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Non-stationary vibration feature extraction method based on sparse decomposition and order tracking for gearbox fault diagnosis

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ABSTRACT

Vibration signals of gearboxes working under time-varying conditions are non-stationary, which causes difficulties to the fault diagnosis. Based on the techniques of signal sparse decomposition and order tracking, a novel method is proposed to extract fault features from non-stationary vibration signals of gearboxes. The method contains two key procedures, the quasi-steady component separation in angle domain and the impact resonance component extraction in time domain. The sparse dictionary including quasi-steady sub-dictionary and impact sub-dictionary is specifically designed according to the time-frequency characteristics of steady-type fault and impact-type fault. The former sub-dictionary consists of cosine functions and is based on the order spectrum information of angle domain signal. The latter sub-dictionary consists of the unit impulse response of multiple-degree-of-freedom vibration system whose modal parameters are self-adaptively recognized by the method of correlation filtering. An improved matching pursuit algorithm on segmental signal is designed to solve sparse coefficients and reconstruct steady-type fault components and impact-type fault components. The simulation analyses show that the proposed method is capable to process the signal with 30% speed fluctuation and −1.5 dB signal-to-noise ratio (*SNR*), in which the *SNR* of impact-type fault components is as low as −14.6 dB. The effectiveness is further verified by experimental tests on a fixed-shaft gearbox and a planetary gearbox.

1. Introduction

Since the vibration signal of gearbox contains abundant dynamic information, vibration analysis is particularly applicable to monitor the operation condition and diagnose faults [1,2]. The vibration signal will have distinct characteristics when the gearbox works in a healthy state or suffers different kinds of faults [3]. Since the gearbox often works in variable speed condition due to some external factors, such as load fluctuation [4], acceleration and deceleration [5], the response signal becomes non-stationary, which is greatly different from that of gearbox working in stationary condition. Many feature frequencies are time-varying with the operation speed, making many difficulties to the feature extraction and fault diagnosis of the gearbox.

The order tracking analysis is a powerful method for the non-stationary signal processing. The sampling points in each rotation period are identical, which makes the order spectrum free from the time-varying rotation speed. In recent years, the most commonly used method is computed order tracking based on the interpolation theory [6–8]. In Ref. [6], a generalized phase demodulation based order tracking methodology was presented for bearing and gear diagnostics in relatively large speed variations. In Ref. [7], aiming at gearbox failure detections, such as gear crack and tooth broken, a diagnosis approach combined order tracking technique with local mean decomposition was presented for various shaft speed conditions. In Ref. [8], a novel order tracking method based on discrete spectrum correction technique was proposed to analyze the non-stationary vibration of the wind turbine gearbox for health monitoring and fault diagnosis. In Ref. [9], for order tracking analysis of gearbox's non-stationary vibration signal, a dual path optimization ridge estimation method was proposed to extract the instantaneous frequency from a weak vibration signal. In Ref. [10], an exponential window was applied to the cepstrum to separate the non-stationary response signal into components dominated by the forcing function and those dominated or carried by resonant responses. The latter components were processed by order tracking to diagnose gearboxes under variable speed conditions. In Ref. [11], a specific spectral analysis method was proposed to express the order-frequency spectral correlation of cyclo-non-stationary signals, which was jointly in the time domain and the angular domain. And the cyclo-nonstationary signals require a spectral correlation diagram with temporal frequency on the "carrier" axis and modulation signal features on the order axis.

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Sparse decomposition can decompose a signal into the linear combination of atoms in a redundant dictionary [12]. Since the decomposition is not very strict in orthogonality of atoms, the analyzed signal can be sparsely represented by different types of atoms. Owing to its superiority in signal processing, the sparse decomposition has been utilized to extract fault features from multi-component signal of rotating machinery in recent years [13–17]. In Ref. [13], the gearbox signal was separated into the high and low resonance components by the resonance-based signal sparse decomposition (RSSD). And a comb filter was used to extract the weak fault features, whose fundamental frequency is obtained from the envelope demodulation spectrum of resonance components. In Ref. [14], the high-oscillatory signal related to gear mesh component and low-oscillatory signal represented impact fault feature were reconstructed by the split augmented Lagrangian shrinkage algorithm (SALSA) based on the tunable Q-factor wavelet dictionary. In Ref. [15], the matching pursuit algorithm was applied to extract gearbox's vibration fault features, whose atoms were constructed based on the characteristic waveform of the analyzed signal. In Ref. [16], the transient feature of gearbox fault was extracted by the sparse representation of wavelet bases. It was found that the type of wavelet basis directly affects the matching precision of reconstructed signal. In Ref. [17], a novel method based on matching pursuit and correlation filtering was proposed for separating the coupling modulation vibration signal of gearbox. The steady modulation sub-dictionary and impact modulation sub-dictionary, which respectively consist of cosine basis and impulse response function basis, have definite physical meaning and good adaptability.

So far, diagnostic methods based on the signal sparse decomposition are primarily applied to extract fault features of stationary rotation speed condition. However, they are not suitable for the operation condition with a time-varying rotation speed. In this study, combining the superiority of order tracking analysis on non-stationary signal processing, a novel method for sparsely decomposing gearbox's non-stationary vibration signal is developed on the basis of the proposed method in Ref. [17]. The method successively performs the quasi-steady component separation in angle domain and the impact component extraction in time domain. Two sub-dictionaries are specifically designed according to the wave characteristics of non-stationary fault signal. Before the procedure of quasi-steady component separation, the original signal is firstly resampled to the angle domain, and a segmented matching pursuit algorithm is designed to solve sparse coefficients and reconstruct the quasi-steady component. Before extracting the impact fault component, the residual signal is resampled to the time domain again, and the correlation filtering method is applied to recognize the inherent parameters for constructing impact dictionary. Finally, the residual signal is sparsely decomposed by a segmented matching pursuit method and then the impact fault feature is reconstructed. Both the simulation analysis and experimental tests are applied to verify the effectiveness of the proposed method.

2. Vibration signal characteristic and order tracking analysis of gearbox

2.1. Vibration signal characteristic of gearbox

The vibration response of a healthy gearbox contains the mesh frequency f_z and its harmonics, as shown in Fig. 1. It can be described as the following $x_1(t)$.

$$x_1(t) = \sum_{m=1}^{M} A_m \cos(2\pi m f_z t + \theta_m) \tag{1}$$

where f_z is the mesh frequency, A_m and θ_m are the amplitude and phase of the m^{th} harmonic of gear mesh frequency, respectively.

When a steady-type fault such as tooth profile error, run-out error and axial misalignment happens on the gearbox, the vibration spectrum mostly contains two parts: (a) the rotation frequency f_n and its harmonics corresponded to the faulty shaft or gear, (b) modulation sidebands with the harmonics of mesh frequency as carrier frequencies and f_n as the modulation frequency [3]. The spectrum characteristic is shown in Fig. 2, and the signal model can be described as the following $x_2(t)$.

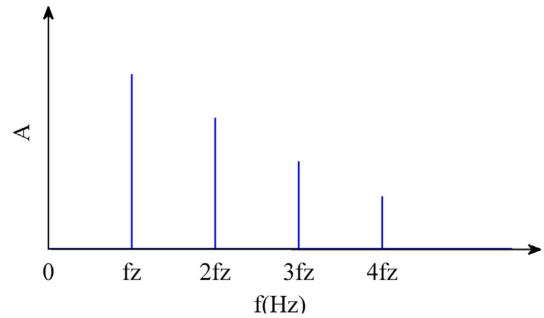

Fig. 1. The vibration spectrum characteristic of a healthy gearbox.

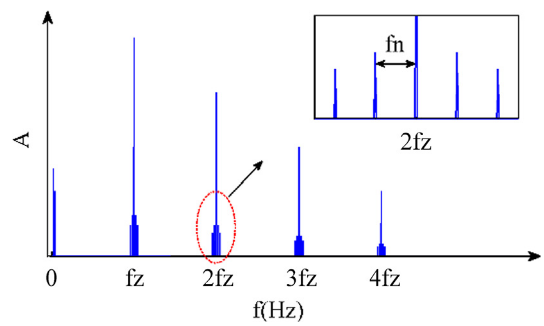

Fig. 2. The vibration spectrum characteristic of gearbox with a steady-type fault.

$$x_2(t) = \sum_{k=1}^{K} B_k \cos(2\pi k f_n t + \beta_k) \sum_{i=0}^{I} A_i \cos(2\pi i f_z t + \alpha_i) \tag{2}$$

where f_n is the rotation frequency of the faulty shaft or gear; B_k and β_k are the amplitude and phase of the kth harmonic of the rotation frequency, respectively; A_i and α_i respectively correspond to the amplitude and phase of the ith harmonic of the mesh frequency; moreover, f_z equals zf_n, where z is the number of teeth on the faulty gear.

If there exists an impact-type fault such as pitting and broken tooth in the gearbox, the vibration response caused by the impulsive force sequence can be modeled as a periodic sequence of the impulse response function as shown in Fig. 3(a). The impulsive response waveform depends on gearbox's modal parameters. The vibration spectrum is characterized by impact modulation sidebands as shown in Fig. 3(b). The carrier frequencies are the natural frequencies evoked by the impulse forces and the modulation frequency equals the reciprocal of impulse response period related to the rotation frequency of the faulty gear. This signal model can be described as the following $h(t)$.

$$h(t) = \sum_{i=1}^{I} \sum_{j=1}^{J} A_{ij} \exp\left[\frac{-2\pi\zeta_j}{\sqrt{1-\zeta_j^2}} f_{dj}(t-\tau-iT)\right] \sin[2\pi f_{dj}(t-\tau-iT)],\ t \geqslant \tau_i \tag{3}$$

where f_{dj} and ζ_j are respectively the jth natural frequency and damping ratio; A_{ij} is the amplitude of the ith impulse response under the jth natural frequency; T is the impulse period and τ corresponds to the happens.