

Development for extracting method of engine speed from inboard noise

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A method of estimating engine speed is proposed in this paper. The inboard noise contains frequency information generated in combustion noise of the main engine. Using this frequency information, it is expected to estimate the speed of the main engine. Three sound processing filters (volume filter, Simple moving average filter, Coefficient of variation filter) were created to extract this information. Results of estimation using actual measurement data showed the average accuracy about 90%.

Keywords: Inboard noise, Engine speed, Frequency analysis, Boat, Estimation

1. Introduction

In this research, authors propose a method to estimate engine speed using inboard noise. The inboard noise is separated into phase information and power spectrum using frequency analysis. Authors studied a method of estimating the engine speed using this power spectrum. The frequency analysis produces a fundamental frequency component generated by the combustion noise of main engine. Indicating the fundamental frequency as f_0 [Hz], the engine speed as N [rpm], the cycle constant K ($K=2$ for 4cycle, $K=1$ for 2 cycle) and the number of cylinders as m , the relation between engine speed N and fundamental frequency f_0 can be described the following expression.

$$f_0 = \frac{N \times m}{60K} \quad (1)$$

This means, that if the fundamental frequency f_0 can be extracted from the inboard noise on navigation, the main engine speed can be calculated. Therefore, in this research authors created a sound processing filter to extract the fundamental frequency f_0 [Hz] and analyzed the results.

2. Boat A where sound was recorded and recording conditions

2.1 Boat under test

The inboard noise was collected from a sample.

Table 1 shows the main characteristics of the Boat A. The idling speed is 580[rpm], and the rated speed is 1880[rpm]. Since the main engine contains 6 cylinders with 4 stroke, the fundamental frequency range of the Boat A that can be taken is calculated as $27.5 \leq f_0 \leq 94$ [Hz] using expression(1).

Table 1 Boat A principal particulars

Gross tonnage	LOA	Rated speed / Rated output
1 9 GT	19.8m	610kW/1880rpm
Beam	Navigation speed	m / K
4.42m	20knot	m=6 / K=2

2.2 Recording conditions

In this experiment the inboard noise was recorded using two devices. The sampling points was set to $N_s = 65536$. These conditions provided frequency resolution $\Delta f = 0.67$ [Hz] and resolution of estimated engine speed 13.46[rpm]. The time window length was set to 1.49[sec], its shift width was set to 0.8[sec], and a rectangular function was used as the window function.

3. Main sound processing for engine speed estimations

The example of the frequency analysis result for 1700 rpm engine speed is shown on Fig.1. The fundamental frequency has stronger power spectrum than other frequency components. However, under other operating conditions, the fundamental frequency does not necessarily have

strong power spectrum. For this reason, authors created multiple sound processing filters to extract the fundamental frequency f_0 from the frequency information of inboard noise. In this chapter we described three of them in detail.

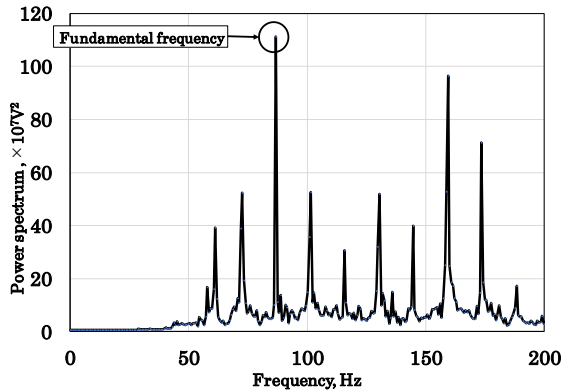


Fig.1 Frequency analysis at 1700rpm

3.1 Sound volume filter

3.1.1 Relationship between sound volume and engine speed

The volume filter is a band pass filter that uses the relationship between the inboard noise and the engine speed. Several graphs of relationships between boats sounds and the engine speed are shown on the fig.2. A certain degree of correlation between sound volume and engine speed can be seen.

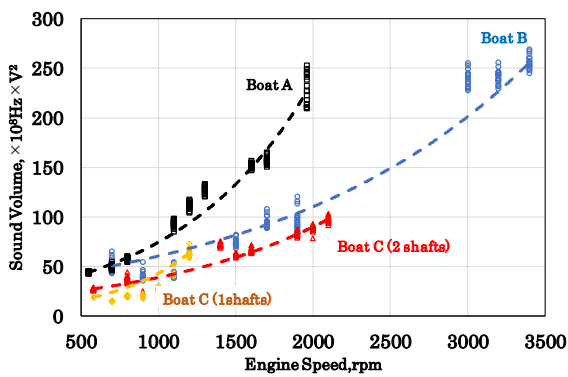


Fig.2 The relationship between engine speed and sound volume

Also, the inclination of the sound volume graph differs depending on the rated speed and output of the main engine. In this research this characteristic was used in the band pass filter. The sound volume S [$\text{Hz} \times \text{V}^2$] is defined in this study as follows.

$$S = \sum_{n=0}^b P_{n \times \Delta f}$$

The power spectrum $n \times \Delta f$ [Hz] is defined as $P_{n \times \Delta f} [\text{V}^2]$, where n is positive integer. To exclude the high frequency range from the calculation of the sound volume S , the end point of integration b is defined as shown below.

$$b = \frac{1}{\Delta f} (2f_{\text{rated}})$$

The f_{rated} [Hz] is set as the maximum value of the fundamental frequency f_0 .

3.1.2 Creating the sound volume filter

Fig.3 shows the band pass filter created using the relationship between the sound volume and engine speed of the Boat A. Sound volume changes depending on the operating conditions of the main engine. The variation of the measured values is used to define band width of the band pass filter.

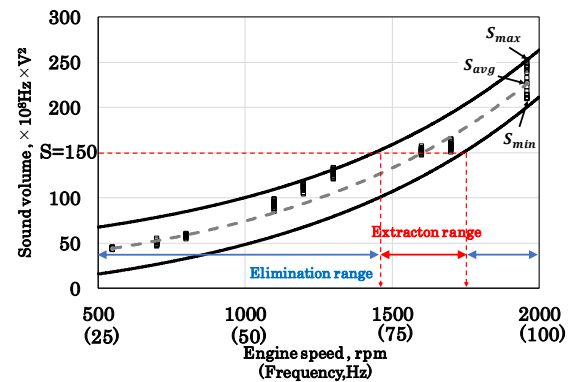


Fig.3 Sound volume filter of Boat A

The average sound volume for the rated engine speed is defined as S_{avg} . Defining the maximum volume as S_{max} and minimal value as S_{min} , we calculate the difference between these values and S_{avg} . The result is denoted as S_{large} . If we define the function derived from the relationship between the engine speed N and sound volume S as $S=f(N)$. The bandwidth $f(N)_{\text{band}}$ can be defined as follows.

$$S_{\text{large}} = \max\{S_{\text{max}} - S_{\text{avg}}, S_{\text{avg}} - S_{\text{min}}\}$$

$$f(N)_{\text{band}} = f(N) \pm S_{\text{large}}$$

In the example shown on Fig.3, if the sound volume $S=150$ for engine speed 1700rpm the calculated extraction range will be from 1474[rpm] to 1765[rpm]. This is converted to the frequency range from 73.72[Hz] to 88.28[Hz].

3.2 Simple moving average filter

As shown in Fig.1, the engine noise includes clear frequency components. It must be noted that the fundamental frequency is one of those components. The calculation load on sound processing can be reduced by removing beforehand all information other than clear peaks. A simple moving average processing is applied to achieve this. This method works by continuously calculating the average value of data within a certain range and analyzing the change trend of the whole data. Defining the number of points for moving average as L , and the power spectrum after simple moving average as $\overline{P_{\Delta f \times n}} [V^2]$, we can produce the following expression.

$$\overline{P_{n \times \Delta f}} = \frac{P_{\{n - \frac{(L-1)}{2}\} \times \Delta f} + \dots + P_{n \times \Delta f} + \dots + P_{\{n + \frac{(L-1)}{2}\} \times \Delta f}}{L}$$

Here L is an odd number.

Fig.4 shows the simple moving average value $\overline{P_{\Delta f \times n}}$ and the frequency analysis result for engine speed of 1700rpm.

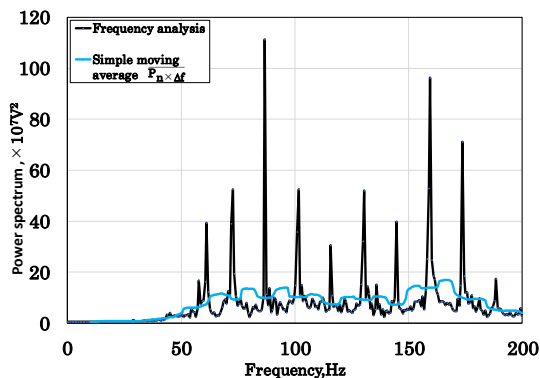


Fig.4 Frequency analysis and simple moving average at 1700rpm

Weak frequency components are removed by calculating the difference between the frequency analysis and the simple moving average value.

3.3 Coefficient of variation filter

When the sound volume and the simple moving average filters are applied to the analysis result shown on Fig.1, the candidates for the fundamental frequency are narrowed down to two (see Fig.5). To specify the fundamental frequency $f_0=85$ [Hz], the coefficient of variation is calculated.

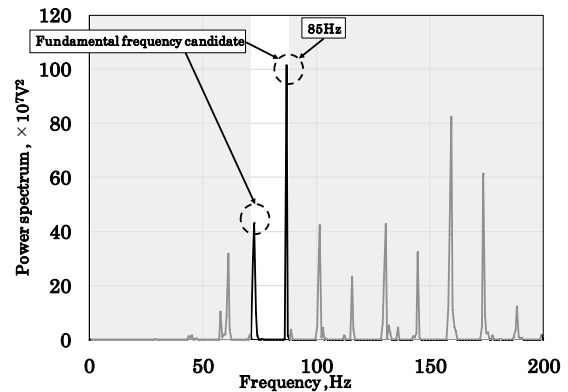


Fig.5 Extracted sample about fundamental frequency candidate

Fig.6 shows a time frequency analysis at 1700rpm.

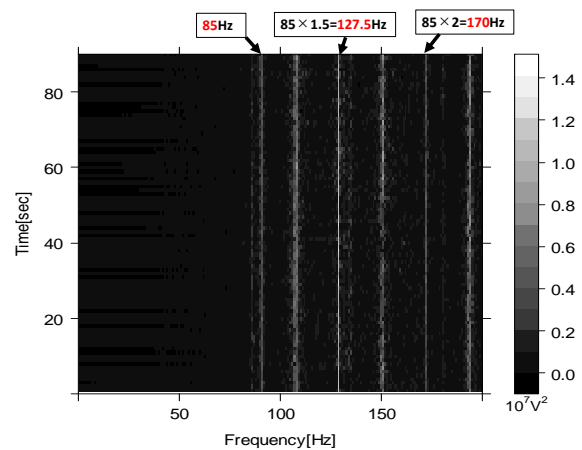


Fig.6 Time frequency analysis at 1700rpm

At the fundamental frequency $f_0=85$ [Hz] and its harmonics, the same level of power spectrum intensity become continuous on the time axis. When the speed of main engine is constant, the engine sound is continuous. However, unexpected noise is not continuous. In other words, there is possibility that the frequency components caused by the combustion

noise of the main engine will be continuous. Thus, in this research, it is assumed that the temporal continuity of the power spectrum intensity is remarkable in the fundamental frequency and its harmonics. To evaluate the time variation in the power spectrum intensity, a coefficient of variation is calculated. Using 3.1 and 3.2, we can extract fundamental frequency candidates f_j [Hz]. Let us define the time window length as t [sec], its shift width as s [sec], and the power spectrum of the f_j generated each s [sec] period as P_{qs+t, f_j} . Defining the average value of the power spectrum of q data part as \overline{P}_{f_j} , we can produce the following expression.

$$\overline{P}_{f_j} = \frac{\sum_{k=1}^q P_{ks+t, f_j}}{q}$$

The coefficient of variation CV_{f_j} is defined as follows.

$$CV_{f_j} = \frac{1}{\overline{P}_{f_j}} \sqrt{\frac{1}{q} (\sum_{k=1}^q (P_{ks+t, f_j} - \overline{P}_{f_j})^2)}$$

Here j and q are positive integers. Since there are two fundamental frequency candidates on Fig.5, the value of j is equal to 2. Also, the larger the value of q , the higher the reliability of the variation evaluation.

Similarly, let $CV_{1.5f_j}$ be the coefficient of variation

for the frequency $\frac{1}{2}$ octave higher than the

fundamental frequency, and CV_{2f_j} be the coefficient

of variation for the frequency 1 octave higher than the fundamental frequency.

The final evaluation criterion CV_{f_j} for the fundamental frequency is defined as follows.

$$CV_j = \frac{CV_{f_j} + \min\{CV_{1.5f_j}, CV_{2f_j}\}}{2}$$

The fundamental frequency candidate f_j with the minimum CV_{f_j} is extracted as the fundamental frequency f_0 . By substituting the f_0 extracted by the

above process the engine speed can be estimated.

4 .Estimation results and considerations

Table 2 shows the estimation accuracy by using proposed processing mentioned above. The average accuracy was about 90%. The accuracy decreases at specific engine speed. It is presumed that the accuracy decrease at specific engine speed is due to the engine load fluctuations caused by external disturbance. The external disturbance causes pressure fluctuation inside cylinders, and this pressure fluctuation leads to sound volume fluctuation. This sound volume fluctuation reduces the effect of the coefficient of variation filter, and possibly lowers accuracy.

Additionally, difference in accuracy depending on recording device is observed. As for the reason of the accuracy variation between recording devices, it can be caused by difference in microphone characteristics. However, this difference in the accuracy was not large.

Therefore, we can conclude that three filters showed high performance to specify the fundamental frequency.

Table 2 Result of estimation

Engine speed[rpm]	Accuracy[%]	
	device 1	device 2
550	100	100
700	95	100
800	80	70
1100	90	85
1200	90	100
1300	95	100
1600	80	95
1700	95	100
1880	95	95

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