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Local maximum synchrosqueezing transform: An energy-concentrated time-frequency analysis tool

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ABSTRACT

Time-frequency (TF) analysis (TFA) is an effective tool to analyze time-varying signals. The reassignment method (RM) and synchrosqueezing transform (SST) are high-resolution TFA methods that have attracted much attention recently in the signal-processing field. However, the RM and SST methods suffer from some drawbacks, such as unavailable signal reconstruction and poor energy concentration that hinder their applications in real-world data analysis. To overcome these drawbacks, we propose a novel SST-based technique that can achieve more concentrated representations than RM and SST. Meanwhile, we prove that it allows for perfect signal reconstruction. Furthermore, the ridge detection method and synchroextracting operator are combined to form an adaptive mode decomposition algorithm. The numerical validation shows that the proposed method can be used to sensitively discover the amplitude-weak modes and effectively address signals with heavy noise. In the experimental validation, we first analyze the gravitational-wave (GW) signal. The analysis results show that the proposed method can provide a better time-varying description for the generation procedure of the GW signal. Moreover, the reconstructed signal has a high consistency with the general relativity proposed by Einstein. The experimental analysis on fault bearing shows that the proposed method can discover more detailed features that are helpful for diagnosing bearing faults. Comparisons with other TFA methods demonstrate the superiority and effectiveness of the proposed method.

1. Introduction

Time-frequency (TF) analysis (TFA) method is an effective tool to analyze time-varying signals, and the method has drawn considerable attention in recent decades [1]. Classical linear methods, such as short time Fourier transform (STFT) and wavelet transform, can expand one-dimensional (1D) time-series signal into the two-dimensional (2D) TF plane. From this TF plane, we can observe the time-varying features and achieve decomposition of different mono-component modes. However, restricted to the Heisenberg uncertainty principle, TF representations generated by conventional methods are often blurry and cannot provide a precise TF description for time-varying signals. Recent developments of TFA methods include designing high-resolution methods and retaining the invertible ability to recover the original time-series signal [2–4]. Thus, we are able to obtain detailed time-varying features and precisely decompose each mono-component mode.

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To improve the readability of the original TF representation, a reassignment method (RM) is proposed as the post-processing tool for classical TFA methods [5]. The newly reassigned position of each TF point is first calculated based on the TF phase information, and then the 2D reassignment integral is executed to the TF representation, which is expected to generate much sharper TF results. However, the post-processing way of RM is based on the absolute TF representation, which leads to a loss of the signal reconstruction ability.

Recently, synchrosqueezing transform (SST) has become a promising TFA method because it greatly enhances the TF resolution of classical TFA methods and allows for precise signal reconstruction [6,7]. The SST method has been applied in many fields, such as studies on machine fault diagnosis [8,9], radar chirp signals [10], speech processing [11,12], and gravitational waves [13]. However, with the increasing understanding of the SST, some drawbacks are recognized. One drawback is that when addressing strongly frequency-modulated (FM) signals, the TF representation energy generated by SST smears heavily. To solve this problem, many concentrated SST methods were proposed.

In [9,14], the authors proposed a three-step SST method that first demodulates the time-varying signal into a purely harmonic version and then uses SST technology to enhance the TF resolution of the first-step result. Finally, the time-varying TF features are recovered by an inversely demodulated procedure. In [8,15], an improved three-step SST combined with generalized demodulated decomposition was proposed to address multi-component signals with distinct FM laws. In [16–18], a matching demodulated SST based on the extended polynomial or the Fourier mathematical model was proposed, which can match the time-varying FM law in a short time progressively, such that the energy of the TF representation can be effectively concentrated. From the above analysis, the demodulated processing method has been accepted as an effective way to enhance the original SST representation. To demodulate a signal, the precise time-varying FM law of the signal is needed in advance. However, due to the complexity and diversity of practical cases, it is difficult to determine the precise demodulated parameters, especially when addressing a multi-component signal with distinct FM laws [19,20].

The non-parameter and adaptive SST technique is more suitable for processing real-world data [21,22]. Based on the RM framework, the authors proposed a second-order SST that can provide a high-resolution TF representation like RM and retain the reversible ability [4,23,24]. Recently, the same group further proposed a much higher-order SST that was designed to obtain more concentrated TF results [25]. However, with the increasing SST order, greater computational burden will be introduced. For instance, the original SST needs to execute only one STFT operation, while the fourth-order SST needs to execute eleven STFT operations.

The method in [27] is a positive attempt of our group to achieve a highly concentrated TFA method. It provides a significantly sparse TF representation and has a low computational burden. Although it can be used to decompose the mono-component mode, it does not allow for perfect signal reconstruction, which may lead to large reconstruction errors when addressing strong FM signals. Our group is attempting to improve this method and more research on this method will be performed in the future.

Considering the shortcomings of the currently developed methods, improvements of the TFA method should be directed at (1) well-characterizing the multi-component signal with concentrated TF energy, (2) no requiring an extended mathematical model to demodulate the FM signal, and (3) allowing for perfect signal reconstruction and adaptive mode decomposition. In this paper, we propose a novel SST technique that more closely approaches the above-mentioned targets than other TFA methods. We first provide a detailed analysis of the pros and cons of the SST and RM methods, which helps in designing the novel SST technique. By detecting the local maximum of the spectrogram in the frequency direction, we construct a novel frequency-reassignment operator that can generate a more highly concentrated TF representation than the original SST and RM methods. Meanwhile, we prove that the proposed method allows for perfect signal reconstruction. To decompose the mono-component modes, the ridge detection method and synchroextracting operator are combined together to form an adaptive mode decomposition algorithm. Numerical validation shows that it can sensitively discover the amplitude-weak modes and effectively address signals with heavy noise. In the experimental validation, we first select the gravitational-wave (GW) signal for analysis. GW signal detection just won the 2017 Nobel Prize, and GW signal analysis is a very challenging task. The analyzed results show that the proposed method provides the best time-varying description for the generation procedure of the GW signal and that the reconstructed signal is highly consistent with the general relativity proposed by Einstein. Then, the second experimental analysis focuses on diagnosing the time-varying features of fault bearing. The diagnosis results show that the proposed method can discover more detailed bearing faults information than other methods.

The remainder of this paper is organized as follows. In Section 2, the RM and SST methods are reviewed. Section 3 provides details of the proposed method and framework of the adaptive mode decomposition. Numerical and experimental validations are provided in Sections 4 and 5, respectively. Conclusions are drawn in Section 6.

2. Reassignment method and synchrosqueezing transform

2.1. STFT method

This study begins with the framework of STFT. The STFT of function $s \in L^2(\mathbb{R})$ with respect to the real and even window $g \in L^2(\mathbb{R})$ is defined by