Through separating the noise sources of diesel engine, the obtained independent noise source can provide basis for the vibration noise reduction and monitoring diagnosis. In the separation of noise source, the combustion noise and piston slap noise are seriously aliased in time domain and frequency domain. In order to separate them, the EWT-RobustICA method is proposed. The vibration and noise test of diesel engine is designed. In order to shield the other cylinder interference noise, the outer surfaces of cylinder body are carried out the silencer cotton and lead cover treatment, with only No. 6 cylinder parts exposed. Firstly, the EWT method is used to decompose the measured single-channel noise signal. Then the obtained empirical mode components which have a high correlation coefficient with the measured noise signal are selected. The selected empirical mode components and the measured noise signal are put together to form a new signal group. Finally, the RobustICA algorithm is utilized to extract independent components. The separated results are further identified by FFT, continuous wavelet transform, coherent analysis and back-drag test. The experimental results show that the proposed EWT-RobustICA method can obtain more accurate and pure combustion noise and piston slap noise than EMD-RobustICA method. The frequency of combustion noise and piston slap noise are concentrated at 3813 Hz and 1675 Hz, respectively.

Keywords: acoustics, diesel engine, noise source, empirical wavelet transform, independent component analysis

1. Introduction

Internal combustion engine structure is complex, and it can produce many noise sources. The noise sources of internal combustion engine can be divided into combustion noise, mechanical noise and aerodynamic noise [1, 2]. At present, many scholars utilize the multi-channel method such as cyclic Wiener filtering method [3], independent component analysis method [4, 5], an improved spectrofilter method [6], multiple regression method [7], three-sensor coherence method [8] and so forth to separate and identify the noise sources of internal combustion engine.

When multi-channel method is employed to separate the noise sources, the vibration noise signals of multiple channels are required. However, in engineering practice, it needs to use fewer sensors to separate the noise sources. Later, Scholars adopted the single-channel separation method to identify the noise source of internal combustion engine. Yu et al. [9] utilized EMD-RobustICA method to separate the combustion noise and piston knock noise of diesel engine. Bi et al. [10] applied EEMD-RobustICA method to separate the combustion noise, piston knock noise and exhaust noise of the gasoline engine. Zhang et al. [11] combined with EEMD, coherent power spectrum method and improved analytic hierarchy process to identify the diesel engine oil pan, body side, gear box and other noise sources. Zheng et al. [12] employed EEMD and generalized S transform to
identify combustion noise, piston knock noise and gear meshing noise of internal combustion engine.

However, the EEMD-based single channel method exist some problems. The most important problem is EMD (Empirical modal decomposition) algorithm lacks strict mathematical theory, and it is easy to cause the problem of end-point effect and modal aliasing. Although the EEMD (Ensemble empirical mode decomposition) can overcome the problem of end effect and modal aliasing, it requires to add Gaussian white noise before each step of EMD. Thus, the calculation cost will be greatly increased [13, 14]. To solve these problems, Gilles [15] put forward the EWT (empirical wavelet transform) method that has a solid theoretical basis. It is widely used in mechanical fault diagnosis [16, 17].

In this paper, the diesel engine noise source separation method based on EWT and RobustICA is proposed.

2. Basic theory

2.1 EWT

EWT is a signal decomposition method proposed by Gilles. Empirical scale function and empirical wavelet function are two important functions, and they are defined as follows.

\[
\hat{\phi}_n(\omega) = \begin{cases} 
1, & |\omega| \leq (1-\gamma)\omega_n \\
\frac{\pi}{2} \beta \left( \frac{1}{2\gamma\omega_n} (|\omega| - (1-\gamma)\omega_n) \right), & (1-\gamma)\omega_n \leq |\omega| \leq (1+\gamma)\omega_n \\
0, & \text{otherwise.} 
\end{cases} 
\]

\[
\hat{\psi}_n(\omega) = \begin{cases} 
1, & (1+\gamma)\omega_n \leq |\omega| \leq (1-\gamma)\omega_{n+1} \\
\frac{\pi}{2} \beta \left( \frac{1}{2\gamma\omega_{n+1}} (|\omega| - (1+\gamma)\omega_{n+1}) \right), & (1-\gamma)\omega_{n+1} \leq |\omega| \leq (1+\gamma)\omega_{n+1} \\
\sin \left[ \frac{\pi}{2} \beta \left( \frac{1}{2\gamma\omega_{n+1}} (|\omega| - (1-\gamma)\omega_{n+1}) \right) \right], & (1-\gamma)\omega_n \leq |\omega| \leq (1+\gamma)\omega_n \\
0, & \text{otherwise.} 
\end{cases} 
\]

where \( \omega \) indicates the frequency of the signal, \( \omega \in [0, \pi] \). \( \omega_n \) is the midpoint of two adjacent maxima points in the signal Fourier spectrum. \( \beta(x) = x^2 (35 - 84x + 70x^2 - 20x^3) \). \( \gamma < \min_n (\frac{\omega_{n+1} - \omega_n}{\omega_{n+1} + \omega_n}) \).

EWT is constructed according to the construction method of classical wavelet transform. The detail coefficients \( W^\text{c}_f(n,t) \) and approximate coefficients \( W^\text{a}_f(0,t) \) of EWT are defined as follows.

\[
W^\text{c}_f(n,t) = \left\langle f, \psi_n \right\rangle = \int f(\tau) \overline{\psi_n}(\tau-t)d\tau = (\hat{f}(\omega)\overline{\psi_n}(\omega))^* 
\]

\[
W^\text{a}_f(0,t) = \left\langle f, \phi \right\rangle = \int f(\tau) \overline{\phi}(\tau-t)d\tau = (\hat{f}(\omega)\overline{\phi}(\omega))^* 
\]

where \( \overline{\psi}_n(\omega) \) and \( \overline{\phi}(\omega) \) are respectively represent the Fourier transform of \( \psi_n(t) \) and \( \phi(t) \). \( \overline{\psi}_n(\omega) \) and \( \overline{\phi}(\omega) \) are respectively represent complex conjugate of \( \psi_n(\omega) \) and \( \phi(\omega) \).

The reconstructed formula of original signal \( f(t) \) is defined as follows.

\[
f(t) = W^\text{a}_f(0,t)^* \overline{\phi}(t) + \sum_{n=1}^{N} W^\text{a}_f(n,t)^* \overline{\psi}_n(t) = (W^\text{a}_f(0,0)^* \overline{\phi}(0) + \sum_{n=1}^{N} W^\text{a}_f(n,0)^* \overline{\psi}_n(0))^* 
\]

where * symbol represents the convolution operation. \( W^\text{a}_f(0,0) \) and \( W^\text{a}_f(n,0) \) are respectively represent the Fourier transform of \( W^\text{a}_f(0,t) \) and \( W^\text{a}_f(n,t) \).

According to the above formula, the empirical mode function is as follows.

\[
f_0(t) = W^\text{a}_f(0,t)^* \overline{\phi}(t) 
\]
ICA is a blind source separation method that finds its inherently independent and non-Gaussian factors or components from multivariate (multidimensional) data.

Assuming \( X(t) = x_i(t), i=1,2,\cdots,n \) is a set of n-dimensional observed value generated by a number of implicit variables. ICA is required to find the variables \( X(t) = x_i(t), i=1,2,\cdots,n \) implied in the n-dimensional observation signal.

The estimated signal \( Y(t) \) can be obtained by ICA as follows.

\[
Y(t) = WX(t) = WAS(t)
\]

where \( Y(t) \) represents the estimated signal. \( W \) represents a despreading matrix. \( X(t) \) represents an observation signal. \( A \) represents a hybrid matrix. \( S(t) \) represents the source signal.

The FastICA algorithm [18] and RobustICA algorithm [19] are the commonly used ICA algorithms. When the correlation of source signal is high, FastICA algorithm has a poor separation effect. RobustICA algorithm has the faster computational speed, higher separation performance and higher robustness than FastICA algorithm [20]. Therefore, the RobustICA algorithm is adopted to extract the independent components in this paper.

### 2.3 EWT-RobustICA method

The EWT-RobustICA method is proposed to separate the independent noise sources of diesel engine. Firstly, the EWT algorithm is utilized to decompose the measured single-channel near-field radiated noise signal into multiple empirical modal components \( F_i \). Secondly, correlation coefficient between empirical mode components and measured noise signal is calculated. Then the suitable empirical mode components are retained, and combined them with the measured noise signal to form a new group. Finally, the RobustICA algorithm is adopted to extract the independent components. The FFT (Fast fourier transform), CWT (Continuous wavelet transform), coherence function method and drag test are carried out to further identify the separated noise sources.

### 3. Experimental setup

#### 3.1 Test platform

The test is carried out in a semi-anechoic chamber. The ceiling and surrounding walls are covered with spiked silencers, and the ground is flat ground. The test object is WP10-240 high-speed 6-cylinder diesel engine. Due to the diesel engine has many noise sources, if it is directly analysed the noise sources of whole machine, there will be a very large error. For separating combustion noise and piston slap noise more accurately, from the aspect of experimental design to simplify the model. The diesel engine is wrapped by silencer cotton and lead, and only the No. 6 cylinder part is left bare. This can as much as possible to abandon the interference source produced by other cylinders. The lead covering effect of diesel engine is shown in Fig. 1.
3.2 Test measurement system

The test measurement system contains NI9234 and NI9205 acquisition module. Cylinder pressure sensor is Kistler7013C that the range is 25MPa, and with a single channel charge amplifier 5018A1000. The type of electret microphone is DGO9767CD, the sensitivity is 50mV / Pa, and the frequency response range is 20 Hz - 20 kHz. The type of acceleration sensor is LC0158T, the sensitivity is 30mV / g, and the frequency range is 0-15kHz. The M-12-100 magnetic sensor is used to collect the top dead center (TDC) signals. The test measurement system is shown in Fig. 2 (a).

The microphone is arranged at 1cm distance away from the No. 6 cylinder body side to measure the near field radiated noise signals. At the same time, the acceleration sensor is arranged at No. 6 cylinder body side to measure the piston slap vibration signals. In fact, it is very difficult to measure the independent piston slap noise. In the work of a diesel engine, the piston impacts the inner wall of cylinder liner. The impact can produce vibration, and the vibration produces the piston slap noise. Thus, the measured piston slap vibration can be utilized to evaluate the accuracy of the separated piston slap noise. According to the structure of internal combustion engine and movement trajectory of piston, the specific measured points of microphone and accelerometer are shown in Fig. 2 (b).

3.3 Test conditions

When the diesel engine is running at a high speed, it will generate many noise sources. Moreover, these noise sources are seriously aliased with each other, thus it will be very hard to separate these noise sources. When the diesel engine is running at a low speed, it can be relatively easy to separate these noise sources. In the test, the diesel engine is running at 600 rpm and no-load stable operating condition. The time domain waveforms of cylinder pressure (P1), cylinder head vibration (a) and body side radiated noise signal (P2) are shown in Fig. 3.

In addition, the diesel engine is also carried out in back-drag test to measure the piston slap vibration of the No. 6 cylinder.
4. Separation and identification noise sources of diesel engine

4.1 EWT-RobustICA method

Firstly, the EWT algorithm is adopted to decompose the collected single-channel near-field radiated noise signal into empirical mode components \( F_i \), and 19 empirical mode components are obtained. In order to improve the computational efficiency of the subsequent algorithms, the empirical modal components with high correlation coefficients of the measured noise signal are selected for further calculation. The calculation results of the correlation coefficients \( r \) between empirical mode components and measured noise signal are shown in Table 1.

<table>
<thead>
<tr>
<th>( F_i )</th>
<th>( r )</th>
<th>( F_i )</th>
<th>( r )</th>
<th>( F_i )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>0.7535</td>
<td>F8</td>
<td>0.1090</td>
<td>F15</td>
<td>0.0096</td>
</tr>
<tr>
<td>F2</td>
<td>0.5556</td>
<td>F9</td>
<td>0.0116</td>
<td>F16</td>
<td>0.0120</td>
</tr>
<tr>
<td>F3</td>
<td>0.2395</td>
<td>F10</td>
<td>0.0175</td>
<td>F17</td>
<td>0.0103</td>
</tr>
<tr>
<td>F4</td>
<td>0.1925</td>
<td>F11</td>
<td>0.0121</td>
<td>F18</td>
<td>0.0094</td>
</tr>
<tr>
<td>F5</td>
<td>0.0924</td>
<td>F12</td>
<td>0.0238</td>
<td>F19</td>
<td>0.0118</td>
</tr>
<tr>
<td>F6</td>
<td>0.0816</td>
<td>F13</td>
<td>0.0198</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F7</td>
<td>0.0535</td>
<td>F14</td>
<td>0.0162</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to Pearson correlation coefficient theory [21], if the correlation coefficient is greater than 0.3, the correlation between two variables is better. But considering that the diesel engine has many complex noise sources, and there are many noise disturbances in the measurement process. In the actual research, if the threshold of correlation coefficient is set to 0.3, there are only few empirical mode components are retained, and they are contain less information. For the sake of retaining more information of the noise source signal, when the correlation coefficient of empirical mode components is greater than 0.08, these empirical mode components are selected for further analysis. Thus, the F1, F2, F3, F4, F5, F6, F8 are retained. Then RobustICA algorithm is employed to further extract the individual components.

The main purpose of this paper is to separate combustion noise and piston slap noise. Through analysing, the IC1 and IC2 maybe the combustion noise and piston slap noise. The time domain waveform, FFT and CWT of IC1 and IC2 are shown in Fig. 4 and Fig. 5, respectively.

![Fig. 4 Time domain waveform, FFT and CWT of IC1 by EWT-RobustICA method](image)

From Fig. 4, in the aspect of time domain waveform, the amplitude of IC1 changes greatly at 370°CA. The firing sequence of diesel engine is 1-5-3-6-2-4, and the firing angle of No. 6 cylinder is around 370°CA. The change in the amplitude of IC1 is consistent with the ignition angle of No. 6 cylinder. In terms of frequency, the frequency of IC1 is concentrated at 3813 Hz. The coherence function of cylinder pressure and cylinder head vibration is shown in Fig. 6. In the vicinity of 3813 Hz, the coherence between cylinder pressure and cylinder head vibration is fine. The cylinder pressure changes will cause cylinder head vibration. Moreover, the frequency energy of No. 6 cylinder
is larger than the other cylinders. This is due to the use of lead covering method to isolate the interference noise caused by other cylinders. Thus, the diesel engine is firing at 370°CA, the cylinder pressure has changed dramatically, resulting in combustion noise. Therefore, the IC1 is combustion noise.

![Fig. 5 Time domain waveform, FFT and CWT of IC2 by EWT-RobustICA method](image)

From Fig. 5, in the aspect of time domain waveform, the amplitude of IC2 changes greatly at 370°CA. It is coincided with the firing angle of the No. 6 cylinder. In terms of frequency, the frequency of IC2 is concentrated at 1675 Hz. Integrated with Fig. 6, the correlation between cylinder pressure and cylinder head vibration near 1675 Hz is not good. In order to further determine the noise component of IC2, in the back-drag test, the piston slap vibration signal is measured. As the unit of IC2 component and measured piston slap vibration signal is inconsistent, thus normalized is carried out on them. The spectrum of IC2 and piston slap vibration is shown in Fig. 7. From Fig. 7, it can be seen that the spectrum of IC2 is consistent with the spectrum of measured piston lap vibration signal. Thus, it can be determined that IC2 is the piston slap noise.

![Fig. 6 Coherence function of P1 and a](image)

![Fig. 7 IC2 and piston slap vibration spectrum](image)

### 4.2 Discussion

In order to show the effectiveness of the EWT-RobustICA method, the EMD-RobustICA method is carried out to separate the combustion noise and piston slap noise. The separation results by EMD-RobustICA method are shown in Fig. 8 and Fig. 9.

![Fig. 8 Time domain waveform, FFT and CWT of IC1 by EMD-RobustICA method](image)
Compared Fig. 4 with Fig. 8, there are many interference components in the separated combustion noise by the EMD-RobustICA method, and it is shown in the yellow circle in Fig. 8. Compared Fig. 5 with Fig. 9, it exists many interference components in the separated piston slap noise by the EMD-RobustICA method in Fig. 9. Therefore, through EMD-RobustICA method, the calculated combustion noise and piston noise have many other interference components. The separation effect is not good. By EWT-RobustICA method, the combustion noise and piston slap noise are pure. Thus, the separation effect and stability of EWT-RobustICA method is better than the EMD-RobustICA method.

5. Conclusions

(1) In terms of experimental design, the lead covering method is adopted to isolate the interference noise from No. 1-5 cylinders. From the physical source level, it can effectively shield the interference noise to ensure accuracy of the measured data.

(2) The multi-cylinder diesel engine noise source separation method based on EWT-RobustICA is put forward and realized. The proposed EWT-RobustICA method is utilized to separate the measured single channel noise signals. It can effectively solve the problem of separating the multiple noise source signals from the single channel noise signal.

(3) The proposed EWT-RobustICA method is employed to separate the single channel near field radiated noise signal of No. 6 cylinder when the 6-cylinder diesel engine is at 600 rpm and no load stable operation condition. The experimental results show that the proposed EWT-RobustICA method can accurately and steadily separate the combustion noise and piston slap noise. Compared with EMD-RobustICA method, the proposed method can get more pure independent noise sources.

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