Fault Diagnosis of Wind Turbine Based on Empirical Mode Decomposition

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Abstract. The structure of the gearbox of wind turbine is complex. The working environment is bad and the load is heavy which results in frequent failure of the gearbox parts and huge economic losses. In this paper, the signal processing method combined with empirical mode decomposition and improved bispectrum is used to diagnose the gearbox of wind turbine and the condition of wind turbine is monitored by a portable inspection. The feasibility and applicability of this method in the fault diagnosis of wind turbine gearbox are checked by an example.

1. Introduction
Wind power has become a key research area in the world. Once the wind turbine fails, it will cause serious economic losses. Therefore, it has great economic and social value for the status monitoring and fault diagnosis of wind turbines.

In this paper, the empirical mode decomposition and improved bispectrum vibration signal analysis method are combined with the monitoring method of the inspection, which is introduced into the fault diagnosis process of the fan gearbox, and combined with the production example for fan fault diagnosis.

2. Experimental

2.1. Signal processing methods
The vibration signal of wind turbine has strong nonstationarity and nonlinear (caused by coupling of vibration signals during meshing of multiple pairs of gears). This brings great difficulty to the fault diagnosis of the gearbox of the wind turbine. The vibration signal of wind turbine is very complicated so it is necessary to use powerful signal analysis tools to extract useful information.

2.2. Empirical mode decomposition (EMD)
The EMD algorithm can decompose the input signal into several narrowband components (IMFs) of different frequencies, and the result of the decomposition is several IMFs and one residual signal:

\[ x(t) = \sum_{i=1}^{n} IMF_i(t) + r_n(n) \quad (1) \]
\[ \sum_{i=1}^{n} \text{imf}_i(t) : \text{The sum of IMF signals, } r_n(n) : \text{Residual signals} \]

The eigenmode function should satisfy two conditions:
① The difference between the sum of the maxima and minima points contained in the eigenmode function and the number of zero crossings is not more than 1;
② The sum of the upper and lower envelopes of all points is zero among the eigenmode function signals.

The empirical mode decomposition algorithm can be divided into the following 2 steps: ① Solving the IMF component of \( x(t) \). First, find all the maxima and minima points of \( x(t) \). Linear fitting of all maxima and minima points with a 3-time spline function and find the maximum value envelope \( e^+(t) \) of the input signal and the minimum value envelope \( e^-(t) \). By calculating the mean of \( e^+(t) \) and \( e^-(t) \) in order to obtain the mean envelope \( m_i(t) \) of \( x(t) \):

\[
m_i(t) = \frac{e^+(t) + e^-(t)}{2}
\]

(2)

Subtracting equation (2) with \( x(t) \) gives a new input signal \( h^1_1(t) \).  
\[
h^1_1(t) = x(t) - m_i(t)
\]

(3)

Determine the \( h^1_1(t) \) by using the condition established by the eigenmode function. If the judgment of \( h^1_1(t) \) fails, the equations (2) and (3) are continuously calculated; If \( h^N_1(t) \) satisfies the condition that the eigenmode function is established at the Nth time of the loop, then the first-order IMF component \( \text{imf}_1 \) of the signal can be obtained:

\[
c_1(t) = \text{imf}_1(t) = h^N_1(t)
\]

(4)

Subtract the first-order IMF component \( c_1(t) \) from \( x(t) \) to obtain a signal \( r_1(t) \) that removes the first-order IMF component of the original signal; By solving \( r_1(t) \), a second-order IMF component \( \text{imf}_2 \), \( c_2(t) \), can be obtained.

③ Similarly, \( c_2(t) \) is iteratively solved by the process, when the nth-order eigenmode function component \( \text{imf}_n \) is not greater than the pre-calculation set value or the residual quantity \( r_n(t) \) of the nth-order eigenmode function is When the monotonic function is completed, the entire empirical mode decomposition process ends.

2.3. Improved bispectrum

2.3.1. Bispectrum and biscoherent spectrum. The standard tool for detecting quadratic phase coupling is bispectrum and its normalized form biscoherent spectrum.

Assume \( X(f) \) is Fourier transform of Real signal \( x(n) \), which we can get:

\[
X(f) = \sum_{n=-\infty}^{\infty} x(n)e^{-2\pi jm}
\]

(5)
The power spectrum of the signal $x(n)$ is defined as:

$$P(f) = E[X(f)X^*(f)]$$

(6)

Bispectrum is defined as

$$B(f_1, f_2) = E\{X(f_1)X(f_2)X^*(f_1 + f_2)\}$$

(7)

The bispectrum is often normalized to obtain the bis-coherent spectrum.

$$b(f_1, f_2) = \frac{|B(f_1, f_2)|}{\sqrt{P(f_1)P(f_2)P(f_1 + f_2)}}$$

(8)

2.3.2. Improved double spectrum. In order to solve the deficiency of bispectral analysis of amplitude modulation signal Stack J R proposed an improved bispectrum. The definition is as follows:

$$D(f_1, f_2) = E\{X(f_2 + f_1)X(f_2 - f_1)X^*(f_2)X^*(f_2)\}$$

(9)

The normalized form is:

$$d(f_1, f_2) = \frac{|D(f_1, f_2)|}{\sqrt{P(f_1)P(f_2)P(f_2 + f_1)P(f_2 - f_1)}}$$

(10)

3. Diagnostic example
First, the first test and analysis are performed as reference data.

Figure 1: Vibration signal observed from measuring Point of Gear Ring of Gear Box (sampling Frequency 8000 Hz).

Figure 2: Corresponding power spectrum.

Figure 1. Ring gear vibration signal of a gearbox B07 of a wind farm (first sampling).
It can be seen from this that the vibration signal of the fan is very complex and it takes powerful signal analysis tools to extract useful information.

Figure 3 is the result of empirical mode decomposition (EMD) of the vibration signal. The left side of the diagram is the intrinsic modal function component of each order column and the right side is the corresponding power spectrum. The uppermost edge is the IMF component which is decomposed from the original sequence with the smallest amplitude and the highest frequency. The amplitude of each IMF component increases gradually and the frequency decreases gradually until the very low frequency component. By observing the decomposition process of EMD we can find that EMD can be regarded as an adaptive filter bank. Each IMF component is a "feature component" contained in the original signal. The bandwidth is determined by the characteristics of the signal itself. EMD is a good signal preprocessing method because it is carried out completely in time domain.

3.1. Comparative Analysis of Vibration Detection Data of B07 Unit

The vibration amplitude of the ring gear of B07 has increased significantly. Under the same conditions (wind speed 6.7m/s, wind wheel speed 11.8r/min, high speed shaft speed 1230r/min), the effective value of vibration (acceleration) increased from the last 0.724m/s\(^2\) to 1.01m/s\(^2\).

Perform empirical mode decomposition of the acquired vibration signal. The fourth intrinsic mode component is amplified as showed in FIG. 4, and FIG. 5 is the corresponding power spectrum. It can be seen that there are obvious frequency components at 20, 40, 60, 80 and 100Hz. This is the planetary gear meshing frequency. For single-stage planetary gearboxes, the sun gear-planetary and planetary gear ring gears have the same meshing frequency. The calculation formula is

\[
f_m = f_c Z_R
\]

(11)

\(f_m\): Meshing frequency; \(Z_R\): Ring gear number; \(f_c\): Planet carrier rotation frequency;
Figure 3. Empirical mode decomposition of the signal of Figure 1.

Figure 4. Intrinsic modal component of ring gear vibration signals of gearbox B07 of a wind farm (second sampling).

Substitute the parameter to get:

\[ f_m = \frac{11.8}{60 \times 104} = 20.4 \text{Hz} \]

This indicates that the B07 windbox gearbox sun gear or a planetary gear has failed. At present, we are in contact with the wind farm, pay close attention to the operation of the B07 fan, and verify the diagnosis conclusion during the overhaul.
3.2. Comparative analysis of vibration detection data of B28 unit

There is damage to the high speed shaft bearing of the B28 fan gearbox. In the second test, it was found that the vibration amplitude of the high-speed shaft of the B28 gearbox increased, and in the same case (the rotation speed was basically the same), the vibration effective value increased by about 20%. Figure 6 shows the collected vibration signal (sampling frequency 5000 Hz). It can be seen that there are many impact components, but it is impossible to determine which type of fault.

Gearbox high speedshaft bearing type is SKF 31322 XJ2 taper roller bearing. According to the calculation formula of fault characteristic frequency of rolling bearing:

\[
f_a = \frac{Z}{2} \left( 1 - \frac{d_B \cos \beta}{D_p} \right) \times f_r,
\]

\[
f_i = \frac{Z}{2} \left( 1 + \frac{d_B \cos \beta}{D_p} \right) \times f_r,
\]

where:

- \( f_r \): Bearing rotation frequency;
- \( Z \): Number of teeth on roller;
- \( d_B \): Outer diameter of roller;
- \( D_p \): Bearing pitch diameter;
- \( \beta \): Contact angle.

It can be calculated: with the test speed (1460r/min), bearing outer ring fault characteristic frequency \( f_o = 161 \text{ Hz} \), bearing inner ring fault characteristic frequency \( f_i = 299 \text{ Hz} \).

Perform empirical mode decomposition on the signal, and then select the third intrinsic modal component for improved bispectrum analysis. Figure 7 shows the results of the improved bispectrum analysis. A number of larger peaks appear on the normalized improved bispectral contour plot, and the horizontal axis represents the amplitude modulation of the bearing vibration signal at these frequency pairs. Note that the vertical axis shows that the first line has a distinct peak at about 161 Hz, while the second and third lines have frequencies that are multiplied (322 Hz and 483 Hz), while the horizontal axis shows these peaks are spaced approximately 161 Hz apart. 161 Hz is the characteristic frequency of the bearing outer ring fault. Improving these peaks on the bispectrum indicates damage to the outer ring of the high-speed output shaft bearing of the gearbox. The removal and removal of the bearing during the inspection also confirmed the diagnosis.
4. Conclusion

In this paper, the method of signal analysis by decomposing empirical mode and improving bispectrum is studied combining with the inspiration mode in order to fault diagnosis and condition monitoring for Gearbox of Wind Turbine. It has been proved that the work condition of wind turbine unit can be monitored and fault diagnosis can be made in the way of inspection. Ensure long-term safety and full load operation of wind turbine.

It is proved that the empirical mode decomposition and improved bispectral signal processing method are suitable for the fault diagnosis of wind turbine gearbox. The empirical mode decomposition (EMD) and improved bispectrum are applied to the complicated signal fault diagnosis of the gearbox of wind turbine which can effectively and accurately separate the fault characteristic information.

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