

Fault Diagnosis Method of Wind Turbine Bearing based on Variational Mode Decomposition and Spectrum Kurtosis

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ABSTRACT: Aiming at the problem that fault feature of wind turbine bearing is difficult to extract, a new fault diagnosis method based on variational modal decomposition (VMD) and spectral kurtosis (SK) is proposed in this paper. Firstly, vibration signal collected from wind turbine is decomposed into several intrinsic mode functions (IMFs) by VMD. Secondly, Fourier transform is applied to each IMF and the absolute values of spectral signals are calculated. Thirdly, using the filter characteristics of spectral kurtosis (SK), the resonance frequency band caused by defects is selected to construct the optimal envelope. Finally, the defect of wind turbine bearing can be diagnosed by analyzing the envelope spectrum. The experimental results show that the VMD-SK method can successfully extract the fault characteristic frequency and effectively distinguish the bearing fault of wind turbine.

KEYWORD: Wind Turbine; Fault Diagnosis; Variational Mode Decomposition; Spectrum Kurtosis; Bearing

1 INTRODUCTION

Due to the advantages of clean, efficient and renewable, wind energy has become one of the most promising energy. However, wind turbine is prone to failure under bad operation conditions and complex force situation (Gong 2013). Furthermore, engine room is always located in tens of meters high altitude, leading to extremely high maintenance cost. As one of the critical components of wind turbine, bearing is very easy to failure (Hu 2015). Therefore, research on fault diagnosis method of wind turbine bearing is of vital importance for reducing equipment maintenance costs, improving economic efficiency and enhancing the operation stability of unit.

As an adaptive signal processing method, empirical mode decomposition (EMD) caused extensive concern of the scholars in the field of mechanical fault diagnosis and has been successfully applied in the rolling bearing fault feature extraction (Du 2007, Li 2006). However, the EMD method is essentially a binary filter bank, which makes the EMD method inevitably has the shortcomings in processing bearing fault signal (Feng 2012). Dragomiretskiy et al proposed an adaptive signal processing method—variable modal decomposition (VMD) in 2014, which can adaptively realize the effective separation of signals in the frequency domain partition (Dragomiretskiy 2014).

Spectrum kurtosis (SK) can detect the transient components of vibration signal containing noise as a statistics (Antoni 2006a). Vrabie defined spectral kurtosis as a Gaussian distance metric and applied SK to fault diagnosis of rolling bearing (Antoni 2006b, Su 2010). In general, spectrum kurtosis of non-stationary signal is positive and that of stationary signal is zero. Therefore, SK can be used to filter out the non-stationary signal components.

At present, the application of VMD in the wind turbine fault diagnosis field has seldom been reported in the references. However, VMD behave better than the EMD in many aspects. Therefore, fault diagnosis research based on the VMD-SK method is of significant value in theory and application.

2 VARIATIONAL MODE DECOMPOSITION

In the VMD algorithm, the intrinsic mode function (IMF) $u_k(t)$ is redefined as an amplitude modulation signal, which can be described as follows:

$$u_k(t) = A_k(t) \cos(\phi_k(t)) \quad (1)$$

where $A_k(t)$ = instantaneous amplitude of $u_k(t)$, $\phi_k(t)$ = instantaneous phase of $u_k(t)$.

The VMD algorithm gets rid of the cyclic sieving stripping pattern of EMD algorithm in obtaining IMF components (Upadhyay 2015). The signal decomposition process is transferred to the variational

framework, which calculates optimal solutions of constraints variational model to achieve adaptive signal decomposition. The central frequency and bandwidth of each IMF component are constantly updated in the process of iteration solution. Finally, vibration signal can be adaptively decomposed into a number of narrow-band IMF components according to frequency characteristics of the actual signal.

Assuming that vibration signal is decomposed into K components, the corresponding constraint variational model can be expressed as follows:

$$\begin{aligned} \min \{ \sum_k \| \partial t [(\delta(t) + j/\pi t) * u_k(t)] e^{-j\omega_k t} \|_2^2 \} \\ \text{s.t. } \sum u_k = f \end{aligned} \quad (2)$$

where $\{u_k\} = \{u_1, u_2, \dots, u_K\}$ = K IMF components decomposed by VMD; $\{\omega_k\} = \{\omega_1, \omega_2, \dots, \omega_K\}$ = central frequencies of each IMF components.

In order to obtain the optimal solution of the constrained variational problem, augmented Lagrange function is introduced into the following form:

$$\begin{aligned} \Gamma(u_k, \omega_k, \lambda) = \alpha \sum_k \| \partial t [(\delta(t) + j/\pi t) * u_k(t)] e^{-j\omega_k t} \|_2^2 \\ + \| f - \sum u_k \|_2^2 + \langle \lambda, f - \sum u_k \rangle \end{aligned} \quad (3)$$

where α = penalty function; λ = Lagrange multiplier.

The alternating direction multiplier algorithm is utilized to calculate saddle points of the augmented Lagrangian function, namely the optimal solution of constrained variable model, thus original vibration signal is decomposed into K IMF components.

3 SPECTRUM KURTOSIS

Spectral kurtosis (SK) is firstly proposed by Dwyer, which is a frequency-domain statistical tool developed in order to overcome the disadvantage of kurtosis in engineering application (Dwyer 1983). As a statistical tool, SK can not only measure non-Gaussian components in vibration signal but also pick out the band of non-Gaussian components. Antoni carried out in-depth research on spectral kurtosis and formally defined SK based on the fourth order cumulant.

For a non-stationary signal $x(t)$, the fourth order cumulant $C_{4X}(f)$ can be described as follows:

$$C_{4X}(f) = S_{4X}(f) - 2S_{2X}^2(f), f \neq 0 \quad (4)$$

Where $S_{4X}(f)$ = the fourth order time-average moment; $S_{2X}(f)$ = the second order time-average moment.

The more the non-stationary signal $x(t)$ deviates from the Gauss signal, the greater the value of the fourth order cumulant $C_{4X}(f)$. The spectral kurtosis of signal $x(t)$ is defined as the energy normalized four order cumulant, which can be described as follows:

$$K_x(f) = \frac{C_{4X}(f)}{S_{2X}^2(f)} = \frac{S_{4X}(f)}{S_{2X}^2(f)} - 2, f \neq 0 \quad (5)$$

Spectral kurtosis defined according to equation (6) has the following properties: for a non-stationary signal $Z(t) = x(t) + N(t)$, where $N(t)$ is an independent stationary noise, the SK $K_Z(f)$ can be described as follows:

$$K_Z(f) = \frac{K_x(f)}{[1 + \rho(f)]^2} + \frac{\rho(f)^2 K_N(f)}{[1 + \rho(f)]^2}, f \neq 0 \quad (6)$$

where $K_x(f)$ = the SK of signal $x(t)$; $K_N(f)$ = the SK of noise $N(t)$; $\rho(f)$ = signal to noise ratio (SNR).

When $N(t)$ is an stationary white noise, equation (6) can be simplified as follows:

$$K_Z(f) = \frac{K_x(f)}{[1 + \rho(f)]^2}, f \neq 0 \quad (7)$$

According to equation (7), it can be discovered that $K_Z(f)$ closes to zero at the frequency components of high SNR and approximately equals to $K_x(f)$. Spectral kurtosis can minutely examine the whole frequency domain by applied to different bands, thus picking out the band where fault signal can be best detected.

4 FAULT DIAGNOSIS METHOD BASED ON VMD-SK

Due to the weak periodic shock vibration signal, it is difficult to identify the low frequency fault feature directly from the spectrum. Based on the filtering effect of spectral kurtosis, this paper proposed the VMD-SK method to diagnose wind turbine bearing. The principle of VMD-SK is to select the IMF components related with fault characteristic by calculating spectral kurtosis, thus automatically constructing optimum envelope for fault diagnosis. The fault characteristics can be clearly observed by analyzing frequency components near the fault characteristic band (Rai 2007). The steps of fault diagnosis method proposed in this paper are as follows:

(1) Firstly, the vibration signal of wind turbine bearing is decomposed by VMD, and the non-stationary vibration signal $x(t)$ is decomposed into a series of IMF components with different characteristic scales.

(2) Each IMF component is analyzed by Fourier transform and its square envelope is calculated. Based on the above analysis, the spectral envelopes of IMF components with different frequency bands are utilized to calculate the spectrum kurtosis $K_Y(f)$.

(3) Using the filter characteristics of spectral kurtosis, the IMF components corresponding to the largest and the second high value of $K_Y(f)$ are select-

ed to reconstruct bearing vibration signal, and the optimal envelope signal can be obtained.

(4) The envelope spectrum is obtained by applying FFT to the optimal envelope, thus the bearing fault can be diagnosed.

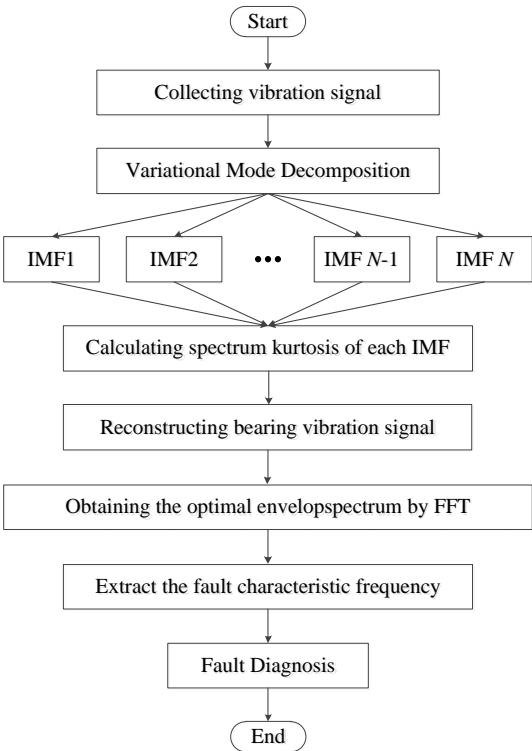


Figure 1. Flow chart of wind turbine bearing fault diagnosis method based on VMD-SK

5 EXPERIMENTAL ANALYSIS

In order to test the effectiveness of bearing fault diagnosis method based on VMD-SK in practical application, the proposed method is applied to analyze the actual vibration signal collected from a wind turbine bearing. During the experiment, electric spark is utilized to make pitting failure in bearing outer race. According to rolling bearing fault characteristic frequency calculation formula, it can be obtained that the fault characteristic frequency of outer race is 53 Hz, the fault characteristic frequency of inner race 78 Hz and the fault characteristic frequency of rolling elements is 26 Hz.

Figure 2 shows the waveform in time domain, amplitude spectrum and envelope spectrum of outer race fault signal. It can be seen from figure 1 that the original waveform is very complex and it is difficult to distinguish the specific characteristics. The high frequency noise components occupy a large proportion in spectrum, leading to the low characteristic frequency submerging in the strong noise background.

The original signal is processed by the variational modal decomposition (VMD) algorithm and five IMF components are obtained, which are shown in

Figure 3. According to spectrum kurtosis it can be discovered that the fault characteristic frequency band is contained in C1 and C3. Then IMF C2 and C3 are selected to reconstruct vibration signal and calculate the optimal signal envelope. At last, FFT is utilized to calculate the optimal envelope spectrum analysis. The analysis results of VMD-SK are as shown in Figure 4. As shown in Figure 4b, it can be seen that amplitudes at the outer race fault characteristic frequency (53Hz), second harmonic frequency (105Hz) and third harmonic frequency (159Hz) are very prominent, which indicates that there is damage in outer race of wind turbine bearing. The analysis results are consistent with the actual situation analysis and the effectiveness of VMD-SK is verified.

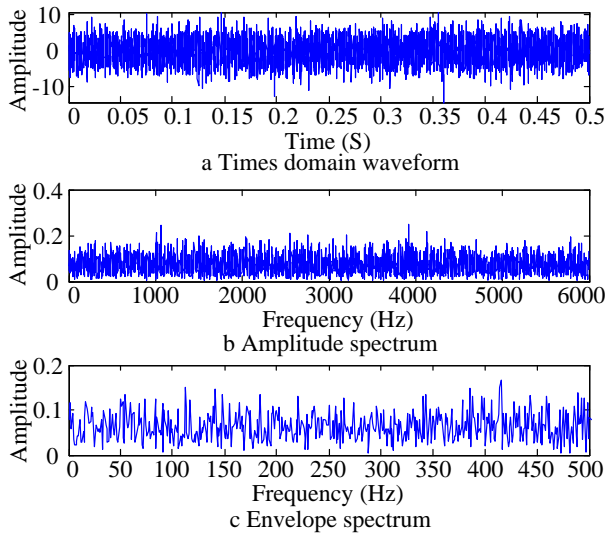


Figure 2. Outer race fault signal of wind turbine bearing

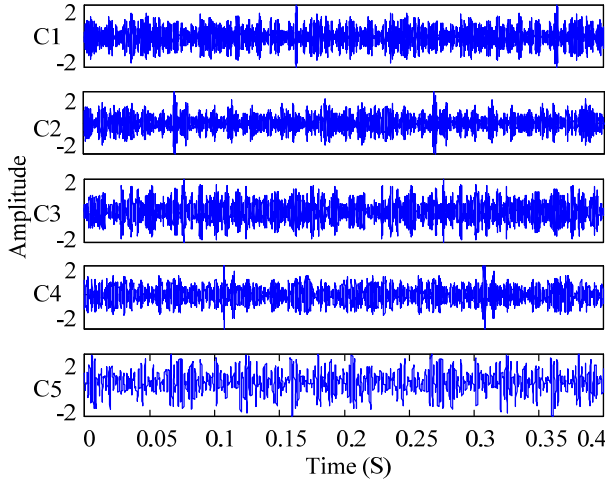


Figure 3. Results of outer race fault signal analyzed by VMD

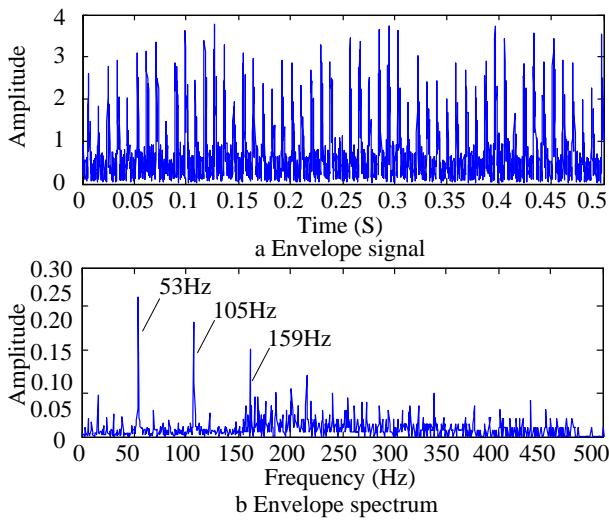


Figure 4. Analysis results of outer race fault signal by the VMD-SK method

6 CONCLUSION

As a new signal processing method, variational mode decomposition (VMD) has rarely been applied in the fault diagnosis field. The VMD can effectively avoid the modal mixing problem caused by impact signal in dealing with the practical vibration signal, which provides an effective new method for fault diagnosis of wind turbine.

Spectral kurtosis is utilized to select multiple resonance frequency of high signal-to-noise ratio for demodulation analysis, which can enhance the weak characteristic and improve the fault diagnosis effect of bearing.

The fault feature of wind turbine bearing is very weak and it is relatively difficult to extract fault feature. The VMD-SK method can effectively extract the weak feature information in analyzing vibration signal of bearing. The experimental analysis results show that compared with the traditional amplitude spectrum and envelope spectrum, the proposed method in this paper is more accurate, effective and better in diagnosing the bearing fault.

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