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Objective evaluation of the knocking sound of a diesel engine considering the temporal and frequency masking effect simultaneously

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ABSTRACT

In this paper, we present a novel method for an objective evaluation of knocking noise emitted by diesel engines based on the temporal and frequency masking theory. The knocking sound of a diesel engine is a vibro-acoustic sound correlated with the high-frequency resonances of the engine structure and a periodic impulsive sound with amplitude modulation. Its period is related to the engine speed and includes specific frequency bands related to the resonances of the engine structure. A knocking sound with the characteristics of a high-frequency impulsive wave can be masked by low-frequency sounds correlated with the harmonics of the firing frequency and broadband noise. The degree of modulation of the knocking sound signal was used for such objective evaluations in previous studies, without considering the masking effect. However, the frequency masking effect must be considered for the objective evaluation of the knocking sound. In addition to the frequency masking effect, the temporal masking effect occurs because the period of the knocking sound changes according to the engine speed. Therefore, an evaluation method considering the temporal and frequency masking effect is required to analyze the knocking sound objectively. In this study, an objective evaluation method considering the masking effect was developed based on the masking theory of sound and signal processing techniques. The method was applied successfully for the objective evaluation of the knocking sound of a diesel engine.

1. Introduction

Vehicles using diesel fuel must satisfy exhaust gas regulations, such as EURO 6. In order to address this issue, many car manufacturing companies have adopted efficient diesel engines. Since a diesel engine injects fuel under high pressure, it achieves good fuel efficiency but generates undesirable noises. A particularly unpleasant sound emitted from a diesel engine is a periodic impulsive sound with the character of an amplitude-frequency modulated signal [1,2]. This impulsive sound is called the "diesel knocking sound." The signal of the knocking sound includes the carrier frequencies of specific frequency bands; these frequencies are correlated with the resonance frequencies of the engine structure [3]. Therefore, the knocking sound of a diesel engine is composed of the sum of the amplitude-modulated signals in specific frequency bands [4,5]. In general, amplitude-modulated

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sounds have a trembling character and become a source of unpleasant noise in the cabin of a vehicle. A number of studies have been performed on the objective evaluation of the knocking sound. Conventional studies earlier suggested narrow-band modulation analysis as an objective evaluation method based on the calculation of the degree of modulation (DM) [4] and proposed the diesel knocking index (DKI). The DKI has been applied for an objective evaluation of the interior and exterior sounds of commercial vehicles [5]. However, this method did not consider the masking effect by the auditory system of humans [6–9]. Therefore, the weighting factor should be changed according to the subjective evaluation of the test engine and be applied only to a fixed engine speed and a fixed brake mean effective pressure. A recent study introduced the combustion knocking index (CKI), which efficiently accounts for the masking effect of the human auditory system [10]. The CKI calculates the DM for a signal processed independently by time masking [11] and frequency masking [12] and adopts the most effective approach between the two masking methods. However, the time and frequency masking effects should be considered simultaneously to reflect the masking function of the human auditory system.

In this paper, a novel method is proposed for the objective evaluation of the knocking sound by considering the temporal and frequency masking effect simultaneously. In this work, masking theory [13] was applied to synthesized sound signals based on a mathematical model, numerical simulation, and signal processing [14]. A subjective evaluation of the synthesized sounds was performed to validate the method. From the several existing subjective evaluation methods [15], the rating method was used in the present study. A sound metric correlated with the subjective rating of the knocking sound is required to develop an objective evaluation method. In this work, a sound metric based on the DM was developed. The DM was used to determine the diesel sound quality index (DSQI) based on the sound quality evaluation used in automotive field engineering [16–23].

Finally, the developed method was applied successfully to perform an objective evaluation of the knocking sound of a commercial diesel engine and was validated by a subjective evaluation. In Section 2, the sound emitted by a diesel engine is modeled and synthesized for a simulation used for the development of the objective evaluation method. In Sections 3 and 4, the masking theories for temporal and frequency masking are described. In Section 5, the process of calculating the DM is explained. In Section 6, the temporal and frequency masking effect is simulated and validated using synthetic sounds and a subjective evaluation. In this subjective evaluation, the masking effect was verified by correlation analysis between the DMs and the subjective rating of the synthetic sounds. Finally, in Section 7, the results of the application of temporal and frequency masking are reported for the quantification of the realistic sounds of a diesel engine. The DSQI was developed for an objective evaluation of the knocking sound.

2. Mathematical modelling and numerical simulation of combustion sound

The combustion sound signals emitted by a diesel engine were synthesized numerically based on signal processing and a mathematical model. The synthesized sound signals were used to validate the proposed method.

2.1. Mathematical model of combustion sound

The sound emitted from an internal combustion engine is composed of the harmonic-order components of the rotation speed of the crankshaft [16]. In general, the amplitude of the harmonic-order components with low frequency is higher than those with high frequency. These harmonic-order components are expressed mathematically as follows:

$$P_{\text{harmonic}} = \sum_{i=1}^{\infty} A_i \sin(2\pi i f_i t + \phi_i) \tag{1}$$

Here, A_i is the amplitude of the i^{th} harmonic-order component, which has rotation frequency f_i, and ϕ_i is the phase associated with the frequency f_i. The frequency, f_i, can be expressed as rpm/60. In a diesel engine, because the cylinder block and oil pan are excited by the combustion force with a high level of cylinder pressure, they emit a periodic impulsive vibro-acoustic sound with amplitude modulation that is correlated with their structural resonances at specific frequency bands [3]. This is called the "diesel knocking sound," and this impulsive component is written mathematically as

$$P_{\text{knock}} = \sum_{i=1}^{\text{band.freq}} \sum_{j=-(n-1)/2}^{(n-1)/2} B_{i,j} \sin(2\pi(f_{b,i} + 0.5 j f_i)t + \varphi_{i,j}) \tag{2}$$

where $B_{i,j}$ is the amplitude of the jth signal with the ith specific frequency, $f_{b,i}$, and $\varphi_{i,j}$ is the phase corresponding to that signal. The frequency of the jth signal is given by $f_{b,i} + 0.5jf_i$. The number of amplitude-modulated signals in this specific frequency band is n. Finally, the remaining background noise is expressed as

$$P_{\text{noise}} = C * \text{WN} \tag{3}$$

where C is the magnitude of the broadband noise (WN), expressed by