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Generalized demodulation with tunable E-Factor for rolling bearing diagnosis under time-varying rotational speed

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ABSTRACT

Generalized demodulation (GD) is one of the most effective approaches to demodulating the time-varying frequency component. However, it is sensitive to the initial frequency value. Theoretically, the slower the rotational speed is, the lower frequency estimation precision based on the time-frequency representation (TFR) will be. Therefore, for the vibration signal whose phase function is estimated by the instantaneous frequency extracted from the TFR under lower initial speed, the demodulation error is significant. As such, the concept of energy factor (E-Factor) is defined. E-Factor represents the frequency coordinate value of the target instantaneous frequency on the demodulated time-frequency plane, i.e., the energy of the instantaneous frequency can be converted to a changeable parameter E-Factor, rather than the fixed initial value. Based on it, we propose the generalized demodulation with tunable E-Factor (GDTEF), which can map the trajectory of time-varying frequency to a line parallel to time axis with the frequency coordinate E-Factor in the time-frequency domain, and further exploit its merit to bearing fault detection. First, extract the instantaneous fault characteristic frequency (IFCF) from the TFR of the envelope obtained by the joint application of Hilbert transform and short-time Fourier transform (STFT). Second, configure E-Factor adaptively according to the IFCF fitting function, and then reconstruct the original signal according to the E-Factor. Then, finalize the phase function of the reconstructed signal based on the fitting function. Finally, identify the fault pattern via the demodulation spectrum. It is validated that the novel method can enhance the demodulation precision by processing the simulated and measured signals. What's more, the proposed method possesses stronger noise immunity in processing the time-varying frequency vibration signal.

1. Introduction

Rolling element bearings are widely used in the drivetrain of rotating machinery due to its compact structure, high capacity and low friction coefficient. However, they are prone to damage because of the harsh operating conditions such as overload and variable speed [1,2]. If there is a local fault on rolling element bearing, the collision between the fault and its contacting surface will generate a series of shocks. These shocks not only stimulate the high frequency resonance of the mechanical components, but also modulate the amplitude of the signal in time domain [3]. Therefore, the bearing vibration

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Abbreviations

AM	Amplitude-modulated
ANN	Artificial neural network
COT	Computational order tracking
DRT	Demodulated resonance technique
E-Factor	Energy factor
FCC	Fault characteristic coefficient
FCF	Fault characteristic frequency
FM	Frequency-modulated
ICA	Independent component analysis
IFCF	Instantaneous fault characteristic frequency
GD	Generalized demodulation
GDTEF	Generalized demodulation with tunable E-Factor
NFFT	Number of frequency points used to calculate the discrete Fourier transforms
Noverlap	Number of samples each segment of the signal overlaps
OT	Order tracking
PSD	Power spectral density
RF	Rotational frequency
RFS	Rotating frequency sideband
SNR	Signal-to-noise ratio
STFT	Short-time Fourier transform
TFR	Time-frequency representation

signal can be regarded as amplitude-modulated (AM) signal whose amplitude is modulated by fault characteristic frequency (FCF) with the natural frequency as carrier frequency. Demodulated resonance technique (DRT) [4,5] can identify the fault pattern by demodulating the amplitude of the AM signals, but a steady shaft rotational speed has to be required in the application [6]. However, in practical engineering, the speed may vary over time (e.g., in starting/stopping process and load fluctuation), which results in aperiodic vibration signals. What's more, when the shaft speed fluctuates, the modulation characteristic is more obvious. Correspondingly, the signal contains much more abundant fault information. Therefore, the research on extracting the fault characteristics from vibration signals under time-varying speed is of great significance.

Recently, many researchers have focused on the mechanical fault detection under time-varying rotational speed. Order tracking (OT) [7,8], in which extra auxiliary equipment for determining the phase discriminator may be involved, is one of the most effective methods to remove the spectrum smearing induced by speed fluctuation. Although the computational order tracking (COT) [9–11] is free from the dependence on auxiliary equipment, the computational accuracy cannot be guaranteed [12]. In fact, the process of transforming the raw signal into angular domain signal entails the computational efficiency trouble. Besides the angular domain analysis, many different domains such as kurtosis, power spectral density (PSD), entropy of information and independent component analysis (ICA) are also employed to obtain the bearing fault information [13–15]. However, the application of these domain signals is usually dependent on the combination with intelligent detection methods (e.g., fuzzy clustering, expert system, artificial neural network (ANN)) [16,17]. These intelligent methods are complicated because of the requirements of a great deal of prior data containing the permutations and combinations of defect position, size and the operation conditions such as speed and load.

The generalized demodulation (GD) time-frequency analysis algorithm [18] can convert the instantaneous frequency whose time-frequency distribution is slant and nonlinear into the frequency trend parallel to time axis. Since it is very suitable for dealing with the non-stationary AM and frequency-modulated (FM) signals, it has already been applied to mechanical fault detection [19,20], especially to the gearbox defect identification. In these applications, the energy of the instantaneous frequency component to be analyzed is demodulated to the initial value and thereby the demodulation accuracy is very sensitive to the initial frequency. Therefore, if the phase function of the time-varying frequency is calculated by the estimated instantaneous frequency, high fitting precision in the initial frequency region must be required to ensure the demodulation accuracy.

The frequency estimation algorithm based on time-frequency representation (TFR) is the most commonly used approach to extracting instantaneous frequency trend [10]. The time-frequency analysis methods, such as short-time Fourier transform (STFT) and wavelet analysis, are essentially subject to the constraint of Heisenberg uncertainty principle [21,22]. Although the resolution of Wigner-Ville distribution [23] is higher, it is limited by the cross-term interference which affects the identification of demodulation signal. Researchers have made great contributions to enhancing the time-frequency resolution [24–26]. For instance, Feng [27] improved the time-frequency resolution by the application of iterative generalized