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Numerical algorithms of marine diesel engine instantaneous speed based on Hilbert-Huang Transform

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Abstract. As is known to all, there are lots of measurement noises and ambient noises among diesel engine instantaneous speed signal, for the warship engine room environment is not convenient to install precise equipment, such as photoelectric encoder etc. The instantaneous speed signal processing method of diesel engine should be thoroughly studied. The Hilbert-Huang transform is introduced to decompose the instantaneous speed signal by EMD empirical mode and to analyze the spectrum. The IMF component which affects the fluctuation of the speed is superimposed to obtain the HHT (Hilbert-Huang Transform)-based filtering curve. Then a low pass filter is designed to solve the attenuation signal problem in the useful signal based on the HHT filter. Subsequently the filter technical parameters are determined according to the spectrum analysis of the IMF component. Experimental results show that the filtering effect of the designed algorithms is fairly well.

1. Introduction

The instantaneous speed of diesel engine is the integrated results of gas torque, inertia torque, friction torque and load torque. It contains rich information and it is an integrated reflection of engine running status. Extracting and processing the instantaneous speed can be widely applied to the fault diagnosis and condition monitoring of diesel engine. In recent years, scholars have been doing extensive research about the application of the instantaneous speed of diesel engine, such as analyzing the changes in the instantaneous speed signal in different conditions and speed to extract the failure of each cylinder working in-homogeneity[1]; Accurate identification of misfire fault and the location of the fault cylinder by using instantaneous speed and vibration impact phase signal[2]; using instantaneous speed indicating to estimate torque of diesel engine[3]; and using the fluctuation of instantaneous speed to estimate the in-cylinder pressure[4], and studying on the seal and combustion of cylinder[5]according to the fluctuation of instantaneous speed in the multiple cycles. The instantaneous speed is measured by magnetic or photoelectric sensors in most cases, but during measuring, the results contained a large number of interference signals which are made up of the measurement noises and random noises caused by the unevenness, torsional vibration and high frequency vibration of the wheel gear, and the interference signal increase in proportion with the increase of revs, the interference signal makes it very difficult to extract the eigenvalues based on the instantaneous speed signal. To solve this problem, scholars seek solutions from two aspects, first, influencing factors of measurement accuracy from the angle of instantaneous speed measurement; second, decomposition and filtering of instantaneous speed signals from the angle of signal processing [6].

For warship diesel engine, the number of teeth on the fly wheel is a fixed value, and the optoelectronic encoder is not allowed to install at the free end. In many cases, the instantaneous speed is measured by installing a flywheel magnetoelectric sensor. As a result, in this paper the problem of the signal processing of the instantaneous speed of the warship diesel engine is studied, and a low pass filter is developed based on the passband cut-off frequency, stopband lower limit cut-off frequency and attenuation value based on the time frequency diagram. The instantaneous speed signal is filtered and processed, the accuracy of the speed after treatment is verified according to the temperatures of each cylinder.

2. Methods and principles based on Hilbert- Huang transformation

In 1998, Norden E. H et al. put forward the method of empirical mode decomposition and introduced the concept of Hilbert spectrum and the method of Hilbert spectrum analysis, which was named by national aeronautics and space administration (NASA) as a Hilbert-Huang Transform. This is an adaptive nonlinear non-stationary time-frequency analysis method, which is considered to be a major breakthrough in the analysis of linear and steady-state spectra based on Fourier transform in recent years. This is an adaptive nonlinear non-stationary time-frequency analysis method, which is considered to be a major breakthrough in the analysis of linear and steady-state spectra based on Fourier transform in recent years.

2.1. EMD decomposition method

Empirical Mode Decomposition (EMD) algorithm is the core algorithm of HHT transformation. The purpose is to decompose the signal with poor performance into a set of better performance intrinsic mode functions (IMF). IMF must satisfy two properties: the number of extreme points and zero crossing points of signal is equal or the maximum difference is one; the average value of the upper envelope composed of local maximum and the lower envelope composed of local minimum is zero.
The calculation steps of the EMD algorithm are as follows:

(1) Find all the maximum and minimum values of x(t), and then use the three splines interpolation algorithm to get the upper envelope h (t) and the lower envelope L(t). All the signals are located between the upper and lower envelopes, and the average m (t) is calculated.

$$m(t) = (h(t) + L(t))/2 \tag{1.1}$$

(2) Set the variable to be:

$$x_1(t) = x(t) - m(t) \tag{1.2}$$

If the two standards of IMF is satisfied, it can be used as the first IMF and is recorded as $c_1(t)$.Otherwise the original signal will repeat the above steps until the first IMF component is obtained. In order to ensure that the IMF component has a clear physical meaning in both amplitude and frequency, an empirical formula is used to limit the number of iterations of the sieving:

$$S_D = \sum_{t=0}^{T} \left[\frac{\left| x_{1(k-1)}(t) - x_{1(k)}(t) \right|^2}{x_{1(k-1)}^2(t)} \right] \tag{1.3}$$

Here S_D is called the filter gate limit value, and the screening process is over if it is less than the threshold value.

(3) Calculate the residual signal $r_1(t) = x(t) - c_1(t)$,as a new signal, repeat (1) and (2) steps until all IMF components are extracted. When the remaining signal is a non-oscillatory monotone function or a constant less than the predetermined value, it is considered to be decomposed. The original data is finally decomposed into n-IMF and a residual component $r_n(t)$, that is:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{1.4}$$

2.2. The Hilbert transform

The Hilbert transformation of each inherent modal component $c_i(t)$obtained by EMD decomposition is recorded as [7]:

$$H[c_i(t)] = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{c_i(\tau)}{t-\tau} d\tau \tag{1.5}$$

The real signal is transformed into a complex signal by the Hilbert transform:

$$Z_i(t) = c_i(t) + H[c_i(t)] = \alpha_i(t) \cdot e^{j\Phi_i(t)} \tag{1.6}$$

It can obtain instantaneous amplitude function and instantaneous phase function respectively:

$$\alpha_i(t) = \sqrt{c_i^2(t) + H^2[c_i(t)]} \quad (1.7)$$

$$\Phi_i(t) = \arctan\frac{H[c_i(t)]}{c_i(t)}$$

Its instantaneous frequency is defined as:

$$\omega_i(t) = \frac{1}{2\pi}\frac{d\Phi_i(t)}{dt} \quad (1.8)$$

Ignore residual function $r_n(t)$, the original signal $x(t)$ can be expressed as：

$$x(t) = \mathrm{Re}\sum_{i=1}^{n} \alpha_i(t)\, e^{i\int \omega_i(t)dt} \quad (1.9)$$

3. Instantaneous speed treatment of diesel engine based on the HHT

3.1. Measurement and acquisition of instantaneous speed

The instantaneous speed of this paper is collected on the experimental platform of WD615 diesel engine. The main parameters of the test machine are shown in table 1.

Table 1. Main technical parameters of the test machine.

Type	WD615.63
Cylinder diameter	126/mm
Stroke	130/mm
Compression ratio	16:1
Ignition sequence	1-5-3-6-2-4
Calibration power (speed)	120/kW(1500/r•min^{-1})
Maximum torque (speed)	1160/N•m(1300/r•min^{-1})

Install the first magnetoelectric sensor outside the flywheel housing, use the motor to drive the first cylinder to the Top Dead Center, install the magnetic chip on the other side of the flywheel, and install the second magnetoelectric sensor on the magnetic chip. Use NI-9222 high speed synchronous acquisition card, the maximum sampling frequency is 500KHz. At the same time, the two - way gear pulse signal and the Top Dead Center signal are collected.

The fixed angular velocity measurement method is adopted, which is to measure the time interval of two adjacent pulses to determine the velocity.

A high frequency clock pulse with a known frequency of fc is used to trigger sampling for the acquisition card. If the readings of the high-frequency clock pulse between each gear pulse are m, the engine speed is n（$n = 60 \cdot \frac{fc}{Nm}$）, where N is the number of teeth of the flywheel.

The initial instantaneous speed waveform of the test machine running at the calibrated speed 1500rpm (output power 50Kw) is calculated as shown in figure 1.

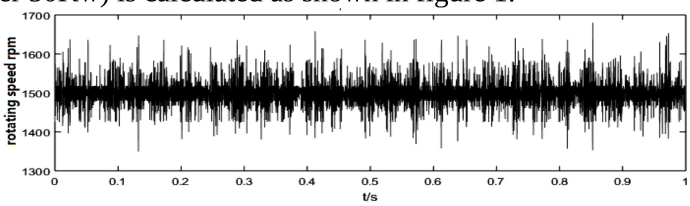

Figure 1. Initial waveform of instantaneous speed.

3.2. The instantaneous speed signal processing based on HHT

The calculated instantaneous speed signal is decomposed by EMD, and eleven IMF components and one residual components are obtained. Then each IMF component is Hilbert transformed to get the instantaneous frequency of each component. Finally, every IMF component is transformed by FFT, and the spectrum of each component is obtained.

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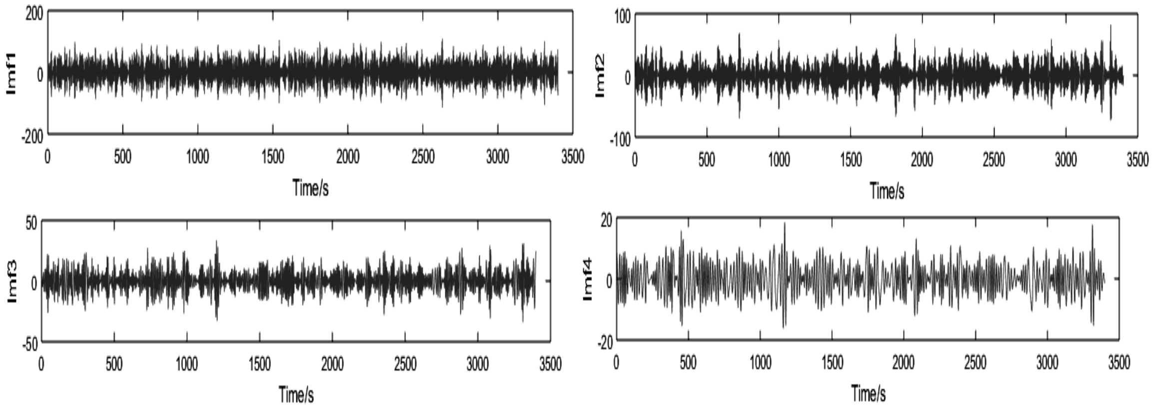

Figure 2. IMF1 to IMF4 component waveform diagram.

The test machine is a six-cylinder machine, the speed is 1500rpm, so the frequency of cylinder firing is 75Hz. The waveform of IMF1 to IMF4 is shown in figure2. It can be seen from the images that the frequency of IMF1 and IMF2 components are more than 1000Hz, and the main energy is ten times more than the frequency of ignition frequency. It can be seen that the IMF1 and IMF2 components are composed of high harmonic components, unequal gear disks and high frequency vibration caused by random noises of the environment. IMF3 and IMF4 components are mainly distributed from 150Hz to 500Hz. The IMF3 frequency is concentrated at 500HZ, and the frequency of IMF4 is concentrated on 177HZ.The analysis shows that IMF3 and IMF4 are mainly caused by the two to four times harmonic of the gas pressure of the cylinder. The frequency fluctuation of IMF3 is larger, it can be seen that the harmonic attenuation of signals whose frequency are higher than three times is fast, which is in line with the principle of engine. The spectrums are shown in figure 3.

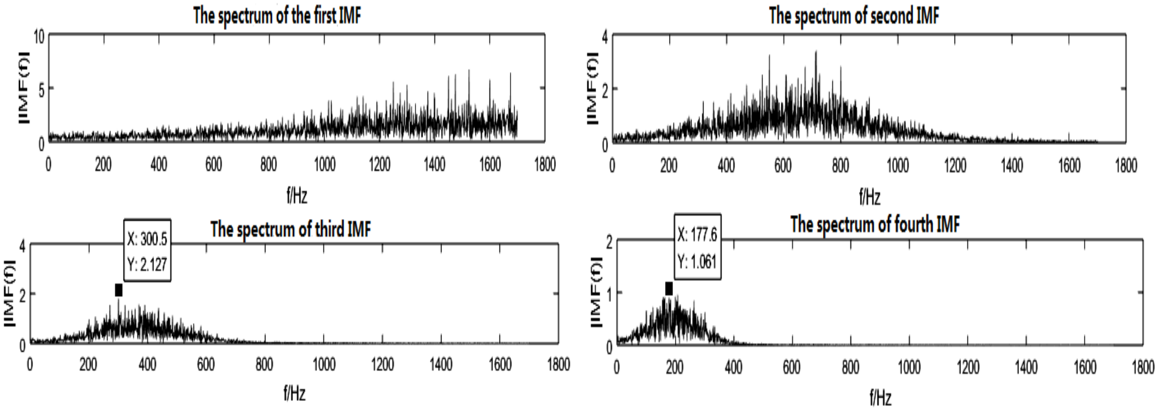

Figure 3. Spectrum of IMF1 to IMF4 components.

In the IMF5, the amplitude peak frequency is 74.71 HZ, which coincides with the engine cylinder firing frequency 75 HZ, which indicates that the IMF5 component fluctuation is caused by the ignition of diesel engine cylinder. The IMF6 ~ IMF8 is a component that is less than the firing frequency, the frequency concentration is 24~75HZ, and the wave fluctuation is small, the waveform is not attenuated. Therefor it is considered that the 0.3 to 1 times harmonic of the cylinder gas pressure and the pulse of the cycle, which is consistent with the engine speed. The IMF9 to IMF11 waveform fluctuation is small, the amplitude is also small, negligible. IMF12 is the residual component, which is the average speed. The waveform diagram of IMF5 to IMF12 are shown in figure 4, and their spectrums are shown in figure 5.

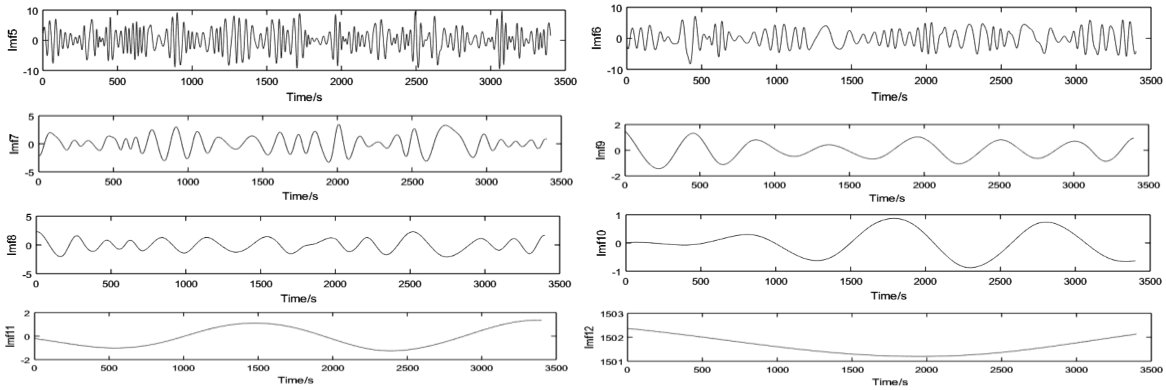

Figure 4. IMF5 to IMF12 component waveform diagram.

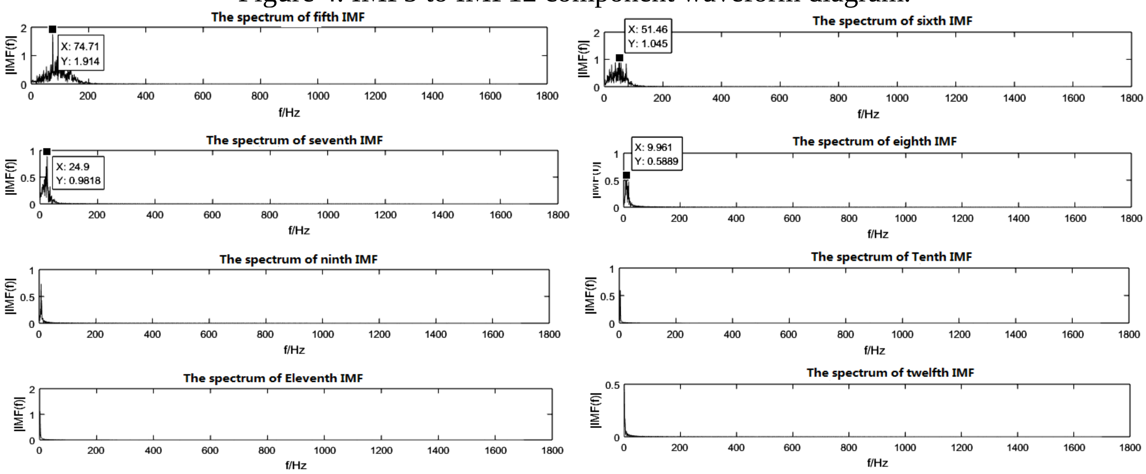

Figure 5. Spectrum of IMF5 to IMF12 components.

3.3. *Instantaneous speed filtering based on HHT*

The influence of instantaneous speed fluctuation is the firing of cylinders. Based on the analysis above, the IMF5~IMF8 and residual component IMF12 can be superimposed to get the instantaneous speed waveform that fits the engine's running rule. The cycle is determined according to the Top Dead Center point signal and the instantaneous speed waveform of a complete cycle is obtained, as shown in figure 6.

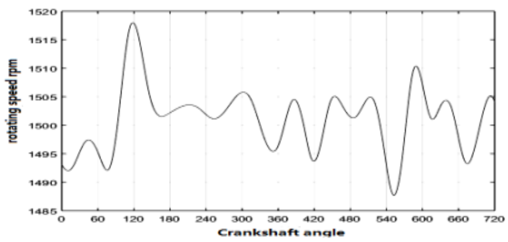

Figure 6. Filter cycle speed curve based on the HHT

It can be seen from the image that the filtering mode superposed by the EMD decomposition cannot reflect the periodic fluctuation of the diesel engine well. The reason is that in the IMF5 component, although the maximum frequency of the amplitude is due to engine firing, there is a signal greater than the firing frequency. Because of the two conditions of the EMD algorithm, the components obtained through the envelope curve have not been able to filter out the signal of the excess influence fluctuation very well. But according to the component, we can know that the redundant signal exists in the 75Hz~200Hz band of the IMF5 component, and the signal waveform of the frequency band is more attenuated, and the attenuation signal still affects fluctuation of the speed. And according to the previous analysis, it is known that the frequency that affects the speed fluctuation is within 1 times the frequency of the ignition. Therefore, the low pass filter is introduced to filter the speed signal.

4. Design of low-pass filter based on HHT

4.1. Selection of filters

The filter plays an important role in the actual signal processing and is the basic means to remove the noise in the signal. The filter can be divided into four types: low-pass, high-pass, band-pass and band-stop filter.

For the amplitude frequency characteristic of the filter is ideal, it cannot be realized in fact. For low pass filters, the sampling response or impact response is a sin function and the frequency response has a mutation from one band to another. In practical applications, the design filters are all approximate to the ideal filter under certain criteria. For physical realization, it is necessary to set up a transition zone from one belt to another, and the frequency response in the pass-band and stop-band should not be strictly one or zero, a smaller tolerance should be given. When designing filters, these limitations are the technical specifications of the filter, which are pass-band cut-off frequency, stop band cut-off frequency, pass-band maximum attenuation and stop-band minimum attenuation respectively.

The diesel engine speed is expected to get a smoother curve, while the Butterworth filter is characterized by the maximum level of frequency response curves in the pass band, and gradually decreases to 0 in the resistance band. Therefor， in this paper, the Butterworth filter is selected.

4.2. Determination of filter technical indicators

The Butterworth low pass filter can be expressed by the formula of the square pair frequency of the following amplitude:

$$|H(\omega)|^2 = \frac{1}{1+\left(\frac{\omega}{\omega_s}\right)^{2n}} = \frac{1}{1+\epsilon^2\left(\frac{\omega}{\omega_p}\right)^{2n}} \tag{3.1}$$

Among, n represents filter order number ,ω_s represents the cutoff frequency, and ω_p represents the edge frequency of the pass band.

The value at the edge of the pass band is:

$$\frac{1}{1+\epsilon^2} = |H(\omega)|^2 \tag{3.2}$$

According to the results of EMD decomposition, it is known that the signal frequency that affects the speed fluctuation of diesel engine is less than 75Hz, and the frequency of abnormal fluctuation of circulating speed is 75~200Hz at the time of decomposition and superposition. Due to the fact that the ideal filter does not exist, the cut-off frequency cannot be defined as 75Hz. From the previous analysis, it is known that the signals that affect the speed fluctuation in the 75Hz~200Hz band are mostly attenuated. Therefore, the cut-off frequency of the pass band is fixed to 200Hz, and the maximum attenuation of the pass band is 1dB. The cut-off frequency of the stop-band is determined to be 300Hz, and the minimum attenuation value of the stop-band is set to 50dB.

4.3. Butterworth filter filtering process

After determining the technical indexes, the initial speed signal is filtered. The filtered signal is transformed by FFT to observe the spectrum. The rotational speed image after the filter is provided as figure 7. The spectrum diagram before and after the filtering is shown in figure 8.

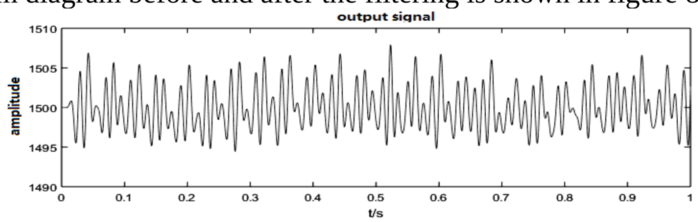

Figure 7. Waveform diagram for instantaneous speed after filtering

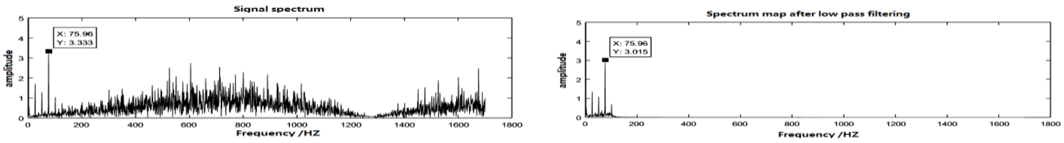

Figure 8. Comparison diagram of waveform spectrum before and after filtering.

The frequency spectrum analysis shows that the maximum frequency of the prefix filter is 75.96Hz, and the amplitude of the wave is 3.333, which is in line with the engine firing frequency. After filtering, the maximum frequency of the amplitude is 75.96Hz, and the amplitude of the wave is 3.015. Obviously, part of the signal filter was cut off. Therefore, the three technical indexes of pass-band cut-off frequency, pass-band maximum attenuation and stop-band minimum attenuation remain unchanged. The stop band cut-off frequency is calculated by control variable method. The condition of termination is the minimum amplitude difference before and after filtering. The cut-off frequency of the stop-band is 400Hz. After the band stop frequency is 400Hz, the filtered spectrum is like figure 9.

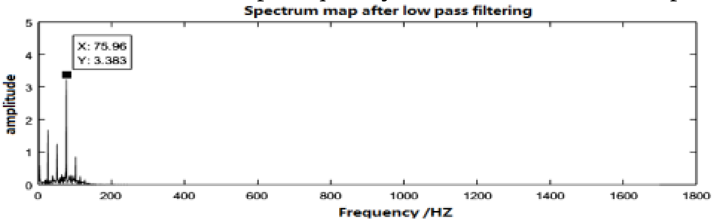

Figure 9. The frequency spectrum of the instantaneous speed after 400Hz filtering.

The amplitude before and after filtering is 3.333 and 3.383 respectively. At this point, the revolving speed fluctuation diagram is shown in figure 10.

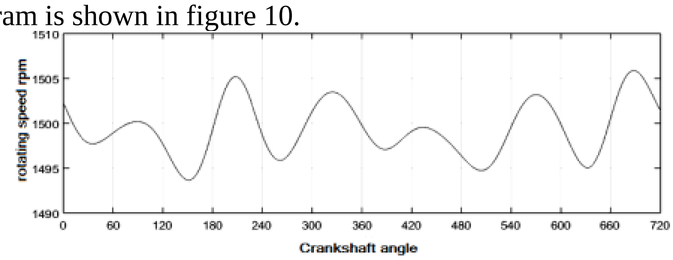

Figure 10. Figure after filtering circulation speed fluctuations

5. Filtering results analysis

In this paper, the speed of a variety of working conditions is measured, and the parameters of the filter are determined according to the component frequency after the EMD decomposition. As is shown in table 2.

Table 2. Selection of filter technology parameters under different working conditions.

speed / r•min^{-1} power /kW	Firing frequency /Hz	component main frequency /Hz	component maximum frequency /Hz	pass band cut-off frequency /Hz	stop band cut-off frequency /Hz	amplitude error before and after filtering
1100/30	55	54.78	149.71	150	300	0.007
1100/60	55	54.78	152.84	150	300	0.037
1300/30	65	65.47	198.62	200	400	0.03
1300/80	65	65.47	152.51	150	300	0.12
1500/30	75	75.54	196.73	200	400	0.033
1500/80	75	75.54	248.23	250	500	0.047

The following conclusions can be obtained from the table 2: When the filter is designed, the IMF component that is consistent with the frequency of the firing is selected. Then the pass band cut-off frequency is determined according to the maximum frequency of the component. At the same time to calculate the stopband cut-off frequency according to the amplitude error of the firing frequency before and after the filtering. It can be found from the result that it is best to select the two times frequency effect of pass-band cut-off frequency.

6. Conclusions

In this paper, the problem of signal processing of diesel engine instantaneous speed is studied, and the following conclusions can be obtained:

(1) When dealing with the instantaneous speed waveform of diesel engine, the EMD empirical mode analysis can better decompose the details of the instantaneous speed. According to the Hilbert transformation of the IMF component, the physical meaning of each component can be judged effectively.

(2) According to the spectrum and time-frequency analysis of the IMF, the technical parameters of the filter can be obtained, and instantaneous speed filter is designed according to the criteria. The cut-off frequency of the stop band needs to be corrected by the maximum frequency amplitude before and after the filter.

(3) The choice of passband cut-off frequency of filter is consistent with the maximum frequency of firing frequency component. The best choice of stop band cut-off frequency is two times of pass band cut-off frequency.

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