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A fault diagnosis scheme for planetary gearboxes using adaptive multi-scale morphology filter and modified hierarchical permutation entropy

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ABSTRACT

The fault diagnosis of planetary gearboxes is crucial to reduce the maintenance costs and economic losses. This paper proposes a novel fault diagnosis method based on adaptive multi-scale morphological filter (AMMF) and modified hierarchical permutation entropy (MHPE) to identify the different health conditions of planetary gearboxes. In this method, AMMF is firstly adopted to remove the fault-unrelated components and enhance the fault characteristics. Second, MHPE is utilized to extract the fault features from the denoised vibration signals. Third, Laplacian score (LS) approach is employed to refine the fault features. In the end, the obtained features are fed into the binary tree support vector machine (BT-SVM) to accomplish the fault pattern identification. The proposed method is numerically and experimentally demonstrated to be able to recognize the different fault categories of planetary gearboxes.

1. Introduction

Planetary gearboxes are widely used in wind turbines due to its large transmission capacity in a compact structure, and increasing attention has been aroused in the fault diagnosis of planetary gearboxes [1–4]. The fault forms of planetary gearboxes are diverse after experiencing a long term service especially under tough operating conditions. Such unexpected damages can make the machines breakdown and result in significant maintenance cost [2,5].

Nowadays, the fault diagnosis of planetary gearboxes has been the subject of extensive research [6–8]. Vibration-based signal processing method is one of most powerful tools for gearbox fault detection and diagnosis, such as statistical approaches [9,10], spectral kurtosis [6], wavelet transform (WT) [11], ensemble empirical mode decomposition (EEMD) [12] and local mean decomposition (LMD) [13]. Among these methods, the main limitation is that the fault diagnosis largely depends on the expertise of the investigators. It is difficult to accomplish effective diagnosis for common users. The fault features combined with fault classification methods become an effective way to solve this problem.

Many vibration analysis techniques have been developed to detect the gear fault of a planetary gearbox. Qu et al. applied support vector machine to classify the pitting fault degrees of planetary gearboxes [7]. Lei et al. applied the multiclass

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Nomenclature

adaptive multi-scale morphological filter AMMF
modified hierarchical permutation entropy MHPE
Laplacian score LS
binary tree support vector machine BT-SVM
wavelet transform WT
ensemble empirical mode decomposition EEMD
local mean decomposition LMD
grey relational analysis GRA
permutation entropy PE
multi-scale permutation entropy MPE
morphological filter MF
multi-scale morphological filtering MMF
structure element SE
difference DIF
standard deviation SD
Gaussian white noise GWN
broken tooth on planet gear BTPG
broken tooth on ring gear BTRG
broken tooth on sun gear BTSG
cracked tooth on sun gear CTSG
pitted tooth on sun gear PTSG
hierarchical sample entropy HE

relevance vector machine to identify the different health conditions of planetary gearboxes [8]. Liu et al. recently proposed a new feature selection method for fault levels diagnosis of planetary gearboxes [14]. Cheng et al. integrated physical model and grey relational analysis (GRA) for crack levels estimation [15]. Among these methods, the key step is the fault feature extraction.

Entropy is one of the most powerful tools to detect dynamic characteristics of time series [16–20]. Due to the advantage of quantifying the uncertainty and dynamic change for a given time series, increasing attentions have been aroused in applying entropy in the fault diagnosis. Two methods are widely used, sample entropy [21] and permutation entropy (PE) [22]. Compared with sample entropy, PE is simpler to use, more robust to noise, and more efficient in calculation. Therefore, PE has been applied in many fields [18,23]. Based on PE, the multi-scale permutation entropy (MPE) was developed to enhance the physical meanings and statistical sense of PE [19]. However, the coarse-grained procedure used in MPE essentially represents a linear smoothing, which only captures the low frequency components using the averaging technique and ignores the fault information hidden in the high frequency components [20].

In this paper, a new approach called modified hierarchical permutation entropy (MHPE) is proposed to extract the fault features. MHPE considers the fault information embedded in both lower frequency and higher components. The lower frequency and higher components are generated by moving-averaging procedure and moving-difference procedure in MHPE, respectively. Therefore, MHPE can provide a comprehensive evaluation of irregularity and uncertainty for a given time series.

Nevertheless, the periodic impulses induced by a localized damage are often submerged in the strong background noise. It is essential to preprocess the vibration signals of planetary gearboxes before the fault extraction. Morphological filter (MF) was recently proposed by Serra [24], which can provide an alternative means of extracting impulse features in the time domain [25,26]. However, many sidebands around the tooth-meshing frequency and its harmonics may spread over a wide frequency range [27,28]. The single-scale analysis ability of MF may suffer from the lack of completeness in the extraction of impulsive features.

Multi-scale morphological filtering (MMF) was put forward by Maragos [29] to extract the morphological features over different scales. It has been demonstrated that MMF is more effective than the single-scale analysis in the fault feature extraction. However, the MMF is not adaptive in terms of defining the structure element (SE). To overcome this drawback, Zhang et al. [30] proposed adaptive multi-scale morphological filter (AMMF). The filtered signal after AMMF can reduce the fault unrelated frequency components and consequently emphasize the fault symptoms.

In this study, after obtaining the fault features using AMMF-MHPE, Laplacian score (LS) is introduced to reduce the dimensions of features [31]. In addition, the Binary Tree Support Vector Machine (BT-SVM) is applied to recognize different fault types of planetary gearboxes. BT-SVM has not only good generalization ability as general SVM, but better learning ability for small samples [18]. Overall, in this paper, a new fault diagnosis strategy based on the AMMF, MHPE, LS and BT-SVM is proposed to classify different fault types of planetary gearboxes. The proposed method is numerically and experimentally demonstrated to be able to identify five gear fault types of planetary gearboxes.