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New procedure for gear fault detection and diagnosis using instantaneous angular speed

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ABSTRACT

Besides the extreme complexity of gear dynamics, the fault diagnosis results in terms of vibration signal are sometimes easily misled and even distorted by the interference of transmission channel or other components like bearings, bars. Recently, the research field of Instantaneous Angular Speed (IAS) has attracted significant attentions due to its own advantages over conventional vibration analysis. On the basis of IAS signal's advantages, this paper presents a new feature extraction method by combining the Empirical Mode Decomposition (EMD) and Autocorrelation Local Cepstrum (ALC) for fault diagnosis of sophisticated multistage gearbox. Firstly, as a pre-processing step, signal reconstruction is employed to address the oversampled issue caused by the high resolution of the angular sensor and the test speed. Then the adaptive EMD is used to acquire a number of Intrinsic Mode Functions (IMFs). Nevertheless, not all the IMFs are needed for the further analysis since different IMFs have different sensitivities to fault. Hence, the cosine similarity metric is introduced to select the most sensitive IMF. Even though, the sensitive IMF is still insufficient for the gear fault diagnosis due to the weakness of the fault component related to the gear fault. Therefore, as the final step, ALC is used for the purpose of signal denoising and feature extraction. The effectiveness and robustness of the new approach has been validated experimentally on the basis of two gear test rigs with gears under different working conditions. Diagnosis results show that the new approach is capable of effectively handling the gear fault diagnosis i.e., the highlighted quefrency and its rahmonics corresponding to the rotary period and its multiple are displayed clearly in the cepstrum record of the proposed method.

1. Introduction

Vibration signals collected from the accelerometer usually carry a great deal of information to reflect machine health conditions. This makes vibration-based fault detection research much more prevalent during past few years. However, in practice, vibration-based signal analysis still has insurmountable limitations like structure noises and dominant component interferences for fault diagnosis of the complex gearbox systems. Specifically, vibration signals acquired from a multistage gearbox are easily susceptible to the interference of the transmission channel since the accelerometer is always mounted on the outer surface of the gearbox case near the main bearing housing [1,2]. Due to the factors mentioned above, useful information is inevitably corrupted, which makes it difficult to diagnose gearboxes from such vibration signals [3]. Thus, the

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signal source selection becomes somewhat of a challenge in obtaining particular gear conditions accurately.

Recently, the research field of Instantaneous Angular Speed (IAS) has attracted significant attention from the research community, which is attributable to its own advantages over conventional vibration analysis [1,4,5]. The idea behind using IAS signal as a fault detection tool is that any fault in the rotating machine has a direct impact on the angular speed of the rotary shaft. It usually contains a considerable amount of information on fault components reflecting health and usage status of rotating machinery [6]. Arising from these benefits, different advanced IAS-based techniques have been developed so far in some specific occasions such as in: rotors [4], diesel engines [7,8], bearings [9], induction motors [4,6] and so on. Even so, because of complexity and non-stationary, little literature has applied the IAS signal for gear fault diagnosis and hence it remains a poorly understood area. Besides, due to the high sample frequency in collecting the raw signal, a great deal of data can be generated, which will bring a heavy burden for further analysis and computation. On closer observation, it is noticeable that the peaks above a certain threshold are dramatically reduced, which means the IAS signal is oversampled using the original sample frequency.

Fortunately, many pragmatic identification approaches such as time–frequency representation, empirical mode decomposition (EMD), wavelet transform, spectral kurtosis have been successfully established to enhance the signal feature and simultaneously provide potent proofs for maintenance decision-making [10–14]. Among these diagnostic technologies, the EMD technique and ensemble empirical mode decomposition (EEMD) have been widely used to analyze vibration signals in the field of fault diagnosis, particularly for signals in non-stationary cases and signals with a larger size [11,15]. EEMD, developed by Wu and Huang [16], is able to eliminate the problem of mode mixing effectively by means of adding finite white noise to the raw signal, but it also increases the computing time since many tries and interactions have to be taken into account. In addition, both EMD and EEMD try to decompose a signal into different intrinsic mode functions (IMFs), or mono-component functions. Nevertheless, not all IMFs are sensitively and closely related to the faults. The selection of IMFs are usually relied on the user's experience by visual inspections. To figure out this issue, Ricci et al. [11] introduced the merit index to assist the IMF selection and Hilbert transform. Satisfactory results were achieved when the automatic IMF selection was used to deal with the vibration signals from spiral bevel gears. However, the specific parameter k used in that paper relied on the mechanical system and the default threshold should be also specified initially. In the literature [15], Lei et al. proposed another procedure to divide all the IMFs into two clusters, and both the simulation and experiment were engaged to demonstrate the effectiveness of the IMF selection. However, for this method, the normal signal must be considered.

In order to obtain the diagnosis information more sufficiently, recently two improved cepstrums have been developed successively [17,18]. Both Local Cepstrum (LC) analysis and its improved form Autocorrelation Local Cepstrum (ALC) focus on achieving the maximum utility of the local (partial) spectrum information. By searching for the optimal frequency band of interest, local cepstrum is capable of effectively addressing the crucial issue of interference reduction of aperiodic components [18]. However, the optimal frequency band selection is usually time consuming and quite difficult in the LC calculation. Meanwhile, the noise reduction performance of LC is also limited since it does not concern too much about the signal de-nosing issue. As a simple yet effective method, ALC has been successfully developed by combining LC with autocorrelation and successfully utilized to deal with the gearbox diagnosis using vibration signals [17]. On the consideration of IAS spectrum signatures, it is worth noting that both LC and ALC are very convenient and suitable for IAS signal processing with intensive frequency distributions and they are capable of emphasizing periodic fault components with the background noise and other components minimized.

After adequately considering the issues mentioned above, in this paper, different issues will be fixed using different methods. First of all, signal reconstruction is delivered as a pre-processing method to deal with the oversample obstruct. Then, a new feature extraction and fault diagnosis method in terms of EMD and ALC for the sophisticated multistage gearbox is established. Meanwhile, the cosine similarity measure [19,20] that is most widely reported for similarity measurement will be introduced for the sensitive IMF selection.

The main structure of this article is briefly organized as follows. Section 2 provides the principle and measurement of the conventional IAS. In Section 3, some relevant theories that support the proposed method, including signal reconstruction, EMD, ALC, are reported successively. Then study cases including two types of gearboxes are investigated in Section 4. Besides, the fusion method is applied to these two gearboxes under different health statuses and some results and discussions are established thereafter in this section. Finally, some important conclusions and future works of this article are carefully drawn.

2. Measuring principles of the instantaneous angular speed

In this section, the IAS measuring principles are mainly described. The reason why signals extraction based on speed fluctuations has the ability to deal with the fault diagnosis is primarily put forward. Then, the measuring model is briefly introduced.

2.1. Foundations of angular signal characteristic analysis

IAS signals acquired from some complex machineries such as a multistage gearbox, can be treated as a combination of