Piston Pin Fault Detection Using A-AWH Algorithm

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Abstract. Engine vibration signal contains significant noise. It always is unstable in the time domain. It’s difficult to detect the piston pin with improper eccentricity using vibration signal features. For improving the effectiveness of fault detection, a new algorithm using Angle domain synchronous average. Wavelet packet analysis and Hilbert transform (A-AWH) is proposed, which mainly contains: the method of equal angle sampling is adopted to acquire the rotational vibration signal from an engine; To acquire de-noised signal, the algorithm of angle domain synchronous average is then used; and the de-noise signal are processed by wavelet packet analysis; finally, the angle domain fault features are extracted by Hilbert transform. The effectiveness of the A-AWH algorithm is verified by applying it to the signals recorded from the engine with an eccentric piston pin. With this algorithm, some useful features can be extracted from the vibration signal, which demonstrates that the A-AWH algorithm can provide a new approach of engine faults detection.

Introduction

Eccentricity of a piston pin is a common machining error in piston machining. A piston with proper eccentricity will decrease the side-thrust of the piston, while a piston with improper eccentricity will intensify the effect of piston slap, which lead to an increase of cylinder block’s vibration level. However, engine vibration signals contain strong noise and instability in the time domain. It's difficult to extract the piston slap impact and detect fault for the piston pin with improper eccentricity using signal features.

In 1995, SAM D. HADDAD investigated piston motion of a diesel engine, and a computer program was written to predict optimum designs for low noise [1,2]. S.-H. CHO proposed an analytical model to predict engine block’s vibratory response caused by the piston slap [3]. H. Zheng presented finite element model of piston-cylinder liner in a diesel engine. And the vibration response caused by piston slap was analyzed by adopted finite element method [4]. Z. Geng proposed a nonlinear model of a piston-cylinder liner, and analyzed the effect of cylinder block surface’s vibration characteristics on fit clearance of piston-cylinder liner [5]. Yeow-Chong Tan acquired motion characteristics of the piston in a two-stroke engine, and analyzed the effect of piston-slap impact on lubricating oil, rotating speed of the engine and so on [6]. Xianhua Liu and C. Servière extracted piston slap impact by using blind source separation algorithm respectively [7,8]. Kamal Jafarian investigated the misfire and valve clearance faults using the multi-sensor vibration signal [9].

In conclusion, previous methods of piston-slap impact extraction and piston pin fault detection have focused on the study of engine vibration signal features in the time domain and in the frequency domain. Vibration signal from engines contains strong noise and instability. The characteristics of piston slap impact signals can’t be easily extracted using traditional methods. In order to improve the precision of piston pin with improper eccentricity fault detection and diagnosis, a new algorithm using Angle domain synchronous average, Wavelet packet analysis and Hilbert transform (A-AWH) is proposed, which mainly contains: the method of equal angle sampling is adopted to acquire the rotational vibration signal from an engine; To acquire de-noised signal, the angle domain synchronous average algorithm is then used; and the de-noise signal are processed by wavelet packet analysis; finally, the fault features of engine vibration signal are extracted by Hilbert
transform. The effectiveness of the A-AWH algorithm is verified by experimental results of engines with an eccentric piston pin. The algorithm shows a new approach of engine incipient faults detection and diagnosis.

A-AWH Algorithm

In order to detect the piston pin fault, A-AWH algorithm is proposed. Figure 1 refers as the flowchart of this algorithm.

![Flow chart of piston pin fault detection.](image)

**Equal Angle Sampling**

As the parameter of the sample data points, time is usually used to measure dynamic signals in the time domain. But vibration signals from engines are unstable in the time domain because of crankshaft motion including some fluctuations of rotational speed. As the angle domain sample parameter, the crank angle is used to control the sample interval in the method of equal angle sampling. During every operating cycle, the sample spacing of angle domain signal is repeated accurately. The recorded signal is then more clearly deterministic, the engine vibration signal can be regarded as a periodic signal in the angle domain, and the influence of speed fluctuations is eliminated [10].

**Angle Domain Synchronous Average**

Engines generate impact excitations because of complicated internal structures and mechanisms. Background noise will overwhelm piston slap signals. The noise can be suppressed by using the algorithm of angle domain synchronous average [10]. The specific algorithm is as follows.

If the sampling sequence in the angle domain is \( x(\theta) \) with an interval \( \Delta \theta \), \( \theta = 1, 2, 3, ..., N_1 \), the algorithm of angle domain synchronous average can be expressed as [11]:

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\[ y(\theta_i) = \frac{1}{L} \sum_{k=0}^{L-1} x(\theta_i - kN) \quad \theta_i = N_i - N + 1, N_i - N + 2, \ldots, N_i \] (1)

Then, \( y(\theta_i) \) is a new sequence in the angle domain after synchronous average, where \( L \) is the number of average periods; and \( N \) is the number of samples in each average, \( N = \frac{360n}{\Delta \theta}, n = 1, 2, 3, \ldots \).

It is known that the power of random noise reduces to \( \frac{1}{L} \), and the signal-to-noise ratio can increase by \( \sqrt{\frac{1}{L}} \) after synchronous average.

### Wavelet Packet Analysis

Piston slap signals can be extracted by using wavelet packet analysis [5] in angle domain. If equal angle sampled signal is \( x(\theta), \theta = 1, 2, 3, \ldots, N \), which is decomposed as \( a \) layers by wavelet packet decomposition algorithm, there can be \( 2^a \) son order signals and \( 2^{J-a} \) data points in each son order signal, where \( J = \log_2 N, a = 1, 2, 3, \ldots, J \). It can be shown as Figure 2.

![Wavelet packet decomposition algorithm](image)

Each son order signal correspond to a certain mother order signal after wavelet packet decomposition in angle domain, and the degree of correlation between son order signal and mother order signal is reflected by the correlation coefficient of them, which can be considered as a standard that information of son order signal inherit from mother order signal. According to this, the correlation coefficient of son order signal and mother order signal can be expressed as:

\[ \rho_{a,c} = \frac{\sum_{n=1}^{N} x(a,b) \sum_{n=1}^{N} x(a+1,c)}{\sqrt{\sum_{n=1}^{N} x(a,b)^2 \sum_{n=1}^{N} x(a+1,c)^2}} \] (2)

Where \( x(a,b) \) — \( a \) th layer, \( b \) th group order signal after wavelet packet decomposition in angle domain; and \( x(a+1,c) \) — Son order signal of \( x(a,b), c = 2b, 2b+1 \);

The son order signal corresponding to \( \max \{\rho_{a,c}\} \) can be defined as characteristic order signal of equal angle sampled signal reasonably.

### Hilbert Transform

If equal angle sampled signal is \( x(\theta) \), Adopting Hilbert transform, \( x(\theta) \) can be repressed as [12]:

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\hat{\theta}(\theta) = H \{ x(\theta) \} = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\theta)}{\theta - \phi} d\phi \tag{3}

The analytic signal consists of \( x(\theta) \) and \( \hat{x}(\theta) \). It can be repressed as [12]:

\[ z(\theta) = x(\theta) + j\hat{x}(\theta) \tag{4} \]

The envelope signal can be repressed as [12]:

\[ \alpha(\theta) = \sqrt{x^2(\theta) + \hat{x}^2(\theta)} \tag{5} \]

The envelope signal is processed by using order analysis, and the envelope spectrum of angle domain signal from engine can be acquired. It embodies the information of piston slap, which will be a proof of piston pin fault detection.

**Experimental Results and Discussion**

**Engine bench test and signal collecting system**

![Engine bench test and signal collecting system](Figure 3. Engine bench test and signal collecting system.)

The engine bench test and signal collecting system contain: single-cylinder four-stroke engine, encoder, accelerometer, signal conditioner and data acquisition card. The signal collecting system is shown in Figure 3. The measuring point is located on the cylinder block's liner of engine. The encoder is installed in the front of the engine crankshaft. 360 electrical impulses can be triggered per cycle, which are viewed as triggers for the samples to be obtained. Figure 4 shows the fault setting, which is an improper eccentricity of piston pin. The experiment conditions are shown in Table 1.

![Piston pin with improper eccentricity](Figure 4. Piston pin with improper eccentricity.)
Table 1. Experiment conditions.

| Operating Condition | Δ [mm] | Rotational Speed [r/min] | Load [N·m] |
|---------------------|--------|--------------------------|------------|
| Normal              | 1      | 1200                     | 0          |
| Fault#1             | 0.5    | 1200                     | 0          |
| Fault#2             | 0      | 1200                     | 0          |
| Fault#3             | 1.5    | 1200                     | 0          |
| Fault#4             | 2      | 1200                     | 0          |

Angle domain signal features in normal condition

![Figure 5](image1.png)

Figure 5. Angle domain signal in normal condition ((a) Original signal; (b) De-noised signal).

Figure 5 refers as the original angle domain vibration signal and the de-noised vibration signal of a stroke in normal condition. Figure 5 shows that the algorithm of angle domain synchronous average can suppress white noise, and increase the signal-to-noise ratio effectively. Choosing mother function db3, de-noised angle domain signal is processed by 4 layers wavelet packet decomposition, and the correlation coefficients of son order signal and mother order signal are calculated. The decomposition result is shown as Figure 6, and the correlation coefficients are shown as Table 2.

![Figure 6](image2.png)

Figure 6. The result of angel domain vibration signal is processed by wavelet decomposition in normal condition.
Table 2. Correlation coefficients of son order signal and mother order signal in normal condition.

|    | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0  |     | 1   |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| 1  |     |     | 0.74|     |     |     |     |     |     |     |     |     |     |     |     |     |
| 2  |     | 0.95|     | 0.32|     | 0.89|     |     |     |     |     |     |     |     |     |     |
| 3  | 0.53 |     | 0.85|     | 0.76| 0.78|     | 0.63|     | 0.54|     | 0.84|     |     |     |     |
| 4  | 0.45| 0.89| 0.33| 0.94| 0.69| 0.73| 0.82| 0.57| 0.63| 0.78| 0.58| 0.82| 0.60| 0.80| 0.77| 0.64|

After angle domain vibration signal is processed by 4 layers wavelet packet decomposition, the correlation coefficients of son order signal and mother order signal are shown as Table 2. From Table 2, the order signal (4, 3) is defined as the characteristic order signal, and the signal is shown as Figure 7 (a).

Figure 7 refers as the analysis results of angle domain signal in normal condition, and the characteristic order signal (4, 3) is shown as Figure 7 (a). Figure 7 (a) show that there are four times of piston slap impacts in one stroke. Among them, twice impacts occur at top dead center, and other twice impacts occur at bottom dead center. The signal is processed by using Hilbert transform and order analysis, and the order envelope spectrum of the characteristic order signal is acquired, which is shown as Figure 7 (b). Figure 7 (b) shows that the characteristic signal contains 0.5-order component, 1-order component and 2-order component. The meaning of 0.5-order is that it appears once for every two turns of the engine crankshaft, and it relate to the signal of combustion excitation. The meaning of 1-order is that it appears once for every crankshaft turn, and it relate to the signal of engine crankshaft rotation. The meaning of 2-order is that it appears twice for every crankshaft turn, and it relate to the impact signal caused by piston slap. Among them, the 2-order component is more dominant than the others. Therefore, the impact signal caused by piston slap can be effectively extracted by using A-AWH algorithm.

Fault Detection for Piston Pin with Improper Eccentricity

Through engine equal angle sampling experimental platform, angle domain vibration signals of the single-cylinder four-stroke engine are acquired under five conditions, which are shown as Figure 8. The vibration signals are processed by using A-AWH algorithm, and the analysis results are shown as Figure 9.
Conclusions

Engine vibration signals contain significant noise and instability. It's difficult to extract the piston slap impact and detect fault for the piston pin with improper eccentricity using signal features in the time domain.

The method of piston pin fault detection based on A-AWH algorithm is proposed here. The algorithm extracts piston slap impact signal and improves precision of the piston pin fault detection and diagnosis effectively.
From the experimental work involving piston with improper eccentricity, the effectiveness of the new fault detection and diagnosis method based on A-AWH algorithm is verified.

References

[1] Sam D. Haddad, Kek-Tjent Jan, An Analytical Study of Offset Piston And Crankshaft Designs And the Effect of Oil Film on Piston Slap Excitation in A Diesel Engine, Mech. Mach. Theory. 30 (1995) 271-284.

[2] Sam D. Haddad, Theoretical Treatment of Piston Motion in I.C. Piston Engine for the Prediction of Piston Slap Excitation, Mech. Mach. Theory. 30 (1995) 253-269.

[3] S.-H. Cho, S.-T. Ahn, Y.-H. Kim, A Simple Model to Estimate the Impact Force Induce by Piston Slap, Journal of Sound and vibration. 255 (2002) 229-242.

[4] H. Zheng, G. R. Liu, J. S. Tao, FEM/BEM analysis of diesel piston-slap induced ship hull vibration and underwater noise, Applied Acoustics. 62 (2001) 341-358.

[5] Z. Geng, J. Chen, Investigation into piston-slap-induced vibration for engine condition simulation and monitoring, Journal of Sound and Vibration. 282 (2005) 735–751.

[6] Yeow-Chong Tan, Zaidi Mohd Ripin, Frictional behavior of piston rings of small utility two-stroke engine under secondary motion of piston, Tribology International. 44 (2011) 592–602.

[7] Xianhua Liu, R.B. Randall, Blind source separation of internal combustion engine piston slap from other measured vibration signals, Mechanical Systems and Signal Processing. 19 (2005) 1196-1208.

[8] C. Servière, J.-L. Lacoume, M. El Badaoui, Separation of combustion noise and piston-slap in diesel engine-Part II: Separation of combustion noise and piston-slap using blind source separation methods, Mechanical Systems and Signal Processing. 19 (2005) 1218–1229.

[9] Kamal Jafarian, Mohammadsadegh Mobin, Ruholla Jafari-Marandi, et al, Misfire and valve clearance faults detection in the combustion engines based on a multi-sensor vibration signal monitoring, Measurement. 128 (2018) 527–536.

[10] Yimin Shao, Yan Ding, Chris K. Mechefske, Engine Fault Detection using Angle Domain Signal Envelope Algorithm, Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering. 227 (2013) 541–551.

[11] Kang Haiying, Qi Yanjie, Luan Junying, et al, Fault Diagnosis of Rolling Bearing Based on Wavelet packet and Order Envelope Spectrum, Bearing. 2 (2007) 37-40.