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Planetary gearbox fault diagnosis based on data-driven valued characteristic multigranulation model with incomplete diagnostic information

Jun Yu [a], Yongjun He [b,*]

[a] School of Automation, Harbin University of Science and Technology, Harbin 150080, China
[b] School of Computer Science and Technology, Harbin University of Science and Technology, Harbin 150080, China

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A B S T R A C T

There are many uncertain factors that may result in incomplete diagnostic information of planetary gearboxes, such as sensor malfunctions, communication lags, and data discretization, etc. Therefore, incomplete diagnostic information of planetary gearboxes may simultaneously contain two categories of unknown attribute values. However, existing fault diagnosis methods of planetary gearboxes are hard to realize fault diagnosis using incomplete diagnostic information that simultaneously contains two categories of unknown attribute values. To overcome this issue, a fault diagnosis method of planetary gearboxes based on data-driven valued characteristic multigranulation model with incomplete diagnostic information is proposed. First, a calculation method of characteristic similarity degrees among cases is introduced, and a data-driven valued characteristic relation is defined. The data-driven valued characteristic relation is used to analyze and process incomplete diagnostic information that simultaneously contains two categories of unknown attribute values. Then, a data-driven valued characteristic multigranulation model is defined according to multigranulation model. An attribute reduction algorithm based on pessimistic data-driven valued characteristic multigranulation model is employed to extract fault diagnosis decision rules. Finally, naive Bayesian classifier is constructed to identify planetary gearbox conditions. The effectiveness of this method is validated and the advantages are investigated using a fault diagnosis experiment of planetary gearbox. Experimental results demonstrate that this method can accurately determine indiscernibility relation among cases, reduce computational complexity, and enhance fault diagnosis accuracy.

1. Introduction

Planetary gearboxes have been extensively applied in complex mechanical equipment, such as wind turbines, helicopters, and power plants to derive benefits from their merits of compact structure, large transmission ratio, smooth operation, and high transmission efficiency [1–3]. Because of heavy load, high speed, and harsh working environment, planetary gearboxes

* Corresponding author.
E-mail address: wanghai121222@163.com (Y. He).

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are prone to various faults [4,5]. Such faults may result in the entire system shutdown, huge economic losses and even casualties. Consequently, fault diagnosis of planetary gearboxes has played an important role to avoid catastrophic accidents.

In recent years, major efforts have been made in fault diagnosis of planetary gearboxes. Researchers have proposed many fault diagnosis methods. Among these fault diagnosis methods, data-driven fault diagnosis methods remove the requirement of the prior knowledge and accurate dynamic models. Therefore, they have been extensively used in planetary gearbox fault diagnosis. In the data-driven fault diagnosis methods, feature space is mapped into decision space, and functional relation is constructed between the two spaces to identify fault modes. Typical data-driven fault diagnosis methods of planetary gearboxes consist of deep neural networks (DNNs), fuzzy logic (FL) scheme, and support vector machine (SVM), etc. DNNs with deep architectures have been widely applied in machine fault diagnosis owing to their strong representation ability and simple structure [6–9]. Jia et al. [7] proposed a novel DNN-based method for rotating machinery fault diagnosis. A tangent function is regarded as the active function of DNNs. A five-layer DNN is constructed to identify fault types. Planetary gearbox dataset was used to assess the effectiveness of the proposed method. Compared to traditional methods, this method obtains the highest diagnosis accuracy. Chen et al. [8] presented an integrated fault diagnosis scheme of planetary gearboxes based on deep belief networks (DBNs) in order to enhance diagnosis accuracy. A dimensionality reduction algorithm is introduced to acquire a sensitive and lower dimensional feature set. Then these features are regarded as the input of DBNs to classify planetary gearbox fault modes. Experimental results demonstrate the presented scheme possesses high classification accuracy. Wang et al. [9] put forward a wind turbine gearbox fault diagnosis approach using DNNs. A DNN is used as a prediction model to identify impending faults. Compared to other data-driven fault diagnosis methods, the DNN model possesses the highest accuracy without high computational complexity. However, training of DNNs' structure and parameters requires a great of training samples. Slow convergence speed during training remains unsolved.

FL scheme is a common inference strategy for fusing identification results, which has been successfully applied in mechanical system fault identification [10–12]. Chen et al. [11] proposed a remaining useful life (RUL) prediction approach based on neuro-fuzzy inference. A UH-60 helicopter planetary gearbox plate was used to evaluate the proposed approach. Experimental results indicate that the diagnosis accuracy of the proposed approach outperforms conventional RUL prediction method. Chen et al. [12] introduced a diagnosis method using fuzzy entropy and adaptive neuro-fuzzy inference system (ANFIS) to identify planetary gearbox faults. Fuzzy entropies are regarded as the input of ANFIS model. Although FL scheme can achieve diagnostic results by fuzzy inference rules, the process of acquiring fuzzy rules may be time-consuming. Furthermore, these rules from human's expertise are not reliable.

SVM, as a powerful machine learning algorithm [13,14], has been used for planetary gearbox fault diagnosis owing to its high accuracy and excellent generalization ability. Liu et al. [15] introduced a feature ranking criterion of multi-class SVM. Feature effectiveness is estimated by its contribution to mode identification, which is evaluated by a kernel function. Lei et al. [16] presented a fault diagnosis method using mRVM to classify seven conditions of planetary gearboxes. Accumulative amplitudes and energy ratio are adopted as the input of the mRVM to identify the seven conditions. Experimental results demonstrate this method possesses high classification accuracy and good robustness. Li et al. [17] put forward a fault diagnosis scheme of planetary gearboxes combining modified multi-scale symbolic dynamic entropy and minimum redundancy maximum relevance (mRMR). Refined fault features by mRMR are considered as the input of least square support vector machine to identify fault patterns. Nevertheless, the procedure of optimizing kernel function parameters is very complicated and many optimization algorithms are not satisfactory.

Data-driven fault diagnosis methods do not require additional prior knowledge or accurate analytical models, and classify fault modes by training samples. Therefore, data-driven fault diagnosis methods possess important application value in planetary gearbox fault diagnosis. However, there are many uncertain factors that may result in incomplete diagnostic information of planetary gearboxes, such as sensor malfunctions, communication lags, and data discretization, etc. It brings a great challenge to the application of data-driven fault diagnosis methods. In order to deal with this problem, Wang et al. [18] proposed a rule extraction method from incomplete decision table using granular computing for fault diagnosis of helicopter gearbox. Semantic analysis of missing attribute values is performed by characteristic relation. Then, information granules are built to obtain optimal decision rules. These decision rules can be utilized to recognize fault conditions. Wang et al. [19] presented a rule extraction method based on maximum characteristic granule (MCG) for fault diagnosis from incomplete historical test records. MCGs defined according to characteristic relation are employed to construct a resolution function matrix. General decision rules are acquired by equivalent forms of propositional logic. It can be noted that decision rule extraction is the key of planetary gearbox fault diagnosis with incomplete diagnostic information. However, most of the existing rule extraction methods can be utilized to process incomplete diagnostic information that only contains one category of unknown attribute values. Although some rule extraction methods can acquire diagnosis knowledge from incomplete diagnostic information that simultaneously contains two categories of unknown attribute values, the similarity degrees among cases cannot be quantitatively described. It results that the extraction decision rules are not reliable.

To overcome this issue, a fault diagnosis method of planetary gearboxes based on data-driven valued characteristic multigranulation model with incomplete diagnostic information is proposed in this paper. First, a data-driven valued characteristic relation is defined to analyze and process incomplete diagnostic information that simultaneously contains two categories of unknown attribute values. Then, an attribute reduction algorithm based on pessimistic data-driven valued characteristic multigranulation model is employed to extract fault diagnosis decision rules. Finally, naive Bayesian classifier (NBC) is constructed to identify planetary gearbox conditions. Experimental results demonstrate that this method can