Modern society uses a variety of vehicles for transport. While these vehicles are often indispensable to their users, they can also generate unpleasant noise. The field of signal measurements and design of engine sound require that analyzing the correlation of signals among each observation points and extracting the objective components of signal since they cannot be detected with ordinary measuring instruments. In the view of analysis, the frequency analysis is widely used in sound and vibration analysis, but is not always effective in the analysis of non-stationary sounds. Stationary signals can be analyzed the correlation between them using a coherence function, but this method cannot be used for time-varying signals. To solve these problems, we proposed a method that uses an Instantaneous Correlation Function (ICF) that can analyze time-varying signals in time-frequency analysis based on the real-signal wavelet. We also introduced the idea of limiting the bandwidth using filters to improve the precision of our method and applied this method to the running sounds of a motorcycle and the ship’s interior noise to clarify the signal correlation of the components of the engine. As a result, it was possible to observe the running condition relating to the engine sound buried in the noisy environment effectively. This will contribute to the sound design of the engine sounds, separation of sound sources and active noise control.

1. INTRODUCTION

The production concept of car engine sound has been changing from finding a solution to noise to designing sound. Although many studies have been conducted on creating comfortable car-engine sound, the fields of signal measurement and acoustic design of engines both require an analysis method that correlates the signals from the various observation points and extracts the target components of the signal. Frequency analysis is widely used in sound and vibration analysis, but is not always effective in the analysis of time-varying sounds. Stationary signals can be analyzed by correlating them using a coherence function, but this method cannot be used for time-varying signals. To solve these problems, we proposed a method that uses an Instantaneous Correlation Function (ICF) [1-3] that can analyze time-varying signals in time-frequency analysis. In this study, we applied this method to the running sounds of a motorcycle and to the noise of a ship’s interior to clarify the signal correlation method and to extract the components of an engine noise signal. Analysis of the correlation of time-varying signals will lead to improvements in engine sound design, the separation of sound sources, and active noise control.
2. INSTANTANEOUS CORRELATION FUNCTION ANALYSIS

ICF analysis is based on the Wavelet Transform (WT) [4,5]. The WT is written as

\[ W(u, s) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{s}} \psi^*(\frac{t-u}{s}) f(t) dt, \quad s > 0, \]  

(1)

where \( f(t) \) is a signal, \( \psi(t) \) is a function, \( \psi^*(t) \) is its complex conjugate, and \( s \) and \( u \) are the scale and shift parameters, respectively [4,5].

In the conventional WT, a basis function is used as the Analyzing Wavelet (AW). In the proposed ICF analysis, a part of the actual signal is used as the AW. The ICF analysis is described by

\[ ICF(t, a) = k_a \int_{-L_a/2}^{L_a/2} s(\tau, a) f(t + \tau) d\tau, \]  

(2)

where \( s(\tau, a) \) is the part of the actual signal that is used as the AW, \( L_a \) is the length of the window function, \( k_a \) is a normalization parameter, and \( a \) and \( \tau \) are the scale and shift parameters, respectively. Figure 1 shows an overview of the ICF analysis process [1-3].

In ICF analysis, the short term signal is first extracted from the measured signal to act as the AW, and other AWs are made by compressing and/or extending the original AW. The compressed AWs are equivalent to the high frequency components of the signal, and the extended AWs are equivalent to the low frequency components. Then, we calculate the inner products of the compressed/extended AWs and the observed signal while shifting each AW along the time axis.

If part of the observed signal is taken to be \( s(\tau, a) \), it becomes possible to analyze the self-similarity between the AW and the observed signal. When analyzing two signals, it is possible to detect the similarities of \( s(\tau, a) \) between these signals. This technique can be applied to the analysis of observed signals that have a fundamental frequency and harmonic components. Therefore, when analyzing a signal with a harmonic structure, the features that correspond to the fundamental frequency and the harmonic components are detected simultaneously; we thus expect to be able to identify any changes that occur in these features.

We can extend this method to complex analysis by introducing the complex AW \( (s^*(\tau, a)) \) to improve the accuracy of the ICF analysis. The complex instantaneous correlation function (CICF) analysis is written as

\[ CICF(t, a) = k_a \int_{-L_a/2}^{L_a/2} s^*(\tau, a) f(t + \tau) d\tau. \]  

(3)
This method is more accurate than the conventional ICF analysis because the phase information is added by expansion from the actual signal to the complex signal.

### 3. ANALYSIS OF MOTORCYCLE SOUNDS

We measured the sounds of a running motorcycle (see Table 1) with a four-stroke inline four-cylinder engine in a steady-running state (3rd gear, 60 km/h) and in an acceleration/deceleration cycle (idle - full throttle - idle, over a 1.5 s period).

We then used CICF analysis to analyze the correlation of these signals. The running motorcycle sounds consist of the engine sounds (intake and exhaust sounds), wind noise, and road noise. The engine sounds are stronger when the motorcycle accelerates, the road noise is stronger when driving on rougher roads, and the wind noise is stronger when driving at high speeds. The intake sound is an important part of the engine sound when considering the overall engine sound quality. Analysis of how the intake sound contributes to the engine sound from the vantage point of a rider’s ears is helpful in engine sound design. We therefore used CICF analysis to focus on the relationship between the intake sound and the sound at the rider’s ears.

To confirm that relationship, we first conducted a coherence analysis [6] of the motorcycle in a steady-running state. The coherence analysis is described by

$$\gamma_{xy}^2 = \frac{|W_{xy}|^2}{W_{xx} \ast W_{yy}},$$

where $\gamma_{xy}$ is the coherence function, $W_{xy}$ is the cross-spectrum, and $W_{xx}$ and $W_{yy}$ are the power spectra of each of the signals [6]. This analysis shows that strong correlations exist between the fundamental frequency of the intake sound and its harmonic, which confirms the effectiveness of our method (see Figure 2).

We then conducted the CICF analysis of the motorcycle’s running sounds. We selected the intake sound for use as the AW and the sound at the rider’s ears as the signal to be analyzed.

First, we conducted the CICF analysis for the steady-running state to confirm the validity of the analysis method for stationary signals, which also confirmed the steady running state of the engine. Next, we analyzed the motorcycle sound during acceleration and deceleration, and the results confirmed the correlation between the intake sound and the sound at the rider’s ears. Here, the acceleration interval is from 0.1 s to 0.5 s, and the deceleration interval is from 0.5 s to 1.0 s.

These results support the possible use of correlation analysis for time-varying sounds. In contrast, confirmation of the correlation was difficult when using conventional methods, such as those based on use of a spectrogram or WT. These results confirm the effectiveness of the CICF analysis method. Figure 3 shows the results of analyses of the acceleration/deceleration cycle. Figure 3 (a) shows the results of the CICF analysis, while Figure 3 (b) and (c) show the results that were obtained using the spectrogram and the WT, respectively.

<table>
<thead>
<tr>
<th>Measured points</th>
<th>Measured signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake duct</td>
<td>Sound</td>
</tr>
<tr>
<td>Cleaner box</td>
<td>Sound</td>
</tr>
<tr>
<td>Rider’s ears</td>
<td>Sound</td>
</tr>
<tr>
<td>Engine</td>
<td>Engine pulse signal</td>
</tr>
</tbody>
</table>
4. ANALYSIS OF SHIP INTERIOR NOISE

We measured the noise in the interior of a ship; specifically, we measured the sound, vibration and pulse signals from the main engine (see Table 2) in the steady-running (350 rpm) and deceleration (from 350 rpm to 280 rpm over 8 s) states. This ship (length: 41.9 m; weight: 228 t) had a sunken forecastle and a four-stroke diesel engine.

To extract the engine sound components from the ship’s interior noise using CICF analysis, we focused on the relationship between the rotary pulse of the engine and the sound in the mess room. We found that the rotary motion of the engine was transmitted as both vibration and sound.

To confirm this relationship, we first conducted a coherence analysis for the steady-running state to confirm the relationship between the engine’s rotary pulse signal and the sound in the mess room. The coherence function had high values at frequencies of less than 500 Hz (see Figure 4).

Subsequently, to validate the results of the CICF analysis in a noisy environment, we evaluated the noise robustness in terms of the Signal-to-Noise Ratio (SNR). The SNR is defined as

$$SNR = 10 \log_{10} \frac{P_S}{P_N},$$

where $P_S$ is the power of the signal and $P_N$ is the power of the noise component. In this study, we confirmed the performance of the CICF analysis method in detection of the features of the target signal and the noise components. Here, the target signal and noise were a chirp sound and white noise, respectively. Figure 5 shows that the signal features can be detected successfully in a noisy environment (SNR:-12 dB) using CICF analysis. The validity and efficiency of the proposed method were thus confirmed.

We then conducted the CICF analysis of the interior noise in the ship. Here, we selected the rotary pulse of the engine as the AW and used the sound in the mess room as the signal to be analyzed.

First, we conducted the CICF analysis under steady-running state conditions to confirm the validity of CICF analysis for stationary signals. Although we could confirm the steady running state of the engine, the results were not sufficiently precise, because most of the components of the engine sound were often buried in the noise. The feature detection process was ineffective because the AW bandwidth was too broad to localize the viewpoint of its frequency resolution. To solve this problem, we used Band-Pass Filters (BPFs) to limit the AW bandwidth. The BPFs were set to the fundamental frequency and its harmonic. The AW then allowed us to detect the components of the engine sound precisely.
Next, we applied our method to analysis of the engine sounds during deceleration. We were able to confirm the deceleration process, which was buried in the noise, and obtain its starting point by this method. With the proposed method, it was shown that the frequency of the relevant components of the engine sound begins to fall at approximately 3 s from the start of deceleration. Our method may therefore be useful for detection of abnormal engine conditions. In contrast, finding the starting point and confirming the deceleration itself was difficult when using conventional methods such as those based on the use of a spectrogram or WT.

These results confirm the effectiveness of the CICF analysis. Figure 6 shows the results of the various analyses of the deceleration interval. Figure 6 (a) shows the results of the CICF analysis, and Figure 6 (b) shows the results of the CICF analysis (with BPFs), while Figure 6 (c) and (d) show the results that were obtained with conventional methods based on a spectrogram and a WT, respectively.
Table 2. Measured signals

<table>
<thead>
<tr>
<th>Measured points</th>
<th>Measured signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mess room</td>
<td>Sound</td>
</tr>
<tr>
<td></td>
<td>Wall vibration</td>
</tr>
<tr>
<td>Control room</td>
<td>Sound</td>
</tr>
<tr>
<td>Engine room</td>
<td>Sound</td>
</tr>
<tr>
<td></td>
<td>Engine shaft vibration</td>
</tr>
<tr>
<td></td>
<td>Engine pulse signal</td>
</tr>
</tbody>
</table>

Figure 4. Coherence between the engine pulse and sound in the mess room.

Figure 5. SNR for a chirp sound as the signal and white noise at -12 dB.

5. CONCLUSIONS

We proposed the CICF time-frequency analysis method for the extraction and correlation analysis of two types of target signal, which were the sounds from a motorcycle and a ship’s interior noise under both steady-running states and acceleration/deceleration cycles. The results confirmed that our proposed method can extract the target components of the signals and can perform the correlation analysis of each signal. This method will be useful for the sound design of engines, the separation of sound sources, and active noise control applications.
In future work, we intend to apply our method to other types of time-varying sound.

Figure 6. Results for the deceleration interval.
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REFERENCES


