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Fault Diagnosis and Analysis of Diesel Engine Valve Mechanism Based on ITD

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Abstract: In order to better diagnose and analyze faults in diesel engine valve train, this paper first simulates four working conditions: normal valve clearance, small clearance, large clearance, and coupling of strut bending by adjusting valve clearance and replacing the tappet. Cylinder head vibration signals are collected at idle speed of 700 rpm; Then, the ITD algorithm is used to decompose the signal, extract marginal spectral features, and select 12 frequency domain features to construct a fault feature vector; finally
Using ITD marginal spectrum and Mahalanobis distance for fault identification, the results showed that there were significant differences in ITD marginal spectrum under different operating conditions. Among the 12 test samples, there were 0 false positives, and the diagnostic accuracy reached 100%. Research has shown that the ITD marginal spectrum can effectively characterize the fault characteristics of diesel engine valve mechanisms, providing a new approach for fault diagnosis of non-stationary vibration signals.

Keywords: diesel engine valve mechanism; Inherent time scale decomposition; marginal spectral analysis; fault diagnosis

1. INTRODUCTION

Diesel engines have numerous excitation sources and complex structures, and their vibration signals have typical non-stationary and nonlinear characteristics. Therefore, traditional signal analysis methods based on the assumption of signal stationarity are difficult to achieve satisfactory results in diesel engine vibration analysis. In recent years, non-stationary signal analysis methods represented by EMD and LMD have been successfully applied in diesel engine fault diagnosis. However, EMD has problems such as "over enveloping" and "under enveloping", while LMD has difficulties in selecting sliding step sizes and decomposition non convergence caused by demodulation. The ITD method utilizes bilinear transformation of extreme points to obtain baseline signals, thereby avoiding the "over envelope" and "under envelope" problems caused by spline interpolation in EMD. The ITD algorithm is significantly superior to EMD and LMD methods in terms of computational efficiency and endpoint effects. It has been successfully applied in the analysis of EEG signals and bearing vibration signals. In this chapter, the ITD method is introduced into the analysis of diesel engine cylinder head vibration signals, and the ITD marginal spectrum is used to diagnose typical valve mechanism faults in diesel engines.

2. VIBRATION SIGNAL ACQUISITION OF DIESEL ENGINE VALVE TRAIN

Valve mechanism failure is a relatively high proportion of diesel engine failures. A small valve clearance can cause the valve to close loosely, resulting in air leakage and often causing erosion of the working surface between the valve and the valve seat. Excessive valve clearance can reduce valve opening, leading to increased intake and exhaust resistance and decreased intake volume. In addition, it will increase the impact force of the transmission mechanism on the valves, resulting in abnormal noise and "rebound" phenomenon during the operation of the valve mechanism. A small or large valve clearance will cause the opening and closing timing, as well as the rising and falling patterns of the valves, to be inconsistent with the original design requirements, resulting in a significant decrease in the power and economy of the engine.

Table 1. Vibration signal type setting

	Intake valve clearance(mm)	Exhaust valve clearance(mm)	Working condition
1	0.30	0.50	Normal
2	0.20	0.40	relatively small Valve Clearance
3	0.40	0.60	Excessive valve clearance
4	0.40	0.60	Coupling

Due to the direct impact of the valve mechanism on the cylinder head and the convenience of installing sensors on the cylinder head without damaging the diesel engine structure, as well as the minimal interference from neighboring cylinders at a certain cylinder head, the vibration acceleration sensor was arranged on the first cylinder head in this experiment.

Three common faults of the valve train were simulated on the experimental platform. The abnormal valve clearance fault was achieved by adjusting the valve bolt with a caliper, and the bending fault of the tappet was achieved by replacing the faulty tappet. In order to make fault detection as simple as possible, reduce speed fluctuations and fuel consumption during the experimental process, the test speed is selected as idle speed of about 700 rpm. Based on the above settings, vibration signals of the diesel engine under normal and three fault conditions are collected. Several samples are collected for each condition, and each sample corresponds to a complete diesel engine working cycle with 4389 sampling points. The time-domain waveforms of cylinder head vibration signals under normal and 5 fault conditions are shown in Figures 1 to 4.

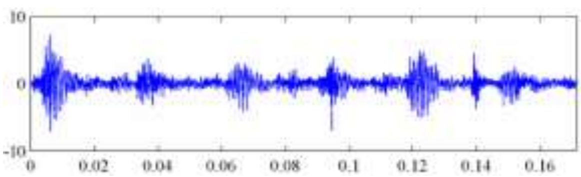

Figure. 1 Vibration signals of the diesel engine in normal condition

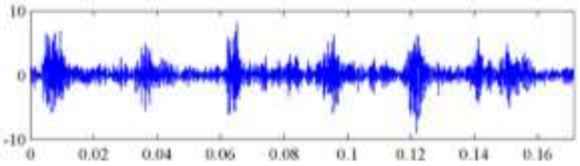

Figure. 2 Vibration signals of the diesel engine valve train in slightly tight clearance condition

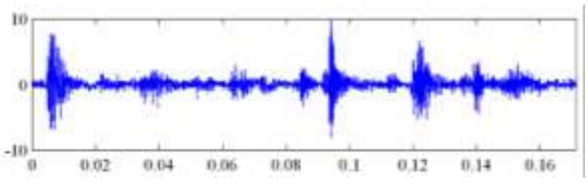

Figure. 3 Vibration signals of the diesel engine valve train in slightly excessive clearance condition

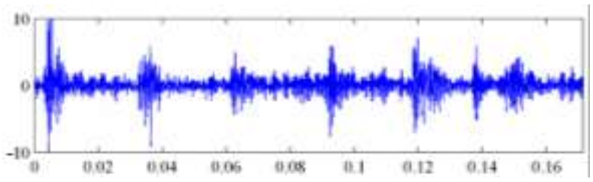

Figure.4 Vibration signals of the diesel engine valve train in excessive clearance with bent valve tappet condition

3. FAULT DIAGNOSIS OF DIESEL ENGINE VALVE MECHANISM USING ITD MARGINAL SPECTRUM

Introduce the ITD algorithm into diesel engine fault diagnosis and explore its application in valve mechanism fault diagnosis through marginal spectral analysis.

Perform Hilbert transform on all PRC_i components,

$$H=[\mathrm{PRC}_i(t)]=\frac{1}{\pi}\int_{-\infty}^{\infty}\frac{\mathrm{PRC}_i(t')}{t-t'}dt' \quad (1)$$

$$s(t)=\mathrm{PRC}_i(t)+jH[\mathrm{PRC}_i(t)]=a_i(t)\cdot e^{j\phi_i(t)} \quad (2)$$

Calculate the instantaneous amplitude $a_i(t)$ using formula (2)

$$a_i(t)=\sqrt{\mathrm{PRC}_i^2(t)+H^2[\mathrm{PRC}_i(t)]} \quad (3)$$

Using formula (3) to calculate the instantaneous corresponding value of $\phi_i(t)$

$$\phi_i(t)=tg^{-1}\frac{H[\mathrm{PRC}_i(t)]}{PRC_i(t)} \quad (4)$$

Calculate instantaneous frequency using formula (4)

$$\omega_i(t)=\frac{1}{2\pi}\frac{d\phi_i(t)}{dt}=\frac{\theta_i(t)}{2\pi} \quad (5)$$

Combine all $a_i(t)$ and $\omega_i(t)$ to obtain the time-frequency distribution of the signal

$$H(\omega_i t)=\mathrm{Re}\sum_{i=1}^{n}a_i(t)\mathrm{e}^{j\int\omega_i(t)dt} \quad (6)$$

In the formula, Re is the real part operation and j is the imaginary unit.

Define ITD marginal spectrum

$$h(\omega)=\int_0^T H(\omega,t)dt \quad (7)$$

In the formula, T is the signal time length.

Diesel engine fault diagnosis method based on ITD marginal spectrum and Mahalanobis distance, the specific process is as follows

Step 1: Obtain 30 samples for each of the six operating conditions of the diesel engine valve mechanism through experiments;

Step 2: Calculate the ITD marginal spectrum of each sample, The marginal spectra of each operating condition sample are shown in Figures 5 to 8. Due to the length of the article, only one ITD marginal spectrum of each sample is provided for each operating condition;

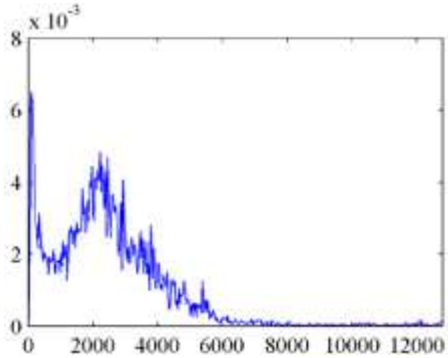

Figure.5 ITD marginal spectrum of the diesel engine in normal condition

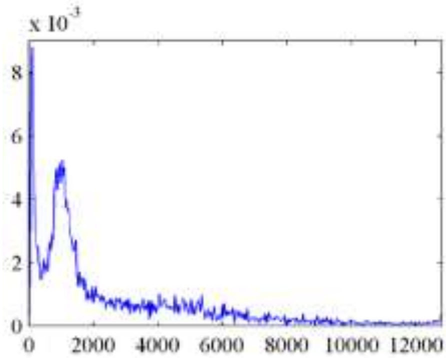

Figure.6 ITD marginal spectrum of the diesel engine valve train in slightly tight clearance condition

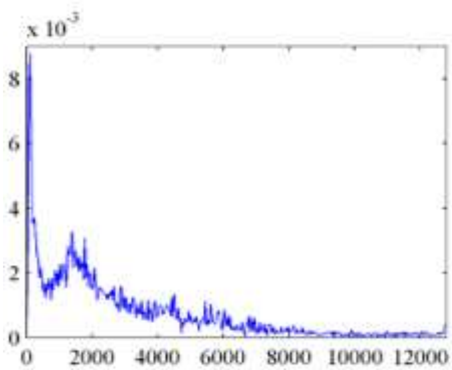

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Figure.7 ITD marginal spectrum of the diesel engine in slightly excessive condition

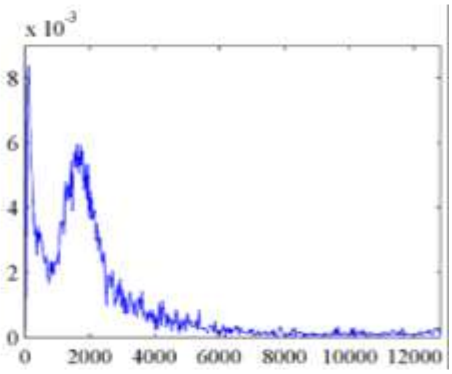

Figure.8 ITD marginal spectrum of vibration signal in valve clearance coupling state

Step 3: By observing the ITD marginal spectra of vibration signals in different states, it can be found that there are significant differences in the ITD marginal spectra of vibration signals in different states. In addition, the ITD marginal spectra of vibration signals in the same state are relatively similar. Valve seat impact mainly causes changes in the 1KHz-9KHz frequency band, with particularly significant changes in the 2KHz-6KHz frequency band. Therefore, the 1KHz-9KHz frequency band is selected for analysis;

Step 4: Randomly select 20 samples from each working condition as training samples, and use the remaining 10 sets of samples for testing;

Step 5: Calculate 12 frequency domain features of ITD marginal spectrum sensitive frequency bands as fault features; In order to eliminate the influence of various feature value ranges on the fault diagnosis results, all fault features were normalized to between 0 and 1, and some fault feature vectors are shown in Table 2;

Table 2. Part of the fault feature vectors

State	Fault feature vector					
Normal valve clearance	f_1	0.02	f_5	0.91	f_9	0.31
	f_2	0.76	f_6	0.85	f_{10}	0.67
	f_3	0.91	f_7	0.85	f_{11}	0.39
	f_4	0.14	f_8	0.95	f_{12}	0.14
Small valve clearance	f_1	1.00	f_5	0.21	f_9	0.74
	f_2	0.44	f_6	0.08	f_{10}	0.04
	f_3	0.29	f_7	0.22	f_{11}	0.38
	f_4	0.56	f_8	0.07	f_{12}	0.13
Large valve clearance	f_1	0.23	f_5	0.32	f_9	0.45
	f_2	0.91	f_6	0.17	f_{10}	0.55
	f_3	0.94	f_7	0.82	f_{11}	0.37
	f_4	0.03	f_8	0.84	f_{12}	0.07
Coupling fault	f_1	0.85	f_5	0.45	f_9	0.04
	f_2	0.10	f_6	0.21	f_{10}	0.99
	f_3	0.12	f_7	0.58	f_{11}	0.86
	f_4	0.87	f_8	0.48	f_{12}	0.65

Step 6: Calculate the class centers and covariance matrix C_i of all training samples under each operating condition. i=1, 2, 3, 4, 5, and 6 correspond to the six working states of the diesel engine mentioned above.

Step 7: Calculate the Mahalanobis distance between the test sample S_c and the center of each category:

$$d_i = (S_c - \bar{S}_i) C_i^{-1} (S_c - \bar{S}_i)^T \quad (i = 1,2,3,4,5) \qquad (8)$$

Step 8: Compare d_1, The size of d_2, d_3, d_4, d_5, d_6, and the fault type of the test sample correspond to the category of the minimum distance.

Table 3. Part of the fault diagnosis results

	d_1	d_2	d_3	d_4	d_5	d_6	result
1	12.09	563.57	1555.29	934.42	573.17	1165.71	smaller
2	13.35	556.59	1543.97	926.06	574.30	1169.61	smaller
3	6.71	564.63	1553.15	934.70	571.87	1165.12	smaller
4	1607.44	1295.37	105.25	1050.40	1746.05	2196.03	normal
5	1575.53	1413.83	356.47	1275.92	1611.77	1946.96	normal
6	1562.99	1279.53	27.08	1056.19	1689.34	2119.44	normal
7	1072.21	561.80	958.52	152.37	1452.53	2063.63	larger
8	946.95	417.01	1020.68	93.00	1314.79	1960.74	larger
9	937.23	405.04	1044.08	50.78	1319.41	1958.72	larger
10	1268.99	1744.08	2181.35	2057.27	903.85	113.46	coupling
11	1069.87	1551.82	2032.85	1869.66	714.29	100.85	coupling
12	1474.42	1955.10	2373.04	2275.44	1066.14	325.12	coupling

The diagnostic results showed that there were 0 false positives in the 12 test samples, with a diagnostic accuracy of 100%. Some diagnostic results are shown in Table 3. The diagnostic results indicate that the use of ITD and Mahalanobis distance can provide a more accurate diagnosis of valve mechanism faults.

4. CONCLUSION

This article introduces commonly used adaptive time-frequency analysis methods and studies the basic principles of ITD methods. Introducing the ITD method into diesel engine fault diagnosis, a diesel engine valve train fault diagnosis method based on ITD marginal spectrum and Mahalanobis distance is proposed. The diagnostic results show that this method can accurately identify typical valve train faults.

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