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Biphase randomization wavelet bicoherence for mechanical fault diagnosis

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ABSTRACT

Wavelet bicoherence is one of the most useful tools for quadratic nonlinear behavior identification of stochastic system, which has been used in many fields. However, current wavelet bicoherence algorithm can neither eliminate the spurious peaks coming from components with long coherence time, nor distinguish the quadratic phase coupling and non quadratic phase coupling signals, which may constraint the application of wavelet bicoherence. In this article, biphase randomization wavelet bicoherence technique is proposed to solve this problem. In this method, an ensemble average biphase randomization algorithm is established, in which the biphase randomization is employed to damage the biphase dependence among bispectrum samples. The spurious bicoherence coming from long coherence time waves and non phase coupling waves is eliminated efficiently by using the proposed method. Based on that, two diagnosis features are established for mechanical fault diagnosis. Simulation and experiment results demonstrate that the performance of the proposed method is much better than that of current wavelet bicoherence method.

1. Introduction

Since the early work of Brillinger [1] and Hinich [2], the bispectrum and bicoherence have been recognized as useful techniques for nonlinear behavior identification of stochastic systems, which have been widely applied in fields as diverse as oceanography [3], electro-encephalography [4,5], economics [6], fluid mechanics [7] and plasma physics [18]. In the past few years, these techniques were also introduced in condition monitoring and fault diagnosis of mechanical systems, because structural damage always bring nonlinearity in signals [8,9]. Rivola et al. [10] used the normalized bispectrum to detect cracks in an experimental beam and the actual structures, which shows high sensitivity to the presence of the fatigue crack in the structure. Gelman et al. [11] used the real and imaginary components of the bicoherence for fatigue crack diagnosis of compressor blades from an aircraft engine. Subsequently, Gu et al. [12] proposed a diagnostic feature namely normalized bispectrum peaks for fault classification of downstream mechanical equipment. In associated with the kurtosis value of the raw current signal, the reliable faults can be classified clearly. Combet et al. [13] focused on gear fault diagnosis, and an instantaneous bicoherence was proposed for localized fault detection. Generally, if there is a fault in the mechanical structures, the performance of the mechanical system will degrade, more and more impacts will appear in the vibration signals. These impacts may cause phase coupling among the demodulation bands in vibration signal, particularly the quadratic phase coupling (QPC) – a strong indicator of the nonlinear mechanical signal [14]. This type of vibration signal is nonlinear and non-stationary in nature, which makes the stationary assumed methods not appropriate [15]. Fourier bispectrum and bicoherence are effective in detecting the phase coupling in this type of nonlinear vibration signals, However, they are not appropriate for

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the vibration cases associated with short-time duration nonlinear interactions. Recently, a wavelet-based bicoherence (WB) method is proposed for nonlinear and non-stationary signal analysis, which combines benefits of both wavelet transform and bicoherence analysis [16]. Compared with the Fourier bicoherence, WB has its advantage in preservation of temporal information, thus it is more suitable for transient detection. Nonetheless, it is reported that some inevitable problems exist when it is applied to real-world experiment. These problems are mainly due to the inherently features of WB itself [13,17]. Commonly, in computing of bicoherence by current WB method, the signal with long data record length is firstly divided into a series of epochs. Then, the reliable bicoherence estimation of the signal can be obtained by averaging the WB of all epochs. But, for the real-world experimental signal, simple segmentation can yield potential problems.

(1) If the coherence time of the signal is relatively short in comparison with the time interval of the epoch, the phase component is independent over each epoch. Then, the estimation of the reliable bicoherence values can be obtained by using the current WB method accurately.
(2) Some real-world experimental signals often have very long coherence time, which make the biphase component dependence over each epoch. Thus, bicoherence estimated by current WB method may include incorrect QPC detection results, especially when used in the case coupled and uncoupled waves present at the same frequency.

In this study, a biphase randomization wavelet bicoherence is established to overcome this problem. In this method, an ensemble average biphase randomization algorithm is proposed for reliable bicoherence estimation, which can automatically eliminate the spurious bicoherence resulting from long coherence time waves and non phase coupling waves. The remaining parts are organized as follows. In Section 2, the definition of WB is reviewed firstly, and the limitation of current WB method is discussed subsequently. After that, a biphase randomization wavelet bicoherence is established in Section 3, and the performance of the proposed method is investigated through simulations in Section 4. In Section 5, this new biphase randomization wavelet bicoherence is applied to fault diagnosis of the rolling element bearing. Finally, conclusions are given in Section 6.

2. Current wavelet bicoherence method

2.1. Wavelet bicoherence

Given a signal $x(t)$, the continuous wavelet transform (CWT) of this signal is defined as the convolution of $x(t)$ with the scaled and normalized wavelet. We write

$$W_\psi(f,t) = \frac{1}{\sqrt{|s|}}\int_{-\infty}^{\infty} x(t')\psi^*\left(\frac{t'-t}{s}\right)dt' \tag{1}$$

where the * indicates the complex conjugate, $\psi(t)$ is an admissible mother wavelet, s is the scale variable, t is the time shift variable, f is the equivalent Fourier frequency.

The wavelet bispectrum is firstly introduced by van Milligen as follows [16].

$$B_{W,T}(f_1,f_2) = \int_T W_\psi(f_1,t)W_\psi(f_2,t)W_\psi^*(f_3,t)dt \tag{2}$$

where the * indicates the complex conjugate, T is the finite time interval of the signal, frequency values f_1, f_2 and f_3 satisfy the relationship $f_3 = f_1 + f_2$. The wavelet bispectrum is a complex value. So, it can be also expressed by its magnitude $A(f_1, f_2)$ and biphase $\varphi\,(f_1, f_2)$ as follows

$$B_{W,T}(f_1,f_2) = A(f_1,f_2)e^{i\varphi(f_1,f_2)} \tag{3}$$

where the biphase $\varphi\,(f_1, f_2)$ can be calculated by

$$\varphi(f_1,f_2) = \varphi_1(f_1) + \varphi_2(f_2) - \varphi_3(f_3) \tag{4}$$

where $\varphi_1(f_1)$, $\varphi_2(t)$ and $\varphi_3(t)$ are, phase uniformly distributed within $(-\pi, \pi]$, obtained by CWT.

The WB, a normalized version of wavelet bispectrum, is defined as [16].

$$b^2_{W,T}(f_1,f_2) = E\left(\frac{|B_{W,T}(f_1,f_2)|^2}{\int_T|W_\psi(f_1,t)W_\psi(f_2,t)|^2\mathrm{dt}\int_T|W_\psi(f_3,t)|^2\mathrm{dt}}\right) \tag{5}$$

where $E[*]$ denotes an average operator.

WB characterizes the QPC among different frequency components of the signal. The peaks in the WB indicate the phase and frequency coupling at bifrequency (f_1, f_2) during the time interval T, and the value of the peaks is bounded between 0 and 1.

2.2. Limitation of current wavelet bicoherence

For quadratic nonlinear systems, the response for two inputted sinusoids can be modeled as

$$x(t) = a_1\sin(2\pi f_1 t + \varphi_1) + a_2\sin(2\pi f_2 t + \varphi_2) + a_3\sin(2\pi f_3 t + (\varphi_3)) + n(t) \tag{6}$$

where $n(t)$ is white Gaussian noise with zero-mean and unit variance, f_1, f_2 and f_3 satisfy the relationship $f_3 = f_1 + f_2$. φ_j (j = 1,2,3) is the initial phase distributed within $(-\pi, \pi]$ uniformly. If there is QPC in $x(t)$, then $\varphi_3 = \varphi_1 + \varphi_2$. If non-QPC exists in $x(t)$, then φ_3 is randomly distributed within $(-\pi, \pi]$.

Morlet wavelet is used in this article. The CWT of each term in (6) can be obtained as follows (the details of the deduction for (7) can be found in Appendix A).

$$W_\psi(f_j,t) = \left\{\pi^{-1/4}\pi a_j\sqrt{\frac{2\pi}{s_j^2}}e^{\frac{1}{2}[(2s_j\pi f_0+it)-(2\pi f_0)]}\right\}\cdot e^{i\varphi_j} \tag{7}$$

where the first term can be considered as a constant series.

Substitute the CWT of each term in formula (5), the WB is obtained as