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A coarse-to-fine decomposing strategy of VMD for extraction of weak repetitive transients in fault diagnosis of rotating machines

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ABSTRACT

Variational Mode Decomposition (VMD) has attracted much attention and been used to analyze different kinds of signals, such as mechanical signals, medical data, and financial time series, etc. However, the VMD is still confronted with some dilemmas during the applications, including the determination of the number of the decomposed modes, the selection of the balance parameter, and so on. To address these problems of the VMD, a coarse-to-fine decomposing strategy is proposed for weak fault detection of rotating machines in this paper. Firstly, through extensive numerical simulations, the characteristics of the relative bandwidths of the decomposed modes are given with the change of the balance parameter and the number of the decomposed modes. Then, motivated by the bandwidth characteristics, the rationalities and advantages of iterative decomposition of the VMD and the fine adjustment of the balance parameter are discussed in detail, respectively. Subsequently, the new coarse-to-fine decomposing strategy of the VMD is developed to obtain the optimal mode and extract the weak repetitive transients of rotating machines. The analysis results of the simulated signals and the experimental signals measured from two run-to-failure cases show that the proposed method can well-detect the weak repetitive transients in the signals with heavy noise and overcome the drawbacks of the original VMD. The superiority of the proposed method for faint repetitive transient detection is also demonstrated by comparing with the existing methods.

1. Introduction

Extraction of repetitive transients caused by mechanical incipient defects from the measured vibration signals of rotating machines has attracted much attention in machinery fault diagnosis because the repetitive transients can be used to reveal the working conditions of the machines [1]. For instance, if a bearing or gear has a defect occurring on its surface, repetitive transients will be generated in the mechanical vibrations when the local defect is struck by other coupled components during the rotations. However, in modern industry, with the development of the rotating machines in size, precision and speed, the detection of the potential faults in the machines becomes more and more difficult [2,3]. Specifically, the repetitive transients caused by a weak incipient defect are prone to be overwhelmed by heavy noise, abnormal shocks, strong low-

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frequency vibration components, gear meshing frequency components, etc., which make the extraction of the repetitive transients become a great challenge.

Advanced signal processing techniques are commonly used tools to analyze the collected raw signals to reveal the fault characteristics in fault diagnosis of rotating machines, including time series analysis [4,5], frequency transform [6], envelope demodulation [7,8], time-frequency analysis [9–11], and so on. Due to no transform basis incorporated and adaptive filtering merit, the adaptive signal decomposition methods have been extensively studied and widely applied in fault diagnosis of rotating machines, such as empirical mode decomposition (EMD), ensemble empirical mode decomposition (EEMD) [2], local mean decomposition (LMD) [12], intrinsic time-scale decomposition (ITD) [13], etc.

In consideration of the natural lack of mathematical theory, and the problems of recursive sifting and mode mixing in the extraction process of intrinsic mode function (IMF) by the EMD, Variational Mode Decomposition (VMD) was proposed recently in [14] as an alternative to the EMD for dividing multi-component signals into different modes, which is based on a clear variational model by comparing to the intrinsic modes of the EMD. Because of the advantages in noise resistance due to Wiener filter-like procedure, the balance of the backward error due to non-recursive sifting, and a narrow-band definition of the meaningful modes, the VMD has been successfully used for fault diagnosis of rotating machines and delivers excellent performance in feature extraction of nonstationary data. In literature, many researchers have verified the superiorities of the VMD over other adaptive signal decomposition methods, such as EMD, EEMD, and empirical wavelet transform (EWT) [15], etc., in application to machine condition monitoring. Wang et al. [16] employed the VMD to extract features of rub-impact fault in the rotor system, investigated the equivalent filtering characteristics of the VMD and demonstrated the validity of the VMD in detecting the rubbing-caused multiple signatures than the EWT, EMD, and EEMD. Zhang et al. [17] explored the ability of the VMD in rolling bearing fault diagnosis of the multistage centrifugal pump. The results show that the performance of the VMD is better than the EMD. An et al. [18] demonstrated the better performance of the VMD for the pedestal looseness fault diagnosis as comparing to the EMD and wavelet transform. The VMD has also been combined with other methods for fault diagnosis of rotating machines under bad working conditions. An intelligence fault diagnosis method based on the VMD and multi-kernel support vector machine was proposed in [19]. Li et al. [20] utilized the VMD and spectral regression-optimized kernel Fisher discrimination to diagnose the hybrid gear failures of coal cutters. In [21], the convolutive blind-source separation (BSS) and the VMD were combined to analyze the bearing-crack signals collected from the wind turbines with large driving-speed variations. Zhang et al. [22] studied the chatter detection in milling process based on the energy entropy of the decomposed modes by the VMD and the wavelet packet decomposition (WPD). In our previous work, the VMD was used to identify the multi-resonance bands induced by a bearing local defect by combining the multi-Teager energy operator (MTEO) [23].

Due to the fact that the VMD performance is strictly subject to the decomposition parameters, including the number of the decomposed modes and the bandwidth control parameter (also named balance parameter), the selection of the proper decomposition parameters has been investigated by some researchers. The effect of the balance parameter given in the VMD on the filter bank properties has been qualitatively analyzed in [24] by extensive numerical simulation studies. Li et al. [25] presented an independence-oriented VMD method using correlation analysis to combine the similar modes to solve the problem of over number of decomposed modes. Liu et al. [26] introduced a correlation coefficient criterion to determine the number of the decomposed modes of VMD adaptively. An intelligence optimization algorithm was included in the VMD to determine both the number of the decomposed modes and the balance parameter [27]. Liu et al. [28] developed a de-trend fluctuation method to define the number of the decomposed modes. Huang et al. [29] selected the number of the decomposed modes via using the difference between the central frequencies of the decomposed modes progressively. Spectrum-envelope and the energy ratio between the central frequency components and all the modes were used to determine the number of the decomposed modes and the balance parameter in [30]. Gao et al. [31] introduced the scale-space method to calculate the number of the decomposed modes. In our previous work in [32], the effective decomposition parameters of the VMD were explored to track the intricate trend component buried in the mechanical signals.

According to the literature review stated above, it can be concluded that, to fully apply the VMD, the optimization problem of the decomposition parameters is desired to be addressed. Some researchers select the suitable parameters based on their personal experience [21], on some priori criteria [29,30], or on the qualitative analysis [24]. An optimization algorithm can also be used to search the optimal decomposition parameters [27]. However, the reasonability of the used parameters and the operability of the decomposing strategy of VMD are seldom discussed. In this paper, we uncover that the mode bandwidth extracted by the VMD is associated with both the number of the decomposed modes and the balance parameter, which has not been adequately reported in the accessible literature. Consequently, motivated by the analysis results of the bandwidth property, a new coarse-to-fine decomposing strategy of the VMD is developed to extract the weak repetitive transients of rotating machines. In the proposed method, an iterative decomposing strategy of VMD is firstly proposed with one decomposed mode in each iteration to locate the target mode roughly. Subsequently, an optimization procedure is employed to pick the optimal balance parameter for the target mode, in which the repetitive transients are dominant. Finally, the fault condition of the rotating machine is revealed via envelope spectrum analysis of the target mode. The coarse-to-fine decomposing strategy overcomes the difficulties of the parameter selections, and is adaptive to the analyzed signal, thus can be easily operated, and has the potential of vast applications.

The remainder of this paper is organized as follows. In Section 2, the basic theory of the VMD is reviewed. In Section 3, some motivations of this study are given and the new coarse-to-fine decomposing strategy of the VMD is proposed for the extraction of the weak repetitive transients. The simulation signals are studied using the proposed method in Section 4. The