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An optimized time varying filtering based empirical mode decomposition method with grey wolf optimizer for machinery fault diagnosis

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ABSTRACT

A time varying filtering based empirical mode decomposition (EMD) (TVF-EMD) method was proposed recently to solve the mode mixing problem of EMD method. Compared with the classical EMD, TVF-EMD was proven to improve the frequency separation performance and be robust to noise interference. However, the decomposition parameters (i.e., bandwidth threshold and B-spline order) significantly affect the decomposition results of this method. In original TVF-EMD method, the parameter values are assigned in advance, which makes it difficult to achieve satisfactory analysis results. To solve this problem, this paper develops an optimized TVF-EMD method based on grey wolf optimizer (GWO) algorithm for fault diagnosis of rotating machinery. Firstly, a measurement index termed weighted kurtosis index is constructed by using kurtosis index and correlation coefficient. Subsequently, the optimal TVF-EMD parameters that match with the input signal can be obtained by GWO algorithm using the maximum weighted kurtosis index as objective function. Finally, fault features can be extracted by analyzing the sensitive intrinsic mode function (IMF) owning the maximum weighted kurtosis index. Simulations and comparisons highlight the performance of TVF-EMD method for signal decomposition, and meanwhile verify the fact that bandwidth threshold and B-spline order are critical to the decomposition results. Two case studies on rotating machinery fault diagnosis demonstrate the effectiveness and advantages of the proposed method.

1. Introduction

Rotating machinery are used widely in industries including water treatment, mining and quarrying, manufacturing and petrochemicals. However, they usually service under adverse working conditions, which makes the key components such as gears and bearings easy to breakdown. To guarantee the functionality and reliability of equipment as well as avoid accidents, machinery condition monitoring and fault diagnosis techniques are critical in engineering practices [1–3]. Vibration-based analysis has been a most effective technique in recent years because of the sensitivities of vibration signals to machinery health conditions [4–6]. Besides the common time-domain analysis and frequency-domain analysis methods, various novel methods have been developed for machinery fault diagnosis, such as wavelet transform (WT) [7,8], wavelet packet transform

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(WPT) [9,10] and signal sparse decomposition methods [11,12]. However, WT and WPT are non-adaptive signal processing methods because wavelet basis functions need to be chosen in advance [13,14]. Even though signal sparse decomposition (e.g., matching pursuit [11] and basis pursuit [12]) are self-adaptive signal processing methods, they demand a powerful computer computing and storage capabilities, so these methods may be helpless for massive data processing in industry [15].

Empirical mode decomposition (EMD) is proposed as an adaptive nonstationary and nonlinear signal processing method which can decompose complex, multi-component signals into an ensemble of intrinsic mode functions (IMFs) [16]. EMD-based time–frequency analysis method can quantitatively describe the relationship between frequency and time to achieve a complete and accurate analysis of time-varying signals. With these advantages, EMD has been applied widely in the field of machinery fault diagnosis. For instance, Yu and Cheng [17] developed a roller bearing fault diagnosis method based on EMD and energy entropy and ANN. Li and Zhang [18] designed a bearing fault diagnosis method using EMD based Wigner-Ville distribution. Shen et al. [19] introduced an intelligent gear fault diagnosis model based on EMD and multi-class transductive support vector machine. Li et al. [20] proposed a new ranged angle-EMD method for the fault diagnosis of abnormal clearance between contacting components in a diesel engine. Although EMD has been proven noticeably effective in machinery fault diagnosis, some issues still need to be further studied. One of these issues is separation problem [21] which refers to that EMD fails to discriminate the components whose frequencies lie with an octave. Another issue is the intermittence problem [21]; that is, EMD is susceptible to intermittence such as noise. As a result, a single IMF may either consist of signals of widely disparate scales, or a signal of a similar scale reside in different IMF components, known as the mode mixing problem. Both separation problem and intermittence problem may lead to mode mixing, so various improved EMD methods [22–25] have been developed to address these two problems.

In the field of machinery fault diagnosis, noise-assisted methods including ensemble empirical mode decomposition (EEMD) and some improved EEMD methods are widely reported. For instance, Lei et al. [26] applied EEMD method to rotor fault diagnosis of rotating machinery. Guo and Peter [27] proposed a signal compression method based on optimal EEMD for bearing vibration signals. Feng et al. [28] investigated the fault diagnosis of wind turbine planetary gearboxes based on EEMD and energy separation. Wu and Chung [29] used a hybrid method of EEMD and pure EMD to decompose the complicated vibration signals of rotating machinery into a finite number of IMFs, so as to extract the fault features. Jiang et al. [30] proposed an improved EEMD with multiwavelet packet for rotating machinery multi-fault diagnosis, in which multiwavelet packet was used as the pre-filter to improve EEMD decomposition results. Although EEMD-based methods can partly address the intermittence problem so as to alleviate the mode mixing, these noise-assisted methods still have some drawbacks [21]. (1) The amplitude of added noise and ensemble number are difficult to determine, which causes these methods are no longer adaptive. (2) They still cannot solve the aforementioned separation problem. Besides the noise-assisted methods, another widely used improved EMD method in machinery fault diagnosis is a filtering-based method called variational mode decomposition (VMD) [31] which is based on the Wiener filtering. Wang et al. [32,33] investigated the filter bank properties of VMD and used it to detect rub-impact fault of the rotor system. Gupta and Raju [34] applied VMD in the rolling bearings fault diagnosis and achieved good results. Yang and Jiang [35] proposed a casing fault diagnosis method based on VMD, local linear embedding and support vector machine. Li et al. [36] developed a multi-dimensional VMD method for bearing-crack detection in wind turbines with large driving-speed variations. Although VMD method has proven to be robust to noise, its filter cut-off frequencies are constant with respect to time, which makes it usually difficult to obtain satisfactory decomposition results in machinery non-stationary vibration signal analysis and fault diagnosis.

Recently, a time varying filtering based empirical mode decomposition (TVF-EMD) method was proposed by Li et al. [21] to solve the mode mixing problem, whose sifting process is completed using a time varying filter technique (i.e., B-spline approximation filter). Compared with the most existing methods, the main characteristics of TVF-EMD can be summarized as follows. (1) TVF-EMD can fully address the separation problem and the intermittence problem, while many of the existing methods dispose of the two problems separately, like EEMD and multivariate empirical mode decomposition (MEMD) [24] etc. (2) TVF-EMD adopts time varying filter in shifting process, so it can address the mode mixing problem and synchronously maintain the time varying features, which cannot be achieved by many other methods including EEMD and VMD. (3) The stopping criterion is improved, which makes TVF-EMD able to achieve a robust performance under low sampling rates. In Ref. [21], TVF-EMD demonstrated the abovementioned advantages through simulation and real signal analysis studies. However, two parameters, namely bandwidth threshold and B-spline order, which have significant effects on the decomposition results of TVF-EMD, need to be carefully selected. Bandwidth threshold directly influences the separation performance, and B-spline order is related to the filtering performance of the time varying filter [21]. If the parameters are inappropriate, the method may fail to solve the mode mixing problem. In original TVF-EMD method, the parameter values are assigned in advance without any prior information of the signal. Therefore, selecting appropriate combination of parameters is a difficult and critical problem for TVF-EMD method.

Based on the above introduction, an optimized TVF-EMD method based on grey wolf optimizer (GWO) algorithm for machinery fault diagnosis is proposed in this paper. Firstly, a synthetic measurement index termed weighted kurtosis index is defined as objective function for TVF-EMD parameter optimization and measurement index for the selection of sensitive IMF that contains the main fault information. The construction of the weighted kurtosis index fully considers the merits and drawbacks of kurtosis index and correlation coefficient, and this index takes into account the impact properties of IMFs but also the correlation between IMFs and original signal. Thus, using this index as optimization objective function and sensitive mode selection criterion can furthest avoid the information loss problem. Secondly, a novel optimization algorithm called GWO is employed to search for the optimal TVF-EMD parameter combination that matches with the input signal. GWO