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Deep neural networks: A promising tool for fault characteristic mining and intelligent diagnosis of rotating machinery with massive data

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ABSTRACT

Aiming to promptly process the massive fault data and automatically provide accurate diagnosis results, numerous studies have been conducted on intelligent fault diagnosis of rotating machinery. Among these studies, the methods based on artificial neural networks (ANNs) are commonly used, which employ signal processing techniques for extracting features and further input the features to ANNs for classifying faults. Though these methods did work in intelligent fault diagnosis of rotating machinery, they still have two deficiencies. (1) The features are manually extracted depending on much prior knowledge about signal processing techniques and diagnostic expertise. In addition, these manual features are extracted according to a specific diagnosis issue and probably unsuitable for other issues. (2) The ANNs adopted in these methods have shallow architectures, which limits the capacity of ANNs to learn the complex non-linear relationships in fault diagnosis issues. As a breakthrough in artificial intelligence, deep learning holds the potential to overcome the aforementioned deficiencies. Through deep learning, deep neural networks (DNNs) with deep architectures, instead of shallow ones, could be established to mine the useful information from raw data and approximate complex non-linear functions. Based on DNNs, a novel intelligent method is proposed in this paper to overcome the deficiencies of the aforementioned intelligent diagnosis methods. The effectiveness of the proposed method is validated using datasets from rolling element bearings and planetary gearboxes. These datasets contain massive measured signals involving different health conditions under various operating conditions. The diagnosis results show that the proposed method is able to not only adaptively mine available fault characteristics from the measured signals, but also obtain superior diagnosis accuracy compared with the existing methods.

1. Introduction

In order to fully inspect the health conditions of rotating machinery, condition monitoring systems are used to collect real-time data from machines and therefore massive data are acquired after long time operation of the machines [1]. As the data is generally collected faster than diagnosticians can analyze it [2], there is an urgent need for diagnosis methods that

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can effectively analyze massive data and automatically provide accurate diagnosis results. This kind of methods is called intelligent fault diagnosis methods, in which artificial intelligence techniques, such as artificial neural networks (ANNs), support vector machine (SVM), fuzzy inference, etc., are used for distinguishing machinery health conditions [3–5]. Based on the results produced by the intelligent diagnosis methods, it is possible to take appropriate maintenance actions and ensure healthy operation of the machines [6]. Correspondingly, intelligent fault diagnosis methods have been widely investigated and applied in the field of fault diagnosis of rotating machinery [7]. Samanta [8] extracted time-domain features and employed three optimized neural networks to detect pump faults. In addition, Samanta et al. [9] utilized time-domain features to characterize the bearing health conditions and employed ANNs and SVM to diagnose faults of bearings. Statistical features were extracted by Tran et al. [10] for representing the health conditions of induction motor and then decision tree and adaptive neuro-fuzzy inference system (ANFIS) were utilized for distinguishing the faults. Moreover, Tran et al. [11] calculated features from thermal imaging based on bi-dimensional empirical mode decomposition, and then input selected features into relevance vector machine (RVM) for fault classification. Two features were proposed by Lei et al. [12] to characterize health conditions of planetary gearboxes and ANFIS was applied to recognize these health conditions. Widodo et al. [13] calculated statistical features from the measured signals and carried out RVM and SVM to diagnose the bearing faults. Lai et al. [14] introduced cumulants as input features and used radial basis function network as the fault classifier. A method was presented by Bin et al. [15], utilizing wavelet packets-empirical mode decomposition for feature extraction and multi-layer perceptron network for fault classification.

Through the literature review, we notice that ANNs are one of the most commonly used classifiers in the intelligent fault diagnosis methods, which generally include two main steps, i.e. fault feature extraction using signal processing techniques and fault classification using ANN classifiers. Feature extraction involves mapping of measured signals onto representative features characterizing the health conditions of machinery. And fault classification is to distinguish the health conditions based on the extracted features. Thanks to the representative features from the measured signals and adaptive learning capability of ANNs, the ANN-based methods are supposed to displace diagnosticians for making decisions and work well in intelligent fault diagnosis [7]. The ANN-based methods reported in literature, however, have two obvious deficiencies: (1) The features input into classifiers are extracted and selected by diagnosticians from the measured signals, largely depending on prior knowledge about signal processing techniques and diagnostic expertise. In addition, the features are selected according to a specific diagnosis issue and probably unsuitable for other issues. Thus it is necessary to adaptively mine the characteristics hidden in the measured signals to reflect the different health conditions of machinery, instead of extracting and selecting features manually. (2) The ANNs commonly adopted in intelligent fault diagnosis of rotating machinery have shallow architectures, which means that only one hidden layer is included in an ANN architecture, like the ANNs in Refs. [8,9,14,15]. Such simple architectures limit the capacity of ANNs to learn the complex non-linear relationships in fault diagnosis issues. Thus it is necessary to establish a deep architecture network for distinguishing the health conditions of machinery.

Deep learning [16] holds the potential to overcome the aforementioned deficiencies in current intelligent diagnosis methods. It refers to a class of machine learning techniques, where many layers of information processing stages in deep architectures are exploited for pattern classification and other tasks [17]. Using deep learning, deep neural networks (DNNs) with deep architectures can be established. Due to the deep architectures, DNNs are able to adaptively capture the representative information from raw data through multiple non-linear transformations and approximate complex non-linear functions with a small error. Since the idea of deep learning appeared in *Science*, it has attracted lot of attention from researchers in different fields [18]. Dahl et al. [19] proposed a pre-trained deep neural network hidden Markov model for large-vocabulary speech recognition and obtained an accuracy improvement compared with traditional models. Krizhevsky et al. [20] developed a DNN-based method in large scale visual recognition challenge involving millions of labeled images, and got the best result. Deep learning methods were utilized by Baldi et al. [21] to search for exotic particles in high-energy physics and the results demonstrated that the methods can improve the searching ability of collider. The aforementioned applications prove that deep learning is a promising tool in dealing with massive data. But it attracts few attentions in the field of fault diagnosis. Based on Teager–Kaiser energy operator and deep belief network trained by deep learning, Tran et al. [22] proposed a new method for diagnosing faults of reciprocating compressor valves. In this method, they treated deep belief network as a classifier and still manually extracted features to input the classifier, which ignored the ability of the network in mining fault characteristics.

Based on DNNs trained through deep learning, this paper proposes a novel intelligent diagnosis method to overcome the two deficiencies of the ANN-based methods in fault diagnosis of rotating machinery. In this method, DNNs are utilized to implement both fault feature extraction and intelligent diagnosis. The DNNs are first pre-trained by an unsupervised layer-by-layer learning and then fine-tuned with a supervised algorithm, where the unsupervised process helps the fault characteristic mining and the supervised process contributes to construct the discriminative fault characteristics for classification [23]. The merits of the proposed method are summarized as follows. (1) It is able to adaptively mine fault characteristics from the measured signals for various diagnosis issues. (2) The method is good at establishing the non-linear mapping relationship between the different health conditions of machinery and the corresponding measured signals. Therefore, the proposed method is expected to obtain higher diagnosis accuracy compared with the methods based on shallow ANNs. The rest of this paper is organized as follows. Section 2 briefly introduces the theoretical background of DNNs. Section 3 is dedicated to a description of the proposed intelligent diagnosis method. In Section 4, the effectiveness of the proposed method is validated using four rolling element bearing datasets and a planetary gearbox dataset. The bearing datasets contain thousands of signals with different fault categories and severities under various operating loads. And the gearbox dataset includes tens of thousands of signals with different fault modes and locations

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