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Gear wear monitoring by modulation signal bispectrum based on motor current signal analysis

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ABSTRACT

Gears are important mechanical components for power transmissions. Tooth wear is one of the most common failure modes, which can present throughout a gear's lifetime. It is significant to accurately monitor gear wear progression in order to take timely predictive maintenances. Motor current signature analysis (MCSA) is an effective and non-intrusive approach which is able to monitor faults from both electrical and mechanical systems. However, little research has been reported in monitoring the gear wear and estimating its severity based on MCSA. This paper presents a novel gear wear monitoring method through a modulation signal bispectrum based motor current signal analysis (MSB-MCSA). For a steady gear transmission, it is inevitable to exist load and speed oscillations due to various errors including wears. These oscillations can induce small modulations in the current signals of the driving motor. MSB is particularly effective in characterising such small modulation signals. Based on these understandings, the monitoring process was implemented based on the current signals from a run-to-failure test of an industrial two stages helical gearbox under a moderate accelerated fatigue process. At the initial operation of the test, MSB analysis results showed that the peak values at the bifrequencies of gear rotations and the power supply can be effective monitoring features for identifying faulty gears and wear severity as they exhibit agreeable changes with gear loads. A monotonically increasing trend established by these features allows a clear indication of the gear wear progression. The dismantle inspection at 477 h of operation, made when one of the monitored features is about 123% higher than its baseline, has found that there are severe scuffing wear marks on a number of tooth surfaces on the driving gear, showing that the gear endures a gradual wear process during its long test operation. Therefore, it is affirmed that the MSB-MSCA approach proposed is reliable and accurate for monitoring gear wear deterioration.

1. Introduction

Gears are commonly used as a means of power transmission in many industrial applications. Gear wear is a progressive material loss from contacting tooth surfaces, which is an inevitable phenomenon in the service lifetime of gears. Apart from the direct material loss, surface wear also affect significantly time-varying meshing stiffness [1–5], dynamic transmission

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error [4–6], and load fluctuation [4,5,7,8]. As one of the major failure modes of gears, severe wear can lead to the occurrence of other types of gear failures such as surface pitting, scuffing and broken teeth [9]. Therefore, the subject of gear wear monitoring and diagnosis is receiving a lot of attention in the field of condition monitoring (CM).

For gear wear monitoring, the wear debris analysis is mostly used [9,10], and there is an endeavor for its replacement by more popular vibration monitoring techniques [10–12] and acoustics analysis [13]. The wear debris analysis is carried out off-line and time-consuming. Moreover, wear particles analysis cannot timely reveal changes in gear transmission dynamic features, which can be used to examine if gears still work properly. Vibration based methods have several drawbacks, such as significant signal background noise caused by external excitations, over-sensitive to resonance distortions, and invasive measurements. Similarly, the noise signature is also affected by the interfering sources, transmission paths and background noise [13]. The above mentioned methods also require accessibility to the gearbox, either to collect samples or to mount the transducers on or near the gearbox.

To avoid these shortages of prevalent techniques, the motor current signature analysis (MCSA) for the CM of motor-operated gearbox [14–20] has received growing attention in recent years and achieved considerable advancements. These publications show many interesting achievements in this direction. In all these publications, the use of MCSA for the detection of gear faults has been limited in that no deterministic approaches have been demonstrated. One of the main reasons for this lack of diagnostic clarity is that the harmonic content and noise contained within the real measured signals are high or the fault signals are low. Moreover, the gear transmission system usually produces significant nonlinear coupling phenomenon that will present sum and difference frequency components when the failure occurs. The methods such as fast Fourier transform [14,15] and power spectrum analysis [16] used in the above mentioned achievements, are based on stationary signals and are difficult to solve the nonlinear phenomenon and suppress noises. As a result they can be insufficient to properly correlate the stator current data with faulted conditions. Therefore, many researchers have investigated alternative signal analysis methods, such as empiric mode decomposition (EMD) [17], wavelet demodulation analysis [18] and combined methods [19,20], for analysing current signals for more accurate feature extraction. Although these efforts have shown promising results, they may be still deficient because these signal analysis methods possess limited noise reduction capability.

Higher order spectra (HOS) are useful signal processing tools that have shown significant benefits over traditional spectral analyses because HOS have unique properties of nonlinear system identification, Gaussian noise elimination and phase information retention [21–25]. Therefore, HOS analysis has received high concentrations. In [26], conventional bispectrum (CB) was applied to motor current signals for detecting different degrees of tooth breakage of a two-stage helical gearbox. Ref. [27] introduced MSB which is a significant improvement of the CB in that it enhanced CB to apply the modulation signal efficiently. The results showed reliable fault diagnosis and revealed that random noise can be suppressed effectively, being much better than that of the power spectrum (PS) and CB for diagnosing different seeded faults, such as tooth breakage and shaft misalignment. However, MSB method has not been evaluated for gear wear monitoring and severity assessment, which may be more challenging as the wear may induce current signatures far weaker than tooth breakages.

To examine the performance and extend the applications of using MSB based MCSA to the monitoring of gearboxes, this paper investigates monitoring the deterioration process of an industrial multi-stage helical gearbox based on motor current measurements and MSB analysis. It applies MSB to current signals measured progressively from a run-to-failure experiment to obtain accurate modulation characteristics and their evolution behaviours with operating times, and thereby implementing the gear wear monitoring and severity evaluation. The paper has four sections. Section 2 presents the theoretical basis of gear wear detection based on the MSB-MCSA. Section 3 describes the run-to-failure experimental setups for validating the proposed method. Then, Section 4 shows the monitoring results in conjunction with critical interpretations and finally, Section 5 is the conclusion.

2. Theoretical basis of gear wear detection based on MSB-MCSA

2.1. Motor current model for gearbox condition assessment

When a motor driving mechanical transmission such as a gearbox is operating under healthy conditions, the ideal electromagnetic relationship of the driving motor can be examined by using just one of the three phases. To simplify analysis process, the electromagnetic relationships are examined in phase A and the higher harmonics in the phase is not considered. Referring to supply voltage, the current signal in phase A for a healthy motor drive can be expressed as

$$i_A = \sqrt{2}I\cos(2\pi f_s t - \alpha_I) \tag{1}$$

Correspondingly, the magnetic flux in the motor stator is

$$\varphi_A = \sqrt{2}\varphi\cos(2\pi f_s t - \alpha_\varphi) \tag{2}$$

The electrical torque produced by the interaction between the current and flux can be expressed as

$$T = 3P\varphi I\sin(\alpha_I - \alpha_\varphi) \tag{3}$$