Application of Variational Mode Decomposition in Brake Sheet Defect detection

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Abstract: In view of the difficulty in detecting the internal defects of the brake pad, the internal defect detection of brake pads is realized by processing the knocking sound of brake pads. Firstly, the original signal is intercepted, then the intercepted signal is decomposed by using the theory of variational mode decomposition (VMD), and then the feature is extracted. By analyzing the frequency center and bandwidth of each mode layer, two important parameters of the variational mode decomposition algorithm are optimized: the number of modes K and the penalty factor alpha. The validation of K nearest neighbor (KNN) algorithm shows that the optimized variational mode decomposition method can improve the accuracy of internal defect detection of brake pads.

Keywords: *Brake Pad Internal Defect Modal Decomposition Feature Extraction*

I. INTRODUCTION

The development of automobile industry is very fast in recent years, Brake pad is an important part of vehicle safety guarantee, effective braking provides guarantee for safe driving, Therefore, the brake pad quality inspection is a very important procedure in the automobile production line, Because the brake pads are made of a variety of chemicals after being mixed and pressed, if there are cracks, foreign matters, bubbles and other problems inside[1], it is difficult to find them by naked eyes, so it can effectively solve this problem by analyzing the feedback sound of striking the brake pad to diagnose whether there is any defect in the brake pad.

At present, sound signal processing is widely used in defect detection, but it is rarely used in brake pad internal defect detection[2], in addition, the detection accuracy is generally not high,Due to the complexity of the collected brake pad sound signal, it is very difficult to extract features directly. The more complex the signal is, the more space it takes, the slower the computer processing speed will be, thus affecting the detection efficiency of the brake pad. In order to solve this problem, this paper applies the theory of variational mode division[3] (VMD) to the detection of internal defects of brake pads. Variational mode decomposition is an adaptive, quasi orthogonal, completely non recursive decomposition method, which can decompose the multi-component signal into several natural modes with limited bandwidth, and most of these modes are closely around its corresponding central frequency. By analyzing the frequency center and bandwidth of each layer mode, two important parameters of the algorithm are optimized: the number of modes K and the penalty factor α. After optimization, the decomposed AM-FM component signal will not produce modal aliasing[4], which is more conducive to the extraction of defect features and greatly improves the accuracy of classification.

II. INTERCEPTION OF ORIGINAL SIGNAL

The sound signal collected after the brake pad is knocked will show a certain rule[5], the amplitude at the knock point is large, and then the amplitude drops sharply with time to zero, Because the collected signal records the whole knocking process, no amplitude or small amplitude sound signal has little effect on feature extraction, but these data will occupy a certain memory space, the larger the memory, the slower the processing speed of the computer, and affect the detection efficiency. In order to obtain representative and effective signal information, the original sound signal is intercepted, as shown in Figure 1. After many experiments, it is determined that we intercept the data of the first 10 sampling points and the last 245 sampling points for subsequent experimental analysis[2].

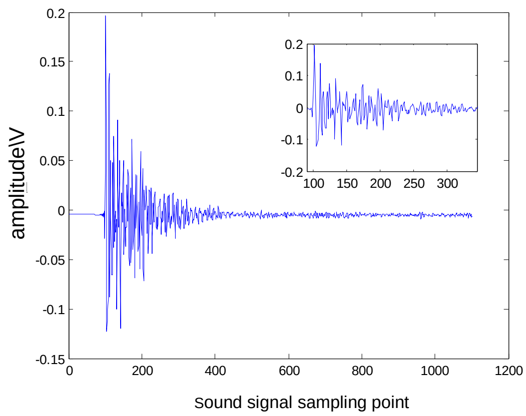


Figure 1 original sound signal interception

III. SIGNAL PROCESSING BY VARIATIONAL MODE DECOMPOSITION

Variational mode decomposition (VMD) is a new adaptive signal processing method proposed in 2014. At present, this method is widely used in signal processing. Its decomposition process is essentially the iterative solution of variational problem[2]. The specific algorithm process is as follows:

1、n=0，initialization $\{\hat{u}_k^1\}$, $\{w_k^1\}$, $\{\hat{\lambda}^1\}$;

2、Let k = 0, k = K + 1 update μ_k 、 ω_k according to formula (1) and formula (2)；

$$\hat{u}_k^{n+1}(w) = \frac{\hat{f}(\omega) - \sum_{i\neq k}\hat{u}_i(\omega) + \frac{\hat{\lambda}(\omega)}{2}}{1+2\alpha(\omega-\omega_k)^2} \quad (1)$$

$$\omega_k^{n+1} = \frac{\int_0^\infty \omega |\hat{u}_k(\omega)|^2 d\omega}{\int_0^\infty |\hat{u}_k(\omega)|^2 d\omega} \quad (2)$$

3: update λ :

$$\hat{\lambda}^{n+1}(\omega) \leftarrow \hat{\lambda}^n(\omega) + \tau\left[\hat{f}(\omega) - \sum_k \hat{u}_k^{n+1}(\omega)\right] \quad (3)$$

τ indicates the noise tolerance parameter;

4、Repeat steps 2 and 3, and stop the iteration according to the given discrimination accuracy $e > 0$ until the following formula is met.

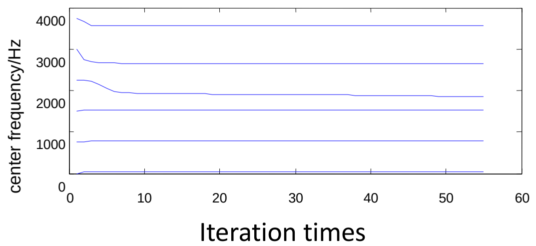
$$\frac{\sum_k \left\|\hat{u}_k^{n+1} - \hat{u}_k^n\right\|_2^2}{\left\|\hat{u}_k^n\right\|_2^2} < e \quad (4)$$

A. Determination of the number k of VMD modes

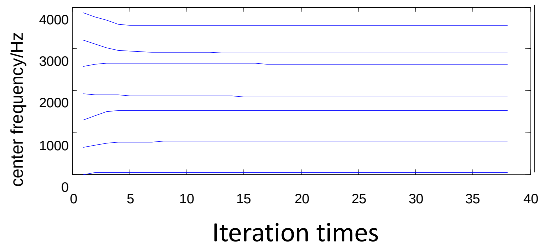
The number of modes K needs to be preset for VMD decomposition. At present, there is no effective method to determine the number. Empirical and test methods are often used to determine the number[6], If the value of K is set too small, there will be under decomposition and incomplete decomposition. If the value of K is set too large, there will be over decomposition, which will make the frequency overlap and increase the calculation pressure. The specific process of optimization parameters proposed in this paper is as follows:

1. VMD decomposition of input signal data operation, Penalty factor, noise tolerance parameter and discrimination precision adopt VMD default value: $\alpha = 2000$, τ=0, ε=1.0×10^{-7};
2. Through experience and test, the signal spectrum is given initial value of K, K=3;
3. To judge whether the center frequency overlaps, set the threshold value to 5%, and judge the overlaps based on the definition that the difference between the center frequencies of adjacent modal frequencies is less than 5% compared with the result of upper and lower frequencies, Namely $(f_{n+1} - f_n)/f_n < 5\%$, So as to realize automatic judgment;
4. If the center frequency overlaps, k-1 reduces the number of modes until the phenomenon of center frequency overlaps no longer occurs, and outputs K value;
5. If the center frequency does not overlap, increase the number of modes at K + 1 until the center frequency overlaps, and output the value of k-1。

After many calculations, we can see that the mode center frequency is overlapped when k = 7 according to the mode center frequency iteration curve under the two K values when k = 6 and K = 7. Therefore, the VMD decomposition layer number k = 6 is determined, as shown in Figure 2.



(a) K=6

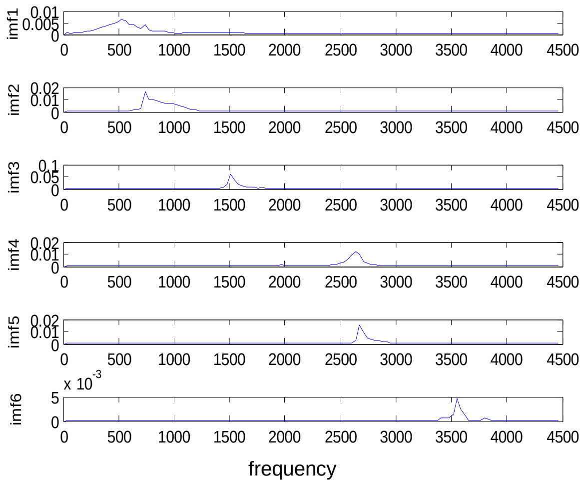


(b) K=7

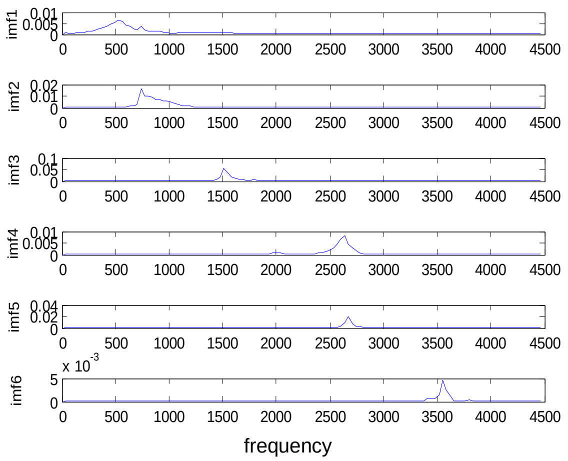
Figure 2: Convergence process of central frequency at k = 6 and K = 7

B. Determination of penalty factor α

In order to change constrained variational problem into unconstrained variational problem, penalty factor α is introduced. Different α setting values will get different decomposition effects of VMD, which mainly affects the bandwidth and convergence speed of each mode[7]. The smaller α is, the larger the bandwidth of the IMF component is. The larger α is, the smaller the signal bandwidth of the modal component is[8]. Too small or too large a value will affect the calculation time. In this paper, the α value is determined by experiments. The range of α value is from 200-10000. The effect of different values on decomposition results is observed. When the penalty factor is small, the bandwidth is obviously large, and the same frequency component appears in two modes, resulting in mode aliasing, which exists when the α value is between 200-2000.When the α value is between 2000-8000, the phenomenon of modal aliasing is reduced, the bandwidth is narrowed and the spectral difference is smaller. Only two decomposition results are listed in limited space, as shown in Figure 3:



(a) α=800



（b）α=2000

Figure 3: Effect of penalty factor on decomposition results

In addition, through the MATLAB calculation time statistics, it is found that when the value of α is too low or too large, the calculation time will increase, as shown in Table 1. Finally, through repeated experiments, it is determined that α=5000 is suitable for the data in this paper

Table 1 impact of penalty factors on calculation time

Penalty factor	VMD run time（s）
200	0.7135
400	0.5648
800	0.4298
1600	0.4246
3200	0.3623
6400	0.4034
12800	0.3821

When k = 6, α = 5000, VMD decomposition results and modal spectrum are shown in Figure 4 and figure 5:

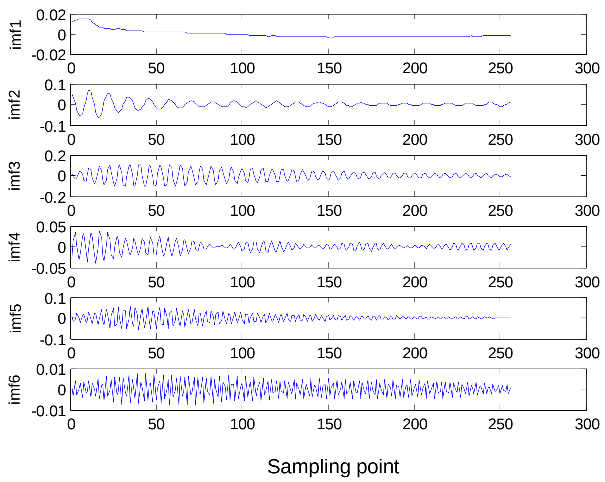


Figure 4: VMD decomposition results

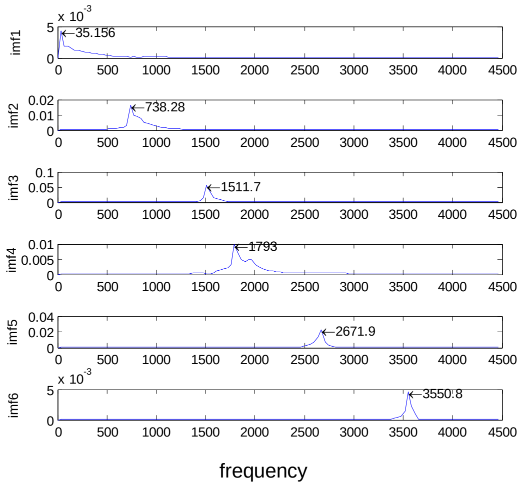


Figure 5 spectrum of modes

IV. VMD energy feature extraction and classification

The frequency band energy ratio of the modal components generated by VMD decomposition is taken as the eigenvector[9], and the steps of energy feature extraction are as follows[2]：

VMD is used to decompose the signal to be measured, and 6 modal components $u_i(i=1,2,3\ldots6)$ are obtained；

2、Calculate the energy of each mode separately, $E_i=\sum_{n=1}^{N}|u_i|^2(i=1,2,3\ldots6)$,N is the number of sampling points, and the total energy is $E=\sum_{i=1}^{6}E_i$ ；

3、Obtaining energy characteristics，$P_i=\frac{E_i}{E}(i=1,2,3\ldots6)$.

The internal defects of brake pads are mainly composed of four situations. According to different defect forms, the energy of various defect characteristics is calculated as shown in Table 2.

Table 2: Energy characteristics of VMD

type / Modality	good	foreig n body	Layer ed	Latera l fissure
IMF1	0.0576	0.0543	0.0873	0.0832
IMF2	0.2303	0.3130	0.2790	0.4659
IMF3	0.4299	0.3916	0.2999	0.1764
IMF4	0.1779	0.1851	0.2212	0.1651
IMF5	0.0262	0.0418	0.0569	0.0627
IMF6	0.0781	0.0142	0.0557	0.0466

According to the statistical energy characteristics of VMD decomposition and wavelet packet decomposition, the k nearest neighbor algorithm is used for three times of verification, and the results are shown in Table 3.

Table 3: Accuracy of KNN classification

Number of experiments	Wavelet packet decomposition	VMD decomposition
The first time	82.5%	90.9%
The second time	82.6%	91.3%
The third time	81.2%	92.2%

CONCLUSION

In this paper, the variational mode decomposition theory is studied. The number of modes K and the parameter of penalty factor α are analyzed. The number of decomposition layers K is determined by judging whether the center frequency is overlapped or not. The effect of penalty factor on decomposition effect and calculation speed is tested to determine α . the modal energy characteristics are extracted and the energy distribution is compared. Through the test of k nearest neighbor classification [10] algorithm, the theory of variational mode decomposition (VMD) is applied to the detection of internal defects of brake pads to improve the accuracy of classification.

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