Local fault diagnosis of non-stationary gearbox based on order envelope analysis

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ABSTRACT

Gear tooth local fault is usually observed in gear system, it’s of significance to detect the gear tooth local fault during the operation process of the gearbox. However, the gearbox usually working in a non-stationary condition, namely the rotating speed or load are time varying, which increases the difficulty of fault diagnosis since the statistic features and spectrum vary by time. In this paper, an order envelope analysis method is proposed for fault diagnosis of a two-stage gearbox with local spalling fault and crack fault under non-stationary working conditions. Firstly, an accelerometer and an encoder are mounted on the gearbox to acquire non-stationary vibration data and rotating speed, respectively. After that, the angular resampling method is applied to convert the non-stationary time domain signal to angle domain signal by interpolation algorithm. Then envelope analysis is employed for the angle domain signals to detect the local fault characteristic frequency components in envelope spectrum. Finally, a new health inductor is proposed to detect spalling faults and crack faults in different working conditions. The fault diagnosis results show that the new method can effectively detect the gear local fault in various non-stationary working conditions.

Keywords: Fault diagnosis; non-stationary; angular resampling; order envelope analysis; tooth fault.

1. Introduction

Gearboxes are the most important mechanisms in industrial machinery, wind turbines, and our daily lives to transmit power and produce high rotational speed changes and/or change the direction of motion. However, due to heavy duty and tough working conditions some local gear faults, i.e. tooth root crack and spalling, are easily observed in gearbox [1, 2]. It is indicated that gear faults account for 80% of transmission break-down [3]. Thus, research on fault diagnosis of gearbox has attracted a lot of attention from scholars around the world.

Vibration-based method is proven to be one of the most popular techniques in fault diagnosis of rotating machinery, and it is convinced that there will be some changes in the vibration signals when there are some faults, e.g. crack, spalling [4-6]. In practical cases, gearbox working in a non-stationary condition, namely speed or load are time varying, traditional statistical analysis [7] and spectral analysis [8] suffer degradation in detecting the gear fault. Some scholars tried to use some new methods to deal with this problem. One of these new methods is time–frequency analysis (TFA), which study a signal in both time and frequency domains, so that both the constituent frequency components and their time variation features in non-stationary condition can be revealed and analyzed, some famous TFA methods include short time Fourier transformation (STFT), Wigner–Ville distribution (WVD), continuous wavelet transform (CWT), Hilbert-Huang transformation (HHT) etc. [9-11].

For instance, Feng et al. [12] presented a TFA method to reveal the constituent frequency components of non-stationary signals and their time-varying features for planetary gearbox monitoring. Saidi et al. [13] introduced a joint method of bi-spectrum and EMD to analyze non-stationary vibration signals’ behavior for bearing failures detection. He [14] proposed a novel nonlinear time–frequency feature based on a time–frequency manifold (TFM) technique to overcome the effects of noise and condition variance issues in sampling signals.

Above all, though TFA and EMD methods can extract fault features in non-stationary working conditions for fault diagnosis, both the two methods are time consuming and require users have a good knowledge of vibration signals. Angular resampling is considered as a classic and effective technique of the non-stationary vibration analysis for rotating machinery, which can overcome the disadvantage of the spectral smearing of signal in the angle domain [15]. For instance, André et al. [16] made a comprehensive comparison between the angular sampling and angular resampling methods that applied on the vibration monitoring of a gear meshing in non-stationary conditions. Cheng et al. [17] presented a gear fault diagnosis method based on order tracking technique and local mean decomposition to detect the modulation feature of gear fault vibration signal in run-ups and run-downs. Villa et al. [18] presented the development of an angular resampling algorithm for applying in conditions of high speed variability in wind turbines. Bonnardot et al. [19] propose an enhanced method that uses an unsupervised order tracking algorithm to perform noise cancellation in the angular domain rather than in the time domain.
Above all, angular resampling technique is widely used in fault diagnosis of rotating machinery. In this paper, a hybrid method that including angular resampling technique and envelope analysis method [20] is applied to analysis the non-stationary vibration signals. Besides, a new health indicator based on order envelope spectrum is proposed to detect the gear local faults. The rest of the paper is organized as follows: background of angular resampling technique is introduced in section 2 briefly. Then the fault diagnosis method based on order envelope analysis is proposed in section 3. In section 4, experimental setup are introduced. Test results are shown and discussed in section 5. Conclusions of this paper are drawn in section 6.

2. Background of angular resampling

Spectral analysis method is usually used in fault diagnosis of gearbox, however, most gearboxes commonly working in a non-stationary condition, i.e. time-varying rotating speed and load. Therefore, the characteristic frequencies in spectrum derived from the non-stationary time domain signal will be time-varying and this phenomenon is named as “frequency smearing”, as shown in Figure 1, which increases the difficulty to distinguish the characteristic frequencies in spectrum directly no mention to fault diagnosis.

In order to overcome the disadvantage of spectrum-based method for fault diagnosis of gearbox under non-stationary working conditions, angular resampling method is usually employed, where vibration signals are sampled at constant increments of shaft angle instead of at constant time interval, and encoder is used to provide trigger impulse at each shaft angle.

However, many useful information in the signal may be lost if the angular sampling rate is too low or there are multi-stages in the gearbox. Therefore, time domain vibration signal as well as encoder signal are acquired simultaneously with a high sampling frequency, then angle domain signal is derived by resampling from time domain signal, as shown in Figure 2. Firstly, the time indexes of the rising edges of the encoder signal are obtained as,

\[ T^\theta = [t^\theta_1, t^\theta_2, ..., t^\theta_i, ..., t^\theta_M] \]

Then angle domain signal can be derived from time domain signal by Lagrange interpolation method,

\[ y(t) = x(t_j) + \frac{x(t_{j+1}) - x(t_j)}{t_{j+1} - t_j} (t^\theta_j - t_j), \quad t_j < t^\theta_j < t_{j+1} \]  

3. Fault diagnosis method based on order envelope analysis

When there is a local fault in a gear pair, impulsive shock is expected to be observed in every rotation, and these shocks will be modulated by meshing frequency and its harmonic frequencies, which leads to complex sidebands in frequency spectrum. Therefore, after obtaining the angle domain signals, envelope analysis is done to extract the impulsive shocks caused by local fault. First Hilbert transformation of the angle domain signal is obtained,

\[ \hat{y}(\theta) = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{y(\theta - \tau\theta)}{\tau\theta} d\tau\theta \]  

Then the analytic signal of \( y_a(\theta) \) and the envelope signal \( A(\theta) \) are obtained,

\[ y_a(\theta) = y(\theta) + j\hat{y}(\theta) = A(\theta)e^{j\phi(\theta)}, \quad j = \sqrt{-1} \]  

And finally order envelope spectrum can be derived after FFT of the envelope signal,

\[ S_{o\omega}(\omega) = \int_{-\infty}^{\infty} A(\theta)e^{-j2\pi\omega\theta} d\theta \]  

where, \( o \) is the angle order and \( \theta \) represents the angle.

The proposed signal processing procedure is shown in Figure 3. First of all, raw signal including acceleration signal and encoder signal is acquired, then based on Lagrange interpolation method time domain signals is converted to angle domain signal to reduce the non-stationarity caused by speed fluctuation. After The proposed signal processing procedure is shown in Figure 3. First of all, raw signal including acceleration signal and encoder signal is acquired, then based on Lagrange interpolation method time domain signals is converted to angle domain signal to reduce the non-stationarity caused by speed fluctuation. After that Hilbert transformation and FFT are used to extract the order envelope spectrum to identify the fault characteristic frequencies.
Figure 3. Fault diagnosis procedure based on order envelope analysis

4. Experimental descriptions

Figure 4 shows the gearbox test setup, which consists of a two-stage gearbox, a motor, a magnetic powder brake, several flexible couplings and control unit. The teeth number of the first stage and second stage gear pair are 23/39 and 25/53 respectively, Table 1 give the design parameters of gears. The rotating speed of the 3-phase induction motor is controlled by the frequency converter and the load of magnetic powder brake is controlled by a load controller, which allow the tested gear to operate under various speeds and various loads.

Table 1. The parameters of gears

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module</td>
<td>3</td>
<td>Pressure angle</td>
<td>20°</td>
</tr>
<tr>
<td>Tip clearance</td>
<td>0.25</td>
<td>Addendum</td>
<td>1</td>
</tr>
<tr>
<td>Tooth width (mm)</td>
<td>60</td>
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A tooth spalling fault and a tooth root crack are seeded in the second-stage gear pair respectively, as shown in Figure 4. The manufacture parameter of the spalling fault is shown in Figure 5 a), two kinds of spalling faults are manufactured with $w$ equals to 3mm, $d$ equals to 1 mm and spalling length $l$ equals to 15 mm and 30 mm, respectively. The manufacture parameter of the crack fault is shown in Figure 5 a), two kinds of crack faults are manufactured where $\alpha_c$ is 75° and $q_0$ equals to 2 mm and 4 mm, respectively. Totally 5 different experiments are done, as listed in Table 2. It is noted that the 5th experiment is a speed-up and speed-down situation and the load is 0 Nm. An accelerometer is mounted on the bearing case of the middle shaft of the gearbox, then a LMS SCADAS is used to collected the vibration data, the sampling frequency is 5120 Hz, and time length is 32 s.

Figure 4. Schematic of the test system

5. Results and discussions

The dataset of the speed-up and speed-down experiment is analyzed by the proposed method as an example. Figure 6 shows the time domain signal and its zoomed plot, a clear amplitude increase and decrease trend can be observed as the rotating speed go up and down, as shown in Figure 6 a), and some impulse shocks can be found in Figure 6 b), the time interval between the two marked shocks is 0.155s which almost equals to the rotating speed period of the middle shaft at 700 rpm. Figure 7 shows the corresponding spectrum of the time domain signal after FFT, the spectrum density concentrates around 506.3 Hz as shown in Figure 7 a), however it is neither the meshing frequency components at 500 rpm nor at 700 rpm, because the meshing frequencies of the gearbox are 191.7 Hz (first gear pair) and 122.9 Hz (second gear pair) at 500 rpm respectively and 268.3 Hz (first gear pair) and 172 Hz (second gear pair) at 700 rpm respectively. And it is also found that there exist “frequency
smearing phenomenon in the spectrum, as shown in Figure 7 b). The envelope spectrum of the dataset is shown in Figure 8, and the characteristic frequency cannot easily be distinguished due to meshing modulation.

![Time domain signal](image1)

**Figure 6.** Time domain signal and its zoomed plot

![Time domain zoomed plot](image2)

**Figure 7.** Spectrum and its zoomed plot from 485 Hz to 510 Hz

After converting the time domain signal to angle domain, FFT is employed to derive the order spectrum as shown in Figure 9 a), where 1 order equals to the rotating frequency of the middle shaft. It can be observed that the spectrum distribution concentrates at 78 order, 64 order and 50 order, 78 order is the 2nd harmonics of the meshing frequency of the first gear pair, and 50 order is the 2nd harmonics of the meshing frequency of the second gear pair, but there is no corresponding frequency for 64 order which resulting from the coupling of the first and second gear pair meshing. The modulation sidebands can be observed in Figure 9 b), where 78±1 order are obvious, so after the envelope analysis the order envelope spectrum can be obtained as shown in Figure 10, distinct spectral components of order 1 and its harmonics can be found compared to Figure 8.

![Order spectrum](image3)

**Figure 8.** Envelope spectrum

![Order spectrum’s zoomed plot](image4)

**Figure 9.** Order spectrum and its zoomed plot from 75 order to 82 order

![Order spectrum’s zoomed plot](image5)
Aiming to monitor the health condition of the gearbox, a health indicator is defined in this paper, it is the summation of the amplitudes near the defect orders and its harmonics based on order envelope spectrum (SDOE), and the vibration signal acquired from the faulty gearbox is expected to have a higher SDOE value.

\[
SDOE = \sum_{m=1}^{4} \sum_{n=1}^{N} \sum_{o=m}^{n+bw} S_{\text{envelope}}^m(o) \tag{6}
\]

where, \(S_{\text{envelope}}^m(o)\) denotes the amplitude of the \(o\)th spectrum line of the \(m\)th order envelope spectrum, \(m\) means the order envelope spectrum that calculated around different meshing orders, in this paper, \(m=1\) means the sub-band around the 25th order frequency, \(m=2\) means the sub-band around the 50th order frequency, \(m=3\) means the sub-band around the 39th order frequency and \(m=4\) means the sub-band around the 78th order frequency. \(n\) indicates the 1st order of the fault frequency, \(N\) is the number of harmonics, the value of \(N\) is set to 3 in this study, \(bw\) is the order band width around the fault orders which is chosen as 0.1.

The SDOE indicator is first used to detect the spalling faults in experiment 1 and experiment 2, as shown in Figure 11 a) to d), where \(x\) label denotes the feature No. and \(y\) label is the amplitude of SDOE. It is noted that the vibration signal is divided into 30 segments, in each segment the SDOE value is calculated. It can be observed that the SDOE value can distinguish the spalling faults from the normal in all conditions. Besides, the SDOE value also can distinguish the small spalling fault from the large spalling fault. Then SDOE indicator is used to detect the crack faults in experiment 3 and experiment 4, as shown in Figure 12 a) to d). It can be observed that the SDOE value can distinguish the crack faults from the normal in all conditions except the 500 rpm and 0 Nm condition, in which the large crack fault seems has same SDOE value with normal situation.
The mean values of SDOE of gear tooth faults under various working conditions are compared, as shown in Figure 13 a) and b), where x label denotes different working conditions and y label is the mean value of SDOE. It can be found that, in Figure 13 a) the spalling faults yield larger mean value of SDOE than normal situation in all conditions, and as the growth of load or speed the mean value of SDOE will increase, the loading condition has a larger effect on the mean value of SDOE than speed. However, in most working conditions the small spalling fault achieves larger mean value of SDOE than large spalling fault, this may result from that in the calculation process of SDOE, there only four sub-band signals are taken into consideration, and the large spalling fault may modulate more sub-bands than small spalling fault. Similarly, in Figure 13 b) the crack faults yield larger mean value of SDOE than normal situation in all conditions except the first working condition, and as the growth of load or speed the mean value of SDOE will increase too, the loading condition also has a larger effect on the mean value of SDOE than speed.

Figure 12. SDOE between normal and crack fault situation under various working conditions

b) SDOE of crack faults under 500 rpm and 20 Nm working condition

c) SDOE of crack faults under 900 rpm and 0 Nm working condition

d) SDOE of crack faults under 900 rpm and 20 Nm working condition

Figure 13. Comparisons of mean values of SDOE of gear tooth faults under various working conditions

6. Conclusions

This paper proposes an order envelope analysis method for fault diagnosis of a two stage gearbox with local gear fault under non-stationary working conditions. First the time domain vibration signal is converted to angle domain based on angular resampling technique to reduce the influence of non-stationarity that caused by time-varying working condition. Then envelope analysis is applied to the angle domain signal to detect the gear fault characteristic frequencies and its harmonics. Besides a new health indicator is proposed based on the order envelope spectrum to detect the gear faults. The experimental results show that the order envelope analysis method is effective in eliminating the non-stationarity of the signal, useful frequency components can be found; and the proposed health indicator SDOE see its success in detecting both the spalling and crack fault under various working conditions.

Acknowledgements

The authors are grateful for the financial support provided by Ningbo Baoxin Stainless Steel Co., Ltd. and the National Natural Science Foundation of China under Contract No. 51475053.

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