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Envelope synchronous average scheme for multi-axis gear faults detection

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ABSTRACT

An envelope synchronous average scheme for multi-axis gear faults detection is proposed in this paper. In the proposed approach, the vibration from a gearbox is picked up at first. Then, the complex envelope of the vibration is extracted by the fast kurtogram algorithm, which can determine an optimal resonant zone for amplitude demodulation. Subsequently, the envelope is re-sampled by the equal-angular increment sampling scheme to eliminate the possible frequency blur phenomena caused by the speed fluctuation. Moreover, a multi-axis synchronous average strategy is employed to remove the random components in the envelope. Finally, the vibration features of gear faults can be clearly exposed by the envelope order spectra. Compared with the conventional synchronous averaging scheme or the envelope analysis approach, the proposed method is robust for the incipient local fault detection of gears. Experiments are conducted to verify the validity of the proposed method.

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1. Introduction

Localized gear faults are important sources of noise and vibration in a rotating machinery. They often lead to poor quality products and even catastrophic accidents. The vibration monitoring of gear faults has been studied and widely employed for decades [1]. However, vibrations from gear faults take some unique features such as non-stationary, modulation and complex transmission path, but do not fit for the direct spectrum analysis in general. With this regards, some techniques have been developed specially for the gear faults monitoring and diagnosis. The synchronous averaging (SA) [2,3] and the narrowband demodulation (include amplitude and phase demodulations of meshing frequency) analysis [4,5] are two kinds of popular vibration approaches in the feature extraction and diagnosis of localized gear faults.

As well known, the vibration generated by localized gear faults of the cracked or broken gear teeth has a periodic impulsive feature [6], which is distinguished with the random vibration feature from the rolling element bearing (REB) [7] and other background noises in a rotating machinery. The SA is generally utilized to reduce the random disturbances and the amplitudes of some periodic components, whose periods may not integer times of the period of the specified rotating shaft used for the SA [3,7] in the picked raw vibrations. By this way, the periodic components generated by localized gear

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faults become prominent in the vibration after the SA.¹ On the other hand, the resonance demodulation analysis or high-frequency resonant analysis is generally employed for the REB incipient fault detection, and can also be employed to expose the periodic impulsive feature generated by localized gear faults [6]. However, the popular Time Synchronous Averaging (TSA) is a preconditioning step before the resonance demodulation, it makes the conventional resonance demodulation analysis not applicable for the detection of the localized gear faults in varying-speed conditions of the gearbox in principles. It should be noted that the conventional narrowband demodulation analysis for the detection of the localized gear faults is different from the resonance demodulation analysis. In a word, the carrier of the former is a meshing frequency or its harmonics, but that of the latter is a resonant frequency. Although the narrowband demodulation of the meshing frequency has been widely used for more than 30 years, the resonance demodulation analysis has its unique advantage on revealing the characteristic frequencies of faults. The strong low-frequency interferences can be isolated by a band-pass filtering scheme, and the weak impulsive vibration generated by incipient faults can be enhanced in the resonant zone at the same time. Based on above viewpoints, an envelope SA approach is proposed in this paper by combining the SA approach and the resonance demodulation analysis for the detection of gear faults. The advantages of the combination of the SA and the resonance demodulation analysis are listed as follows. Firstly, it can be utilized for the early fault detection of gears due to the amplitude amplification in a resonant zone. Secondly, the SA is employed for removing the disturbances in the extracted complex envelopes, which makes interesting components more prominent. Thirdly, the gear faults of a multi-axis gear transmission system can be exposed clearly by performing the envelope SA to different shafts one by one. Finally, simulation and test results showed that the proposed method is effective for the incipient local faults detection of gears.

The paper is arranged as follows. The briefs on the SA and the resonance demodulation analysis will be introduced in Section 2. Subsequently, the proposed approach will be presented in Section 3. Simulations and experiments will be shown in Section 4, and conclusions will be drawn in Section 5.

2. Briefs on the SA and the resonance demodulation analysis

The SA and the resonance demodulation analysis are two popular signal processing techniques for the feature extraction and faults identification. In this section, the briefs on the SA and the resonance analysis will be introduced as follows, respectively.

2.1. Synchronous averaging

The originally proposed and widely employed SA technique is the TSA [2,3]. In the TSA, a trigger or synchronizing reference signal phase-locked with the angular position of the specified rotating shaft is utilized to divide the original data series into a number of data blocks with the same length at first. Then, the data with the same index in the divided data blocks are averaged one by one to realize the waveform averaging with an integer multiple of the period of the synchronizing reference signal, which is given as in [7] by

$$x_a(n) = \frac{1}{M} \sum_{m=0}^{M-1} x(n+mL), \quad (n = 0, 1, 2, \dots, L-1), \quad (1)$$

where x and x_a represent the original and averaged data series, respectively, n indicates the index of the data series, M is the total number of the data blocks, L denotes the number of points of each data block. It is worth pointing that the key of a successful averaging by Eq. (1) is that L should be an integer multiple of the period of the synchronising signal, which is determined by the trigger, and it should also be a constant to ensure that each data block has the same length for averaging. But L cannot meet these two conditions at the same time when the shaft speed fluctuates.

In real-word applications, the speed fluctuation is inevitable since the load of an operating machinery cannot always keep a constant. If the rotating speed is not a constant when the SA is done, the period of the synchronising signal will be shifted. In this case, it will lead to the inaccurate result. Reference [6] pointed out that even a little speed fluctuation (for example, 0.1%) will cause a notable information loss after averaging. To address this issue, the SA in the angular domain has been developed [7,8] by combining the TSA with the equal-angular increment sampling scheme in the computed order tracking (COT) [9], where the data series are re-sampled and interpolated with a constant angle increment θ about a reference shaft. The SA in the angular domain is also called Rotation Domain Averaging (RDA) in [8]. The corresponding algorithm is very similar to Eq. (1) except the data involved in the angular domain. The RDA can be given by

$$y_a(\theta_i) = \frac{1}{M} \sum_{m=0}^{M-1} y(\theta_i + m\theta_L), \quad (i = 0, 1, 2, \dots, L-1), \quad (2)$$

where y represents the equal-angle increment re-sampled data series in the angular domain, which is obtained by re-sampling the time domain data series x in Eq. (1) with a constant angle increment about the reference shaft (it ensures that

¹ In theory, the SA can be explained as a comb filter selecting the harmonics of the specified periodic frequency. See [7] for the details. In this study, the specified periodic frequency for the SA is the rotating frequency of the gear shaft.

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