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Succinct and fast empirical mode decomposition

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ABSTRACT

Empirical mode decomposition (EMD) has been extensively studied and widely utilized in various areas. In this paper, order-statistics filters are used to replace the traditional interpolation methods and estimate envelopes of the EMD method. Window size selection criteria are proposed to optimize the processing results. Both simulated and experimental signal are applied to investigate characteristics and effectiveness of the proposed method. The results demonstrate that the envelope estimation procedure provides a tremendous enhancement of the EMD method. In the proposed method, application of the order-statistics filter can simplify the process of estimating envelopes and minimize the end effect of the traditional EMD method. Moreover, sifting stop criterion and window width selection are optimized to improve the decomposition speed and processed results. Hence, the processed method is fast, time efficient and effective, and is named as succinct and fast EMD (SF-EMD) in this paper. An application of multiple fault diagnosis for a rotor test rig verifies its potential in practical engineering.

1. Introduction

Empirical mode decomposition (EMD) is a relatively new method in the area of signal processing. The complete process of decomposing a signal into its intrinsic mode functions (IMFs) and finding the time frequency distribution is known as Hilbert-Huang transform (HHT) [1]. The EMD method does not use any predetermined filter or wavelet function, and thus, it is a fully data-driven method [2]. The IMFs indicate the natural oscillatory mode embedded in the processed signal, which are determined by the signal itself. Therefore, it is a self-adaptive signal processing technique and is able to separate stationary and non-stationary components from a signal [2–4]. Since EMD was introduced in 1998, it has been extensively studied and widely used in many areas, such as process control [5,6], modeling [7–9], surface engineering [10], medicine [11], voice recognition [12] and system identification [13,14].

Extraction of each IMF requires several iterations. Although the method has shown outstanding performance in processing non-stationary signals, the EMD method has some weaknesses, such as lacking a theoretical foundation, end effects, sifting stop criterion, extrema interpolation and computational efficiency. These weaknesses restrict its application to some extent and therefore, in the literature, efforts have been doing to improve its performance [15,16]. For example, Wang [17] proved that the time complexity of EMD/EEMD is related to the length of the signal, Shi [18] proposed a method based on AMD-EEMD for rotating machinery fault diagnosis, and Xue [19] proposed an adaptively fast EEMD (AFEEMD) method combined with CEEMD for the treatment of the EMD problems.

Moreover, to address sensitivity of the original EMD algorithm with respect to noise and sampling, more improved methods have been proposed such as variational mode decomposition (VMD) [3] and empirical wavelet transform (EWT) [4]. In these methods,

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extraction of local extrema and their interpolation for obtaining envelope is substituted by more robust constraint optimization techniques.

In this paper, a novel EMD approach is proposed, which replaces the interpolation step by a direct envelope estimation method. In the processed method, order-statistics filters (OSF) are used to replace the traditional interpolation methods of the EMD method, such as cubic spline, trigonometric and cosine interpolation [20–22]. Moreover, each IMF can be obtained in a certain iteration times at each decomposition level. Hence, both the envelope obtaining and iteration process can help shorten the computational time greatly. Window size of the OSF is optimized to improve performance of the proposed method. Both the left and right ends of the decomposed signal are thought extrema or not does not affect the decomposition results, and therefore there is almost no end effect in the proposed method. Since the OSF is very concise, the proposed EMD process is fast and adaptive. This method is named succinct and fast EMD (SF-EMD) in the present study. Characteristics of the SF-EMD are systematically analyzed by using simulated signals. Furthermore, vibration signal is applied to verify its effectiveness in fault diagnosis for rotating machinery.

2. Succinct and fast EMD (SF-EMD)

The EMD method decomposes a signal into its IMFs and a residue based on the local spatial scales [1]. An IMF is a function that satisfies two conditions: (1) in the whole data set, the number of extrema and the number of zero-crossings must either equal or differ at most by one; (2) at any point, mean value of the upper envelope and the lower envelope is zero. Each IMF can be obtained from an iterative process of finding the upper and lower envelopes. Cubic-spline is the most popular interpolation method. However, number of extrema decreases with the decomposition process, resulting in cumulative error in obtaining the envelopes. The error will be taken into the next IMFs and may finally cause failure of decomposition.

To solve the above-mentioned problems of the EMD method, some improved methods were developed, such as ensemble EMD (EEMD) [23], wavelet packet transform-based EMD (WPT-EMD) [24], and B-spline EMD (BS-EMD) [25], which improved performance of the EMD method. However, these much more complicated decomposition processes greatly increase computational time. Fast and effective EMD algorithm is very important in some applications, such as online health monitoring and fault diagnosis for mechanical systems.

SF-EMD method is proposed and IMF of this method is named fast IMF (FIMF) in the present study. Steps of the proposed method are given in Table 1. In the method, smooth processing should be used either to the upper and lower envelopes in Step (3), or to the mean envelope in Step (4), so as to obtain better FIMFs.

2.1. Searching for the extreme sequences

Error in every iteration process of the EMD method can be transferred to or even magnified in the following iterations. Hence, one of key issues of the EMD method is searching for extrema. The SF-EMD differs from the original EMD, basically in the steps of estimating the envelopes and limiting the number of iterations of each IMF to one. In the proposed method, extreme is thought as the local maximum (or minimum) only when it locates at the middle of a local window, which is named as median extreme. For a signal $x(n) = [a_1, a_2, \cdots\cdots, a_N]$ with length N, a_m is the mth element, size of the window w_n is odd, and local extreme can be defined as

$$a_m \text{ is} \begin{cases} \text{local maximum, } a_m > a_k \text{ for all } k \\ \text{local minumum, } a_m < a_k \text{ for all } k \end{cases} \tag{1}$$

where k is integer from $(m - \frac{w_n - 1}{2})$ to $(m + \frac{w_n - 1}{2})$.

The window width w_n is set 3 to illustrate the process of searching for the extreme sequences. Larger local window size results in less extrema, which is not good to obtain the envelopes. Extreme searching method is schematically shown in Fig. 1. The black rectangle indicates the sliding local window. If the extreme is at the left or right end of the sliding window, value at this position is set 0, as shown in Fig. 1(b) and (c). For two group of sliding window data [3,4,7] and [5,6,6], the local maxima are 7 and 6, respectively. But both extrema are at the end of the sliding window, values should be set 0. Meanwhile, for the sequences [4,6,7], [3,6,7] and [2,3,5], the local maxima are 7, 7 and 5, respectively. Because these extrema are not at the end of the sliding window, maximum values are 7, 7 and 5, respectively. The search for the minimum sequence is same as that of the maximum sequence. For [5,6,6] and [3,5,7], the local maxima are 5 and 3, respectively. Because these extrema are not at the end of the sliding window, minimum values are 5 and 3. This searching process is so simple that the processing time is very short..

End effect is one of the most complicated problems of the traditional EMD method. In the literature, a number of methods have been proposed to try to solve this problem [26,27]. However, effectiveness of these methods is very limited and greatly increases the processing time. In the SF-EMD method, a partial mirror extension is applied to decide whether the data at the end of signal is the maximum or minimum. The process is:

(1) Decide size of the local window w_n;
(2) Extend the two ends of the original signal with length $(w_n - 1)/2$ using mirror method.

2.2. Width of order statistics filter (OSF)

In the EMD method, after obtaining the maximum and minimum sequences, it is required to create the upper and lower