

## Time-frequency Characteristics Analysis on Vibration Signals of a Three-supported Rotor System with Misalignment

Xiaoxuan Qi<sup>1,2</sup>, Meiling Wang<sup>3</sup>, Lijing Lin<sup>3</sup>, Jianwei Ji<sup>1</sup> and Qingkai Han<sup>\*3</sup>

<sup>1</sup>. School of Information & Electric Engineering, Shenyang Agriculture University, Shenyang, China

<sup>2</sup>. School of Information Engineering, Shenyang University, Shenyang, China

<sup>3</sup>. School of Mechanical Engineering & Automation, Northeastern University, Shenyang, China

qi\_xx@yahoo.com.cn \* qhan@mail.neu.edu.cn (Corresponding author)

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**Abstract.** In light of the complex and non-stationary characteristics of misalignment vibration signal, this paper proposed a novel method to analyze in time-frequency domain under different working conditions. Firstly, decompose raw misalignment signal into different frequency bands by wavelet packet (WP) and reconstruct it in accordance with the band energy to remove noises. Secondly, employ empirical mode decomposition (EMD) to the reconstructed signal to obtain a certain number of stationary intrinsic mode functions (IMF). Finally, apply further spectrum analysis on the interested IMFs. In this way, weak signal is caught and dominant frequency is picked up for the diagnosis of misalignment fault. Experimental results show that the proposed method is able to detect misalignment fault characteristic frequency effectively.

### Introduction

Misalignments always occur in the rotor system of rotating machinery, which can cause excessive and complex vibration of the rotor and lead correspondingly to the failure of the whole system. Statistics show that misalignment faults account for nearly 60% of the total faults number. A range of dynamic effects inimical to the device will be introduced to the rotor systems with misalignments such as rotor-stator rubbing, coupling deflection, incipient faults of bearings, unstable emulsification of fuel film, the flexural deformation and etc, which may cause abnormal vibration and are extremely hazardous [1]. Moreover, increasing requirements of high rotating speed and high efficiency make the possibilities of failure occurrence increasing. Therefore, further research on features and the mechanism of misalignments has the important theoretical significance and engineering practical value.

During the operating process, a lot of information as vibration, temperature and deformation can be utilized to diagnose failures. Among which, vibration is the most effective one. It can reflect the real estate of the rotor system more directly and rapidly. So far, misalignment diagnosis of rotor systems is chiefly implemented by vibration information at home and abroad. Current misalignment diagnosis methods of rotor systems are based mostly on the multiplication of the shaft fundamental frequency. In such cases, environmental noise can not be neglected and will degrade the diagnosis quality. In addition, impact signals caused by the occurrence of misalignments will lead directly to non-stationary characteristic. At present, most efforts have been aimed at studying the characteristics of the misalignments with advanced signal processing methods in an attempt to perform effective feature extraction. While effective analysis of misalignment signal is a difficult issue all the while due to the non-stationary, complex and noise-polluted characteristics. Many time-frequency signal processing methods begin to be widely utilized, among which wavelet packet (WP) analysis and empirical mode decomposition (EMD) are the typical ones. WP and EMD can decompose complex signal into different scales and take into account both the time and frequency characteristics. It is superior to the traditional methods based on fast Fourier transform (FFT) in terms of non-stationary signals and has achieved successful application in a variety of areas as fault diagnosis, information detection, biomedical industry and etc.[2-4]. WP analysis can solve the contradiction between time and frequency resolution well and provides an ever finer way of non-stationary signal analysis. It can

decompose signal into a series of decomposition sequence distributed in different narrow sub-frequencies within the pass-band and provide a way of choosing appropriate frequency sequences adaptively according to the specific signal characteristics. EMD is extensively applied in all kinds of applications, which is developed to analyze non-stationary and nonlinear signals. It is essentially a process that makes signal smooth and reduces the features interference and coupling between signals.

In this paper, a signal processing method in the joint time–frequency domain is proposed based on wavelet packet (WP) as well as empirical mode decomposition (EMD). WP analysis decomposes the signal into a set of narrow band signals prior to EMD to remove noises. EMD is used to extract feature frequencies. It is an adaptive method that is very suitable for complex and non-stationary signal analysis.

### Methodologies

Three types of misalignment under different working conditions are researched, shown in Table 1.

Table 1 Fault Type Description

| Type      | Misalignment degree<br>[mm] | Rotating speed<br>[RPM] |
|-----------|-----------------------------|-------------------------|
| Fault I   | 5.7                         | 1620                    |
| Fault II  | 5.7                         | 2160                    |
| Fault III | 5.7                         | 2520                    |

The experimental process can be described as follows:

- 1) Acquire misalignment vibration signals from the test-bed with current vortex sensors;
- 2) Apply WP analysis to the raw signal to decompose it into narrow sub-frequency bands and reconstructed the signal on selected bands for the succeeding EMD;
- 3) Perform EMD on the reconstructed signal after WP analysis to obtain a certain number of IMFs;

Analyze the IMFs and select interested IMFs. Perform the fast Fourier transform (FFT) on the selected IMFs and then obtain the corresponding characteristic frequency. Utilize the acquired time-frequency characteristics to diagnose misalignment faults of the rotor system.

### Frequency Band Division of Vibration Signals based on Wavelet Packet

Raw signals are firstly preprocessed by three-layer WP analysis to be divided into eight narrow frequency band. Then, useful frequency bands are selected according to the information they contained.

#### A. Principal of Wavelet Packet

The wavelet packet method is a generalization of wavelet decomposition that offers a richer range of possibilities for signal analysis and analyzes the low and high-frequency domains simultaneously [5]. It has perfect performances of decomposing and reconstructing signals, as is shown respectively in Eq. 1 and Eq. 2.

$$\begin{cases} d_l(j, 2n) = \sum_k a_k - 2ld_k(j+1, n) \\ d_l(j, 2n+1) = \sum_k b_k - 2ld_k(j+1, n) \end{cases} \quad (1)$$

Where  $a_k$  and  $b_k$  are the conjugate filter coefficients of wavelet decomposition.

$$d(j+1, n) = \sum_k [p_{l-2k} d_k(j, 2n) + q_{l-2k} d_k(j, 2n+1)] \quad (2)$$

Where,  $p_k$  and  $q_k$  are the conjugate filter coefficients of wavelet reconstruction.

#### B. Selection of Frequency Bands

Wavelet function is the key of WP analysis, because different wavelet functions will lead to different analysis results in term of the same signal. In practical applications, its selection still lacks of systematic approach and guiding principles and needs to be determined according to the specific signal. In this paper, db44, one of the Daubechies wavelet family, is chosen.

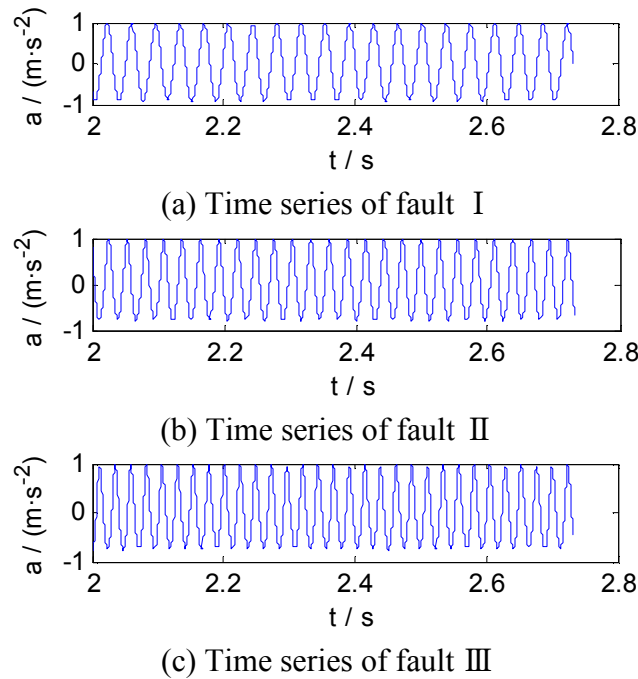


Figure 2 Time Series of the Three Misalignment Signals

Time series of the three misalignment faults are shown in Fig. 2. Use WP to decompose these raw signals on different scales and reconstruct them. Fig. 3 illustrates the reconstruction coefficients of the signal by a three-layer WP at the third level.

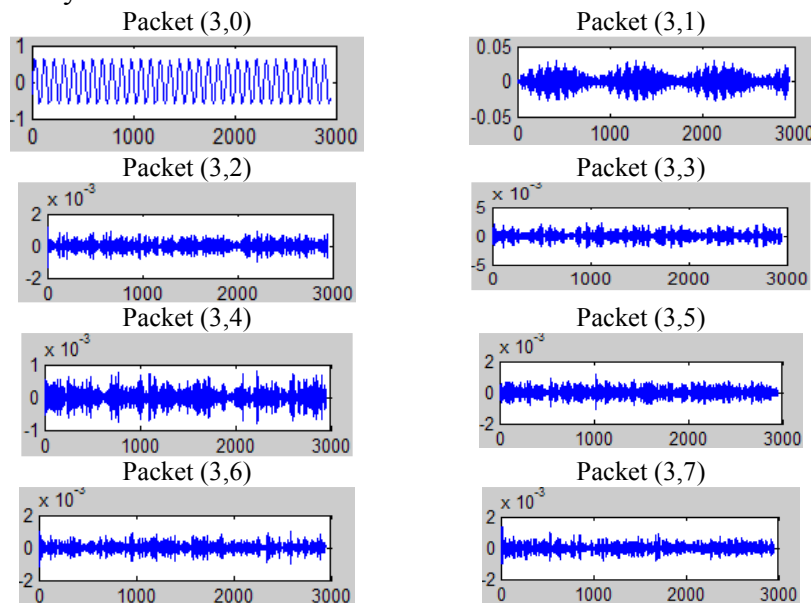


Figure 3 Reconstruction of Fault I Signal by WP

Packet (3,0) represents the first wavelet packet node in the third level, and so on. Each node, corresponding to a sub frequency band and carries different energy information. Thus we can lay emphasis on the interested frequency scale to draw detail information.

The obtained total energy percentage of packet (3,0) and packet(3,1) accounts for nearly 98%. Therefore, in the succeeding step, we select signals in the first two sub-frequency bands of each signal for EMD analysis.

### EMD after WP analysis

Huang et.al [6] proposed a new approach, named EMD, to analyze non-linear, non-stationary signals. The aim of EMD is to decompose the signal into a sum of Intrinsic Mode Functions (IMF). An IMF is a function that satisfies two conditions: one is that the number of extreme and the number of zero

crossings must either be equal or differ at most by one during the whole dataset; the other is that, at any instant, the mean value of the envelop defined by local minima is zero. EMD can analyze either the linear and stationary signals or non-linear and non-stationary signals. A complex signal can be decomposed into a number of IMFs and a residue. The decomposition sequence starts from the mode function that is the smallest characteristic time scale. The sifting process of EMD on signal  $x(t)$  is as follows [7]:

- 1) Find out the envelopes defined by the local maxima and minima separately;
- 2) Calculate the mean value of envelopes and define it as  $m(t)$ ;
- 3) Calculate  $h(t) = x(t) - m(t)$ ;
- 4) If the sifting result  $h(t)$  satisfies the two IMF supposes, then  $h(t)$  is the first IMF. Otherwise, treat  $h(t)$  as original signal and repeat step 1-3. The stopping condition is

$$\sum_t \frac{[h_{k-1}(t) - h_k(t)]^2}{h_{k-1}^2(t)} < SD \quad (3)$$

where  $h_k(t)$  is the sifting result in the  $k$ th iteration, and SD is the standard deviation, typically set between 0.2 and 0.3.

- 5) The above procedure is repeated  $n$  times and  $n$  IMFs and a residue of the signal are obtained;
- 6) The decomposition process can be stopped when  $h_n(t)$  becomes a monotonic function from which no more IMF can be extracted. Finally, we get

$$x(t) = \sum_{i=1}^n h_i + r_n \quad (4)$$

The first IMF component from the data contains the highest oscillation frequencies found in the original data  $x(t)$ . Based on the above principle, we have decomposed a misalignment signal of fault I. The raw signal data is shown in Fig. 2. EMD decomposition results are shown in Fig. 5.

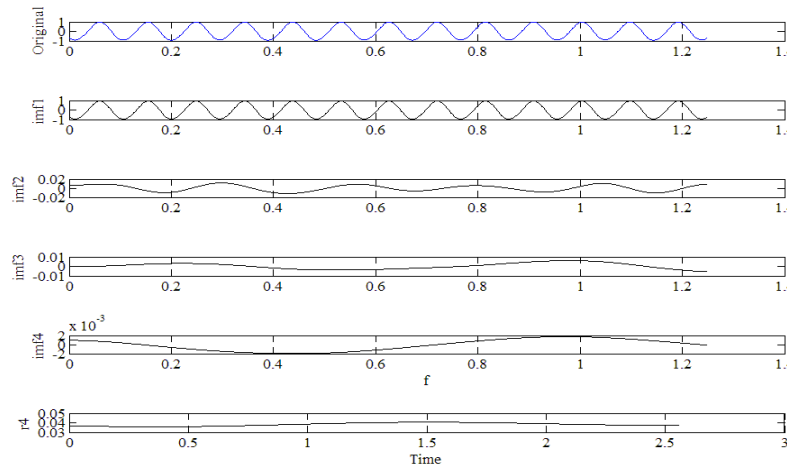


Figure 5 EMD of the Reconstructed Signal based on Packet (3,0) and Packet (3,1) for Fault I. We can see from Fig. 5 that the IMFs, from imf1 to imf4, tend to be more stable and their periodicity become more obvious. EMD is superior to other signal processing methods in that it can generate basic function automatically, filtering adaptively and the IMF has modulation features.

## Experimental Results

The experimental investigation was carried out on the aforementioned test-bed to verify the presented method. Vibration signals with misalignments were sampled at 1600 Hz for 5 seconds at different working conditions. Fig. 2 shows time series of the three misalignment faults.

The three misalignment signals were decomposed by WP into three levels respectively and then reconstructed. Energy proportional distribution of reconstructed signal on the narrow sub-frequency bands for fault I is described in Fig. 4. The other two occasions of fault II and fault III are quite similar. According to the energy proportional distribution, we know that information contained in the first two frequency bands are quite important, especially the first one. So, in the next step, EMD was

carried out on the reconstructed signal based on packet (3,0) and packet(3,1) for each fault signal. With EMD, waves on different scales in the complex vibration signal were decomposed step wisely and correspondingly generated a number of IMFs with different scales. EMD result of the reconstructed signal based on Packet (3,0) and Packet (3,1) for Fault I is shown in Fig. 5. It tells that imf1 is the most important one among all the IMFs, which holds the most information of original signal. While energy holds by other IMFs are too small to be considered. In this regard, spectrum analysis was carried on imf1 for further research. FFT is utilized on imf1 to get correspondingly their frequency spectrum.

From the frequency spectrum of the prominent IMF of the three signals, we can see that frequencies of the misalignment faults concentrated in the range of 0-60Hz. In the meanwhile, the amplitude changes with the increasing of working speed. Frequency components of 27.02 Hz can be seen from frequency spectrum of Fault I, which is in accordance with its working speed 1620 RPM. And frequency components of 36.02 Hz can be seen from frequency spectrum of Fault II, which is in accordance with its working speed 2160 RPM. 42.02 Hz can be seen from frequency spectrum of Fault III, in accordance with its working speed 2520 RPM.

## Conclusion

To overcome the limitations of traditional methods based on FFT when processing complex and non-stationary signals, this paper presented a hybrid method of analyzing the time-frequency characteristics of rotor system misalignments, which combines EMD with WP. Due to the fact that EMD analysis result is not ideal for signal with noises, WP is utilized to extract characteristic frequency bands prior to EMD. EMD is an adaptive signal processing method and IMFs acquired after EMD contain and highlight local feature frequencies in raw vibration signals. Then, spectrum analysis of the interested IMF will indicate the characteristic frequencies of misalignment fault. The advantage of such a method is that it can remove interference in vibration signals and is more adapt to the complex and non-stationary signals. Experiments results on the three-supported rotor system test-bed showed the effectiveness and efficiency of the proposed method.

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