IDENTIFICATION OF NOISE SOURCE BASED ON PARTIAL COHERENCE ALGORITHM

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Combustion noise and piston slap noise are major part of engine’s noise source, and thus the identification, separation and quantification of them are of far-reaching significance to evaluating and controlling engine’s noise. However, it is difficult to separate all kinds of noise sources from each other due to the aliasing problems existing in both time and frequency domain. Therefore, this paper explores the separation of engine combustion noise and slap noise based on a multi-input/single-output model and a partial coherence algorithm. Firstly, the influences on separation performance of the partial coherence algorithm brought by various noise sources’ aliasing level and different signal-to-noise ratio are investigated with simulation signals and results show that the partial coherence algorithm can efficiently eliminate the mutual coupling effects between inputs. Besides, it can also effectively separate the parts generated from a single input as well as the ones caused by the interaction of multiple inputs. Finally, the algorithm is applied when using a diesel engine’s measured signals to separate the combustion noise, piston slap noise, etc., and then the structural response function of combustion noise is further computed in order to obtain the main controlling frequency range.

Keywords: partial coherence analysis, contribution rate, separation performance, noise separation

1. Introduction

With the improvement of living standards, the noise problem has attracted more and more people's attention. At present, noise pollution has become an important source of pollution. With the improvement of living standards, the noise problem has attracted more and more people's attention. At present, noise pollution has become an important source of pollution. Prolonged exposure to noisy environments can cause hearing loss, heart disease, stroke, anxiety, stress, depression, learning difficulties, work performance, sleep disturbances, and decreased cognitive ability [1]. Engine noise is also an important source of noise. How to reduce engine noise has become an urgent problem to be solved.

Combustion noise and piston slap noise are major part of engine’s noise source. The key to controlling and reducing engine noise is to identify, separate, and quantify the noise of various parts of the engine[2]. There are many ways to identify noise sources at present. Traditional noise source identification methods (such as lead overlay method, reverse drag method, and spectrum analysis method) are simple and easy to implement, but the accuracy and accuracy of noise source identification is low. The noise source identification methods based on acoustic array technology are mainly sound in density method, acoustic holography method, and beam forming method [3, 4]. The noise source identification method based on
acoustic array technology is mainly used to determine the distribution of the radiation noise space on the surface of the internal combustion engine or the sound source localization, and it is impossible to separate independent noise sources such as combustion noise and piston slap noise. The noise source identification methods based on modern signal processing technology mainly include independent component analysis method [5], filtering method [6], multiple regression analysis method [7], EEMD-based method [8] and so on. The noise source identification method based on modern signal processing can accurately identify, separate and quantify the internal combustion engine noise source, compared with the previous two methods of noise source identification.

Combustion noise and piston slap noise in the noise source of the internal combustion engine are difficult to separate from each other due to the aliasing problems existing in both time and frequency domain[9]. The partial coherence algorithm is considered to be a separation algorithm that can eliminate the coupling between inputs [10, 11]. Therefore, this paper explores the separation of engine combustion noise and slap noise based on a multi-input/single-output model and a partial coherence algorithm. Prior to this, a set of simulated signals was used to explore the different aliasing levels of noise sources and the effect of different signal-to-noise ratios on the identification performance of the partial coherence algorithm. Finally, the algorithm is applied when using a diesel engine’s measured signals to separate the combustion noise, piston slap noise, etc., and then the structural response function of combustion noise is further computed in order to obtain the main controlling frequency range.

This paper is organized as follows. Section 2 describes the basic theory and algorithm performance analysis of the partial coherence algorithm based on the multi-input single-output model. Section 3 introduces the experimental situation of a diesel engine and uses the off-coherent calculation to identify and analyze the combustion noise and piston slap noise. Finally, Section 4 summarizes the conclusions of this study.

2. Partial coherence

2.1 Related theory

The coherence coefficient between input and output in the theory of coherent analysis is defined as follows [12]:

$$\gamma_{xy}^2(f) = \frac{S_{xy}(f)}{S_{xx}(f)S_{yy}(f)}$$

$$\gamma_{xy}^2(f)$$ : Coherence for the input and output.

$$S_{xx}(f), S_{yy}(f)$$ : Self power spectral density.

$$S_{xy}(f)$$ : Cross power spectral density.

For a single-input/single-output system, the contribution of the input to the output is easily obtained by coherence analysis, considering that the interference noise is not correlated with the input. In a multi-input system, there is generally a certain correlation between the input signals. In order to eliminate the influence of the relevant parts between the inputs, the partial coherence analysis method emerges. Partial coherence analysis can effectively eliminate the mutual coupling between inputs and separate the output into separate parts, so that the influence of each input on the output can be clearly analysed.

The partial coherence coefficient is defined as follows [13]:

$$\gamma_{xy}^2(\omega_{i-1}) = \frac{|S_{xy}(\omega_{i-1})|^2}{S_{xx}(\omega_{i-1})S_{yy}(\omega_{i-1})}$$

$$2$$
\[ S_{ij}^{(r)} = S_{ij}^{(r-1)!} \frac{S_{ij}^{(i-1)!}}{S_{ij}^{(i-1)!}} \] (3)

In the above three equations, \( i \) and \( j \) indicate the input order, \( (i-1)! \) indicates the effect of the \( (i-1) \) inputs before removal.

\[ \gamma_{ij}^{2} (f) : \text{Partial coherence for input } (X_i) \text{ and output } (Y) \]

\[ S_{ij}^{(r)} : \text{Conditional power spectrum} \]

Therefore, \( \gamma_{ij}^{2} (f) \) represents the partial coherence coefficient, and the magnitude represents the independent contribution of the input \( X_i \) to the output.

Using the partial coherence algorithm for noise separation, the self-power spectrum and the cross-power spectrum between each input and output are first calculated. Then, according to the partial coherence theory, the conditional spectrum and the partial coherence coefficient are calculated, and the contribution of each part is obtained. Finally, the noise of each part is calculated according to the contribution of each part.

### 2.2 Performance analysis of partial coherence algorithm

Taking the two-input/single-output system as an example, the simulation signal is used to explore the influence of different aliasing levels of noise sources and different signal-to-noise ratios on the separation performance of the partial coherent algorithm.

Inputs \( X_1 \) and \( X_2 \) in Figure 1 become \( Y_1 \) and \( Y_2 \) after passing through systems \( H_1 \) and \( H_2 \), respectively. After considering the effect of noise \( N \) on the overall system, the total output is \( Y \). According to the theory of partial coherence, the partial coherence coefficient between \( X_2 \) and the output as follow:

\[ \gamma_{21}^{2} (f) = \frac{S_{21}^{*} (f)^2}{S_{22} (f) S_{11} (f)} \] (4)

The output \( Y_{2,1} \) caused by \( X_2 \) can be further calculated by the contribution calculated by Eq. (4). After the output \( Y \) is separated by the partial coherence algorithm, two parts of independent \( Y_1 \) and \( Y_{2,1} \) can be obtained (Fig. 2). This makes the separated noise sources independent of each other, and thus can effectively analyse each part.

According to the two-output/single-output model, it is assumed that the simulated signal includes two voltage signals having different frequency characteristics, two different linear systems and one white noise signal \( N \). Two input signals and one output signal are input to the prepared partial coherence separation algorithm to obtain two parts, \( Y_1 \) and \( Y_{2,1} \). Since the window function selection and the power spectrum calculation method are not the focus of this paper, the hamming window and Welch’s averaged, modified periodogram method of spectral estimation are used in the subsequent calculations.

Define the signal-to-noise ratio \( SNR = 10 \lg (P_Y / P_N) \), where \( P_Y \) and \( P_N \) represent the effective power of the noisy signal and noise, respectively, in dB. In order to better meet the actual situation, each input
signal randomly selects 10 frequency points in the analysis frequency band 0-100 Hz, and each frequency point corresponds to 10 random amplitudes within 1-5, and the sinusoidal signals at these frequency points superposition as an input. The signal-to-noise ratio is used to simulate the interference of the signal during acquisition by the acquisition system. The specific parameters are as follows:

<table>
<thead>
<tr>
<th>Input</th>
<th>Frequency (Hz)</th>
<th>Amplitudes (V)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>9,17,23,41,53,71,72,85,87,94</td>
<td>4,3,3,1,4,2,4,2,3,2</td>
<td>30</td>
</tr>
<tr>
<td>X₂</td>
<td>4,13,17,28,45,59,60,61,73,83</td>
<td>2,3,4,2,3,5,3,1,1,2</td>
<td>30</td>
</tr>
</tbody>
</table>

Firstly, the influence of different aliasing degree on the separation performance of the partial coherence algorithm is discussed. In order to facilitate the analysis, the purpose of changing the aliasing degree is achieved by changing the frequency resolution. Offsetting the power spectrum of the output signal (red) makes observation easier (Fig. 3). The blue line indicates the portion produced by the first input, and the green colour indicates the portion produced by only the second input. All peaks can be separated from the output at higher signal to noise ratios. At a frequency resolution of 1 Hz (Fig. 3-b), it can be distinguished that 83 Hz and 85 Hz are generated by two input signals respectively, which is consistent with the known input signal and has only one peak in the band 71-73 Hz. When the frequency resolution is increased to 0.25 Hz (Fig. 3-a), the input signal with an interval of 1 Hz can be clearly identified. Therefore, when the frequency resolution is less than or equal to 1/4 of the aliasing degree, a better separation can be achieved by the partial coherence separation algorithm.

![Figure 3: The PSD of original signal and identified signal. (a) Frequency resolution=0.25 Hz. (b) Frequency resolution=1 Hz.](image)

The effect of the actual noise signal $N$ on the separation effect will be discussed below. By changing the SNR, the separation effect of the partial coherence algorithm is evaluated by the peak relative error of 17 Hz and the number of peaks (Fig. 4). In order to reduce the random error, a mean of 5 times is used. Both the white noise signal $N$ (Fig. 4-a) and the colour noise $N$ are considered (Fig. 4-b).

In the case of white noise interference, since the frequency component included in the noise has the same portion as the input signal, as the SNR decreases, the maximum peak relative error increases, and the identified peak decreases. In the case of colored noise interference, the maximum peak relative error hardly changes with the signal-to-noise ratio. Due to the interference of the signal during acquisition by the acquisition system with 30 dB signal to noise ratio, the number of peaks separated increases with the proportion of cooler noise energy. However, by comparing the relative sizes of the peaks, it can be found that the peak generated by the input signal is almost equal to the present value. Other peaks, although present, are relatively small relative to the output signal. In general, partial coherence algorithm can
efficiently eliminate the mutual coupling effects between inputs. Besides, it can also effectively separate the parts generated from a single input as well as the ones caused by the interaction of multiple inputs. In particular, the separation effect of this algorithm is better when the interference noise is not correlated with the input.

![Graph](image)

Figure 4: The average separation effect. (a) White noise interference. (b) Colored noise interference.

3. Identification and analysis of combustion noise and piston slap noise

3.1 Experiment

The test object was MAN B&W 6L16/24 diesel engine. Considering the actual situation of the engine and the test bench, the 4\(^{th}\) cylinder was selected as the experimental object, and the engine was operated at 650-1000 rpm with 0% load. In order to be able to separate and identify the noise source of one cylinder of the internal combustion engine, shield the interference noise generated by other cylinders, and use three layers for other cylinders (2 cm thick flame retardant cotton + 2 mm thick high density Lead plate + 2 cm thick flame retardant cotton) cover the package. A melamine sound absorbing tip is set to absorb reflections and ambient noise.

The vibration and noise test and measurement system of the internal combustion engine is composed of sensor equipment, NI acquisition module, NI cDAQ-9172 data acquisition chassis, NI 9234 data acquisition card, computer, etc. The test system framework is shown in Fig 5. The experimental data is simultaneous acquisition, the sampling frequency is 25.6 KHz, and the above-mentioned dead-point sensor signals are signs, and the data of an integer number of engine running cycles are intercepted.

![Diagram](image)

Figure 5: Experimental system frame and sensor installation location diagram

3.2 Results and discussion

In order to define the noise contributions from different excitation mechanism in an engine, the following basic assumption has been made in this project for the methodology development:
TN = MN + CN + ON
TN: Total engine Noise
CN: Combustion Noise
ON: Other Noise (The noise except for TN and CN)

In general, the combustion noise is considered to be caused by the pulsation of the pressure in the cylinder, so the cylinder pressure becomes one of the input signals. The piston slap noise is caused by the piston striking the cylinder liner, so the knocking side vibration signal of the cylinder liner becomes the second input signal. The sound pressure signal collected by the sound pressure sensor is used as the output signal. The total noise includes combustion noise, piston stroke noise and other noise. It is assumed here that other noise is not related to combustion noise and piston slap noise. Taking into account the human ear's ability to perceive sound and the convenience of observation, the separation results are displayed in 1/3 octave.

Figure 6 shows the noise separation of the engine at different speeds. It has been observed that combustion noise accounts for a major contribution throughout the analysis frequency band. As the rotational speed increases, the overall level of noise increases in the high-frequency part, and the frequency corresponding to the peak value of other noises around 200 Hz also increases with the increase of the rotational speed. The piston slap noise is generally maintained at a relatively stable level with a small relationship with the rotational speed. Focusing on the noise of the 900 rpm engine (Fig. 6-b), the piston slap noise is the smallest in the entire frequency band, and the combustion noise and other noise are large, because the entire diesel engine is in an idle state. Combustion noise accounts for a large proportion below 1000 Hz, especially 100-1500 Hz. Other noises have a greater contribution at 250 Hz, and 800-1000 Hz has the largest combustion noise and is the main source of noise. Therefore, controlling the combustion noise will significantly improve the noise level of the diesel engine.

![Figure 6: SPL of noise. (a) At 700 rpm. (b) At 900 rpm.](image)

After changing the order of the input signals, the common frequency band of combustion noise and piston tapping noise can be obtained by comparing the previous results, as shown in Fig. (7). A common part of the presence of combustion noise and piston slap noise is clearly observed in the two bands of 100-300 Hz and 700-800 Hz. This is also a big advantage of the partial coherence algorithm.

Since the structure of the diesel engine does not change during the test, it is generally considered that the structural response function has a little change. Therefore, the validation of the coherence approach can be performed by the structure response results of engines with respect to combustion excitation. The engine structure response is defined as [14]:

\[ SR = \frac{CN}{CE} \]

SR Structure response of engine
CE Combustion noise (TN) obtained by the partial coherence approach
CE Combustion Excitation within cylinder (Cylinder pressure)
As shown in Figure 8, the overall trend of the transfer function is the same at different speeds, and the maximum amplitude difference is within 8 dB. The differences are mainly again due to the change of the oil film between rotating and sliding engine parts, e.g. in the oil films of the crank train slider bearings and the oil film between piston and liner. The speed and load effecting have an effect on the stiffness and damping characteristics of these oil films. From the trend of the combustion transfer function, as the frequency increases, the transfer function decays gradually and peaks at 1000 Hz. This also reflects the greater rigidity of the diesel engine.

4. Conclusions

The partial coherence algorithm can efficiently eliminate the mutual coupling effects between inputs. Besides, it can also effectively separate the parts generated from a single input as well as the ones caused by the interaction of multiple inputs. However, this algorithm cannot be applied when the interference noise is strongly correlated with the input signal.

The calculation of combustion noise and piston slap noise separation based on the partial coherence algorithm can separate the combustion noise and the piston slap noise, and also obtain the common part of the combustion noise and the piston slap noise. Further, the structural response function of the combustion noise can be calculated. In general, combustion noise is an important source of noise for the engine, with a focus on the control band of 100-1500 Hz.

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REFERENCES


