Journal of Sound and Vibration 431 (2018) 70–87

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Revised empirical wavelet transform based on auto-regressive power spectrum and its application to the mode decomposition of deployable structure

Zhijun Luo [1], Tao Liu [1], Shaoze Yan [*], Mengbo Qian

State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 10084, People's Republic of China

ARTICLE INFO

Article history:
Received 18 August 2017
Received in revised form 27 April 2018
Accepted 1 June 2018

Handling Editor: K. Shin

Keywords:
EMD
EWT
Power spectrum
Auto-regressive
Mode decomposition

ABSTRACT

Noise and non-stationary components may result in false boundaries when empirical wavelet transform (EWT) is applied to mode decomposition. In this paper, a revised method named AR-EWT is proposed to overcome this problem. The AR-EWT detects boundaries in the auto-regressive (AR) power spectrum using the Burg algorithm. In the AR power spectrum, white noise and non-stationary factors can be considerably suppressed; therefore, the correct boundaries of different mono-components are successfully detected in the power spectrum. Decomposition results of simulation signals indicate that signals added with white Gaussian noise and non-stationary components can be correctly decomposed using the AR-EWT, which cannot be achieved using the original EWT. Furthermore, comparative analysis with other revised methods is conducted. The results show AR-EWT has superiority over these algorithms. Finally, an application of mode decomposition to the vibration signal of a deployable structure shows that the AR-EWT is more powerful than the original EWT.

1. Introduction

Deployable structures, such as solar arrays, are widely applied to satellites because of their capability to improve the utility rate of space. Vibrations induced by structure unfolding, satellite moving, and temperature changes will last for a long time because damping in space is small [1,2]. This problem has seriously affected the stability of satellites. For example, the Hubble Space Telescope has been disturbed by vibrations of its solar arrays [3].

Extracting and analyzing vibration modes play important roles in the parameter identification and vibration control of deployable structures. Because of variable damping, friction, joint clearance, and flexible materials, vibration signals of deployable structures are non-linear and non-stationary and contain intensive modes [4–6]. Therefore, many time-frequency analyzing approaches are used to analyze the vibration modes. Typical effective methods are short-time Fourier transform (STFT), wavelet transform (WT) [1,7] and Hilbert-Huang transform (HHT) [12].

However, there still are some inherent problems with these methods: Time–frequency resolution of STFT is fixed because length of window is unchangeable. WT solves this problem by using a wavelet-based function with adaptively changeable

* Corresponding author.
E-mail addresses: yansz@tsinghua.edu.cn, yansz@mail.tsinghua.edu.cn (S. Yan).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.jsv.2018.06.001

length and frequency [8], but the selection of a suitable wavelet basis is a hard task [9]. In recent years, some researchers proposed adaptive wavelet methods to solve this problem and obtained effective results in related fields [37,38], and yet, it still needs more researches to prove the universality of the revised methods. In addition, the highest frequency and time resolution cannot be simultaneously achieved with either STFT or WT because of the restriction of the Heisenberg uncertainty principle [1]. HHT is a relatively new method, which utilizes empirical mode decomposition (EMD) to adaptively decompose a signal into intrinsic mode functions (IMFs) and then obtains a higher time−frequency resolution through Hilbert transform (HT) [11,12]. Excepting lack of mathematic theory, the major problem with HHT is mode mixing caused by EMD, i.e., IMFs sometimes are not mono-component, which results in spurious instantaneous frequency and amplitude when using HT. Although, numerous researchers have applied HHT to engineering practice [16–18] and have proposed several revised methods to improve EMD, such as ensemble EMD (EEMD) and complementary EEMD [13,35], mode mixing remains an unresolved problem occurring when the ratio between a relatively low frequency and a relatively high frequency (low frequency/high frequency) becomes close to 0.75 [1,14].

Recently, a novel method, called empirical wavelet transform (EWT), was proposed by Gilles in 2013 to overcome the shortcomings of EMD [15]. EWT extracts the different modes of a signal by designing an appropriate wavelet filter bank in the Fourier spectrum [15]. This method combines the advantages of EMD and WT, and thus, it not only can adaptively decompose signals with the same high frequency resolution as fast Fourier transform (FFT) but also has a definite mathematical theory based on WT.

After EWT was introduced, many researchers applied it to engineering and achieved positive results. Kumar used EWT to decompose an electrocardiograph (ECG) signal into different modes and then obtained suitable thresholds of each mode for signal compression [19]. Hu employed EWT to extract meaningful information from wind series [20]. Merainani utilized EWT to detect early tooth crack damage in a gearbox [21]. Bhattacharyya used EWT to decompose electroencephalogram (EEG) signals into rhythms and then recognized focal and non-focal signals [22]. Cao adopted EWT to diagnose wheel-bearing faults of trains [23]. Chen employed EWT to implement generator bearing fault diagnosis [24]. Jiang proposed a new compound faults detection method for rolling bearings based on EWT [25]. Liu introduced EWT into seismic time-frequency analysis [26].

Although these cases all proved the advancement of EWT, the most important shortcoming of EWT is that FFT is very susceptible to noise and non-stationary factors, which can result in spurious local extremum in the boundaries detection [32]. To overcome this problem, Gilles proposed a scale-space algorithm to automatically detect meaningful modes in the Fourier spectrum; this method is based on the behavior of local minima in a scale-space representation [27]. However, if local minima are false for noise and non-stationary factors, then the boundaries are false too. Based on scale-space algorithm, Zheng proposed a revised method to overcome the shortcomings of HT and applied it to rotor rubbing fault diagnosis [28]. Also based on scale-space algorithm, Pan proposed a modified method which chooses empirical modes for mechanical fault diagnosis by adaptively merging mono-components based on their envelope spectrum similarity [29]. Hu proposed another idea, which utilizes the envelope approach based on the order statistics filter to find the dominant frequency peaks and then applies three criteria to select useful frequency peaks; however, severely overlapped spectra cannot be decomposed successfully [30]. Shi introduced an enhanced empirical wavelet transform based on segmenting the envelope of Fourier spectrum and applied it to feature extraction of turbine condition monitoring signal [31]. However, this method is based on the envelope idea too and meets the same problem with Hu's. Since Fourier spectrum is susceptible to noise, Amezquita-Sanchez proposed a new music-empirical wavelet transform methodology which detects boundaries in the pseudo spectrum calculated by MUSIC algorithm instead of Fourier spectrum [32]. Although MUSIC algorithm can greatly suppress noise and has high resolution, it is dependent on the exact order of signal subspace which is sometimes hard to be established without a prior knowledge of the signal environment [33].

Considering that the number of components in complex vibration signals of deployable structure is always unknown, in this study, we present a revised method named AR-EWT that detects boundaries in the autoregressive (AR) power spectrum calculated by Burg algorithm, and apply it to mode decomposition in the impact vibration experiment of solar arrays. In addition, the comparisons with other revised methods based on test signals are implemented to show the superiority of AR-EWT.

The remainder of this paper is organized as follows. Section 2 briefly explains the principle of EWT and tests the shortcomings of EWT by decomposing test signals. In Section 3, the principle of the AR-EWT method is introduced and a comparative analysis with the original EWT and other three major revised methods is performed. In Section 4, an experiment is presented and comparative analysis with original EWT is conducted. Finally, Section 5 concludes the study.

2. EWT

The principle of EWT is introduced in this section; a test signal with white Gaussian noise simulating the vibration of a deployable structure and a non-stationary test signal are constructed respectively to demonstrate the disadvantage of EWT.

2.1. The principle of EWT

The IMFs are AM−FM components with a compact support Fourier spectrum centering on a specific frequency; therefore, decomposing modes is equivalent to segmenting the Fourier spectrum. Following this ideal, EWT applies a filter bank