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Gear fault diagnosis method based on local mean decomposition and generalized morphological fractal dimensions

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ABSTRACT

Aiming at gear fault diagnosis, a fusion method of local mean decomposition (LMD) and generalized morphological fractal dimensions (GMFDs) is proposed. Firstly, a signal is decomposed by LMD into several product functions (PFs) which have physical meanings. Secondly, mutual information entropy value between each PF and original signal can be computed, and the PF corresponding to the maximum value is considered as containing the richest feature information of original signal, thus the PF is used as data source. Lastly, GMFDs are extracted from the data source, and some GMFDs which can quantitatively and comprehensively characterize nonlinear information of gear running states are adopted as feature vectors, hence gear faults can be diagnosed by kernel fuzzy c-means (KFCM). In order to demonstrate superiority of the proposed method, the GMFDs are extracted from signals of different lengths, ones sampled under three different working conditions of load and speed, ones without decomposition of LMD. The gear signals are tested and verified, and the result demonstrates that the proposed method is superior and can diagnose gear faults accurately.

1. Introduction

Rotating machinery has been widely used in the fields of aeronautics, astronautics, metallurgy, petrochemical engineering and construction machinery, thus high speed, large load and other mal-conditions can lead to its high damage probability. And faults can result in equipment health deterioration and even breakdown [1,2]. As a rotating machinery, gear is also faced the problems, thus a lot of scholars and engineers have done much work on its condition monitoring and fault diagnosis [3,4].

Local mean decomposition (LMD) is a data-driven and novel self-adaptive analysis method in time–frequency domain. It was proposed by Smith in 2005 and firstly applied to electroencephalogram signal successfully [5]. The multi-component signal can be decomposed to a series of mono-components which are product functions (PFs), therefore each of them is the product of an envelope signal and a purely frequency modulated signal. The instantaneous amplitude of PF can come from an envelope signal, and the well-defined instantaneous frequency can be calculated from a purely frequency modulated signal. In essence, each PF is an amplitude-modulated and frequency-modulated signal (AM–FM signal) [6–11].

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In order to get the length of an irregular curve, Minkowski proposed "Minkowski cover" method. The method is used to dilate the curve by forming the union of disk structure elements (SE) in different scales. Based on this, Bouligand proposed an improved method called "Minkowski–Bouligand dimension" method. The method replaced the disk that SE "Minkowski cover" method adopted with any kind of planar SE, but two-dimension of planar SE leads to quadratic computational complexity. Aiming at the shortcoming, Maragos proposed an improved method named "Morphological covering" method. It replaced two-dimension SE with one-dimension one, thus computational complexity is reduced, and he firstly applied the method to fractal dimension estimation of a one-dimensional signal. If height parameter of SE is set as 0, Minkowski–Bouligand dimension is completely independent from signal covering area [12,13], thus flat SE is adopted in this study.

The above fractal dimension estimation method is based morphological technique, and it can be named morphological fractal dimension (MFD). And traditional fractal dimension is often based on box-counting method, and the method is based on regular generation of grids in signal covering area, thus fractal dimension estimation is greatly dependent on relationship between grid positions and the covering area, and grid positions are not fixed relative to the signal, hence it leads to random error of fractal dimension estimation [14,15]. The single fractal dimension (FD) cannot characterize nonlinear information of a signal more comprehensively than generalized fractal dimensions (GFDs), but GFDs from box-counting method also has that kind of error. Thus Li proposed a method of generalized morphological fractal dimensions (GMFDs), and it is applied to fault diagnosis of gear successfully [16], and the result shows that Li's method is superior to the other method of GMFDs proposed by Xia [17], and there is doubt that it is also superior to traditional method of GFDs.

But GMFDs directly extracted from a signal without de-noising can lead to incorrect character of rotating machinery nonlinear information. Although a signal is de-noised and then MFD is extracted, the single MFD can only characterize one-sided nonlinear information of running states.

Aiming at the problems, the fusion method of LMD and GMFDs is proposed in this study. Firstly, a signal is decomposed by LMD, and the product functions (PFs) which have physical meanings can be obtained. Secondly, mutual information entropy value between each PF and original signal is computed based on mutual information theory [18,19], and the PF corresponding to the maximum value is considered to be the closest to original signal, and it can be regarded as containing the most amounts of feature information of original signal, thus the PF is selected as data source. Lastly, GMFDs are extracted from the data source, and some GMFDs which can characterize quantitatively and comprehensively nonlinear information of gear running states are adopted as feature vectors, hence kernel fuzzy c-means (KFCM) can diagnose faults effectively.

The paper is organized as follows. Section 2 describes principles of LMD, KFCM and mutual information theory. In Section 3, principle of GFDs is presented. In Section 4, principle of GMFDs is detailed. Section 5 briefly depicts the fusion method. In Section 6, examples of applying GMFDs to synthetic fractal signal analysis are presented. In Section 7, GMFDs are applied to characterize nonlinear information of gear running states, and gear faults are diagnosed by KFCM. In Section 8, the conclusions are drawn.

2. Principle of LMD, KFCM and mutual information theory

2.1. Principle of LMD

In traditional time-frequency analysis method of wavelet transform, there are still some limitations such as mutual constraint of time and frequency resolution, low matched-degree of kernel function and signal and so on, furthermore, selection of kernel function is another difficult point. As a new self-adaptive analysis method in time-frequency domain, LMD overcomes above limitations and can adaptively decomposed a multi-component signal of nonlinear and non-stationary signal into a set of mono-component AM–FM signals (PFs) in different time scales based on morphological features of a signal. In essence, each AM–FM signal is the product of a purely frequency modulated signal and an envelope signal [5–11].

2.2. Principle of KFCM

KFCM is developed based on FCM, and it is an unsupervised learning algorithm. With kernel function, samples in original feature space can be nonlinearly mapped into kernel space, and intrinsic different information among samples can be extracted adequately, therefore the information can be highlighted and amplified accurately in kernel space. And samples in kernel space are clustered according to their attributes, as a result, samples in the same cluster are in high similarity, and the ones in different clusters are in high dissimilarity [20,21].

Clustering quality can be evaluated by partition coefficient and partition entropy, and they are listed as follows:

$$P = \frac{1}{n}\sum_{i=1}^{c}\sum_{j=1}^{n} u_{ij}^{2}. \tag{1}$$

$$E = -\frac{1}{n}\sum_{i=1}^{c}\sum_{j=1}^{n} u_{ij}\ln u_{ij}. \tag{2}$$