state/control equations and the current state of bearing, which can be used for initialization parameters extraction, the remaining useful life of rolling bearing is derived and calculated. Considering the noise in bearing state monitoring data, filtering algorithms like Kalman filter [20] and particle filter [21] are commonly adopted for signal preprocessing in order to improve the performance of the model-based prediction method. Theoretically, model-based prediction method is able to reflect the nature and the law of a system adequately. The established system model is expected to fully describe the mechanism and characteristics of bearing degradation process, thus model-based method has the potential to produce a reasonable forecasting result with high accuracy. However, since there exists various affect factors for bearing degradation process and some effect mechanisms are unclear or unpredictable, so it is usually quite difficult or even impossible to establish a precise and reliable mechanism model for bearing remaining useful life prediction problem. It is for this reason that model-based prediction method can only be used in very limited application fields.

By leveraging the advantages of accumulated technical experience or knowledge on the relevant issue, knowledge-based method makes prediction or judgment without the need of precise system mechanism model. Accumulation of domain knowledge and reasonable judgment of application situation are the crucial aspects of the knowledge-based prediction method. Expert system [22] and fuzzy logic [23] are commonly used classic knowledge-based decision-making techniques. Knowledge and experience are fully used to support the decision-making process. Knowledge-based prediction method is widely adopted in various application fields, especially in some qualitative decision making scenarios. However, knowledge-based method has limitations in solving high precise quantitative prediction problems. Thus, knowledge-based prediction approaches may have difficulty in providing satisfactory forecasting results of bearing remaining useful life.

Data-driven prediction method learns the latent association relationships among bearing degradation process and its affect factors automatically from the sensor monitoring data of rolling bearing by utilizing machine learning algorithms or other intelligent data analysis techniques. Then the well-trained data-driven prediction model can be used for bearing remaining useful life prediction. The forecasting precise depends on the quality and quantity of the available training data as well as the effectiveness of the learning algorithm. Data-driven prediction method has advantages in both modeling aspect and quantitative prediction aspect, but it requires the support of numerous high-quality available learning data as well as effective data analysis techniques. Rapid development and widely application of Internet-of-Things and cyber manufacturing techniques as well as advances in intelligent data analysis and high-performance computing techniques create new opportunities for research of data-driven prediction method and promote its development as well.

As the selected signal features and learning model varies, there exists various data-driven prediction models for rolling bearing remaining useful life forecasting problem. However, only if features of high representational capability and suitable high efficient