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Generalized stepwise demodulation transform and synchrosqueezing for time–frequency analysis and bearing fault diagnosis

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ABSTRACT

The energy concentration level is an important indicator for time–frequency analysis (TFA). Weak energy concentration would result in time–frequency representation (TFR) diffusion and thus leading to ambiguous results or even misleading signal analysis results, particularly for nonstationary multicomponent signals. To improve the energy concentration level, this paper proposes a generalized stepwise demodulation transform (GSDT). The rationale of the proposed method is that (1) the generalized demodulation (GD) can map the original signal into an analytic signal with constant instantaneous frequency (IF) and improve the energy concentration level on time–frequency plane, and (2) focusing on a short window around the time instant of interest, a backward demodulation operation can recover the original frequency at the time instant without affecting the improved energy concentration level. By repeating the backward demodulation at every time instant of interest, the TFR of the entire signal can be attained with enhanced energy concentration level. With the GSDT, an iterative GSDT (IGSDT) is developed to analyze multicomponent signal that is subjected to different modulating sources for their constituent components. The IGSDT iteratively demodulates each constituent component to attain its TFR and the TFR of the whole signal is derived from superposing all the resulting TFRs of constituent components. The cross-term free and more energy concentrated TFR of the signal is, therefore, obtained, and the diffusion in the TFR can be reduced. The GSDT-based synchrosqueezing transform is also elaborated to further enhance the GSDT(IGSDT) yielded TFR. The effectiveness of the proposed method in TFA is tested using both simulated monocomponent and multicomponent signals. The application of the proposed method to bearing fault detection is explored. Bearing condition and fault pattern can be revealed by the proposed method resulting TFR. The main advantages of the proposed method for bearing condition monitoring under variable speed conditions include: (a) it can simultaneously improve energy concentration level of signals of interest and remove interferences in the TFR, (b) it is resampling-free and hence can avoid the resampling related errors, and (c) it yields instantaneous frequencies for fault and shaft rotation and thus can carry out both fault detection and diagnosis tasks.

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1. Introduction

Time–frequency analysis has been widely used in analyzing nonstationary signal as it helps reveal insight into the complex structure of a signal containing multiple components [1,2]. Various TFA methods have been investigated in the literature. The most common one is the linear TFR [3] that is characterized by the inner product with a dictionary of time–frequency (TF) atoms, such as the short time Fourier transform (STFT) and wavelet transform (WT). However, the effectiveness of this class of TFA methods is often undermined by the ill-selected dictionary and resolution paradox reflected by the Heisenberg uncertainty principle. More specifically, the performance of such methods is highly dependent on the selected basis, and the accurate time localization is compromised by low frequency resolution and vice versa. Another category of TFA methods is the quadratic (bilinear) transform, which includes the well-known Wigner–Ville distribution (WVD) and its variants [4]. Though such methods have desirable theoretical characteristics, the interference terms in the TF plane have made it very challenging to apply them in real applications [5].

The effectiveness of TFA methodologies lies in their capability of concentrating the energy of TFR at or around the true IF in the TF plane. Targeting at this, the synchrosqueezing wavelet transform is proposed in [6]. This technique eliminates the ambiguity in frequency (scale) dimension via squeezing the TFR along the frequency (scale) axis, thereby acquiring a better frequency resolution. However, the synchrosqueezing transform (ST) is restricted to frequency (scale) variables of the continuous wavelet transform (CWT) [7,8]. There exists a time offset corresponding to time variable in addition to frequency (scale), which could also cause diffusion in time dimension and cannot be ignored when dealing with noisy and amplitude–frequency modulated (AM–FM) signals. To resolve the bi-dimensional smear problem, Li and Liang [8,9] proposed the generalized ST based on the generalized demodulation (GD) which paves the way towards achieving a much more concentrated TFR by a combination of multiple TF plane manipulations in one operation. This technique significantly improves the energy concentration in TF plane. However, many signals often consist of nonstationary multiple components and each of the components can be subjected to different modulating sources. Thus, one time application of the GD cannot demodulate all components and map their IFs into constant frequencies. As a result, the TF blur still occurs for such multicomponent signals. To overcome the problem of the GD in handling multicomponent signals, an iterative generalized synchrosqueezing transform is developed by Feng et al [10] to decompose a complex multi-component signal into monocomponent ones and then transform all constituent components with time-variant frequencies into constant ones. In doing so, the requirement of monocomponent and constant frequency can be satisfied to facilitate the ST. Nevertheless, this method has a drawback of strong dependence of the initial IF estimation. The inaccurate IF estimation would lead to confusing or even wrong results. In addition, this method is tailored for planetary gearbox fault diagnosis under time-varying speed. The capability of such TFA methods for bearing fault diagnosis under variable speed has not been adequately explored.

Bearings are widely used in mechanical systems for their capacity of constraining relative motion and reducing friction between moving parts. Their failure could result in machine breakdowns or even catastrophic accidents [11,12]. As such, bearing health monitoring has been an important topic for industry and academic community. Though various bearing monitoring techniques have been reported in the literature, many of them are not effective for time-varying speed cases as the speed fluctuation may cause “smearing” of the discrete frequencies in the frequency representation. Therefore, fault-related frequencies may no longer appear as discrete frequency lines [13] and the fault features cannot be easily captured. Hence bearing fault diagnosis under variable speed is much more challenging than under constant speed and has attracted the attention of many researchers in recent years. For example, Teotrakool et al [14] investigated bearing fault detection in adjustable-speed drives via motor current signature analysis and wavelet packet decomposition. Renaudin et al [15] reported a novel method for bearing fault detection based on angular measurement of true instantaneous angular speed. In their work, they demonstrated that localized bearing faults created small angular speed fluctuations which could be measured by optical or magnetic encoders. Gong and Qiao [16] studied the bearing fault diagnosis for direct-drive wind turbines operating at unstable rotating speed conditions by joint application of appropriate current frequency, amplitude demodulation algorithm and a 1P-invariant power spectrum density algorithm. Yang et al. developed a method based on the variable predictive model based class discriminate (VPMCD), order tracking technique and local mean decomposition (LMD) for analyzing bearing vibration signal measured under variable speed condition [17]. It has been reported that their methods can detect bearing faults and identify fault types accurately. An approach named reversed sequence squared envelope spectrum (RS-SES) is described by Borghesani et al [18], which is exploited to address the inherent problem of the traditional squared envelope spectrum (T-SES) in real applications. This approach consists of band-pass filtering, squaring enveloping, resampling and discrete FT. The rotating speed in [18] is picked up by a tachometer. More recently, an innovative technique for bearing fault detection under time-varying condition is proposed by Wang et al [19]. They proposed an amplitude-based peak search algorithm for STFT to extract the instantaneous fault characteristic frequency (IFCF) and then resample the non-stationary signal in accordance with the extracted IFCF. In this way, the non-stationary signal in the time domain is transferred into stationary fault phase angle (FPA) domain signal, and then the FPA domain signal is further transformed into the fault characteristic order (FCO) domain, thereby the classical technique like Fourier transform becoming applicable. The final diagnosis decision can be made based on the FCO spectrum.

The aforementioned work has enriched the literature on bearing fault diagnosis under nonstationary working conditions. Meanwhile, it can be seen that the key step for these methodologies is the order tracking which can remove the effect of speed variations and convert the non-stationary signal in the time domain into a stationary one in the angular domain