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Time–frequency signal analysis for gearbox fault diagnosis using a generalized synchrosqueezing transform

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ABSTRACT

The vibration data, especially those collected during the system run-up and run-down periods, contain rich information for gearbox condition monitoring. Time–frequency (TF) signal analysis is an effective tool to detect gearbox faults under varying shaft speed. However, the feature of the amplitude modulated–frequency modulated (AM–FM) gearbox fault signal usually cannot be directly extracted from the blurred time–frequency representation (TFR) caused by the time-varying frequency and noisy multicomponent measurement. As such, we propose to use a generalized synchrosqueezing transform (GST)-based TF method to detect and diagnose gearbox faults. With this method, the original vibration signal is first mapped into another analytical signal to facilitate synchrosqueezing of the TF picture. A time-scale domain restoration process is then applied to recover the instantaneous frequency profile with concentrated TFR. The gearbox fault, if any, can then be detected by observing the presence of the meshing frequency and sideband components in the TFR. The faulty gear can be identified via frequency relation analysis of AM–FM components. The proposed method is evaluated using both simulated and experimental gearbox vibration signals. The results show that the proposed approach is effective for gearbox condition monitoring.

1. Introduction

The vibration signals during the run-up and run-down periods of a gearbox contain a wealth of condition information. Some fault features that are insignificant during stationary operations may be highlighted in the transient process of the gearbox [1]. The meshing frequency and its harmonic components are modulated by the shaft rotational frequency and its harmonics for a faulty gearbox [2]. This amplitude modulated–frequency modulated (AM–FM) vibration signal is often composed of meshing frequency and sideband components, and thus the gearbox fault may be identified via detecting the presence of the sidebands [3]. However, both the modulation and carrier frequencies vary during the transient process of the gearbox. This leads to blurred sideband components on the spectra of the vibration measurement that is difficult to be recognized.

Time–frequency (TF) signal analysis is a powerful tool in detecting the gearbox fault under variable speed [4]. One of the key aspects of the TF signal analysis is the TF representation (TFR), which provides insight into the complex structure

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of a signal with varying frequency and multiple components. Although there exist several TFR approaches, most of them fall into either signal decomposition or energy distribution category.

The wavelet transform (WT) and Hilbert–Huang transform (HHT) are two popular decomposition-based TF methods [5,6]. The WT, although having solid mathematical foundation and many successful applications, cannot achieve high resolutions in time and frequency domains simultaneously [7]. On the other hand, the HHT can adaptively decompose a multicomponent signal into intrinsic mode functions (IMFs), whose instantaneous frequencies (IFs) have some implications in signal analysis. However, the HHT algorithm contains several steps that are heuristic in nature and lack solid mathematical foundation. The energy distribution-based TFRs usually lead to higher time and frequency resolutions [8]. Wigner–Ville distribution (WVD) is one of the most widely adopted methods to project the signal onto the TF plane by distributing the energy of the signal over the two description variables: time and frequency. However, the TFR of a multicomponent signal resulting from the WVD method is often complicated by the interference terms between the TFRs of individual components. Though some improved versions of WVD can partially avoid this problem, this is achieved at the expense of reduced TF resolution and high computational complexity.

A critical issue of these TFR methods is their readability, which means both the improved concentration and eliminated misleading interference terms. Efforts have been made in this direction by some researchers [9–11]. For example, Auger and Flandrin [12] developed an assignment method to postprocess TFRs. The assignment of the TFR transfers the value computed at any point (t, f) to the center (t', f') of gravity of the signal energy distribution. According to its principle, the reassignment can be regarded as a bi-axial (both time and frequency axes) enhancement method. As the operation is only applied to the TFR rather than the signal itself, the deformation for a curved IF profile often occurs during the reassignment. Daubechies et al. [13] proposed a wavelet-based TFR enhancement method, which was called synchrosqueezing. The synchrosqueezing is a special case of the reassignment method that concentrates the TFR in the scale dimension. Compared to other TFR enhancement methods, the synchrosqueezing offers better adaptability, less deformation for IF profile and an exact reconstruction formula for constituent components [14]. As pointed out by Daubechies and Maes [15], however, this transform is limited to processing scale variable of the continuous wavelet transform (CWT). However, in addition to scale, time offset is also an important variable to consider [16] as the time dimension diffusion also leads to blurred signal even if “perfect” enhancement can be achieved in the scale dimension.

Considering the time-varying, multicomponent AM–FM nature of many gear vibration signals, a generalized synchrosqueezing transform (GST) is applied to enhance their TFR. Instead of a direct bi-dimensional squeezing transform that often results in a deformed IF profile and excessive computational burden, the proposed GST produces much more condensed TFR by mapping and restoring the IF profile of the signal. The GST is no longer a simple postprocessing approach like the aforementioned TF enhancement methods. The joint application of signal transform (IF profile mapping) and the TF enhancement by the GST leads to a much more vivid TFR for the noisy, multicomponent AM–FM signal of the gearbox with less computational effort. The enhanced TFR is subsequently employed to detect sideband(s); hence gear fault. Both the simulated and experimental vibration signals of the gearbox with time-varying speed are analyzed using the proposed method. The results indicate that the proposed method is effective in detecting gear faults.

The rest of the paper is structured as follows. The GST for wavelet TFR is introduced in detail in Section 2. The comparisons with other TFR tools are also made in this section. Section 3 presents the gearbox fault diagnosis steps based on the GST. The simulation test of the method is reported in Section 4 to evaluate the proposed approach. In Section 5, the performance of the GST-based method is further examined using our experimental data. Finally, the conclusions are drawn in Section 6.

2. Generalized synchrosqueezing transform of wavelet TFR

A novel GST approach is illustrated in detail in this section to enhance the wavelet TFR of a signal. With this method, the original signal is first mapped in time domain to an analytical signal with a constant frequency to eliminate the time dimensional blur of the TFR. The time-scale representation of this mapped signal is subsequently produced by CWT. This is followed by the IF profile restoration and synchrosqueezing in the time-scale domain. The proposed GST yields a much more concentrated TFR, which replaces the time dimensional squeezing with the signal mapping. This not only creates less deformation of the IF profile, but eases the computational burden as well.

2.1. Signal mapping towards IF transform

An arbitrary mono-component real signal $s(t)$ can be expressed as

$$s(t) = A(t)\cos(\varphi(t)) \tag{1}$$

where $A(t) \geq 0$ is the instantaneous amplitude and $\varphi(t) \in [0,2\pi)$ is the instantaneous phase.

The analytical form $\tilde{s}(t)$ of the original signal $s(t)$ is given by

$$\tilde{s}(t) = s(t) + i\mathcal{H}(s(t)) = A_s(t)\exp(i\varphi_s(t)) \tag{2}$$