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A new rotating machinery fault diagnosis method based on improved local mean decomposition

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ABSTRACT

A demodulation technique based on improved local mean decomposition (LMD) is investigated in this paper. LMD heavily depends on the local mean and envelope estimate functions in the sifting process. It is well known that the moving average (MA) approach exists in many problems (such as step size selection, inaccurate results and time-consuming). Aiming at the drawbacks of MA in the smoothing process, this paper proposes a new self-adaptive analysis algorithm called optimized LMD (OLMD). In OLMD method, an alternative approach called rational Hermite interpolation is proposed to calculate local mean and envelope estimate functions using the upper and lower envelopes of a signal. Meanwhile, a reasonable bandwidth criterion is introduced to select the optimum product function (OPF) from pre-OPFs derived from rational Hermite interpolation with different shape controlling parameters in each rank. Subsequently, the orthogonality criterion (OC) is taken as the product function (PF) iterative stopping condition. The effectiveness of OLMD method is validated by the numerical simulations and applications to gearbox and roller bearing fault diagnosis. Results demonstrate that OLMD method has better fault identification capacity, which is effective in rotating machinery fault diagnosis.

1. Introduction

Roller bearings and gearbox are widely used and key components of rotating machinery and their condition monitoring techniques are always a central topic for the maintenance of rotating machinery [1]. Because of the direct relationship between the vibration and the structure of the rotating machine, the vibration-based signal processing techniques are widely used in the diagnostic field and have been proved to be effective in fault diagnosis of gearbox and roller bearing [2]. There are many signal processing techniques that can extract the fault information from the response signal such as time-domain features, envelope spectrum, wallet transform, demodulation analysis and so on [3–5]. Nevertheless, the traditional signal processing methods have their own limits. Such as the windowed Fourier transform (WFT), once the window function is fixed, the size of the time–frequency window is unchangeable [6]. Wavelet transform (WT) can decompose multi-scales into several scale time–frequency components, which has ability of processing the non-stationary and nonlinear signals, it has been widely used to diagnose the rotating machine. In fact, WT is essentially an adjustable window Fourier transform, which doesn't have the nature of self-adaptive feature [7,8].

Unlike aforementioned analysis methods, Empirical mode decomposition (EMD) method can self-adaptively decompose signal into a series of intrinsic mode functions (IMF), each of which consists of the natural oscillations embedded in the vibration signal [9]. Since the IMFs are determined by signal itself, rather than pre-determined kernels, EMD method is a totally self-adaptive signal processing method, which especially suits for processing the non-stationary and nonlinear signals. Although EMD method has been widely applied to various fields, it has many problems such as boundary effect, mode mixing and over- and undershoot problems [10], etc. Furthermore, when we apply Hilbert transform (HT) to each IMF, it usually results in doubtful negative IF [11].

Recently, a novel adaptive time–frequency analysis method called local mean decomposition (LMD) is proposed by Jonathan S. Smith, which has been successfully used in EEG field [12]. LMD can decompose a superimposed signal into a number of product functions (PFs) and a residual. Each PF component is equal to the product of an envelope signal $a(t)$ and a pure frequency modulation (FM) signal $s_n(t)$. Envelope signal is the product of IA and IA is obtained by the pure FM signal. Therefore, LMD method can adaptively decompose any multi-component signal into several single-component AM–FM signals [11]. Compared with EMD method, the prominent advantage of LMD is that it directly gives

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access to the calculations of the IA and IF of each PF, avoiding performing the HT. LMD has been validated remarkable effectiveness in the rotating machinery fault diagnosis. Wang et al. [13] proposed an improved LMD and application to extract the rub-impact fault features from the vibration signals. Cheng et al. [14] applied LMD method to fulfill the gear and roller bearing fault diagnosis. Also LMD method is employed to complete the fault diagnosis on a rolling bearing and gear of locomotive bogies by Chen et al. [15].

As a novel time–frequency analysis algorithm, some technical difficulties are encountered in the practical application of LMD method [13]. In original LMD algorithm, moving average (MA) approach is performed to construct the local mean and envelope estimate functions in the sifting process, it is time-consuming and may result in inaccurate decomposition results. It is well known that the decomposition results of LMD highly depend on the step sizes selection of MA, and the unsuitable sliding step sizes of MA has an adverse impact on the final calculation of IA and IF significantly. Unfortunately, the mathematic definition of the best step size in theory is non-existent and the better way to select the optimum step size of MA algorithm is still an unsolved problem [16]. Furthermore, the MA approach is time-consuming in the actual time series analysis, and there remains need for an efficient method that can perform the decomposition accurately and efficiently.

To overcome the drawbacks of original LMD, many researches in recent years have focused on the alternative algorithm designation. Since the cubic spline interpolation has good convergence and high smoothness, L. Deng introduced the cubic spline interpolation approach to construct the local mean function $m(t)$ and envelope estimation function $a(t)$ [16]. B-spline approach is introduced to improve the analytical performance by Chen et al. [17]. However, the cubic spline interpolation is performed to construct the envelopes with outstanding over- and undershoot problems [18]. Recently, Lin et al. introduced cubic Hermite interpolation approach to fit the envelope of a signal with the extreme points and then obtain local mean and envelope estimate functions [19]. However, the cubic Hermite interpolation can't adaptively adjust the shape of the curve with the changing local characteristics of the waveform in the sifting process, it requires further research and improvement.

It is also needed to refer to the work by Zhang et al., whereby the rational spline interpolation is introduced to replace the MA in the extraction process [20,21]. However, the rational spline-based LMD (RS-LMD) method has the following problems: (a) The selection of the tension parameter is difficult, which needs extended numerical computation. Moreover, the unsuitable tension parameter p makes the decomposition results worse than the traditional spline-based LMD method; (b) In the Pegram and Zhang's publications, once the tension parameter is fixed, it is unchangeable in the whole decomposition process. The fixed tension parameter in the whole sifting process is unreasonable. Since the waveform and fluctuating trend of the maxima and minima of the produced new time series may be quite dissimilar with the original signal, it requires the tension parameter is changeable in the sifting process. Therefore, the proposed approach in references [20,21] needs further research.

Focused on the aforementioned problems, an optimized local mean decomposition (OLMD) method is proposed in this paper. The proposed method adopts rational Hermite interpolation to construct the local mean function and envelope functions. In order to select an optimal shape controlling parameters in each rank, an optimization process is designed. In this manner, the smoothing errors of MA are decreased, leading to a significant performance enhancement. Meanwhile, a signal extending approach based on mirror extending method is used to extend the signals in order to solve the boundary distortion problem. Also the orthogonality criterion (OC) is applied to guarantee that the obtained pre-OPFs almost meet the PF definition.

To further investigate the performance of the proposed method, four evaluating indicators are introduced. Finally, the OLMD method is introduced into the simulation signal analysis and a comparison is conducted with original LMD and RS-LMD methods. The comparison results verify the superiority of the proposed method. Furthermore, the vibration signal of the incipient bearing fault and gearbox with crack fault is preprocessed by OLMD method and the envelope analysis technique is utilized to find out the fault frequency. Unlike the existing algorithms, the main contributions of this paper are succinctly stated below:

- Development of a new envelope interpolation method called optimized rational Hermite interpolation method (OLMD), which has a shape controlling parameter compared with the cubic Hermite interpolation algorithm.
- Introduction of the bandwidth criterion to implement the optimization procedure in each step, leading to significant performance enhancement;
- Validation of the proposed fault detection and type identification algorithms by a bearing run-to-failure test and gearbox with crack fault test.

This work is organized as follows. Section 2 reviews the main steps of LMD. In addition, the definitions of rational Hermite interpolation as well as the OPF selection criterion are introduced briefly. In Section 3 the main steps of OLMD method are described. Simultaneously, the comparisons of simulation signal analysis among OLMD, RS-LMD and original LMD methods are discussed in Section 4, which show that the better decomposition results can be obtained by the proposed method. The analysis results of the fault vibration signal collected from the roller bearings and gearbox are given in Section 5. Finally, the conclusions about the diagnostic capability of OLMD are drawn in Section 6.

2. Local mean decomposition and the definition of optimum PF

2.1. Review of LMD method

LMD is originally developed to decompose a multi-component amplitude-modulated and frequency-modulated (AM–FM) signal into a sum of product functions (PFs), each of which is the product of an amplitude envelope signal and a frequency modulated (FM) signal [14]. Given any signal $x(t)$, it can be decomposed by LMD method as follows:

(1) Find out all local extrema n_i of the original signal $x(t)$, and calculate the mean value m_i of two successive extrema n_i and n_{i+1}, then the ith mean value m_i can be expressed as

$$m_i = (n_{i+1} + n_i)/2 \tag{1}$$

Note that all the mean values m_i are firstly connected by straight lines and then smoothed by using MA to form a varying continuous mean function $m_{11}(t)$.

(2) The envelope estimate a_i is calculated according to Eq. (2).

$$a_i = \left|n_{i+1} - n_i\right|/2 \tag{2}$$

MA approach is also applied to construct the local envelope function $a_{11}(t)$ in the same way as in step (1).

(3) Subtract the local mean function $m_{11}(t)$ from the original data $x(t)$, and then residual signal $h_{11}(t)$ can be written as

$$h_{11}(t) = x(t) - m_{11} \tag{3}$$