LOCAL FAULT DIAGNOSIS OF NON-STATIONARY GEARBOX BASED ON ORDER ENVELOPE ANALYSIS

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Abstract: Tooth root crack is a common fault in gear system, it's of significance to detect the crack fault during the operation process of the gearbox. However, the gearbox usually working in a non-stationary condition, namely 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 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 angle domain signals are derived from the non-stationary vibration data by interpolation algorithm. Then envelope analysis is employed for the angle domain signals to detect the crack characteristic frequency components in envelope spectrum. Finally, the proposed approach is assessed by seeded tooth root crack fault in different working conditions, results show that the new method can effectively detect the tooth cracks in various non-stationary working conditions.

Key words: Fault diagnosis; non-stationary; order envelope analysis; tooth crack

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. In practical cases, gearbox working in a non-stationary condition, namely speed or load are time varying, traditional statistical analysis [4] and spectral analysis [5] suffer degradation in detecting the gear fault. Some scholars tried to use some new method to deal with this problem. For instance, Feng presented a time–frequency (TF) analysis method to reveal the constituent frequency components of non-stationary signals and their time-varying features for planetary gearbox monitoring [6]. Saidi introduced a joint method of bi-spectrum and empirical mode decomposition (EMD) to analyze non-stationary vibration signals' behavior for bearing failures detection [7]. He 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 [8]. Above all, though EMD and TF methods can extract fault features in non-stationary working conditions for fault diagnosis, both the two method are time consuming and require users have a good knowledge of vibration signals. Order tracking 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 order domain [9]. Thus, order tracking technique will be employed in this paper. The rest of the paper is organized as follows: section 2 describes the fault diagnosis method based on order envelope analysis. In section 3, experimental setup are introduced. Test results are shown and discussed in section 4. Conclusions of this paper are drawn in section 5.

Fault diagnosis method based on order envelope analysis: 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, frequency values in spectrum derived from the non-stationary time domain signal will be time-varying too and this phenomenon is named as "frequency smearing", as shown in Figure 1, which make is difficult to distinguish the characteristic frequency value in spectrum directly no mention to fault diagnosis.

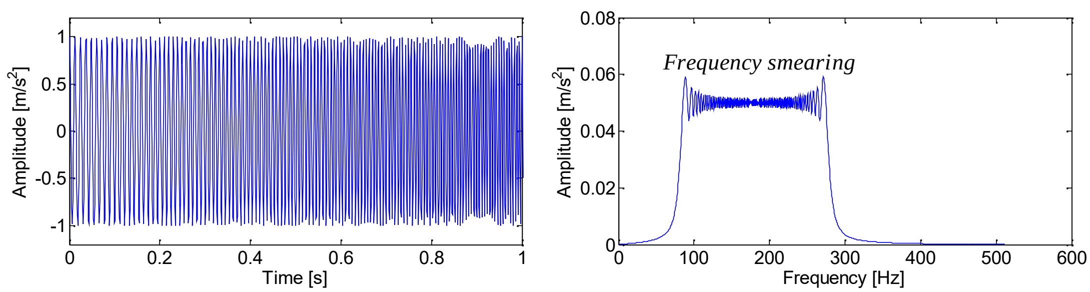


Figure 1: Time domain signal and spectrum in time-varying rotating speed condition

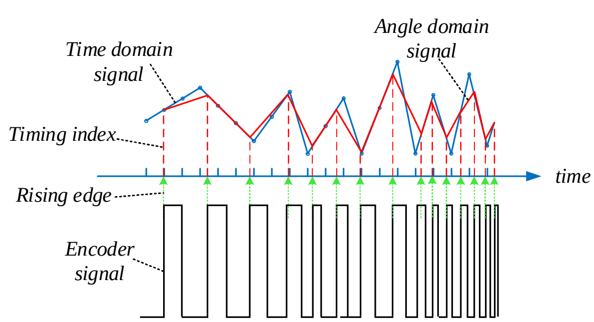


Figure 2: Resampling process of the angle domain signal

In order to overcome the disadvantage of spectrum-based method for fault diagnosis of gearbox under non-stationary working conditions, order tracking 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 angle domain 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, 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,

$$TI^{\theta} = [t_1^{\theta}, t_2^{\theta}, \ldots t_i^{\theta}, \ldots, t_M^{\theta}] \tag{1}$$

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

$$y(i) = x(t_j) + \frac{x(t_{j+1}) - x(t_j)}{t_{j+1} - t_j}(t_i^{\theta} - t_j), t_j < t_i^{\theta} < t_{j+1} \tag{2}$$

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, 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,

$$\hat{y}(\theta) = -\frac{1}{\pi}\int_{-\infty}^{+\infty} \frac{y(\theta - \tau)}{\tau} d\tau \tag{3}$$

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

$$y_a(\theta) = y(\theta) + j\hat{y}(\theta) = A(\theta)e^{j\varphi(\theta)}, \quad j = \sqrt{-1} \tag{4}$$

where, $A(\theta) = \sqrt{y^2(\theta) + \hat{y}^2(\theta)}$ and $\varphi(\theta) = \arctan(\hat{y}(\theta) / y(\theta))$.

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

$$S_{oea}(o) = \int_{-\infty}^{\infty} A(\theta)e^{-j2\pi o t} d\theta \tag{5}$$

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.

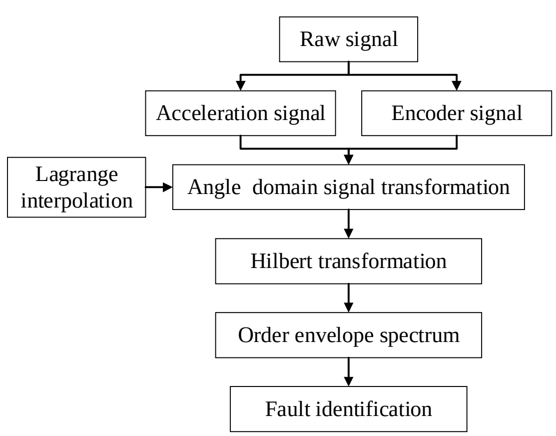


Figure 3: Fault diagnosis procedure based on order envelope analysis

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. A tooth root crack is seeded in the second-stage gear pair as shown in Figure 4, the manufacture parameter of the crack is shown in Figure 5(a), where α_c is 75° and q_0 equals to 1.8 mm.

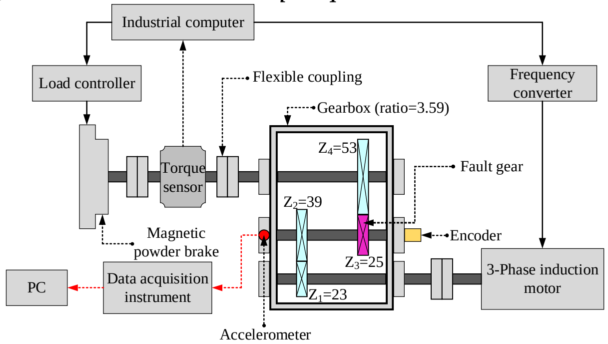
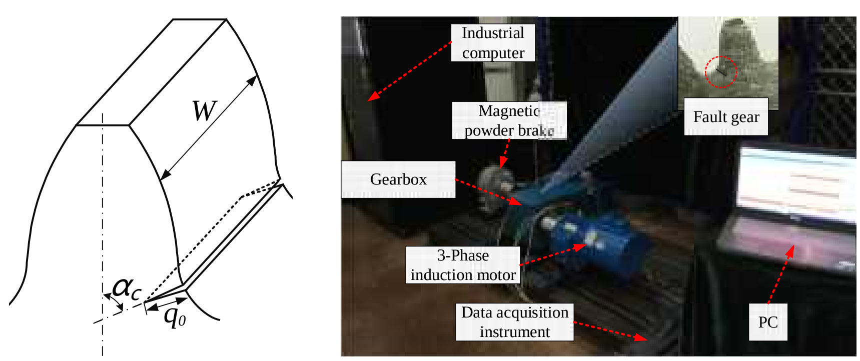


Figure 4: Schematic of the test system

Table 1: The parameters of gears

Parameter	Value	Parameter	Value
Module	3	Pressure angle	20°
Tip clearance	0.25	Addendum	1
Tooth width (mm)	60		



(a) (b)

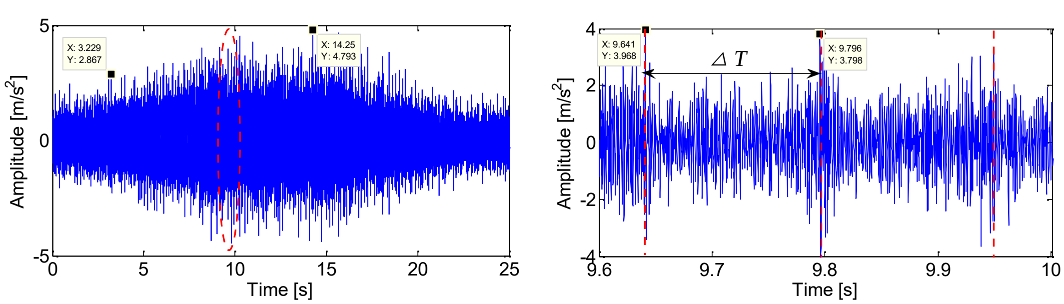
Figure 5: (a) Schematic diagram of tooth root crack and (b) photograph of the test system

One accelerometer is mounted on the bearing casing of the gearbox and an encoder (360 p/r) is mounted at the end of the middle shaft, a LMS data acquisition system (DAQ) and a PC with the data acquisition software are used to acquire the vibration data and encoder signal for further processing, Figure 5(b) shows the photograph of the data collection process. Vibration data is acquired under 4 loading conditions: 0 Nm, 20 Nm, 40 Nm and 60 Nm. Rotating speed ranges from 500 rpm to 700 rpm then to 900 rpm, the signal length for each dataset is 6 seconds. For each loading condition, there are 15 datasets collected and totally 120 datasets collected for both normal and fault situation. In addition, a speed-up and speed-down dataset is collected as an example for order envelope analysis. The sampling frequency is 5120 Hz. Table 2 gives more detailed description of various datasets.

Table 2: Detailed description of various datasets

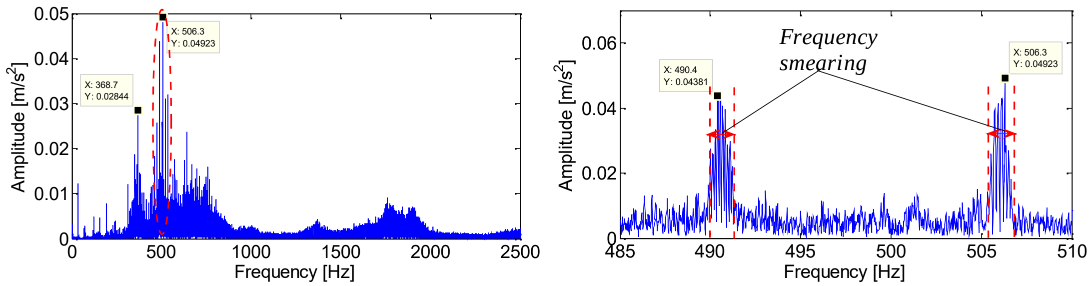
Fault severity	Motor speed (rpm)	Load (Nm)	Time length (s)
Normal	500-700-900	0/20/40/60	6
Cracked	500-700-900	0/20/40/60	6
	500-700-500	0	25

Results and discussions: The speed-up and speed-down dataset 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.



(a) (b)

Figure 6: (a) Time domain signal and (b) its zoomed plot



(a) (b)

Figure 7: (a) Spectrum and (b) its zoomed plot from 485 Hz to 510 Hz

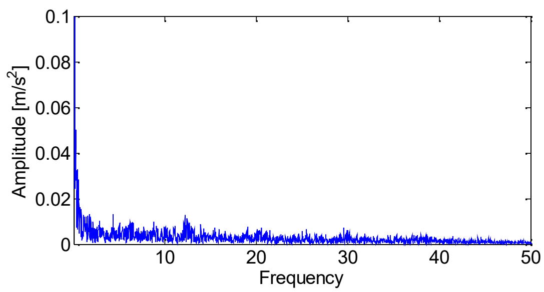


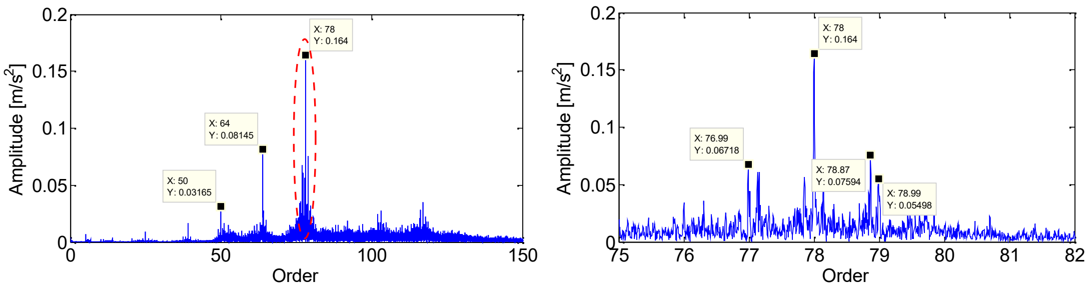
Figure 8: Envelope spectrum

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 density 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 may 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.

Aiming to monitor the health condition of the gearbox, a health indicator is defined as 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*.

$$SDOE = \sum_{n=1}^{N} \sum_{o=n-bw}^{n+bw} S_{oea}(o) \quad (6)$$

where, S_{oea} () denotes the amplitude of the o^{th} spectrum line of the order envelope spectrum, 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.



(a) (b)

Figure 9: (a) Order spectrum and (b) its zoomed plot from 75 order to 82 order

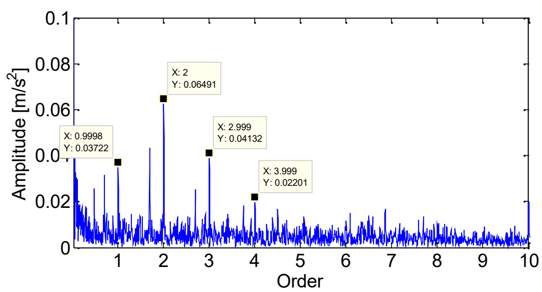
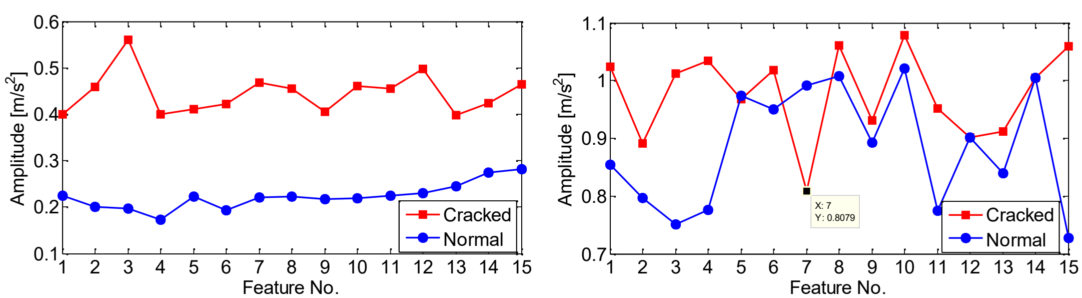
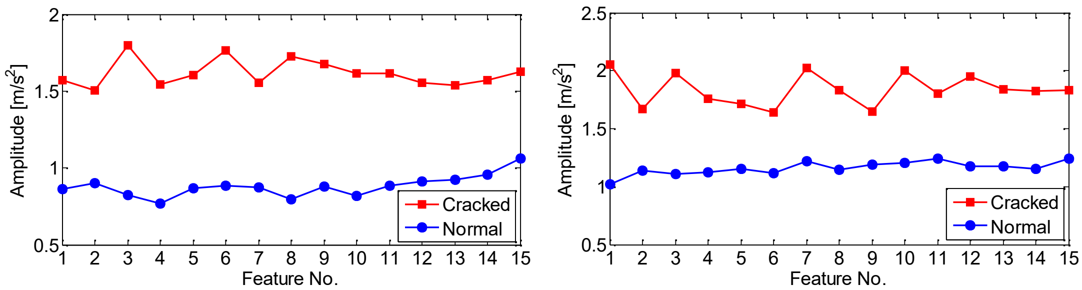


Figure 10: Order envelope spectrum

Comparisons of *SDOE* between normal and cracked situation are shown in Figure 11 (a) to (d) under various loading conditions, where *x* label denotes the dataset No. and *y* label is the amplitude of *SDOE*. It can be observed that the *SDOE* indicator can distinguish the cracked situation from normal situation in most times, however there is a large variation for the *SDOE* of normal situation in 20 Nm loading condition, as shown in Figure 12, there is an increasing trend for both normal and cracked *SDOE* indicator. And the *SDOE* of cracked situation always yields higher mean value than normal situation. So conclusion can be drawn that *SDOE* is a useful indicator in detecting early tooth root crack.



(a) (b)



(c) (d)

Figure 11: Comparisons of *SDOE* between normal and cracked situation under (a) 0 Nm (b) 20 Nm (c) 40 Nm and (d) 60 Nm conditions

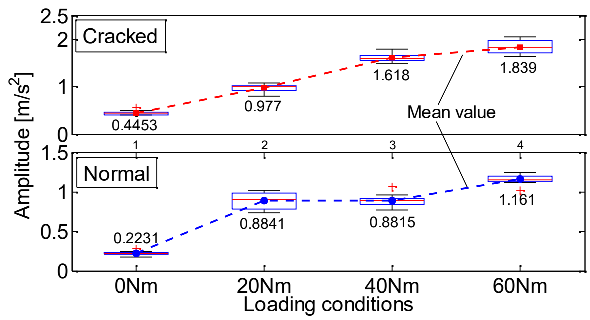


Figure 12: Boxplot comparisons between normal and cracked situation

Conclusion: This paper propose an order envelope analysis method for fault diagnosis of a two stage gearbox with local crack fault under non-stationary working conditions. First the time domain vibration signal is converted to angle domain to reduce the influence of non-stationarity caused by time-varying working condition. Then envelope analysis is applied to the angle domain signal to detect the crack characteristic frequency components. After that a useful health indicator is proposed to detect the crack fault. It is concluded that the order envelope analysis 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 crack fault under various working conditions.

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