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A new strategy of instantaneous angular speed extraction and its application to multistage gearbox fault diagnosis

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ABSTRACT

Owing to its unique benefits, Instantaneous Angular Speed (IAS) has become the focus of a great deal of research for monitoring mechanical parts of rotating machines in the past few years. However, the efficacy of IAS-based signal processing techniques essentially depends on the estimation method of IAS and the complexity of the mechanical system. When it is applied to complex systems like turbines, gearboxes, conventional IAS itself still has some flaws and insufficiencies such as longer data stream, quantization noise and structural noise. In order to address these issues, this paper proposes an alternative IAS estimation approach named Instantaneous Angular Phase Demodulation (IAPD) IAS together with an improved procedure involving signal reconstruction, empirical mode decomposition (EMD) and envelope analysis. Thereafter, two kinds of multistage gearboxes under different working conditions are developed to experimentally demonstrate the accuracy and effectiveness of the new IAS measurement. Analysis results suggest that the quantization noise can be significantly reduced or even avoided in the IAPD-IAS signal compared with the conventional IAS signal. Moreover, by means of the new procedure, the computational efficiency can be greatly improved and fault characteristics are dramatically enhanced in the envelope spectrum where deterministic frequency component and its harmonics corresponding to fault characteristics are displayed clearly.

1. Introduction

As a crucial component, gear's operational status has significant implications for the machining accuracy, efficiency and reliability, and hence faults occurring in gears may bring in severe accidents and significant economic losses. Currently, vibration analysis is the most commonly accepted strategy for machinery fault detection and diagnosis [1]. However, in practice, vibration analysis still has inherent limitations for diagnosis of the complex gear systems, in which vibration signals are easily contaminated by a large amount of interference such as the transmission channel, since sensors like accelerometers, mounted on the outer surface of the gearbox case cannot measure the actual operation information straightly [2,3]. Furthermore, apart from the unexpected noises, other internal vibration sources like bearings, rotors, may also introduce interference effect or even distort the entire vibration signals. As a consequence, the vibration signal is inevitably corrupted with a low signal-to-noise ratio, which makes it difficult to diagnose a gearbox from such vibration signal accurately [4].

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Instantaneous Angular Speed (IAS) with superior noise suppression performances has attracted significant attention in recent years. It is commonly considered as non-stationary with the characteristics of frequency modulation (FM) [5]. The idea behind using IAS signal is based on the hypothesis that any fault occurring in a rotating machine has an instantaneous impact on the angular speed of the output shaft where the IAS sensors like optical encoder, hall effect tooth wheels, are mounted or connected directly. Compared with vibration signals, IAS measurement offers several distinct benefits as follows [6,7]: non-invading; less noise contamination; directly related to machine dynamics; inexpensive sensor with high precision; easy to install; no periodic calibration is needed, etc. Owing to these unique advantages, so far, many advanced IAS-based techniques have been developed and applied to various rotary components such as: rotors, gears, diesel engines, bearings and induction motors [2,7–12]. For example, to effectively detect the tooth fault in multistage helical gearbox, researchers used the well-known FFT to the synchronously averaged IAS signal under different working conditions [13]. In order to diagnose gear faults in the rotational axis of a 4-axis milling and turning machining center, Zhou et al. [14] employed EEMD to decompose the IAS signal into intrinsic mode functions (IMFs) and applied power spectrum thereafter to the envelope of the determined IMF and obtained satisfactory analysis results. Li et al. [9] proposed a fusion method to fix the underdetermined blind source separation problem by combining empirical mode decomposition (EMD), kernel independent component analysis (KICA), Wigner bi-spectrum with support vector machine (SVM) on IAS signals for the multi-class fault recognitions of the marine diesel engine. In [15], Renaudin et al. tried to use the time duration of successive encoder gratings to substitute the instantaneous angular speed, and delivered IAS measurement to monitor the bearing conditions successfully. Recently, Li et al. [16] developed a new approach named auto-correlation local cepstrum to enhance the capacities of EMD and successfully applied it to IAS signals for the purpose of signal denoising and feature extraction for multistage gearbox.

Although IAS signal shows high potential for condition monitoring and fault diagnosis on rotating machinery, it is undeniable that the IAS signal is inevitably influenced by various noises, e.g., random load fluctuations, structural noises, shaft misalignment filtering and digitalization [5]. These noises can more or less deteriorate the IAS estimation accuracy and hence the fault diagnosis results. Therefore, to accurately obtain the hidden information from particular gear conditions, the fault detection requires proper signal processing techniques [13], while the efficacy of IAS-based signal processing techniques are potentially related to the proper estimation of IAS which becomes somewhat of a fundamental and decisive factor [14].

Despite remarkable success, most of the aforementioned studies still rely on the conventional IAS (the elapse time method [15,17]) and little research has been fundamentally devoted to raising the accuracy and efficiency of the IAS estimation. Accordingly, the accuracy and efficiency of prevalent IAS are usually weakened by several aspects, such as sensor irregularities, interpolation algorithms, resolution of the encoder, frequency aliasing, quantization effect and estimation method [18]. Due to the inherent limitations, quite few fault features can be extracted using the conventional IAS (C-IAS) when other sources of perturbation significantly smear the amplitude of critical frequencies especially for the complex mechanical system like gearbox [5]. Besides, in order to achieve the best effect of reducing the frequency aliasing, the usual approach uses an encoder with higher resolution [18,19], which unfortunately will increase the sample frequency and data length of the raw encoder recorder. Thus, a high-performance computer with advanced analytical capabilities has to be considered to deal with these data, which will greatly increase the research difficulty and measurement instrumentation cost.

Focus on these issues, this paper fulfills these insufficiencies by introducing a new IAS estimation approach named Instantaneous Angular Phase Demodulation (IAPD) IAS and an effective signal preprocessing method. In Section 2, the principle of C-IAS is briefly reviewed and IAPD-IAS that overcomes some of the limitations of the C-IAS is exhaustively described. And an improved procedure is subsequently introduced for the purpose of performance evaluation. The accuracy of the IAPD-IAS estimation and the effectiveness of the procedure are validated respectively by two different gearboxes under different working conditions in Section 3. Finally, some important summaries and conclusions of this research are carefully discussed in Section 4.

2. General framework of instantaneous angular speed

First of all, in this section, based on the encoder signal, the C-IAS is briefly reviewed and the new IAPD-IAS estimation method is proposed in detail. Finally an efficient procedure is described for the purpose of fault detection and diagnosis.

2.1. C-IAS measurement

According to the prior research [13], encoder signals have been utilized to improve the measurement performance based on two basic principles: counting the number of pulses in a given time duration and measuring the elapsed time for a single cycle of the encoder signal. In addition, the IAS signal measurement can be simply categorized into two groups: timer/counter methods and analog-to-digital converter (ADC)-based methods [15,17]. Although the latter generates a large amount of data at a low acquiring speed compared with the former, there is an elegant solution for the software upgrade of the measuring system originally on the basis of remarkable increase of speed and memory capacity of modern computers [17]. As a consequence, in the subsequent sections, this paper focuses on ADC-based methods to handle the fault detection and diagnosis issue. Theoretically, the ADC is similar to the elapsed time method (ET) in which the number of turning points represents the angular displacement and two successive turning points define a cycle [20]. Moreover, the constant elapsed time (CET) method can provide accurate measurement results for both high and low angular speeds by combining the