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An improvement EMD method based on the optimized rational Hermite interpolation approach and its application to gear fault diagnosis

Yongbo Li, Minqiang Xu *, Yu Wei, Wenhu Huang

Department of Astronautical Science and Mechanics, Harbin Institute of Technology (HIT), No. 92 West Dazhi Street, Harbin 150001, People's Republic of China

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ABSTRACT

A demodulation technique based on improvement empirical mode decomposition (EMD) is investigated in this paper. Firstly, the problem of the envelope line in EMD is introduced and the drawbacks of two classic interpolation methods, cubic spline interpolation method and cubic Hermite interpolation method are discussed; then a new envelope interpolation method called optimized rational Hermite interpolation method (O-EMD) is proposed, which has a shape controlling parameter compared with the cubic Hermite interpolation algorithm. At the same time, in order to improve the envelope approximation accuracy of local mean, the parameter determining criterion is put forward and an optimization with Genetic Algorithm (GA) is applied to automatic select the suitable shape controlling parameter in each sifting process. The effectiveness of O-EMD method is validated by the numerical simulations and an application to gear fault diagnosis. Results demonstrate that O-EMD method can improve the reliability and accuracy significantly compared with traditional EMD method.

1. Introduction

Vibration analysis techniques have been widely used in the detection of gear faults and the crux is how to extract fault feature from the vibration signals [1]. Currently, the fault characteristic information extraction techniques are time–frequency analysis, which have been proved to be effective for the gear faults identification [2].

However, the common time–frequency analysis methods have their own limits. Such as the windowed Fourier transforms (WFT), once the window function is fixed, the size of the time–frequency window is unchangeable [3]. Wavelet transform (WT) can decompose a multi scales into several scale time–frequency components, which has ability of processing the non-stationary and non-linear signals, it has been widely used to diagnose the rotating machine. In fact, WT is essentially an adjustable window Fourier transform, which does not have the nature of self-adaptive feature [4].

Empirical mode decomposition (EMD) can adaptively decompose a non-linear and non-stationary signal into a number of intrinsic mode functions (IMFs, as defined in Section 2), which indicate the natural oscillations embedded in the vibration signal [5]. Because the decomposition is according to the inherent characteristics of the signal, EMD is a self-adaptive signal processing method, which especially suits for the non-stationary and non-linear signals. Due to the adaptive analysis and high robustness nature, EMD has been applied across a wide range of research areas, such as automatic control [6], medicine and biology [7], and nonlinear system identification [8].

* Corresponding author.
E-mail addresses: liyongbo0532@126.com (Y. Li), xumqhit@126.com (M. Xu), weiyu1219@126.com (Y. Wei), leobo28@foxmail.com (W. Huang).

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However, the major problem of EMD method is to fit the local extrema of the signal with the cubic spline interpolation. The cubic spline-envelope exists outstanding over and undershoot problems, which needs to further study. Spline type selection is the key step in EMD method, which will influence the results directly [5]. Many researches have carried out research on the spline type selection. Alternating taut spline with cubic spline indicates slightly improvement was noted by Huang et al. (1998). Cubic spline interpolation is better than the liner was suggested by Rilling et al. [9]. To change the extreme interpolation, Hawley et al. replaced the cubic spline with trigonometric interpolation [10]. Rather than fitting the maxima and minima to construct the upper and lower envelopes, Chen et al. used the B-splined to fit the combined extrema and then obtained the local mean [11]. Qin et al. introduced a new envelope algorithm of Hilbert–Huang Transform to fit the envelope of a signal with the extreme points [12]. Pegram et al. proposed an alternative spline methodology called rational spline, which has a tension parameter compared with the traditional cubic spline [13]. Kopsinis et al. analyzed how to select better interpolation points to get the best envelope possible approximation and introduced the GA-based optimization of the piecewise polynomials interpolation [14].

Since the piecewise cubic Hermite interpolation depends on the first derivatives of the interpolation points, it exhibits more flexibility than the cubic spline interpolation. Moreover, the cubic Hermite interpolation has high computation efficiency [15]. Applying the cubic Hermite interpolation to fit the local extrema can not only ensure the continuity and smoothness of the successive points but also have the excellent characteristic of shape preservation, which is especially suitable for processing the non-stationary and non-linear signal.

However, the cubic Hermite interpolation cannot adaptively adjust the shape of the curve with the changing local feature of the waveform in the sifting process, which needs further research and improvement. Focuse on the above problems, O-EMD method is proposed in this paper, which introduces an alternative interpolation methodology called rational Hermite interpolation to construct envelope curves between extreme points. Compared with the cubic Hermite interpolation, it has a shape controlling parameter. The rational Hermite interpolation can control the shape of the curve by the parameter λ. Therefore, when applying the rational Hermite interpolation to construct the envelope, the shape controlling parameter λ can be varied in the sifting process. Furthermore, one fitness function combined with Genetic Algorithm is used to automatically select the shape controlling parameter in each sifting process.

In addition, after we obtain an IMF component, a demodulation technique is required to calculate the time–frequency distribution. Hilbert transform (HT) is often applied to analyze the multi-component amplitude-modulated and frequency-modulated (AM–FM) signal. However, HT is limited by the end effect and it may lead to the negative frequency. To overcome the weakness of HT, a novel demodulation method called empirical envelope demodulation (EED) is introduced and employed to analyze the OIMFs derived from O-EMD method [16]. Hence, a new time–frequency method based on O-EMD and EED is proposed in this paper. To further investigate the performance of the proposed method, four evaluating indicators are introduced. Finally, the O-EMD method is introduced into the simulation signal analysis and a comparison is conducted with traditional EMD method. The comparison results show the superiority of the proposed method. Furthermore, the vibration signal of the gearbox with wearing fault is preprocessed by using O-EMD method and the envelope analysis technique is utilized to find out the fault frequency. The practical vibration signal analysis results demonstrate the validity and effectiveness of the proposed method in gear fault diagnosis.

The rest of this paper is organized as follows: the main steps of EMD and the over and undershoot problems of the cubic spline interpolation are discussed in Section 2. In Section 3 the rational Hermite interpolation is introduced. The shape controlling parameter selection process and four evaluating indicators are described. Simultaneously, the comparisons of simulation signal analysis between O-EMD and traditional EMD 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 gearbox vibration signal with worn-teeth fault are given in Section 5. Finally, the conclusions about the diagnostic capability of O-EMD method is drawn in Section 6.

2. EMD algorithm and the cubic spline interpolation problem

EMD is an adaptive approach to decompose non-linear and non-stationary time series into a set of IMFs and a residual. A detailed description of EMD algorithm is in Huang et al. [3]. The IMF in EMD is defined to satisfy two conditions: (a) in the whole date, the number of zero crossing and extrema differ at most by one; (b) at any point, the mean value of the upper and lower envelope determined by the local maxima and minima is zero. The procedures of EMD decomposition are shown as follows.

(1) Identify all the local extrema of the signal being analyzed and connect the local maxima and minima to construct the upper and lower envelopes by a cubic spline interpolation.
(2) Calculate the mean m_{11} of the upper and lower envelopes and designate the difference between the signal $x(t)$ and the $m_{11}(t)$ as new series $h_{11}(t)$.

$$x(t) - m_{11}(t) = h_{11}(t) \tag{1}$$

If $h_{11}(t)$ satisfies the two conditions, take it as the first IMF. Otherwise take $h_{11}(t)$ as the original signal and the above processes are repeated until the $h_{1k}(t)$ is an IMF and set the $h_{1k}(t)$ as $c_1(t)$.

$$c_1(t) = h_{1k}(t) \tag{2}$$

Usually, the standard deviation (SD) is used to evaluate the repetitiveness. The repeating subtracting