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Adaptive spectral kurtosis filtering based on Morlet wavelet and its application for signal transients detection

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ABSTRACT

Spectral kurtosis (SK) provides a valuable tool for detecting the signal transients buried in noise, which makes it very powerful for designing a filter to extract the signal transients. However, SK requires the selection of a time–frequency frame for decomposition based on Short Time Fourier Transform (STFT). This paper presents an adaptive spectral kurtosis filtering technique to extract the signal transients based on Morlet wavelet. The Morlet wavelet is used as a filter bank whose center frequency is defined by the wavelet correlation filtering. Different bandwidth filter in the filter bank is used to select the optimal filter for extracting the signal transients as the one that maximizes the SK. Effectiveness of the proposed technique is verified through the transient extraction of a simulate signal. For the gear fault feature detection of vehicle transmission gearbox, the proposed technique is applied in the extraction of the signal transients that shows the gear fault, which proves the effectiveness of the proposed technique in extracting the signal transients in the practical application.

1. Introduction

Gears are widely used in various machinery and often subjected to harsh working conditions. Therefore, they have received a lot of attention in the field of vibration analysis as they represent a common source of fault and one of the key issues is to capture the signal transients. The signal transients with the characteristics of short duration and wide frequency band can be seen as the response to impulse-like impacts which excite the structural resonance of the mechanical system caused by fault. Thus, the detection of signal transients is one of the key issues in the mechanical fault diagnosis.

An early developed and widely used technique to tackle this issue is the envelope analysis. The major challenge in the application of this method is the proper selection of center frequency and the bandwidth of a filter which are mostly based on the existence of historical data and the experience of the user. To address this issue, many techniques such as Wavelet transform and Hilbert–Huang transform are employed. Wavelet transform is widely used to detect the signal transients because of the properties with good time–frequency localization [1]. However, the realization of time–frequency localization analysis based on the inner product calculation between the signal and the mother wavelet which can scale and shift largely depends on the selection of wavelet basis, its adaptability is not perfect [2]. Hilbert–Huang transform is the latest development method of time–frequency analysis by introducing into instantaneous frequency and has a perfect local adaptability through decomposing the signal from its own scale characteristic, it is flexible and effective in signal processing [3]. However, some shortages also exist, such as the end effect and the mode mixing that can lead to serious distortion for result of decomposition [4,5].

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In recent years, a novel technique for detecting signal transients has been proposed based on the Spectral Kurtosis (SK). SK is a sensitive tool for detecting non-stationary components (transients) in a signal and that can indicate the frequencies that the transients occur.

SK was first introduced by Dwyer, as a complement to the power spectral density [6], and later Antoni and Randall proposed it formally as the energy-normalized fourth-order spectral cumulant and its estimation based on the STFT [7] (STFT-based SK) and applied to the fault detection of rolling element bearings and gears [8]. The fast kurtogram has been used to extend the SK method to a wider class of non-stationary signals [9]. However, this method may not be practical because it is difficult to find the optimal filter by examining all the window lengths used in the STFT-based SK. Zhang and Randal proposed an optimal resonance demodulation technique using the combination of the fast kurtogram and genetic algorithm [10]. However, it involves taxing computation due to the adopted genetic algorithm. Wang and Ming proposed an adaptive SK technique based on window superposition and got a favorable result in the application for fault detection of rolling element bearings [11]. However, the optimal merging window associated with the highest SK does not match better with the signal transient feature (whose bandwidth can cover the whole frequency band of transient feature and the center frequency is transient feature frequency) in the case of the transient impulse decay slowly.

In this paper, we propose an adaptive SK filtering method based on Morlet wavelet. The new technique can select the optimal filter adaptively guided by the SK value from the Morlet wavelet filter bank whose center frequency is determined by the wavelet correlation filtering, so the proposed technique ensures that the optimal filter matches better with the signal transient feature and recovers the signal transients as soon as possible. Effectiveness of the proposed technique is proved through the transients extraction from the simulate signal with strong background noise. For the gear fault detection, the proposed method is applied in the extraction of the impulse response that shows the gear fault, which proves the effectiveness of the proposed method in extracting the signal transients.

2. The signal transients detection with the SK

2.1. The concept of SK

The SK of a signal $Y(t)$ is defined as the energy-normalized fourth-order spectral cumulant:

$$K_f(f) \triangleq \frac{C_{4Y}(f)}{S_{2Y}^2(f)} = \frac{S_{4Y}(f)}{S_{2Y}^2(f)} - 2 \text{ with } S_{nY}(f) = \langle H|(T,f)|^n \rangle \; f \neq 0 \quad (1)$$

where $C_{4Y}(f) = S_{4Y}(f) - 2S_{2Y}^2(f)$ is the fourth-order spectral cumulant, $S_{2Y}^2(f)$ the power spectral density of $Y(t)$, $H(t,f)$ the complex envelope of the signal $Y(t)$ and $< \cdot >$ the time averaging operator.

2.2. The principle of transients detection with the SK

The SK was interpreted [7] as a measure of temporal dispersion of the time–frequency energy distribution $|H(t,f)|^2$ of a signal $Y(t)$ at each frequency f. Thus, the SK can be used to design a filter that extracts the signal transients $X(t)$ from a signal $Y(t)$ with the stationary Gaussian noise $N(t)$ and indicates at which frequency that transient occurs.

$$Y(t) = X(t) + N(t) \quad (2)$$

The relation of the SK between the sum signal $Y(t)$ and the signal transients $X(t)$ can be expressed by [7]

$$K_Y(f) = \frac{K_X(f)}{[1+\rho(f)]^2} \quad (3)$$

where $K_Y(f)$ denotes the SK of the sum signal $Y(t)$, $K_X(f)$ the SK of the signal transients $X(t)$ and $\rho(f) = S_N(f)/S_X(f)$ the ratio of the power spectral densities of $N(t)$ and $X(t)$, representing a local noise-to-signal ratio – the reciprocal of signal-to-noise ratio (SNR) – at each frequency.

The signal-to-noise ratio is high ($\rho(f) \approx 0$) in the transient feature bandwidth and low outside. Thus, the $K_x(f)$ is close to $K_Y(f)$ within the transient feature bandwidth and tends to zero elsewhere according to Eq. (3), so it can be used to detect the signal transients in different frequency bands through canvassing the whole frequency domain gradually. Based on those, the SK can be estimated by a filter bank decomposition at a given frequency. It can be expressed by

$$K_Y(f_{m\,i})_{\Delta f_i} = SK(\Delta f_i, f_{m_i}) \quad (i = 1, 2, 3, \ldots, n) \quad (4)$$

where Δf_i stands for the bandwidth of a filter in the filter bank and f_{m_i} a given frequency in the frequency domain (the center frequency of a filter). Thus, the problem of detecting the signal transients turns to locate the best combination of Δf and f_m where the SK is maximum.

3. Adaptive spectral kurtosis filtering based on Morlet wavelet

3.1. Morlet wavelet filter bank

3.1.1. Morlet wavelet

The wavelet transform provides a combination of time and frequency localization, and thus is important for analyzing non-stationary signals. By considering the signal transients as the response of impulse, the time–frequency structure of the Morlet wavelet matches the typical transients best [12–13]. Besides, its "box spectrum" is suitable as a filter. The Morlet wavelet is defined as a complex exponential function in the time domain and has a shape of Gaussian window in the frequency domain as follows:

$$\psi(t) = e^{\frac{-\zeta}{\sqrt{1-\zeta^2}}[2\pi f_m(t-\tau)]^2} \cdot e^{-j2\pi f_m(t-\tau)} \quad (5)$$

$$\Psi(f) = e^{-\left[\frac{\sqrt{1-\zeta^2}}{\zeta}/(2f_m)^2\right](f-f_m)^2} \quad (6)$$

where $\Psi(f)$ is the Fourier Transform of $\psi(t)$, ζ is the damping ratio, f_m is the center frequency of Morlet wavelet window and τ denotes the time parameter.