The influence of friction component buckling on the vibration characteristic of the wet clutch

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Abstract. The multi-disc wet clutch is widely used in high-power vehicles and large construction machinery due to its capacity for high torque transfer and compact efficiency. However, the early-stage failure such as the buckling of the friction disk is hard to detect since its external performance is not obvious, which can impair the reliability of the system largely. This paper presents an online fault diagnosis method for wet clutch based on vibration signal analysis to detect the deformation of the friction components. A bench test is designed to acquire the vibration signal of the clutch pack with four different fault levels. Then an online monitoring method for clutch early fault based on wavelet analysis and EMD algorithm is proposed. The analysis shows that the method can extract the abnormal vibration characteristics and shock signals caused by the local deformation of the clutch pair, which can be feasible in the engineering practice of online fault diagnosis for multi-disc clutch early failure.

1. Introduction

The wet clutch is widely used in the automobile industry and plays an important role in torque transfer [1, 2]. A typical structure of the wet clutch is shown in Figure 1. During the engagement, the separate and friction disks are pushed together tightly by the piston, the variance of sliding speed between the disks decreases dramatically to zero within a second [3], thus to create massive heat transiently in the system which would potentially cause the deformation of the disks [4]. Consequently, the repetition of this process finally leads to the deformation or buckling of the friction components. Figure 2 shows a classic way of buckling, the inner ring of the friction disk has an apparent gap to the ground and the surface is curved. Many researchers have studied the damage due to the buckling. Zagrodzki, P presents the formation of hot spots due to uneven contact [5]. Heyan Li and Mingyang Li investigate the buckling induced thermoelastic instability (TEI) via a bench test, the experiment meets their prediction on the glazed spots[6]. Er-hui Zhao proposes a contact model to demonstrate the impact of the buckling on the temperature field, the huge temperature variance between contact and non-contact will escalate the deformation in return [7].

Therefore, the fault diagnosis for the buckling degree of clutch disks becomes vital. In fact, this signal-based fault diagnosis has been vastly studied in rotating machinery, especially for the gearbox.

In the studies devoted to gearbox diagnostics, the wavelet transform (WT) is more and more often one of the stages of the diagnostic procedure [8,9], [10] Compares the vibration signals of the damaged and undamaged gearbox and verify the difference using the wavelet transform and mathematic morphology. However, researchers have barely studied the vibrational signal-based fault diagnosis for wet clutch because many believe the signal analysis is inapplicable here. Firstly, from the experiment perspective, test bench always creates massive noise concerning the target signal of the clutch pack, which obstacles the signal processing drastically.
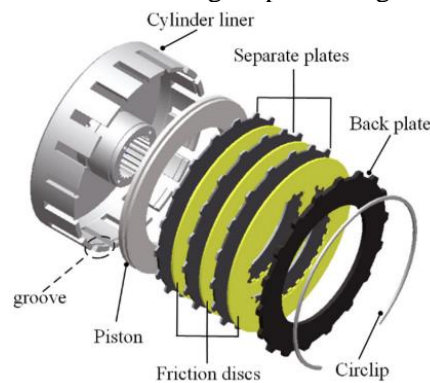

Figure1. 3D sketch of the clutch system

Figure 2. A typical deformation of the friction disk

The paper aims to apply a valid method to investigate the features of clutch disks with distinct buckling degrees based on the vibration signal. The bench test is conducted to collect vibration data, and then a signal processing based on wavelet transform and empirical mode decomposition (EMD) is applied to identify the difference in signal patterns. Finally, the conclusions are presented.

2. Experiments
In order to analyze the signal difference caused by the buckling of the clutch disks, a bench test was established to collect vibration data of different deformation disk pairs.

2.1. Quantification of the deformation degree
Firstly, four pairs of disks are selected based on their deformation degree. Compared to the original thickness of the disks, which is 2 mm for separate disk and 3 mm for the Cu-based friction disk. As shown in Figure 3, for each disk, the absolute value of 4 points is used to quantify the deformation. Four groups have been marked as A, B, C, D, where A represents healthy condition while D means disks are in severe buckling. The measured values and the average buckling heights are listed in Table 1 for reference.

Figure 3. Measured points of the clutch disks

Table. 1 Measured height of 4 pairs (mm)

Health state	Separate Disk		Friction Disk	
	2.03	2.15	3.05	3.22
A	1.93	2.14	3.08	3.14
Normal condition	Average	2.06	Average	3.12
	3.31	3.39	4.03	3.93
B	3.33	3.48	4.05	3.98
Slight buckling	Average	3.37	Average	3.40
	4.17	4.21	4.57	5
C	4.2	4.1	4.7	4.5
Medium buckling	Average	4.17	Average	4.69
	6.78	6.9	7.45	7.55
D	6.79	6.78	7.26	7.3
Stringent buckling	Average	6.81	Average	7.39

2.2. A subsubsection Test bench& Experimental procedure.
As shown in Figure 4, the test bench mainly consists of two parts: the driveline system and the signal acquisition system. The driveline system consists of four parts: an electromotor, a speed-torque sensor, a clutch pack and a braking system. The driving end of the wet clutch is rotated by the motor while the driven part is fixed by the brake. Once the motor activates, the speed of the motor could simulate the speed variance between the friction disks and the separate disks during the disengagement stage of the clutch.
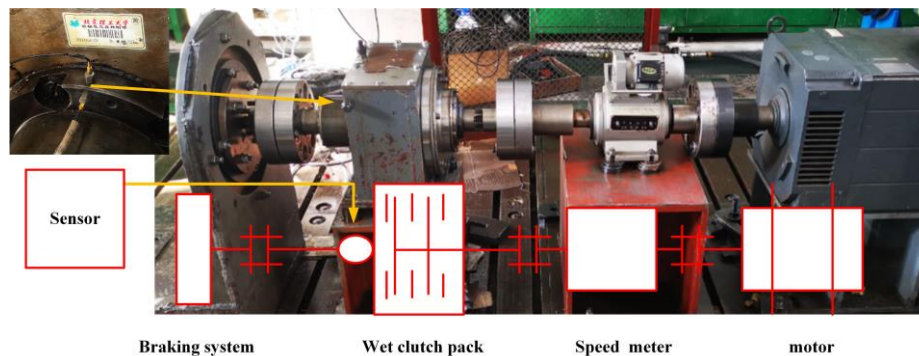

Figure 4. Test bench and signal acquisition system

The signal acquisition system consists of sensors and a data pre-processing system, which are provided by B&K Company. The two accelerometers are mounted on clutch pack at the driven side, they are arranged vertically and axially to the transmission system. The sampling rate is 6.4kHz.

During the experiment, the lubrication oil is set to be the ambient temperature; each collecting process lasts 5 seconds and conducts at a steady rotating speed.

3. Denoising processing based on wavelet transform
The accuracy of experimental data can be affected by many factors, such as the arrangement of the sensors, the error of the acquisition instrument and the complexity of the test bench itself, especially the other larger vibrating components. These factors make the collected data contain considerably high

noise, so the experimental data processing aims to reduce the influence of noise so that to reveal the hidden nature of the vibration signal data. The wavelet transform analysis is selected for noise processing.

Wavelet transform is a time-scale method with multi-resolution features, it deals with local signal representation in both time and frequency domain [11]. Wavelet analysis uses different time-frequency basis functions to analyze signal structures with different sizes. The original signal is projected into the wavelet basis function and provides a mapping from the time domain to the time-frequency domain.

The partial data of 0.1 second is selected and the noise reduction results of the db4 and sym6 basis functions are compared. The results are shown in figure 5. The db4 basis function is selected because it better reflects the signal saltation.
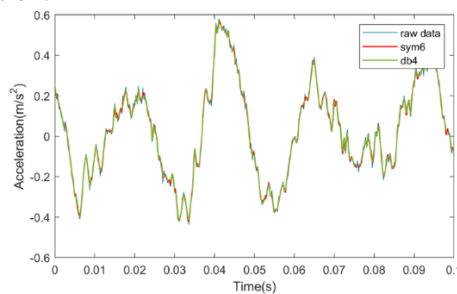

Figure 5. Noise reduction of different basis function

The main steps in the wavelet transform are the decomposition and reconstruction of the signal. To decompose a noise-containing signal S into a lower layer which contains a high-frequency signal D1 and a low-frequency signal A_1. The process continues until the decomposed signal satisfy the requirement of the layer. The specific decomposition process is shown in Figure 6. The noise is mainly concentrated in the high-frequency region. In the reconstruction process, according to the number of decomposition layers, n, only the low-frequency signal A_n is chosen as an approximation of the original signal to represent the denoised signal. After a comparative analysis of different iterations, it is found that the results are almost unchanged after the 3rd order, so 3 iterations is used in this paper.
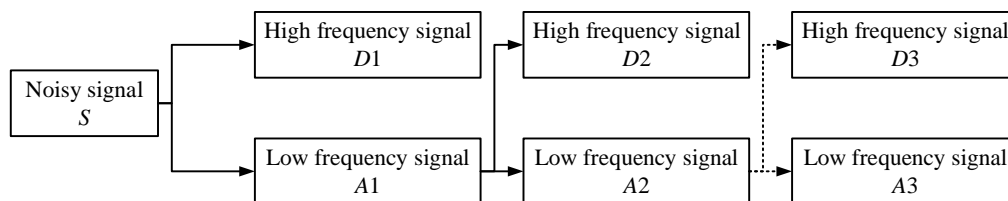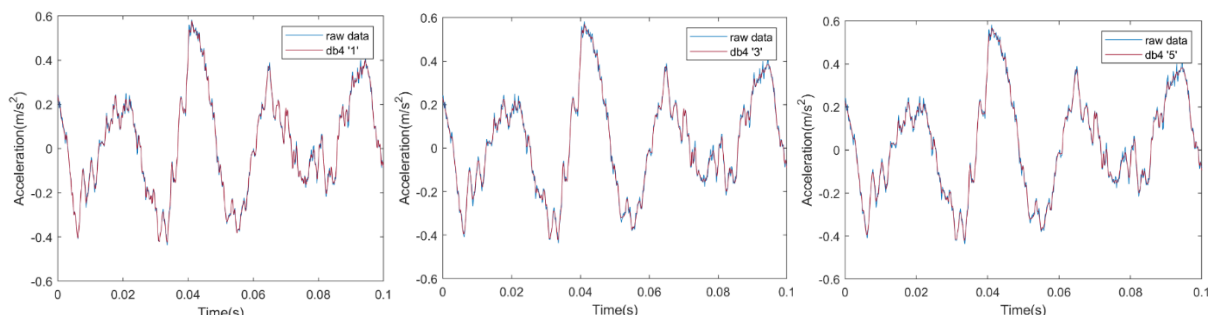

Figure 6. Flow diagram of the WT processing

Figure 7. comparison of different orders of WT decomposition

4. Results and discussion

This section analyzes the experimental data of the denoise process in Section 3. All signals are composed of an infinite number of Intrinsic Mode Functions (IMFs), if these functions are not

independent then it will form a composite signal. Therefore, it is necessary to use the empirical mode decomposition (EMD) to decompose the signal. The EMD method assumes that all signals are composed of different IMFs. In this paper, the experimental data is firstly decomposed by EMD and the first three orders of IMF are taken for further analysis. The Hilbert transform is applied to the IMF component, the specific steps are as follows:

Determine the Hilbert transform of the sampled data. The Hilbert transform for each $C_J(t)$ is expressed as:

$$C_J(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{C_J(\tau)}{t - \tau} d\tau \tag{1}$$

where $C_J(t)$ is the j-th IMF.

The analytical signal consists of a sample-data-based real part and Hilbert-transform-based imaginary part, it can be written in the following form:

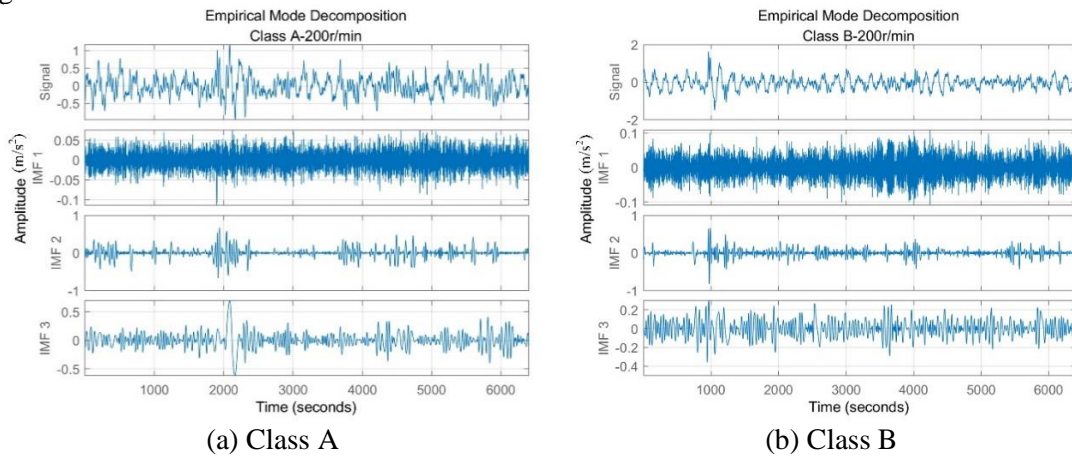$$Z_j(t) = C_j(t) + jC_j(t) = b_J(t)e^{j\varphi_j(t)} \tag{2}$$

where $b_J(t)$ is the instantaneous amplitude function, $\varphi_j(t)$ is the instantaneous phase function, by ignoring the residual function:

$$a_t = Re \sum_{j=1}^{n} b_j(t)e^{j\varphi_j(t)} = Re \sum_{j=1}^{n} b_j(t)e^{j \int w_j(t)dt} \tag{3}$$

where $a_{(t)}$ is the original signal

Perform modulo to obtain the envelope of the signal and apply low-pass filtering to the envelope. Then the modulation frequency and its higher harmonics can be found by taking a fast Fourier transform.

Taking the vibration signal in the axial direction as an example when the rotation speed is 200r/min. The signals are performed by EMD and the first three order decomposition vibration signals are shown in Figure 8.

(a) Class A   (b) Class B

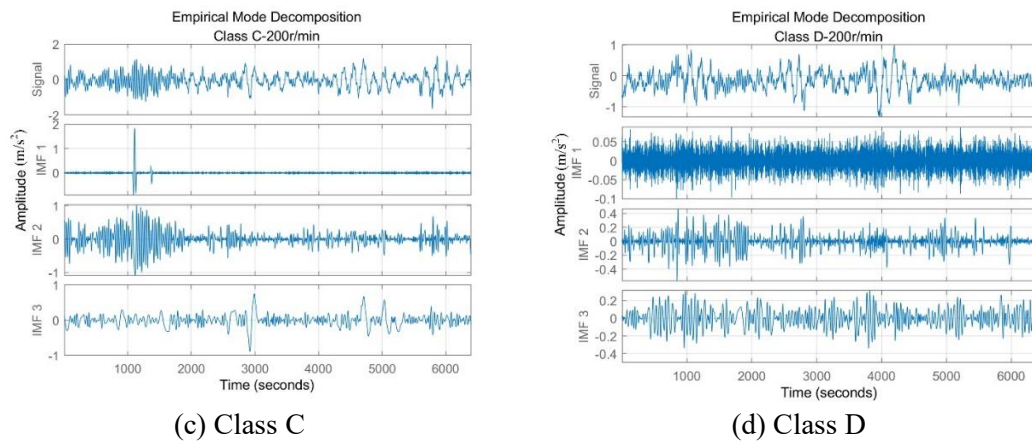(c) Class C   (d) Class D

Figure 8. EMD results of different degree of buckling

Figure 9 shows the envelope analysis in first-order IMF obtained by Hilbert transform.
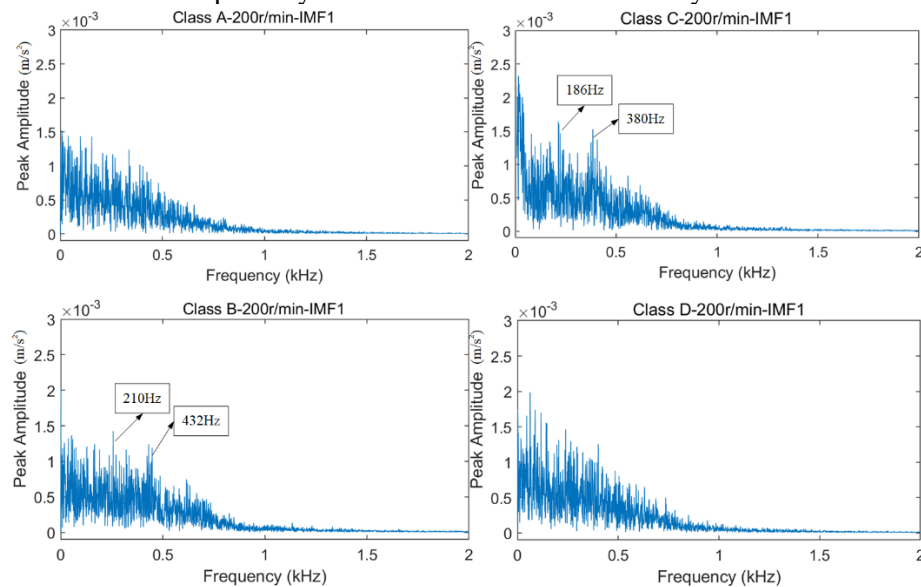

Figure 9. Envelope analysis of the four signals

As can be seen from Figure 9, the waveforms of state A and D are substantially the same while the waveforms of state B and state C are substantially the same. Higher peaks at 186 Hz and 210 Hz are found in the vibration signals of the B and C, respectively. Moreover, similar peaks are found at their double frequencies, which is quite different from A and D.

In order to intuitively express the abnormality of the vibration signal of the wet clutch in the early failure state. As shown in Figure 10, the spectrograms of four signals are attained by taking 3D-FFT to observe the change of the frequency in the time dimension. Where the lateral axis represents time, the vertical axis is frequency, and the graphic color represents amplitude.
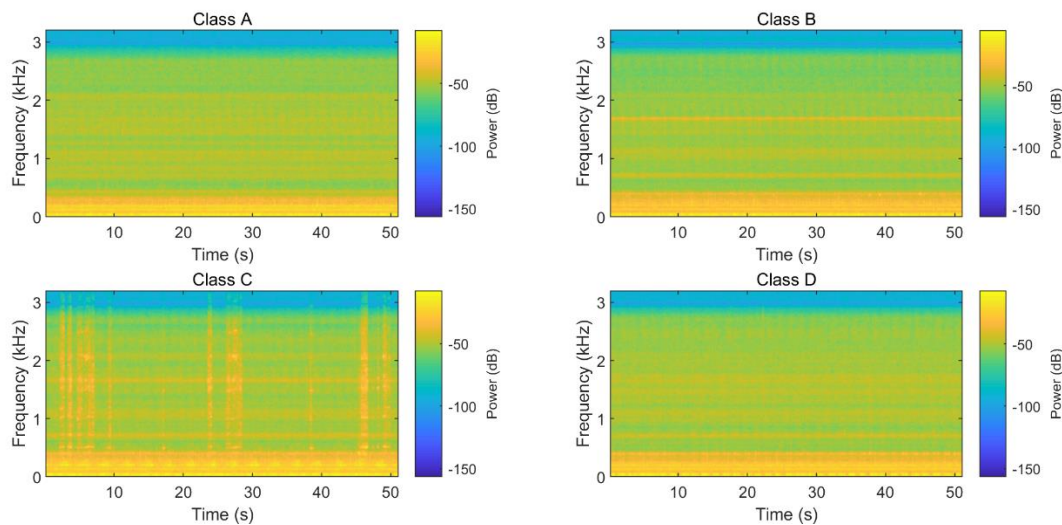
Figure 10. Envelope analysis of the four signals

The figure shows that clear longitudinal fringes appear in the spectrogram in class C, indicating that the system exhibits a full-band equal-amplitude vibration at a certain moment, which means a shock signal is generated periodically. This suggests that the buckled separate disk and friction disk in class C experiences collision during the rotation process thus to produce a detectable periodic vibration signal.

However, no obvious impact signals are detected in the B and D. For class D, this may be due to the severe buckling of the pair that leaves zero space in the clutch pack, so the disks are continuously slipping instead of contact occasionally. As for state B, friction disks are in slight buckling, so the gap between the friction pairs is larger than state C, therefore no obvious collision behavior occurs.

5. Conclusion
In this paper, the axial and circumferential vibration signals of wet clutches with different degrees of failure, namely normal condition, slight buckling, medium buckling, and severe buckling, are collected respectively. Then wavelet transform and empirical mode decomposition (EMD) are used to denoise and analyze the original signal, and the following conclusions are obtained:

(1) In the early failure stage of the wet clutch—the buckling of clutch disks would cause an abnormal shock vibration signal periodically due to the clutch rotation during the separated state.

(2) When the friction disk is seriously buckled, the clutch separation gap disappears although the clutch is in disengagement state. The buckled friction pairs are still in slip condition but the shock vibration signal is not obvious.

(3) Although the current signal processing methods have a limitation on the analysis of friction vibration, the signal based online monitoring has a prospect value for fault diagnosis of the wet clutch.

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