NOISE SOURCE CONTRIBUTION OF ACCELERATING CARS AND AUDIBILITY EVALUATIONS

Shunsuke Ishimitsu

University of Hyogo
Department of Mechanical Engineering
2167, Shosha, Himeji, Hyogo, 6712201, Japan

ABSTRACT

Recently, many researches who work with time-frequency analysis using wavelet transform have focused on analyzing wavelets that are derived using a mathematical approach. In the present analysis, a measured signal is adopted as the wavelet, and we analyze the correlation between acoustic signals in the car cabin and suction noise signals by applying the proposed system. Because traditional calculations of correlation repeat the averaging procedure, the original signal must be stationary. Consequentially, a technique for separating and identifying noises from each part of the engine has been used for noise source contribution analysis. To apply the method to time-varying signals, the concept of an instantaneous correlation factor (ICF) is introduced, and we prove that a dominant feature of the correlation can be estimated by the ICF. The time-varying correlation for noise source contribution analysis of an accelerating car is analyzed. In addition, a fundamental experiment on audibility impressions in that case was also conducted.

1. INTRODUCTION

Frequency analysis based on the Fourier transform is widely used for extracting the features of audio signals. However, this analysis assumes that the signal being analyzed is periodic and stationary. In order to accurately represent general physical signals, it is necessary to analyze time characteristics as well as frequency characteristics; this is known as time-frequency ($t - f$) representation. Typical methods of analysis include the spectrogram, Wigner Distribution (WD)[1] and wavelet transform (WT)[2]. The $t - f$ resolution features of WT are characterized by a multiple structure, which has high frequency resolution in the low frequency range, and high time resolution in the high frequency range. This method, which is used in applications in a wide range of fields [3], performs analysis using the affine transformations (similarity transformations and translations) of a base function known as an analyzing wavelet (AW), whose distribution is localized in both time and frequency.

On the other hand, in the engine sound on the acceleration, a suction noise is an element important when considering the sound design in the car, and is conducting contribution analysis to a sound of a suction noise in the car by the maker.In the correlation analysis, the technique of separating each part is used in the present condition. As for this technique, a man day starts very much, and a simple method of carrying out contribution analysis at the time of acceleration is desired.

The present study performed examined correlation analysis of non-stationary signals, for the purpose of identifying sound sources in the interior of an automobile. Instantaneous correlation functions (ICFs) $ICF(t, f)$ and $ICF(t, a)$ based on the WT analysis method [4],[5] were used along with the time-time analyses (TT). First, the effectiveness of the ICF was verified using simulation signals, and then the contribution of intake noise (which is one of engine noise) to car interior noise was investigated during acceleration. Using an ICF in which signals relating to each noise source are selected for the actual signal AW, we showed that this technique is also useful for contribution analysis. A fundamental experiment about audibility impressions in that case was also conducted.

2. CAR INTERIOR NOISE AND CONTRIBUTION ANALYSIS

The elements which constitute car interior noise are engine noise (intake noise, exhaust noise), the whoosh sound of the car passing through the air, and road noise. It is known that the sounds which are auditorily conspicuous are engine noise during acceleration, road noise when driving on a rough road, and the whoosh of air when driving at high speeds [6]. During ordinary driving, the contribution of each noise can be determined using a coherence function, however, acceleration is the time when the effect of engine noise becomes conspicuous, and under acceleration conditions it is impossible to perform the average processing necessary to derive the coherence function. The coherence function technique therefore cannot be used for contribution analysis. Nevertheless, among the engine noises present during acceleration, intake noise is a critical factor when we consider the timbre of car interior noise, and it is thus important to manufacturers to be able to analyze the contribution of intake noise to car interior noise. A coherence function cannot be used, and the method presently in use is an extremely labor-intensive technique which involves isolating each contributor to the noise. Furthermore, although autoregressive vector modelling of a set of measurement signals has been applied to time-varying noise signals [7], this measurement is also highly labor-intensive. In the present study, we incorporate the ICF into the correlation analysis method to clarify the contribution of intake noise and to confirm the effectiveness of this simple method.

3. THE INSTANTANEOUS CORRELATION FUNCTION (ICF)

3.1. Wavelet transform (WT)

WT can be obtained by calculating the inner product of the signal $f(t)$ and AW$\psi_{a,b}(t)$ in the following formula:

$$WT_f(b,a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \psi^*_{a,b}(\frac{t-b}{a}) f(t) dt \qquad (1)$$

Here, a is the scale parameter and b is the shift parameter. These variables perform, respectively, a similarity transformation and the translation of $\psi_{b,a}(t)$. The WT is originally expressed in the time-scale ($t - s$) plane, but it can be regarded as an approximation of the $t-f$ distribution by using an AW which is localized in terms of time and frequency.

3.2. WT taking the actual signal as the analyzing wavelet (AW)

Correspondence with the scale parameter a in Formula (1) is achieved by using a similarity transform of the actual signal (used as the AW), and correspondence with the shift parameter b is achieved by translating each similarity-transformed signal along the time axis. That is, when represented by an actual signal $s(t,a,b)$ used as an AW, the affine transformation analysis for the similarity transform and translation is given by Formula (2) below. $s(t,a,b)$ is defined as the actual signal wavelet.

$$C_f(b,a) = k_a \int_{-\infty}^{\infty} s(t,a,b) f(t) dt \qquad (2)$$

Here, k_a is a normalized constant for the analysis length, just like $1/\sqrt{a}$ in Formula (2).

This method also enables analysis using $s(t,a)$ with the frequency components of the harmonic structure. For example, if a Gabor function [2] is used, a wavelet for extracting a single frequency component (ω_p) is used. If the AW

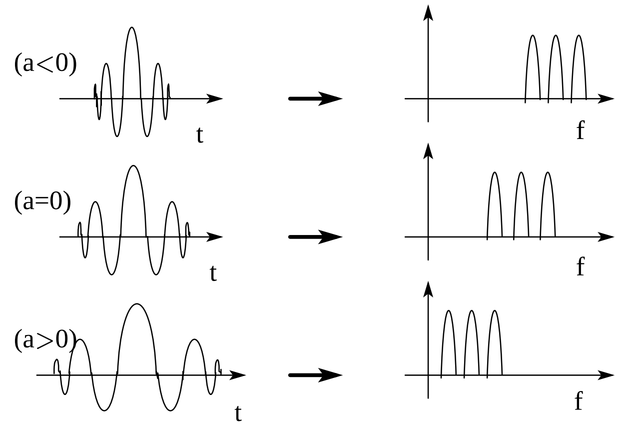

Fig. 1. Harmonic AWs

also has a structure like that shown in Fig. 1 when using this technique, the technique can be applied to the analysis of observed signals which have a fundamental frequency and the harmonic components of this frequency. Therefore, when analyzing a signal with a harmonic structure, features due to the fundamental frequency and its harmonic components are simultaneously detected, and it is thus anticipated that changes in features with a harmonic structure can be identified.

3.3. Definition of ICF

In the present research, the WT which uses $s(t,a)$ as a base function is defined in accordance with Formula (3) as the ICF $ICF(t,a)$:

$$ICF(t,a) = k_a \int_{-L_a/2}^{L_a/2} s(\tau,a) f(t+\tau) d\tau \qquad (3)$$

where L_a is the window length determined by compression/extension. The value of $ICF(t,a)$ varies depending on L_a, and this value is normalized by k_a using an autocorrelation function. Calculation while shifting by τ is the same operation as using the shift parameter b in Formula (1). If $a = 0$ in Formula (3), a correlation function is applied. If $a \neq 0$, compression occurs if $a < 0$, and extension occurs if $a > 0$. If part of the observed signal is taken to be $s(t,a)$, then it is possible to analyze self-similarity between the AW and the observed signal in some instances in which where $a \neq 0$. In the analysis of two signals, it is possible to detect similarity between $s(t,a)$ removed from one signal, and another different signal.

4. ANALYSIS OF A CHIRP SIGNAL

At first, we analyzed a chirp signal. A basic AW signal can be cut at the center of that signal and is half its length. The

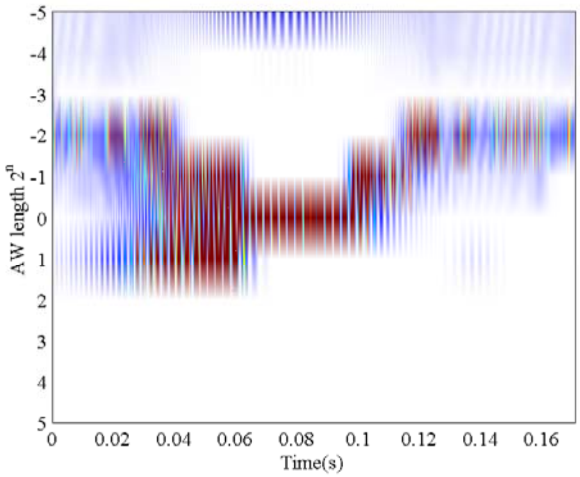

Fig. 2. Analysis of a Chirp Signal.

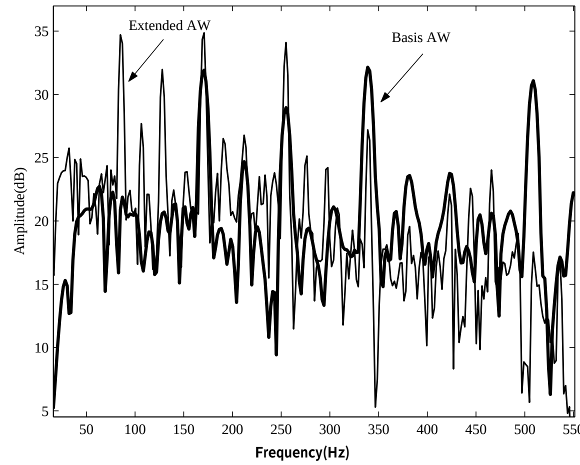

Fig. 3. Dilation of a basis AW

analyzed result is illustrated in Fig. 2. The vertical axis means the length of the AW, which is varied in 2^n with respect to the basic AW length. In this case, as this analysis is an auto-correlation at the center of this observation time (80ms, 0), the dilation and contraction rate is zero and the correlation value can be robust. At the edge of this observation time, the values are shifted toward the construction. This part means mutual-similarity analysis. Thus, the correlation analyses of the time-varying signals allow including the mutual-similarity feature.

5. APPLICATION TO TIME-TIME ANALYSIS

As the influence of the degree ratio of Base AW in ICF is fixed, a new method was developed so that a time-varing composition analysis could be performed. A definition such as formula (4) by considering the case in which a time-varying AW, $g(t)$, is introduced into ICF as Time-Time (TT) analysis [8]. If the relation between the acceleration time and rotation speed is known, the rpm-rpm expression can also be attained. Equation (4) defines

$$tt(t_1,t_2) = k_a \int_{t_2-L_a/2}^{t_2+L_a/2} g(t_2+\tau)w_a(\tau)f(t_1+\tau)d\tau, \tag{4}$$

where w_a is an analysis window of length L_a, which changes according to the rotation speed. By this technique, the time-variation of a degree ingredient is introduced into ICF.

6. ICF ANALYSIS OF CAR INTERIOR NOISE

6.1. Subject of Analysis

The subject of analysis in the present study was a sedan with a left-side steering wheel and an in-line 4-cylinder engine. A dummy head was installed in the passenger seat, and analysis was carried out to determine the correlation between the signals obtained from eardrum microphones in the dummy head and the intake noise signals obtained near the intake duct. The engine running conditions were full acceleration at 3 speeds. Engine rotation speed varied from 1000rpm to 6000rpm, and the acceleration period was approximately 20 seconds. With an in-line 4-cylinder engine, the engine fires twice in each rotation, generating a secondary vibration force, and these higher harmonics are the main component of noise. As noted earlier, engine noise is dominant during acceleration, and this noise (which has a harmonic structure) is the most auditorily conspicuous. Intake noise has a large effect on this engine noise, and the correlation between the intake noise signal and interior noise during transitions is therefore important.

6.2. ICF Analysis of Car Interior Noise

An AW was selected to act as the basis for ICF analysis of car interior noise. The basis AW was created using intake noise data from normal running at both 2000rpm and 5000rpm as reference data, and an extra experiment was conducted. Better results were obtained using 5000rpm (which extends the basis AW) as the basis AW. Fig. 3 shows the frequency characteristics when the basis AW is extended. The advantage of using the signal from normal running at 5000rpm as the basis is that the case in which the AW is extended corresponds to low-order analysis, so the analysis bandwidth is smaller and higher harmonics can easily be captured. Fig. 4 shows the results of ICF analysis of car interior noise during acceleration using this basis. Our results indicate that the effect of intake noise is great at low-speed rotation, and that the contribution gradually becomes weaker, but then increases when a high rotation speed is reached at the end. This result is expressed not by the components of each order, but as the total correlation value of their energy. In results of order analysis, it was observed that the power of the 2^{nd} order components is large near 1000–2000rpm, and that 4^{th} order components make a large contribution near 1000rpm and 5000rpm. The ICF analyzes the degree of contribution of all harmonic components, and high values were obtained near 1200rpm (taking ICF (1200, 3.8) to be the center) and near 5000rpm for ICF (5000, 0). Our results are thus consistent with those previously acquired using conventional techniques. In. Fig. 5, the same basis was used to perform contribution analysis together with noise near the exhaust manifold in the engine compartment. Fig. 5 differs from Fig. 4 in that a high value was obtained near 2000rpm (taking ICF (2000, 1.5) to be the center), implying that the constituent elements of engine noise contribute to the structure at each rotation speed.

Fig. 6 is the result of conducting TT analysis using formula (4). In this case, $g(t)$ is the suction noise and $f(t)$ is the car interior noise. Such analysis is possible because the acceleration signal is synchronized. When taking into consideration the harmonic structure by Time-varying AW $g(t)$, a difference with ICF around 5000rpm, and serves as a value slightly lower than the ICF value. This result shows that the power of the 4th and the 6th ingredients is small around 5000rpm. In addition, the energy ingredient that appears near 1000rpm in the right-hand side of the figure is the influence of the noise; these measures become a necessity from then on.

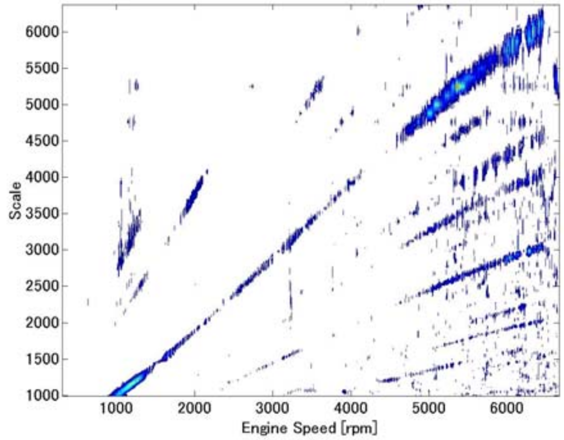

Fig. 4. ICF of car interior noise:$ICF(t, a)$

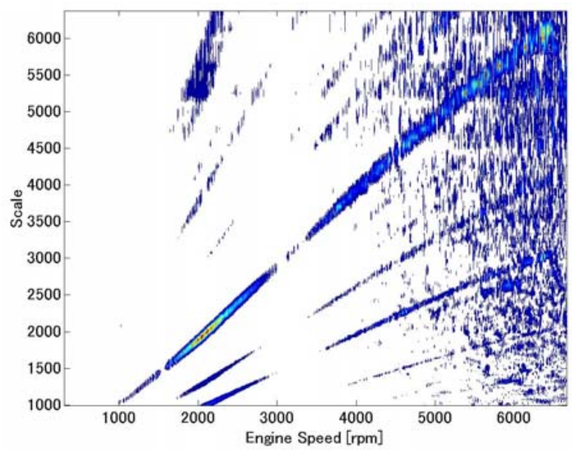

Fig. 5. ICF of engine exhaust noise:$ICF(t, a)$

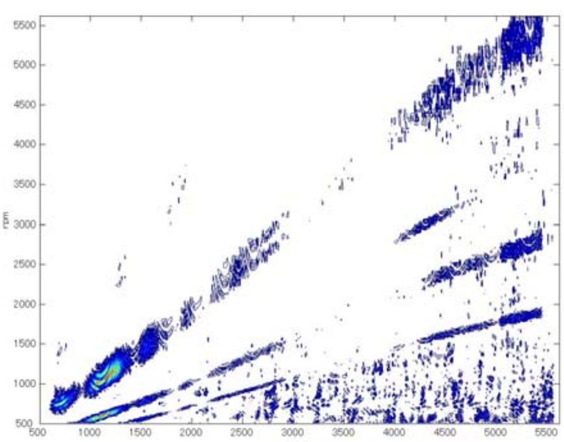

Fig. 6. TT of car interior noise:$TT(t_1, t_2)$

6.3. Subjective evaluation

Although it was clearly shown that it is possible to analyze the time-varying correlation characteristic of suction noise, the correspondence between the time change and the audibility impression of suction noise remained unclear. Thus, the inclination of the time change on a $t - f$ plane and amplitude were changed as a basic experiment, and an examination in which descriptive adjectives were selected by human subjects was performed. Six kinds of sound sources were delivered twice to 20 subjects (16 males; 4 females) of normal hearing aged 19 to 21, and they were asked to evaluate each. Evaluation was performed by subjective selection between 13 related pairs of adjective measures. The sound sources were as follows:

(1) Acceleration sound of a full throttle.

(2) A sample with 0.67 times inclination of the time change on a $t - f$ plane of (1).

(3) A sample with 1.5 times inclination of the time change on a $t - f$ plane of (1).

(4) A sample with one-half the amplitude of (1).

(5) A sample with one-half the amplitude of (2).

(6) A sample with one-half the amplitude of (3).

Among the data in which the adjective selections suggested a predominant difference, there was a tendency for a large time change on the $t - f$ plane to incline toward the positive factor. Table 1 shows the correlation coefficients for the adjectives suggesting the significance of the frequency time rate of change and sound pressure levels. It turns out that the pairs showing correlation with the $t - f$ plane demonstrate an inclination toward an energy ingredient, such as ”fast-slow”, ”alive-paralyzed”, ”sporty-not sporty”, ”dynamic-calm”, ”metallic - dull”, ”rough-smooth”, ”bright-dark” and ”high-low”.

Table1: Correlations between adjectives

Adjective pair	Correlation coefficient
fast - slow	0.796948
strong - weak	0.40073
alive - paralysed	0.705082
sporty - not sporty	0.761852
metallic - dull	0.695459
pleasant - annoying	0.422132
dynamic - calm	0.748415
expensive - cheap	0.27309
luxurious - simple	0.286475
rough - smooth	0.767504
dark - bright	0.67921
high - low	0.749835

7. CONCLUSION

The aim of the present study was to analyze the correlation of non-stationary signals, for which purpose we introduced an ICF that uses actual measured signals as AWs. The interior noise of a sedan with an in-line 4-cylinder engine was analyzed using this technique. Among the components of engine noise (which is considered to be auditory-dominant during acceleration), we focused on intake noise, using the ICF to analyze the correlation of intake noise with interior noise during acceleration. Our results agreed with previously established data, and we thus conclude that the ICF may offer a method which could replace the present labor-intensive technique.

Our research introduced a method for TT analysis. It can be expected that this analysis can provide results nearer to the actual case since it can incorporate the time-varying structure of a degree ratio. Still, there is room for improvement.

Moreover, subjective evaluation confirmed that the audibility impression of acceleration is dependent on the inclination of the time change on the time-frequency plane. However, since the differences were delicate, inclination and volume were not able to acquire a strong correlation. It is thought that there is room for further such examination. In the future, we plan to analyze signals other than intake noise, and to continue developing our technique so that it can be used to clarify the component elements of engine noise during acceleration.

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