Vehicle Interior Noise Evaluation Using Brain Magnetic Field

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ABSTRACT
In recent years, the focus of production concepts regarding car engine sound has changed from finding a solution to noise, to designing specific sounds. Although many studies have been conducted to create subjectively pleasant car-engine sounds, the psychoacoustic effects of the time-varying rate of accelerating engine sounds are still unclear. The present study investigated auditory impressions of internal car noise using psychological and neurophysiological methods. To represent the half-order sound of an engine, we used harmonic complex tones that simulate acceleration noise with a sinusoidal model as stimuli. Neuronal activity in the auditory cortex evoked by these stimuli was measured using magnetoencephalography (MEG). Subjective evaluations were examined using paired-comparison tests. At the same time, we recorded responses in the MEG alpha-wave range (8-13 Hz), and analyzed them using the autocorrelation function (ACF). The results of a jury test confirmed that changes in the level of half-order sound were associated with changes in subjective annoyance, and everyday drivers preferred engine noise that included a high level of half-order sound. MEG analyses revealed a relationship between subjective annoyance and the effective duration of the ACF in MEG activity between 8 and 13 Hz.

Keywords: Vehicle Interior Noise, Brain Magnetic Field, Magnetoencephalography, Sinusoidal Model

1. INTRODUCTION

Associations exist between specific products and certain sounds for most people. The focus of production concepts of car engine sound has changed in recent years, from finding solutions to noise to designing particular sounds. That is, most research no longer focuses on reducing engine noise, but seeks to make it subjectively pleasant [1][2][3]. One problem in the control of engine sound is finding a suitable method for evaluating the differences in auditory impressions. Designing such a method is difficult, because components of engine sound change as the engine speed increases.

Increasing the volume of engine sound gives listeners particular auditory impressions, such as "sporty" and "accelerating". One report [4] indicated that when the level of half-order sound of an engine increased, listeners' preference decreased. Half-order sound occurs as a result of half-order multiple rolling moments. These moments are caused by torque fluctuation in an engine, which have a different working point and a different phase angle in each cylinder [5]. However, the psychoacoustic effects of half-order sounds have not been sufficiently studied using comparison analysis methods, and obtaining reliable results with only these methods is difficult. Therefore, a method of evaluation that is quantitative and objective is required.

Most previous studies have used well-established bioinstrumentation methods for objective sound quality evaluations [5]. A number of studies have been carried out to examine the relationships between alpha activity in the cortex and subjective preference and annoyance measurements for sound fields [6],[7]. These studies have reported that the subjective annoyance and effective duration of the autocorrelation function (ACF), \( \tau_e \), of the magnetoencephalography (MEG) alpha wave were negatively correlated. That is, the brain repeated a similar rhythm during exposure to preferred sound

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fields. However, establishing a similarly clear relationship is much more difficult with structurally complex sounds, such as half-order sounds.

In the current study, we investigated the possibility of using the relationship between subjective annoyance and alpha activity during exposure to half-order engine sound as an objective evaluation of auditory impressions. Moreover, auditory impressions were examined using subjective evaluation with the semantic differential (SD) method, and pairs were examined using paired-comparison analysis. In addition, we simultaneously measured MEG activity in the alpha-wave range (8-13Hz) and analyzed it using the ACF.

The results of the scale values of subjective annoyance and the parameters of the ACF of the MEG alpha wave were compared.

2. SOUND QUALITY EVALUATION

2.1 Stimuli

In an accelerating car, the components of the engine sound change as the engine speed increases. The time-varying nature of the components can induce auditory impressions such as “sporty” and “accelerating” in listeners. In the current study, the psychoacoustic effects of sound level and its modulation were investigated. Acceleration noise was measured using a straight-four engine and harmonic complex tones that simulated acceleration noise were used as stimuli.

In a 4-cylinder engine, the engine fires twice with each rotation, generating a secondary vibration force, and these higher harmonics constitute the main component of the noise. Figure 1 shows a spectrogram of the sound of a 4-cylinder engine, recorded at the intake. In this figure, the engine sound consists of the harmonic components and other components. One of the main causes of poor sound quality in a passenger car is the high contribution of multiple half-order components of in-line 4-cylinder vibration. Half-order multiple rolling moments caused by the torque fluctuation, and combined torsional moments act on the cylinder block around the crankshaft axis as internal forces. As such, the torsional vibration shape is excited as half-order multiples of the engine rotation [5].

A previous report [4] indicated that when the level of half-order sounds in an engine increases, listeners' preference for the sound decreases. In the current study, the relationship between subjective annoyance and alpha activity in response to half-order engine sounds were investigated as an objective evaluation of auditory impressions. Model sound sources, created as harmonic complex tones, were comprised of even-numbered order sounds and half-order sounds, as well as the main components of the straight-four engine noise. Each stimulus of the half-order sound level was changed by +20 dB, +10 dB, 0 dB, 10 dB, and then eliminated.

2.2 Sinusoidal Model

Artificial acceleration noises were created by changing the frequencies of each component over time using the sinusoidal model [9].
Figure 2 – Analysis-by-synthesis with Sinusoidal Model

Sinusoidal modeling is an analysis-by-synthesis technique that sequentially extracts the parameters for each sinusoidal component. The model implements analysis, transformation and synthesis for sound waves, as shown in Fig.2. The peaks of the spectrogram in each analysis frame were extracted using short-term Fourier transform (STFT), and partial sounds were determined by the information regarding instantaneous magnitude, frequency and phase included in the peaks.

In this study a 2.3L straight-four sedan engine was employed as an object, and the driving condition was set to full acceleration in third gear. The recording position is shown in Fig.3.

Figure 3 – Recording position

2.3 Experiment

Sound quality evaluation for each level of half-order sound was examined using Scheffe's paired comparison tests.

Ten subjects (20-40 years old; six male, four female) with normal hearing participated in this experiment. Six subjects drove more than four days a week, while the other four drove rarely. Subjective evaluations and recordings of brain magnetic fields were conducted at the same time in a magnetically-shielded room kept at a comfortable temperature. During the experiments, subjects were seated in a chair with their bodies fixed in a vacuum cast. They were asked to close their eyes and to concentrate fully on the sound stimulus.

Pairs of sounds were presented, and subjects were asked to judge their preferred accelerating car engine sound.

Paired-comparison tests were performed for all combinations of pairs of sound stimuli. The model sounds consisted of 10 pairs (N(N-1)/2, N = 5) of stimuli. The inter stimulus interval (ISI) was set at 1.0 s. Subjects were instructed to report their decision by pressing one of two switches after they heard a signal sound, which was an 80-ms 1 kHz tone presented 2.0 s after the pair of sounds. The scale values of the preference were calculated according to Case V of Thurstone’s theory. Sound stimuli were presented through plastic tubes and earpieces (ER-2, Etymotic Research Co.) inserted into the ear canals.

2.4 Results

Figure 4 shows the relationship between the half-order sound level and annoyance rating value, which was obtained by subjective evaluation. The results revealed that when the level of the half-order sound increased, the level of annoyance was increased for some listeners, but decreased for others.

The three subjects reporting increased annoyance were everyday drivers, whereas six of the seven subjects who reported decreased annoyance drove rarely.

From the perspective of acoustic metrics, the roughness of engine sounds would be expected to
increase as half-order sound level increased. However, it is likely that everyday drivers had a positive impression of engine sounds that were close to their own car engine sound, including half-order sound.

![Figure 4](image.png)

**Figure 4** – Scale values of annoyance and intensity of the half-order component for subjects.

### 3. MAGNETOENCEPHALOGRAPHY MEASUREMENT

#### 3.1 Methods

The neuronal activity evoked in the auditory cortex was measured with MEG to establish an objective evaluation index of the subjective evaluation of annoyance. MEG is well suited for studies of the auditory cortex [10].

MEG recordings were conducted at the same time as the subjective evaluation. Twenty tests were conducted for each pair of sounds. The inter stimulus interval (ISI) was set at 2.0 s. MEG was conducted using a 122-channel whole-head DC superconducting quantum interference device (DC-SQUID) magnetometer (Neuromag-122TM, Neuromag Ltd.). Neuromag-122TM magnetometers have two pick-up coils in each position, which measure two tangential derivatives. One coil measures the orthogonal tangential derivatives of the magnetic field normal to the surface of the head along the latitude, while the other measures those along the longitudinal axis, as shown in Fig. 1. MEG data were sampled at 400 Hz after being band-pass-filtered between frequencies of 0.03 and 100 Hz.

![Figure 5](image.png)

**Figure 5** – Examples of recorded MEG.

#### 3.2 Analysis

In MEG, alpha activity is typically defined as fluctuations at frequencies between 8 and 13 Hz that can be detected on the occipital area. Similar oscillatory activity, observed over the auditory cortex, is referred to as the τ rhythm. In this study, we extracted the alpha wave by filtering activity between 8 and 13 Hz, and 52 channels that were located around the temporal and the occipital area selected for the ACF analysis. Each response corresponding to one stimulus was analyzed by ACF for each subject. We investigated the relationships between the degree of preference and averaged τ_e values at 26 sites, measured at two tangential derivatives.

The autocorrelation function (ACF) is a mathematical tool for detecting periodicities in patterns,
and provides the same information as the power spectral density of a signal. Figure 6 (a) shows an example of a measured ACF. As shown in Fig. 6 (b), a straight-line regression of the ACF can only be produced using the initial declining portion. In most cases, the envelope of decay of the initial part of the ACF can be a straight line. The values of $\tau_e$ were analyzed for 2.0 s after the presentation of the sound stimuli. The values of $\tau_e$ were normalized within each subject with respect to the maximum value, $\tau_e_{\text{max}}$.

In this study, the $\alpha$ wave was analyzed, which appeared 1-3 s after stimulus presentation. The effective continuance time $\tau_e$ also calculated.

![Image](image_url)

Figure 6 – (a) Examples of normalized ACF of MEG activity between 8 and 13 Hz. (b) Examples of determining the $\tau_e$.

3.3 Results

We examined the relationship between subjective evaluations of annoyance and MEG activity, particularly the effective continuance time $\tau_e$ of the alpha wave measured over the occipital region. Fig. 7 shows the results of everyday drivers, and Fig. 8 shows the results of people who drive rarely. The error bar represents standard error of the mean ACF. For both everyday drivers and rare drivers, we observed significant differences in annoyance ratings in some subjects (for FD a, FD b, FD d, IFD h, IFD i, $p < 0.01$. For FD c, $p < 0.05$). Among subjects exhibiting a significant difference in annoyance ratings between average and strong stimuli, FD d showed a shortened $\tau_e$ in response to sounds rated as less annoying. On the other hand, for FD i, $\tau_e$ was lengthened. These results suggest that subjective annoyance related to differences in half-order sound level affects the effective continuance time, $\tau_e$, of the alpha wave detected over the occipital region.

![Image](image_url)

Figure 7 – Relationships between subjective annoyance and values for FD subjects.
4. CONCLUSION

In this study, we investigated the neural correlates of sound quality evaluation of internal car noise using MEG. The results revealed a relationship between subjective preference and MEG alpha activity in response to accelerating car noise. Specifically, we found that the effective duration ($\tau_e$) of the ACF of MEG activity between 8 and 13 Hz was lengthened in response to the presentation of preferred accelerating engine sounds. In both everyday drivers and rare drivers, we observed significant differences in annoyance ratings between subjects. These results suggest that subjective annoyance related to differences in half-order sound level can influence the effective continuance time, $\tau_e$, of the alpha wave detected over the occipital region.

Similar methods could be used in the evaluation of sound designs for a range of industrial applications.

REFERENCES