COMBUSTION RELATED FUALT DIAGNOSIS OF LARGE DIESEL ENGINE BY ANALYSIS OF IAS BASED ON EEMD

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Large diesel engines with a high number of cylinders usually have high speed, complex crankshaft and load, which strongly complicate the diagnostics based on the instantaneous angular speed (IAS). In order to improve the discrimination of the fault features, the ensemble empirical mode decomposition (EEMD) is proposed to analyze the IAS signal. Experiments are performed on a V12 diesel engine whose injection timing is alternately 50°/70° in crank angle. First, the demodulated IAS signal is decomposed with EEMD into serial intrinsic mode functions (IMFs). Physical meaning of each IMF is explained. Then, normal and fault condition are compared by time-frequency spectrum of Hilbert-Huang transform (HHT) and FFT analysis. The results show that misfire fault can be successfully diagnosed, including identified by FFT of IMF10 and fault cylinder localization by the polar presentation method.

1. Introduction

Large diesel engines are used for main propulsion on board ship and are the prime mover in many industrial applications. It is so important to ensure reliability of their service that a lot of condition-monitoring and diagnosis techniques have been developed for these engines. Compared with the others, IAS based method has the advantages of less noise contamination, easy installation, economical price, which make this method practical and useful [1].

IAS is essentially the crankshaft torsional vibration. Recently, the analysis of it has drawn a lot of attention. Gu and Yang et al. [2-3] investigated the IAS time waveforms to extract the statistical characteristics for identifying misfire. Scott X C proposed harmonic order analysis method based on the relationship between combustion and IAS to detect the fault [4]. Sun, Liu and Matteo [5-7] employed the time-frequency approach such as Wigner-Ville distribution, short time Fourier transform (STFT) and wavelet transform (WT) to analyse the IAS both in time and frequency domain. Most methods are aimed at small engines with low speed and have achieved a very good performance on many engines. However, their applicability to large diesel engine is strongly contested due to the high number of cylinders and the complex load and crankshaft which complicate the IAS [8].

In order to solve the above mentioned problems, the EEMD-based method is proposed to improve the discrimination of faulty features. This research focuses on a V12 diesel engine driving a generator. First, the IAS signal is decomposed into serial IMFs. Each IMF is explained to represent the possible physical meanings. Then, the identification of misfire fault is carried out by comparing the healthy condition with the misfiring condition. At last, the polar presentation of IMF10 is used to locate the faulty cylinder [9].
2. EEMD method

Huang proposed an adaptive time-frequency analysis method named Empirical Mode Decomposition (EMD) to decompose signal into IMFs in different scales in 1998. Each IMF is a narrow-band signal (seen as mono-component signal) that will make the instantaneous frequency meaningful. The combination of EMD and Hilbert transform (HT) is called Hilbert-Huang transform (HHT).

**IMF** satisfies the following two conditions:

1. The number of extrema must either equal to or differ at most by one with the number of zero crossings in the whole data.
2. The mean value of the envelope defined by local maxima and the envelope defined by local minima is zero at any point.

With the definition, EMD can be described as follows [10]:

1. Identify the signal \( x(t) \) all local maxima and minima, then compute the upper envelope \( u \) and lower envelope \( v \), \( m \) is the means of \( u \) and \( v \)

\[
m = (u + v) / 2
\]

2. The difference between \( x(t) \) and \( m \) is the first component \( h(t) \), i.e.

\[
h(t) = x(t) - m
\]

If \( h(t) \) is not an IMF, repeat steps (1), (2), then the first component of \( x(t) \) is \( c_1(t) \);

3. Extract \( c_1(t) \) from \( x(t) \), the signal becomes \( r_1(t) \)

\[
r_1(t) = x(t) - c_1(t)
\]

Treat \( r_1(t) \) as the original signal \( x(t) \), repeat the above process until it can’t sift the new IMF.

4. The signal \( x(t) \) can be rewritten as the following equation

\[
x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t)
\]

Residue \( r_n(t) \) represents the mean trend of \( x(t) \). \( c_j(t) \) is the \( j^{th} \) IMF.

The complete algorithm is as shown in Figure 1.

![Flowchart of Empirical Mode Decomposition](image-url)
EEMD is presented to overcome the mode mixing problem of EMD by Huang et al. The statistical characteristics of white noise is made use of to perturb the signal in this new approach. Sifting an ensemble of white noise-added signal and treating the means as the final result are the main ideas. The white noise will be averaged out with enough number of trials. A more complete description can be found in reference [11]. Its main procedure is as follows:

1. Add a white noise series to the targeted signal;
2. Decompose the noise-added signal into serial IMFs;
3. Repeat steps (1) and (2) over and over, but with different white noise series each time;
4. Obtain the means of IMFs as the final result.

3. Experiments

3.1 Test-rig

Table 1 is the specifications of the V12 diesel engine. Its consecutive firing angle is alternately 50° and 70° in crank angle, which is not equally spaced. The engine is set to operate at 25% load and 1000 rpm rated speed. Both healthy and misfiring conditions are tested. IAS original signal is measured by the magnetic sensor mounted to the flywheel. To identify the firing of the specified cylinder for a four-stroke engine, the top dead centre (TDC) sensor and the accelerometer are used. The installation of sensors is shown in Figure 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>V 50°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed</td>
<td>1000 r/min</td>
</tr>
<tr>
<td>Rated power</td>
<td>2850 kW</td>
</tr>
<tr>
<td>Cylinder/Stroke</td>
<td>12/4</td>
</tr>
<tr>
<td>Flywheel teeth</td>
<td>270</td>
</tr>
<tr>
<td>Engine cylinder firing order</td>
<td>A1-B6-A5-B2-A3-A4-A6-B1-A2-B5-A4-B3</td>
</tr>
</tbody>
</table>

(a) diesel engine. (b) sensors.

Figure 2: Field measurement.

3.2 IAS Extraction

Extraction of IAS from the measured signal is critical, because condition monitoring and fault diagnosis demands that the IAS estimation be as accurate as possible [12]. Vakman has pointed out that the frequency-domain method gains the higher precision of IAS estimation than the zero-cross and time-domain methods [13]. So the frequency-domain method is adopted in this paper.

First, the signal with a length of 20 engine cycle is truncated and its mean is also removed. Then, the centre frequency of the signal is recognized by the FFT analysis, here is 4500Hz. After smoothed by a band-pass filtering [3500, 5500], the data are typical frequency modulated (FM) signal. At last, IAS is calculated by differentiating the angular displacement of the analytic signal which is constructed by HT. 100Hz is the firing frequency of the engine in rated speed. To smooth the IAS waveform, the high frequency noise (10 times of the firing frequency) is abandoned, but care must be taken in this process as the real components may be related.
4. EEMD-based fault diagnosis

4.1 Identification of misfire fault based on EEMD

Complex crankshaft, generator load and overlapping combustion events are involved in the V12 engine, these factors will strongly complicate the diagnostics based on IAS. Figure 3 shows the IAS waveforms under healthy and B1 misfiring conditions. The change in IAS waveforms between normal and faulty conditions is very little (almost the same), which may make it impossible to extract the time-domain discrimination features. Figure 4 shows the frequency spectra of IAS. It can be clearly seen that there are a few frequency peaks with high amplitudes below firing frequency when the engine is at normal condition. Comparing the B1 misfiring condition with the normal, no very distinctive difference is found. Further research indicates that the low frequency, especially 0.5 harmonic order (8.3Hz) has a relatively subtle change when the engine is at fault. However, 0.5 harmonic order just has a small amplitude, which is easily influenced by the spectral leakage, trend terms and nonlinear factor. If directly judged by the amplitude of 0.5 harmonic order, the diagnostic accuracy can’t be guaranteed, sometimes it even gives out a false alarm. Hence the EEMD method is applied to extract a better discrimination feature of fault in this paper. EEMD is an adaptive signal analysis method that makes itself viable for the non-stationary IAS signal.

![Figure 3: Comparison of normal and fault condition.](image1)

![Figure 4: Instantaneous angular speed spectrum.](image2)

To make the EEMD effective, the amplitude of the added noise should not be too small. And to reduce the effect of the added white noise to a negligibly small level, the ensemble number should be big enough. Generally, a very accurate result will be produced by a few hundred ensemble number. For balance, 0.05 times and 300 trials are finally regarded as the amplitude of noise and the ensemble number. Figure 5 shows the EEMD results of the IAS data. It consists of 13 IMFs and a residual component Res. The IMF1~IMF5 are noise and high frequency components of IAS. These components can be processed to improve the signal to noise ratio (SNR). The IMF6~IMF10 are probably produced by the gas exciting torque, inertia torque, load torque and so on. The last three IMFs (IMF11~IMF13) may be caused by the fluctuation between two engine cycle and random interference. This research focuses on misfire (faulty cylinder firing), only the gas exciting torque will be changed under misfire. Thus, just IMF6~IMF10 need a further discussion in this paper.

The EEMD results under B1 misfiring condition are shown in Figure 6. Compared with Figure 5, it is found that an obvious change appears in IMF7, IMF9 and IMF10. In detail, the amplitude of IMF7 under misfiring condition is 1.2 times of the one under normal condition, the amplitude of IMF9 is 1.5 times, and the amplitude of IMF10 is 2.5 times. To identify the misfire fault, the HHT time-frequency method is also used to analyze IAS signal. Figure 7 and Figure 8 show the HHT time-frequency spectrum of IAS under normal and B1 misfiring conditions respectively. A new frequency band appears in the Hilbert spectra band when B1 cylinder is abnormal. The frequency band is centered in 8.3Hz, exactly as the FFT analysis above. Therefore, it is concluded that the HHT time-frequency spectra can be used to detect the misfire fault.

The FFT analysis shows that 8.3Hz is the dominant frequency of IMF10 which has a strong relationship with misfire. The FFT amplitude under B1 misfiring condition is 0.21, which is 7 times of
the one in normal condition. The change is obvious when the engine is at fault, so the FFT amplitude of IMF10 can be regarded as the discrimination feature of misfire. In order to verify the conclusion, misfire fault has been carried out in different cylinder. First, each IAS signal is decomposed by EEMD, then IMF10 is separately analyzed by FFT. All results are listed in Table 2. It shows that the value under A6 misfire is 6.7 times of the normal, and it is 8.7 times of either B5 or B3 misfire; the others are between the two conditions. Hence, the diagnosis effect of IMF10 is demonstrated.

Figure 5: Decomposition of normal condition.

Figure 6: Decomposition of misfire condition.

Figure 7: Time-frequency analysis of normal signal.

Figure 8: Time-frequency analysis of misfire signal.
Table 2: the amplitude of intrinsic mode functions10.

<table>
<thead>
<tr>
<th>Working condition</th>
<th>Spectrum amplitude of intrinsic mode functions10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.03</td>
</tr>
<tr>
<td>B1# cylinder misfire</td>
<td>0.21</td>
</tr>
<tr>
<td>B5# cylinder misfire</td>
<td>0.26</td>
</tr>
<tr>
<td>B3# cylinder misfire</td>
<td>0.26</td>
</tr>
<tr>
<td>A2# cylinder misfire</td>
<td>0.22</td>
</tr>
<tr>
<td>A6# cylinder misfire</td>
<td>0.20</td>
</tr>
</tbody>
</table>

4.2 Fault Location based on polar presentation

Figure 9 shows the polar presentation of one cycle of sine wave. The difference of the phase between the two sine wave is 90°, which is clearly presented in Figure 9 (a) and (b). In other words, the polar presentation can be seen as another way to present the phase of sine wave.

\[ \text{IMF10 component} \text{ is} \text{ a typical amplitude-modulation (AM) signal, so the error of its FFT phase will be very big. To make better use of the key information about faulty location contained in IMF10, the polar presentation method is introduced. Figure 10 shows the polar presentation of IMF10 under B1 misfire. It is clearly seen that a concave field appears when the engine is faulty. The concave field is then used as a reference (pointing at B1 cylinder directly). The firing angle of the V12 engine is alternatively 50°/70°. Based on the theory of engine dynamics, the angle of 0.5 harmonic order between consecutive firings will be 25°/35°, as shown in Figure 11. If the cylinder number is ranked in polar presentation (Figure.10) according to IAS vector of 0.5 harmonic order (Figure.11), the faulty cylinder will be easily located when misfire occurs again.} \]

To verify the polar presentation method, the polar plots of IMF10 with respective A2, A6, B5 and B3 cylinder misfire are shown in Figure 12. It is clearly seen that the cylinder can be correctly located by polar presentation when either A2 or A6 becomes faulty. However, sometimes the concave
field points at the area between B5 and A2 when B5 is the faulty cylinder. And it also points at the area between B3 and A4 when B3 is the faulty cylinder. To quantify the errors of the polar presentation, the phase of concave field is then calculated, as seen in Table 3. It can be found that the results are completely compatible with the polar presentation. By further research, it is speculated that these errors may be caused by the following aspects:

1. The transfer function used to describe the relationship between the gas exciting torque and IAS may be different from each cylinder, so it leads to the deviation between 0.5 harmonic exciting torque vector and 0.5 order IAS vector in theory.
2. When the engine is in normal condition, a certain value exists in IMF10, some errors will be caused by this fact.
3. As an AM signal, the phase of IMF10 is hard to be measured accurately.

Table 3: Phase of intrinsic mode functions 10 (°).

<table>
<thead>
<tr>
<th>Working condition</th>
<th>phase of concave field</th>
<th>phase difference referenced to B1# cylinder</th>
<th>theoretical phase difference</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>B1# cylinder misfire</td>
<td>328.64°</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>B5# cylinder misfire</td>
<td>12.45°</td>
<td>43.81°</td>
<td>60.00°</td>
<td>16.19°</td>
</tr>
<tr>
<td>B3# cylinder misfire</td>
<td>72.67°</td>
<td>104.03°</td>
<td>120.00°</td>
<td>15.97°</td>
</tr>
<tr>
<td>A2# cylinder misfire</td>
<td>0.21°</td>
<td>31.57°</td>
<td>25.00°</td>
<td>6.57°</td>
</tr>
<tr>
<td>A6# cylinder misfire</td>
<td>286.92°</td>
<td>318.28°</td>
<td>325.00°</td>
<td>6.72°</td>
</tr>
</tbody>
</table>

Though some problems need further study, the polar presentation method has shown its advantage of visualization. With the help of this method, the diagnosis can be made much more intuitive. Taking error into account, the diagnosis rule is set up as follows: when misfire is identified, the first step is to examine the cylinder where the concave field points at; if no fault is found, then examine the nearby cylinders whose firing order is next. Step by step, the faulty cylinder will be located.
5. Conclusions

In this paper the EEMD method is applied to analyse the IAS signal of the V12 diesel engine. The conclusions are as follows:

1. More diagnosis information can be obtained when IAS is decomposed into serial IMFs by EEMD.
2. The IMF10 component can be regarded as the discrimination feature of misfire. Together with the HHT method and FFT analysis, the fault can be successfully identified.
3. The misfiring cylinder can be located by polar presentation of IMF10.

Subsequently, it is intended to test the proposed method with smaller combustion faults such as fuel injection faults, cam valve malfunctions, etc. which will be studied in the future.

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REFERENCES