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Weak fault signature extraction of rotating machinery using flexible analytic wavelet transform

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ABSTRACT

Extracting and revealing the weak periodic fault vibration impulses is reasonable for damage detection of rotating machinery. However, the widely used dyadic WT suffers fixed frequency partition manner and low oscillating bases which would weaken its performance in weak fault detection. A new method based on flexible analytic wavelet transform (FAWT) is proposed in this article. Employing fractional and arbitrary scaling and translation factors, FAWT possesses attractive properties such as flexible time–frequency (TF) covering manner, better shift-invariance and tunable oscillatory nature of the bases, offering proper wavelet frame and bases shape to match the weak fault components. Moreover, FAWT is effective in revealing the amplitude modulation feature of the periodic fault impulses that occur in some damaged rotating components. The applications to a rolling bearing, a planetary gearbox of, and a flue gas turbine unit show that the proposed method is effective in extracting weak impulsive fault signature.

1. Introduction

Fault diagnosis of rotating machinery, especially at the early stage, has gained wide attention for its significance in preventing potential catastrophic accidents and beneficially guarantee sufficient maintenance time [1–3]. Vibration-based analysis has been used extensively due to its intrinsic advantage of revealing the machinery fault signature [4–6].

From mechanical fault mechanism, periodic impulses occur in the vibration measurements when local defect appears in the key rotating components such as rolling bearing, rotor, gearbox, etc. [7,8]. Also in some cases the periodic fault impulses exhibit amplitude modulation feature due to the transfer path from damage meshing location to the fixed accelerometer varying during one revolution. Thus, the accurate revelation of both impulses and their amplitude modulation feature is strong evidence to enhance the certainty of fault diagnosis. However, these fault impulses usually are weak because they are buried in strong vibration responses from other mechanical components and severe background noise [9,10], and the signal-to-noise ratio (SNR) will be further weakened for the early-stage defect. Thus proper signal processing technique is a critical prerequisite for clear identification of fault signature [11,12].

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Wavelet filter-based denoising method is a promising way to detect fault signature of mechanical impulse-like defects [13]. Wavelet transform (WT) enjoys fine TF concentration and multi-resolution analysis capacity and is a powerful mathematical tool for processing non-stationary signals [14]. Harmonic wavelet (HW) can easily obtain arbitrary location and bandwidth of the wavelet filters and is introduced for enhanced weak defect identification in rotating machinery systems [15,16]. However, this continuous WT (CWT)-type operator suffers restricted computation efficiency.

Enjoying efficient implementation using dyadic dilation and translation parameters [17], various dyadic wavelet transforms (WTs) have been investigated and widely used in mechanical vibration analysis and fault detection [18,19]. Wang and McFadden used Db4 wavelet as the wavelet function to perform discrete wavelet transform (DWT) on gearbox vibration signal for measuring its tooth-broken defect [20]. Djebala conducted a DWT-based adaptive filtering operation for fault diagnosis of rolling bearing [21]. However, DWT suffers shift-invariance and poor resolution at its high frequency subbands, which weaken its performance in detecting transient components with high-frequency characteristics. As an enhancement of DWT, wavelet packet transform (WPT) improves the high-frequency resolution through a parallel decomposition of both the high- and low-frequency bands [22,23]. Liu proposed an optimal WPT basis selection method from two sets of basis functions for fault diagnosis of rotating machinery [24]. Dual-tree complex wavelet transform (DTCWT) employs complex bases and has been demonstrated to enjoy enhanced shift-invariance due to its analytic frequency response [25,26]. Wang studied DTCWT-based signal denoising method for multiple fault signature detection [27]. Chen et al. utilized DTCWT to reveal periodic fault signature of gearbox [28]. The second-generation wavelet transform (SGWT) provides users with much flexibility for building different bases for engineering problems via a lifting scheme with prediction and update operation [29]. Despite fruitful achievements in vibration analysis and fault diagnosis, the effectiveness of dyadic WTs is weakened due to some intrinsic drawbacks like low-oscillatory basis and fixed wavelet frame [30].

To effectively detect the fault impulses, the shape and location of wavelet filters should be adjustable to adaptively match the locally concentrated frequency spectrum of the periodic fault impulses. This can be further explained from the view of inner product. WT detects the transient fault features through inner product of the input signal and predetermined bases in the TF plane [31]; thus the location and shape matches of wavelet bases and fault impulses play a key role in the weak fault detection performance. Accordingly, the success of feature extraction is determined by two factors: wavelet frame and basis oscillation.

(1) Wavelet frame for location match. Wavelet frame is a set of bases dilated and translated from the mother wavelet, and determines the sampling of the TF plane. In a tight wavelet frame, dilation parameter cites the center locations of wavelet bases along the frequency axis, while dilation and translation parameters cite those along the time axis. Considering the weak fault impulses are located in some local position of the TF plane, it will be feasible to reveal the weak signature by employing proper wavelet frame with appropriate dilation and translation factors.
(2) Basis oscillation for shape match. Viewing from the inner product, WT exhibits the largest value when the signal and the wavelet basis are the most correlative. A high oscillatory basis could easily detect the high oscillatory impulses, which commonly occur in damaged rotating machinery.

However, for dyadic WTs, the TF partition manner is rigid and octave due to the dyadic dilation and translation parameters. Besides, the oscillation of dyadic wavelet bases is low and would weaken its performance in matching highly oscillatory fault impulses.

In this article, a novel method based on the flexible analytic wavelet transform (FAWT) is proposed to address the limitations of dyadic WTs and enhance the performance of weak fault features detection in rotating machinery. FAWT was originally investigated by Bayram [32]. FAWT allows employing arbitrary sampling rates in both the lowpass and highpass channels, which leads to a flexible TF partition manner where the dilation and translation factors can be easily set. Additionally, via regulating the width of frequency transition bands, the FAWT can attain desirable oscillatory bases to detect different oscillatory impulses. Accordingly, for damaged rotating component such as planet gear, the periodic fault impulses and its amplitude modulation feature can be extracted via using proper FAWT basis.

Furthermore, the construction of the optimal wavelet basis should be data-driven in application because prior knowledge of the impulse being extracted is hardly available. In this paper, the genetic algorithms (GAs) are adopted to select the optimal control parameters based on characteristic kurtosis spectral entropy (CKE) maximization principle. Kurtosis is a widely used indicator of impulses. However, kurtosis is more sensitive to single strong impulse than to weak periodic impulses. Considering that the single or sporadic impulses sometimes occur in the subband signals, especially when narrow bandwidth filter is adopted, an improved indicator termed 'CKE' is presented to reveal both the impulsive and periodic behaviors of signals and suppress the sensitivity of kurtosis to sporadic impulsive shocks. The proposed method is applied to both laboratory and engineering tests for defects detection of rolling bearing, planetary gearbox, and a flue gas turbine unit. Compared with classical dyadic WTs, HWT, SK and denoising method, the proposed method is validated to be effective to detect weak fault signature.

The rest of this article is organized as follows. The summary theories of dyadic WTs are briefly introduced in Section 2. In Section 3, the theory and attractive properties of FAWT are explicated. Accordingly, the fault features detection approach is proposed in Section 4 and experimental studies are performed in Section 5. Additionally, discussions are followed after each application case. Finally, the conclusions are summarized in Section 6.