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Time-frequency representation based on robust local mean decomposition for multicomponent AM-FM signal analysis

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ABSTRACT

Local mean decomposition (LMD) is a promising approach to implement time-frequency representation (TFR) for multicomponent amplitude-modulated (AM) and frequency-modulated (FM) signal analysis; however, its performance usually suffers from end effect and mode mixing problems. To address this issue, this paper proposes a novel comprehensive scheme to improve LMD performance. The novel scheme can automatically determine the fix subset size of the moving average algorithm and the optimal number of sifting iterations in a sifting process. Extensive simulations have been explored for multicomponent AM-FM signal analysis by means of TFR with the improved LMD. Moreover, the improved LMD shows potential application in bearing fault diagnosis in conjunction with the well-known fast kurtogram.

1. Introduction

One of the most important aspects in signal processing is to extract and present useful information from a signal, usually as a function of time, from physical or mechanical systems. Amplitude-modulated (AM) and frequency-modulated (FM) signals are such useful information, and thus, accurate location and representation of AM-FM signals is quite important to interpret systems' health status.

Frequency representation occupies a central role in the vast subject of signal processing. The combination of Hilbert transform (HT) and Fourier transform (FT) is a common approach of frequency representation for AM-FM signals. However, there are two limitations when it is used to analyze multicomponent AM-FM signals [1]. First, HT estimates the instantaneous amplitude and frequency data for monocomponent signals only, and thus, for multicomponent signals, the interference among multiple components leads to a mode mixing problem in HT. Second, the representation of the FM part is more crucial compared to the representation of the AM part due to the fact that the parametric estimation of the time-varying amplitude given the time-varying frequency is always linear. Therefore, locating and representing useful information for multicomponent AM-FM signals is quite challenging in signal processing. The former limitation concerns information location. The most common solution uses signal separation methods, e.g., filters, to extract monocomponent signals from multicomponent signals. The aforementioned HT and FT can further process each monocomponent. The latter limitation concerns information presentation. To alleviate this limitation, time-frequency representation (TFR) is an approach to depict

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AM-FM signals. Recently, a new trend of combining signal separation and the TFR method as a hybrid solution, e.g., Hilbert-Huang transform (HHT), has emerged to address the two aforementioned limitations for multicomponent AM-FM signals. Inspired by HHT, local mean decomposition (LMD), which Smith [2] pioneered, demodulates multicomponent AM-FM signals into a set of product functions (PFs), each of which is the product of an envelope signal and FM signal. Each PF can be considered a monocomponent AM-FM signal, and TFR can be derived based on instantaneous amplitude and frequency data from all of the PFs. LMD has many promising properties; in particular, it avoids the limitation of doubtful negative instance frequency occurring in HT [3] because LMD can generate instantaneous amplitude and frequency data without using HT, as HHT does. Moreover, LMD is specifically designed for AM-FM signals, whereas this property is not reflected in HHT. From the above evidence, LMD is a suitable and promising technique to process multicomponent AM-FM signals [4,5]. However, end effect and mode mixing problems are two main limitations in LMD. These two limitations can be alleviated by proper parameter selection with regard to boundary condition, envelope estimation, and sifting stopping criterion [6].

Most reported studies that aim to improve the performance of LMD can be grouped into three categories corresponding to the above three parameters. Among them, boundary condition and envelope estimation have been the two main focuses over the past ten years. Regarding boundary condition, most researchers try to extend the left and right side ideally by a variety of methods, e.g., the boundary processing method [7], mirror extension method [8], neural networks [9], self-adaptive waveform matching [10], and integral local waveform matching [11]. Regarding envelope estimation, researchers have put forward new methods in roughly two directions. One uses the moving average algorithm as the smoothing algorithm and tries to find an optimal fixed subset size for better envelope estimation, e.g., a third of the longest local mean [2], and a local mean step-based strategy [7]. The other focuses on alternative smoothing algorithm design, e.g., the rational Hermite interpolation method [12], B-spline interpolation method [13], cubic spline interpolation method [14,15], and cubic Hermite interpolation method [16]. In addition, Cheng et al. [17] proposed an ensemble LMD that uses noise to alleviate the limitation of mode mixing. Smith [2] already defined the principle of sifting stopping criterion in LMD; however, it is so ideal that cannot be directly realized in a numerical computation. Some referable criteria have already been proposed and used in EMD, e.g., the standard deviation criterion [18], three-threshold criterion [6], bandwidth criterion [19], and orthogonality criterion [20]. The sifting process is similar between EMD and LMD; however, the effectiveness of the above criteria still needs to be validated when they are embedded in LMD. Regarding sifting stopping criterion, a few methods that transform the original principle of sifting stopping criterion to a practical expression have been reported. Zhang et al. [21] introduced an orthogonality criterion into LMD. Cheng et al. [5] proposed a two-condition criterion that makes decisions based on evaluation of condition 1: $1-\delta \leq$ smoothed local magnitude (i.e., $a_{1p}(n)$ in Section 2) $\leq 1+\delta$ and condition 2: $-1 \leq$ pure frequency signal (i.e., $s_{1p}(n)$ in Section 2) ≤ 1, where δ is a predefined variation. Li et al. [22] and Jiang et al. [23] have adopted this criterion with the condition 1.

It is notable that boundary condition, envelope estimation, and sifting stopping criterion are all associated with the end effect and the mode mixing problems. In other words, LMD performance cannot be thoroughly enhanced unless all three parameters are properly tuned. Considering the key role of LMD in the proposed method, a comprehensive solution is proposed in this paper to improve the performance of TFR for multicomponent AM-FM signal analysis. Finally, the proposed method will be extensively validated on simulated multicomponent AM-FM signals and tested for its effectiveness in bearing fault diagnosis.

This paper is organized as follows. Section 1 introduces the background, motivation and a brief literature review of the progress of current research. Section 2 introduces the theoretical basis of LMD, which is necessary in the following sections. Section 3 proposes the robust LMD based TFR, and improvements on LMD's three aspects are also detailed. Numerical validations with simulated signals and real-world signals are carried out in Sections 4 and 5, respectively. Finally, Section 6 provide the final conclusion of this paper.

2. LMD fundamentals

LMD is an iterative signal process that aims to extract a set of "best fit" product functions (PFs) of a pure FM signal and an envelope signal. The algorithm of LMD includes a nested loop structure, which is a loop within a loop, i.e., an inner loop within the body of an outer one. The outer loop in LMD aims to extract PFs from an original discrete signal, whereas the inner loop aims to extract pure FM and envelope signals from a PF. In the following, we briefly introduce LMD, which provides basic fundamentals for the proposed scheme. The materials in this section are mostly based on [2].

With a sampling frequency F_s or sampling period T_s ($T_s = 1/F_s$), a continuous signal $x(t)$ is sampled to a discrete signal $x(n)$, where $n = 1, 2, 3, \ldots, N_s$, and N_s is the total number of sampling points. The signal $x(n)$ can be decomposed into a set of PFs by LMD with the following steps.

Step 1. Find all local extremes, including maxima and minima, in the signal $x(n)$. The extreme points are denoted as e_k, and the corresponding extreme values are denoted as $x(e_k)$, where $k = 1, 2, 3, \ldots$.

Step 2. Calculate the smoothed local mean $m(n)$ and the smoothed local magnitude $a(n)$. This is achieved through two substeps. First, the preprocessed local mean $m^0(n)$ and local magnitude $a^0(n)$ are computed following Eqs. (1) and (2), respectively. Obviously, the above two signals are step functions.