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Data-driven time-frequency analysis method based on variational mode decomposition and its application to gear fault diagnosis in variable working conditions

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ABSTRACT

The data-driven time-frequency analysis (DDTFA)-method-based initial phase selection directly influences the convergence and calculation results of the algorithm. The central frequency accuracy of each component by means of variational mode decomposition (VMD) is high, the calculation speed of VMD is fast, and the method shows satisfactory noise resistance, but the decomposed components are sensitive to noise. A VMD method that is complementary to the DDTFA method is introduced in this paper to estimate the initial phase of DDTFA, and the VMD-DDTFA method is proposed for time-varying non-stationary signals. This method first analyzes the time-varying non-stationary signal through VMD and estimates the initial phase of each signal component, then uses DDTFA to sparsely decompose the signal after phase smoothing. To examine the analytical ability of VMD-DDTFA on time-varying non-stationary signals, the five aspects of the VMD-DDTFA method, accuracy, noise resistance, efficiency, applicability and anti-mode-mixing ability, are analyzed. The VMD-DDTFA method compares with the current commonly used signal analysis methods of VMD and ensemble empirical mode decomposition (EEMD) and the comparison results confirm that VMD-DDTFA has a superior decomposition accuracy, satisfactory noise resistance and efficiency. In addition, VMD-DDTFA features strong anti-mode mixing and applicability even under strong noise. The VMD-DDTFA method is applied to the fault diagnosis of measured gear crack and broken tooth in variable working conditions. In addition, the results of the VMD-DDTFA method are compared with those obtained by VMD and EEMD; the results verify the effectiveness and superiority of the method.

1. Introduction

Vibrational signals of mechanical equipment operating under variable working conditions consist of time-varying non-stationary signals. When the mechanical transmission system is a multi-axial system, the vibrational signal is a multi-component time-varying non-stationary signal [1,2]. For the analysis of multi-component non-stationary signals, commonly used methods include adaptive signal analysis methods [3,4,18,21,22], such as empirical mode decomposition (EMD) and ensemble empirical mode decomposition (EEMD), and sparse decomposition methods [6,12,23,24], such as basis pursuit

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(BP) and matching pursuit (MP). However, these methods all contain limitations. For instance, over-envelopes, under-envelopes, mode mixing and other issues arise in the EMD method. Although the EEMD method exhibits improved mode mixing to a certain extent, selection of a suitable range of white noise is challenging. The sparse decomposition method has drawbacks, such as the requirement of signal characteristics to build a dictionary, complex matching processes, and large amounts of calculation.

Inspired by the EMD method and the compressed sensing (CS) theory, Hou and Shi proposed the adaptive sparse time-frequency analysis method (ASTFA) [15] in 2011. After in-depth study of the theory, they presented the data-driven time-frequency analysis (DDTFA) method [13]. This method finds the sparsest expression of an analyzed signal in the time-frequency domain from the largest possible dictionary containing the intrinsic mode functions. The method has a well-defined mathematical theoretical basis that can effectively implement the decomposition of multi-component non-stationary signal, more accurately extract the instantaneous frequency of each component, and offer strong noise resistance [14,16]. However, the sparsest expression is actually a complex non-linear optimization problem. To solve this problem, DDTFA uses a Gauss-Newton iterative algorithm. It is well known that the results of the Gauss-Newton iterative algorithm are highly dependent on the selection of the initial value. Therefore, the selection of the initial phase function directly affects the convergence and calculation results of DDTFA [13,16,17]. However, the initial phase function required by DDTFA does not need to be completely consistent with the theoretical value, the DDTFA method can converge as long as the initial phase function is within the certain range. Based on this finding, the way to quickly and accurately estimate the phase function of time-varying non-stationary signals is the key to the application of DDTFA method to mechanical equipment, particularly for fault diagnosis of mechanical equipment in variable working conditions. At present, the initial phase function of time-varying non-stationary signal in connection with DDTFA is rarely studied; Aiming at the existing problems of initial phase selection, Chen et al. proposed the adaptive sparsest narrow-band decomposition (ASNBD) algorithm [17,25] based on narrowband signal decomposition, which transforms signal decomposition into a filter optimization process, and applied this technique to the fault diagnosis of a fixed speed rotor and roller bearing.

Variational mode decomposition (VMD) is a completely non-recursion-based variational modal decomposition model [5,7] proposed by Dragomiretskiy et al. in 2014. In the process of obtaining the decomposed component, the center frequency and the bandwidth of each component are determined by an iterative search of the variational model optimal solution, so that the frequency domain segmentation of the signal and the effective separation of each component can be implemented adaptively. Because VMD finds the optimal solution of the variational model by applying the iterative frequency-domain non-recursion solution method with high efficiency, this method can quickly and accurately estimate the center frequency of each component in the analyzed signal to further analyze the multi-component non-stationary signal [7–11] with superior accuracy. Therefore, the method has been widely used in the field of fault diagnosis [8–11] in recent years. In VMD signal processing, the center frequency accuracy of each component is high, the calculation speed of VMD is fast, and the method shows satisfactory noise resistance; however, poor noise resistance is inherent in the decomposed component [7]. Therefore, we incorporate the VMD method into the initial phase estimation of each component of a time-varying non-stationary signal to combine it with the strong noise resistance and excellent signal resolution ability of DDTFA [13] to present VMD-DDTFA method, which was applied to time-varying non-stationary signal analysis and verified by diagnostic examples. In the actual mechanical context of variable working conditions, the gear vibration signal typically contains strong background noise, which may cause certain errors in VMD initial phase estimation. Because DDTFA provides convergence ability [16] in terms of the initial phase within a certain error range, VMD-DDTFA can accommodate time-varying multi-component non-stationary signals. The results of analysis by means of the time-varying non-stationary simulation signals and measured gear fault signals under variable working conditions confirm the proposed method's feasibility and validity of gear fault diagnosis.

The content of the remaining part of this article is as follows: The second part reviews theories related to the DDTFA and VMD methods. The third part presents the VMD-DDTFA method and introduces its principle and implementation steps. In the fourth part, the proposed method is further analyzed in five aspects based on the time-varying multi-component non-stationary simulation signal: accuracy, noise resistance, efficiency, applicability and anti-mode mixing ability, and it is compared with the VMD and EEMD methods to verify the effectiveness of the VMD-DDTFA method. In the fifth part, the VMD-DDTFA is introduced into the gear crack and broken tooth fault diagnosis experiments of variable working conditions and compared with VMD and EEMD. The results indicate that this method can effectively diagnose the gear fault of a gear transmission system in variable working conditions. The final part provides a summary.

2. Brief review

DDTFA and VMD are adaptive signal processing methods proposed in recent years. Both methods have their own advantages and disadvantages. The following provides a brief review:

2.1. Data-driven time-frequency analysis

The DDTFA method is a self-adaptive signal decomposition method inspired by the EMD method and CS theory. The key idea is to transform the sparse decomposition of a signal into a nonlinear optimization problem and to solve the nonlinear optimization problem through the use of nonlinear matching pursuit to complete the sparse decomposition of the signal.