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Practice article

Measurement of Instantaneous Angular Displacement Fluctuation and its applications on gearbox fault detection

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ABSTRACT

Recently, Instantaneous Angular Speed (IAS) measurement is successfully established and prevalently applied to a wide variety of machines due to the hypothesis that the speed fluctuation of rotating machinery carries plentiful dynamic responses. Nevertheless, exploration and application based on angular signal are still insufficient. Under the same hypothesis, in this paper, we introduced an extended algorithm named Instantaneous Angular Phase Demodulation (IAPD), together with the selection of optimal sideband family to extract the Instantaneous Angular Displacement Fluctuation (IADF) signal. In order to evaluate the performance of IADF signal, an effective approach was demonstrated using IADF signal to address the fault detection and diagnosis issue. After extracting the IADF signal, a much effective method was developed to deal with the large amount of data generated during the signal collection process. Then, we used the well-developed techniques, i.e., empirical mode decomposition (EMD) and envelope analysis, to undertake the signal de-noising and feature extraction task. The effectiveness and capability of the IADF signal were evaluated by two kinds of gearboxes under differentconditions in practice. In particular, the prevalent IAS signal and vibration signal were also involved and testified by the proposed procedure. Experimental results demonstrated that by means of the IADF signal, the combination of EMD and envelope analysis not only provided accurate identification results with a higher signal-to-noise ratio, but was also capable of revealing the fault characteristics significantly and effectively. In contrast, although the IAS signal had the potential ability to diagnose the serious fault, it failed for the slight crack case. Moreover, the same procedure even its improvements, i.e., ensemble empirical mode decomposition and local mean decomposition, all failed to recognize the faults in terms of vibration signals.

1. Introduction

As a crucial component for power and motion transmission, gears are widely employed in industry. Meanwhile, faults occurring in gears may lead to fatal breakdowns in rotating machinery and such failure can result in unwanted downtime, severe accidents and significant economic losses [1]. It is therefore imperative to monitor gear's working conditions in a reliable and timely manner to prevent the malfunctions of the machines.

Nowadays, traditional fault detection and condition monitoring processes in the gearbox are based primarily on wear particle/debris, lubricant monitoring and vibration analysis, each of which has its unique advantages associated with the monitoring and fault diagnosis of machinery [2]. However, all of these three technologies still suffer from inherent limitations respectively [1]. For example, it is usually difficult to determine whether the changes in common capacitive sensors are caused by debris or acid, water, etc., since the effectiveness of wear debris depends not only on the total volume of particles, but also their size, shape, and chemistry information [2,3]. As for the lubricant method (namely oil analysis), sometimes, when it is difficult to obtain oil or grease samples from the rotational equipment, faults such as foreign particle contamination or incorrect viscosity can be mistakenly identified. On the other hand, although vibration analysis could offer unique information about anomalies within the machine's internal structure, extraction of fault features from gear system is still an enormous challenge as gearboxes are operated within harsh environments, which makes vibration signals rather complex [4–7]. Thus, with the increasing complexity of equipment requirements, vibration-based analysis faces an unprecedented challenge in the mechanical systems for

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condition monitoring and fault diagnosis.

Specifically, the main goal of technological improvement in fault diagnosis is to achieve more detailed and valuable information from the measured data. As for fault diagnosis of rotating machinery like gears, its critical task is to detect fault characteristics timely and make optimal maintenance decision effectively. For the sake of identifying different gear faults, industrial demand has increased the requirements to develop new analytical techniques or explore effective signal sources with much higher SNR. Considerable investigations represent that extraction of impulsive periodic features in noisy gear signals is vitally important for gear fault diagnosis [8–11]. Unfortunately, vibration signals are usually picked up by an accelerometer mounted on the gearbox case near the main bearing on the test gear. They are usually non-linear and non-stationary and the signal-to-noise ratio (SNR) is so low that feature extraction of signal components is very difficult [10,11]. Focus on this issue, fault diagnosis based on new methodologies has been frequently developed by exploring time domain, frequency domain and time-frequency domain analysis. Because of the non-linear and non-stationary properties of signals, time-frequency analysis such as wavelet transform [9,12], empirical mode decomposition (EMD) [13,14], local mean decomposition (LMD) [15], generalized synchrosqueezing transform [8], has been prevalent in studies and extensively adopted for gear fault diagnosis. However, research based on these technologies has different drawbacks and is sensitive to different types of damage modes or operational conditions. Furthermore, the calibration steps using time-frequency analysis sometimes suffer from time-consuming issue [16].

In search of a different signal source with a high SNR, recently, the Instantaneous Angular Speed (IAS) arising from angular domain has attracted considerable attention from the research community due to its specific advantages over vibration analysis [17–19]. The main benefits of IAS measurement are briefly listed in Refs. [20,21]: non-invading; less noise contamination; directly related to machine dynamics; low price and high precision; easy to install; no periodic calibration; clear data presentation and so on. Based on these benefits, different IAS-based technologies have been developed in some specific machines such as in: rotors [18], diesel engines [21,22], bearings [23], induction motors [18,24], gearboxes [17,25] for condition monitoring, control and fault diagnosis.

The main idea of using IAS signal as a fault detection tool is that any fault in a rotating machine directly affects the angular speed. In addition, speed fluctuation, has been regarded as a useful and potential parameter for fault diagnosis since it contains a large amount of information on fault components to reflect health and usage status of the rotating machinery [24,25]. Despite that, the investigation remains monotonous for extracting signals from angular domain; the accuracy of prevalent IAS is also affected by several inevitable factors like: interpolation algorithms, encoder resolution, high sampling frequency, frequency aliasing, quantization effect and poor estimation methods [26,27]. Moreover, noise contamination further smears the amplitude of critical frequencies simultaneously [28]. Therefore, signal source exploration becomes somewhat of a determinant factor in accurately obtaining the gear's current operational conditions.

This paper intends to fulfill this object by utilizing an algorithm named Instantaneous Angular Phase Demodulation (IAPD) to extract a new angular signal source, i.e., Instantaneous Angular Displacement Fluctuation (IADF) signal, which has been proved to be very precise and useful for the gearbox's fault detection and diagnosis with high accuracy and strong robustness.

The main structure of the paper is briefly organized as follows. Section 2 provides the relevant principles of the proposed method and the optimal frequency-band selection for the narrow-band filtering. Subsequently, some relevant signal processing techniques such as signal reconstruction and empirical mode decomposition are briefly described in Section 3. The implementation and verification of the proposed technique based on encoder signals on two separate rigs are established in the next section. In Section 5, some important results are achieved in which the excellent capabilities and merits of the IADF signal are also demonstrated by further comparing with the IAS signal and vibration signal. Finally in Section 6, some summaries and conclusions of this paper are introduced.

2. Introduction on Instantaneous Angular Phase Demodulation

In this section, based on the encoder signal, the IAPD procedure is particularly introduced and the parameter determination of the narrow-band filtering is further investigated.

2.1. Principle of the Instantaneous Angular Phase Demodulation

Theoretically, gear with a localized defect will generate a series of periodical perturbations as the gear shaft continuously rotates. Every time when a gear tooth passes through the disturbance, an instantaneous speed fluctuation generates, which intuitively enables the rotary speed to contain dynamic responses of faulty components. During the steady rotary speed, these fluctuations are generated periodically and usually related to the location of the defect. Furthermore, the speed fluctuation will undoubtedly result in the angular displacement variation even though the displacement variation usually changes much slowly. Therefore, it is fairly conclusive that the displacement variation can be treated as frequency modulation and supply useful information for condition monitoring and fault diagnosis as well.

2.2. Instantaneous Angular Phase Demodulation procedure

The flowchart of the proposed method is illustrated in Fig. 1. When a square signal is treated using the IAPD method, the following steps will be concerned. Firstly, in order to improve the accuracy of phase demodulation calculation and reduce computational complexity, the original square signal is normalized to remove the influence from amplitude variation since the IADF signal only relates to the frequency variation or frequency modulation directly. After removing the mean value, Fast Fourier Transform (FFT) is applied to analyze the normalized square waveform. Theoretically, as a symmetrical square wave with a duty cycle of 50% and a cycle frequency of X Hz, only dominant frequency lines at $f =$ X, 3X, 5X, etc. can be noticed in the spectrum [29]. Take a square $y(t)$ with a cycle frequency of f and amplitude of A as an example.

$$y(t) = \begin{cases} A & 0 < t \le \dfrac{1}{2f} \\ -A & \dfrac{1}{2f} < t \le \dfrac{1}{f} \end{cases} \tag{1}$$

The Fourier expansion of the ideal square signal $y(t)$, can be denoted as

$$\begin{aligned} y(t) &= \frac{4A}{\pi}\sum_{k=1}^{\infty}\frac{\sin(2\pi(2k-1)ft)}{2k-1} \\ &= \frac{4A}{\pi}\left(\sin(2\pi ft) + \frac{1}{3}\sin(2\pi\cdot 3ft) + \frac{1}{5}\sin(2\pi\cdot 5ft) + \cdots\right) \end{aligned} \tag{2}$$