Mechanical Systems and Signal Processing 91 (2017) 57–80

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Multicomponent decomposition by wavelet modulus maxima and synchronous detection

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ARTICLE INFO

Article history:
Received 24 January 2015
Received in revised form 17 July 2015
Accepted 2 January 2017

Keywords:
Wavelet scalogram
Instantaneous frequency estimation
Noise compatibility
Wavelet parameter optimization
Gearbox fault diagnosis

ABSTRACT

There are various signal decomposition methods, but none of them is satisfactory and all have their own drawbacks. It is worth exploring a new signal decomposition approach with better performance for processing the complex vibration signals. By employing the wavelet modulus maxima and synchronous detection, a novel multicomponent signal decomposition method is proposed in this paper. Firstly, the wavelet modulus maxima of a multicomponent signal are calculated by optimized complex wavelet transform, then the highest instantaneous frequency (IF) is extracted by searching the wavelet modulus maxima with the smallest scales at all the time instants. With the obtained IF, the synchronous detection method is used to calculate the phase offset and the instantaneous amplitude. It follows that the corresponding component with highest IF can be reconstructed. Then the used wavelet modulus maxima in this iteration are removed from the wavelet scalogram and the next IF is sequentially computed. By repeating this process, all components are successively separated from high frequency to low frequency. Compared with ensemble empirical mode decomposition and Hilbert vibration decomposition, it has been proved by three typical multicomponent signals with different noise intensity that the proposed signal decomposition method has higher accuracy, frequency resolution and is more robust to noises. Moreover, the application results further show that the proposed method can be more effectively applied to fault diagnosis of gearboxes, especially when the operating condition is varying or the fault feature is weak.

1. Introduction

Most of natural signals and engineering signals have multicomponent characteristic, such as mechanical fault signals, power signals, seismic signals, biological signals, etc. Traditional time-frequency analysis methods, e.g. short time Fourier transform (STFT) [1], Gabor transform [2], Wigner-Ville distribution (WVD) [3], wavelet scalogram [4], can be used to analyze such multicomponent signals. Unfortunately, it is difficult and inconvenient to further process the obtained time-frequency spectrum by Fourier transform or envelope analysis. Multicomponent demodulation can also be employed to analyze multicomponent signals. For example, iterative Hilbert transform [5] and multicomponent AM-FM demodulation approach based on energy separation and adaptive filtering [6] have been successfully applied to mechanical fault diagnosis.

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http://dx.doi.org/10.1016/j.ymssp.2017.01.002
0888-3270/

However, multicomponent demodulation methods abandon the phase information of each component. Therefore, the best way is to use a suitable signal decomposition approach, by which a multicomponent signal could be decomposed into a sum of monocomponent signals. Then, all resulting monocomponent signals can be further processed to extract the useful feature information.

In the past two decades, various signal decomposition methods have been developed. The discrete wavelet transform was early used to decompose the signal [7]. But the frequency resolution at each scale is coarse due to the dyadic time-frequency grid. To improve the time-frequency resolution, overcomplete wavelet transform has been widely researched and used to analyze multicomponent faulty vibration signals [8,9]. Huang et al. [10] proposed another powerful multicomponent decomposition approach, namely the empirical mode decomposition (EMD). However, the frequency resolution of EMD is not very satisfactory owing to mode aliasing and its decomposing accuracy is easy to be influenced by noise [11,12]. Thus, ensemble empirical mode decomposition (EEMD) was developed by Wu and Huang [13] based on the statistical properties of white noise, but the computation complexity of EEMD was higher than that of EMD. Recently, Feldman developed an effective method, called Hilbert vibration decomposition (HVD) [14]. HVD has good frequency resolution and can distinguish various narrowband components [15]. Unfortunately, HVD is also sensitive to additive random noise. To improve the decomposing performance for nonlinear multicomponent signals, generalized demodulation time–frequency method and its improved methods were proposed [16–18]. These methods have fine resolution, but it is very important to precisely calculate the appropriate phase functions. More recently, Qin et al. [19] developed a sparse decomposition method based on different transform basis, which has high decomposition accuracy, but its computation speed is relatively slow. In this paper, we expect to explore a new multicomponent signal decomposition method with desirable comprehensive decomposing performance, such as high accuracy, good anti-noise capacity, low computation complexity and fine frequency resolution.

It is easy to note that an arbitrary monocomponent signal can be calculated by its phase function and instantaneous amplitude. To obtain the phase function of one component, we need firstly calculate its instantaneous frequency (IF). Via wavelet modulus maxima, the IF of each component in a multicomponent signal can be obtained. Then, the synchronous detection method can be used to compute the phase function and instantaneous amplitude, by which the corresponding component is reconstructed. From high frequency to low frequency, all components are successively separated. In the decomposition process, complex Morlet wavelet is used. Since this family of wavelets has good time-frequency localization property, the proposed multicomponent decomposition method has high accuracy. Particularly, if the signals have some random noise, the proposed method has better decomposing performance than the commonly-used multicomponent decomposition methods. The simulation results show the superiority of the proposed method. Finally, it is successfully applied to the fault diagnosis of two two-stage gearboxes with different faults.

2. Preliminaries

2.1. Multicomponent model

A multicomponent AM-FM model for the signal $x(t)$ can be represented as

$$x(t) = \sum_{i=1}^{N} A_i(t)\cos[\phi_i(t)] \tag{1}$$

where $A_i(t)$ and $\phi_i(t)$ represents the instantaneous amplitude (IA) and the phase function of the ith component respectively, N is the number of components. And $\phi_i(t)$ can be denoted as [13]

$$\phi_i(t) = \omega_{ci}t + \omega_{mi}\int_0^t q_i(\tau)\mathrm{d}\tau + \theta_i \tag{2}$$

where ω_{ci} is the carrier angular frequency, ω_{mi} is the maximum angular frequency deviation from ω_{ci}, $q_i(t)$ is the normalized frequency modulating signal, θ_i is the phase offset of the ith component. $A_i(t)$ and $q_i(t)$ are assumed to be slowly time-varying signals compared to the carrier wave, and ω_{ci} is assumed to be a constant.

Particularly, if $x(t)$ is a multicomponent harmonic signal, its model can also be represented by Eq. (2), but the phase function $\phi_i(t)$ should be defined as

$$\varphi_i(t) = \omega_i t + \theta_i \tag{3}$$

where ω_i denotes the frequency of the ith harmonic component.

2.2. Wavelet modulus maxima and IF estimation

With continuous wavelet transform, we can describe the time-frequency representation of an arbitrary signal. In the time-frequency spectrum, the wavelet modulus maxima are closely related to the IFs (or ridges) of the signal.

Let $\psi(t)$ be an asymptotic complex wavelet, which is expressed as

$$\psi(t) = g(t)\exp(i\omega_0 t) \tag{4}$$