Engine Fault Detection Approach Based on Angle Domain Signal Model

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Abstract. Engine vibration signals include strong noise and non-stationary signals. By the time domain signal processing approach, it is hard to extract the failure features of engine vibration signals, so it is hard to identify engine failures. For improving the success rate of engine failure detection, an engine angle domain vibration signal model is established and an engine fault detection approach based on the signal model is proposed. The angle domain signal model reveals the modulation feature of the engine angular signal. The engine fault diagnosis approach based on the angle domain signal model involves equal angle sampling and envelope analysis of engine vibration signals. The engine bench test verifies the effectiveness of the engine fault diagnosis approach based on the angle domain signal model. In addition, this approach indicates a new path of engine fault diagnosis and detection.

1. Introduction

Engine is a kind of typical reciprocating and rotating machinery, featured by a complex structure, multiple excitation sources and unstable running. Therefore, engine failure diagnosis is always a difficulty in failure diagnosis. In 2003, Zunmin Geng put forward an engine vibration signal model, and extracted the failure feature of engine valve clearance by the wavelet packet decomposition approach [1]; A.P.Carlucci studied the relation between internal parameters and block surface vibration of IC engine by means of the conventional Fourier transform approach and the time-frequency analysis approach [2]; S. Vulli extracted the combustion impact signal in multiple excitation sources of a three-cylinder engine by the short-time fourier transform approach [3]; Fuzhou Feng applied the bispectrum and genetic neural algorithm to diagnose piston pin failures in diesel engines [4]; Wang Chengdong classified the failure degree of engine valve clearance using WVD and the neural network [5]; Chi-man Vong diagnosed the engine ignition system failure using the wavelet packet transform and the K-means clustering algorithm [6]; Based on the statistical approach, S.BabuDevasenapati used the decision tree approach to diagnose and classify misfire failures of a four-stroke engine [7]; Liu Jianmin established a BP neural network model to locate and diagnose the misfire failure of a diesel engine [8]; Kamal Jafarian used linear and non-linear approaches to detect the misfire and valve clearance failures of a single-cylinder engine [9]; K.L.P Tharanga extracted the combustion impact signal from the multiple excitation sources of the diesel engine and uses the signal to detect the running state of the diesel engine [10].

Some progress has been made in engine failure diagnosis approaches for angle domain signals. Yujun Li proposed an empirical mode decomposition approach based on the angular domain signals and extracted the failure features of piston ring wear by this approach [11]; Yimin SHAO detected the failure of the connecting rod bearing clearance of a single-cylinder engine in the angular domain [12]. To sum up, engine vibration signals are mostly analyzed in the time domain or the frequency domain in conventional engine failure diagnosis approaches, while the conventional angle domain analysis approach is also susceptible to strong noise and multiple excitation sources. The failure features of the
engine vibration signal, as a kind of non-stationary signal with strong noise, cannot be extracted accurately by the conventional analysis and processing approaches. For more accuracy of engine failure diagnosis, an engine angle domain vibration signal model is founded in this paper, based on which a new engine fault detection approach is proposed. The angle domain signal model reveals the modulation feature of the engine angle domain signal. The failure detection approach involves equal angle sampling and envelope analysis of engine vibration signals. The failure bench test of the connecting rod bearing clearance has verified the effectiveness of this algorithm, and some valuable theories are obtained, which provides a new path for the research of engine failure detection and diagnosis approach.

2. Engine Angle Domain Signal Model Based on Order Feature

When the engine runs normally, the vibration signals acquired by the sensor are composed of vibration signals of internal engine assemblies and vibration signals transmitted from other machinery or equipment. The components which are irrelevant to the vibration signal of internal assemblies can be regarded as noise signals. Therefore, the basic model of engine vibration signal can be represented as:

\[ s(\theta) = x(\theta) + r(\theta), \theta = 1, 2, 3, ..., N \]  

(1)

Where \( s(\theta) \) are signals acquired by the sensor, \( x(\theta) \) are signals of engine internal assemblies, \( r(\theta) \) are noise signals.

Due to the speed fluctuation, the engine vibration signals in the time domain are non-stationary, and such signals are not periodic. In the equal angle sampling, the crankshaft angle position signal can be accurately repeated in each revolution, which is a deterministic signal. Therefore, engine vibration signals are transformed from non-stationary signals in the time domain to stationary signals in the angular domain, eliminating the influence of random fluctuations in crankshaft speed [12].

According to the principle of equal angle sampling, the angular domain signals of engine internal assemblies can be perceived as stationary signals, which can be expressed by the following function:

\[ x(\theta) = \sum_{m=0}^{M} x_m \cos\left(\frac{2\pi \theta}{360} + \varphi_m\right) \]  

(2)

Where \( x_m \) is vibration amplitude at point \( m \) of angle domain vibration signal, \( \varphi_m \) is vibration phase at point \( m \) of angle domain vibration signal, \( \theta \) is crankshaft rotation angle.

When an engine operates, its internal assemblies (such as connecting rod bearing assembly and crankshaft assembly) will periodically collide with each other, thus generating periodic impact signals. Such impact signals often excite the natural frequency of the internal assemblies, which are modulated by the natural frequency of the system to generate modulated vibration signals of the engine. The vibration signals of the internal assemblies can be represented as:

\[ x(\theta) = \sum_{n=0}^{N} A_n \cos\left(\frac{2\pi O_n n \theta}{360} + a_n\right) \sin\left(2\pi O_c \frac{\theta}{360}\right) \]  

(3)

Where \( A_n \) is amplitude of order-\( n \) component of envelope signal, \( a_n \) is phase of order-\( n \) component of envelope signal, \( O_n \) is order component of envelope signal, \( O_c \) is order component of carrier signal.

Vibration signals of engine internal assemblies mainly include: gas impact signals, impact signals caused by reciprocating inertial force of piston, crankshaft rotation signals, piston knock signals, valve seating impact signals, impact signals generated by collision of lubricating oil with crankshaft case, impact signals of discharge valve fluid, etc. In this paper, gas impact signals and crankshaft rotation signals of engines are mainly considered, and other signals are regarded as noise signals. Thus, the angle domain vibration signal model in the normal state of an engine can be established as:
Where \( O_r \) is order component of gas impact signal, \( O_q \) is order component of crankshaft rotation signal.

In case of an engine failure, the component of the vibration signal due to the failure should also be considered. Therefore, in the failure state, the engine angle domain vibration signal model can be represented as follows:

\[
s(\theta) = \sum_{n=0}^{N} A_n \cos\left[ \frac{2\pi(O_r + O_q)n\theta}{360} + a_n \right] \sin\left(2\pi O_r \frac{\theta}{360}\right) + r(\theta)
\]

(4)

Where \( O_f \) is order component of vibration signal caused by failure.

3. Fault Detection Approach Based on Angle Domain Signal Model

The engine fault detection approach based on angle domain signal model is shown in figure 1.

![Engine fault detection approach based on angle domain signal model](image)

**Figure 1.** Engine fault detection approach based on angle domain signal model.

3.1. Equal Angle Sampling

According to the principle of equal angle sampling, as demonstrated in figure 2, the crankshaft rotation angle is taken as the sampling signal, the crankshaft angle position signal can be accurately repeated in each revolution. Therefore, engine vibration signals are transformed to stationary signals in the angular domain from non-stationary signals in the time domain, eliminating the influence of random fluctuations in crankshaft speed [12].
3.2. Envelope Analysis
According to the engine angle domain vibration signal model, the engine vibration signals have obvious modulation features. The internal impact signals include gas impact signal, crankshaft rotation signal, vibration signal caused by failure, etc., which will be modulated by the natural frequency of the system, thus generating the modulated vibration signals of the engine, as shown in formula (5). Therefore, the envelope signals of engine vibration signals include gas impact signals, crankshaft rotation signals and vibration signals caused by failures, and the envelope analysis and the envelope spectrum can be used to extract and identify the vibration signals, including gas impact signals, crankshaft rotation signals and vibration signals caused by failures, so as to detect the operating state of the engine.

4. Test Results and Discussion
4.1. Engine Bench Test

The data acquisition system is shown as figure 3. The system includes RT160 single-cylinder engine, accelerometer, optical encoder, signal conditioner, data acquisition card and computer. The optical encoder is set in the front of the crankshaft, together with the rotation of the crankshaft. The encoder can trigger 360 electrical impulses per cycle, which are regarded as the triggered signal, a sample is obtained when a pulse is triggered, and equal angle sampling will be realized. The monitoring point lies on the crankshaft bearing pedestal, with the piston moving in the same direction, and the failure setting is a fit clearance between the connecting rod and the crankshaft journal, as demonstrated in figure 4. The test conditions are detailed in table 1.
Figure 4. Drawing of connecting rod bearing with fit clearance.

Table 1. Test conditions.

| Operating Condition | Δ (mm) | Rotational Speed (r/min) | Load (Nm) |
|---------------------|--------|--------------------------|-----------|
| Normal              | 0.04   | 1800                     | 0         |
| Fault #1            | 0.07   | 1800                     | 0         |
| Fault #2            | 0.13   | 1800                     | 0         |
| Fault #3            | 0.19   | 1800                     | 0         |
| Fault #4            | 0.28   | 1800                     | 0         |

4.2. Signal Analysis under Normal Operating Conditions

Figure 5 shows the results of engine angle domain vibration signals and envelope analysis under normal operating conditions. Figure 5 (a) shows the original signal in angle domain. Because the engine vibration signal is featured by strong noise and signal modulation, the impact signal caused by the fit clearance of connecting rod bearing cannot be accurately identified only from the signal itself. Figure 5 (b) shows the envelope signal of the angle domain signal, and figure 5 (b) shows that the envelope signal of the angle domain signal has a relatively obvious periodic component, and an order analysis can be performed on the signal. Figure 5 (c) shows the envelope spectrum of the angle domain signal, and figure 5 (c) indicates that the signal mainly contains two components of 0.5-order and 1-order. Among them, the 0.5-order corresponds to the order component of the gas impact signal, which characterizes once occurrence every two revolutions of the crankshaft; and the 1-order corresponds to the order component of the impact signal caused by the fit clearance of the connecting rod bearing, which characterizes once occurrence every revolution of the crankshaft. In figure 5 (c),
the peak value of 1-order component is very clear, which can be used to extract the signal feature of the connecting rod bearing failure and detect the failure of the engine.

4.3. Comparison with Time domain Processing Approach

Figure 6. Comparison between the new approach and the time domain processing approach: (a) Envelope spectrum of angle domain signal; (b) Envelope spectrum of time domain signal.

The comparison of analysis results between the new method and the traditional time domain processing method under normal working conditions is shown in figure 6. Figure 6 (a) shows the envelope spectrum of angle domain signal, and figure 6 (b) shows the envelope spectrum obtained by using the traditional time domain signal analysis method. According to figure 6 (b), this signal mainly contains frequency components of 15 Hz and 30 Hz, respectively corresponding to the gas impact signal and the impact signal caused by the connecting rod bearing clearance when the crankshaft rotates at 1800 r/min. However, due to the fluctuation of engine speed, obvious frequency smears appear in the envelope spectrum of time domain signal, especially at 30 Hz, which makes it difficult to identify engine failure features. Compared to traditional analysis methods, the 0.5-order and 1-order components in figure 6 (a) are very clear, which helps to marking up the success rate of engine failure monitoring. Therefore, compared to the traditional time domain processing approach, the engine failure monitoring approach based on angle domain signal model has more advantages in failure feature recognition and extraction.

4.4. Analysis Results under Different Operating Conditions

Figure 7. Results comparison under five conditions: (a) Normal; (b) Fault #1; (c) Fault #2; (d) Fault #3; (e) Fault #4; (f) Waterfall spectrum.

The comparison of engine angular signals under five operating conditions is indicated in figure 7. Figure 7 indicates that the 1-order component caused by the fit clearance of the connecting rod bearing appear clearly in the analysis results of the five operating conditions, and with the increase of the fit clearance, the impact signal energy generated by the fit clearance increases gradually, and the amplitude of the 1-order component also gradually increases. Therefore, the signal processing
approach based on the angle domain vibration signal model can effectively obtain the information of engine failure, and the 1-order component in the analysis results can also be regarded as the basis of failure detection. By extracting this order component, the failure of the connecting rod bearing of the engine can be monitored.

5. Conclusion

Engine vibration signals contain strong noise and non-stationary signals. With the time domain signal processing approach, it is hard to extract the failure features of engine vibration signals, so it is hard to detect and diagnose engine failures.

The engine fault detection approach based on angle domain signal model is presented in this paper. The engine angle domain signal model reveals the stationary signal feature of engine angle domain signals and expounds the obvious modulation feature of engine vibration signals. Angle domain signal model takes into consideration the engine failure information and abundant information generated during the operation and can be taken as the theoretical basis for failure monitoring.

With the new fault detection approach, the gas impact signal as well as the impact signal caused by the fit clearance of the connecting rod bearing can be effectively extracted. Compared to the traditional time domain signal processing approach, this new fault detection approach can effectively obtain the engine failure information, thus increasing the success rate of engine failure monitoring.

The engine bench test has proved the effectiveness of the engine fault detection approach based on the angle domain signal model.

References

[1] ZunminGeng, Jin Chen and J.Barry Hull 2003 Analysis of engine vibration and design of an applicable diagnosing approach International Journal of Mechanical Sciences (vol 45) pp 1391-1410.

[2] A.P.Carlucci, F.F.Chiara and D.Laforgia 2006 Analysis of the relation between injection parameter variation and block vibration of an internal combustion diesel engine Journal of Sound and Vibration (vol 295) pp 141-164.

[3] S.Vullia, J.F.Dunne and R.Potenza 2009 Time-frequency analysis of single-point engine-block vibration measurements for multiple excitation-event identification Journal of Sound and Vibration (vol321) pp 1129-1143.

[4] Fuzhou Feng, Aiwei Si and Hongxing Zhang 2011 Research on fault diagnosis of diesel engine based on bispectrum analysis and genetic neural network Procedia Engineering (vol 15) pp 2454-2458.

[5] Wang Chengdong, Zhang Youyun and Zhong Zhenyuan 2008 Fault diagnosis for diesel valve trains based on time–frequency images Mechanical Systems and Signal Processing (vol 22) pp 1981 -1993.

[6] Chi-man Vong, Pak-kin Wong and Weng-fai Ip 2011 Case-based expert system using wavelet packet transform and kernel-based feature manipulation for engine ignition system diagnosis Engineering Applications of Artificial Intelligence (vol 24) pp 1281-1294.

[7] S.BabuDevasenapati, V.Sugumaran and K.I.Ramachandran 2010 Misfire identification in a four-stroke four-cylinder petrol engine using decision tree Expert Systems with Applications (vol 37) pp 2150-2160.

[8] Liu Jianmina, Li Xiaolei and Zhang Xiaoming 2011 Misfire diagnosis of diesel Engine based on rough set and neural network Procedia Engineering (vol 16) pp 224-229.

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

[10] K.L.P Tharanga, Shuyong Liu and Shuai Zhang 2020 Diesel Engine Fault Diagnosis with Vibration Signal Journal of Applied Mathematics and Physics (vol 8) pp 2031-2042.

[11] Yujun Li, Peter W.Tse and Xin Yang 2010 EMD-based fault diagnosis for abnormal clearance between contacting components in a diesel engine Mechanical Systems and Signal Processing (vol 24) pp 193-210.
[12] Yimin SHAO, Yan Ding and Chris K. Mechefske 2013 Engine Fault Detection using Angle Domain Signal Envelope Algorithm. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering (vol 227) pp 541–551.