Research on gear crack diagnosis of the planet gear transmission

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Abstract: Objected to the planetary gear transmission, research on the fault diagnosis of gear cracks is mainly carried out with method of EEMD decomposition and Envelope demodulation. During the process, EEMD decomposition is used to the experiment data and continuously parameters of the root mean square (RMS) value, peak-to-peak (PtP) value, kurtosis (Kr), and other parameters of the IMF components are computed. According those parameters, the signal is reconstructed and after band-pass filtering the Hilbert transform and the envelope demodulation are carried out. The results showed that the power spectrum information obtained by using the EEMD decomposition and Hilbert transform could effectively response fault characteristics of the gear crack in the planetary transmission. The research is beneficial to the gear meshing fault diagnosis of the planetary transmission quickly and accurately and has a positive engineering value.

1 Introduction

The planetary gear transmission is the main kind of the power transmission systems in the wind turbine. Under the time-varying winding and different loading, continuous high-frequency interference and external excitation always act on the device. So, researching on fault diagnosis and developing the monitoring system based on the actual operating environment has a favourable effect on the core technology breakthrough of large-scale wind power equipment in the transmission device, which is conducive to the realisation of the rapid promotion of large wind turbine transmission equipment maintenance schedule and research design.

As a key transmission part, the planetary gearbox will be liable to damage and failure during a long and unstoppable working station. In many of its fault forms, the gear damage is more likely to account for 60%, the bearing failure is 19%, the failure of the gear shaft is about 10%, the failure of the gearbox case is about 7%, and the other types of fault form account for about 4% [1]. The gear failure is mainly caused by gear surface wear, gear surface pitting, gear root cracks, fracture of teeth etc.

The diagnosis about gear fault mainly usually use many kinds of signals such as the kinematics, acoustic, infrared, oil, ultrasonic, acoustic emission diagnosis etc. The impact signal, caused by the mechanical structure and working station of the planetary gearbox, usually causes the typical periodic responses. Many feature signal extraction methods are used such as frequency domain analysis [2], wavelet analysis [3–5], independent component analysis [6, 7], hologram analysis [8] etc. Now methods of impact signal process usually are with three types, which are envelope analysis, blind deconvolution, and waveform decomposition. G. Nikolaou and L.A. Antoniadis used the adaptive complex translation Morlet wavelet to automatically extract the impact waveform of the bearing failure [9] and analyse the feasibility and effectiveness of morphological operators in the envelope extraction of periodic impact response signals. Huang ZC and Zhang JF used a blind deconvolution algorithm based on kurtosis (Kr) maximisation to extract and enhance the impulse impact from the signal caused by the bearing’s internal and external fault [10]. Feng ZP used the pursuit method to process the experimental data and extract the periodic impulse impingement of gear's local fault for identification about the pitting defect [11, 12]. The spectral correlation density and demodulation are used to extract the characteristic parameters for bearing fault diagnosis and gear fault [12, 13–20]. A lot of experimental on planetary gear transmission system dynamics are carried out for the dynamic characteristics of the system under dynamic loading [12, 14–16–19]. J. Yang designed the test prototype of the wind power gear box and carried out the test for the empty loading, the stable working and the variable working conditions, under which conditions the comparisons were continued for the vibration characteristics [17].

The references show that by using the appropriate separation method to decompose the exact signals from the experimental data the fault diagnosis could effectively be carried out. In the current research, the fault diagnosis of the tooth root crack in the gear fault is carried out by using EEMD decomposition and Hilbert Huang transform.

2 Methods

Based on the laboratory planetary transmission system showed in Fig. 1, the fault diagnosis method with the EEMD decomposition and Hilbert Huang transform method would be used to the failure analysis about planetary gear root cracks. First, the EEMD decomposition is carried and then the root mean square (RMS) value, peak-to-peak (PtP) value, Kr etc., of IMFs are computed. According to those parameters, the reconstructed signal would be obtained from the IMFs. After band-pass filtering, the Hilbert transform and Huang transform are performed to the reconstructed signal for the fault diagnosis (Fig. 2).

2.1 EEMD decomposition method

EEMD method is essentially a kind of improved EMD algorithm, which is proposed by Wu and Huang-based EMD decomposition. After the normal white noise is added to the original signal, the signal is becoming continuous in different scale and avoiding modal could be achieved. The process is showed in Fig. 3. \( x(t) \) is the original experimental data, \( \tilde{x}(t) \) is coupled with Gauss’s white noise, \( \delta_k \) is the overall average of IMF signals.

2.2 Envelope demodulation method

The demodulation is widely used to extract modulation information from the signals and from which its intensity and frequency could be obtained to damage diagnosis. Through the Hilbert transform, the instantaneous signal extraction is achieved.
2.3 Theoretical calculation method of gear fault

For the distributed fault of the planetary gearbox, the amplitude and the instantaneous frequency of the gear meshing are changed periodically when the fault gears are engaged. While the planet gear is in fault, it would rotate a single relative revolution to the ring gear; and the amplitude and the instantaneous frequency of the meshing movement is changed periodically. When the sun gear or the ring gear ring is in fault, it would rotate a single relative revolution to the frame, and the amplitude and the instantaneous frequency of the meshing vibration are changed periodically. When a distributed fault occurs, the meshing movement is modulated with the rotating frequency of the fault gear relative to the ring gear and when a distributed fault occurs in the sun gear or the ring gear, the meshing movement is modulated by the rotating frequency of the gear relative to the frame.

The distributed frequencies of the distributed faults of the sun wheel, the planetary gear, and the ring gear are, respectively, as \( f_{ds} \), \( f_{dp} \), and \( f_{dr} \), which are described as (1), (2) and (3).

\[ f_{ds} = \frac{f_m}{z_s} \]  
\[ f_{dp} = \frac{f_m}{z_p} \]  
\[ f_{dr} = \frac{f_m}{z_r} \]

where \( z_s \), \( z_p \), and \( z_r \) are teeth number of the sun gear, planetary gear, and ring gear; \( f_m \) is the meshing frequency; \( f_c \) is the rotating frequency of the frame.

For the local fault of the planetary gearbox, the gear with local damage engage in contact with others’ would cause impact phenomenon, which will be repeated periodically. The frequency of the impact caused by the local damage of the gear is related to the speed of the gearbox, the number of teeth of each gear, and the number of the planetary gear. The characteristic frequency of the local fault is equal to the repetition frequency of the impact sequence, which is the meshing times of the fault gear and other teeth.

The local frequencies of the distributed faults of the sun wheel, the planetary gear, and the ring gear are, respectively, as \( f_{ls} \), \( f_{lp} \), and \( f_{lr} \), which are described as (5), (6), and (7). \( N \) is number of the planetary gear.

\[ f_{ls} = \frac{f_m}{z_s} N \]  
\[ f_{lp} = 2 \frac{f_m}{z_p} \]  
\[ f_{lr} = \frac{f_m}{z_r} N \]

2.4 Process

Considering the fault signal characteristics of the planetary gear transmission, with the methods of EEMD decomposition and envelope demodulation, the process could be shown as in Fig. 4. In the process, the RMS value, PTP, Kr, variance (Vr), median frequency (MF) etc. are used to determine the IMF components chosen to restrict the signal; the band-pass filter is built up according to the meshing frequency and its octave.

3 Experiments and results

The experiments are carried out with a planetary transmission system showed in Fig. 1, which are including a driving motor, a planetary gearbox, two torque measuring devices positioned at before and after the gearbox, acceleration sensors positioned on the
box of the gearbox, a magnetic particle break and a monitoring system DASP V10(Coinv, China). The driving motor’s velocity is changed between 1000 and 2000 rpm with step of 60 rpm and the load is changed between 0 and 2 Nm with step of 1 Nm. The monitoring parameters are with sampling frequency of 20 KHz and sampling term of 30 s. The experiments are carried out with two statement, the normal state and the state with planetary gear cracks.

Tables 1–4 are the parameters of the planetary gearbox.

### Table 1 Gears’ parameters of the gearbox

| zₘ | zₚ | zᵣ |
|----|----|----|
| 18 | 44 | 108 |

### Table 2 Meshing frequencies and rotating frequencies of the gearbox with two certain velocities

| v, rpm | fₘ, Hz | rₛ, Hz | rₚ, Hz | rᵣ, Hz |
|--------|--------|--------|--------|--------|
| 1350   | 347.1  | 22.5   | 4.7    | 3.2    |
| 1650   | 370.2  | 26.8   | 5.3    | 3.9    |

### Table 3 Local fault frequencies of the gearbox with two certain velocities

| v, rpm | fₛ, Hz | fₛ₀, Hz | fₛₑ, Hz |
|--------|--------|---------|---------|
| 1350   | 57.9   | 7.9     | 9.6     |
| 1650   | 70.8   | 9.6     | 11.7    |

### Table 4 Distributed fault frequencies of the gearbox with two certain velocities

| v, rpm | fₛ, Hz | fₛ₀, Hz | fₛₑ, Hz |
|--------|--------|---------|---------|
| 1350   | 19.3   | 7.8     | 3.2     |
| 1650   | 23.6   | 9.6     | 3.9     |

3.1 Results for rotating velocities of 1650 rpm

The y direction refers to the along radial direction and vertical to shell of the planetary gearbox. Figs. 5–9 are curves in y direction of the normal state for the planetary gearbox with 1650 rpm including acceleration curve, spectrum, curves between parameters (RMS, Kr, PtP), and IMFs, reconstructed curve and envelope spectrum, respectively. Figs. 10–12 are the curves of state of the planetary gearbox with planetary gear cracks including curves between parameters (RMS, Kr, PtP) and IMFs, reconstructed curve and envelope spectrum, respectively. After the decomposition of EEMD, the RMS, Kr, and PtP of all IMF components are taken as evaluation indexes, and IMF components containing fault information could be selected to reconstruct the signal.

From Fig. 7, it could conclude that the RMS and PtP values of the second IMF components are the largest, the Kr of the first IMF components is the largest, and the three indexes of the third IMF components are larger. The residual component is IMF 17th. So the IMF components of the first, second, third and seventeenth are used to reconstruct the signal.
From Fig. 8, it could conclude that the maximum amplitude is at the frequency of 1274 Hz, which is equal to \(3f_{mc}\). So, the band-pass filter with bandwidth of 160 Hz at the centre frequency of 1274 Hz is continued and the filtered signal is demodulated by Hilbert. The envelope spectrum is shown in Fig. 9.

Under the normal condition, the planetary gear box plays a major role in the amplitude modulation of the meshing vibration due to the passing effect of the planetary gear, and its vibration signal is modulated by the rotation frequency of the planet carrier, which is well in accord with [12].

From Fig. 10, it could conclude that the IMF components of the second, third, fourth, and seventeenth are used to reconstruct the signal. From Fig. 10, the band-pass filter with bandwidth of 160 Hz at the centre frequency of 1264 Hz is continued and the filtered signal is demodulated by Hilbert. The envelope spectrum is shown in Fig. 12.

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Compared with the normal state at the same speed, the frequencies 5.7, 9.6, and 13.5 Hz are included. It could conclude that the fault frequency of planetary gear is equal to 9.6 Hz, the planetary rotation frequency is equal to 5.7 Hz exactly, and the frequency of 13 Hz is the sum of the two frequencies. These new peak frequencies are related to the frequency of the fault of the planetary gear and the rotation of the planetary gear, which indicates that the planetary gear has a local damage. The results are in accordance with the fault mechanism of the planetary gear and are in conformity with the actual conditions.

3.2 Results for rotating velocities of 1350 rpm

In the same way, the method is used to deal with normal state and the planetary gear cracks state with 1350 rpm. From the envelope spectrum, compared between Figs. 13 and 14, it could conclude that the frequencies 4.7, 7.9, 11.1, and 14.3 Hz are appeared. With 1350 rpm, the local fault frequency of the planetary gearbox is equal to 7.9 Hz, and the planetary rotation frequency is equal to 4.7 Hz exactly. The frequency of 11.1 Hz is the sum of 7.9 and 3.2 Hz, which are the frequency of the planetary gear local fault and one times the frequency of the frame. The frequency of 14.3 Hz is the sum of 7.9 Hz and \(3.2 \times 2 \text{ Hz}\), which are the frequency of the planetary gear local fault and two times the frequency of the frame. These new peak frequencies are all related to the local fault frequency of the planetary gear and the rotating frequency of the planetary gear, which also indicates that the planetary gear has local damage.

4 Conclusions

In current research, research on the fault diagnosis of gear cracks is mainly carried out with method of EEMD decomposition and envelope demodulation to the fault analysis. EEMD decomposition is carried out to the experiment data and continuously the Kr, intensity, and other parameters of the IMF decomposition data are...
computed. According those parameters, the signal is reconstructed and after band-pass filtering, the Hilbert transform and the envelope demodulation are carried out.

The results showed that the envelope spectrum information obtained by the process could be effectively response fault characteristics of the gear crack in the planetary transmission. According to comparisons of the normal state and the fault state, we could use the new peak points in envelope spectrum and those side frequencies to determine the practical fault. According to this method, the automatic analysis process could be easily implemented. When the input rotating velocity and the loading changes, the results are still well coupled with the practical.

In the process parameters of the RMS value, PtP value, Kr of the IMFs are used to reconstruct the signal. The PtP value is not increased from normal state to the fault, while its relative difference is increased. So statistical analysis of parameters should be more as experimental data. In addition, other parameters could be included such as MF, mean power frequency, correlation dimension, stability margin etc.

The research is beneficial to the gear meshing fault diagnosis of the planetary transmission quickly and accurately, and has a positive engineering value.

5 Acknowledgments

The research are supported by the National Natural Science Fund (51575055),the Beijing Construction of high level innovative team Fund (IDHT20180513), the open subject of the Key Laboratory of Modern Measurement and Control Technology Ministry of Education (KF20171123206).

6 References

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